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Doctoral thesis

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Abstract

Lately, the distribution grid has been under a significant transformation, with a pervasive integration of Information and Communication Technology (ICT) for an enhanced operation and management of the grid. Some of the driving forces behind these changes are the spread of new and cheap technologies for generation and storage of electrical energy, along with the policies to reduce greenhouse emission, and the incentives for an increasing contribution of renewable energy into the global energy industry. These massive changes, especially the large scale use of distributed energy resources, have not only brought benefits, but also some new challenges. In order to deal with the new challenges, an extensive use of ICT has been introduced. In fact, the smart grid has now become a complex interdependent system of system in which the dependability of ICT has a significant impact on the overall dependability. Considering the grid's role in the society, it is very important to carefully investigate the interdependency between the power system and the newly introduced ICT support systems.

The thesis aims to develop a modeling framework that can be used to study and analyse the dependability of future distribution grid where ICT plays a major role. In doing this, a literature survey is first conducted to identify the open challenges in modelling the future distribution grid, as well as the new behaviours that may arise due to the extensive use of ICT in the future grid. A modelling framework is then developed and the impact of the identified new behaviours and challenges on the dependability of the distribution grid is assessed using the framework.

The framework is based on Stochastic Activity Networks (SAN) using the Mobius tool. The core part of the modelling framework mainly uses the SAN based simulation to model the most relevant properties, often described as discrete activities, such as failure processes, repair processes as well as the interactions and dependencies between the ICT support system and the underlying power system. The method employed for the SAN modelling is a bottom up approach. First, individual models are created for all the components. Then, these models are combined to represent a subsystem or the whole system in a second tier model where interaction and dependencies between the component models are defined. The framework is also extended with an integration of external C++ based simulator that are used to model some activities that can only be expressed in the continuous time domain.

In the process of the research work, the framework has been customised and extended for different use cases which are defined to study the impact of the identified future challenges on the dependability of the grid. The investigations on these challenges show that the growing dependency on ICT has a significant influence on the dependability of the grid. The analysis shows that investigation of the ICT's impact should not be limited to the usual conventional (omission) failure mode assumptions. Investigation on the effect of assuming different failure modes of ICT showed how a small variations on these assumptions have a significant influence on the dependability of the grid. Meanwhile, studies conducted on the effect of introducing new ICT technologies and architectures revealed that the IEC 61850 for substation automation and the use of 5G for monitoring and protection systems could improve the dependability measures significantly.

Preface

The thesis is submitted in partial fulfilment of the requirements for the degree of Philosophiae Doctor (PhD) at the Norwegian University of Science and Technology (NTNU). The work has been performed at the Department of Information Security and Communication Technology (IIK), NTNU, Trondheim with Professor Bjarne E. Helvik as main supervisor and with Professor Poul E. Heegard and Professor John Krogstie as co-supervisor. This research work has been funded by the Open and Autonomous Digital Ecosystems (OADE) under the Faculty of Information Technology, Mathematics and Electrical Engineering (IME). In addition to the research work, this position also included mandatory courses corresponding to one full-time semester study, and one year teaching assistance at IIK, NTNU.

Acknowledgement

First and foremost, praises and thanks to God, the Almighty. Several people have directly or indirectly contributed to this work. I would like to express my deep and sincere gratitude to my supervisor Bjarne E. Helvik for his invaluable guidance through each stage of the process. I am grateful to my supervisor not only for teaching me the methodology to carry out and present the research work, but also for the many advises and tips from his rich experience which helped me a lot in excelling as a person and in preparing for my future carrier. I would like also to thank my co-supervisors Poul E. Heegaard and John Krogstie for their support. Many thanks go to my colleagues and office mates: Álvaro Fernández, Charles Adrah and Michele Garau for the many enjoyable discussions and collaborations in some cases. I would like to use this opportunity to thank my family back in Ethiopia, especially my mother and sister, for their support throughout my life. My wife Mistre and my daughters Esetemariam & Maedot, I would like to thank you for your constant support, inspiration, love and patience. Life would have been boring with out you.

Contents

List of Tables

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List of Acronyms

AMI Advanced Metering Infrastructure

AN Activity Networks

CAIDI Customer Average Interruption Duration Index

CPS Cyber Physical System

CT Current Transformer

DA Distribution Automation

DAS Distribution Automation System

DER Distributed Energy Resources

DMS Distribution Management System

DNP3 Distributed Network Protocol: version 3

DR Demand Response

DSL Digital Subscriber Lines

DSO Distribution System Operators

DSPN Deterministic and Stochastic Petri Nets

EMS Energy Management System

ENS Energy Not Supplied

FAN Field Area Networks

FLISR Fault Location, Isolation and Service Restoration

FMI Functional Mockup Interface

GOOSE Generic Object Oriented System Event

GPRS General Packet Radio Service

GSM Global System for Mobile communication

GSPN Generalized Stochastic Petri Nets

HAN Home Area Networks

HIL Hardware in the loop

HLA High Level Architecture

HMI Human to Machine Interface

ICT Information Communication Technology

IED Intelligent Electronic Device

IP Internet Protocol

LAN Local Area Network

MU Merging Unit

MMS Manufacturing Message Specification

NAN Neighbourhood Area Network

NFV Network Function Virtualization

PEV Plug-in Electric Vehicle

PLC Power Line Communications

PMU Phasor Measurement Unit

PRP Parallel Redundancy Protocol

PT Potential Transformer

RBTS Roy Billinton Test System

RES Renewable Energy Source

RG Research Goal

RTS Reliability Test System

RTU Remote Terminal Unit

SAIDI System Average Interruption Duration Index

SAIFI System Average Interruption Frequency Index

SAN Stochastic Activity Networks

SAS Substation Automation Systems

SCN Substation Communication Network

SCADA Supervisory Control And Data Acquisition

SDG Smart Distribution Grid

SDN Software Defined Networking

SPN Stochastic Petri Nets

SRN Stochastic Reward Nets

SV Sampled Value

TCP Transmission Control Protocol

QoS Quality of Service

WAN Wide Area Networks

WAMC Wide Area Monitoring and Control

WAMPAC Wide Area Monitoring, Protection and Control

WAMS Wide Area Measurement Systems

WASA Wide Area Situational Awareness system

List of Included Papers

The following papers have been produced during the research work and constitute the thesis. They are included in the Part II of this document.

- **Paper A**
  Tesfaye Amare, Bjarne E. Helvik, Poul E. Heegaard, ”A Modelling Approach for Dependability Analysis of Smart Distribution Grids”, 21st Conference on Innovation in Clouds, Internet and Networks and Workshops (ICIN), Paris, France, February 2018.

- **Paper B**
  Tesfaye Amare, Bjarne E. Helvik, ”Dependability Analysis of Smart Distribution Grid Architectures Considering Various Failure Modes”, IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Sarajevo, Bosnia and Herzegovina, October 2018.

- **Paper C**
  Tesfaye Amare, Bjarne E. Helvik, ”Dependability of Smart Distribution Grid Protection Using 5G”, The 3rd International Conference on Smart Grid and Smart Cities ICSGSC 2019, Berkley, USA, June 2019.

- **Paper D**
  Tesfaye Amare, Michele Garau, Bjarne E. Helvik, ”Dependability Modelling and Analysis of 5G Based Monitoring System in Distribution Grids”, VALUETOOLS 2019 Proceedings of the 12th EAI International Conference on Performance Evaluation Methodologies and Tools, Palma, Spain, March2019.

- **Paper E**
  Tesfaye Amare, Charles M. Adrah, Bjarne E. Helvik, ”A Method for Performability Study on Wide Area Communication Architectures for

Smart Grid", The 7th International Conference on Smart Grid (ic-SmartGrid 2019), New-castle, Australia, December 2019.

- **Paper F**
  Tesfaye Amare, Michele Garau, Bjarne E. Helvik, "Effect of Communication Failures on State Estimation of 5G-Enabled Smart Grid", IEEE Access, vol.8, pp. 112642–112658, 2020.

Part I

THESIS INTRODUCTION

Chapter 1

Introduction

In modern societies, there is a growing dependence on electric power infrastructure. The electric power system has become one of the critical infrastructure as almost all service sectors (business, financial, transport etc.) are dependent on a reliable power system infrastructure for their electricity supply. The power grid plays a key role in the electric power system, i.e., to transport electricity from producers to consumers, and constitutes key infrastructure in any modern society.

The concept of smart grid implies a significantly extended use of Information and Communication Technology (ICT) in the management and control of the power grid, to improve the performance, reliability and quality of service of the electric system [CMPS10]. As the grid is among the most critical infrastructures, the quality (performance and dependability) of its service is indispensable to study and investigate.

Traditional grids are essentially hierarchical and designed for centralised power generation [GSK+12], where large scale generating stations were connected to form a network and electricity flows from these stations to consumers on the other end. However, this radial (hierarchical) system found to be inadequate, having operated the same way for decades resulting in frequent occurrence of blackouts in the last 40 years. In addition, factors such as population growth, climate change, equipment failures, demand for resilience and the reduction of fossil fuels are identified as reason for the enhancement and creation of a new infrastructure for power distribution [AMS+19].

The power grid is undergoing a massive change, where the major portion of this change is in the distribution part of the network. There has been less use of ICT in the distribution network and this part of the grid has been outside the real-time control of Distribution System Operators (DSO) [Far10]. However, nowadays more ICT-based control and support systems are being introduced to the distribution grid and much more use of ICT is anticipated in the near future. The distribution grid is going through a massive transformation to make it smart, intelligent and fully automated with the ability to reliably transfer power in both directions.

The main driver of this digitisation can be ascribed to the spreading of distributed energy resources. The addition of intelligent nodes, small size Renewable Energy Source (RES), electric vehicles, along with flexible market policies, are modifying the traditional operation of the power system (making it less predictable and more challenging to manage and control). This development requires a real time monitoring and control of the state of the system through a pervasive integration of ICT. An automated operation of the future smart distribution grid will need thousands of field devices such as sensors, actuators and Intelligent Electronic Devices (IEDs) with software on top of these devices, making it a complex cyber physical system. Architectural changes, such as the deployment of multiple micro-grids within the distribution grid, have been also increasingly introduced into the distribution grid.

All these changes bring more tight and strong dependencies between the ICT support system and the physical grid. When the grid becomes to highly rely on the ICT support, it puts strict dependability requirements on the communication technologies to be used. Recently, there has been different research studies and standards that propose communication architectures and technologies for the future distribution grid. Hence, it is important to study not only whether they meet the functional requirements or not, but also if they are able to meet the dependability, performance and security requirements.

1.1 Motivation

The research focus is on dependability study of next generation smart distribution grids. As discussed above, most of the transformation of the grid is in the distribution network. Close to 90% of all power outages and disturbances have their roots in the distribution network [GSO12, FJ19]. This situation together with the fact that the distribution grid is becoming complex with the introduction of Distributed Energy Resources (DERs) and ICT as a support, has enforced researchers in the academia and experts in the industry/utilities to investigate and enhance the reliability of the next generation distribution grid.

Lately, dependability assessment of smart distribution grids has received a great attention. There are many modelling approaches proposed and used in studying smart grids for different purposes. A handful of them are used to study the dependability of the grid. These approaches often work based on one or a combination of well established reliability assessment techniques such as mathematical analysis and simulation. Considering the undergoing transformation in distribution grids, most of these commonly used approaches are still inadequate for modelling the complexity and interdependency among the components and subsystems of the future distribution grid with an appropriate and balanced level of detail. The approaches often focus on modelling either the power system or the ICT system in detail, and a simpler abstraction of the other. This makes it difficult to properly capture the interdependence and interaction of the two subsystems and its impact on the dependability of the grid.

One of the challenge is the fact that the two constituent subsystems, ICT and power system, have their own peculiar characteristics; ICT systems are often described with discrete event simulation while the dynamic behaviour of the power subsystem is often described by mathematical models in the continuous domain. As ICT will be a significant part of the future distribution grid, modelling ICT and power grid together to study the interaction and interdependence is going to require new methodological approaches.

Another issue is the uncertainty on how the introduction of ICT affects or influences the dependability of the grid. The power grid and its operation is becoming increasingly complex. The main reason behind introducing "smartness" by ICT is to handle this complexity and get an enhanced operation, management, and reliability of the grid. However, this may also introduce another challenge which needs a careful investigation; The ICT system also fails, and in the worst case, the failure may also propagate and affect the operation of the power grid. In classic distribution grid studies, it is only hardware failures of ICT components that were often considered, but it is also important to note that ICT systems may also have various failure modes due to software faults, mis-configuration, operational mistakes etc.

The use of ICT in distribution grid is attracting the attention of many researchers. As the ICT industry is quite dynamic, there are a lot of recent technological options such as 5G that can be used in the transformation of the distribution grid. Hence, it is also interesting to study and investigate how the application of new and emerging ICT technologies and infrastructures are going to affect the dependability of the distribution grid. Overall, a modelling approach suited for analysing the application of new communication technologies and architecture, along with the new challenges for the next generation distribution grid is vital.

At this initial stage, we can ask the following general questions in relation to the main objective of the thesis, the dependability of the next generation distribution grid :- i) How can the dependability aspects of next generation distribution grid be modelled and analysed ? ii) What modelling approaches (has been) can be used in studying the next generation distribution grids ? iii) What are the impacts of ICT failures on the dependability of a highly digitised distribution grid? and, how can it be made more dependable ? iv) What kind of new architectures and ICT technologies can be used to meet the dependability requirements of the future distribution grid ?

The state of art presented in Section 3 will review the literature in regard to these main questions. The open challenges and research questions that the thesis has focused are introduced afterwards.

1.2 Thesis structure

The thesis is a collection of academic/scientific papers which is in accordance with the NTNU's regulation for PhD Studies. It consists of two main parts; **Part I** which is an introduction to the thesis work showing the interrelationship of the papers, and **Part II** which presents the papers included in the thesis.

In **Part I**, a comprehensive summary of the thesis is organised as follows: Section 2 gives a brief background on basic characteristics of smart distribution grid and dependability concepts. In Section 3, the state of art in modelling the distribution grid is presented together with open challenges identified during the literature survey. Then, the research goals to address the open challenges and the methodology employed are discussed in Section 4. Section 5 presents the contributions of the thesis work. Finally, the thesis conclusions and potential future work recommendations are summarised in Section 6.

In **Part II**, six peer reviewed papers (published) that make up the thesis are presented.

Chapter 2

Background

In this chapter, a review of the background in the main research areas of the thesis report is presented. It aims to give the reader the relevant facts and concepts in the area of dependability, smart grid and its communication infrastructure, and the Stochastic Activity Networks (SAN) modelling approach employed in the thesis work. The main features and characteristics of the smart distribution grid are discussed in Subsection 2.1, while an overview on dependability and reliability concepts from an ICT and power system perspectives is given in Subsection 2.2. In subsection 2.3, a brief introduction to the concept of Stochastic Activity Networks (SAN), an approach used at the core of the framework developed during the thesis work, is presented.

2.1 Smart Grid

Smart grid is a term referring to the next generation power grid in which the electricity distribution and management is upgraded by incorporating advanced two-way communications and pervasive computing capabilities for improved control, efficiency, reliability and safety [YQST13]. It can be defined by the concept of Cyber Physical Systems (CPS), where a physical system, in this case the power system, is merged with a cyber system that provides the physical system with computational and communication capabilities.

The traditional power grids are generally used to carry power from a few central generators to a large number of distributed users or customers. In contrast, the smart grid uses two-way flows of electricity and information to create an automated and distributed advanced energy delivery network [FMXY12]. It incorporates the legacy electricity grid and the benefits of modern communications to deliver real-time information and enable the near-instantaneous balance of supply and demand management [YQST13].

The existing electricity grid is a strictly hierarchical system in which power plants at the top of the chain ensure power delivery to customers' loads at the bottom of the chain [Far10]. The grid can be divided into three main parts; Generation, transmission and distribution network.

In a traditional power grid, the generation sub-system relies on a small number of large power plants using conventional (hydropower, coal, oil, natural gas, and nuclear) resources to produce electricity. Then, high-voltage transmission lines, which form the transmission network, are used to transfer electricity across long distances from power plants to electric substations. A substation includes transformers to change voltage levels from high transmission voltages to lower distribution voltages. Furthermore, substations perform several other important functions, such as grid protection and power control. Substations, medium- and low-voltage power lines, and electric meters form the distribution network [ABC13].

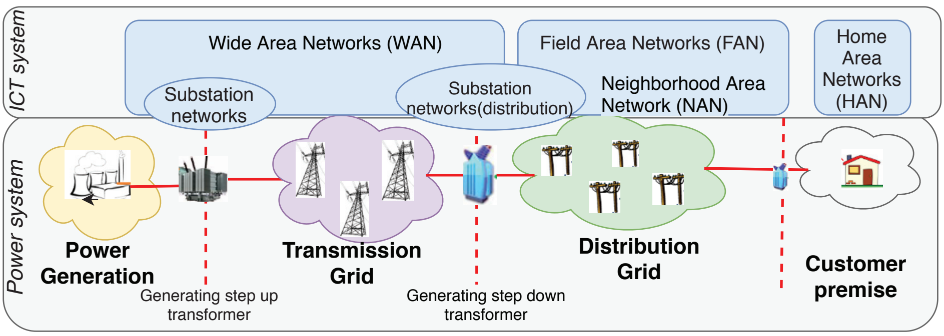

Figure 2.1: An example of smart grid architecture.

The utility companies have introduced various levels of command and control functions, such as the widely deployed system known as Supervisory Control And Data Acquisition (SCADA). Although such systems give utility companies limited control over their transmission network, the distribution network remained outside their real-time control [Far10].

However, the fact that nearly 90% of all power outages and disturbances have their roots in the distribution network [GSO12, FJ19], inability to meet the rising electricity demand with power generation at the top of the chain accelerated the need to modernize the distribution network by introducing technologies that can help with demand-side management [Far10] as well as introducing more distributed generation near to the customers. These has enforced the ”smartness” to be applied and used more and more into the distribution network.

2.1.1 Smart Distribution Grid

Nowadays, the distribution grid is going through a massive change and upgrade to make it more robust and efficient. The main driver of this digitization is the spreading of distributed energy resources. Small size RES generation plants, storage, electric vehicles, along with flexible market policies, are modifying the traditional operation of the power distribution network, requiring a real time monitoring and control of the state of the system through a pervasive integration of the ICT. Below, some of the basic characteristics of the foreseen future smart distribution grid are briefly presented.

- Distributed Generation(DG): The use of distributed generation, such as solar panels, wind turbines etc. DGs are used as a support to conventional power system as the existing electrical capacity fail to provide the growing electricity demand. However, the use of DGs not only brings many benefits but also creates a number of operational issues like power quality, reliability, protection etc.[KC18]

- Bidirectional electricity flows: In traditional power grid, the power flow follows a hierarchical pattern and is functionally unidirectional. i.e., power plants/supply side to the distribution domain (consumer side). The growing use of DERs in the distribution network made it necessary for the power grid to facilitate bidirectional power flows. [NAGD16]

- Advanced data acquisition: Unlike the existing grid, many sensors will be used to improve the monitoring and control of the distribution grid.

- Smart devices: Basic automation devices are brought to a higher level of intelligence to enable distributed data acquisition and decentralised decision-making. A new generation of IEDs is increasingly being deployed throughout the power system. These smart devices can be either efficiently controlled remotely or autonomously operate at the node level as changes and disturbances on the grid occur [DP14]. Additionally, these IEDs not only communicate with centralised control systems, but also among each other, enabling distributed intelligence and control.

- Self-Healing: Coordination between IEDs with distributed intelligence can be applied to automatically detect, respond and neutralize faults in the grid which helps to minimise the impact on end users/customers.

- Demand Response (DR): DR refers to changes in electric usage by end-use customers from their normal consumption patterns in response to price of electricity or high demand [Sia14]. It is used to control/minimize the energy use during peak demand and high pricing periods.

- Smart metering and active customers: there will be informed active customers that may participate in some applications such as demand response i.e. customers may negotiate on the price and demand.

- Prosumers: end users, such as electric vehicles, smart houses, which not only consume power but also produce and share or sell surplus energy back to the grid and other users [ZMR+18].

- Structural changes/architectural changes: Unlike the conventional hierarchical topolgies, the future grid is going to be more interconnected and networked (a transition to mesh type topology).

- Smart micro-grid: is a single, autonomous, self-sustainable power system formed by an interconnection of distributed energy resources, which serves various electricity customers (e.g., residential buildings, commercial premises and small industries) located near one another.

- More efficient operation and maintenance: better overview of the system helps to make targeted improvements, resulting in lower running and maintenance cost. These includes applications such as fault localisation, proactive maintenance etc. which results in dependability improvements.

As the power distribution network is among the most critical infrastructures, the future smart distribution grid ecosystem, with all the above features, puts strict dependability and performance requirements on the ICT support system to be used.

Smart grid applications

There are several smart grid applications with varying degrees of Quality of Service (QoS) and communication requirements. Below are two applications which are considered in the thesis work.

Substation Automation: Substations are key elements of the power grid network and all their devices are monitored, controlled, and protected by Substation Automation Systems (SASs). SAS collects the data and performs actions on it allowing robust routing of power from generators to loads through the complex network of power lines [GSK+13]. Substation Automation uses Machine to Machine (M2M) communication to facilitate advance monitoring, protection and control functions of the substations (e.g. protection signals to relays) and feeder equipment (e.g. automatic re-closers and switches for fault isolation) [NAGD16]. The most commonly used standards for this part of the power grid are the IEC 61850 and Distributed Network Protocol: version 3 (DNP3) or IEEE 1815 standards. The thesis work considers the use of IEC 61850, as it is the most recent, comprehensive and futuristic standard for substation automation.

Wide-Area Situational Awareness (WASA) Systems: WASA can be defined as the integration of a set of technologies for effective power system monitoring and providing an overall dynamic picture of the functioning of the grid [GSK+13]. Abnormalities such as a disturbance in power supply can result in a widespread problem that threatens the overall system reliability and security. WASA, with the deployment of technologies to enhance the monitoring and control of the power system across large geographic areas, are used to mitigate the impact of disturbances and cascading blackouts in a timely manner [ER16]. Synchrophasors or Phasor Measurement Units (PMUs) are often used for the wide-area measurement technologies.

2.1.2 Smart Distribution Grid Communication Infrastructure

The cornerstone of a smart grid is the ability for multiple entities (e.g. intelligent devices, dedicated software, processes, control centre, etc.) to interact via a communication infrastructure [YQST13]. The major requirements, architectures, and technologies of the smart grid communication infrastructures, mainly for the smart grid applications presented in Section 2.1.1, are discussed in the rest of this section.

2.1.2.1 Communication requirements

The communication system should meet the system requirements such as QoS, scalability, flexibility, security and privacy. The thesis mainly focused on the investigation of the following QoS requirements: Dependability (Availability and Reliability) and Performance (Latency).

Dependability: Dependability is described by different attributes and measures. Though the concepts are the same, different terminologies have been used by the ICT and Power system experts. For instance, one of the commonly used attribute is availability which is the ability of the system to deliver service at a given instant of time. For the same concept, power system experts use the term reliability. In this thesis, the ICT definition of dependability attributes are used. A brief discussion on the dependability concepts are presented in Section 2.2.

Performance (Latency): Latency defines the maximum time in which a particular message should reach its destination through a communication network [WXK11]. Smart grid applications have different network latency requirements. Control and protection functions in power systems have very stringt delay constraints and require prompt transmission of information [ABC13]. In WASA, the requirements range from few milliseconds to seconds. If PMUs are used for monitoring, it has a strict requirement ranging from 20 to 200 ms. For monitoring with SCADA sensors, latency requirements is less stringent [ER16]. Whereas, the protection information and message exchange between IEDs in a distribution grid requires a much lower network latency than other applications such as WASA, as low as 4ms -100 ms depending on the type of protection scheme [NAGD16].

2.1.2.2 Communication architecture

The communication infrastructure in smart grid must support the expected smart grid functionalities and meet the QoS requirements. As the infrastructure connects an enormous number of devices and manages the complicated device communications, it is constructed in a hierarchical architecture with interconnected sub-networks where each sub-network takes responsibility of separate geographical regions [WXK11]. In general, the communication networks are often categorised into three classes: wide area networks, field area networks, and home area networks, as shown in Figure 2.1.

- *Wide Area Networks (WAN)*: Wide area networks form the communication backbone to connect the highly distributed smaller area networks that serve the power systems at different locations. When the control centres are located far from the substations or the end consumers, the real-time measurements taken at the electric devices are transported to the control centres through the wide area networks and, in the reverse direction, the wide area networks undertake the instruction communications from control centres to the electric devices.

The thesis assumes the use of wide area networks for WASA systems. Specialised electrical sensors (PMUs or IEDs) at substations are used to get fast, time-stamped and real-time information about the system [TKC09]. The information received from such sensors (PMUs) is used by the Distribution Management System (DMS) or Energy Management System (EMS) at a control centre for improved state estimation, monitoring and control of the grid.

- *Field Area Networks (FAN)/Neighbourhood Area Networks (NAN)*: FANs are often deployed within the distribution system for monitoring and controlling power delivery to the various consumers [BDT+16]. FANs are used for exchange of information between the distribution substation and feeder level equipment such as remote terminal units (RTUs) and IEDs [NAGD16]. NANs are networks that are used to collects all the energy usage data from customer side networks (HANs) to the Utility backbone via its gateway [ER16].

  The thesis has looked into the use of FANs for protection in the distribution grid. Specifically, the investigations focused on the IEC 61850 standard which is widely used for substation and distribution automation within the FAN.

- *Home Area Networks (HAN)*: Home area networks are needed in the customer domain to implement monitoring and control of smart devices in customer premises.

2.1.2.3 Communication technologies

Communication technologies can be classified into two main categories: wired technologies and wireless technologies. In wired technologies, the most commonly used are Power Line Communications (PLC), Digital Subscriber Lines (DSL) and optical communications which are often used to build the communication backbone interconnecting substations with control centres. Meanwhile, the wireless technologies can be classified based on their transmission ranges. Technologies such as Zigbee, IEEE 802.11-based

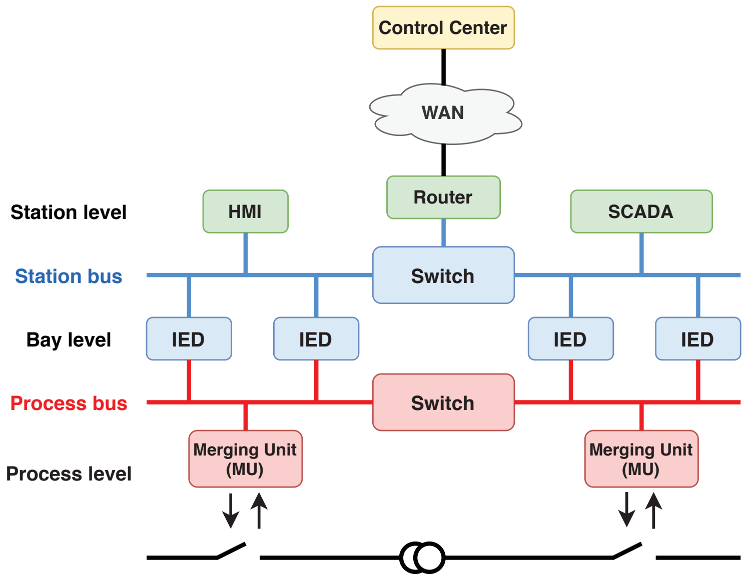

Figure 2.2: Architecture of an IEC 61850 based substation automation system.

networks (WiFi) has low coverage areas while others such as IEEE 802.16-based networks (WiMAX) and Cellular networks provide larger coverage areas [Kab16, ABC13].

The thesis work has looked into cases where mostly wired networks (such as Ethernet based LAN networks, optical fibers) and cellular networks are considered. A special focus is given to the usage of newer technologies such as the application of a 5G architecture in the FAN and WAN as they are potential candidates to meet the QoS requirements of the real time control in future distribution grid.

2.1.3 New Standards and Technologies for Power System Automation

IEC 61850

IEC 61850 is a standard recommended by IEC for the design of substation automation systems [IEC]. It is a recent and most commonly used standard for communication networks and systems in substations. In the IEC 61850 standard, the traditional way of wiring between relays for protection schemes is replaced by standardised Ethernet based communication services for the exchange of critical information between IEDs. Figure 2.2 shows a typical IEC 61850 based substation communication network architecture.

The IEC 61850 standard is based on interoperable IEDs that interacts with each other, either within a substation or on feeders. Recent extensions of the standard also covers the communication between substations and substations to control centre.

The IEC 61850 standard defines several IEDs types and functionalities. The most common types include the breaker (switch) IED, Merging Unit (MU) IED, and Protection and Control (P&C) IEDs. The P&C IED is responsible for supervising the protection and control operations of its serving bay unit. The breaker (switch) IED continuously monitors the state of the corresponding circuit breakers (switch-gears), send status information to the P&C IEDs and receives trip/close command from the P&C IEDs. The MU IED collects the analog voltage and current signals from field Current Transformer (CT) and Potential Transformer (PT), converts them into digital format and then transmits to the P&C IEDs in the form of Sampled Values (SVs) [KK13].

IEC 61850 divides substation communication into three hierarchical levels – station, bay and process level. The process level includes I/O devices, equipment such as CT/PT, intelligent sensors and actuators. Bay level includes the P&C IEDs and the station level contains the Human to Machine Interface (HMI) devices, station controllers and interface with outside substation [MSW09]. While the process bus handles the delay sensitive communication between P&C IEDs and switch-yard devices such as breaker IEDs, the station bus handles communication among different bay and with the station controller as well as communication with the external networks [KK13].

The standard supports two communication principles. The first is a client/server communication which is based on Manufacturing Message Specification (MMS) over TCP/IP and Ethernet. It is typically used for remote communication towards central control unit. The other is a publisher/subscriber communication which is intended for time critical information exchange between IEDs. The publisher/subscriber communication consists of two services that have a major impact on protection: GOOSE(Generic Object Oriented System Event) and the transmission of SVs [Apo11].

The GOOSE messages are used to exchange event and high priority status information such as trip commands or interlocking information in real- time. They use multicast services that allow simultaneous delivery of the same message to multiple IEDs. The IEC 61850 standard also specifies a retransmission scheme to achieve a highly dependable level of GOOSE message delivery. The SV services are used to transfer sampled analog signals and status information from the MU IEDs via the process bus [KK13]. The GOOSE and SV messages are time critical and strictly delay sensitive since they act as the triggering points for the underlying protection and control systems.

The thesis looks into the dependability assessment of IEC 61850 based systems as it is the futuristic architecture for substation communication. The dependability of different state of art IEC 61850 based substation network architectures and the use of GOOSE and SVs for a protection application is studied using the framework developed during the research work.

5G for smart grid

This section reviews basic concepts of 5G technology such as the radio interface enhancements and Mobile Edge Computing (MEC) which are the main enablers for future 5G smart grid applications. Wireless communication technologies have already been integrated to power systems for applications such as monitoring and remotely accessing some control parameters of substations [GLR+14]. The high reliability and tight latency requirements of critical applications such as real time state estimation and protection cannot be satisfied by the current operational technologies (4G-LTE networks) [IBQ+19]. The latest mobile/cellular technology is the 5th Generation (5G) which represents not only an enhancement of 4G-LTE, but entails a complete redesign of the architecture which becomes operational starting from 2020. 5G aims to provide a set of new features such as massive connections, ubiquitous connectivity, ultra-low latency, ultra-high reliability, and very high throughput [IBQ+19]. In order to achieve this, 5G employs the following set of novel concepts [IBQ+19, BFG+17, MHK19]:

- Software Defined Networking (SDN): it separates the control plane and data plane of the current network, promoting flexibility and customisation of the network. The decoupling makes the switches become simple forwarding devices while the routing control actions are taken by a centralised controller, making the network control to become directly programmable.
- Network Function Virtualisation (NFV): The concept of NFV is to decouple the network function and services from hardware devices. As a result, network functions, such as firewalls, load balancers, etc., can be implemented in software. This enhances flexibility and any required upgrade and resource up-scaling can be done in software. In addition, it allows to reduce operating and capital expenditures as the

network functions can be uploaded to cloud platforms.

- Mobile Edge Computing (MEC): it locates cloud-based architectures at the edge of the mobile network, within the Radio Access Network (RAN) and in close proximity of the mobile subscribers, allowing low latency, location awareness, more efficient network and service operations, reduced network congestion and minimised data transmission costs.

- Multi Radio Access Technologies (Multi-RAT): virtualised cloud-based baseband processing of base stations are able to process different Radio Access Technologies in the same 5G infrastructures. It permits harmonising legacy wireless technologies in the same 5G infrastructure and extending the coverage where the new radio access technologies are not available.

- Network Slicing: Network slicing enables network operators to slice/split one physical network into multiple virtual network, where every virtual network is optimised for specific service. The key concept is isolation where multi-tenants co-exist on the same physical network in logical isolation. Cloud computing, NFV and SDN are key enablers for network slicing.

The thesis looks into the use of 5G for smart grid applications such as real-time monitoring and protection applications. Specifically, the dependability of using 5G MEC infrastructure with a high reliability 5G radio technology such as Ultra-Reliable Low-Latency Communication (URLLC) for the selected smart grid applications are investigated.

2.2 Dependability Concepts

In this section, the definition and concepts of dependability from both the ICT and Power system perspectives are presented. The threats and attributes related to dependability are discussed briefly. This section is primarily based on the works from [ALRL04], [Hel09] for the ICT perspectives and [BL94] for the power system perspective.

2.2.1 Threats To Dependability

Dependability is defined as the ability to deliver service that can justifiably be trusted. It is the ability of a system to avoid service failures that are more frequent or more severe than is acceptable [ALRL04]. Based on [ALRL04], the threats to dependability can be characterised into three main categories;

faults, errors and failures. Figure 2.3 shows a summary of the classification in relation to threats to dependability.

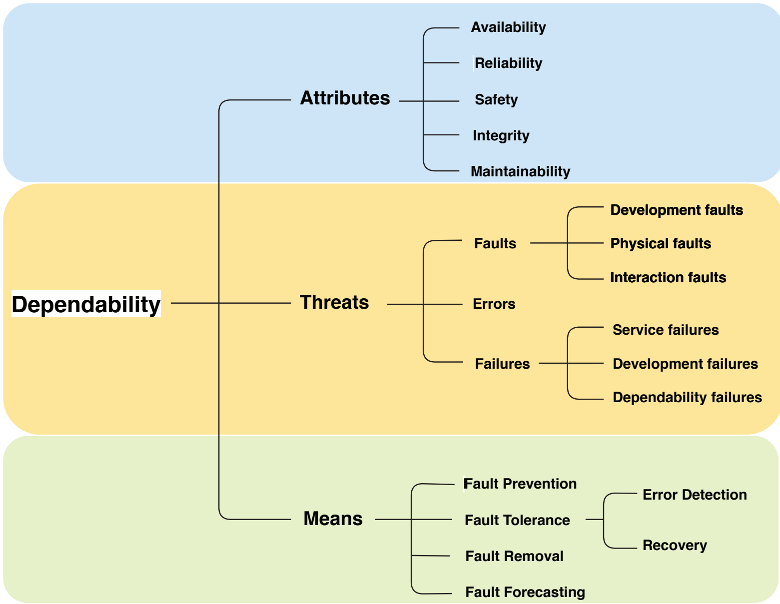

Figure 2.3: The dependability tree from [ALRL04] showing the different aspects of dependability.

Faults

Faults are the adjudged or hypothesized cause of an error [ALRL04]. A fault may be a physical defect, weakness or shortcoming of a hardware component like a short circuit. It may be a disturbance from the environment like electromagnetic noise. It may also be a design or implementation flaw or imperfection in the system's hardware, software and in the interaction or co-design of these [Hel09]. According to [Hel09], Faults can be classified into the following six major groups: Physical, Transient, Intermittent, Design, Interaction or operational and Environment faults. In this work, we mainly consider the classic hardware related faults, physical and environmental faults. Though there has not been much work on software failures in the grid, faults such as transient/intermittent, design and operational faults that may cause a software failures are also considered in some cases.

Errors

Errors are defined as part of a system state that may lead to failure. It is a deviation from accuracy or correctness within a system. The cause of the

Figure 2.4: Chain of fault, error and failure.

error has been called a fault [ALRL04].

Failures

Failure is defined as the transition from correct service delivery to incorrect service delivery. Deviation of the delivered service from the compliance with the specification [ALRL04]. A system fails when it does not do what it is expected to do. According to this definition, it is also a failure when it delivers what it is expected to deliver, but delivers it untimely [Hel09].

The Pathology of failure

Faults may cause an error while errors may result in failures. Faults may have their cause inside or outside the system borders. Errors, however, are confined within the system and may be interpreted as "something wrong in the internal state of the system". When the error becomes visible outside the system borders, we have a failure, i.e., the system does not behave (deliver its service) as specified [Hel09]. When a failure "passes through" the borders of a system, which may be regarded as a component, layer or interacting system, it will cause a fault in the receiving system. A chain of events as illustrated in Figure 2.4 which leads to a failure in the service provided to the end-user [Hel09]. For example, in the context of smart grids, a failure in ICT support system may introduce a fault affecting the underlying power system operation(such as wrong value as an input to the power system control algorithms) which in turn may lead to a deviation in the normal operation or service provided to customers i.e. failure in power system.

Failure modes and semantics

A system may fail in a number of different ways. These are referred to as the failure modes of the system. Complex Systems like the smart grid can fail in an infinite number of ways. Hence, it is necessary to group these into classes. Below is classification based on [Hel09].

1. **Value failure**: A value failure occurs when the value of the delivered service does not comply with the specifications. A value failure may either be consistent, i.e., all system users have the same perception of the failure, or inconsistent(sometimes referred as Byzantine), i.e., the

system users may have different perceptions of a given failure.

2. **Timing failure**: Occurs when the system does not meet its specified timing requirements, but the result is otherwise correct with respect to value - except in the case with the omission faults. Timing failures may be early or late. A late failure may again be either an omission failure, i.e., results that are infinitely delayed, or delayed results.

3. **Omission failure**: It can be regarded as a special case of both value and timing failures. They occur when no service is delivered. If an omission failure is persistent, such that the system stops working until a recovery action is taken, we denote it as a crash failure.

The thesis work consider and study all the above three major failure modes mainly in the ICT support system of the grid, and analyse how would they possibly affect the dependability of the distribution grid.

2.2.2 Dependability Attributes

Dependability is an integrating concept that encompasses the following attributes: availability, reliability, safety, integrity and maintainability [ALRL04] [Hel09]. In this work, the first three attributes are considered.

- Availability - ability to provide a set of services at a given instant of time or at any instant within a given time interval.
- Reliability - ability to provide uninterrupted service.
- Safety - ability to provide service without the occurrence of catastrophic failures

The above definitions of the dependability attributes are the one often used in the ICT domain. Meanwhile, the power system experts use similar terms but sometimes with a different meaning. According to [BL94], Power system reliability is the overall ability of the system to perform its function. It can be divided into two basic aspects; system adequacy and system security. Adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer load demand while Security relates to the ability of the system to respond to dynamic or transient disturbances arising within the system. Most presently available reliability evaluation techniques are in the domain of adequacy assessment. This adequacy assessment interpretation is more similar to the availability definition by [ALRL04], the ICT perspective.

There are many possible indices which can be used to measure the adequacy of a power system. Figure 2.5 shows the power system reliability classification and some of the distribution system indices (to measure the adequacy) listed on [BL94].

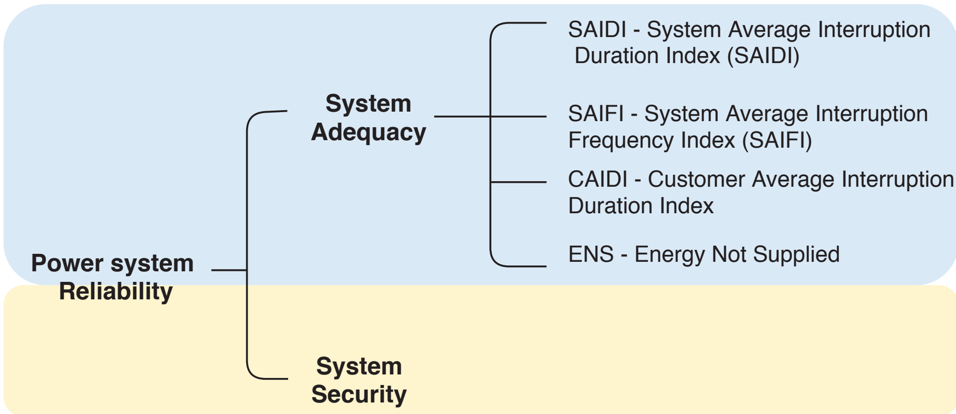

Figure 2.5: Power system reliability definition and classification based on [BL94].

As the presentation above showed, the definitions of the dependability attributes used by the ICT and power experts are different, and sometimes the same term may have different meaning in the other domain. As an example, reliability is the ability to continually provide service (without interruption) for ICT experts. Meanwhile, for power experts, it has almost the same meaning as what ICT experts denote as availability which is the ability to provide the service at a given instant of time. This thesis work adheres to using the attributes and measures presented from the ICT perspective. In addition to the listed attributes, some metrics were also defined and used when assessment of the grid from a different perspective is needed.

2.2.3 Means To Attain Dependability

According to [ALRL04], the means to achieve dependability can be grouped into four major categories:

- *Fault prevention*: means to prevent the occurrence or introduction of faults.
- *Fault tolerance*: means to avoid service failures in the presence of faults.

- *Fault removal*: means to reduce the number and severity of faults.
- *Fault forecasting*: means to estimate the present number, the future incidence, and the likely consequences of faults

The thesis work mainly considers fault tolerance techniques such as using extra resources (redundancy). Fault removal (corrective maintenance of faults that has produced an error) is also considered.

2.3 Stochastic Activity Networks

A brief presentation on the different approaches of modelling smart grid is discussed in the subsequent chapters, Section 3 and Section 4.3. In this thesis work, Stochastic Activity Networks(SANs) are used at the core of modelling and analysing the smart distribution grid. This section presents a short introduction on the basic definition and concepts of stochastic activity networks based on [SM00]. A brief description, based on [GKL+09a], on how SANs can be applied using the Mobius tool is also presented.

There are different techniques, model-based methods, that are used in studying and analysing the non-functional properties of a system, such as its performance, dependability, or performability. One approach in this regard has been the development of stochastic extensions to Petri nets. There are variants of stochastic Petri nets proposed and used for performance and dependability analysis of systems such as Stochastic Petri Nets (SPN) [Mol82], Deterministic and Stochastic Petri Nets (DSPN)[MC86], Generalized Stochastic Petri Nets (GSPN)[AMCB84], Stochastic Activity Networks (SAN)[SM00], and Stochastic Reward Nets (SRN)[CBC+93]. One stochastic extension of these nets, known as "stochastic activity networks," was defined with the purpose of facilitating unified performance / dependability (performability) evaluation as well as more traditional performance and dependability evaluation [SM00]. Since their introduction, SANs have served as the basis for modeling tools such as UltraSAN [SOIQW95] and Mobius [CCD+01], and have been used to evaluate a wide variety of systems.

SANs are a variant of stochastic Petri nets. SANs are built on top of a non-probabilistic model called Activity Networks (ANs). They are simply a probabilistic extensions of activity networks. And, as defined in [Mov86, SM00], ANs are described with the following primitives which also characterize SANs:

- *Activities*: are of two kinds; timed activities and instantaneous activities. Each activity has an action that may be taken upon the completion of an event.

- *Places*: similar to places in Petri nets which may contain a discrete number of marks called tokens. The state of the net is defined by the number of tokens contained in each place. Such distribution of tokens over the places is usually called marking of the net.

  In the thesis work, a special type of places are also used. Extended places are special elements in the SAN formalism that allows models to handle the representation of structures and arrays of primitive places. Each position (place) in this array can carry a certain number of tokens.

- *Input gates*: each of which has a finite set of inputs and one output. Associated with each input gate are an n-ary computable predicate and an n-ary computable partial function over the set of natural numbers which are called the enabling predicate and the input function, respectively. The input function is defined for all values for which the enabling predicate is true.

- *Output gates*: each of which has a finite set of outputs and one input. Associated with each output gate is an n-ary computable function on the set of natural numbers, called the output function.

Timed activities represent the activities of the modelled system whose duration impact the system's ability to perform. Instantaneous activities, on the other hand, represent system activities that are completed in a negligible amount of time [SM00]. Input and Output gates are introduced to permit flexibility in defining enabling and completion rules of the activities. Each input or output gate is connected to a single activity. In addition, each input of an input gate or output of an output gate is connected to at least one place.

To aid in the modelling process, a graphical representation for (stochastic) activity networks is typically employed. An example of SAN (using the Mobius tool) is shown in Figure 2.6. In the figure, places and extended places are represented by circles (*A, B* and *C*). Conventional places are represented by blue colour while extended places are represented by the orange colour. Timed activities (*Transition_1* and *Transition_2*) are represented by the transition with solid bar between the places. Instantaneous activities (*Instant_transition*) are represented by similar transitions but with a thinner bar. An activity may have different probabilistic choices (cases). Cases associated with an activity are represented by small circles on one side of the activity (as on *Transition_1*). An activity with only one case is represented with no circles on the output side (as on *Transition_2*). Gates are represented by triangles: the red triangle boxes are input gates while the black triangles are output gates. Input and output gates may have more than one inputs or outputs as shown by *IG3* and *OG4*.

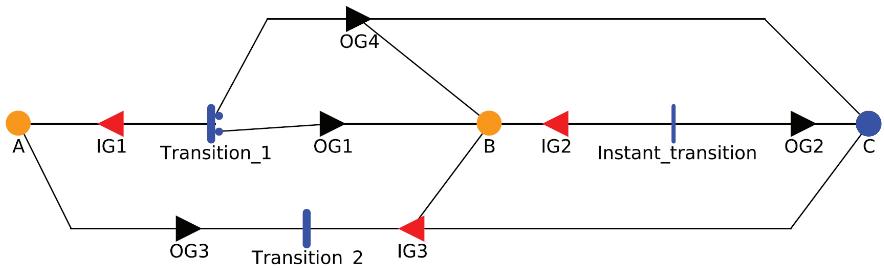

Figure 2.6: An example of graphical representation of SANs in Mobius.

SAN is often used for dependability and performance evaluation. As shown in Eq.2.1, Sanders et al. [SM00] defines stochastic activity network as a five-tuple formed by an activity network (AN), initial marking in which AN is stabilising (μ_0) and adjoining functions C, F,and G, where C specifies the probability distribution of case selections, F represents the probability distribution functions of activity delay times, and G describes the sets of "reactivation markings" for each possible marking.

$$SAN = (AN, \mu_0, C, F, G) \tag{2.1}$$

In the example shown in Figure 2.6, the μ_0 is the initial marking (distribution of tokens) inside place *A, B* and *C*. An activity is enabled/triggered if its input gate hold. i.e., conditions in the input gates are met. Assuming place *A* initially has a token, the activity *Transition_1* will be enabled only if the logical expressions/conditions in input gate *IG1* are fulfilled. Since timed activities represent operations in a modelled system, events must be defined to denote the start and finish of these operations. The start of an operation is signalled by an activation of an activity(as did the conditions in *IG1* enabling the *Transition_1*). Some time after an activity is activated it will either complete or be aborted. The *Transition_1* activity will complete if it remains enabled (input condition of *IG1* holds) throughout its activity time; otherwise it is aborted.

The activity time distribution function (F) specifies (probabilistically) the duration of an activity,i.e., the time between its activation and completion. In the example figure, the *Transition_1* is described by an activity time distribution function (F), and it will hold for a time duration drawn from this function. Any continuous distribution (e.g.,exponential or normal) can be used as an activity time distribution, where the choice of distribution depend on the applicability of the solution methods. Both the distribution type and its parameters can depend on the global marking of the network at the activation time of the activity. Activity times are assumed to be mutually independent random variables.

Two other functions are associated with an activity network to form a SAN. The case distribution (C) specifies (probabilistically) which case is to be chosen upon the completion of an activity. In Figure 2.6, it can be seen that there are two possible actions once the activity *Transition_1* is completed. These probabilities can depend on the markings of the input and output places (A and B) of the activity (*Transition_1*) at its completion time. A reactivation function (G) is also associated with each timed activity. This function specifies, for each marking, a set of reactivation markings. Taking the same example where an activity *Transition_1* is activated, the reactivation function G defines the conditions (described by a set of markings) to restart the activity. Probabilistically, the reactivation of an activity is exactly the same as an activation; a new activity time distribution is selected based on the current marking. This provides a mechanism for restarting activities that have been activated, either with the same or a different distribution.

Mobius tool

Mobius is a tool to describe and analyse stochastic models of discrete-event dynamic systems. Mobius is widely used in academia and industry for the performance and dependability assessment of technical systems [GKL+09a]. One of the formalism and the main/primary language used for expressing a model within the Mobius framework is the Stochastic Activity Networks. It was developed as a natural extension of UltraSAN for its Stochastic Activity Networks formalism [Mov86]. It provides a variety of numerical and analytical techniques for the analysis of specific Markovian models as well as discrete event simulation as a technique that applies to a very general class of models [GKL+09a].

A detailed description of the Mobius modelling tool can be found in [CCD+01]. The details of the Mobius framework and its implementation is given in

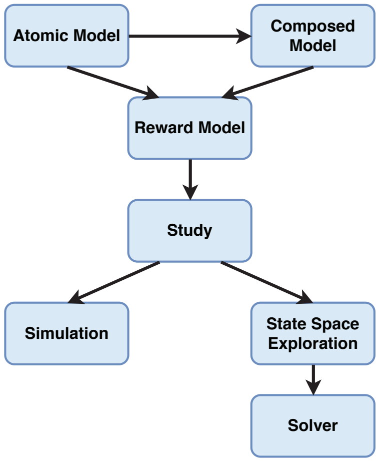

Figure 2.7: Mobius workflow.

[DCC+02]. Generally speaking, Mobius separates different aspects of a model into a set of components that depend on each other. Fig. 2.7 shows the dependency graph of components that need to be developed while working with Mobius.

- *Atomic model*: are the building blocks of the model. This is where the mobius model formalism such as SANs are used to model the real systems. Several atomic models are often created that represent sub-systems of the total system.

- *Composed model*: are used to model systems of great complexity. The composed model formalism provides the flexibility and simplicity for the modeller to mix and match the atomic and other composed models together to build larger and more sophisticated models. A Rep - Join composition formalism enables the modeller to either replicate or join atomic models or other composed models.

- *Reward*: is used to define measures of interest (dependability and performance variables) that the user wants to obtain from the system model. As the model is simulated or numerically solved, the reward model defines what data from the system needs to be collected.

- *Studies*: A study allows a user to specify a series of experiments to be performed on a parameterised model in an automated manner.

- *State Space Generators and Solvers*: are used for a numerical analysis of a Markovian model (transient or steady state) which is in turn used to evaluate rewards of interest.

- *Simulations*: used to perform a stochastic discrete event simulation to obtain results.

For an in-depth introduction to Mobius and the use of SAN with Mobius, see [CCD$^+$01, DCC$^+$02].

Chapter 3

State of the Art

This section discusses the state of art in dependability modelling of the smart distribution grid. Section 3.1 presents a brief review of the literature with a closer insight on how the ICT part of the grid has been modelled. The open challenges, that this thesis work focuses on, are also presented in Section 3.2.

3.1 Review of Literature

A graphical overview of the literature review is presented in Figure 3.1. The figure also shows how the research topics and papers included in the thesis are related to other (reviewed) publication and studies. The organisation of this subsection resembles the structure of Figure 3.1.

3.1.1 Modelling Smart Distribution Grid

In modelling the smart distribution grid, or simply smart grid, one of the major issue is how to model the complex interaction and dependencies between the ICT support system and the physical grid (sub)systems. This literature review looks at previous works on dependability modelling of the smart distribution grid focusing on these interactions and interdependencies between the ICT support and the underlying power grid.

There have been significant amount of previous works towards dependability modelling of the grid. Most of them have applied simulation approaches, but some have addressed this topic using analytic model such as Markov models (upper part of Figure 3.1). Analytic approaches represent the system by a mathematical model and the dependability attributes are evaluated using

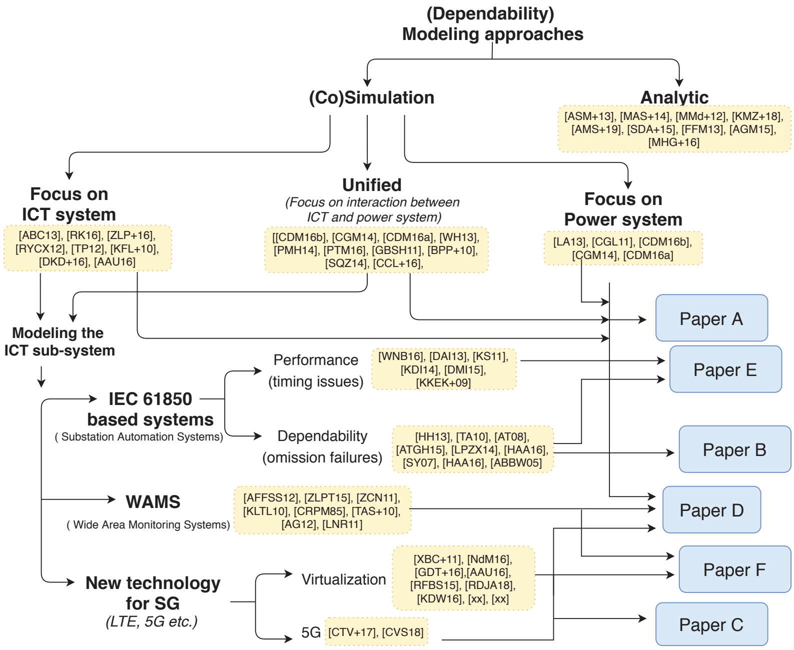

Figure 3.1: Relationship of publication from the literature to the thesis topics and papers.

direct numerical solutions. Analytic(Markov) models and metrics for survivability assessment of the distribution grid network which takes into account the dependency of the grid on the communication infrastructure during failure of power lines is presented in [ASM+13]. Similar Markov models are also presented in [MAS+14] and [MMd+12]. Some recent works such as [KMZ+18] presented a reliability modelling of new smart grid components using Markov models and study their impact on decentralised automation, voltage regulation, etc. Different works has proposed different dependability assessment methods; a methodology based on fault tree formalism in [AMS+19], a boolean logic driven markov Process dependability evaluation in [SDA+15], multiple-state Markov chain model in [FFM13] and analytical formulation using Markov method in [AGM15] for smart distribution grid monitoring systems. A probabilistic model checking for conducting the safety-critical reliability analysis of the protection systems of smart grids is used in [MHG+16].

Though the dependency can be modelled in a simplified way, due to limitations in analytic models, such approaches fails to capture the dynamic and structural complexity of the future distribution grid. It has a limitation in modelling complex interactions and dependencies arising from addition of new components such as IEDs, distributed generators, sensors etc. into the distribution grid. For complex system such as the future grid, analytic models require to make frequent assumptions to simplify the problem and produce a solution within a reasonable time. This significantly affects the representativness of the model and analysis.

In simulation studies, most of the works do either put ample emphasis on the ICT based control infrastructure or on the power system. A significant fraction of them focus on modelling the ICT based control infrastructure with a lesser emphasis on the power grid [ABC13] [RK16] [ZLP$^+$16] [RYCX12] [TP12] [KFL$^+$10] [DKD$^+$16]. Among these works, some mainly discuss about the cyber attack vulnerabilities and impact analysis of the cyber attacks [TP12] [KFL$^+$10], while others such as [DKD$^+$16] [AAU16] proposed SDN - driven ICT infrastructure on top of the power grid.

In some other works, such as [LA13] [CGL11] [CDM16b] [CGM14] [CDM16a], the emphasis has been mainly on the power dynamics with a simplified model of the dependency to the communication infrastructure. However, in next generation future grids, there will be a strong coupling and dependence between communication systems and power grids which could induce large scale failures due to cascading effects as discussed in [SQZ14] [CCL$^+$16]. Hence, it is important to establish a comprehensive framework modelling the structure and behaviours of both (sub)systems, and define the clear relationship and dependence between the two.

There are some studies proposing a unified model to abstract the dependency between ICT based infrastructure and the physical grid. Buldyrev, Gao & al. addresses these issues using a point to point interdependency models where a power node fails if the communication node associated to it fails and vice versa [BPP$^+$10, GBSH11]. However, more recent papers such as Parandehgheibi & al. [PTM16] showed that a 'point-wise' failure model is not appropriate in modelling the dependency between ICT and power system.

Wafler and Heegaard [WH13] propose an approach for the analysis of reliability of the whole smart grid infrastructure using a combination of Markov model and Reliability block diagrams. The Markov model is used to capture the dynamic behaviour while the Reliability block diagrams captures the structure of the system. However, this approach will still not be suited to study and analyse future grid system with a lot of interdependencies and high complexity. Chiaradonna & al. [CDM16b, CGM14, CDM16a] presented a compositional stochastic modelling framework for distribution grid with a focus on dependencies between the control system and the physical grid. Though the paper presented a generic model, it mainly focuses on a detailed representation of the power system side, whilst it lacks a detailed characterisation of the communication system infrastructure.

3.1.2 Modelling and Analysis of ICT Support System in Dependability Studies

The thesis has focused on modelling selected major issues that arise in the development of the future distribution grid, specifically on new architectural changes and different failure behaviours of the newly introduced ICT support system (lower part of Figure 3.1). It looked into some grid applications listed on subsection 2.1.1 aiming to study the dependability issues emerging in sensing, measurement, control and automation technologies of the future grid. Below is the state of art in relation to the dependability study on the impact of new architectural changes and new failure behaviours of the ICT in smart distribution grid.

The communication architecture and technologies used in smart grid are different for the different applications. In the thesis work, the focus has been on substation automation, protection and monitoring systems. In the substation automation domain, the IEC 61850 is the most recent and widely adopted protocol [KK13]. Whereas, for monitoring systems and for protection outside a substation domain, wide area networks with different communication technologies are often used. The literature review below presents dependability studies that has considered the contemporary and futuristic architectures; IEC 6180 based architectures for intra-substation communications and new wireless technologies such as LTE and 5G for inter-substation communications.

Dependability in IEC 6180 based systems
There are some works that has studied the reliability of distribution grids using the IEC 61850 standard for the substation communication network such as [HH13, TA10, AT08, ATGH15, LPZX14, HAA16]. Most of these works focus on proposing a highly reliable communication network architecture assuming hardware failures i.e. omission type of failure mode for the components.

Liu et al. [LPZX14] proposed a reliable network based upon cobweb topology for reliability of substation communication network. Ali et al. [ATGH15] proposed a redundant ring network focusing on the importance of utilizing the redundant critical components/communication paths in achieving high reliability and performance while Sidhu et al. [SY07] presented IEC 61850-based IED models to study the reliability of substation network for different types of network topologies.

A Parallel Redundancy Protocol (PRP) is proposed in the IEC 62493-3 standard which duplicates the LAN in the process bus communication network to provide zero switch over periods in case of any single LAN failure. The study in [HAA16] also presented a PRP scheme where conventional IEDs can be used and cost can be optimised.

Dependability considering different failure modes

Many previous works such as [HH13, AT08, ATGH15, LPZX14, HAA16, ABBW05] focused on improving the reliability and performance of IEC 61850 based distribution grid with an assumption that the failure is of omission type. In such assumption, a failure in ICT domain will not immediately cause a failure in the power system domain. The propagation of failure into the physical grid will occur only if there is a need to use the ICT control system that has failed. However, in advanced smart distribution grid, there can also be a possibility where a failure in cyber components could instantly propagate into the electrical components and result in a more sever consequence.

Most of these works also do not look into timing issues; for e.g. failure to meet the timing requirements are not considered. For the ICT support in a smart grid, timing issues are an integrated part of the system specification (such as the protection application) and the dependability evaluation shall also verify that the system is doing what it should do, in a timely way. Though there are some works such as [WNB16, DAI13, KS11, KDI14, DMI15, SY07, KKEK$^+$09] that have studied the performance of communication systems in smart grid. Paper such as [KDI14, DMI15, KS11, SY07, TA10] looked into performance analysis in SCNs. Kanabar et. al[KS11] evaluates the performance of sampled value packets over the IEC 61850-9-2 based substation. Performance evaluation of various possible communication systems between IEC 61850 based Distribution Automation System (DAS) and DER is presented in [KKEK$^+$09]. Few papers such as [WNB16, DAI13] have also looked into the performance analysis in communication between substations. Ali et. al [DAI13] studied the performance of IEC 61850 for peer-to-peer communications between substations. Most of these papers that have looked into the performance analysis do not consider factors associated with dependability analysis such as failure of components that could also affect the performance. With such approaches (classic individual evaluation of dependability and performance), decision making would be challenging as it lacks the ability to give a comprehensive dependability measure (full picture of the QoS).

Dependability in wide area communication systems

Several articles have also analysed wide area communication systems from a dependability point of view. In [AFFSS12] Aminifar et al. present a methodology for incorporating Wide Area Measurement Systems (WAMS) malfunctions in power system reliability assessment based on Monte Carlo simulation. A Monte Carlo approach is also used in [ZLPT15], where a Wide Area Monitoring, Protection and Control (WAMPAC) system is divided into four subsystems: measurement inputs, communication, actuator and analytic execution, and the influence of different components on the overall system reliability is assessed through sensitivity analysis. Zhu et al. in [ZCN11] address the dependency of Wide Area Monitoring and Control (WAMC) systems on their supporting ICT architecture. Different architectures are compared in a scenario with a PMU based monitoring system, and the reliability of the whole WAMC system is assessed with relation to data loss probability and delay. An extensive number of works [KLTL10, CRPM85, TAS+10, AG12, LNR11] focuses on analyzing the impact on power system state estimation in relationship with a specific cause of data loss and corruption, namely cyber attacks.

All these works aimed at improving the dependability of the current grid with a hardware redundancy and some topological enhancement. Great majority of the listed papers have not looked into the dependability aspects of possible scenarios of the future distribution grid, for instance, impact of structural/architectural changes, technological alternatives and new failure modes of the ICT support system on the power grid. This implies that some research effort is still required in investigating the impact of introducing ICT on the dependability of the grid.

Dependability considering new ICT technologies

There are some works that have introduced the concept of virtualisation into the grid. Xin & al. [XBC+11] proposed a virtual smart grid architecture based on cloud though it does not have a detail dependability modelling /analysis of implementing a smart grid application. There are some works that have considered virtualisation based approaches such as Network Function Virtualisation (NFV) for Advanced Metering Infrastructure (AMI) [NdM16] and Software Defined Networking (SDN) [GDT+16, AAU16, RFBS15, RDJA18, KDW16] for some smart grid applications.

Cosovic et al. in [CTV+17, CVS18] studied how the emerging 5G mobile cellular network, with the concept of mobile edge computing, can be used for distributed state estimation in smart grids. Latency and reliability of distributed state estimation on 5G communication networks are analysed. The effect of noise on measurement process and communication process that corrupt the measurement vector is also studied. However, to the author's knowledge, there was not much work that has considered a comprehensive dependability assessment of newer technologies that embrace virtualisation such as 5G as a communication platform for applications like protection and monitoring of smart distribution grids.

3.2 Open Challenges

From the discussion presented in the background (section 2) and state of art (section 3.1), the following open challenges are identified and serve as a basis for defining the research questions for the thesis work.

1. As indicated by the literature review, there are a number of modelling approaches proposed for studying smart grids. Though, majority of them are made for studying a generic smart grid with different purposes, they can also be applied to the distribution grid. However, in future distribution grids, there is going to be an extensive use of ICT, which brings more complex and stronger dependencies between the ICT support system and the physical grid. This tight coupling between the two subsystems need to be captured by the modelling approach while keeping the appropriate level of abstraction to only consider features relevant for dependability study. Some works such as [CDM16b] provided a framework that jointly model both power system and ICT system. Though, it still lacks a detailed characterisation of the communication system infrastructure.

   Overall, a comprehensive framework suited to model and study the dependability of smart distribution grids, as a system of systems comprising ICT and the physical grid, has not been sufficiently developed yet.

2. The other challenge is to model the two subsystems that has different characteristics. The failures, repairs and reconfiguration actions in both ICT and power subsystems are typically described with discrete

event simulation while the dynamic behaviour of the power subsystem is often described by mathematical models in the continuous domain. In modelling the grid, the approach must be able to merge these two subsystems with different exigencies.

Some papers such as [GCG+17, LVS+12] used co-simulation to address this problem which uses specialised simulators for both subsystems. However, co-simulation has its own challenges such as difficulty in synchronising data and interactions between the two simulators. Especially time management between both simulators is challenging, because each simulator manages their simulation time individually [MOD14]. Recently, some has started to use co-simulation frameworks such as Mosaik [SST11], Functional Mockup Interface (FMI) [BOA+11] and High-Level Architecture (HLA)[SMP+00] for orchestrating the interaction between the simulators. Nevertheless, the use of such frameworks will also add some overhead.

Depending on the objective of the study, it may not be needed to model the detailed dynamics of the system, for e.g. dependability assessment on structure of the system. However, for some cases such as for analysing control strategies as in [CDM16a], it might be important to look into the detailed dynamics of the power system. In general, there is no well established approach to deal with these issues in studying the dependability of next generation distribution grid.

3. There are limited number of research works on the dependability of next generation distribution grid considering the undergoing automation. The behaviour, failure and repair data of the newly introduced ICT based components is less known. How the (massive) introduction of these components affect the dependability of the future SDGs is not adequately investigated.

4. In classic distribution grid studies, it is only hardware failures of ICT components that were often considered, as discussed in section 3.1.2. Most previous work have assumed omission failure mode of the ICT components in studying the dependability of the distribution grid. However, ICT systems could have various failure modes as explained in section 2.2.1.

   One example is value failure mode which can be caused by software faults, mis-configuration, operational mistakes etc. In a value failure mode, a failure in ICT based control system could produce a wrong result which could instantly induce a failure in the physical grid affecting the service provided to end users. Hence, considering a critical infrastructure such as the distribution grid, all possible failure modes has to be thoroughly investigated. With this regard, the literature review has revealed that the different failure modes has not been assessed well. Especially it is less known how the dependability of the next generation distribution grid is affected by the different failure modes such as value and timing failures.

5. The research in studying the use of new and emerging ICT technologies for the future smart distribution grid is limited. Though it may take some time to see the application of such emerging ICT technologies into the grid, they will certainly be used in the near future as these are the technologies that can adequately fulfil the stringent requirements of the future distribution grid applications. Hence, at this stage, it is important to start modelling and studying how the application of new ICT technologies is going to affect the dependability of the distribution grid.

Chapter 4

Research Design

This section presents the research goals of the thesis work in Section 4.1 followed by a brief discussion on the scope of the research work in Section 4.2. Lastly, Section 4.3 discusses the methodology employed to achieve the research goals.

4.1 Research Goals

The ultimate objective of the research work is to develop a modelling framework that can be used to study and analyse the dependability of future distribution grid. This can be broken down to the following research goals (RG) which are established to address the open challenges identified in Section 3.2.

First, a framework that is able to model the two major subsystems of the smart grid, ICT and power system, is needed. The framework has to be suited for a dependability study with an adequate level of detail in both subsystems. Second, the use of the framework to study the dependability of the future smart distribution grid. To achieve this, the new behaviours and challenges of the future smart distribution grid has to be identified. Then, use cases must be designed and analysis has to be made to study the impact of introducing ICT to the distribution grid. Below is a brief discussion of the research questions:-

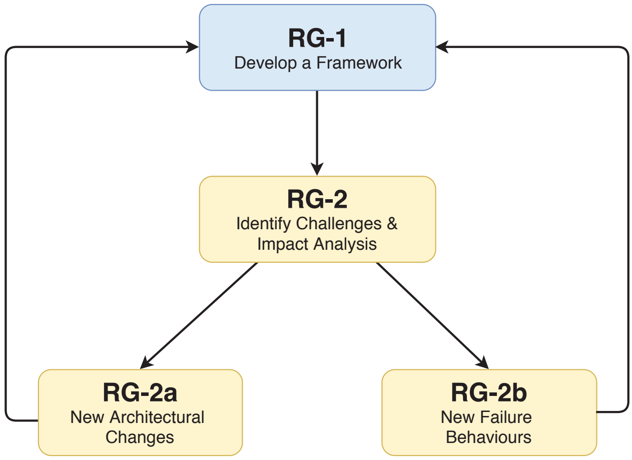

Figure 4.1: Relationship between the research goals.

RG 1 - Develop a comprehensive framework suited to study the dependability of distribution grid focusing on the interdependency with ICT

The first step is to come up with a framework that can address the challenges described in section 3.2 (1) and (2). The modelling approach should be able to model the discrete event failure and repair processes of both ICT and power subsystems and an abstraction of important continuous time processes. It is important to have a balanced view of both the power grid and ICT subsystems with ability to capture the strong coupling and interaction between the two subsystems of the future distribution grid. Furthermore, the framework shall be scalable, easy and flexible to model operational and architectural changes, new emerging technologies, and automation in the distribution grid. Developing such framework is a basis for dependability study of different use cases of the next generation distribution grid.

RG 2 - Identify new behaviours and challenges arising from the tight inter-dependency between the ICT and power system of future distribution grid, integrate them in the dependability modelling framework and perform analysis

The aim of RG-2 is to first identify new challenges that arise from the introduction of ICT to the grid, and study their impact on the dependability of the distribution grid. In order to achieve this, use cases that represent the new behaviour of the grid are created and analysed. The analysis is made using the framework developed in RG-1, with some customisation to suit each use cases. The scenarios investigated are classified into the following two major categories.

RG 2a - New architectural changes: Provide insight on how will the application of new architectures and emerging ICT technology affect the dependability of the distribution grid

This research sub-goal aims at investigating the impact of new architectural changes on the dependability of the distribution grid. The work has a focus on two architectural developments; the IEC 61850 architecture for substations and the use of 5G in smart grids. As pointed out in the literature survey in section 2.1.3, the IEC 61850 is a new standard for substation automation in the distribution grid and it provides a complete framework for communication networks and systems in substations. Though it is becoming the dominant protocol in this field [KK13], it is still not widely operational. In this research focus, it is planned to make a quantitative assessment on the dependability of IEC 61850 based distribution grid. It aims to study how will the failure behaviour of new components such as IEDs and the use of fault tolerant architectures affect the dependability attributes. On the other hand, new technologies such as 5G are expected to play a huge role in hard or soft real time systems. In relation to this, the goal is to propose new architectures for selected grid applications using these new technologies and investigate the dependability of such distribution grid.

RG 2b - New behaviours / failure modes: Study the effect of different failure modes of ICT subsystem in the dependability of the distribution grid

The assumption of omission failures of ICT subsystems will not give a realistic assessment of the future distribution grid where ICT plays a key role. The aim of this research focus is to include other types of failure modes of the ICT subsystem and components into the dependability modelling and study their impact on the operation of the power system and service delivery to end users. In addition to the conventional omission type failure mode, the goal is to study the effect of at-least two other failure semantics; value failure mode and timing failure mode of the newly introduced ICT components to the distribution grid.

Figure 4.1 shows the relationship between the research goals. The first research goal(RG-1) serves as a basis for the second research goal and its sub-goals. It provides the modelling framework where the use cases in RG-2 are studied. RG-2a uses this framework to study the effect of various failure modes of ICT components on dependability of the grid. This requires customisation of the framework to include the different failure mode behaviours of the components. Hence, the works in RG-2 slightly contribute in updating the proposed framework (RG-1). The other research sub-goal RG-2b also use the framework to study the application of new architectures and technologies which needs additional features, component models and customisation of the framework which is shown as a feedback to RG-1 in Figure 4.1.

4.2 Research Scope

The research work is limited to a study on dependability issues in distribution grid that arise from the interaction between the newly introduced ICT and the power system. The work does not look into security issues. Performance analysis, though not a primary objective of the thesis, is included when it is needed to study the influence of performance related factors on the dependability of the grid.

The modelling and analysis does not intend to model the detailed dynamics of both sub-systems. Rather, the focus is on modelling structural and functional dependencies between the ICT and power system. Though, some detailed aspects of the subsystems (such as power flow and state estimation calculations) are considered in a limited way when there is a need to get more insight about the system. Even for such cases, a static load and power generation is assumed. The ICT control of the power system is based on the predetermined rules and strategies (for e.g. re-configuration of the power system network when failure occurs). Dynamic control of the power system is not included in the modelling. In studying the impact of new challenges on the future distribution grid, the work has focused on two smart grid applications; protection application and wide area monitoring systems.

4.3 Research Methodology

This section presents the methodology employed to achieve the research goals identified in Section 4.1. The discussion includes the research methods employed for modelling and analysis as well as validation of the results.

Figure 4.2 shows an overview of the work process of the thesis work. The research started with a literature review on dependability and reliability studies on smart grid, with a focus on distribution network. The background knowledge and the state of art obtained through the literature review leads to identifying the open challenges that needs to be addressed. The high-

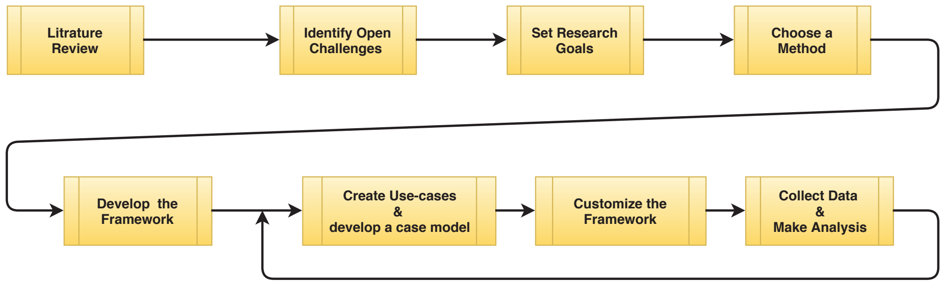

Figure 4.2: Outlook of the work process.

lighted open challenges form the basis for defining the research goal of the thesis.

Then, the next step was to choose a method and develop a framework to address the research questions. Once a template framework is developed, different use cases were created where the framework was extended and customised for each specific studies. In the case studies, input data is collected from literature and some obtained from a grid operator, and analysis has been made to study the dependability of the distribution grid with the customised framework. Below is a brief discussion of the methods employed for a selected major steps of the work process i.e., from choosing the method up to getting the input data and making analysis.

4.3.1 Methods for Modelling the Distribution Grid

Choosing dependability models

In dependability studies, there are two main types of models; static and dynamic models. Classic static models such as fault trees and reliability block diagrams, are widely used in dependability studies of smart grid. Especially, fault trees are frequently used by power system experts. In selecting a proper modelling approach, the basic features and characteristics of the future distribution grid such as the high complexity and dynamics, interdependency between components or subsystems, scale and size of the whole system should be carefully examined. Dependability analysis with static models imposes an assumption of independence of failures and repairs. However, as discussed in section 2.1.1, the future distribution grid is going to have massive use of ICT which brings complex interaction and tight coupling between the different components of power and ICT subsystems. In this regard, static models has a limitation to model large scale dependencies, interactions and dynamism of the future distribution grid ecosystem.

In this thesis work, dynamic model is employed which is capable of capturing the interaction and dependencies among components or subsystems. Furthermore, the future distribution grid will be consisting of many sensors, intelligent components and as many end user smart meters as the number of customers. And, it is dynamic models that are more suited for modelling such large scale systems.

Choosing a modelling approach and formalism

Dynamic models can be represented using different modelling languages and tools such as state transition diagrams/UML type of diagrams, Petri nets, stochastic activity networks (SANs) etc. The selection of the modelling language was mainly motivated by the effort needed to implement the evaluation of dependability attributes, and on its scalability and flexibility to add or modify the model with new features.

The alternatives for the evaluation of the dependability attributes can be classified into (i) analytic or mathematical approaches, (ii) co simulation with synchronisation of specialised simulators for both ICT and power systems, (iii) a comprehensive (integrated) simulation which use one general purpose programming languages. iv) Laboratory based or experimental approaches.

In Analytic approaches, models can be solved mathematically provided that analytical formulation can be derived for the modelled system. However, a mathematical formulation may not be feasible when the size of the model is very large. Even if the formulation can be obtained, the numerical solution may not be feasible due to the size of the state space. Hence, analytic approach has a limitation to include a wide range of ICT and power components, failing to capture the dynamic and structural complexity of future grid systems.

Laboratory based or experimental approach is also a well known method for testing single or small set up of components and it can be used to get accurate results. However, it is not a viable option for the holistic evaluation of the future grid as it is very expensive and inflexible to use it for dealing with large systems.

Co-simulation has the advantage of using an existing simulation models, algorithms, etc. that have already been implemented and validated. However, it has a significant challenge in synchronising data and interactions between the simulators [PVDML+17, MOD14]. In our case, the level of detail needed for studying the dependability of the distribution grid doesn't necessitate to use specialised simulators for capturing the dynamism deeply which requires high effort in setting up the platform and sometimes with a cost of performance penalty due to synchronisation.

The comprehensive simulation approach often uses one general purpose programming language where both the power system and communication network can be simulated in one environment. This approach with a single simulation interface makes the management of time, power and communication system interactions easy and it can be shared among the simulator constituents (ICT and power system). Hence, synchronisation of the data and interactions will not be a problem. The challenge in using this approach is the effort needed to develop the models might be time-consuming and expensive as compared to the co-simulation approaches.

In the thesis, a comprehensive simulation approach is used. To be practical and useful for modelling a large-scale systems, the model must be intuitive, computationally efficient, and able to capture complex scenarios. There are different alternative modelling languages that can be used with the comprehensive simulation approach such as the state transition diagrams/UML type of diagram or other process oriented simulations, Petri nets and stochastic activity networks.

Stochastic activity networks have some benefits when compared with the other approaches. Mostly, approaches such as state transition diagram or process oriented simulation need to develop a pure coding based simulator, which might take a lot of effort and time. In addition, it is not as structured as SANs. Modelling languages such as Petri nets lack the flexibility to model the complex interaction in the system. SANs are extension of Petri nets that provide a structured modelling but with some additional features that can be used to model complex interaction and dependencies in the system. For these reasons, a SAN model based on a well tested tool are preferable. Hence, the thesis uses SAN to develop the framework as it is more intuitive with a structured modelling, equally efficient and takes less time and effort than modelling language that require pure coding based simulators.

4.3.2 Method Used in Developing the Framework

A Stochastic activity network (SAN) model [SM02] is developed to study the smart distribution grid. The model is developed using the Mobius tool [GKL$^+$09b], which supports SAN based modelling with decent graphical interface. The core part of the proposed modelling framework mainly uses the SAN based simulation which is extended with an integration of external C++ based simulators. The methods used in modelling the behaviour, structure and topology of the system as well as methods used in collecting the dependability attributes are presented below.

Method used in modelling the dynamic behaviour of the system

Method for modelling discrete activities

The strength of using a dynamic model (SAN based model) is its ability to model behaviour and interactions in the system. In building the framework, a bottom up approach is used. First, individual(atomic) models are developed for all types of components in the system. These sub-models are designed to capture the relevant functional properties or behaviour and the state of a typical component in the distribution grid. Next, these types are instantiated, i.e. given parameters and variables, to represent the specific individual components of that type in the system. The instances and the system topology are represented using an indexed extended place in the atomic models. Then, these atomic sub-models are combined to form a subsystem (ICT or power system) or the whole distribution grid. Modelling the behaviour on the subsystem or system level including the dependencies and interaction between components, is enabled by sharing certain states among the constituent atomic/component models.

Dependability attributes are often described by discrete activities such as failure and repair processes. A SAN based model is developed as the foundation of the framework to model such activities. As mentioned above, one template atomic model is developed for each component of relevance in the power grid and ICT system. For creating instances, the Mobius tool has an option to use *'Replica'* model formalism which leads to structural symmetries that can eventually result in less time- and space-consuming state-based numerical solution of the model. However, it is not possible to modify and customise individual instances differently. Instead of the replication in Mobius, the employed method exploits the use of extended places for this purpose.

An instance for each of the components is created using an indexed extended places in the atomic models. Extended places are special elements in the SAN formalism that allows the model to handle the representation of structures and arrays of primitive data-types(places) [GKL+09b]. Each position (place) in this array contains a certain number of tokens, and the state of one component (instance) is determined by the number of tokens (marking) in a given position of the extended places.

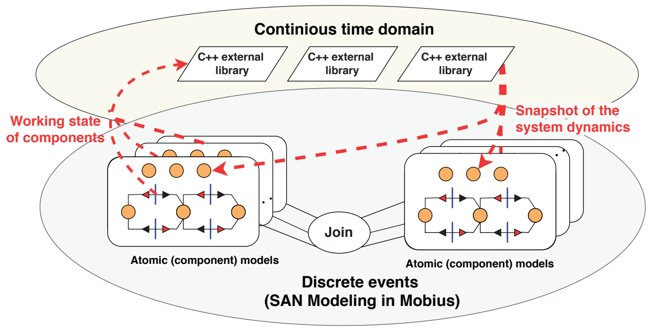

Figure 4.3: Schematic representation of the method employed to extend the use of SAN.

The *'Join'* composed model formalism in Mobius is used to connect the atomic models and model the overall distribution grid. The shared states between the atomic models are defined at this stage of the model. This hierarchical approach makes the model easily extendable with new features; the introduction of new atomic models and refinement of existing allow upgrading the smart grid definition with an enhanced level of details.

Method for integrating the continuous activities/time domain

One of the challenges presented in section 3.2 (b) is to merge power system which is often described in the continuous domain and the ICT system which is typically described with discrete event simulation. The discrete activities or major events such as failure and repair of components are modelled with the SANs as outlined above. However, SAN models are not suitable to model the continuous activities such as the power flow calculation and state estimation. Therefore, a separate external model using numerical analysis is introduced to the framework to address this challenge.

The employed method, shown in Figure 4.3, extends the use of the SAN and the tool to allow dealing with continuous phenomena by exploiting external C++ libraries and link it with the Mobius compiler. As illustrated in the figure, a state transition (failure or recovery event) in the component SAN models of interest triggers the exploitation of external libraries through the input/output gate functions. The working state of the relevant component (SAN) models will be communicated to the external libraries. The functions within the c++ libraries will use these data to determine the snapshot of the power system dynamics (such as power flow) or ICT (latency) dynamics around the state transition in the system. Then, the results are collected and recorded as values in the extended places in Mobius. These results will be used in further analysis in the SAN models to either enforce some decisions or new transitions in the system. The exploitation of external libraries allows to model more dynamics of the system such as improving the power system analysis capabilities with new functionalities (state estimation, network operation strategies, transient simulation analysis, etc.).

Method used in modelling the structure and topology

Another challenge in dynamic models (SAN based models) is that the system structure or topology is not shown explicitly, unlike static models such as block diagram models where modelling the topology is straightforward. In the proposed framework, the structure and interconnection is modelled by embedding it inside the component models. Every component is made to know the state of the component to which it is connected or dependent for its operation. In Mobius, the structure and interconnection between components (atomic models) is modelled using shared places. The shared places are used to model both the physical dependency (topology) as well as other types of functional dependencies and interactions as outlined above. These places, defined in the composed model, are shared among all atomic sub-models whose operation is dependent on these places. For instance, If the enabling conditions for an activity (transition between states) in a component is dependent on the state of another component, the extended place that contain the dependency (state of the other component) will be defined as a shared place and a condition can be set in the first component using this shared place.

Method for analysing the dependability attributes

Reward models [SM92] in Mobius are used to study the dependability of the distribution grid. In Reward models, the dependability attributes are obtained by assigning a reward to states or transitions of interest. Statistics will then be collected every time the system visits this state (the transitions occur). The final result, often a mean value, is proportional to the time the component/system stays in that state or the number of times it enters that state. The dependability attributes discussed in 2.2.2 such as availability and reliability indexes are considered. In addition, some metrics such as safety, mean estimation error and so on are also defined and used to provide additional insight to the ICT and power system interaction.

Input data and validation

One of the challenges in studying future systems is to get data for failure, repair, etc. processes. The input data related to failure and recovery rates of the grid elements is assumed based on data from similar components in the current distribution grid. A literature survey of works on a similar systems and data from distribution grid operators in Norway [sta16] is used. It may look reasonable to reuse data for physical and environmental failures, but not for other type of failures such as software failures. The repair or recovery process is also highly dependent on the intelligence and smartness to be introduced. Considering such uncertainties, some scenarios are tested for a range of values. In addition, for some others, a conservative assumption of the failure and repair data from the literature is also used to investigate potential worst case scenarios of the future grid system.

In validating the model, the following approaches are often used: prototype case study and comparison to similar works, sensitivity analysis, and real-world case study. In this thesis work, a sensitivity analysis is used in some of the use cases to make sure that most probable scenarios are captured by the model. For parts of the model where it was possible to get a comparison, the results are compared to a similar setup with a different tool. The comparison is used to validate and sometimes to calibrate the model developed. For instance, the external c++ functions (libraries) for power flow calculation are validated using Matpower in Matlab.

Chapter 5

Contributions

In this section, the contributions of papers that constituent the thesis are discussed in Section 5.1. Then, a brief discussion on how these papers relate to the research goals are presented in Section 5.2. Lastly, the limitation and applicability of the developed framework and results from the studies are discussed in Section 5.3.

5.1 Contributions of the Papers

The six papers listed below are produced during the PhD study aiming to answer the research questions defined in Section 4.1. Figure 5.1 gives an overview of the papers produced in the research work and their relation with the research goals. This section presents the contribution of each paper and how they are related to each other. The relation of the papers to the research goals is detailed in Section 5.2. Note that a minor editorial changes are introduced in some of the papers.

Paper A:

A Modelling Approach for Dependability Analysis of Smart Distribution Grids
Tesfaye Amare, Bjarne E. Helvik, Poul E. Heegaard
21st Conference on Innovation in Clouds, Internet and Networks and Workshops (ICIN), Paris, February 2018

This paper is the foundation of the proposed framework. It presents a high level description of a comprehensive modelling framework suited to study the dependability of the next generation distribution grid where ICT

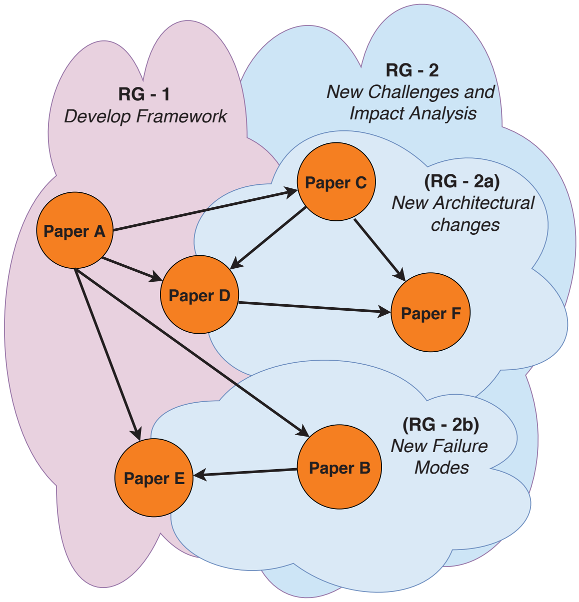

Figure 5.1: Overview of the included papers coupled with the research goals.

will play a crucial role. The focus is on modelling the complex interaction and dependencies between the newly introduced ICT support system and the power-grid. The modelling framework is general and modular based on a stochastic activity networks using the Mobius tool. The modelling starts with developing a model type for components. An atomic model is developed for all components of the smart grid, with an emphasis on the failure and recovery processes. Then, the component models are combined to model the overall system where shared states between the models are used to capture the interconnection/topology and interdependencies.

To illustrate the capability of the framework, this paper also looks into the role of automation and new technologies in IEC 61850 based future distribution grids. It presents a quantitative assessment to identify vulnerabilities and to study alternative design principles and architecture of the automated distribution grids.

Paper B:

Dependability Analysis of Smart Distribution Grid Architectures Considering Various Failure Modes

Tesfaye Amare, Bjarne E. Helvik
IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Sarajevo, Bosnia and Herzegovina, October 2018

This paper looks into the effect of various failure modes of new components of the ICT support system, on the dependability of distribution grid. The stochastic activity network based modeling framework proposed on Paper A is extended and used. In particular, some of the component/atomic models of the ICT support system are extended to incorporate new failure behaviours. The paper specifically look into how omission and value failure modes of ICT components affect the reliability of distribution grids. The study is carried out on an IEC 61850 based Substation Communication Network (SCN), a relatively new architecture for distribution grid automation. The investigation is made on reliability evaluation of the feeder protection function of this IEC 61850 based next generation distribution grid. Furthermore, different architectures of the IEC 61850 based substation communication network, proposed by previous works, are investigated and compared for the different failure semantics considered.

Paper C:

Dependability of Smart Distribution Grid Protection Using 5G
Tesfaye Amare, Bjarne E. Helvik
The 3rd International Conference on Smart Grid and Smart Cities ICSGSC 2019, Berkley, USA, June 2019

This paper discusses the usage of virtualisation and network slicing concepts in 5G technology for protection application in distribution grid. A 5G based architecture using an edge computing infrastructure to hosting the control and protection applications is proposed and its dependability is investigated. Here again, the modelling framework proposed in Paper A is extended and used. New atomic models are developed and some others are customised with additional features to model the 5G infrastructure. A special emphasis is also given for modelling the the radio access of the 5G based architecture considering it as one of the critical element due to environmental factors such as the random fading processes.

Investigations are made to analyse and study the impact of communication failures, with a focus on radio link failures on availability and reliability of protection application and the result is also compared with functionally identical IEC61850 based architecture.

Paper D:

Dependability Modeling and Analysis of 5G Based Monitoring System in Distribution Grids
Tesfaye Amare, Michele Garau, Bjarne E. Helvik
VALUETOOLS 2019 Proceedings of the 12th EAI International Conference on Performance Evaluation Methodologies and Tools, Palma, Spain, March 2019

In this paper, the customised SAN based modelling framework used in Paper C is extended with an integration of external libraries (functions) to include dynamic behaviour of the power subsystem. In smart grids, the power system is traditionally described by mathematical models in the continuous domain, meanwhile in ICT system is typically described with discrete event simulation. Modelling and studying the interdependecies and interaction between the two subsystems opens a methodological problem, since different exigencies must coexist: on one hand, the necessity of reproducing the operation of the system in an accurate way, on the other hand the need of simplifying the system according to the details of interest. To address this issue, this paper presents a novel approach that combines simulation of SAN and numerical analysis, to take into account the continuous and discrete event activities of power system and ICT system. The application of the extended framework and its capabilities are demonstrated through a case study where the performance and dependability of advanced communication technologies, such as LTE and 5G, for supporting monitoring system applications is analysed. Particularly, the study looked into the impact of communication failures on the state estimation of an IEEE standard distribution network.

Paper E:

A Method for Performability Study on Wide Area Communication Architectures for Smart Grid
Tesfaye Amare, Charles M. Adrah, Bjarne E. Helvik
The 7th International Conference on Smart Grid (icSmartGrid 2019), Newcastle, Australia, December 2019

This paper discusses effect of different failure modes of the ICT support system in the dependability of the distribution grid, similar to Paper B, but the focus is on timing failures. The ability of the ICT system to meet the real time requirements of the powers system, even when it is degraded due to failures, is essential. This simultaneous study of dependability (reliability) and performance are referred to as performability. This paper presents a method for a performability study on ICT support system of smart grid. It looks into how performance associated properties (timing failures) can be modelled together with properties affecting dependability such as omission or conventional component failures.

The modelling framework customised in Paper B is further extended and used. The SAN based model from paper B is combined with another tier model using ns-3 and a hardware in a loop setup to study the packet level dynamics of the communication infrastructure. For illustration, an investigation is made on an inter-substation protection function where wide area networks are used. A simulation is conducted to study the reliability and unavailability of an IEC 61850 based communication architecture, where the impact of both timing failures and omission failures are investigated and compared.

Paper F:

Effect of Communication Failures on State Estimation of 5G-Enabled SmartGrid
Tesfaye Amare, Michele Garau, Bjarne E. Helvik
IEEE Access, vol. 8, pp. 112642–112658, 2020

In this paper, the work from paper D is continued. The extended framework in paper D is applied for a dependability and performance analysis of a 5G based Wide Area Monitoring System (WAMS) for state estimation in an IEEE standard distribution network. Different sources of internal failure and external interference such as effect of rain, short term fading in the radio communications are incorporated to the framework developed in Paper D.

In addition, different state estimation approaches; one with conventional SCADA measurement devices and another with combination of SCADA measurement devices and PMUs are considered. The impact of internal and external failures on this two state estimation approaches are analysed and compared in terms of mean estimation error and safety metrics.

5.2 Contribution Summary

This section gives an overview of how the papers relate to the research goals in Section 4.1. Figure 5.1 shows how the paper contributions fit into the research objectives. A brief summary of the papers contribution and their relationship to the research goals is also presented in Table 5.1. Below is a discussion on the contribution of the thesis work for each of the two research goals:

RG 1 - Develop a comprehensive framework suited to study the dependability of distribution grid focusing on the interdependency with ICT

All included papers contributed to this research goal in one way or another. The basic/first version of the framework is presented in Paper A, and more features and extensions are integrated to the framework in the subsequent papers. The thesis work focuses on modelling the tight interaction and interdependency between the power grid and the ICT support system, a distinctive characteristics of the future distribution grid.

There are some previous works, as discussed in Section 3 and Section 4.3, that have presented different approaches and models in this regard. Nevertheless, the contribution of this thesis is to develop a framework that puts adequate emphasis on the two (sub)systems with the right level of abstraction for dependability studies. In addition, the extensions of the framework for the case studies investigated during the thesis work, has also a contribution to provide a wider platform suited for a study of new behaviours and challenges arising from the tight coupling of ICT and power system in the next generation distribution grid.

The thesis work addresses RG-1 with the following contributions: In paper A, the basic interaction and interdependency modelling between power system and ICT support system is presented. Paper D and Paper E discusses how more detail modelling of the dynamics in power system and ICT support system can be integrated to the framework developed in Paper A. The rest of the papers (Paper B, Paper C and paper F) including the case studies of Paper A, Paper D and Paper E extends the framework for modelling specific future grid scenarios, i.e., new challenges arising from the tight coupling of ICT and power system of the future grid. Below is the discussion of major contribution of each paper in relation to RG-1.

Paper A presents a stochastic activity network based framework using the Mobius tool. This early version of the framework is simple with a high level of abstraction. It has a rudimentary abstraction of the physical grid, but with an extended emphasis on modelling the failure processes and dynamics on the communication and control infrastructure. Atomic models are developed for components of the power and ICT system considering their failure, recovery processes and dependency and interaction with other components. The structure, interconnection and interdependencies between components is also embedded to the atomic models. Then, to model the overall system, component models are connected to a meta model where the dependencies and interactions of components are defined as shared states. The power supply dependence of ICT components on the power system components and the dependence of power system components on the ICT for control is described inside component models of the framework. Intra-infrastructure dependencies within the ICT support system or the power system are also modelled with shared states inside the component models. In addition, the framework is also extended for a specific case study showing the effect of automation in fault identification, location and service restoration of distribution grids.

The major contribution of Paper D and E also falls into RG-1. The two papers present a significant extension of the SAN modeling framework by introducing a external sub-models to capture dynamic behaviour in both the power system and ICT system.

In Paper D, external models/libraries are developed to deal with the continuous activities of the power system. The main contribution in this paper is the inclusion of power system analysis functions by exploiting external C++ functionality. Though there are quite many tools that can be used to carry out power flow and state estimation calculation, it was not possible to integrate these tools with Mobius. Two functions, based on standard methods, were implemented (with the external c++ functionality) and validated against other similar tools: one for providing the tool with the capability of performing power flows, and another for performing state estimation calculations. Major events such as failure and repair within power system and ICT systems are modelled in SANs, while continuous activities of the power system are performed with the C++ functions (libraries) linked with the Möbius compiler.

Paper E also extends the framework to deal with more dynamics of the system by including more level of detail, but in the ICT system. It proposes a method to study the performability of ICT support system of smart grid where a light abstraction of the packet dynamics is modelled with an external c++ function (library). This paper proposes a method to model and study performance associated properties (timing failures) together with properties affecting dependability of the ICT support system such as failures and recovery processes. For reasons of efficiency and the use of proven model libraries, a different tier model using Ns-3 (and HIL for verification) is developed to model the packet level dynamics and the measurement from this model is linked to the SAN based framework introduced by Paper A.

The framework is also extended for specific use cases in the remaining papers, Paper B, C and F, which mainly address the research goal RG-2. In paper B, the framework, especially some atomic models are customized for modeling new failure modes on components. Paper C introduces component/atomic models for 5G infrastructure. This paper also presents a wireless channel modeling into the framework considering time dependent factors on the radio links such as fading, interference, etc. In Paper F, the model from Paper D where power system libraries/models linked with the SAN based framework is used but extended with two main features. The first is the addition of detailed radio communication model where the effect of channel fading and the effect of rain is included to the framework. Another is the use of a two stage state estimation model where PMUs are considered.

RG 2 - Identify new behaviours and challenges arising from the tight inter-dependency between the ICT and power system of future distribution grid, integrate in the dependability modelling framework and make analysis

The main contribution of paper B, C and F is towards RG-2; a study on the new behaviours arising from an extensive introduction of ICT to the grid. The use cases of the other papers (Paper A, D and F) have also looked into similar issues. Below is a summary of the contributions of the papers on each of the two research sub-goals of RG-2.

RG 2a - On new architectural changes:

The thesis work looked into two major architectural changes in the distribution grid, an IEC 61850 based substation communication networks and the use of 5G based architecture for selected grid applications. The use of 5G for smart grid is relatively new to the industry. Papers C, D and F has contribution towards proposing and studying new 5G based architectures for protection and monitoring applications in distribution grid. Whereas, the IEC 61850 standard is known in the industry for a while, but it has not been widely used especially in the distribution grid. Papers B (also partly Paper A and E) have some contribution towards investigating the reliability of an IEC 61850 based systems.

The main contribution of paper C is the study on a novel 5G based architecture proposed for a protection application in smart grid that virtualise and move some control logic into an edge cloud in 5G and the investigation on the dependability of this architecture. Its contributions can be

Table 5.1: Paper contribution summary towards the research goals.

Paper	Contribution Summary	Research Goals		
		RG - 1	RG - 2	
			RG - 2a	RG - 2b
Paper A	The basic SAN based framework to model interaction between ICT and Power system.	X		
	Extension of the framework for FLSR study in SDG.	X		
	Investigation on the impact of introducing ICT for automating FLISR on the reliability of IEC 61850 based distribution grid.			X
Paper B	Investigation on the impact of new failure modes (value failures) of ICT components on the operation of SG.			X
	Customization of the framework for modelling new failure modes on components	X		
Paper C	The use of a novel 5G based architecture for protection application in smart grid and its dependability evaluation		X	
	· Component/atomic models for 5G infrastructure (including radio channel models)	X		
Paper D	Extension of the framework to deal with continuous activities of the power system (i.e., power flow and state estimation)	X		
	The use of 5G technology for monitoring (Wide Area Measurement System) in SG and its dependability evaluation		X	
Paper E	Extension of the framework to deal with latency dynamics of the ICT sub-system.	X		
	Assesing the impact of timing failures on the dependability of an IEC 61850 based protection in SG.			X
Paper F	Dependability evaluation of 5G based WAMS with a detailed focus on the impact of external factors such as rain and fading		X	
	Investigation of different state estimation algorithms on the 5G based WAMS architecture.		X	
	Extend some models to include environmental factors such as rain, and fading in the radio channel as well as models for PMU based state estimation.	X		

summarised as: First, a brief qualitative discussion on the benefit and challenges of the proposed 5G architecture in comparison to the IEC 61850 based architecture. Second, an investigation on the availability and reliability of protection functions in the proposed 5G based architecture using the SAN based framework. Lastly, a dependability comparison (quantitative) of the 5G architecture with the functionally identical IEC 61850 based architecture. The investigations showed how significant gain in availability of protection functions can be obtained from using the 5G based architecture. It also showed how critical is the radio access in the 5G based architecture, and the importance of using high channel redundancy to compensate the loss due to fading.

paper D and F discusses the use of 5G technology for a monitoring application. Paper D's contribution for RG-2 is the case study on the 5G model for wide area measurement systems (WAMS) in smart grids, specifically the analysis on the impact of ICT failures of the 5G WAMS on the state estimation of the grid. The case study showed a potential of significant improvements in the performances of the state estimation with a WAMS supported by URLLC-based 5G technologies compared with LTE-based communication infrastructures. Paper F, as extension of paper D, discusses the use of 5G for WAMS, but focuses more on modelling external interferences in the ICT system and studying variants of state estimation approaches in the power system. One of the additional contributions is the detailed modelling of external factors to the WAMS especially the rain effect and fading in the radio subsystem. Another contribution is the investigation on the use of different state estimation algorithms with the proposed 5G architecture; one using the conventional SCADA sensors and another with the use of PMUs together with conventional PMUs. And, the performance of these algorithms are compared in terms of Mean Estimation Error and Safety metrics. The investigations indicated the potential impact of external factors such as fading and rain conditions on the radio channel availability, and hence affecting the state estimation. It also showed how the adoption of PMU measurement in distribution networks could result a dependable system with a significant improvement in the accuracy of voltage estimation.

The case study in Paper B also partly contributes to RG 2a. It discussed how the reliability of variants of IEC 61850 based SCN architectures from the literature, each with different level of redundancy, is affected by various failure modes of ICT components.

RG 2b - On new behaviours / failure modes:

Paper B is the first work in the thesis attempting to study the impact of new (different) failure behaviours of ICT components in the operation of future smart grid. Its main contribution to RG-2b is the investigation on the effect of assuming different failure modes, namely value and omission type failures, on the reliability of the distribution grid. It focuses on studying the possibility where a failure in ICT support system could produce wrong result and induce a failure that may propagate into the electrical components. A simulation study is conducted by varying the ratio of the failure rate between omission and value type failures and an investigation is made if there is a significant change in reliability indexes of the service provided to customers when part of the failure is considered as value failure type.

The paper also showed how these failure behaviours affect some commonly used SCN architectures with different level of redundancy. Putting a lot of redundancy has improved the reliability for omission type failure modes, but fail to do the same when value type failure modes are considered. The investigation revealed the need to consider new/different failure modes (value failures) in designing future ICT support systems for smart grid.

Paper E presented a use case that discusses the impact of timing failures on the dependability of an IEC 61850 based ICT support system for protection in smart grid. The contribution for RG-2 is that it discusses the influence of a delay, which is due to a varying background traffic, on the dependability of the protection application. It presents a definition that characterise timing failures in relation to requirements for the protection application with parameters like maximum delay per packet and maximum number of consecutive delayed packets the protection application can tolerate, and how the reliability and availability is dependent on these requirements.

Additional contribution to RG-2a is the case study in paper A which looked into how the introduction of ICT for automating the Fault Location, Isolation and Service Restoration (FLISR) in IEC61850 based distribution grid. The study investigates the impact of automation on the reliability of grids where the fault detection times (repair times) of feeders and the failure rate for new ICT components such as protection IEDs, and Merging units are varied to conduct a sensitivity analysis. The case study investigation showed that an increase in availability of the service is more dependent on the ability of components to detect and locate failures in a short time (lower repair time) than the dependence on the failure rates of the new ICT based components.

5.3 Limitations and Applicability

The contributions discussed on the above sections are highly dependent on the assumptions, input data and methods employed during the thesis work. This section discusses the limitations and applicability of the results and contributions.

5.3.1 Discussion on RG-1

Applicability of the framework

The development of the framework focused on two main features; to have sufficient detail of modelling in both ICT and power system and to present the right level of abstraction for dependability studies. The SAN based framework in Paper A has both properties. Unlike the previous works discussed in Section 3.1, it gives adequate emphasis on both subsystems. However, the early version of the framework has a relatively high level abstraction of the grid.

The SAN approach using the Mobius tool is chosen for scalability and flexibility reasons. In dependability studies, the most commonly used approaches such as the Markov chain models are often dependent on the current state of the system and has a limitation to model the dynamic and structural complexity of future grid systems. The SAN modelling in Mobius provides a conditioned and flexible configuration of transition between states using the input and output gate functionalities. Input gates are used to control the enabling of activities while output gates are used to define the marking changes that will occur when an activity completes. Extended places are also shared among two or more atomic models and are used to model the shared states between different component/atomic models. The use of shared extended places together with the Input and output gates functionality provides the flexibility to model the complex dependencies and interactions of the ICT and the power system.

The framework is also modular where component models are combined to model the subsystems, and then subsystems are connected to form the overall grid system. This helps to easily add, modify or extend part of the system with new functionalities. The Mobius tool also provides an intuitive graphical user interface which make configuration of the model easy.

Another important feature is scalability. As discussed in Section 4.3.2, the instantiation and system topology are represented using an indexed extended places in the atomic models. The use of extended places makes it feasible to create instances and include a wide range of ICT and power components into the model. However, the instantiation does not apply for transitions between states. In the developed framework, either transitions between states should be created for each instances or single transitions can be used if the modelled activities does not necessarily take place simultaneously. Hence, in its current form, the use of the Mobius tool for the SAN modelling has a limitation in this regard.

On the other hand, the framework is scalable in terms of execution time in such a way that large size systems can be investigated. Tens of years simulation of the grid usually takes few seconds (for hundreds of system elements) to minutes (for thousands of system elements) provided that the study focuses on high level interaction and dependencies between components, i.e., discrete event simulations without power flow or state estimation calculation. Integrating the detail dynamics, such as power flow or state estimation, may significantly increase the simulation time to hours. With increasing system size, this use of external c++ functionality is expected to be the main bottleneck for the scalability.

The core SAN based framework used in Paper A to Paper C is mainly suited for system level dependability studies such as the influence of architectural changes and new interdependencies between components and subsystems. The introduction of external libraries into the SAN framework in Paper D and paper E enabled it to capture more detailed representation of the grid and extends the frameworks capability to model the relevant dynamic behaviour in both subsystems, i.e., representation of the latency dynamics in ICT as well as the power flow and state estimation in power systems. Though this was doable as the thesis work (Paper D, E and F) showed for basic power system and ICT operations, it needs to develop new libraries for the specific purpose to be studied which requires a lot of effort and time. The use of specialised simulators, such as ns-3 for ICT systems and PowerFactory - DIgSILENT for power systems, would have been easy to setup and give more accurate results. However, due to factors inherent to the design of Mobius, I was not able to link and synchronise the simulators with the SAN framework in Mobius. In summary, the developed framework is more useful for high level dependability studies focusing mainly on structural and functional dependencies. Whereas, for a very detailed modelling of the grid, the use of specialised simulators with interface frameworks such as Mosaik [SST11] and FMI [BOA+11] seem to be a good choice.

Failure and recovery times

A Markovian assumption is considered in all the case studies of the thesis work where a negative exponential distribution is used for the failure and recovery processes. For some activities such as a battery backup during power outage, a deterministic distributions are used. Though the Markovian assumption is a commonly used assumption in the scientific community, this might be considered as a limitation as it may not accurately describe the real operational behaviour. In order to get the proper distribution, data from real smart grid system should be collected and data fitting to a known distribution can be used. However, the case studies in the thesis work assumes the future distribution grid which mainly consists of new components and it is almost impossible to get failure and recovery data for them. In addition, for modelling failures due to factors such as weather conditions, rain or fading effects, the thesis work relied on models and approximations obtained from the literature.

5.3.2 Discussion on RG-2

Availability of empirical data

The representativeness of the input data is an important factor when studying the dependability of the future grid. The difficulty in getting a realistic input data for the case studies limits the representativeness of the example cases in the thesis work. For some of the power system components, data from a Norwegian grid operator [sta16] is used. However, it was difficult to get the input data for the newly introduced ICT support system components. For an input data to the ICT system, data from the literature is used in all the six Papers. When there is no enough data from the literature, a conservative estimation based on data from current similar smart grid components is used. In addition, for some of the studies, a sensitivity analysis is applied to investigate the impact of the uncertainty in the input data.

Other failure modes

The components of distribution grid may fail in a number of different ways. Based on [ALRL04], failures can broadly be classified into the following three; omission, value and timing failures. The thesis work looked into all these failure modes and has showed new insights on their effect on the dependability of the grid. Unlike most previous works, the case studies has looked into the impact of unintentional value failures in the ICT support system as well as timing failure in ICT due to a background traffic. However, considering the future smart grid, it is important to look into various potential fault scenarios. For instance, a rigorous study on the impact of intentional/malicious attack on the ICT support system is very crucial as the grid is a critical infrastructure, and nowadays we are witnessing a well organised and advanced attack on such infrastructures.

Avizienis et al.[ALRL04] classified fault types into six as discussed in Section 2.2. The thesis work has mainly looked into physical, environmental and design faults (with software failures). The value failures to some extent falls into one of the other three categories; it could be due to transient, intermittent or operational failures. The thesis work provides some insight to considering different fault types and modes and a future work in this direction especially studying new failure modes of ICT components and a study on the frequent unintentional/accidental faults such as software faults, configuration problems, human error (operational faults) etc. [RBM09] is very crucial.

According to [RPK01], interdependence-related disruptions or outages among multiple infrastructures can be classified in to cascading, escalating, or common cause. The framework can be used to study all the three types of failures. Escalating failures (failures exacerbated by an independent disruption of a second infrastructure) are considered in some of the included papers such as Paper A and paper B where the recovery time of power lines becomes higher if an ICT failure has already occurred. Similarly, cascading failures are also considered in a limited way such as in paper B where a failure in the ICT subsystem induces a failure in the power system. Common cause failures, where a failure occurs in both the power system and ICT at the same time, are not considered in this thesis work.

Representativeness of topology and operational behaviours

The case studies of the thesis work are made on two basic applications of the smart grid: protection application and wide area measurement systems. For these applications, the topology for the power system, basic functional dependencies and interaction between components are mainly obtained from literature. In addition, for wide area measurement systems, a cross disciplinary cooperation effort was carried out in Paper D and F.

One of the challenges in studying the future grid is the lack of empirical data for validating the framework. It is impossible to set a reference system as empirical observation of system level measures for such future system can not be obtained. There are some well known reference topologies/systems such as the RBTS [BL94] which are often used for comparing and validating different approaches in studying the reliability of power systems. However, these reference systems do not reflect the new interaction and interdependencies among the new power system components. They also lack the cyber part and they would not be a good choice to study the complex cyber-power system interdependencies of the future grid.

The thesis work address this challenge by incorporating an ICT support system on top of a power system topology from previous literature. It started with simple power system topology, and at a later stage a standard IEEE distribution network is used. In paper A and Paper B, a simple physical distribution grid topology from [KDS08] is considered. The topology is modified to include new ICT based components where the ICT support system architecture is designed based on the IEC 61850 standard.

The same principle is used on the subsequent papers, but with an IEEE 33-bus standard distribution network [BW89]. The advantage of using an IEEE standard topology is the ability to validate part of the model i.e., power system algorithms such as power flow calculations. For the ICT system, novel 5G based architectures are considered where the placement of sensors and ICT components is made to fit the power system topology. It has to be noted that this could be taken as the first step in studying the future grid. Even tough the placement of ICT components and the design of the ICT support system architecture may not be optimal, the presented case study investigation gave quite useful insight on the potential impact of introducing ICT on the reliability of the grid.

Chapter 6

Concluding Remarks

6.1 Conclusion

In next generation distribution grids, the exploitation of ICT is expected to bring a significant enhancement in the management and operation of the power network, in terms of better performances and reliability. However, the digitisation of the grid has also brought some dependability challenges as the power grid is becoming heavily dependent on ICT for its normal operation. Many more new challenges are anticipated in the future when ICT is used in a larger extent. These new challenges and behaviour of the the future grids can not be studied with the conventional approach and methodologies. Modelling of the next generation grid requires new methods and comprehensive approaches that can be used to study and analyse the interaction and interdependency between power system and the newly introduced ICT support system. The methods should be able to model the new characteristics, challenges and the higher complexity in the future grids.

In this regard, the modelling framework proposed in this thesis is useful to conduct a holistic dependability assessment of future grids. It presented a simple way to model the system level interaction and dependencies that are relevant for a dependability assessment. Another important characteristics for such modelling approaches is the flexibility and scalability. The framework presented provide the flexibility to easily extend the model with new features. It is also scaleable providing the ability to model large size systems.

Most state of art approaches that are used in studying and analysing the smart grid are co-simulation approaches, sometimes extended with the integration of hardware-in-the-loop (HIL). These approaches are often designed to model the detail dynamics of the system, and requires a considerable time and effort to setup and conduct the analysis. However, for dependability studies on a system level properties, architectures or high level interaction and dependencies, the framework presented in the thesis can be considered as a better alternative. It is relatively easy to setup, and require less effort and time.

In developing and testing the framework, some potential future challenges were identified and use cases were created. Dependability investigation using the framework were conducted on these future challenges. The investigations gave insight on how the dependability of the grid is affected by the growing dependency on ICT. Most previous investigations on the reliability and dependability of the grid, either does not consider the dependency on ICT or they have a minimal assumption of the dependency. The work in this thesis showed how severe will be the impact on the overall dependability of the grid when we consider the tight interdependency between the future power system and the ICT support system. A good example is the case on value failures of ICT components. In assuming a small fraction of the ICT failures to be of a value failure type due to malfunctioning, software glitches, human errors or intentional attacks, the analysis showed that these failure modes may result in a significant change on the availability and reliability indexes. In addition, the prospect of using new ICT technologies and architectures were also investigated. The preliminary investigation on the use of new technologies and architectures such as 5G for wide area monitoring systems and the IEC 61850 based architectures for substation automation were promising, tough it needs more rigorous and further detailed analysis for future adoption of these technologies.

6.2 Future work

There are many interesting research directions for future work. One potential future work related to the framework developed in this thesis is to improve its usability. Even tough the framework has strong capability to make a holistic assessment of the grid, setting up the topology may still take some time. The interconnection/topology and interdependencies has to be entered manually. This can be improved by automating the model creation process with partial generation of the topology of the system based on a standard representation (with visual support). There were also some technical challenges in using the Mobius tool such as lack of flexibility to link it with other models or simulator tools. Hence, in automating the process, it may also be considered to use other similar tools that support SAN modelling.

In relation to this, another future work would be to create (component) models and form a library that can be re-used in the future with minor customisation. The use of such generic or standard models will help researchers to save a lot of time and effort in the future.

In regard to new challenges arising in the future grid, an interesting research direction is to look into the trend of applying the virtualisation concept, a well known concept to the ICT industry, to the power grid. Many functions which were performed by a dedicated hardware are nowadays replaced by a software or virtualised system. The intelligence/control logic is often moved to a different place such as a centralised server or a cloud. This will bring many benefits such as more flexibility, better overview and optimised control etc. However, it is important not to blindly rely on these technologies and architectures. The dependability of such systems should be carefully investigated. This thesis has presented a preliminary investigation on the challenge in moving towards the digitisation of some power system functions. In the near future, the softwarisation and virtualisation of power system functions is expected to be widely employed. There will also be new actors such as advanced prosumers, energy communities and other flexibility or ancillary services provided by third parties etc. that can also be benefited from the digitisation of the grid. Therefore, further study and analysis on the dependability and performance of such new technologies and architectures is vital especially for utilities as they need to have a better preparedness for these changes.

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Part II

INCLUDED PAPERS

Paper A

A Modeling Approach for Dependability Analysis of Smart Distribution Grids

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Abstract

The distribution grids are among the most critical infrastructures which integrates advanced control and communication technologies atop of power systems. This paper presents a comprehensive modeling framework suited to study the resiliency and dependability of the next generation distribution grid. It focuses on revealing insight in the complex interaction and dependencies between the ICT based control system and the power-grid. It looks into the role of automation and new technologies in future distribution grids. The objective is through a quantitative assessment to identify vulnerabilities and to study alternative design principles and architecture of the automated distribution grids. The modeling framework is general and modular based on a stochastic activity networks using the Mobius tool. For illustration, a case study is included at the end.

I. Introduction

Smart distribution grid is a modern electric power infrastructure which integrates advanced control and communication technologies in power systems. It is among the most critical infrastructure which can be considered as a system of systems. More ICT-based control system is about to be introduced. Architectural changes such as the deployment of multiple micro-grids within the distribution grid has been also increasingly introduced into the distribution grid. The micro-grids with their own local controllers continually interact to each other and they are also capable of operating independently during some situations. There will be strong interdependencies between the power grid and the ICT based support system. As a result, the resulting quality (performance and dependability) for an end-user is demanding to assess.

This paper aims to presenting a modeling framework that is suited to study the resiliency and dependability of the 'next generation' distribution grid. The main focus is to include the complex interaction and dependencies between the ICT based control system and the physical grid (sub)systems. The intended use, beyond performing a quantitative assessment, is to identify vulnerabilities, provide insight which may guide design principles and architectures of the automated distribution grids.

Significant previous work have been carried out towards this objective, mostly by simulation. However, Menasché and others have presented a Markov model taking into account into account the dependency of the communication infrastructure during power lines failures [1], [2], [3]. A limitation of the analytical approach is the ability to include a wide range of ICT and power components, as well as the dynamic and structural complexity of such systems. Most simulation studies do either put emphasis on i) the ICT based control infrastructure [4], [5], [5], [6], [7], [8], [9], [10], e.g., focusing on cyber attacks [8], [9] or an SDN driven ICT infrastructure on top of the power grid [10], [11], or on ii) the power dynamics [12], [13], [14], [15], [16]. However, there will be a strong coupling and dependence between communication and control systems and power grid that may induce large scale failures due to cascading effects as discussed in [17], [18]. Hence, it is important to establish a comprehensive modeling framework of the structure and the mutual dynamics of both (sub)systems.

Buldyrev, Gao & al. addresses these issues using a point to point interdependency models where a power node fails if the communication node associated to it fails and vice versa [19], [20]. More recent papers by Parandehgheibi & al. [21], [22], though focusing on specific scenarios, showed that 'point-wise' failure model is not appropriate.

Chiaradonna & al. [14], [15], [16] presented a compositional stochastic modeling framework for distribution grid with a focus on dependencies between the control and the physical grid. Though the paper presented a generic model, it still doesn't provide an equal emphasis on the two (sub)systems. It concentrates more on modeling the detail behavior/dynamics of the power grid by capturing system states using Power, Current and Voltage values.

The framework proposed in this paper has a simpler abstraction of the physical grid, but with an extended emphasis on modeling the failure processes and dynamics on the communication and control infrastructure. This approach is chosen for scalability and for modeling new emerging technologies, operational and architectural changes and automation in the distribution grid.

The remainder of this paper is organized as follows. Sect. II presents the smart distribution grid layout comprising the ICT support system and physical grid with the generic assumptions considered. Sect. III introduces the proposed Modeling framework. Then, in Sect. IV a case study scenario showing the effect of automation and introduction of new technologies in fault identification, location and service restoration of distribution grids is presented with an illustration of simulation result. Finally, Section V gives the conclusive remarks and future works.

II. System Description

This section describes the main components, operational behaviors of the distribution grid and some major assumptions considered in the modelling framework. A distribution grid that consists of a physical grid with typical voltage levels below 33 kV and an advanced ICT based support system to enhance its operation is considered.

A. System Topology

The framework is generic and flexible. A distributed architecture consisting micro-grids, a centralized controller architecture with one controller at the substation, or a combination of the two can be used. An example is shown in Figure 11 which provides an overview of cyber-physical distribution grid used for the case study in section IV. The grid can be viewed as consisting of two planes; the physical grid and the ICT based control system. It is assumed that power flow is bidirectional where power can flow from the substation to the customer side and vice versa. The physical grid consists the following main components:

- Feeders: Medium and Low voltage power lines carrying power between substation and customers.
- Substation unit/Generator: main source of energy to the distribution grid. This is used to model the power supply from the transmission grid.
- Distributed Generators: locally installed energy supply to the distribution grid. These are used to model locally controlled renewable, flexible energy source such as wind turbine and solar panels.
- Transformers: used to step up/down voltage.

The plane on top of the physical grid is the ICT based support system. It mainly consists:

- Controllers: These can be a central controller at the substation responsible for an overall monitoring and management of the distribution grid or a local controller monitoring local components in a distributed control architecture.
- Sensors: devices such as Merging Units that are used to monitor and transmit information to control units e.g., controllers and Protection IEDs.
- Actuators: devices such as switches and isolators that are used to regulate (connect and disconnect) power grid components eg. feeders.

- Protection IEDs: devices such as relays installed on the power lines which are assumed to take measures during a failure in the physical grid. These devices are assumed to exchange information among each other and make a decision based on the information received from sensors.
- Smart meters: used to monitor and control customer side equipments and power usage for e.g., during demand response negotiation.

The sensors, control and protection devices are connected to local controllers through a wide area network as the operator often needs to have a full control on the quality of the communication for operational activities involving these devices. Meanwhile, customer side devices (Smart meters) can also be assumed to be connected to a controller through the Internet for scalability reasons as well as for the fact that there are no stringent requirements for operations involving customers such as demand response.

B. Outline of System Behaviour

The major principles and operational behaviours mainly related to failure process and service restoration showing the interdependency between the ICT based control system and the physical grid are discussed below.

All components from both the ICT based control system and the physical grid could fail permanently from random accidental faults which needs to be repaired by a maintenance crew. In addition to the permanent failures, temporary failures are also considered for some ICT based components such as protection IEDs/relays. Though it is not included on this paper, the framework is also suitable to consider simultaneous/weather related failures as well as malicious attacks. For controllers, considering some functionalities to be added due to the introduction of new ICT based components, software failures are also taken into account where a simple restart could neutralize it or it could end up as a permanent failure. The failure processes for all components is assumed to be a Poissonian process. In this study, omission type of failure semantics are considered on both (sub)systems. The framework is also easily extendable for considering other failure semantics such as value and timing failure semantics.

Once a failure occur in a physical grid component, the fault isolation and detection is dependent on the state of associated ICT based component. If the ICT based component is working, it will neutralize/isolate it safely followed by controllers locating the fault and handling the service restoration. Otherwise, if the responsible ICT components are not working, the failure is assumed to propagate failing neighbour power lines (could be up to substation unit) which covers a relatively larger section of the grid unless the ICT components in neighbour lines are in a working state to isolate the failed component.

When a component from the ICT based infrastructure fails, it won't have an immediate consequence on the physical grid. However, their failure will propagate to the physical grid if there is a need to use the failed ICT infrastructure before it get repaired.

After detection of a failure, the controller is responsible for reconfiguration of the grid topology, redistribution of power and updating system state. Distributed generators can be used as a backup during failure restoration. Besides, load shedding as well as demand response (i.e. negotiating with customers to lower their demand) can also be considered if there is a shortage of power supply.

A limited repair resource is considered where there is one maintenance crew at the (sub)systems. For physical grid components, the repair process comprises time to locate the failure which highly depends on the availability of ICT infrastructure during the failure and time needed for handling the maintenance.

III. Modeling Framework

A Stochastic activity network model [23] is developed to study the Smart distribution grid. The model is developed using the Mobius tool [24]. It is a general and composable stochastic model, which is built from atomic block models.

One template, an atomic model, is developed for each type of components in the distribution grid. An example is shown in Figure 1. An instance for each of the components is then created using an indexed extended places in the atomic models. This is similar to the concept of colored tokens where the movement of one token represent a behavior of one component. Extended places are special elements in the SAN formalism that allows the model to handle the representation of structures and arrays of primitive data-types(places) [24]. Each position (place) in this array contains a certain number of tokens, and the state of one component is determined by the number of tokens (marking) in a given position of the extended places.

An atomic model, say a Protection IED, learns about the state of other atomic models such as the feeder through the unconnected places as shown at the top of Figure 1. These extended places are shared among two or more atomic models and are used to model the dependencies and interconnection between components as discussed in section III-C and section III-D. Input gates are used to control the enabling of activities while Output gates are used to define the marking changes that will occur when an activity completes. An Output gate changing the marking in the shared extended places is used to communicate information among atomic models. The overall distribution grid is modelled by connecting the atomic sub-models using a 'Join' composed model formalism as shown in Figure 10.

A. *Atomic models*

Atomic model templates are developed for the individual components of the ICT based control system and the physical grid. These are described in the following subsections.

The ICT based control system comprises seven atomic sub models; Controllers (C), Protection IED, Intelligent Switch (IS), Merging Unit (MU), Communication Links (Comm), Switches/Routers (Switch) and Smart Meters (SM).

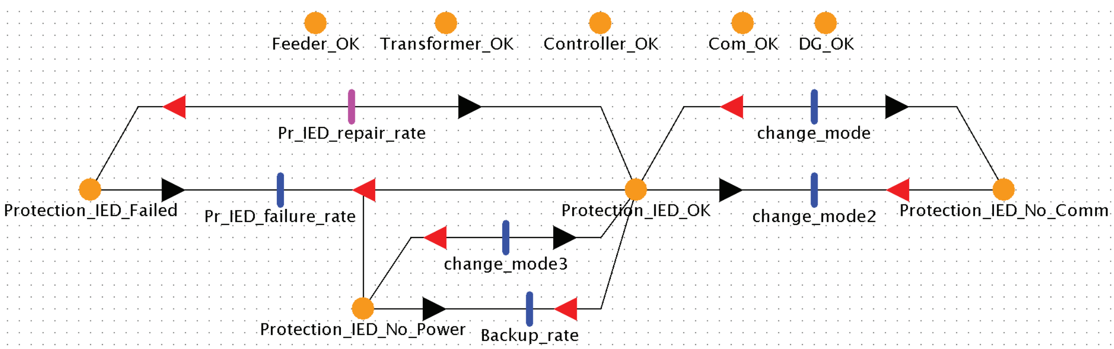

Fig. 1. An atomic model of Protection-IED.

1) Protection IED: Figure 1 shows the atomic model for a Protection IED which is used to model advanced protection devices such as digital relays. It consists of four extended places; Working (PR_IED_Ok), failed power supply - No power (PR_IED_No_Power), failure in communication link - No communication (PR_IED_No_Comm) and Permanent failure (PR_IED_Failed). From initial working state in PR_IED_Ok, a protection IED could end up in a PR_IED_No_Comm state if all the communication nodes/links towards it are not in their working state. A Protection IED could also have a local communication to sensors and actuators it monitors while there is no communication path towards neighbouring protection IEDs or towards the controller. Such cases are modeled by different markings of the PR_IED_No_Comm and PR_IED_Ok extended places.

A working state in PR_IED_OK can either instantly or after some battery time switch to a no power state in PR_IED_No_Power if its power supply is lost i.e. the feeder providing power supply is no more in its working state. Protection IEDs could fail from all other state to a failed state in PR_IED_Failed which needs maintenance. The failure rate in active states (such as PR_IED_Ok) can be set to a higher value than passive states (such as PR_IED_No_power) by using a conditional failure transitions.

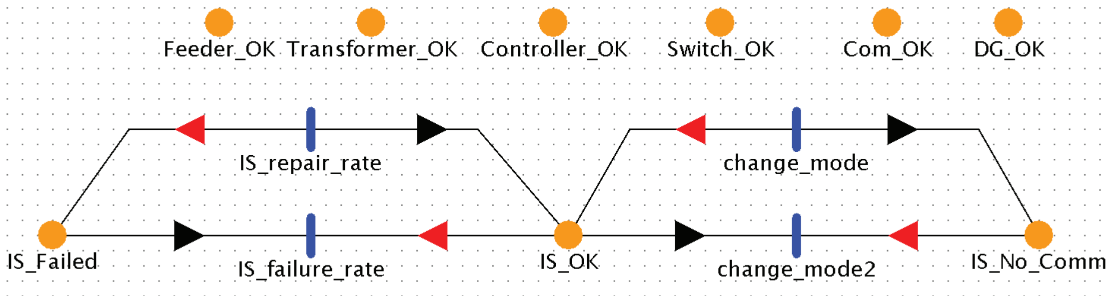

Fig. 2. An atomic model of Intelligent Switch.

2) Intelligent Switch: Figure 2 shows the atomic model for an Intelligent Switch (IS) which is used to model advanced breakers, normally open or close switches that can be remotely operated or tripped. It consists of three extended places; Working (IS_Ok), failure in communication link- No communication (IS_No_Comm) and permanent failure state (IS_Failed). From the initial working state in IS_Ok, an Intelligent Switch could end up in a No communication state in IS_No_Comm if all the communication nodes/links towards it are not in their working state. An Intelligent Switch could also have a local communication with protection IEDs while there is no communication path towards the controller. Such cases are modeled by different markings of the IS_No_Comm and IS_Ok extended places. Intelligent Switches could fail from all other states to a failed state (IS_Failed) which needs maintenance by a repair crew.

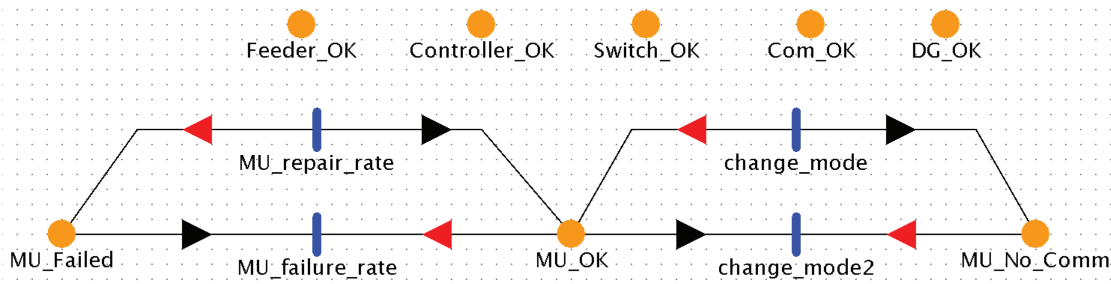

Fig. 3. An atomic model of Merging Unit.

3) Merging Unit: Figure 3 shows the atomic model for a Merging Unit (MU) which is used to model advanced sensors such as current/voltage transformers that can digitize the original current and voltage signals and send them through a communication network. The Merging Unit model consists of three extended places; Working (MU_Ok), failure in communication link- No communication (MU_No_Comm) and permanent failure (MU_Failed). The model's behaviour is similar to the behaviour of Intelligent Switches discussed above.

4) Communication Link: Figure 4 shows the atomic model for Communication links that are used to connect all ICT based components in the grid. It consists of three extended places; Working (Comm_Ok), failure in Switches/routers to which the communication link attached to - No communication (No_Comm)

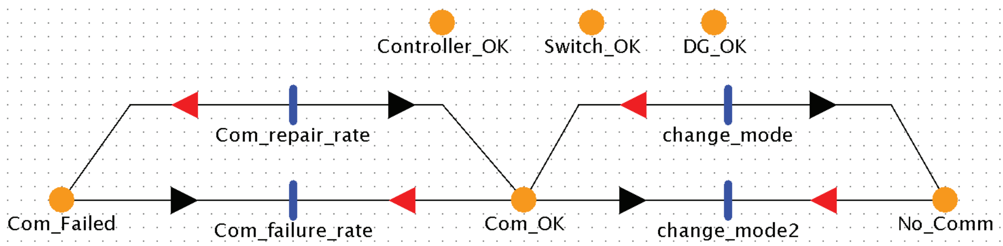

Fig. 4. An atomic model of Communication links.

and Permanent failure (Comm_Failed). From initial working state in Comm_Ok, a Communication link could end up in a No_Comm state if all the switches/routers to which the communication link attached to are not in their working state. There could also be a situation where there is a local communication to/and from the connected switch, but without communication beyond the switch/router. Such cases, providing partial service, are modeled by different markings of the No_Comm and Comm_Ok extended places. Communication links could fail from all other states to a failed state (Comm_Failed) which needs maintenance by a repair crew.

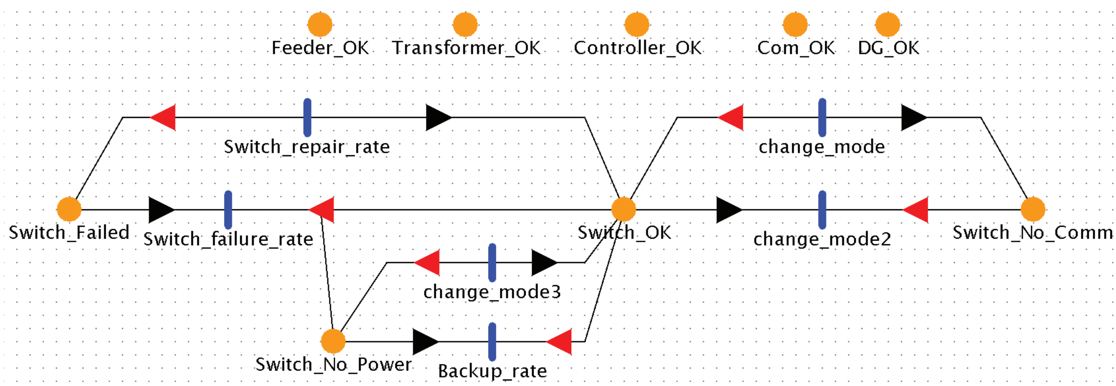

Fig. 5. An atomic model of a Switch.

5) Switch/Router: An atomic model for Switches and/or Routers is shown in Figure 5. It consists of four extended places; Working (Switch_Ok), failed power supply - No power (Switch_No_Power), failure in communication link- No communication (Switch_No_Comm) and Permanent failure (Switch_Failed). The transitions between the extended places are similar to the transitions discussed above in Protection IED atomic model.

6) Smart Meter: Similarly, Smart meters, shown in Figure 6, are also modeled by four extended places; Working states in (SM_Ok), failure in communication link - No communication (SM_No_Comm), Permanent failure (SM_Failed) and No power (SM_No_power). The transitions between the extended places are similar to the transitions discussed above in Protection IED atomic model.

7) Controllers: Figure 7 shows the atomic model for the Controller. It consists of four extended places; Working state (Controller_Ok), Software failure (Controller_Soft_Fail), Permanent failure (Controller_Failed) and No power state (Controller_No_Power). A software failure in controllers is either restored by a restart or it might lead to a permanent failure. The controller could fail permanently

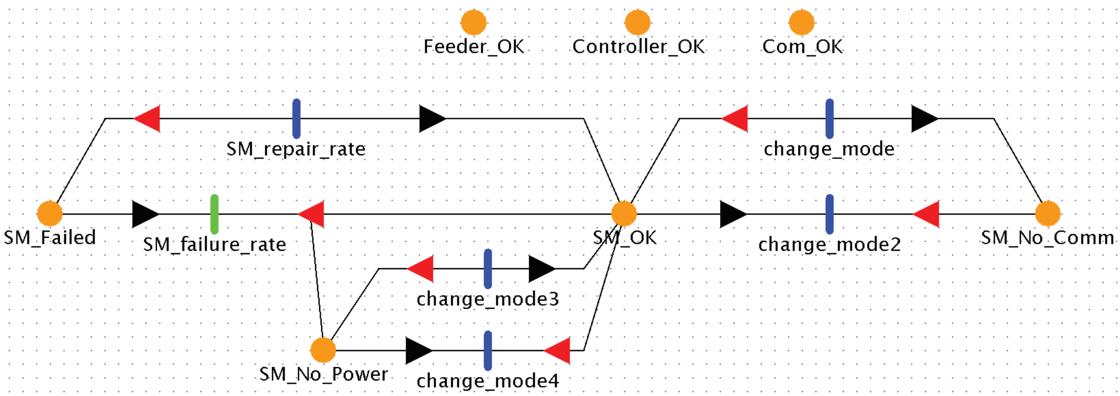

Fig. 6. An atomic model of a smart meter

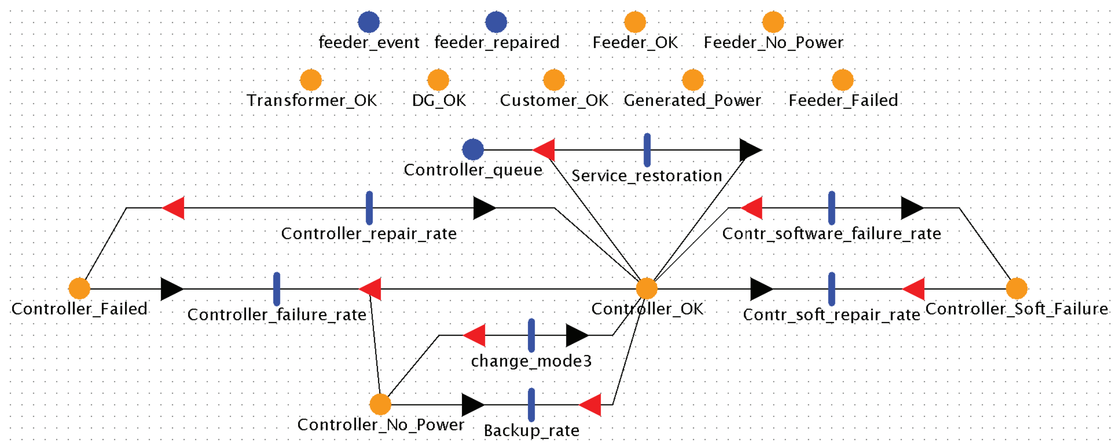

Fig. 7. An atomic model of a controller

from all other state which needs maintenance by repair crew. If the power supply of the controller is lost, the controller changes its state from a working state in Controller_Ok to a no power state in Switch_No_Power after holding for some battery time. Whenever there are faults in major components, the controller is informed through Controller_queue and it will check the stability, reconfigure the topology, manage/regulate all the components and update the system state. Major tasks such as demand response and reconfiguration are assumed to take some time.

Similarly, atomic models for the physical grid are developed for feeders, transformers and distributed generators (DG).

8) Feeders: Figure 8 shows the atomic model for the feeders. It consists of three extended places; Working (Feeder_Ok), Permanent failure (Feeder_Failed) and No power (Feeder_No_power). Failure of a feeder in a working state is either handled by the responsible protection IED (safe fail) if the ICT based control infrastructure is in a working state or it might lead to a failure cascading into upstream feeders if the associated ICT based protection system is also failed. These two failure situations are modelled

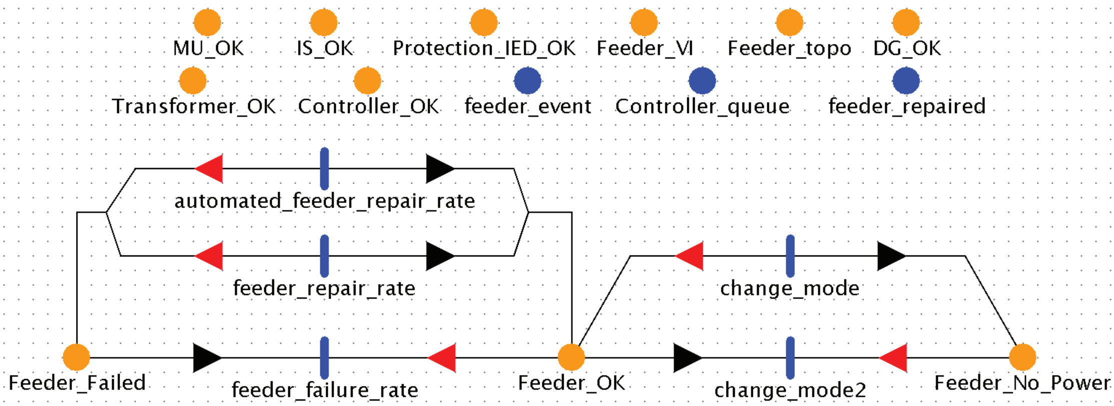

Fig. 8. An atomic model of a Feeder

by different markings in the Feeder_Failed extended place. The feeder could also fail permanently from all other state which needs maintenance by repair crew. Here also, the failure rate in active states (such as Feeder_Ok) can be set to a higher value than passive states such as Feeder_No_power. A feeder in a working state will instantly switch to 'No Power' state if the feeder from which it gets power is not in a working state.

The repair time in a feeder is composed of a time needed to locate the fault and time needed to do the actual maintenance. Time needed to locate the failure is assumed to be dependent on the failure situation modeled in the failed states in Feeder_Failed extended places. A repair of feeder where the ICT support system has also failed will take a longer time. Transformers can also be modeled using a similar atomic model.

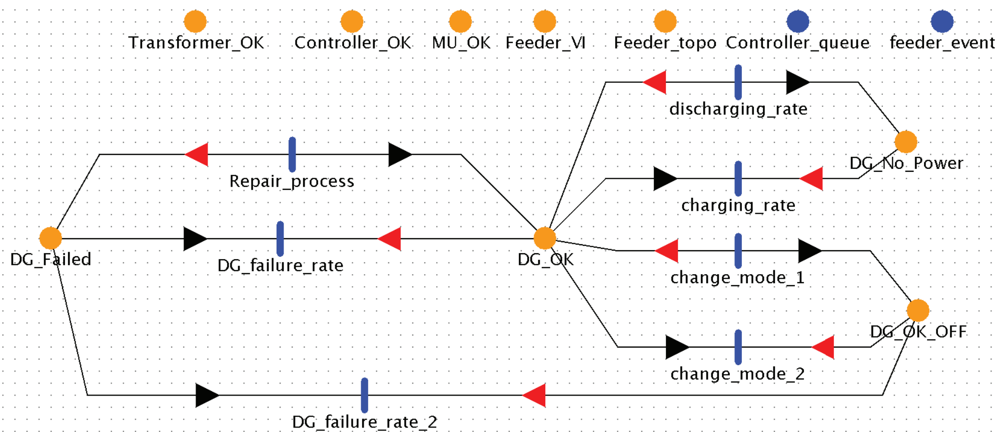

Fig. 9. An atomic model of a Distributed Generator(DG)

9) Distributed Generators: Distributed generators, shown in Figure 9 are modeled by four extended places; Working states (DG_Ok), off state (DG_Ok_OFF), Permanent failure (DG_Failed) and a No power state(DG_No_power). The model assumes that Distributed generator's initial state is 'DG_OFF'. It can be turned on and off by a controller when there is a need/shortage of power. Turning on and off the Distributed generators can also be set regularly based on the load pattern. From the working 'DG_Ok' states, Distributed generators might end up either in 'DG_No_power' state if it has been used continually until it run out of power or in off state in DG_Ok_OFF if the controller decide to turn off it. Distributed generators could also fail permanently from all other states where the failure rate in active states (such as DG_Ok) can be set to a higher value than passive states such as DG_Ok_OFF and DG_No_power.

B. Composed model

The overall distribution grid is modelled by connecting the submodels using a 'Join' composed model formalism as shown in Figure 10. The dependencies as well as interconnection between components are modeled using shared states/places as discussed in the following sections.

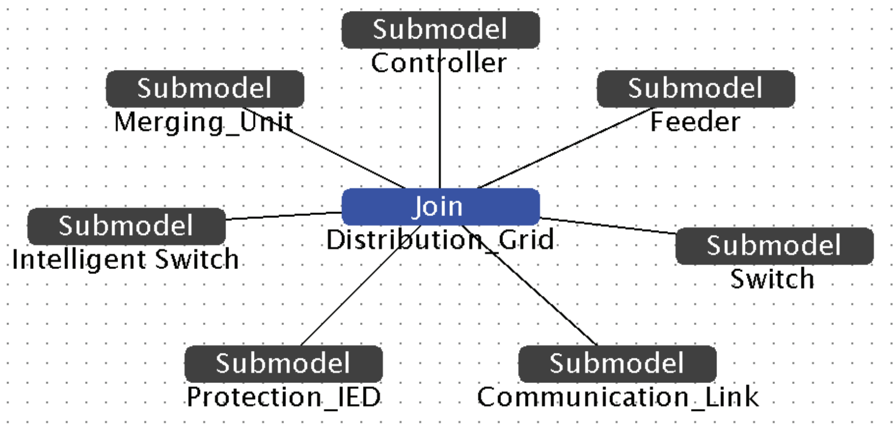

Fig. 10. Composed model of distribution grid

C. Topology modeling

The structure and interconnection between all the components is modeled using shared places. These places are defined in the composed model and are shared among all atomic sub-models whose normal operation is dependent on these places. If the enabling conditions for an activity/transition between states in a component is dependent on the state of another component, the extended place that contain the state of the other component will be defined as a shared place and a condition can be set in the first component using this shared place. Besides, a special extended place Feeder_topo is used to keep track of topology/structural information so that each feeder component can look into this array and learn about the topology i.e., to which feeder it is connected to.

As an example, let us consider the feeder model shown in Figure 8 and assume that this specific component is connected to (getting power from) a transformer. Feeder_Ok is shared among a Feeder atomic sub - model and a Transformer atomic sub- model. The Feeder model will instantly switch (modify the markings) from working state in Feeder_Ok to a no power state in Feeder_No_power if the specific transformer to which the feeder is connected leave its working state. This is done by defining an enabling condition for the transition in the Feeder dependent on the shared extended place Transformer_Ok so that Feeder can look into the component (in this case the transformer) from which it gets power supply. In this way, a failure in one component propagates through out the structure unless there are mitigation and protection mechanisms such as by controllers. Such approach makes it flexible and easy to add and/or remove components in modeling the topology and interconnection among physical grid components as well as ICT based control systems.

D. *Interdependency between Power and ICT based control system*

The interdependency between Power grid and ICT control systems is also modeled using shared places. The model of physical grid components include shared places from the ICT component to which they depend on for their normal operation. Similarly, places from the physical grid components are also included in the model of ICT based control system components to model power supply dependency of ICT components on the physical grid. As an example, looking into the atomic model of the controller on Figure 7, the transition from Working state in Controller_Ok to a no power state in Controller_No_Power is programmed to be dependent on a specific power line feeder to which the controller is connected to. i.e. the transition will be enabled and executed if the failed feeder could not be maintained within a backup battery time. And similarly, the transition from no power state in Controller_No_Power back to the working state in Controller_Ok is also made to be dependent on the working sate of the feeder and it will be enabled as soon as the underlying power node is maintained.

E. *Reward model/Metrics*

Reward models are used to study the dependability and survivability of the distribution grid. In this study, we compute metrics related to Availability of the service and down times (SAIDI indexes) experienced by loads. Metrics are obtained by assigning a reward to states of interest and statistics will be collected every time the system visits this state. The final result, often a mean value, is proportional to the time the component/system stays in that state.

The measurement can be made on any components, but the study focuses on customer/load side measurements at the smart meters. There can be a variety of measures of interest to final customers and the service provider. In this paper, the following two main metrics are used.

- Availability of Service/power: to measure the availability of the service to an end user/load. This can be obtained by assigning a reward of one when the smart meter of an end user is in a working state. In the presentation of numerical results, the unavailability is used, $U = 1 - A$.
- Service downtime (SAIDI): to measure time the end user lose access to the service/power This is also obtained using reward model on smart meters. It is possible to measure aggregated values for the entire system or measure the individual SAIDI values/distributions experienced at any point/load which can give some architectural and topological insight.

IV. Case Study

To illustrate the capabilities/features of the proposed framework, the role of automation in Fault Location, Isolation and Service Restoration (FLISR) in distribution grids is investigated. A sensitivity analysis is used to study the benefit of automation and the effect of new advanced ICT based component failures in the availability of the service/power to end users. See [25], [26], [27], [28] for further information about FLISR.

The FLISR operation consits of two stages; i) detection, fault location and isolation, and ii) service restoration [27]. The following subsections details these stages.

Fault Location Detection and Isolation: When a failure occurs in a working state of a feeder, the appropriate protection IED in charge of the fault location, as per the grid design, detects the fault through its corresponding secondary equipment (Merging units). If the associated ICT support system is working, it isolates the fault area using intelligent switches. If the ICT based control system is failed, the failure will propagate into upstream feeders/components and it may also fail the whole distribution grid. The impact and restoration time required for such active faults depends on the ICT based control's ability in detecting, locating and isolating the fault.

Service Restoration: After fault detection and isolation Using Merging units and Protection IEDs, the substation based controller is responsible to restore power to the maximum possible out-of-service loads/end users within a short time. The restoration process is also dependent on ICT based control system as the controller needs to find suitable backup feeders and transfer the loads in out-of-service areas using remotely controlled intelligent switches. In the proposed framework, the controller prepares a restoration plan that can keep the stability and meet operational constraints of the grid. For this study, a set of alternative topologies are pre-determined and the controller selects a topology that can provide power to most customers.

The physical distribution grid topology from [29] shown in Figure 11, is modified to include new ICT based components and used in this study. The physical grid that consists 16 feeders has a radial topology with normally open intelligent switches providing redundancy between some feeders. Based on IEC 61850 standard topology in [30], the communication network shown in Figure 12 is used for ICT based control system. The ICT based control architecture comprises 6 Protection IEDs, 16 Merging Units, 16 Intelligent switches, 8 switches, 48 communication lines and one substation based controller.

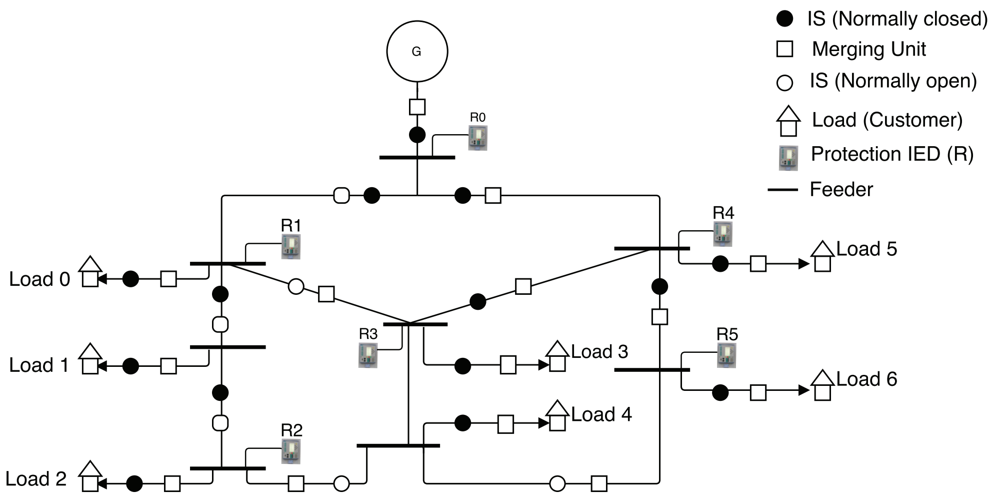

Fig. 11. Distribution grid topology.

It is hypothesized that automation of grids improves reliability by reducing the fault detection and repair times. However this is to our knowledge not thoroughly investigated. In this scenario, the fault detection times (repair times) of feeders are varied to study this. Similarly, the failure rate for protection IEDs, relays and Merging unit is varied to conduct a sensitivity analysis. The failure and repair rates of the grid components are based on [31] and [25] and are presented in Table I. Random times are assumed to be negatively exponentially distributed. For controllers, switches and protection relays, a two hour backup battery is considered during power outages.

Mobius tool supports both numerical solver and simulation with built-in error control measurements. Since the size of the system makes it difficult to use numerical solvers, we have used the simulation solver. The grid is simulated for 90 years and a replication of 20 is used to get a confidence interval range of 10^{-5} and 10^{-6}. The whole simulation, including replications takes around two to ten minutes depending on the ICT component failure rates used. The result for all end users is similar and we have used end user/load 4 as a representative. The resulting Availability of power for end user/load 4 is shown in Figure 13 and the SAIDI values are shown in Figure 14. The results indicate clearly that the Availability and

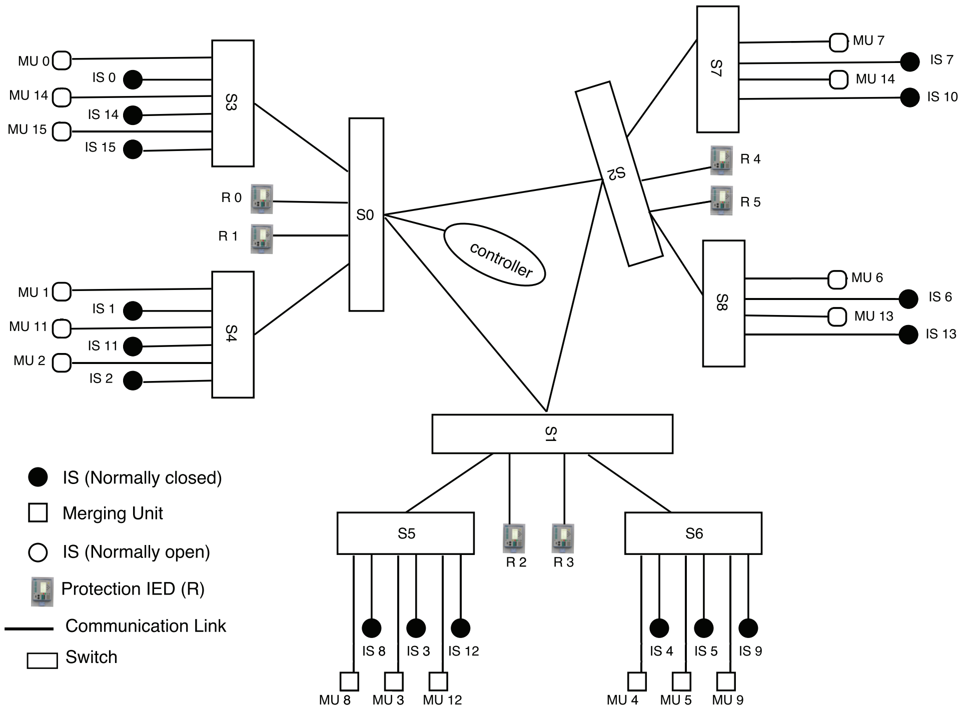

Fig. 12. ICT based control system architecture.

TABLE I
FAILURE RATE AND REPAIR TIME OF THE GRID COMPONENTS

Component type	**Component failure rate (failure/year)**	**Component repair rate (hr/failure)**
Feeder	0.07 per Km	6
Protection IED	0.023	2
Merging Unit	0.0268	2
Intelligent Switch	0.03	2
Communication line	0.068	3
Switches/router	0.2	3
Controller (permanent failures)	0.2	2.5
Controller(Software failures)	12	0.3

SAIDI indices are improved significantly for end users if the new ICT based support system is able to lower the repair time needed for feeders. Considering the assumed dependence of FLISR function on ICT support system, the unavailability is far less sensitive to changes in the failure rate of the new ICT based components as shown in Figure 13. It shows that an increase in availability of the service (lower unavailability) is more dependent on the ability of components to detect and locate failures in a short time (lower repair time) than the dependence on the failure rates of the new ICT based components. This might be due to the conventional, but not entirely realistic assumption, that ICT failures will not induce failure into the power system. It is assumed that the ICT failures could only influence the failure handling

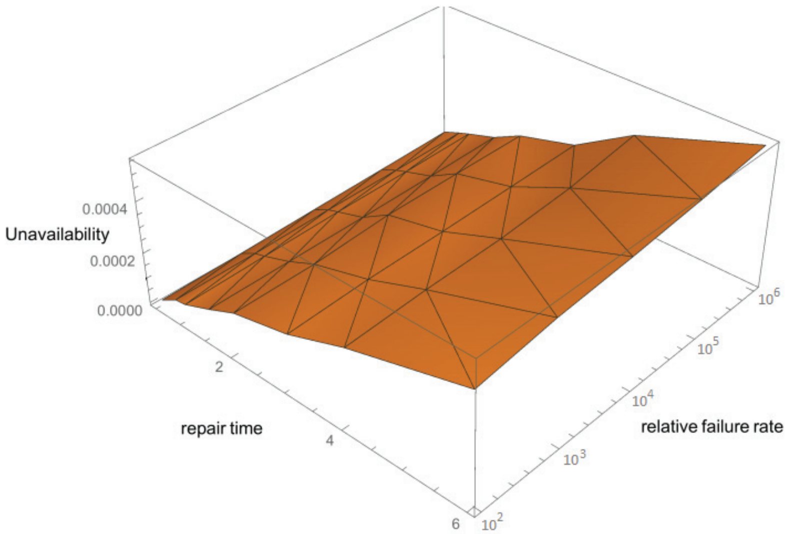

Fig. 13. Unavailability of Load 4. The x-axis is repair time and y axis is the ratio of varying failure rate for protection IED relative to the value in Table I.

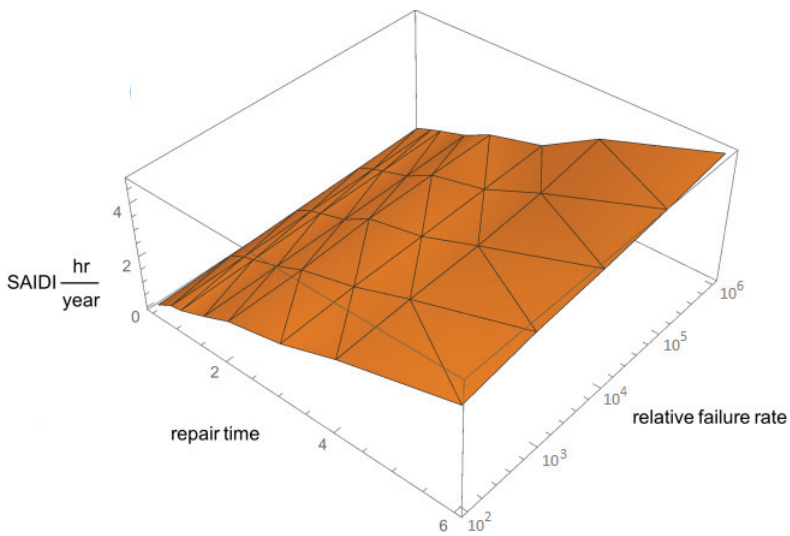

Fig. 14. SAIDI values of Load 4. of Load 4. The x-axis is repair time and y axis is the ratio of varying failure rate for protection IED relative to the value in Table I.

of the power system.

V. Concluding remarks

In advancing smart distribution grids, there will be a strong and complex coupling and dependence between the communication system and the physical grid. This paper has presented a comprehensive and unified approach that provides a balanced view of both communication and power grid subsystems. It is scalable and suited for modeling new emerging technologies that may go into the distribution grid, as well as further autonomic operations, operational and architectural changes. The modelling framework is illustrated by a simple, but realistic, case where the role of automation of Fault Location, Isolation and Service Restoration (FLISR) is investigated.

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Paper B

Dependability Analysis of Smart Distribution Grid Architectures Considering Various Failure Modes

Tesfaye Amare, Bjarne E. Helvik

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Dependability Analysis of Smart Distribution Grid Architectures Considering Various Failure Modes

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Abstract

The future smart distribution grid will be consisting of new components and technologies with enhanced capability whose failure behaviour can not be determined with certainty. In studying the reliability of these distribution grids, it is important to look into various possible failure semantics of the new components and how would they possibly affect the reliability of the distribution grid. This paper aims to investigate/study how the various failure modes of the new components affect the reliability of distribution grids. The focus is on (limited to) reliability evaluation of the feeder protection function of next generation distribution grids considering omission and value type failure semantics. A generic and modular modeling framework based on a stochastic activity networks is used to model the distribution grid. An IEC61850 based automation/substation communication network (SCN) is considered. And, for illustration, different scenarios with different SCN architectures are investigated.

I. Introduction

Advanced control and communication technologies are the key elements in the development of the next generation Smart distribution grid. New components and technologies has been introduced into the distribution grids. There has been also standards such as IEC 61850 which define protocols for Intelligent electronic devices (IEDs) that can monitor and manage the physical grid. The addition of new functions, technologies and control devices will bring new dependencies and failure behaviour that has to be thoroughly studied.

This paper aims to investigate how various failure modes of the new ICT based components will affect the reliability of distribution grids. The focus is on reliability evaluation of feeder protection function in IEC61850 based next generation distribution grids considering omission failures (a failure yield just a lack of response or action) and value/content type failures (An incorrect response is given or a wrong action taken). A brief description of the failure modes is presented in Section II-C. For protection system of a critical infrastructures, such as the distribution grid, insight into the effect of different failure modes/semantics, e.g., caused by malfunction of software/IEDs, is important since value failure may have sever consequences.

There has been some works that has studied the reliability of distribution grids using the IEC 61850 standard for the substation communication network such as [1], [2], [3], [4], [5], [6]. Most of these works focus on proposing a highly reliable communication network architecture assuming omission type of failure semantics for the components. Thomas & al. [2] presented Ethernet-based logical architecture for the substation communication network (SCN) which takes into account fail-stop/omission and timing failures of the IEDs.

Liu & al. [5] proposed a reliable network based upon cobweb topology for reliability of substation communication network. Thomas & al. [4] proposed a redundant ring network focusing on the importance of utilizing the redundant critical components/communication paths in achieving high reliability and performance while Sidhu & al. [7] presented IEC 61850-based IED models to study the reliability of substation network for different types of network topologies.

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A Parallel Redundancy Protocol (PRP) is proposed in the IEC 62493-3 standard which duplicates the LAN in the process bus communication network to provide zero switch over periods in case of any single LAN failure. The study in [6] also presents a PRP scheme where conventional IEDs can be used and cost can be optimized.

To our knowledge, most previous works such as [1], [2], [3], [4], [5], [6], [8] has focused on improving the reliability and performance of IEC based distribution grid with an assumption that the failure is of omission type. In such assumption, a failure in ICT domain will not immediately cause a failure in the physical domain. The propagation of failure into the physical grid will occur only if there is a need to use the ICT control system that has failed. However, in advanced smart distribution grid, there can also be a possibility where a failure in cyber components could instantly propagate into the electrical components and result in a more sever consequence. In a value failure mode, a failure in ICT based control system could produce a wrong result which could induce a failure in the physical grid affecting the service provided to end users. Hence, considering a critical infrastructure such as the distribution grid, all possible failure modes has to be thoroughly investigated [9].

This paper looks into how the reliability of the distribution grid is affected in assuming different failure modes, mainly value and omission type failures. An extended model of a stochastic activity network based model proposed in [10] is used. Furthermore, different architectures of the IEC 61850 based substation communication network, proposed by previous works, are investigated and compared for the different failure semantics considered.

The rest of the paper is organized as follows: The smart distribution grid system and the major assumptions considered in the study are discussed in Sect II. Sect III presents the model. In Section IV, simulation scenarios and an illustration of the results is presented. Lastly, Section V gives conclusive remarks of the work.

II. Major Assumption and System Considered

A. Substation Communication Network (SCN)

The study considers an IEC61850 based substation communication network. The focus is on the protection system which consists of the electronic components such as protection IEDs, Merging Units, Intelligent Switches and circuit breaker IEDs. These components are assumed to be connected to an Ethernet switch through communication links to form a substation communication network.

Merging Unit IEDs collect and transmit sampled value data(current and voltage) to the protection IEDs. Protection IEDs basically receive the sampled values from the Merging Units, perform substation protection functions and send decision/trip signals to circuit breakers connected to the process bus. These devices are also assumed to exchange information such as breaker failure protection or status information among each other by sending Generic Object-Oriented Substation Event (GOOSE) messages. Circuit Breaker IEDs are control device which receive the GOOSE/interlocking commands from protection IEDs and connect/disconnect the physical breaker. Intelligent switch IEDs are operated by controllers to reconfigure the grid topology in fault isolation and service restoration. All IED components are assumed to have a client-server exchange towards substation controller through the communication network. The study is conducted on different IEC 61850 based architectures proposed by some previous works. Below are SCN architectures considered in this study.

1) Architecture A (Arch-A): In this scenario, the substation communication network shown in Figure 1 from [10] is used. It is a traditional IEC 61850 based cascaded SCN where there is no redundancy for either the IED components or the LAN network.

2) Architecture B (Arch-B): The second example SCN architecture considered, shown in Figure 2 is also similar to the above traditional IEC 61850 based architecture but with a single tier of Ethernet switches where protection IEDs, Merging units and breakers are connected to it.

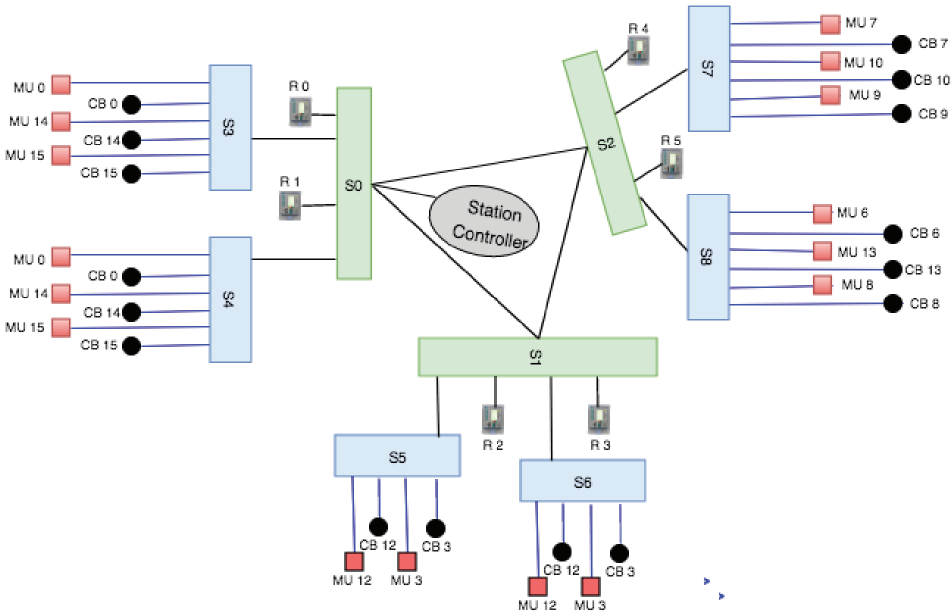


Fig. 1. Substation Communication Network Architecture from [10].

3) Architecture C (Arch-C): A substation communication network proposed by Ali et al. [4], shown in Figure 3 is used. Here, the protection system consists of two redundant and independent protection IEDs. Only one protection IED, i.e., primary, out of redundant protection IEDs works at a time to clear the fault. Each dual-port protection IED, Merging Unit IED and Circuit Breaker IED, are connected to two different local(process-level) Ethernet switches, i.e., with its own bay Ethernet switch and to the adjacent bay Ethernet switch. In case of failure in the communication network of a protection system, the Protection IED transfers the control to the redundant port through dual homing protocol (DHP) port switch over mechanism and uses the alternate communication path for further communication [4]. The whole substation is constructed by forming a ring network of bay/ Ethernet switches which provides an alternate data path to the message flow in case of a link failure.

4) Architecture D (Arch-D): The fourth architecture, shown in Figure 3, is based on Parallel Redundancy Protocol (PRP), IEC 62439-3 standard presented in [6]. It propose duplication of the LAN in the communication network to provide zero switch-over periods in case of any single LAN failure. It also has independent LAN rings at the station bus. The PRP duplicates the incoming message packet and sends them via two different LANs which are independent of each other. On reception the packet which arrives first at the destination is treated as the final packet and the other of the pair is discarded.

B. Physical Grid

The physical distribution grid topology from [10] shown in Figure 5, is used in this study. It consists 16 feeders and has a radial topology with normally open intelligent switches providing redundancy between some feeders.

C. Failure Modes

For a thorough discussion of faults and failure modes of ICT equipment, see [9]. In this paper we study the effect of the two fundamental failure modes: omission failures and value failures.

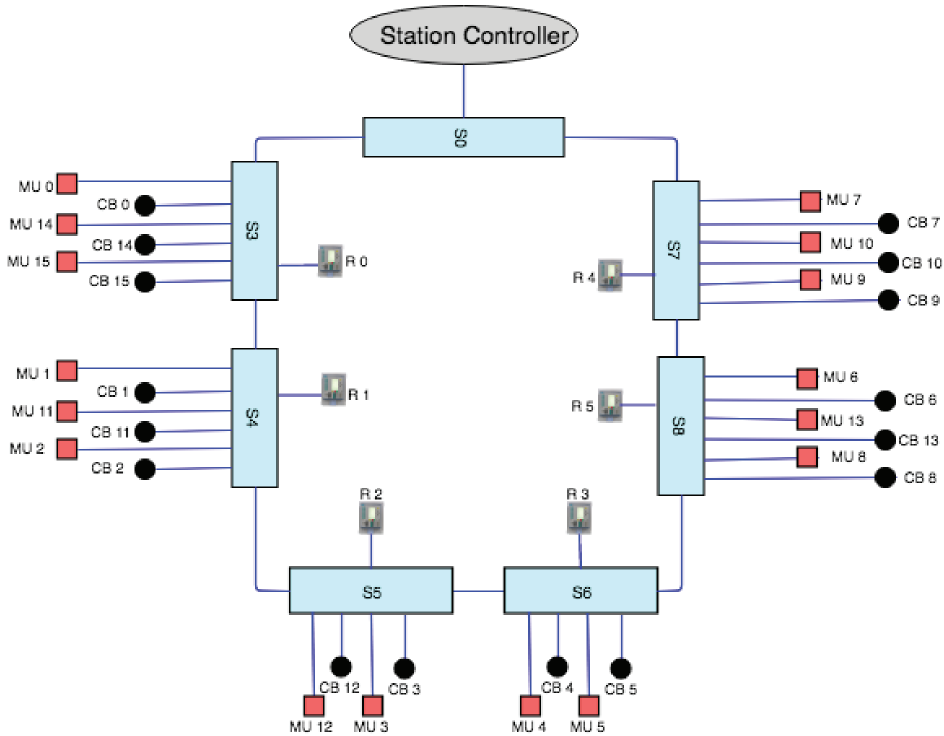


Fig. 2. Substation Communication Network Architecture from [].

1) Omission/Fail-stop Failure Modes: In this failure mode, the component (the Protection IED) stop operation/providing an output when it fails. Other components may detect its failure when trying to communicate with it. In IEC 61850 based substation communications, there are mechanisms/continuous communication exchanges that can be used to detect such failures and trigger a repair process.

2) Value Failure Modes: Here, component may produce wrong values in terms of responses and/or actions that could be interpreted as correct. There may be a wide range of causes of theses failures, among them: software faults, mis-configuration, operation/maintenance mistakes and malicious attacks. Systems may be designed to tolerate some of these, but the authors are not aware of such attempts in the IEC 61850 context. Even with such designs, there is still a probability of vale type of failures. The impact on the power system of such ”active failing” in the ICT system may be significant, and it is important to take them into account in analysis and design.

D. Service Restoration

Once a failure is detected and isolated, the controller is responsible for reconfiguration of the grid topology and updating system state. A limited repair resource is considered for all components. For physical grid components, time to repair is dependent on the availability of ICT infrastructure during the failure.

III. Model

A Stochastic activity network model proposed in [10] is extended and used. The model is developed using the Mobius tool [11]. It is a general and modular stochastic model, which is built from atomic block

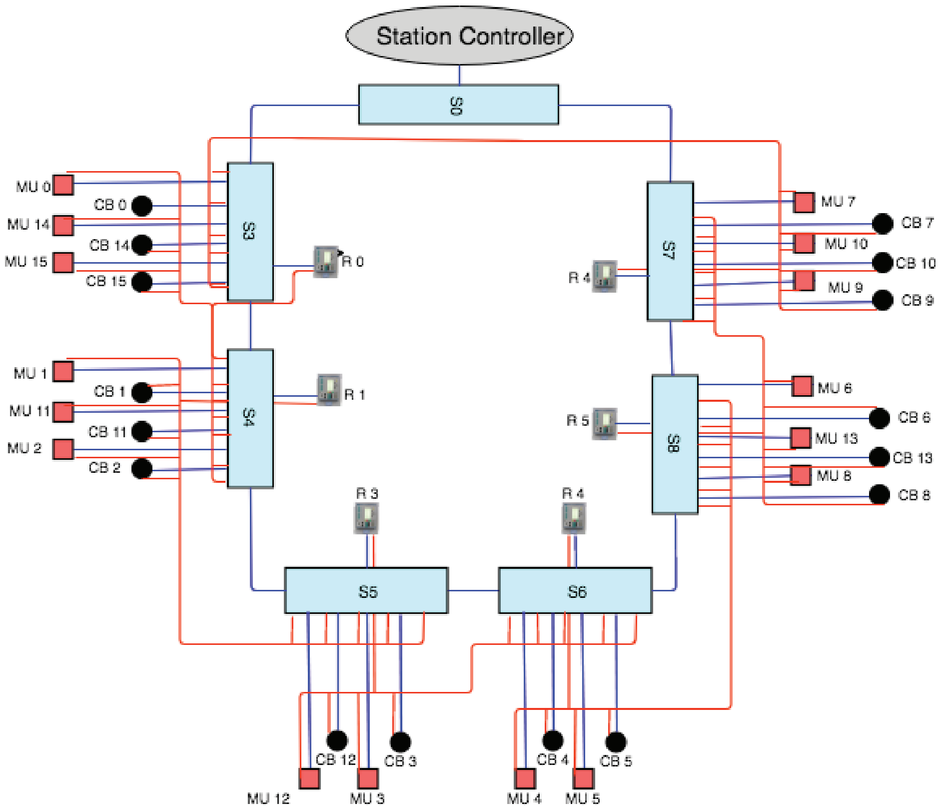


Fig. 3. Substation Communication Network Architecture from [4].

models.

A. Atomic models

Atomic models are developed for the individual components of the IEC 61850 based control system and the physical grid. Detailed models of each the components and a model of the entire distribution grid are presented in [10]. Below is a summary of the atomic models extended for this study. For the complete model cf. [10].

1) Protection IED: The atomic model of a Protection IED is shown in Figure 6. It consists of five extended places; Working (PR_IED_Ok), failed power supply - No power (PR_IED_No_Power), failure in communication link - No communication (PR_IED_No_Comm), value failure (PR_IED_Value_Failure) and Permanent failure (PR_IED_Failed).

Protection IEDs may fail from all other state to a failed state (of omission/fail-stop type) in PR_IED_Failed which needs maintenance by a repair crew. Failures may be of value type that change the state of the protection IED from a working state in PR_IED_OK to a value failure state in PR_IED_Value_Failure.

The state in PR_IED_Value_Failure results in a wrong value/decisions while it is perceived by others as if it is operating normal. This results in a random failing/tripping of circuit breakers under its control until the failure is detected. This is modeled through the shared extended place, CB_STATUS. A failure discovery mechanism may also be included in the model, which may succeed with some probability

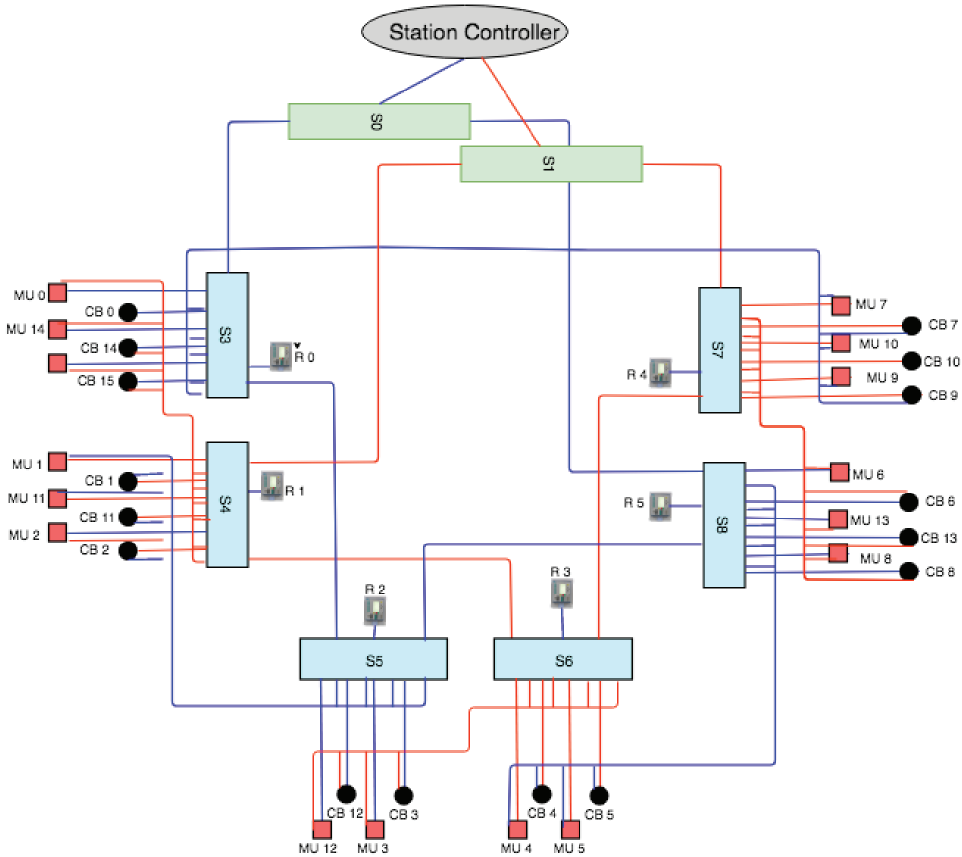


Fig. 4. Substation Communication Network Architecture from [6] .

and result in a change of the value failure state in PR_IED_Value_Failure into omission type failure in PR_IED_Failed. If the failure detection do not succeed, the protection IED stay in the value - failure state.

A protection IED, after being powered by battery for some time, will change to a no power state in PR_IED_No_Power if its power supply is failed, i.e., the feeder providing power supply is not in its working state. From the initial working state in PR_IED_Ok, a protection IED may also end up in a no communication state in PR_IED_No_Comm if none of the outgoing communication links are in their working state. A Protection IED may have a local communication to sensors(MU IEDS) and actuators(CB IEDs) it monitors while there is no communication path towards neighbouring protection IEDs or towards the controller. Such cases are modeled by different markings of the PR_IED_No_Comm and PR_IED_Ok extended places.

2) Circuit Breaker: Figure 7 shows the atomic model for a Circuit Breaker IED (CB_IED) which open or close switches that can be remotely operated or tripped. It consists of three extended places; Working states in CB_Ok, failure in communication link- No communication state in CB_No_Comm and permanent failure state in CB_Failed.

The working state in CB_Ok has basically two states, on and off states, modelled by different markings.

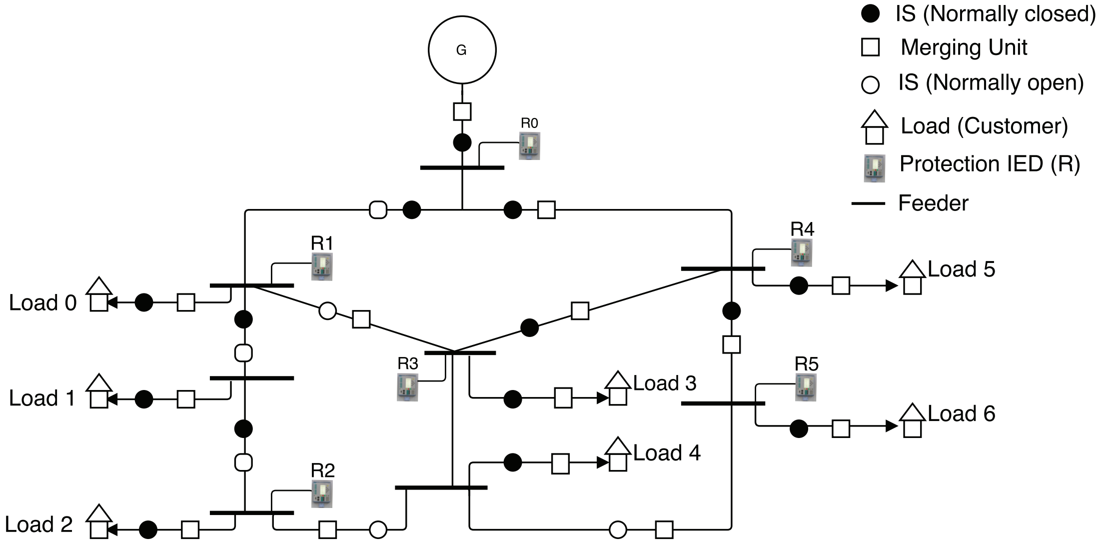


Fig. 5. Distribution grid topology.

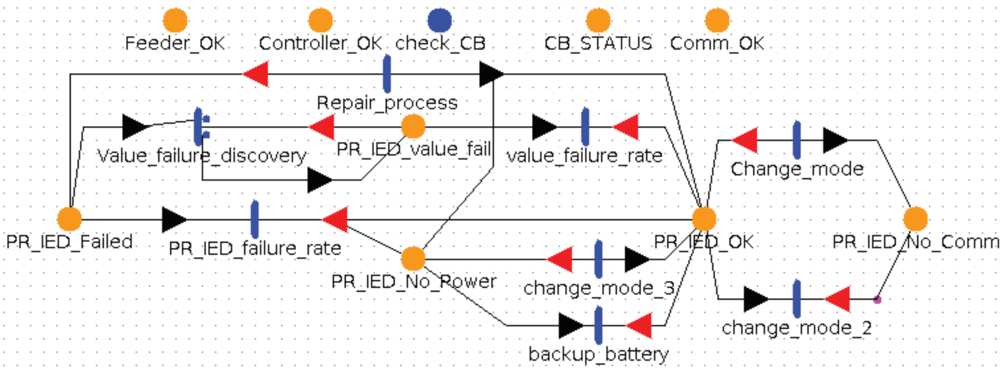


Fig. 6. An atomic model of Protection-IED.

The marking changes made by protection IED in CB_STATUS changes the state of the circuit breaker between on and off states in CB_Ok. From a working state in CB_Ok, a circuit breaker could end up in a No communication state in CB_No_Comm if all the communication nodes/links towards it are not in their working state. A Circuit breaker may have local communication with protection IEDs while there is no communication path towards the controller. Such cases are modeled by different markings of the CB_No_Comm and CB_Ok extended places. Circuit breakers may fail from all other states to a failed state (CB_Failed), needing attention of a repair crew to become operational.

3) Feeders: Figure 8 shows the atomic model for the feeders. It consists of three extended places: working (Feeder_Ok), permanent failure (Feeder_Failed) and no power (Feeder_No_power). Failure of a feeder in a working state is either handled by the responsible protection IED (safe fail) if the ICT based control infrastructure is in a working state or it might lead to a failure cascading into upstream feeders

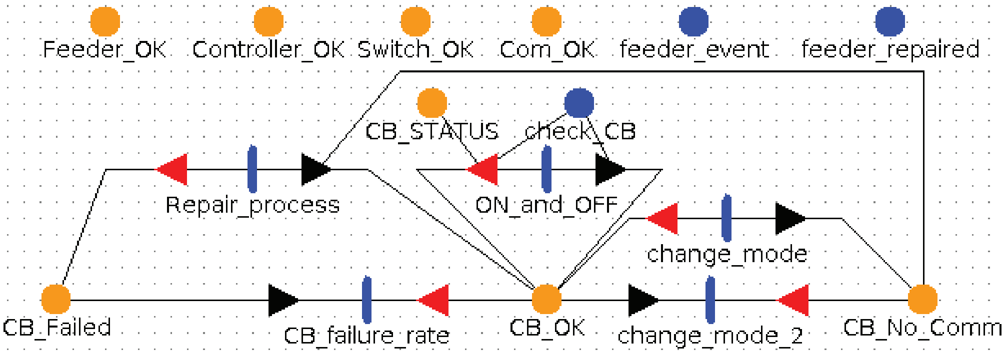


Fig. 7. An atomic model of Circuit Breaker.

if the associated ICT based protection system is also failed. These two failure situations are modelled by different markings in the Feeder_Failed extended place. In addition, a working state in Feeder_Ok could be changed into a failed state in Feeder_Failed if the associated circuit breaker is tripped (off state) due to, say a value failure in the ICT based protection system. This is modeled using a transition dependent on CB_OK place.

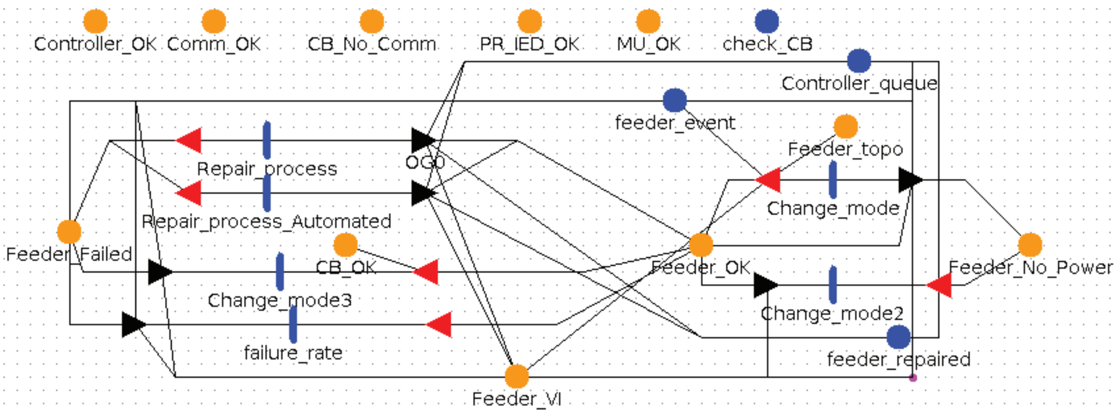


Fig. 8. An atomic model of a feeder.

The feeder may also fail permanently from all other state which needs maintenance by repair crew. A feeder in a working state will instantly switch to 'No Power' state if the feeder from which it gets power is not in a working state. The repair time in a feeder is assumed to be dependent on the failure situation modeled in the failed states in Feeder_Failed extended places. A repair of feeder where the ICT support system has also failed will take a longer time.

B. Composed models

The overall distribution grid is modelled by connecting the atomic sub-models using a 'Join' composed model formalism as shown in Figure 9. Some extended places are shared among two or more atomic models and are used to model the dependencies and interconnection between components as discussed in [10].

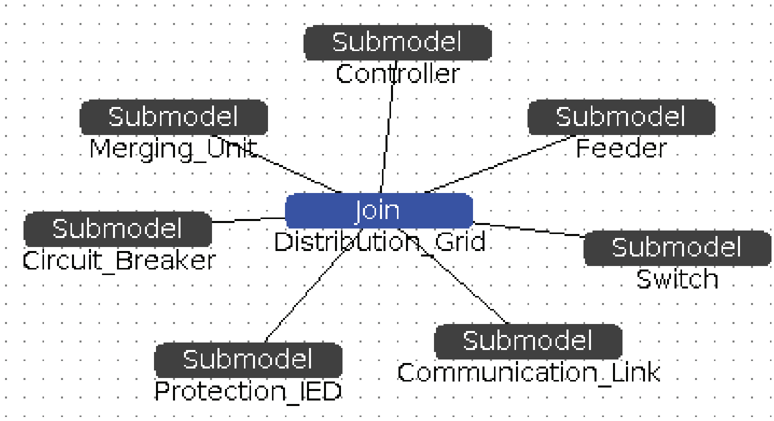


Fig. 9. Composed model of distribution grid

IV. Simulation Study

To demonstrate the effects of different failure modes, a simulation is conducted for measuring the availability of power to the end user considering omission and value type failure semantics of a protection IED. The ratio of the failure rate between omission and value type failures is varied to study the failure mode that cause a sever consequence. The simulation also looks into how different architectures of the substation communication networks, described in section II-A, behave for the assumed failure modes. An illustration and comparison of the resulting Availability of an end user and of the overall system is also shown in Figure 10 - Figure 14.

The case study mainly considers an over-current protection. If there is an over-current in a feeder, the bay protection IED responsible for the faulty feeder zone should neutralize it by sending a trip signal to a Circuit breaker IED. It should also send a status update to neighbouring IEDs stating that it is handling the situation so that neighborhood protection IEDs, which could operate as a backup, will not act/trip their breakers. For protection coordination and interlocking functions, bay IED components should also communicate to the station controller during fault isolation and service restoration.

As discussed in Section II-C, omission type of failures are assumed to be instantly detected as the IEC 61850 standard has an awareness mechanism that can be used for this purpose. For value type failures, it is assumed that the failure can be discovered with some probability if there is a valid path to a neighbouring Protection IEDs and/or to the station controller. A simplistic approach is to use failure discovery mechanisms through a challenge message exchange among Protection IEDs. The model assumes that if there is a valid path to atleast two neighbouring Protection IEDs and/or to the station controller, a value type failure in Protection IEDs can be discovered. And, the faulty Protection IED can be forced to a fail stop mode. There can also be some consistent value failures which could be difficult to detect. These are modeled with a probability that the faulty protection IED will stay for longer time in value failure mode even if there is a connection to other IEDs and to the controller.

A negative exponential distribution, i.e., $P(T_x > t) = e^{-\lambda_x t}$ is assumed for all failure and repair times, where T_x is the firing times for transitions in the SANs in Figures 6 – 8 and λ_x is the rates in Table I, which are based on [12]. A deterministic distribution, i.e., $P(T_y > t) = 1$ when $t \leq 3$hr and $= 0$ when $t > 3$hr, where T_y is used for the backup battery time of controllers, switches and protection relays during power outages. Only 5% of the Value type failures are assumed to be consistent failures. All cases are simulated for 100 years of calender time, each replicated 15 to 20 times for error control. Confidence bands of 95%

TABLE I
FAILURE RATE AND REPAIR TIME OF THE GRID COMPONENTS

Component type	**Failure rate** λ_x[days^{-1}]	**Repair time** λ_x^{-1}[hr]
Feeder	0.0019 per km	6 Manual rep. 2 Automated rep.
Protection IED	0.0025	2
Merging Unit	0.0026	2
Circuit Breaker	0.0026	2
Communication line	0.0028	3
Switches/router	0.005	3
Controller (permanent failures)	0.00059	3
Controller(Software failures)	0.0333	0.3

are shown in Figures 12 and 13 and omitted in the other figures to avoid clutter. The average computational time for one case with replications is in the range 10 to 20 minutes.

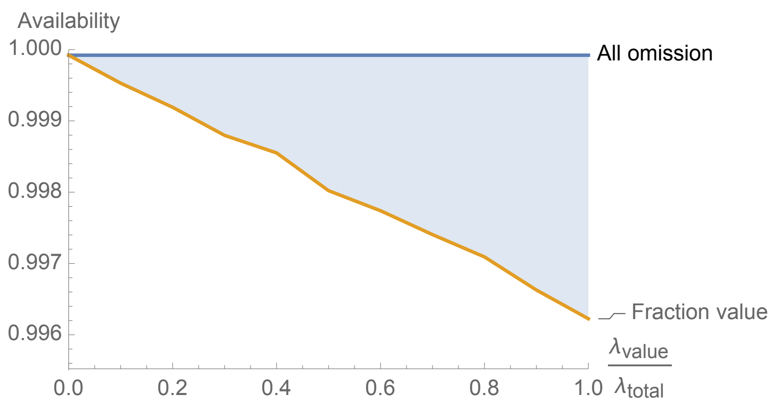


Fig. 10. Availability considering Omission type vs Value type failures

The effect of a fraction of the failures being of the value type failure from none (0) to all (1) is shown in Figure 10 obtained for substation architecture A in Figure 1. Similar results are obtained for all other architectures. It is seen that the availability of power to an end user drops significantly with an increasing ratio of value type failures. There is also a significant drop in the availability of the overall system when there is a fraction of value failures. Figure 11 shows system unavailability condition by N or more simultaneously affected users when 20% of failures are of value type. Note that the relative drop is larger for more than one affected user, i.e., $N > 1$.

Figure 12 shows a comparison of the architectures for omission and value types failures. With only omission failure mode, shown in Figure 12(a), scenario A has the least availability, B slightly better and Scenario C and D has a higher since architecture A and B doesn't have a redundancy in the LAN network while C and D has two LAN networks. Architecture B has a better availability than A due to the placement of protection IEDs closer to the sensors and breaker units.

For value type failure semantics, Figure 12(b), the availability drops from the four nine domain to the

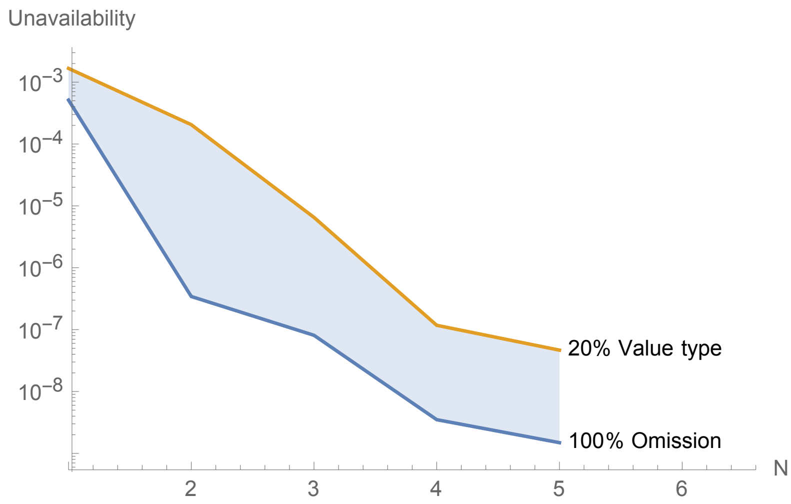
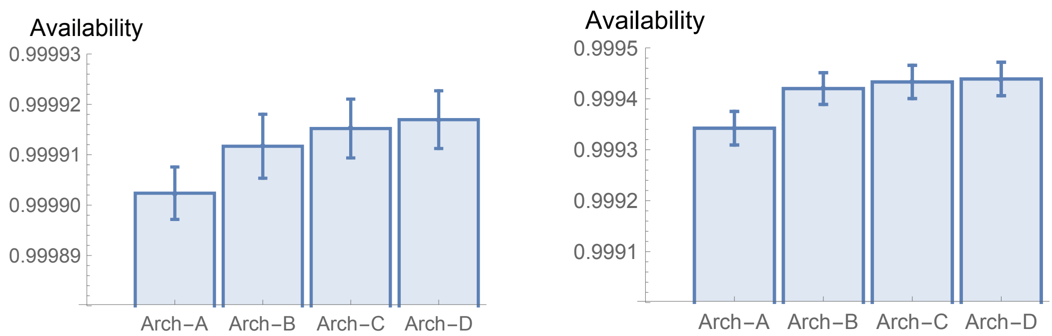


Fig. 11. Unavailability of the service for N or more simultaneous affected users considering the two cases, all failures of omission type, 20% are of the value type

three nine domain for all architectures, with some minor relative changes. This mainly due to all the substation communication architectures being proposed/designed with just omission type failure of ICT components in mind. Here, It is assumed that only 20% of the failures are value type . Considering a potentially higher fraction yield a higher impact.



(a) Omission type of failures only

(b) 20% value type of failures

Fig. 12. Availability of power to end-users for the architectures

Though the change in availability of the final service/power to the end user seems small, archtectures C and D may significantly improve the availability of the ICT support system. The availability of the protection function (ICT support system) considering omission type of failure semantics is shown in Figure 13. The protection function/ ICT support system is considered available if the respective Merging units, protection IEDs, breaker units and the communication network behind them is working, otherwise if one of the components fail, the protection function is assumed to be unavailable. Figure 13 shows the gain of the increased redundancy.

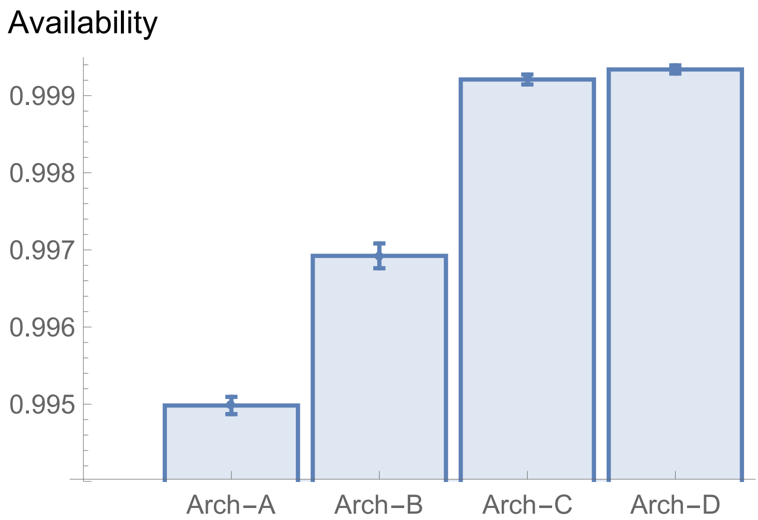


Fig. 13. Availability of the ICT subsystem (Protection function)

Comparison of the architectures on system unavailability shown in Figure 14 for an increasing number of simultaneously affected users. With 20% value type failures, the system unavailability almost independent of the architecture as the value failures are dominant in causing unavailability. However, for only omission type failures, it can be seen that architecture C gives a somewhat lower unavailability than Scenario A and B, especially for more than three simultaneously affected users.

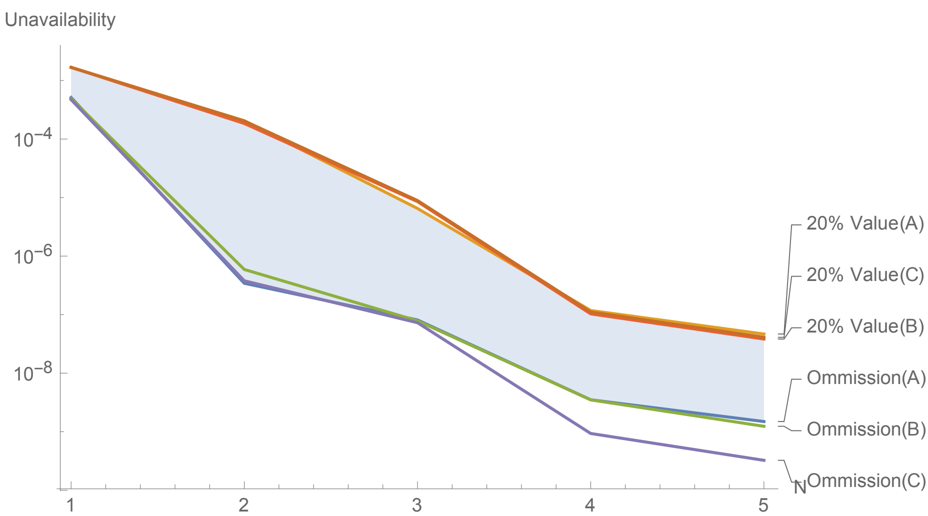


Fig. 14. Unavailability for N or more simultaneous affected users, for the cases with omission failures only and 20% value failures for the architectural options A, B and C

V. Concluding Remarks

In designing a dependable communication architecture for critical infrastructures like distribution grids, it is very important to consider various types of failure modes. This paper has focused on studying how the various failure modes of IEC 61850 based ICT support system components affect the reliability of future distribution grids, by a stochastic activity network simulation model, for four proposed substation communication networks.

The results shows that there will be a significant change in reliability indexes of the service provided to customers if part of the failure is of the value failure type. Some SCN architectures that has improved the reliability for omission type failure modes fail to do the same when value type failure modes are considered. As future smart grids will be highly dependent on new ICT based components, it is important to consider value type failures of ICT based components in the design of substation communication architectures.

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Paper C

Dependability of Smart Distribution Grid Protection Using 5G

Tesfaye Amare, Bjarne E. Helvik

In the 3rd International Conference on Smart Grid and Smart Cities ICSGSC 2019, Berkley, USA, June 2019

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Dependability of Smart Distribution Grid Protection using 5G

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Abstract

The future trends for smart distribution grids will be increasingly characterized by more use of advanced communication technologies, like the function virtualization. The smart grid can benefit from virtualization and emerging standard ICT technologies such as 5G, to become more cost effective. However, stringent performance requirements must be met and higher reliability, robustness, flexibility and scalability must be provided.

This paper discusses the usage of virtualzation concepts in 5G technology for protection function/application in distribution grid. A 5G based architecture using an edge computing infrastructure to hosting the control and protection applications is proposed. A stochastic activity network based model is used to analyze and compare the reliability of the proposed 5G based archtecture with a functionally identical Ethernet based IEC 61850 architecture. The 5G architecture seems to result in a significant gain in availability provided that redundancy on the radio links is used to compensate the loss due to random fading processes.

I. Introduction

Smart distribution grids ares going through a massive transformation to make them more smart and fully automated with the ability to reliably transfer data and power in both directions. An automated operation of the future smart distribution grid will need thousands of field devices such as sensors, actuators and Intelligent electronic devices(IEDs) with software on top of these devices, making it a complex cyber physical system. As the smart grid is one of the most critical infrastructures, the grid ecosystem puts strict dependability and performance requirements on the communication technologies to be used.

This papers aims to study the use of 5G technology for protection function/application in distribution grids. Nowadays, the IEC 61850 standard is often used in substation automation of distribution grids where Ethernet is used for intra-substation communication and different wide area technologies for communication between substations. This study focuses on investigating the reliability of a virtualized protection application using 5G and its comparison with IEC 61850 based protection in distribution grids.

Network function virtualization (NFV) is suggested for softwarizing some network functions of the ICT infrastructure and also for handling of some smart grid functions (eg. protection functions) in the Intelligent electronic devices (IEDs) of IEC 61850 based substations. In order to meet the low latency requirement of protection in distribution grids, an edge cloud computing facility is used to host the control and protection applications.

Introducing the concept of virtualization into the grid has many benefits as compared to the current system. i) Optimized usage of resources by dynamic creation, change or migration of control applications/functions and by reconfiguration of the topology. ii) The edge computing infrastructure provides larger and more flexible processing and storage capacity for more demanding or future smart grid applications. iii) Equipment cost (CAPEX) cost may be reduced by the virtualization replacing dedicated HW and and hardware bound SW with software implemented functions running on inexpensive "off the shelf" computing installations. Using a common 5G platform may also yield a gain due to scale. iv) Virtualization has also the potential of reducing the operation and maintainence cost (OPEX).

Though 5G technology could bring many benefits, how it affects the dependability of the distribution grid need to be carefully investigated especially for critical applications such as protection functions.

The remainder of this paper is organized as follows. Section II gives a background with a survey of the related works. Then Section III and Section IV presents current IEC 61850 based distribution grid communication network architecture and the new architecture based on 5G respectively. The modeling and dependability assessment of these architectures are presented in Section V and VI. Finally we conclude our findings and potential future work in section VII.

II. Related Work

The dependability of IEC 61850 based substation communication network has been studied in few papers. Thomas & al. [1] [2] proposed Ethernet-based logical architecture for the substation communication network (SCN) with a redundant ring network focusing on the importance of utilizing the redundant critical components/communication links in achieving high reliability. Suhail & al. [3] presented an architecture which duplicates the LAN in the process bus communication network where conventional IEDs can be used. All these works aimed at improving the dependability of the grid with a hardware redundancy and some topological/architectural enhancement.

There are some works that have introduced the concept of virtualization into the grid. Xin & al. [4] proposed a virtual smart grid architecture based on cloud computing. However, it does not have a detail dependability modeling /analysis of this kind of implementation of a smart grid application. To our knowledge, there was no paper that has used 5G as a communication platform for protection of smart distribution grids. However, there are some works that has considered virtualization based approaches such as network function virtualization (NFV) [5] and software defined networking (SDN) [6], [7], [8], [9], [10] for other smart grid applications. Cosovic & al. [11] studied how the emerging 5G mobile cellular network, with the concept of mobile edge computing, can be used for distributed state estimation in smart grids.

III. IEC61850 based Substation Communication Network Architecture

A. *IEC61850 based substation*

IEC 61850 standard [12] is a recent commonly used standard for communication networks and systems in substations. In the standard, the traditional way of wiring between relays for protection schemes is replaced by standardized Ethernet based communication services for the exchange of critical information between intelligent electronic devices (IEDs). Figure 1 shows a typical IEC 61850 based substation communication network architecture.

The IEC 61850 defines a data model where Logical Nodes are the core elements. Logical nodes in IEDs represent the information content of functions in the substation automation system (e.g. PDIS, the logical node for a distance protection function). The standard supports two communication principles. The first is a client/server communication which is based on MMS over TCP/IP and Ethernet. It is typically used for SCADA communication towards central control unit. The other is a publisher/subscriber communication, which is intended for time critical information exchange between IEDs. The publisher/subscriber communication consists of two services that have a major impact on protection: GOOSE (Generic Object Oriented System Event) and the transmission of sampled values (SV) [13].

B. *Protection functions*

Merging Units (MU) collect and transmit sampled value data (current and voltage) to the protection IEDs. Protection IEDs basically receive the sampled values from the Merging Units, perform substation protection functions and send decision/trip signals to circuit breakers. The protection IEDs are also assumed to exchange information, such as breaker failure protection or status information, among each other by sending GOOSE messages. Circuit Breaker IEDs are control device which receive the GOOSE/interlocking

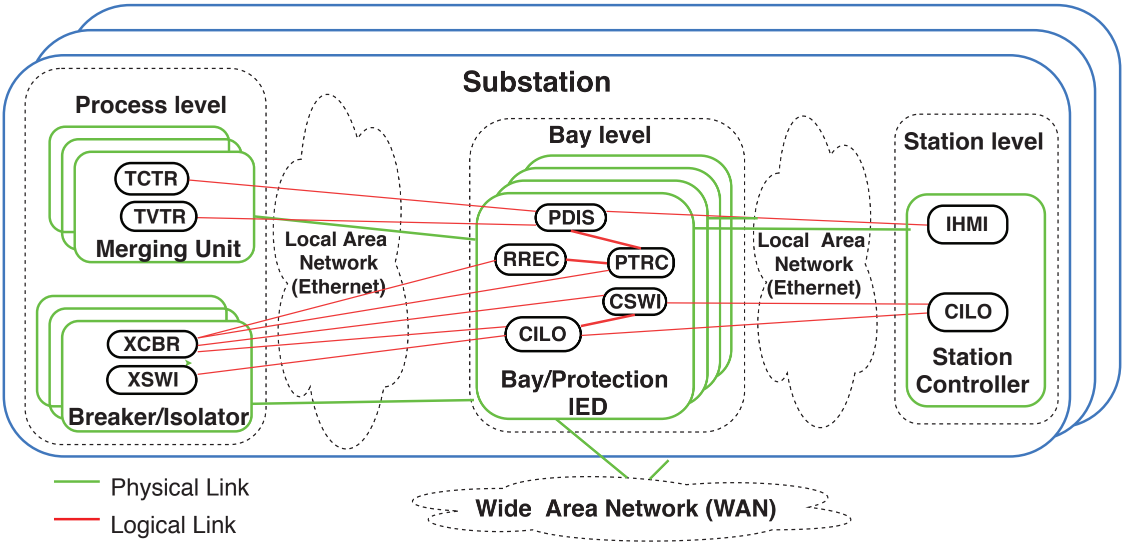

Fig. 1. IEC 61850 Substation Communication Network Architecture.

commands from protection IEDs and connect/disconnect the physical breaker. All IED components are assumed to have a client-server exchange towards substation controller through the communication network.

1) Intra-substation Protection functions: The standard uses Ethernet LAN for communication inside a substation. GOOSE messages are multicasted on the network. Any IED that needs information from a certain IED must subscribe to this IEDs GOOSE. An example is overcurrent protecion inside a substation where Merging Units (MUs) send a multicast message of the measured sample with a constant rate within the LAN. The responsible protection IED will send a trip GOOSE message to the Circuit breaker if a fault is detected and it will also send a status GOOSE message to neighbourhood protection IEDs. The transfer time of these messages should not exceed 4 ms – 10 ms depending on the functional requirements [14].

GOOSE messages are immediately sent when an event occurs and repeated in short intervals to increase reliability in case of a packet loss. In addition to message redundancy, different architectures has also been proposed in order to increase the reliability, e.g., the two LAN network based on Parallel Redundancy Protocol (PRP), IEC 62439-3 standard presented in [3].

2) Inter-substation protection functions: The substation-substation communication refers to functions in substation automation, which are distributed between two substations. Examples are distance protection, differential protection and any kind of automatics including more than one substation. The IEC 61850-90-1 standard is used for the communication between substations. The standard considers two types of wide area networks (WAN) communications: Tunneling through VLAN that allows direct access to functions in remote stations and Gateway approach if the communication link does not support Ethernet [14]. It is also stated that other types of WAN technologies could also be used.

The requirement for the transfer time, i.e., the communication performances requirement between two substations are basically the same as those for communication between two bays within a substation.

C. Challenges

The IEC61850 standard based substation communication architecture uses dedicated LAN for intra-substation communication and WAN for inter-substations which often has to be built by the power system operators. This results in a relatively costly infrastructure, both with respect to CAPEX (installation cost and equipment investment) and OPEX (operational and maintenance cost). Furthermore, reliability is often achieved through putting more hardware redundancy which incurs additional investment and maintenance cost.

Though Using IEC61850 standard brings more flexibility than hard wired systems, IEC61850 based systems are not as flexible and scalable as virtualized systems. For instance, it is not easy to exchange/share data easily between IEDs as it uses multicast messages which hinders the performance. In addition, the communication between substations is also more challenging and costly as it needs advanced WAN technology.

IV. 5G Based Substation Communication Network Architecture

A. 5G concepts relevant for smart grid

This section presents a brief description of the main technologies in 5G which are used in the proposed scheme.

1) Radio interface: High-quality wireless connectivity is essential to introducing virtualization into the grid at a low cost. The next generation 5G radio communication aims to provide different types of services that offer an increased capacity, high reliability and reduced latencies to enable mission critical machine-type communication (MTC) service, i.e., the real-time control and automation of dynamic processes required in distribution grids [15]. To meet this kind of requirements, Ultra Reliable and Low Latency Communications (URLLC) as a communication service category in 5G is considered. It aims to provide stringent latency (end-to-end latencies reach down to 1 ms) and high reliability.

2) Virtualization (NFV): Network functions, which have been executed on dedicated and often specialized hardware before, now run as software applications in virtual machines in a cloud infrastructure. Thus, the operation of dedicated network middle-boxes transfers into the operation of virtual machines and software, which paves the way to reduce capital expenditures by using common-off- the-shelf hardware and to apply existing management practices and tools from the cloud computing space in order to automate network operation tasks and reduce operational expenditures. Moreover, NFV systems could embrace the high- availability model by creating an architecture that builds failure management into every part of the system [16]. A similar approach of using virtual machines can be adopted to replace currently costly hardware control units in distribution grids (such as protection IEDs) to provide similar, yet flexible and cost-effective service.

In virtualization using 5G, there are mainly three layers; the resource layer, the network slice instance layer and the service instance layer. Each of these layers needs to be managed in coordination with other layers and these are handled by Management and Orchestration systems such as the MANO framework by ETSI [17].

3) Mobile edge computing (MEC): Mobile Edge Computing, see for instance [18], provides an IT service environment and cloud-computing capabilities at the edge of the mobile network, within the Radio Access Network (RAN), and in close proximity to end users. It helps to reduce latency, ensure highly efficient network operation and service delivery, and offer an improved user experience [18]. It is characterized by low latency, proximity, scalability, enabling automation and more, which makes it a key technology and architectural concept to realize virtualization of smart grid applications.

4) Network Slicing: Network slicing is a technology that allows multiple logical/virtual self-contained networks to be created on top of a common shared physical infrastructure. Each slice is orchestrated to meet the specific service requirements of the application;in this case smart distribution grid protection. Network slices are used by tenants, [16], a distribution network operator can be such a tenant.

5) SDN: Software Defined Networking (SDN) is a communication network paradigm that decouples the control plane from the forward plane making networks programmable and enabling applications and network services to directly control the abstracted infrastructure. In 5G, SDN can be used in the frontand back-haul network connecting the edge computing nodes and radio transceivers to each other, as well as in the core network.

B. A substation protection architecture based on 5G

In this section, a novel approach/architecture to virtualize and move some control logic (protection application as a use case) into an edge cloud in 5G is presented. Some functions (logical nodes in IEC 61850) are kept near to field devices while the decision making and functions on protection IEDs are proposed to be moved into an edge cloud.

An end to end network slice is considered for the substation protection. The slice is assumed to be completely isolated, i.e., there is no interference from the rest of the network. The 5G based architecture, shown in Figure 2, consists the following main components:

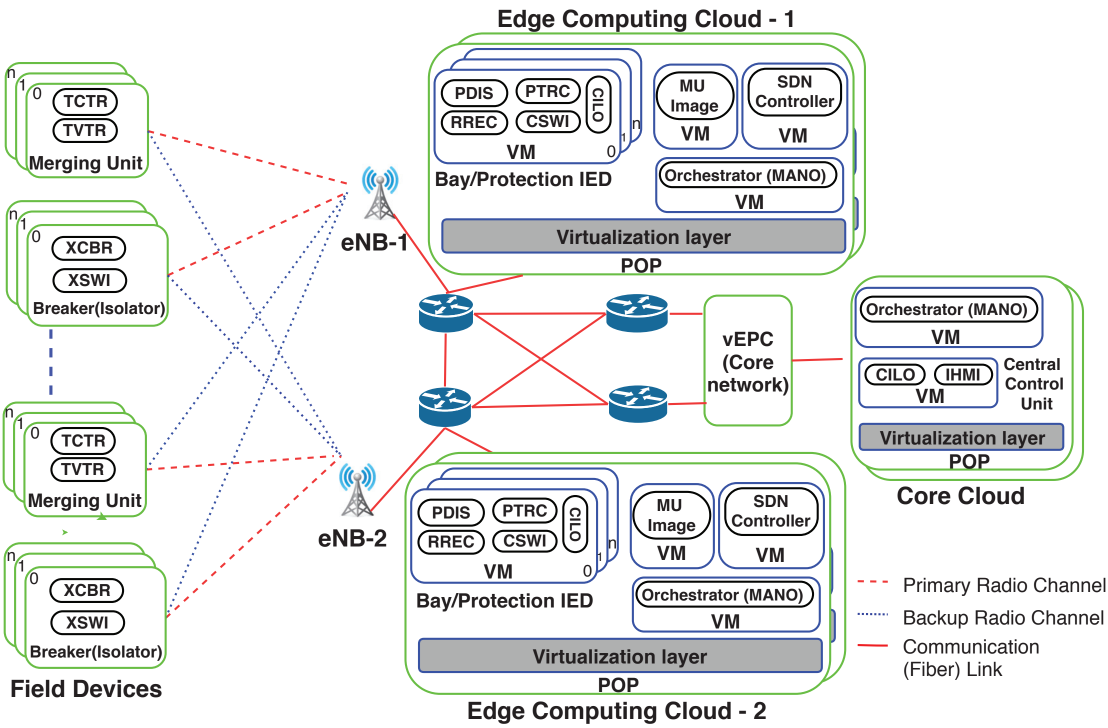

Fig. 2. 5G based Substation Communication Network Architecture.

Field Devices: Sensors and actuators such as Merging Units and Circuit Breakers.

Radio Links: For the radio link, ultra reliable and low latency communications (URLLC) service category in 5G is considered.

eNB: Base stations that handle the radio communication to the field devices.

Edge Computing Infrastructure/PoP: the infrastructure, both general purpose hardware and adapted operating system of the edge cloud.

Virtual Machine (VM): virtualized application environment in the edge cloud which is used to host protection functions of the IEC 61850 IEDs and an image of merging unit data.

Virtual Machine Monitor (VMM): This function is also called a hypervisor. It is used for managment and orchestration of multiple virtual machines that run concurrently on the host edge cloud server.

Communication links: are often fiber links used in the front- and back-haul network to connect edge computing nodes and eNBs to each other as well as to the core network.
Routers: SDN based routers used in the the front- and back-haul network.
SDN controller: Virtualized SDN controller for the front- and back-haul, which is placed either in the edge computing clouds or in a cloud based in the core network.

C. Delay budget

In [19], it is stated that by putting the control servers close to the base station (access point), it could be possible for the round trip latency to be as low as 1 ms. The work assumed that processing and protocol handling on field devices could take around 0.3 ms, the air interface might take 0.2 ms, and signal processing and switching on the edge cloud can take up to 0.5 ms. As the timing requirement in most protection applications in the distribution grid is between 4 ms – 10 ms, 5G may most likely meet the requirements and is a potential/alternative technology that can be used in the future.

D. Advantages

The main advantages of using 5G for distribution grids are flexibility, higher quality of service and reduced cost. 5G based architecture avoid multicasting GOOSE and Sampled values as exchanging/sharing information between IEDs and substations will be easy. This is due to the reason that neighbourhood IED applications will most likely be hosted by virtual machines in the same edge computing infrastructure. The virtualization of functions in 5G will provide flexibility in configuring the network, making some functional upgrades and adding new features easier and with a short lead time, and hence, make room for more innovation etc.

It may also be cost effective. To draw a firm conclusion an in depth the cost analysis is needed, but it is seen that in using 5G, there is no need to invest in building a privately owned communication infrastructure. Distribution grid operators can use the 5G infrastructure or service provided by ICT service providers tailored for their requirements, and, and as in other application domain there is likely to be significant savings in virtualization rather than dedicated hardware and vendor specific solutions.

E. Challenges

5G is yet on the R&D stage, but it will soon be commercial. A new protocol for intra and inter substation communication, like that of IEC 61850, tailored for the wireless radio access network might be needed. In addition, the reliability of the service and the security of the radio access network will be a challenge. Though it is possible to increase the redundancy, and hence, the reliability of the radio access network by introducing multi-homed connections to the eNB, the security of wireless communication in 5G will be a major issue and it must be studied/investigated thoroughly.

V. Modeling

A Stochastic activity network model, [20], [21], developed using the Mobius tool [22]. The smart grid model presented in [23] is extended and used. It is a comprehensive and modular stochastic model, which is built from atomic block models.

The model is developed for both 5G based architecture and Ethernet based IEC 61850 architecture. First an atomic model is developed for the individual components of the architectures. Then, the overall system is modelled by connecting the atomic sub-models. For detail description of the model, cf. [23]. Below is a summary of some atomic models, among these, those extended for the 5G based architecture.

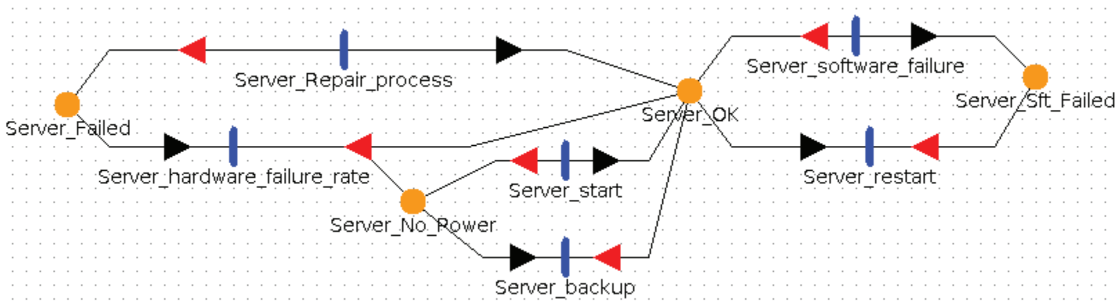

Fig. 3. An atomic model of Server.

1) Edge infrastructure: : Figure 3 shows the atomic model for an edge server. It has four places; working (Server_Ok), Hardware failure (Server_Hr_Failed), Operating system/Software failure (Server_Sf_Failed) and No Power (Server_No_Power) where the corresponding states are modelled by markings of the respective extended places. The atomic model for virtual machine is shown in Figure 4. A virtual machine may have a software failure (VM_Sf_Fail) or a failure in the underneath edge server may change its state into a hardware failure state in VM_Hr_Fail. The unconnected extended places at the top are shared places which are used to share states with other atomic models.

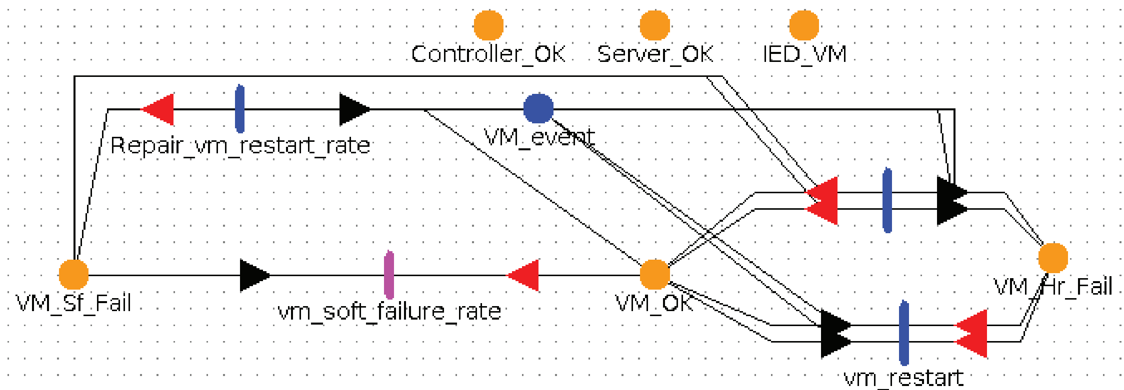

Fig. 4. An atomic model of Virtual Machine.

Figures 5 an 6 show the atomic model for MANO and SDN controller respectively. Here again, there can be a software failure or a hardware failure if the underlying edge server fails. The MANO is responsible for mapping the IED application to a virtual machine(through IED_VM), migration of a virtual machine to a backup edge server if the communication to the backup edge server is ok (checked through Edge_to_Edge). The SDN controller is also responsible to set/update the forwarding path between edge servers (through Edge_to_Edge) and between edge server and the core network(through Edge_to_Core).

2) Radio Channel: Reliability modeling in wireless communication is challenging due to the time dependent factors on the effective links such as fading, interference, hardware failures etc. The wireless channel is often characterized by i) Large-scale fading, due to path loss and shadowing ii) Small-scale fading, due to the constructive and destructive interference of the multiple signal paths. Though the model developed is generic and can be used to study both properties, this study doesn't consider path loss and shadowing, assuming a compensation by link budget/transmit power control [24], [25].

The model assumes that each field component (MUs or Breaker IEDs) is connected to the eNB through n

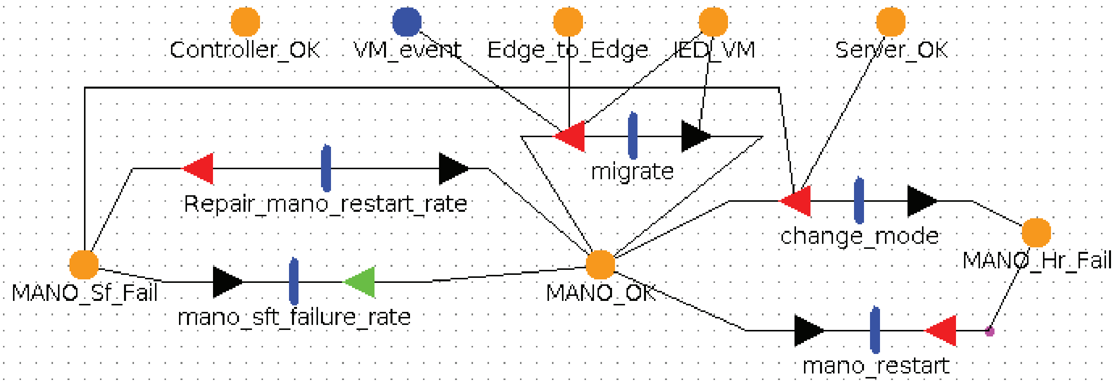

Fig. 5. An atomic model of MANO.

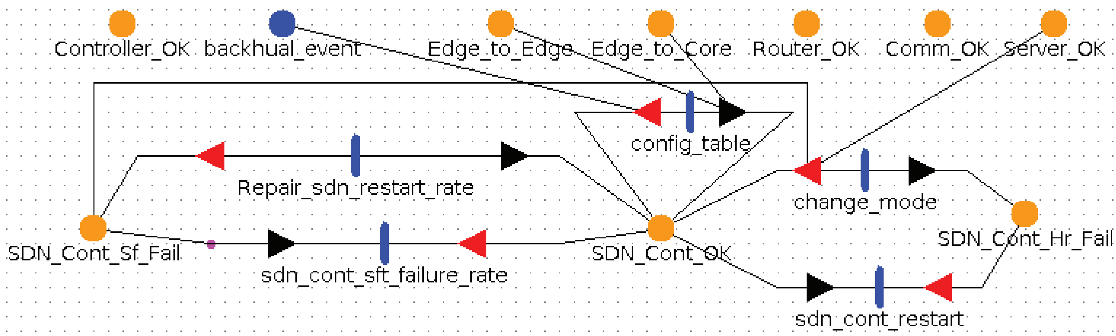

Fig. 6. An atomic model of SDN Controller.

wireless links simultaneously. Assuming each wireless link consists of multiple paths including a dominant component leads to a Rayleigh-fading channel. Considering urban areas where there can be many moving objects that may scatter the radio signal on its way to the receiver, Rayleigh model seems to be a reasonable assumption to consider.

For reliability studies, the fading behaviour can be approximated as a repairable system. The radio transmission can be considered as an alternating renewal process with failure (λ) and recovery (μ) rates where the failure of the transmission is attributed to the fading.

The average fade and non-fade duration of a Rayleigh-faded signal can be determined by level crossing analysis as discussed in [24], [25]. Their reciprocals characterize the transition rates between a working state and a failure state, which is denoted as failure rate λ and recovery rate μ as shown below:

$$\lambda = \sqrt{\frac{2\pi}{F}} f_{\mathrm{D}}, \quad \mu = \frac{\sqrt{\frac{2\pi}{F}} f_{\mathrm{D}}}{\exp \frac{1}{F} - 1}$$

where $F = p_{\mathrm{avg}}/p_{\mathrm{min}}$ represents the fading margin with the average receive power p_{avg}. The maximum Doppler frequency is characterized by $f_D = vf/c$, where f is the carrier frequency of the signal and c is the speed of light. The relative velocity between transmitter, receiver, and scatterers is denoted by v. In smart grid environment, the transmitter and receiver are stationary. Meanwhile, there can be a minor effect from scatters especially in urban areas. Hence, the model assumes a small fraction of the failure due to fading (r) where $f_D = (vf/c) \cdot r$.

The communication between field device and eNB is assumed to be viable as long as one out of the n redundant links is operational.

The radio channel is modeled in two stages. First an atomic model, as shown in Figure 7 is developed for reliability modeling of the wireless channel property (i.e. the short term fading behaviour) of the radio communication that consist n redundant links. Parameters such as failure rate of the radio system, steady state probabilities and mean time to failure (MTTF) from a given state i are obtained from this model. Then, these parameters are used on the second stage atomic models, shown in Figures 8 and 9 which represent the communication link bundle between field devices and the eNB.

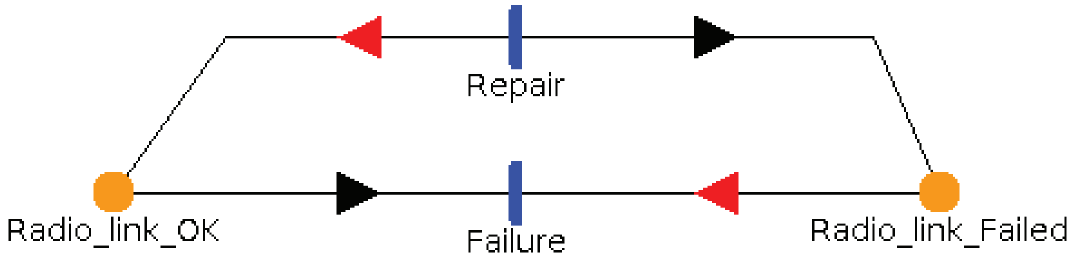

Fig. 7. First stage atomic model of the radio channel.

The first stage atomic model in Figure 7 consists two places; working (Radio_link_Ok) and failure due to fading (Radio_link_Failed). The markings in the two extended places represent how many links are (not-)working. The radio link bundle is said to be failed if all n tokens are present in Radio_link_Failed. The model measures the rate at which the radio communication fail (all links are down) and get recovered by tracking the number of visits to the failure state. The steady state probabilities P_i, where the number of working links is i, are also obtained by measuring the amount of time i token spend in _link_Ok extended place. Given that the initial state of the radio system is state i (i working links), the mean time to failure (MTTF) can be measured by making the failure state in Radio_link_Failed an absorbing state i.e. disabling the Repair transition for the case where all links are down.

The second stage radio communication model, shown in Figure 8, is used to model communication link bundle that is used to connect field devices to the eNB. This model is suited for studying steady state availability. It consists three places; Working (Comm_Ok), failure in ICT components to which the communication link is attached to - No communication (No_Comm) and a failure (Comm_Failed). The failure of a Communication link has different states represented by different marking of the extended place. It could be due to hardware failure on the receiver and transmitters which needs maintenance by a recovery crew or due to fading with a failure rate obtained from the first stage model. The model in Figure 9 is also used for the communication link between field devices and eNBs, but mainly for reliability studies where the interest is capture the detail dynamics and measure the probability that the system is continually working for a certain mission time. It consists the three main places; Working (Comm_Ok), No communication (No_Comm) and a failure (Comm_Failed). The transition between the places are similar to the one presented above, Figure 8, except the fading transition which is modeled differently.

In order to avoid excessive simulation times due to the far larger number of events in the radio channels than in the rest of the system, the fading dynamics is captured only when there is an event (e.g. failure of a power line) where the communication channel is needed. When such an event occur, it is assumed that the radio channels are in stady state. This is a safe assumption since their relaxation times are several orders of magnitude less than the time between events in the power grid. This is implemented be reading the shared state, $check\_Comm$. When the fading transition is activated, the communication link instantly goes to either a failure state or to one of the intermediate working states which represent how many of

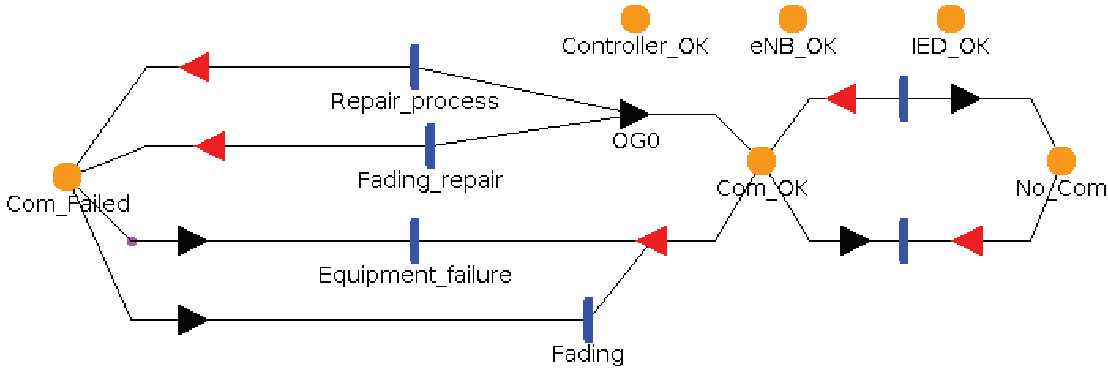

Fig. 8. An atomic model of the radio communication (Option A).

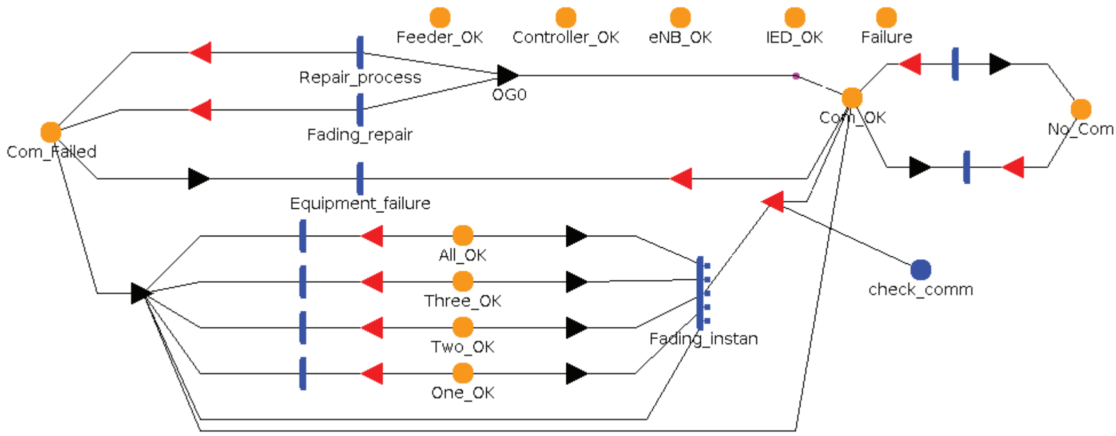

Fig. 9. An atomic model of the radio communication (Option B).

the redundant links are up or down, with a steady state probabilities obtained from the radio channel model(the first stage model). From the intermediate working states, the communication link may goes to a failure state with a TTF (Recurrence time to failure) which is also obtained from the first radio channel model.

VI. Dependability Analysis

A simulation study is carried out to investigate the availability and reliability of protection functions in the 5G based architecture. Corresponding simulations are carried out to enable acomparison with the protection function availability of the functionally identical IEC 61850 based architecture.The following two protection schemes are considered:

Intra-substation protection: such as an over-current protection of a feeder within a substation. The protection function is considered available if a given merging unit, protection IED (application in the cloud in case of 5G), circuit breaker and the communication network connecting them are in a working state.

Inter substation protection: such as distance or differential protection for protecting the line connecting two substations. The protection function is considered available if the two edge protection IEDs or applications, the respective edge merging units, the edge circuit breakers and communication links between them (WAN link in the case of IEC 61850 based architecture) are in a working state.

A. Case Studies

1) Investigations: The following two investigations are made:

1.1) Sensitivity Analysis: For the 5G based architecture presented in section IV-B, failure of the radio channel are frequent due to fading. In this investigation, the aim is to study the impact of 5G-URLLC radio channel failures on the reliability and availability of the protection application. Intra-substation protection function is considered and a sensitivity analysis is conducted to study how the variation in fading margin, number of links in a radio channel etc. affect the availability and reliability metrics.

1.2) Comparison of the 5G and IEC 61850 based architectures: For a selected set of radio channel parameters, the availability of both intra-substation and and inter-substation protection functions of the 5G based architecture is compared with the functionally identical IEC 61850 based architecture. The following four configurations are studied:-

- *Case-A*: The IEC 61850 based substation communication network (SCN) shown in Figure 10 is considered with a wide area network connecting to another substation of the same architecture.
- *Case-B*: a similar IEC 61850 based architecture, but with a backup protection IEDs using the PRP protocol (i.e., with a redundant LAN network) [3].
- *Case-C*: the 5G based architecture functionally identical to A, i.e., Figure 2 where a radio communication between a field device and an edge cloud uses a single primary channel that consists n redundant wireless links.
- *Case-D*: the 5G based architecture functionally identical to B, i.e., backup protected with dual homing in the radio access (each with n redundant links) and a backup IED application running on another edge cloud as illustrated in Figure 2.

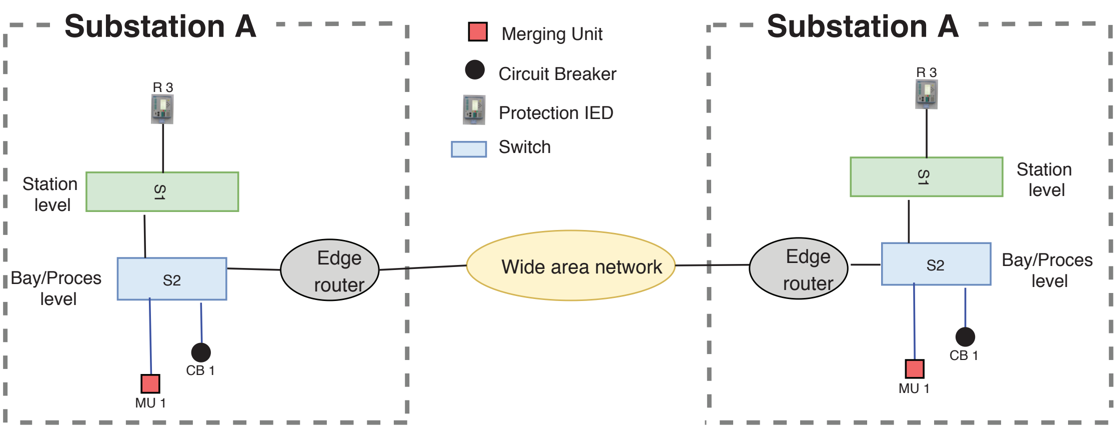

Fig. 10. Substation Communication Network Architecture based on IEC 61850 standard

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2) Metrics: The following metrics are used to quantify the impact of communication failures on the dependability of the protection application in the presented architecture:

- **Availability of protection function** (A_p): measure the steady state availability of protection function. The protection function is assumed to be available if all the the ICT components used by the protection application are in a working state. In the presentation of numerical results, the unavailability is used, $U_p = 1 - A_p$.

TABLE I

FAILURE RATE AND REPAIR TIME OF THE GRID COMPONENTS

Component type	**Failure rate [days^{-1}]**	**Repair time [hr]**
Merging Unit	2.6*10^{-3}	2
Circuit Breaker	2.6*10^{-3}	2
Communication line (fiber)	6*10^{-6}	6
Communication line ((LAN cables))	2.8*10^{-3}	3
Router/Switches	5*10^{-3}	3
Host server (permanent failures)	4.9*10^{-3}	2
Host OS (Software failures)	1.667*10^{-2}	1 (repair) 1.667*$10^{-1}(reboot)$
Virtual Machine Monitor (VMM)	8.3*10^{-3}	1 (repair) 1.667*$10^{-1}(reboot)$
SDN Controller	1.667*10^{-2}	5*10^{-1}
Virtual machines (VM)	1.1*10^{-2}	1
eNB	2*10^{-4}	10 hr
Power supply failure	1.9*10^{-3}	3

- **Availability of the service** (A_s): measures the steady state availability of the service (power) to an end user/load. When power lines fails, the protection function is expected to be in a working state for a certain critical mission time. If the protection function fails during this time, a higher recovery time for the power line is assumed which affect the service to the end users/customers.
- **Reliability** ($R(t)$): measures the probability that the protection function will be continually available for a certain mission time.

3) Failure and repair Models: The failure rates and repair times of the edge computing server components, based on [26] and [27], are presented in Table I. The parameters used for the field devices are from [23]. Failure processes are assumed to be Poisson and repair times negative exponentially distributed. Investigations on reliability of wide area internet connection shows that the major source of failure in connection is due to the links connecting the substation to the internet. For this reason, the wide area network is modeled as a single entity with an assumption that the dominant failures are from components and links connecting the substation to the internet. For the edge cloud server and routers of the 5G based architecture and switches in IEC 61850 architecture, a battery backup of four hours (deterministic) is considered during power outages. During failure of virtual machines, the mean time to migrate a VM is set to 1 second [26].

In modeling the fading behaviour of 5G-urllc radio links, the failure and recovery rates are calculated using equation fading:eq. A typical fading margin $F = 10dB$, medium velocity $v = 10m/s$, carrier frequency $f = 2GHz$, and a 5% fraction of the failure due to fading is considered. Furthermore, the impact of the radio channel on the reliability of the grid is investigated for a range of fading margins and number of redundant links. All n radio links are assumed to be operational at time $t = 0$.

All cases are simulated for 100 years of calendar time, each replicated 15 to 20 times for error control. Confidence bands of 95% are shown in Figures 11 and 13, but are omitted in Figure 12 to avoid clutter. The average computational time for one case with replications is in the range 4 minute to 25 minutes.

B. Evaluation and Discussion

1) Sensitivity Analysis: The radio access failure rate is varied over a range of values to study its impact on the resulting availability and reliability of the proposed 5G based architecture. Simulations are carried out by varying fading margins ($F = 5dB$ up to $F = 25dB$) and number of redundant links ($n = 1$ up to $n = 4$).

Figure 11 shows the unavailability (u_p) of protection function for varying n and F. It can be seen that the failure due to fading has a significant effect on availability of protection functions for a radio channel with low redundancy, $n = 1$ and $n = 2$. For a conservative assumption of fading margin, as low as $F = 5dB$, there is a significant unavailability of protection function even if the number of redundant links are increased up to four. For moderate assumptions of $F = 20dB$, n has to be set to greater than three and four in order to get unavailability figures in the range of 10^{-3} and 10^{-4}. Meanwhile, for optimistic assumption of fading margins $(F >= 25dB)$, similar unavailability figures can be obtained with just two redundant links.

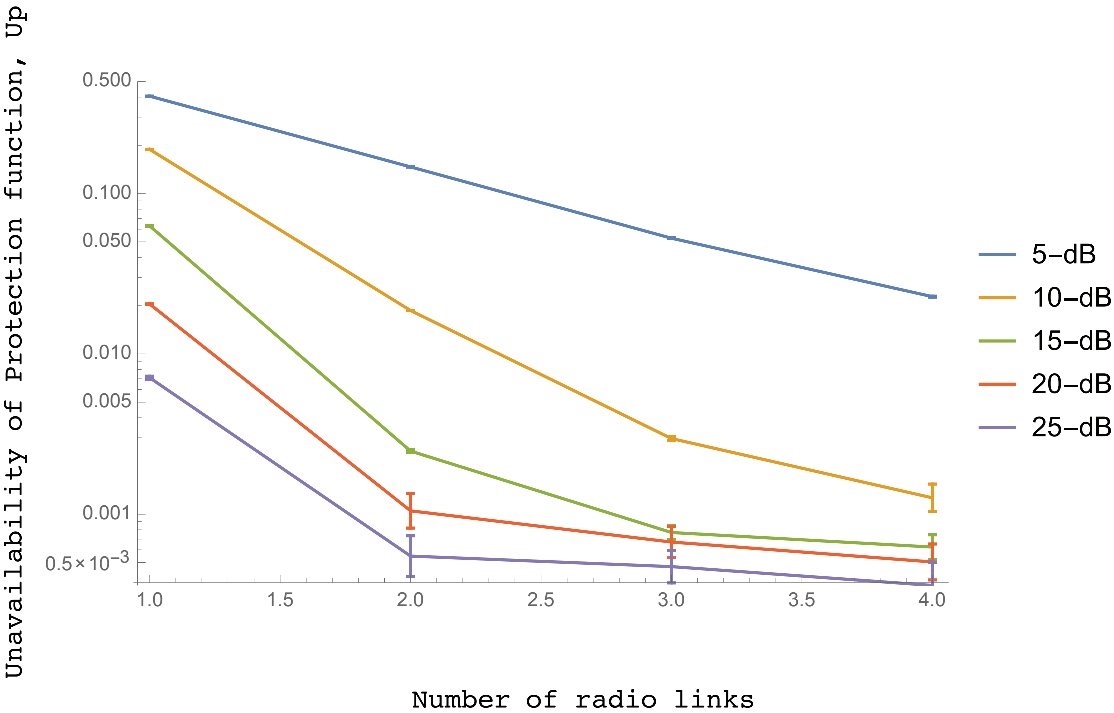

Fig. 11. Unavailability of protection function.

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The mission reliability of the protection function $R(t)$ and availability of the service (power) to end users is shown in Figure 12 where fading margin is set to $F = 20dB$. The metrics are measured for a range of mission time requirements as different protection applications have different critical performance requirements often ranging from 1 ms to 100 ms [14]. The effect of redundancy in the radio channels is also investigated by varying n.

For critical applications such as protection functions, it s very important to have a high mission reliability so that faults can be detected and isolated before causing a severe consequence. It can be seen that the effect of random fading process has a significant impact on the reliability measure. For a lower redundancy ($n = 1$ and $n = 2$), $R(t)$ approaches to zero quickly. In order to have a sufficiently high $R(t)$ for a typical protection application with a mission time of a few milliseconds, redundancy of $n >= 4$ is needed. In contrast, A_s is fairly higher for all the cases as failure in the protection function will not have an immediate effect on it. For a shorter mission time, it is needed that $n > 4$ to get an availability figure in the range of four nines (0.9999), whereas it is possible to get availability in the range of three nines (0.999) with redundancy of $n = 3$.

2) Comparison of 5G and IEC 61850 based architectures: An illustration and comparison of the resulting availability of protection function of intra-substation and inter-substation of the 5G architecture with the Ethernet based IEC 61850 architecture is shown in Figure 13. For the radio channel of the 5G

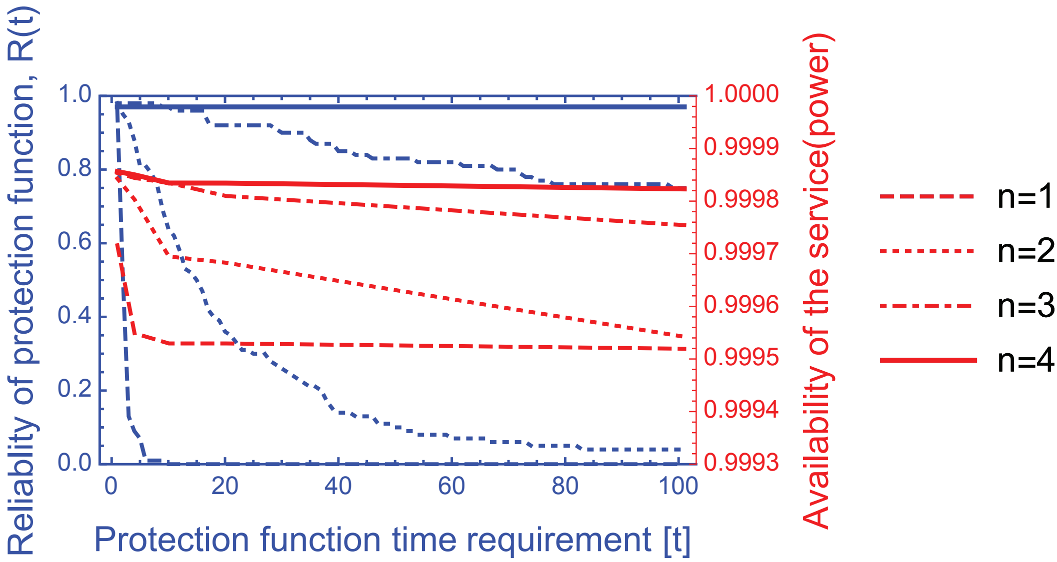


Fig. 12. Mission reliability of protection function and Availability of service, where $F = 20dB$. With 95% confidence interval in the range of 10^{-5} and 10^{-6} .

based architecture, the fading margin is set to $F = 10dB$ and $F = 20dB$ and a single radio access channel is assumed to consist four redundant links, $n = 4$.

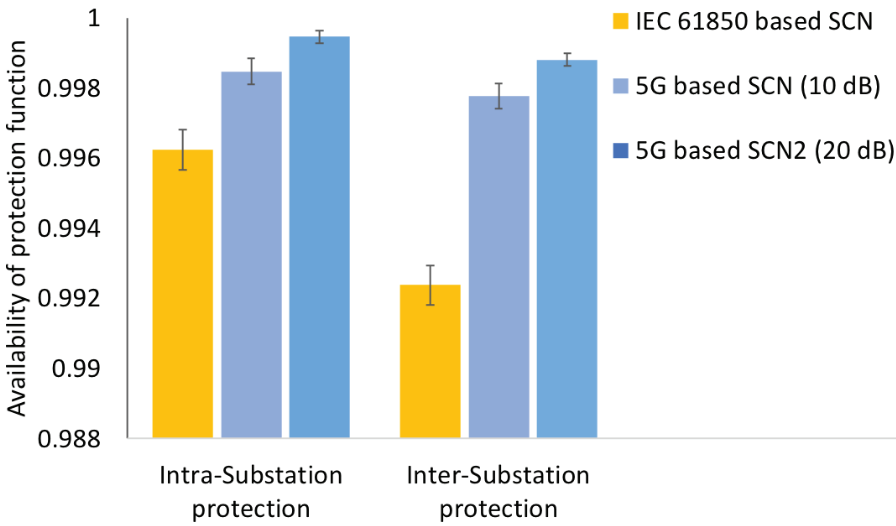
Figure 13(a) shows that the 5G based architecture has a significant change in the availability of intra-substation protection. The gain in availability is much higher in the inter-substation protection function. This is due to the virtualized protection function in 5G based architecture where service restoration can be done in few seconds i.e. migration of virtual machines. Figure 13(a) also shows that the intra and inter-substation availabilities of 5G based architecture are in the same range as compared to the IEC 61850 architecture as the protection applications of two neighbourhood substations might be placed in the same edge server or edge cloud with redundant backhaul network.

Figure 13(b) shows the effect of having a backup protection described in Case B and Case D. There is just a slight gain in availability of both intra- and inter-substation protection functions for 5G. However, the IEC 61850 based architecture's improvment from Case A is at the expense of doubling the whole LAN at the process level, which incurs more cost, while 5G just needs an additional radio access and a virtualized backup function in the edge cloud.

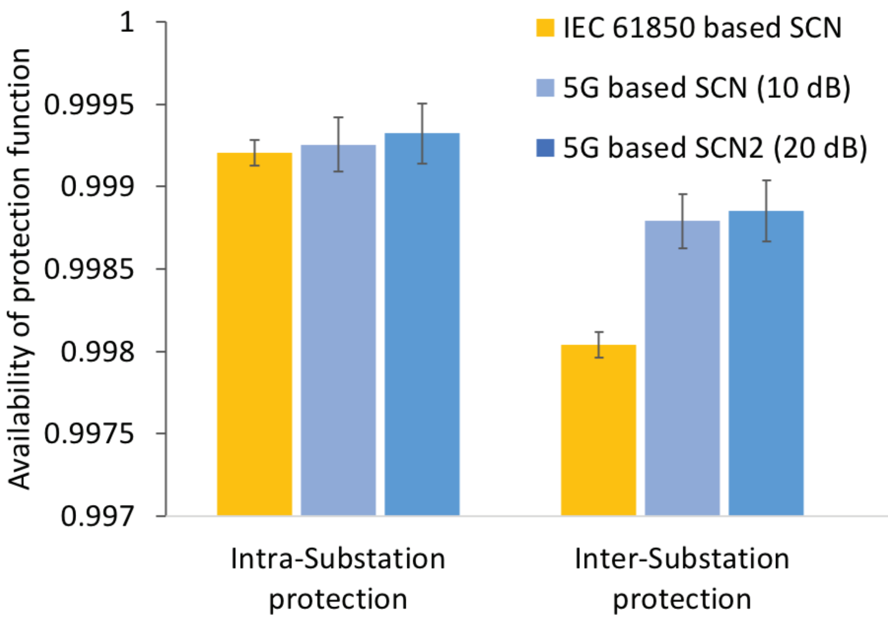
VII. Conclusion and Future Works

The future smart grid can benefit from virtualization and emerging ICT technologies such as 5G. In this paper, we presented a 5G based SCN architecture for protection in distribution grid. The dependability of this architecture is studied by a stochastic activity network simulation model. A simulation is conducted to study the impact of radio link failures on availability and mission reliability of protection application and the result is compared with functionally identical IEC 61850 based architecture.

The simulation reveals that 5G based SCN may results in a significant gain in availability of protection functions. The gain has a slight increase if dual homing at the process level of the architectures is



(a) Comparison without redundancy (Case A and C)



(b) Comparison considering redundancy (Case B and D)

Fig. 13. Comparison of the Availability of the protection function

introduced. The investigations did also show that the radio access of the 5G based architecture is a critical factor that high channel redundancy is necessary to compensate the loss due to random fading processes.

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Paper D

Dependability Modeling and Analysis of 5G Based Monitoring System in Distribution Grids

Tesfaye Amare, Michele Garau, Bjarne E. Helvik

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ABSTRACT

Due to large scale introduction of Distributed Energy Resources (DERs) in the next generation distribution grid, real time monitoring and control is increasingly needed to maintain a stable operation. In such scenario, monitoring systems and state estimation are key tools for getting reliable and accurate knowledge of the grid. These real time applications have strong requirements on communication latency, reliability and security.

This paper presents a method, based on Stochastic Activity Network modeling, for analyzing the performance and dependability of advanced communication technologies, such as LTE and 5G, for supporting monitoring system applications. A novel software tool, based on Möbius linked to external libraries, is developed and employed to analyze the impact of communication failures on the state estimation of a distribution grid. The application of the tool and its capabilities are demonstrated through a case study. The approach is promising both with respect to strength as a modelling tool and the kind of results obtained.

CCS CONCEPTS

• **Networks** → *Network reliability*; • **Computing methodologies** → *Discrete-event simulation*; • **Hardware** → *Smart grid*;

KEYWORDS

Dependability, Stochastic Activity Networks, Smart Grid, 5G

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1 INTRODUCTION

In recent years, the electrical power system is going through the so-called digitalization process as multiple other areas of industry, utilities and services. The concept of smart grid implies a significantly extended use of Information and Communication Technologies (ICT) in the management of the power network, to improve the performance, reliability and quality of service, as well as the operation of the electric system. Smart Grids (SG) can be defined by the concept of cyber physical systems (CPS), where a physical system, in this case the power system, is merged with a cyber system that provides the physical system with computational and communication capabilities. The two parts of the CPS are highly interdependent, although with their own peculiar characteristics. The power system is traditionally described by mathematical models in the continuous domain, meanwhile ICT system is typically described with discrete event simulation.

In order to properly characterize the smart grid as a CPS, proper attention should be focused on the design of the simulation tool, that must be able to merge these two systems and describe the interdependencies among the elements that compose the complex system. This issue opens a methodological problem, since different exigencies must coexist: on one hand, the necessity of reproducing the operation of the system in an accurate way, on the other hand the need of simplifying the system according to the detail of interest.

There is no established approach to deal with these issues in the coming generation of smart grid CPS. Recently, approaches have started to include communication and control systems in the dependability analysis of distribution systems, by adopting Markov chain modeling [15], Petri Nets [11], co-simulation [8], and Stochastic Activity Networks [4]. These are still not sufficient for modeling complex systems with an appropriate and balanced level of detail of the various parts of the system. Hence, their ability to support the analysis of the pros and cons of integrating the smart grid with the forthcoming 5G-network is limited.

In this paper a novel methodological approach is proposed, that combines Stochastic Activity Networks (SAN) modeling and numerical analysis, to take into account the continuous and discrete event activities of power system and ICT system. Based on this method, a simulation tool is developed by extending the Möbius platform, with external C++ libraries, developed by the authors. The tool is used for analyzing the dependability and performance of a 5G based monitoring system for state estimation in an IEEE standard distribution network.

2 MONITORING SYSTEM ARCHITECTURES IN DISTRIBUTION GRIDS

A reliable monitoring system is very crucial in providing a stable operation of the grid. In classic monitoring systems, measurement devices (MDs), or phasor measurement units (PMUs), are used to measure voltage and current. These measurements are typically first gathered by merging units (MU) or phasor data concentrators (PDC) and then forwarded to the control centre via a high bandwidth wide area network.

2.1 A 5G based Architecture

Along the trend towards virtualization, we foresee and propose a novel 5G based Wide Area Measurement System (WAMS) architecture that

moves the monitoring and control logic into an edge cloud in a 5G communication infrastructure. MD and PMU functions (such as conversion of analog measurements to digital) are kept close to field devices

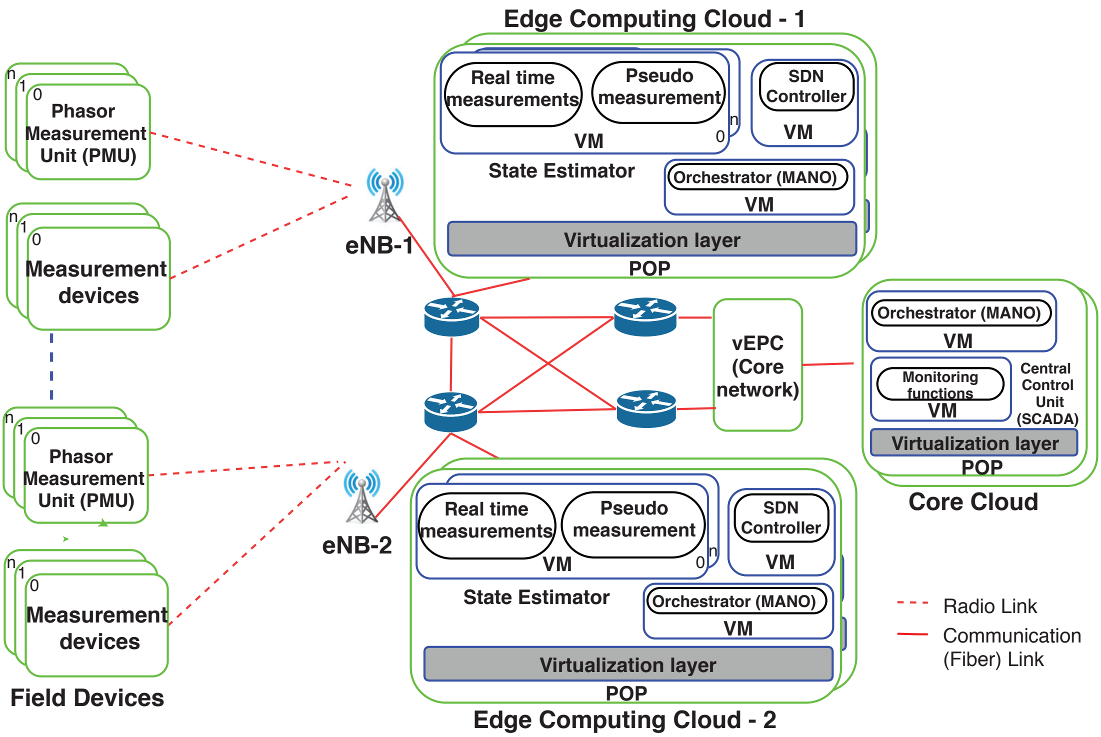

Figure 1: 5G based Architecture for WAMS.

while PDC data processing functions, part of MU functions and Distribution System Operator (DSO) functions are moved into the edge cloud.

The 5G based architecture proposed is shown in Figure 1. Measurement devices are assumed to communicate with the base station (eNB) through a radio links where the ultra reliable and low latency communications (URLLC) service category in 5G is used. Other 5G configurations such as 5G with LTE radio access network can also be considered. The edge computing cloud provides the virtualized application environment, where virtual machines (VM) are used to host monitoring, control and management functions of DSO controllers. A hypervisor is used to manage and orchestrate multiple virtual machines that run concurrently on the host edge cloud server, while a Software Defined Network (SDN) controller is used to manage the backhaul network. A completely isolated end to end network slice is considered, which brings multiple benefits such as guaranteed performance due to lack of interference from other applications

The timing requirement of a real time monitoring applications in the distribution grid is in the range of few milliseconds to one second [12]. 5G, by using URLLC radio links and moving the control servers close to the base station, is expected to meet this requirements, with round trip latencies of approximately one ms [13].

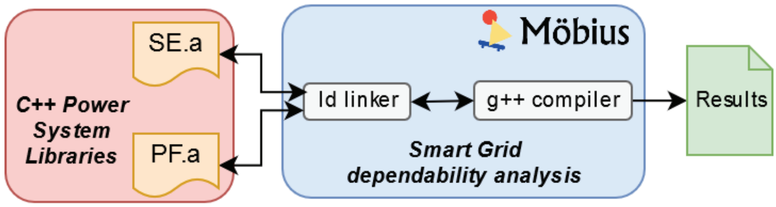

Figure 2: Schematic representation of the tool.

2.2 State estimation

In the Smart Grid paradigm, measurements play an important role. In fact, without an efficient representation of the state of the electrical grid, the active management of the network that underpins the smart grid concept would not be feasible, along with the renowned advantages of its application [6].

State estimation (SE) algorithms are based on the calculation of the electrical quantities that define the state of the network by the data collected from the measurement devices distributed on the electrical network. Typical measured quantities are the active and reactive power flows on the branches, and voltages and reactive and active power injections on the buses. Recently, the spreading of PMUs introduces new capabilities to SE algorithms, such as detecting disturbances and potential cascade events, through the measurement of voltage phasors and global time stamps [9].

Several algorithms have been developed to estimate the state of electrical power systems. The Weighted Least Squares (WLS) algorithm is the most commonly used for obtaining an accurate estimation of the network starting from a set of measures and pseudo-measures [1]. Given a measurement model of a system described by:

$$z = h(x) + e$$

where z is a measurements vector, $h(x)$ is the function that relates the network state variables x to the measurements on the system, and e is the measurement error vector, the WLS approach consists in minimizing the following objective function:

$$J(x) = \sum_{i=1}^{M} w_i \, (z - h(x))^2$$

where w_i is the weight associated to the i^{th} measurement and M is the total number of measures and pseudo-measures.

3 MODELING

The main issue in designing a simulation tool for smart grids is being able to describe the power system and ICT system as a CPS, along with the dynamic interdependencies between its elements. A framework is established using the Möbius tool [7], [2] extending the SAN modelling to deal with continuous phenomena. The main novelty is the inclusion of power system analysis functions by exploiting external C++ libraries developed for this purpose, as illustrated in Figure 2.

Major events such as failure and repair within power system and ICT systems are modeled as SANs, while power flow and grid state estimation calculations are performed with the C++ libraries linked with the Möbius compiler. Two libraries were developed for this study: *PF.a*, which provides the tool with the capability of performing power flows; *SE.a*, which provides the tool with the capability of performing state estimation calculations.

Whenever a failure, recovery or repair event is generated by the SAN simulation in Möbius, power flow and state estimation calculations are carried out by the power system analysis functions, defined within the C++ libraries, based on the working state of each system component extracted from Möbius. The results are recorded as values in the extended places in Möbius, and might be acted upon in further simulations.

3.1 Model description

A model is developed for the different communication infrastructures discussed in 2.1. First, a Möbius atomic model is developed for all individual components of the architecture. Then, the overall system is modelled by connecting the atomic sub-models through a composed model that defines the shared extended places. The reward model functionality in Möbius is used to collect statistics of interest for each state transition of the system (failures and repairs). For a detailed description of the SAN modeling cf. [2].

The estimator application atomic model, shown in Figure 3, is provided as an example. It contains the core setup for the exchange of information between the ICT system and power system libraries.

It consists of three main places: *OK_Initial*, *Estimation* and *Failed*. It has global variables, defined as extended places, to store power system variables from both the power flow analysis and state estimation. A power flow analysis is made on the initial grid state prior to estimation so that the ideal case values are known. Extended places such as *event_to_check* contain the states that are shared with other monitoring system components such as the measurement points (sensors). According to discrete event simulation paradigm, these shared states are used to trigger the state estimation calculation. Both the power flow and estimation libraries are called in this atomic model and the result will be stored in the respective global power system variables. The estimator application may fail from working states in *OK_Initial* and *Estimation* to a failure state in *Fail* if the underlying virtual machine fails to provide service (through *IED_VM*).

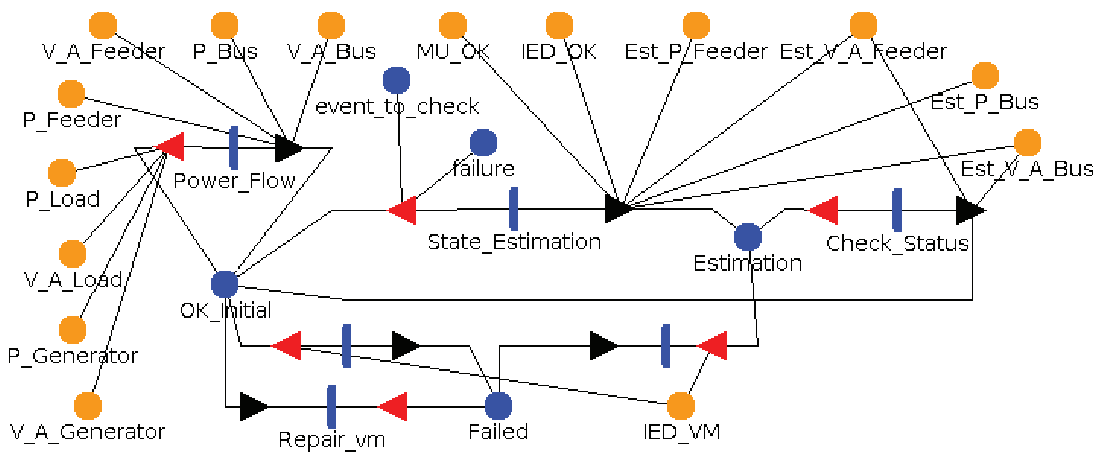

Figure 3: An atomic model of estimator application.

Table 1: Standard deviation for real time and pseudo measurements

Measure-ments	Bus Voltage	Bus load	Branch PF
Real Time	0.004	0.008	0.005
Pseudo	0.03	0.06	0.04

4 DEPENDABILITY ANALYSIS

A simulation study of a distribution network is carried out, focusing on measuring the impact of ICT failures on the state estimation of the grid.

4.1 Scenario

4.1.1 Power Grid. . The analysis is performed on the IEEE 33-bus standard distribution network represented in Figure 4. A mix of sensors for branch power flow, bus load and bus voltage measurements are uniformly distributed along the grid, as shown in Figure 4. Pseudo measurements are also used, that provide the algorithm with assessed measurements based on historical data and improve the observability of the system. Generally, the pseudo measurements are imprecise compared to real-time measurements. Hence, a larger standard deviation is assigned to them. See Table 1 for values used.

4.1.2 ICT System. . The 5G Wide Area Measurement System (WAMS) architecture presented in section 2.1 is studied. This assumes that the measurement points are connected to the estimator application in the edge cloud by a radio access network. The objective of the case study is to quantify the effect of WAMS failures on the power system application, i.e. the grid state estimation. Two 5G options are studied i) 5G

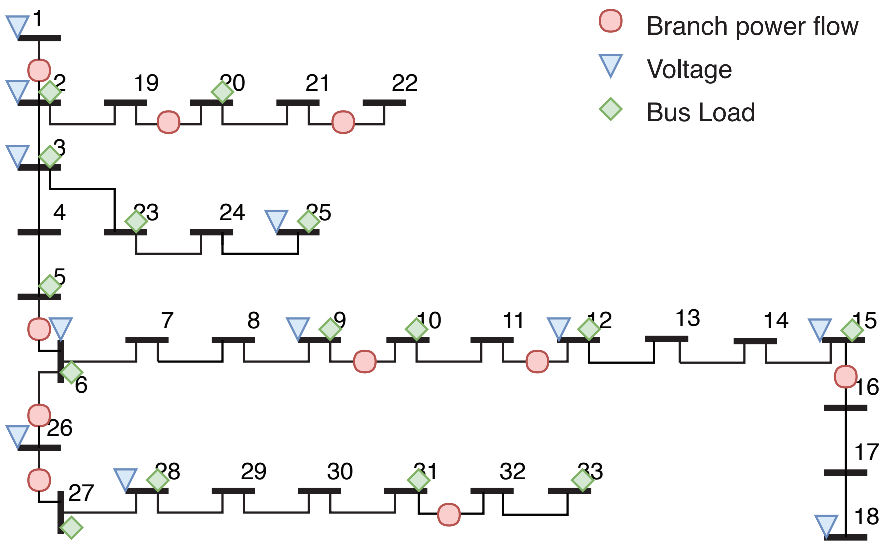

Figure 4: IEEE 33-bus standard distribution network [3].

Table 2: Failure rates and recovery times of the system components [2, 10]

Component type	Failure rate [days^{-1}]	Mean recovery time [hr]
Merging Unit	$2.6 \cdot 10^{-3}$	2
Fiber Line	$6 \cdot 10^{-6}$	6
Router/Switches	$5 \cdot 10^{-3}$	3
Host server (HW)	$4.9 \cdot 10^{-3}$	2
Host OS (SW)	$1.667 \cdot 10^{-2}$	1 (repair) $1.667 \cdot 10^{-1}$ (reboot)
Virtual machines	$1.1 \cdot 10^{-2}$	1
eNB	$2 \cdot 10^{-4}$	10
Power supply failure	$1.9 \cdot 10^{-3}$	3
Radio Link	$8.64 \cdot (10^{0}–10^{1})$	$2.77 \cdot 10^{-4}$ (=100ms)

with URLLC radio access and ii) 5G with LTE radio access (LTE-PHY HARQ RLC ARQ) see [5]), which are compared with iii) fault free WAMS.

4.1.3 Failure and recovery times. . A negative exponential distribution is used for all failure and recovery times. See Table 2 for the parameters and the data sources.

4.1.4 Metrics. . To quantify the impact of WAMS failures on the accuracy of the state estimation of the power grid, the *mean estimation error* is obtained, i.e., the difference between the voltage estimation using the WAMS and the ideal/actual values. The system is simulated for 1 month of calendar time, replicated 15 to 20 times, to achieving confidence bounds sufficiently tight to draw firm conclusions.

4.2 Evaluation and Discussion

4.2.1 Results discussion. Figure 5 compares the mean error in voltage estimation of 5G based configurations described in Section 4.2 with the ideal scenario, where the error is only due to the performance of the SE algorithm. It is observed that the 5G-URLLC behaves closely to the ideal WAMS setup, while the 5G-LTE presents a noticeably higher mean voltage estimation error, mainly due to the higher radio link unavailability of LTE, that introduces a higher measurement error on the SE algorithm. Although the LTE based configurations results in a higher mean estimation error, it is still consistently lower than 10^{-2}, which is commonly used as accuracy threshold for state estimation application in distribution grids. [14].

4.2.2 Tool evaluation. The simulations were run on an Intel Core i7-6700 CPU 3.40GHz quad-core with Linux. In Table 3 the simulation times for a single run of three different modes: (*A*) simulation without grid state estimation; (*B*) simulation with event driven grid state estimation (the proposed approach); (*C*)

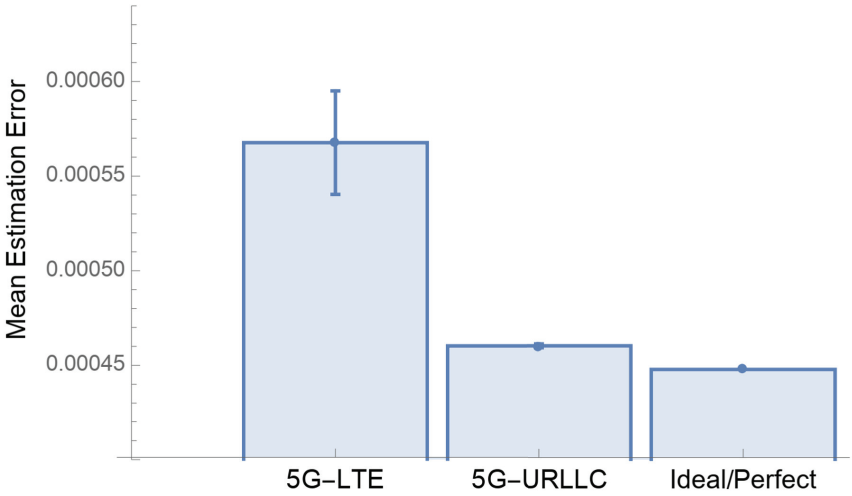

Figure 5: Mean estimation error with different radio access technologies

simulation with continuous (every100 ms) grid state estimation (the naive approach). The simulation tool implemented has proven to be effective in assessing the dependability of the smart grid as CPS with a fairly reasonable simulation time. The mode B introduces a longer simulation time than the mode A, due to the time required by the power flow and state estimation calculation. Nevertheless, the event driven approach adopted for the power system simulation allows saving a considerable simulation time if compared with mode C.

Better computational performances may be obtained with a comprehensive modelling of the smart grid in a single general purpose language, although it requires a higher programming effort for a proper level of abstraction. However, our experience so far is that the methodological approach presented in this paper provides the needed validity and generality.

5 CONCLUSION AND FUTURE WORKS

This paper addresses the challenge of dependability assessment of the coming cyber physical power distribution grid. It presents a Stochastic Activity Network based model for analyzing the performance and dependability of such a system. An extension of Möbius with linked external libraries is developed and employed to analyze the impact of communication failure on the power grid state estimation. The approach is demonstrated through a case study which showed significant improvements in the performances of the state estimation with a WAMS supported by URLLC-based 5G technologies compared with LTE-based communication infrastructures.

Table 3: Simulation performance with different modes

Mode	A	B	C
Simulation time	2-3 min	0.5 - 4 hr	3.5 days

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Paper E

A Method for Performability Study on Wide Area Communication Architectures for Smart Grid

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Abstract

An extensive use of ICT is a key feature in the development of next generation smart grids. The ability of the ICT system to meet the real time requirements of the powers system, even when it is degraded due to failures, is essential. This simultaneous study of dependability (reliability) and performance are referred to as performability.

This paper presents a method for a performability study on ICT support system of smart grid. It looks into how performance associated properties (timing failures) can be modelled together with properties affecting dependability such as omission or conventional component failures. A two tier model using ns-3 and SAN is developed to study the peformability of an IEC 61850 based communication infrastructure for a protection application. For illustration, a simulation is conducted to study the reliability and unavailability of an IEC 61850 based communication architecture, where the impact of both timing failures and omission failures are investigated and compared. The result revealed that the availability and reliability is highly dependent on the requirements for the protection application, maximum delay per packet and maximum number of consecutive delayed packets the protection application can tolerate. It also shows that timing failures have a higher impact than omission failures for a protection application with shorter time requirement.

Keywords

Performability, Smart Grid, Stochastic Activity Networks,IEC 61850, Modeling

I. Introduction

In Smart grid, the electricity distribution and management is upgraded by incorporating advanced ICT support system and extensive computing capabilities for improved control and reliability. Massive use of distributed energy resources, advanced data acquisition, smart metering and automation of the grid operation is increasing the complexity of the grid and forcing the grid to highly rely on the underlying ICT support. Thus, the digital communication between Intelligent Electronic Devices (IEDs) has become a key feature in the development of the next generation smart distribution grid. The grid, being a very critical infrastructure,the dependability (availability, un-interrupted service) and performance (latency/real-time, throughput) of this ICT support system has to be carefully studied.

Dependability and performance are properties of systems that are commonly studied separately and a complete assessment of the system is often obtained by taking the results of each type of evaluations. For ICT systems of even moderate complexity, individual assessment of performance and dependability can not be combined in this fashion to determine the overall quality of service [1]. This is mainly due to properties of one affecting the other. For instance, in a fault tolerant system with redundancy, a fault may not necessarily result in failure of the service, but it may degrade the performance, i.e., the system might be regarded as available (from conventional dependability point of view), but it may not meet the timing requirements. What we refer as *Performability* is used to capture the combined influence of dependability and performance.It measures the ability of the system to provide a particular service with sufficient performance over a certain time, even in the presence of failures [1].

The aim of this paper is to propose a method for a performability study of ICT support system of smart grid. The focus will be on a communication infrastructure for a protection of power lines connecting substations where a wide area network based on IEC 61850 is considered.

The rest of the paper is organized as follows. The next section give a summary of related work on dependability and performance of communication systems for protection in smart grid and put this paper into that context. A brief background knowledge and presentation of the wide area communication architecture is discussed in Section III. Section IV presents the proposed method and model. In Section V, the simulation scenario and an illustration of the results is presented. Lastly, Section VI gives conclusive remarks of the work.

II. Related work

The dependability and performance of communication systems for protection in smart grid has been studied by some, but not in a comprehensive way. Papers such as [2], [3], [4], [5] studied the reliability of an IEC 61850 based substation communication networks (SCN). Various techniques has been used; Chen et al. used reliability block diagrams (RBD) and fault tree techniques, Wafler et. al used RBD and Markov modeling while Zeng et. al used stochastic petri nets for studying the dependability of wide area networks in smart grid substations. A probabilistic model checking for conducting the safety-critical reliability analysis of the protection systems of smart grids is used in [2]. Most of these works has focused on studying the dependability of the SCN focusing on omission failures. They do not look into performance related issues; for e.g. failure to meet the timing requirements are not considered. For the ICT support in a smart grid, timing issues are an integrated part of the system specification (such as the protection application) and the dependability evaluation shall also verify that the system is doing what it should do, in a timely way.

On the other hand, some works such as [6], [7], [8], [9], [10], [11], [12], [13], [14], [15] studied the performance of communication systems in smart grid. Paper such as [9], [10], [8], [11] looked into performance analysis in SCNs. Kanabar et. al[8] evaluates the performance of sampled value packets over the IEC 61850-9-2 based substation. Xiang Lu et. al [12] conducted experimental study on the delay performance of DNP3 over TCP/IP communication in smart grids. In [13], the performance of a communication network for a Nordic 32 power system is studied under different QoS mechanisms. Ferarri et. al [14] studied the delay performance of communication in substations in the case of most common network failures. Performance evaluation of various possible communication systems between IEC 61850 based DAS and DER is presented in [15]. Few papers such as [6], [7] have also looked into the performance analysis in communication between substations. Yiming Wu et. al. [6] presented a study on the effect of bursty traffic on delay measurement on a wide area communication for IEEE 14 bus system. Ali et. al [7] studied the performance of IEC 61850 for peer-to-peer communications between substations. Similarly, most of the papers that has looked into the performance analysis does not consider factors associated with dependability analysis such as failure of components that could also affect the performance. With such approaches (individual evaluation of dependability and performance), decision making would be challenging as it lacks the ability to give a comprehensive measure(full picture) of the QoS.

This paper looks into how performance associated properties (timing failures) can be modelled together with properties affecting dependability of the ICT support system in smart grid. A two tier model is presented where Ns-3 is first used to study the performance characteristics. Then, the result from the Ns-3 model are stored in a C++ static library for a use in the second tier stochastic activity network model which is used to study the reliability and dependability of the communication infrastructure for protection in the smart grid. To demonstrate the capabilities of the model, the impact of timing failures on the dependability of the communication system is investigated and compared with (omission) failure of components.

III. System Considered

The study considers a communication infrastructure for a protection of power lines connecting substations where a wide area network based on IEC 61850 is part of the system. The communication architecture and major assumptions are presented below.

A. Wide area communication in smart grid

Wide area networks form the communication backbone to connect the highly distributed smaller area networks that serve the power systems at different locations [16]. They are used to transport real-time measurements or local SCADA information taken at the electric devices (from substations) to the control centers or to neighbouring substations and carry instruction or actuator commands from control centers to electrical devices in the substations.

B. Communication architecture

An IEC 61850 based wide area communication between substation using a V-LAN tunneling setup is considered. It is a ring architecture, as shown in Figure 1, where gateway switches from each substation are connected through a ring network by a fiber line. The substation networks are connected to the control center or SCADA controller through the gateway switch at substation 4. Each substation are assumed to generate a background traffic (k) from inside which has to be carried through the ring network towards the control center. In addition, all substations are assumed to exchange control information (such as sampled value and GOOSE messages) to each other.

C. Latency requirement

Real time performance, i.e., the latency of packets trough the network, is critical in smart grid communications. The messages communicated between various entities within the smart grid have different network latency requirements. The protection function is among the applications that are most demanding [16]. The protection information exchange between intelligent electronic devices is useful only within a predefined time frame. If the communication delay exceeds the required time window, the information does not serve its purpose and the grid may be damaged. Based on the IEC 61850, the maximum latency for a protection information external to substations, is in the range of 10 to 100 ms [16].

D. Failure Semantics

The communication in smart grid may fail in a number of different ways. In this study the two failure modes *omission* and em timing are considered. Based on [17], the failures where no service /message is delivered are referred as omission failures. In a separate dependability analysis, discussed in the introduction, typically just these are regarded. Timing failures occurs when the system does not meet its specified timing requirements. These are important in smart grids as discussed in section III-C.

IV. Modeling

This section presents the model used for studying the performability, i.e., a comprehensive dependability analysis of the communication system for a protection in smart grid, incorporating the impact of timing failures. It is based on the stochastic activity network (SAN) formalism [18] and uses the Möbius tool [19] in combination with the Ns-3 network simulator [20]. This is described in Subsection IV-A, which gives a high level description of the method employed. Then, the Ns-3 based model for the traffic handling of a single link is presented in Subsection IV-B. Finally, the details on the components SAN model are described in Subsection IV-C.

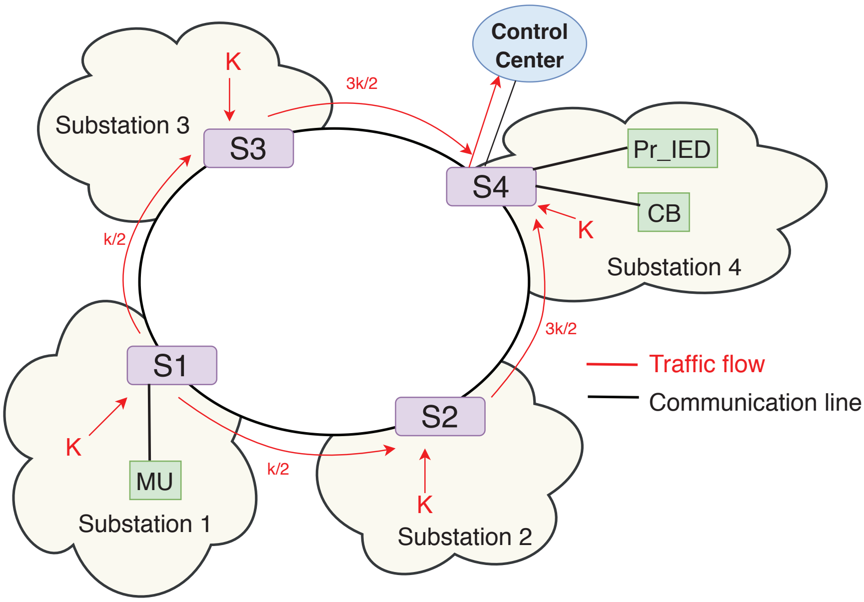

Fig. 1. Ring architecture of the ICT support system.

A. *Method*

In designing the tool, the main goal is to propose a method which is able to model the packet level dynamics of the communication infrastructure, capture timing failures and include these failures into the dependability study of the whole distribution network.

Performance studies often require modeling the packet level detail of the system while reliability/dependability studies usually take into account a relatively rare events such as failures, repairs, dependencies and interaction between components. In order to properly characterize timing failures, it is necessary to model the packet dynamics. However, modeling the ICT support system with such level of detail together with dependability simulation models with rare event failures that occur once in years, will be very time consuming and inefficient. Hence, the main issue in a performability study of the grid is the inclusion of timing failures with the other (omission) failures in the system, despite the two have different characteristics.

Figure 2 shows the employed method and Figure 3 illustrates the schematic representation of the proposed tool. As shown in Figure 2, the communication architecture has to be first identified together with the failure and recovery rates of its components. The types of traffic, traffic flow pattern and traffic parameters have also to be defined and set. Then, the background traffic is classified into a number of sets ranging from the minimum to maximum values the network can potentially carry.

The proposed method has two stages. On the first stage, a simple model is used to study the delay performance on a single link (delay on a switch towards a link). Then, the results from this model are used on another model which is used to study the performability of the whole architecture. The first stage single link model is presented in Figure 4. It consists two end points (MU and Pr_IED) that are connected with an Ethernet switch. As shown in Figure 3, Ns-3 is used to model the single link for a set of cases with the different environment, i.e., a set of possible background traffic scenarios a given link could have. For each background traffic scenario, Ns-3 simulations are done to study and measure the delay introduced to sample values that are sent between the two endpoints. A real time hardware-in-the-loop (HIL) set up is also used to model the single link for the purpose of validation and calibration of the Ns-3 model. For a selected set of background traffic, measurement from the HIL is used to validate the results from Ns-3 simulation.

The measurements from Ns-3 are then used to create a static C++ library (*Delay.a*) that maps the delay measurements with the various set of background traffic. The C++ static library is made for a use in the second stage model where the performability of the ICT support system is studied.

A stochastic activity network model (SAN) is used to study the performability of the whole communication infrastructure. All major events such as failure and repair of components are modeled with the SAN using the Möbius tool [19]. Timing failures are also modeled by SAN, but with the data from the static C++ library externally linked with the Möbius compiler.

The SAN model is developed for an event driven simulation. Whenever an event(for e.g., power failure) that need to use the communication infrastructure occurs in the simulation, the model first determines the state of the traffic through out the communication network. Then, it will use this information to draw the delay measurement of each link (switch towards a link) from the external library.

The collected measurements are then recorded as values in the extended places in Möbius , and might be acted upon in further simulations, i.e., once the measurements are known at all points in the network, decisions are made if there will be a timing failure or not by comparing the aggregated delay from a path (communication line) of interest with a threshold value. The ICT support is considered as unavailable if either a timing failure as stated above occurs or if there is omission failure of components that are necessary for the protection application.

B. *Methods to capture network delays*

In this section, we show how network delays and effects on the single link model are measured. Both approaches, the Ns-3 model for studying all the scenarios and the HIL for validation, are presented.

1) Real time Hardware-in-the-loop prototyping: Hardware-in-the loop testing platform combined with communication network emulator have been proposed for testing of protection algorithms in inter-substations and even wide area networks. It enables modelling of communication network impairments to study impact on overall protection performance [21], [22].

In this work, we set up a simple HIL involving OPAL-RT simulator, communication emulator, practical network switch and relays to measure the delays experience in the network by a specific protection application traffic. Two substations made to share sample value (SV) measurements for a protection application. A separate background traffic which is generated from a simulated video traffic source, is added to the network traffic mix. Then, we measure the delay incurred on the SV traffic for a 1 minute duration. Different background traffic sources are used and the delay impact on the SV traffic is measured for each cases.

2) Ns-3 prototyping: Ns-3 [20] is an open-source discrete event simulator that provides support for network protocol simulations. In studying the various scenarios, Ns-3 model is easy to setup the experiment and gives full control in setting the model/traffic parameters. For these reasons, all cases of network delays incurred on SVs are modelled in Ns-3. However, the Ns-3 may not be as representative as the HIL. To improve the accuracy of the Ns-3 model, HIL results are used to calibrate it before taking measurement for all the scenarios. For a selected background traffics, HIL measurements are used to validate the result from the Ns-3 simulator.

The Ns-3 prototyping is achieved by modelling the SV as a traffic source with the IEC61850 properties. SV are sampled measurements of current and voltage generated from devices called merging units. Assuming $50\,\mathrm{Hz}$ and a sampling rate of $80\,\mathrm{samples/cycles}$, SV generated will be $4000\,\mathrm{packets/second}$. Hence we set our traffic source as a constant bit rate traffic source to achieve this property of $4000\,\mathrm{packets/second}$.

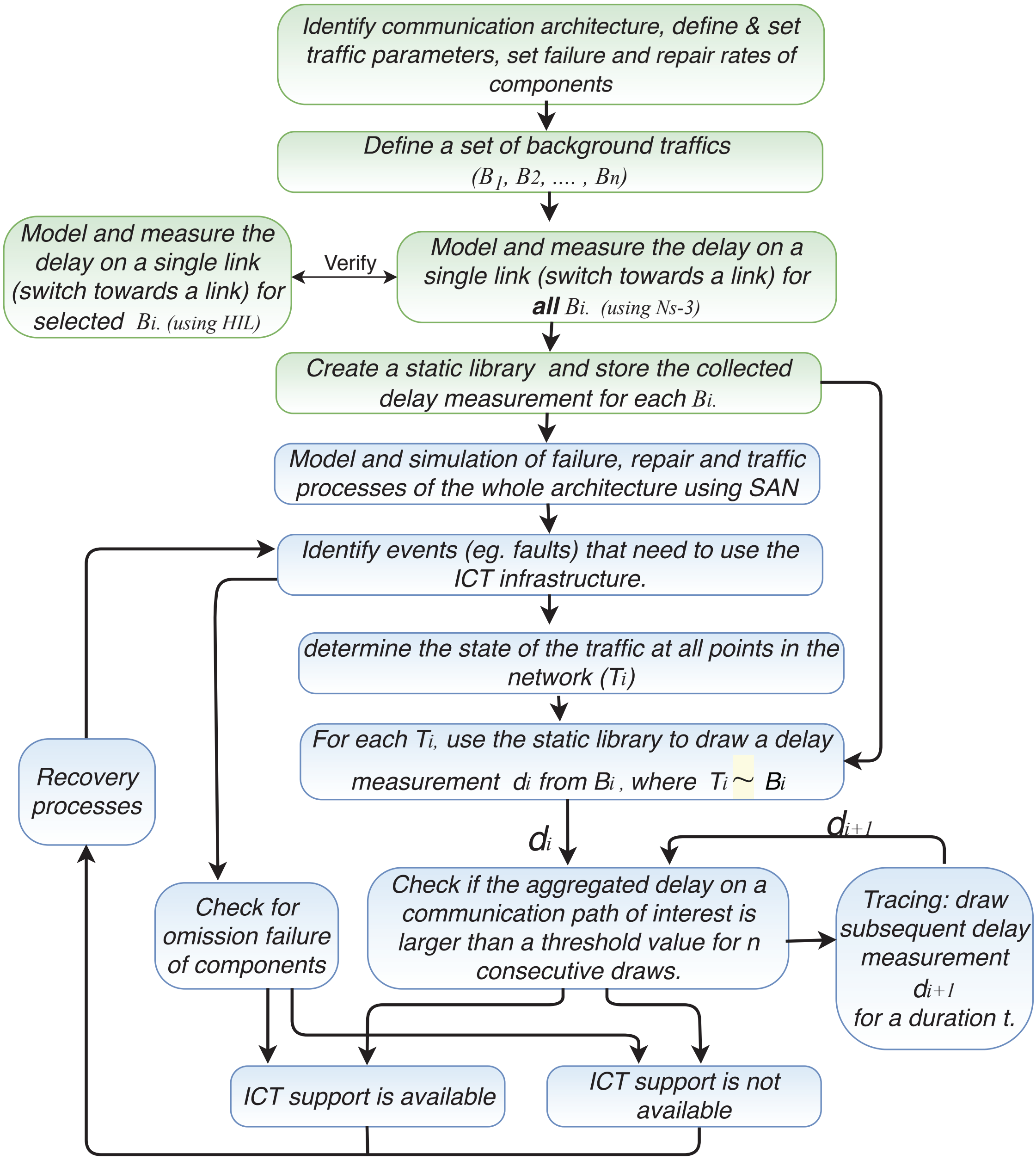

Fig. 2. The proposed method.

The background traffic source is modelled using video trace files obtained from Telecommunication Networks (TKN) Group at Technical University Berlin [23] (The trace library is available at http://www-

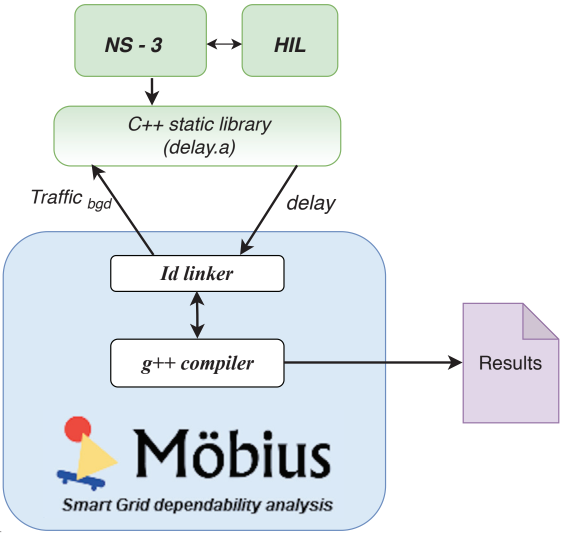

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Fig. 3. Schematic representation of the proposed tool.

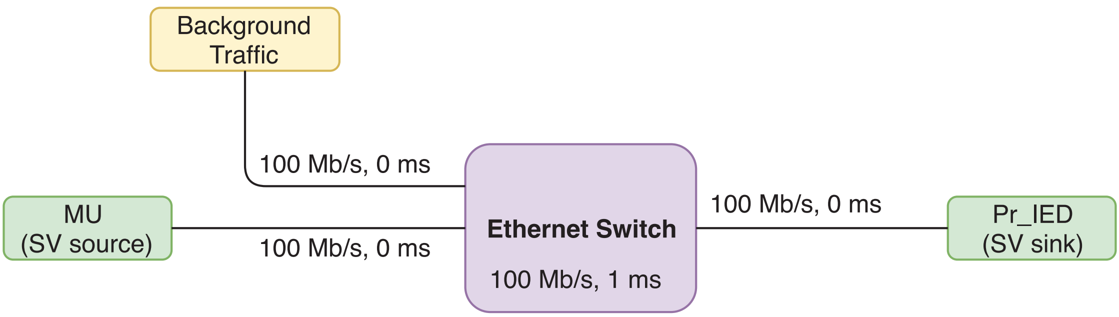

Fig. 4. The single link Ns3-HIL model

tkn.ee.tu-berlin.de/research/trace/trace.html). Different combinations of this sources are used to create different background traffic scenarios. The two sources, SV and background traffic, are then connected to an Ethernet switch as shown in Figure 4. A sink node on the other side of the switch is used to look into the time stamps of the packets and collect the network delay measurements.

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C. SAN models

A Stochastic activity network model using the Möbius tool [19] is used. It is a general and modular stochastic model, which is built from atomic block models. First, a Möbius atomic model is developed for all individual components of the communication architecture proposed in Section III-B. Then, the overall system is modelled by connecting the atomic sub-models using the Join formalism in Möbius . The reward model functionality in Möbius is used to collect statistics of interest.

Atomic models are developed for the individual components of the IEC 61850 based architecture shown in Figure 1. Detailed models of components can be found in [24]. Below is a summary of some of the atomic model types extended for this study. The extended places in Möbius are used to create instances of the model types. Extended places are special elements in the SAN formalism that allows the model to handle the representation of structures and arrays of primitive data-types(places). Input and output gates, red and black boxes of Figure 5 - 7, are used to define the enabling condition and consequences of an activity or state transitions in the model.

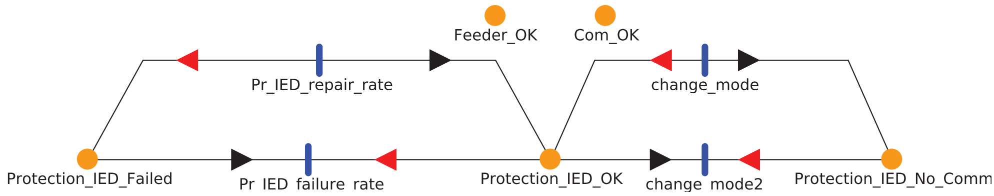


Fig. 5. An atomic model of Protection-IED.

1) Protection IED:- : Figure 5 shows the atomic model for a protection IED, one of the important components in the communication architecture for smart grid protection presented in Figure 1. It consists of four extended places; Working (*PR_IED_Ok*), failed power supply - No power (*PR_IED_No_Power*), failure in communication link - No communication (*PR_IED_No_Comm*) and Permanent failure (*PR_IED_Failed*). From initial working state in *PR_IED_Ok*, a protection IED could end up in a *PR_IED_No_Comm* state if the communication nodes/links towards it are not in their working state.

A working state in *PR_IED_Ok* instantly switch to a no power state in *PR_IED_No_Power* if its power supply is lost. Protection IEDs could fail(omission failure) from all other states to a failed state in *PR_IED_Failed* which needs maintenance. Shared states between the *Protection_IED* and other components are modeled by the unconnected extended places at the top, (*Feeder_OK* and *Com_OK*). This two shared states are used to model the interaction and dependencies with the other atomic models.

2) Background traffic generator:-: Figure 6 shows the atomic model for background traffic generator. It is used to model the varying background traffic carried by the switches of Figure 1. It is also used to determine the delay a packet would experience when it passes through on a certain switch interface towards a link at a given instant of time. In this study, we have considered video traffic (such as for monitoring power lines) as a background traffic which flows from the substations to the control center. It is assumed that an average rate of K Mps is injected to each switches accounting for the video traffic generated from inside the substations.

The model consists of three extended places; *Normal*, *Peak* and *Delay_On_Switch*. A set of regular and peak background traffic values are defined and modeled by different markings of the *Normal* and *Peak* extended places. *Normal* is used to model regular traffic conditions while *Peak* is used to model peak traffic that rarely occurs.

Rates are defined to vary the background traffic either within the normal/peak values or between peak and normal values. The following parameters are used to characterize the background traffic:-

- K_n:-an average rate of the normal traffic in Mbps.
- K_p:- an average rate of the peak- time traffic in Mbps.
- K_{n_var}:- the maximum and minimum variation/deviation within the normal traffic in Mbps. This are modeled by the *normal_var* transitions from/to the *Normal* extended place.
- K_{p_var}:- the maximum and minimum variation/deviation within the peak traffic in Mbps modeled by the *peak_var* transitions from/to the *Peak* extended place.
- $\lambda_{n\_to\_p}$:- the rate at which the peak traffic occurs. It is modeled by the *normal_to_peak* transition
- T_p:- average duration of peak traffic, modeled in the *peak_to_normal* transition.

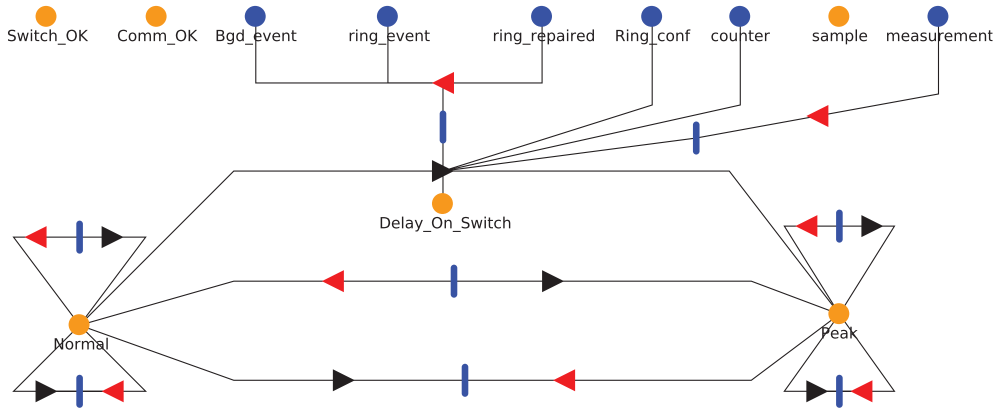


Fig. 6. An atomic model of Background traffic generator.

Whenever a fault in the power system occurs, the background traffic generator learn about it through *measurement* shared extended place. This initiate the process to determine the instant state of background traffic in the network and measurement of delay in the switches. If there are any changes in the topology of the communication system that may affect the traffic, it will be captured through the shared extended places: *comm_event* and *ring_config*. Then, based on the instantaneous traffic values, this model queries the static library (delay.a from the Ns-3 simulation) to obtain the delay measurement for all the switches in the network. The *Delay_on_Switch* extended place is used to store the measured delay values. Once the first measurement is taken, tracing is used to obtain the consecutive measurements until the fault is neutralized. A different marking on *measurement* shared place is used for this purpose, to continually query the static library for a certain mission critical time (a requirement from the protection application).

3) Protection function:-: The protection function atomic model, shown in Figure 7, is used to model the protection function and its performability assessment. It is not a model for a physical component, but rather it is used to model the impact of both timing and component (omission) failures on the availability and reliability of the ICT support for protection application. Timing failures are determined by the requirements for the protection application i.e. how resilient is the protection application to delay in the sampled value packets. This characteristics is mainly described by two parameters; the maximum delay per packet (t_max) and maximum number of consecutive delayed packets (n_max) the protection application can tolerate.

The model consists of four extended places; *Pwr_Line*, *Fault*, *Safe_Mode*, *Unsafe_Mode*. The *Pwr_Line* is used to model a normal working state of a power line while the *Fault* extended place represent the immediate state after a fault occurs in the power line. The fault state is communicated to the traffic model through *measurement* extended place and a different marking on this extended place is used for tracking and tracing the delay measurement from the traffic model until the isolation is done by the protection application.

The fault will be neutralized safely if the protection function is continually available during the critical mission time.This is represented by a transition to *Safe_Mode* extended place. Otherwise, it will go to the *Unsafe_Mode* state.

Considering timing failures, a protection function is said to be unavailable if the packet delay on the switches (those on the communication path of interest) is greater than the threshold (t_max) for n_max consecutive packets. This is modeled by a fault to safe/unsafe mode transitions dependent on the

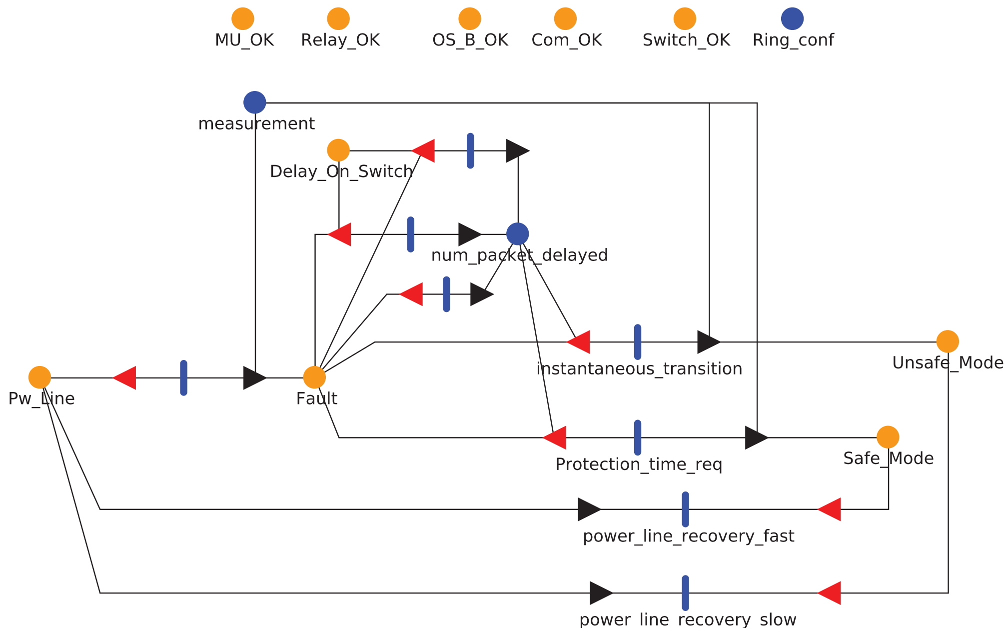


Fig. 7. An atomic model of Protection function.

Delay_On_Switch extended place, which is a shared place with the traffic model. The *num_packet_delayed* place is used to count the number of consecutive packets delayed by more than the threshold value. If the number exceed n_max before the protection IED handle the fault, it will result in unsafe isolation of the power line. Otherwise, if the number of delayed packets is less than n for a protection time t, it will go to safe mode and halt taking the delay measurement (through the *measurement* extended place).

For modeling omission failures, the safe/unsafe mode transitions are made dependent on *MU_OK*, *Protection_IED_OK*, *Switch_OK*, *OS_B_OK* and *Com_OK* extended places which are shared places with different components of the communication architecture shown in Figure 1. If one of these necessary components are in a failure state, the fault will not be cleared safely, a transition to *Unsafe_mode*. Otherwise, it will go to *safe_mode* if there are no timing failures within the protection mission time.

V. Simulation Study

A. Scenario

To demonstrate the capabilities of the proposed method and model, a simulation is conducted for studying the performability of the ICT support for an (over-current) protection application on a power line connecting substations of Figure 1. It is assumed that when there is an over-current in a feeder connecting two substations, a merging unit on one of the substations will send the fault current information (sampled value) to a protection IED on the other substation. And, this protection IED is responsible to neutralize it by sending a trip signal to a Circuit breaker IED under its control.

1) Communication subsystem architecture: The communication architecture shown in Figure 1, is considered. The study investigates the dependability of the communication between substation 1 and substation 4, assuming a protection application for a power line connecting these substations. Substation 1 is represented by a merging unit connected to a gateway switch while substation 4 is equipped with

TABLE I
TRAFFIC PARAMETER VALUES

Traffic Parameters	Values used
$\lambda_{n\_to\_p}$	1 day^{-1}
T_p	2 hr
t_max	4 ms - 15 ms
n_max	8 - 40
K_n	4 - 9 Mbps
K_p	6 - 12 Mbps
K_{n_var} and K_{p_var}	1 Mbps

a protection IED, merging unit IED and a breaker IED connected to its gateway switch. The protection IED in substation 4, with the sampled value information gathered from both substations, is responsible to neutralize the fault on the power line connecting the two substations.

2) Traffic Assumption: The study focuses on the influence of the delay, which is due to a varying background traffic, on the dependability of the protection application. Merging units are assumed to generate a constant traffic of sampled value (SV) packets with a rate of 4000 packets per second. The gateway switches on each substation are also assumed to carry a varying background traffic ranging from 10 to 50 Mbps. In addition, to account for a constant background traffic (for e.g., SV exchange between other devices) and propagation delays, a 1 ms constant delay is introduced to all the switches.

In the considered architecture, a two way ring topology, the traffic can be carried through two alternative directions. This study considers background traffic to be carried through a shortest path towards the control center. In the case of multiple path with equal number of hops, the traffic is assumed to be divided and directed to the controller in both directions. If there is a failure in the ring architecture, all the traffic will be directed through the other/redundant working path of the ring architecture, which may affect the performance i.e. increase the probability of timing failures.

The traffic model parameters used in this study are shown in Table I. Some parameters such as the maximum delay per packet (t_max), maximum number of delayed packets (n_max) and protection function time requirement t are varied to study the impact of timing failures. In all simulations, the background traffic is set into the following three classes:-

- *Lower traffic (T1)*:- The normal average traffic K_n is set to 4 Mbps while the peak traffic is set to 6 Mbps.
- *Medium traffic (T2)*:The normal average traffic K_n is set to 6 Mbps while the peak traffic is set to 9 Mbps.
- *Higher traffic (T3)*:The normal average traffic K_n is set to 9 Mbps while the peak traffic is set to 12 Mbps.

3) Failure and recovery models: A negative exponential distribution, i.e., $P(T_x > t) = e^{-\lambda_x t}$ is assumed for all failure, repair and the rate at which the traffic varies, where T_x is the firing times for transitions in the SANs in Figures 5 – 7 and λ_x is the rates in Table II.

4) Metrics: The following metrics are used to measure the comprehensive dependability (performability) of the communication system considered:

- Availability of the ICT support system(A_p): measure the steady state availability of the ICT support system for the protection function. When only timing failures are considered, a protection function is assumed to be available if the delay requirement on the line between the two communicating substations is met. It is said to be unavailable if n_max consecutive packets are delayed by more than the threshold value, t_max.

  For the cases where all types of failures are considered, a protection function is available if both the delay requirement is met and all the ICT components used by the protection application are in

TABLE II
FAILURE RATES AND RECOVERY TIMES OF THE SYSTEM COMPONENTS

Component type	**Failure rate [days^{-1}]**	**Mean recovery time [hr]**
Protection IED	$6.3 \cdot 10^{-4}$	2
Circuit Breaker	$6.6 \cdot 10^{-4}$	2
Merging Unit	$2.8 \cdot 10^{-4}$	3
Communication Line/cables	$1.8 \cdot 10^{-4}$	6
Router/Switches	$5.7 \cdot 10^{-5}$	3
Power line failure	$1.9 \cdot 10^{-3}$	3

a working state. In the presentation of numerical results, the unavailability is used, $U_p = 1 - A_p$.

- Mission Reliability ($R(t)$): Once a failure occurs that require the intervention from a protection application, this metrics measure the probability that the ICT support for the protection function will be continually available for a certain mission time. i.e. no n_max consecutive packets are delayed by more than t_max ms.

B. Evaluation and Discussion

For the scenario presented in Section V-A, a simulation is conducted to study the performability of the ICT support for protection of a power line between substation 1 and substation 4 of the architecture shown in Figure 1. First, to study the impact of timing failures, a sensitivity analysis is conducted by varying some traffic parameters. Then, for a set of specified traffic parameters, the impact of timing failures is compared with other (omission) failure modes of the ICT components.

All cases are simulated for 30 years of calendar time. A replication of 20 to 30 times is carried out for error control. The average computational time for one case with replications is in the range 20 to 120 minutes.

1) Sensitivity Analysis:-: In this section, the aim is to first study the characteristics of timing failures before incorporating it to a performability assessment where omission failures are also considered. A sensitivity analysis is used to study the effect of timing failures on the performability of the ICT support for a protection application. This study considers traffic class T1 and T2. Some parameters such as the delay threshold (t_max), maximum number of delayed packets (n_max), and the protection time requirement t are varied for a range of values shown in Table I.

Figure 8 and Figure 9 shows how the the mission reliability is affected by the assumption and parameters used to describe the resiliency of the protection application, t_max and n_max. It also shows the impact of background traffic on the reliability measure for the different assumptions of t_max and n_max parameters.

In Figure 8, the maximum delay per packet (t_max) is set to 8 ms and the n_max is varied. For a lower n_max assumption, the result shows that the mission reliability is low for both traffic classes. This is partly due to the fact that t_max is set close to the average delay measured on the switches. Hence, there is a significant probability that eight packets could be delayed by more than the threshold $t\_max = 8ms$, especially during bursty traffic periods. The Ns-3 delay measurements for the traffic class shows that the mean duration between bursty traffic ranges between 55 ms to 70ms which is also manifested by a steep drop upto 60 ms in Figure 8.

Increasing n_max to twelve, $T1$ becomes highly reliable while $T2$ shows some gain but still with a reliability lower than 60% for a protection with a 100 ms requirement. As the duration of bursty traffic in T1 is relatively shorter than T2, increasing the tolerance (n_max) to 12 results in a significant change on T1's reliability while it does not result in a considerable change for T2.

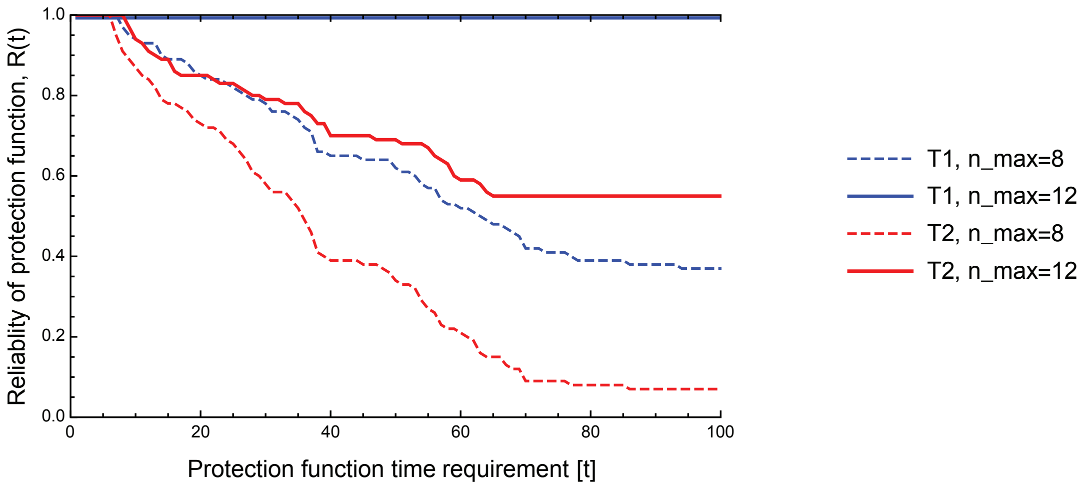


Fig. 8. Reliability of the ICT support system considering different set of background traffic when n_max = 8 and when n_max = 12.

Figure 9 shows the effect of varying the maximum delay per packet where the n_max is set to 8 packets.It shows that traffic class T1, in both $t\_max = 10ms$ and $t\_max = 15ms$ cases, has a relatively higher reliability than T2. For traffic class T1, the average delay measured on the line between substation 1 and substation 4 is around 7.5 ms. Hence, setting the threshold ($t\_max = 10ms$) above the average delay results in a fairly high reliability for T1. Whereas, for traffic class T2, the $t\_max = 10ms$ is lower than the average delay (13 ms) which results in a lower $R(t)$. The figure also shows that setting $t\_max = 15ms$ well beyond the average delay for traffic class T1, results in a very high reliability. However, T2 has some gain but still low $R(t)$.

A sensitivity analysis on the unavailability of the ICT support system for a protection applications with different time requirements is shown on Figure 10. This study investigates two types of protection applications considering traffic class T1; one with a shorter time requirement of 20 ms, and another with a relatively higher time requirement of 100 ms. The two protection applications are assumed to have different characteristics which is described by the maximum number of consecutive delays that can be tolerated (n_max) and the maximum delay per packet (t_max). This investigation assumes that a protection application is said to be failed if n_max packets equivalent to $n\%$ (fraction) of packets expected to be transmitted in protection time t has a delay greater than or equal to t_max.

Figure 10 shows how the unavailability of both the 20 ms and 100 ms protection applications are affected by the n_max (described by $n\%$) and t_max parameters. In Figure 10(a), n is varied between 5% to 20% where the t_max is set to 8 ms. The figure shows that the unavailability for the 20 ms protection application is very high when the 5% and 10% fraction tolerance is considered. Whereas, for the 100 ms protection application, the same assumption results in a ten fold lower unavailability figure. This is due to the fact that the 20ms protection applications has a stricter time requirement and a failure in small number of packets will result in unavailability of the protection function. For $n = 20\%$, the unavailability is very small for both the 20 ms and 100 ms protection application. Prediction mechanisms

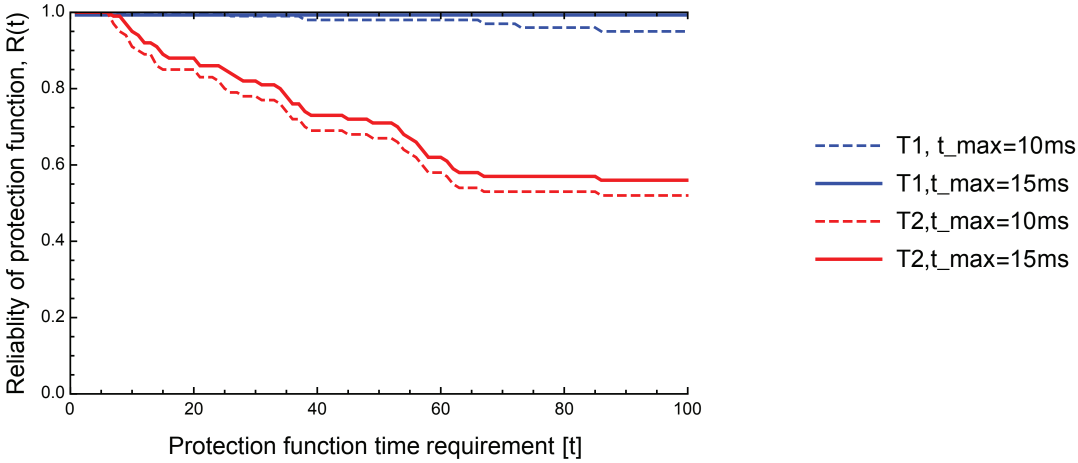


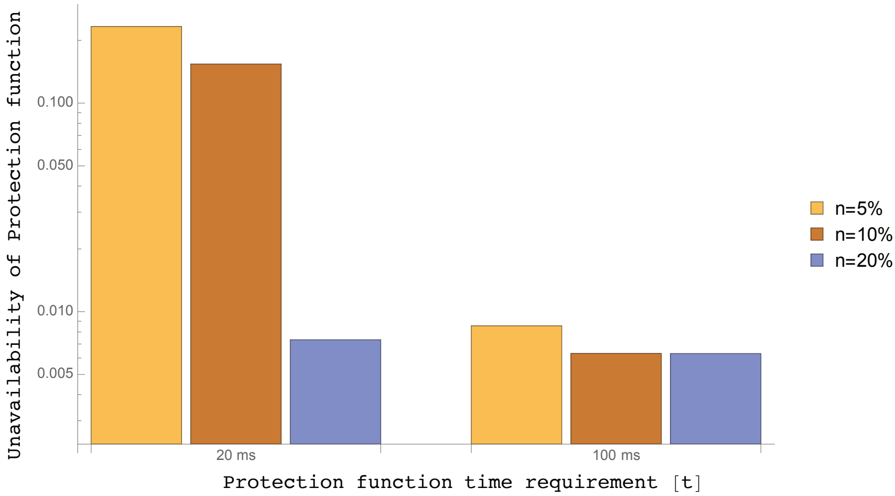
Fig. 9. Reliability of the ICT support system considering different set of background traffic when t_max = 10 ms and when t_max = 15 ms.

in the case of packet losses and delays are taken into consideration for the the $n = 20\%$ assumption. This provide enough room for both protection applications to be available for situations with higher number of packet delays.

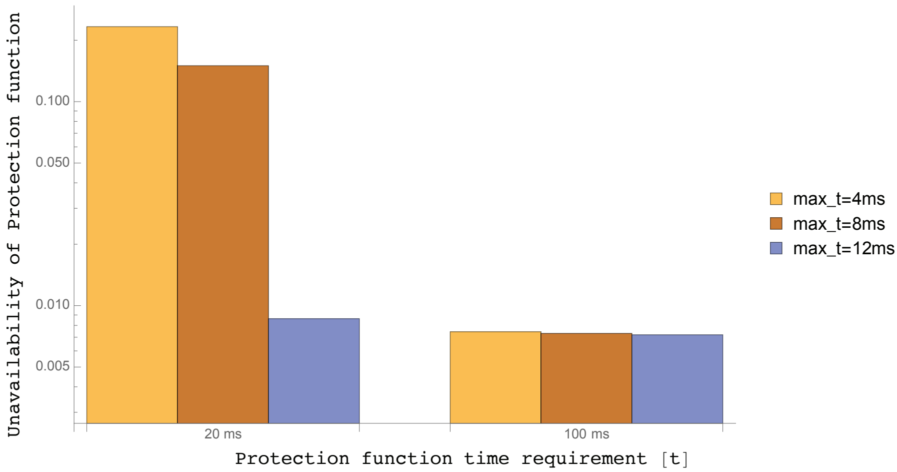
Figure 10(b) shows how the unavailability is affected by the variation in the maximum delay per packet setting the n to 10%. The result shows that the 20 ms protection function has a very high unavailability for $t\_max = 4ms$ and $t\_max = 8ms$. This indicates that when the maximum tolerable delay for a packet (t_max) is lesser or close to the average delay (7.5 ms considering T1), the unavailability of the ICT support become significantly high. However, the 100 ms protection application results in a very small unavailability as it requires large number of packets to be delayed which is a very rare situation considering traffic class T1. When t_max is set to 12 ms, both the 20 ms and 100 ms protection applications will perform good as the t_max is set well beyond the average.

2) Comparative Analysis: Setting the traffic parameters to a certain value, the performability measurements of the case where only timing failures are modeled, is compared with the case where other (omission) failure modes of all the ICT components are considered.

The comparison between timing failures and omission failures is shown on Figure 11. The unavailability of a 20 ms and 100 ms protection application are compared for the three different background traffic classes, where $t\_max = 8ms$ and $n\_max = 10\%$ is considered. It can be seen that the timing failures has a higher impact on the 20 ms protection application. The contribution of omission failure is quite small when compared with the timing failures. The background traffic variation has also significant impact on the unavailability of the 20 ms protection application ranging from 0.13 for T1 to 0.29 for T3. The omission failure is the same in all the cases as it is assumed to be not dependent on the traffic behaviour, i.e., only environmental/hardware failures are considered. For the 100 ms protection application, the impact of timing and omission failure is comparable. The change in unavailability due to a variation in the background traffic is also negligible. This is mainly due to the relatively larger time window and hence



(a)



(b)

Fig. 10. Unavailability of the ICT support system for a varying (a) fraction of packets with a delay greater than th threshold, $t > T\_threshold$ (b) delay threshold for each packet, t_max

larger number of packets has to be delayed for the protection application to be unavailable.

Overall, the results are highly dependent on the assumption of the n_max and t_max parameters. If these parameters were assumed to be more relaxed/increased, the performance of the 20 ms protection application would also become better and comparable with the 100 ms protection application.

VI. Concluding Remarks

In future smart grid, there will be a large scale use of ICT support system which makes it a complex cyber-physical system. It is important to study the totality of such complex systems and determine the combined influence of failures and workloads, i.e., performability. This paper looked into how performance associated properties (timing failures) can be modelled together with properties affecting dependability

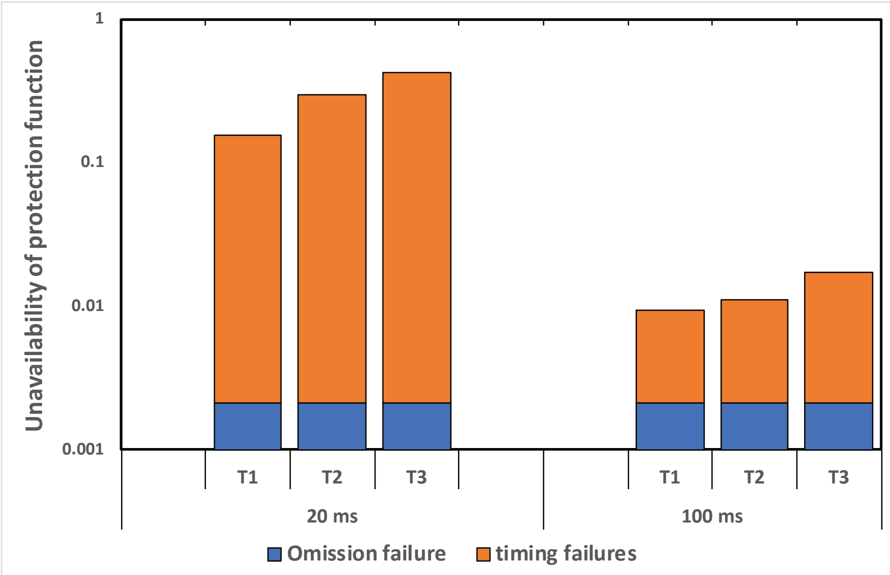


Fig. 11. Comparison of unavailability of timing failures and omission failures for a varying background traffic T.

of the ICT support system in smart grid. A two tier model using Ns-3 and SAN is developed to study the peformability of an IEC61850 based communication infrastructure for protection of lines between substations.

Simulation studies were conducted to illustrate how the method is able to capture the two properties and to study their effect on the reliability and availability of the ICT support system. The result shows that the reliability and availability is highly dependent on the requirements for the protection application, maximum delay per packet (t_max) and maximum number of consecutive delayed packets (n_max) the protection application can tolerate. A higher reliability is observed when the maximum delay per packets is set well beyond the measured average delay and when the maximum number of consecutive delayed packets is set larger than the number of packets that could be sent within the bursty period of the background traffic. The result also showed that timing failures have a significant impact on the unavailability of the ICT support; higher for the critical protection applications with shorter time requirement (20 ms) than those with a relatively higher time requirement (100 ms).

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Paper F

Effect of Communication Failures on State Estimation of 5G-Enabled Smart Grid

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Effect of Communication Failures on State Estimation of 5G-Enabled Smart Grid

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ABSTRACT Information and Communication Technologies (ICT), Wide Area Measurement Systems (WAMS) and state estimation represent the key-tools for achieving a reliable and accurate knowledge of the power grid, and represent the foundation of an information-based operation of Smart Grids. Nevertheless, ICT brings new potential vulnerabilities within the power grid operation, that need to be evaluated. The strong interdependence between power system and ICT systems requires new methodologies for modeling the smart grid as a Cyber Physical System (CPS), and finally analyzing the impact of ICT failures on the power grid operation. This paper proposes a novel methodological approach that combines Stochastic Activity Networks (SAN) modeling and numerical computation for dependability analysis of a 5G-based WAMS. Internal influences such as component failures and external influences such as rain effect are considered, and the impact of these failures are assessed over the WAMS capability to provide reliable data for performing an accurate power network state estimation. Different state estimation approaches (traditional SCADA and PMU-based algorithms) and weather conditions are compared in terms of mean states estimation error and safety. The results highlight that 5G based WAMS result in a close-to-ideal behavior which enforces the prospect of a future adoption for smart grid monitoring applications.

INDEX TERMS Smart grid, state estimation, dependability analysis, 5G, wide area measurement system, stochastic activity network.

I. INTRODUCTION

The digitalization wave has invested many areas of industry, utilities and services in the last decades. New markets were opened as a result of the new opportunities brought by the information and communication technologies (ICT), that allow a peer-to-peer exchange of information, goods and services [1].

The power system has also been involved in this transition. A growing request of connection to the distribution grid by small size distributed generation (DG) units has been recorded. This trend is mainly due to the spread of cheap technologies for generation and storage of electrical energy, along with the increased sensibility towards an environment-friendly energy generation, and the political incentives for an increasing contribution of renewable energy into the global energy industry.

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With the introduction of distributed generation from Renewable Energy Sources (RES), especially in distribution systems, the complexity of power system operation has increased dramatically. The RES power generation is typically difficult to predict, moreover the bidirectional power flow introduces technical and security issues, therefore efficient monitoring, control and protection of the power system becomes critical. In order to deal with these new challenges, ICTs become a fundamental component of the distribution grid.

The exploitation of ICT in power system operation promises to achieve a significant enhancement in the management of the power network, in terms of better performances, reliability and quality of service [2]. In this context, the concept of Smart Grid (SG) implies the transition of the power grid towards a Cyber Physical System (CPS), where the physical system (the power grid) is merged with a cyber system that provides the physical system with computational and communication capabilities.

Information and communication technologies, along with the above mentioned advantages, introduce new vulnerabilities on power systems that may have a crucial impact on the Smart Grid operation. The data gathered by Wide Area Measurement Systems (WAMS) represent the foundation of the information-based operation of Smart Grids. Wrong state estimation may compromise the integrity of Optimal Power Flow (OPF) and threaten the economic and secure system operation [3]. For this reason a reliable communication technology represents the key enabler for allowing the WAMS to guarantee a correct and timely information exchange for the power system operation. Several factors may influence the capability of correctly processing and delivery of the data within a WAMS. These factors can be classified in two main categories:

- External influences: for example the weather conditions for wireless technologies and the orography of the terrain; cyber-attacks can also dramatically affect the behavior of the ICT system, and consequently of the power grid;
- Internal system reliability: on each Smart Grid component (communication links, servers, measurement devices, actuators, etc.) software and hardware failures may occur.

In this context, 5G technologies represent a promising candidate for implementing the communication infrastructure that allows data traffic to be transmitted from measurement devices to control centers in WAMS. In fact, 5G is expected to meet the requirements for a Smart Grid implementation, with highly reliable communication, low latencies, strong security mechanisms to prevent malicious intrusion and high scalability.

Nevertheless, a comprehensive dependability analysis of WAMS is important in order to:

- quantify the impact of the above mentioned external and internal factors that undermine state estimation applications for power systems;
- support decision-making processes in the Smart Grid infrastructure planning.

A. RELATED WORKS

Several articles have analyzed Wide Area Measurement Systems from a dependability point of view.

In [4] Aminifar *et al.* present a methodology for incorporating WAMS malfunctions in power system reliability assessment based on Monte Carlo simulation. The scenarios analyzed show that WAMS network failures, although unlikely, may bring the system to an unobservable state and cause severe cascading events. A Monte Carlo approach is also used in [5], where a wide area monitoring, protection and control (WAMPAC) system is divided into four subsystems: measurement inputs, communication, actuator and analytic execution, and the influence of different components on the overall system reliability is assessed through sensitivity analysis. Zhu *et al.* in [6] address the dependency of Wide Area Monitoring and Control (WAMC) systems on their supporting ICT architecture. Different architectures are compared in a scenario with a PMU based monitoring system, and the reliability of the whole WAMC system is assessed with relation to data loss probability and delay. Rana *et al.* in [7] propose a reliability evaluation of a power system WAMS with a Markov graph theoretic approach. The analysis considers both single component failures and common cause outages and their impact on the overall reliability of the grid. The model proposed takes also into account the variation of the failure rate of different components in WAMS due to aging.

Several works focus on analyzing the impact on power system state estimation in relationship with a specific cause of data loss and corruption, namely cyberattacks. Liu *et al.* in [8] presents how false data injection attacks can be exploited to bypass the existing techniques for bad measurement detection. Cyberattacks can also be used to create topology errors. Ashok and Govindarasu in [9] show how by exploiting the field devices vulnerabilities, corresponding to the critical measurements, it is possible to manipulate the network topology data. These topology errors are also unobservable to bad data detection techniques. The traditional approaches to detect bad data are based on exploiting a high redundancy of measurement data sources, which allow the identification of outliers, and the application of filtering techniques [10]. Nevertheless, these methods hardly apply on distribution level Smart Grids, which typically rely on a relatively low number of measurement points. Weather conditions impact on a WAMC systems, supported by wireless communication technologies, are analyzed in [11]. The analysis is conducted with a co-simulation approach on a rural distribution network served with WiMAX communication, and it shows the high sensitivity of the wireless channel on the distance between antennas and the level of rainfall. Tsitsimelis et el. in [12] investigate the impact of the LTE random access channel reliability on WAMS and, consequently, on the SE accuracy. The study showed state estimation accuracy can be significantly affected by a varying cell coverage range and number of contending devices in the system. Cosovic *et al.* in [13], [14] propose to leverage 5G cellular technologies to enable a distributed state estimation for smart grid. Latency and reliability of distributed state estimation on 5G communication networks are analyzed. The effect of noise on measurement process and communication process that corrupt the measurement vector is also considered.

B. AIM AND CONTRIBUTION

All the articles mentioned in subsection I-A focus on specific issues on the interdependence between communication system and the power grid monitoring. To the knowledge of the authors, this is the first paper that investigates the overall dependability of 5G based wide area monitoring system (WAMS) comprehensively. Both internal influences such as component failures and external influences such as fading and rain effects are taken into account, in order to analyze what is the impact of communication failures in the accuracy of distribution network state estimation. The main contributions in this paper are summarized as follows:

- A novel methodological approach is proposed, that combines Stochastic Activity Networks (SAN) modeling and numerical analysis, to take into account the continuous and discrete event activities of power system and ICT system, respectively. Based on this method, a simulation tool is developed with the Möbius platform, extended with external C++ libraries developed by the authors.
- The dependability of WAMS for state estimation in an IEEE standard distribution network is investigated. Different state estimation approaches are analyzed and compared by taking into account internal and external sources of failures, such as component faults and environmental conditions. This analysis is performed over a novel 5G communication infrastructure proposed by the authors, and the suitability of this communication technology is analyzed in relation with the wide area measurement system requirements.

C. ORGANIZATION OF THE PAPER

The paper is organized as follows. Section II gives a brief introductory background to monitoring system architectures and state estimation. In Section III, a 5G-based WAMS architecture is proposed, and the modeling assumptions and implementations are explained. Section IV illustrates the study cases, where the 5G architecture provides a communication service for monitoring the state of an IEEE standard distribution network. The performances of the state estimation are examined in relation with different sources of failures. Conclusive remarks and future works are summarized in Section V.

II. MONITORING SYSTEM FOR SMART GRIDS

This section presents some background on WAMS, 5G and state estimation. Readers with relevant knowledge on these areas may consider skipping this section. The review starts with WAMS architecture in subsection II-A followed by a discussion on the communication architectures on power grid monitoring in subsection II-B. A brief introduction on the use of 5G for WAMS is presented in subsection II-C. Finally, Subsection II-D gives a short background on state estimation algorithms used in WAMS.

A. WAMS ARCHITECTURE

Wide Area Measurement System (WAMS) is a system that combines the functions of metering devices with the abilities of communication systems to monitor, operate and control power systems in wide geographical areas [15]. In general, a WAMS system collects data from measurement devices and transmits them through the communication system to the control center, where the data is processed and decisions on the operation of the power systems are made [16].

Utilities have been using Supervisory Control And Data Acquisition (SCADA) systems for many years for monitoring and controlling the power grids. SCADA is a generic name given for a computerized system capable of collecting and processing data of a complex industrial process through long distances, and applying operational controls over it [17]. Typically, SCADA systems gather data from Remote Terminal Units (RTUs) associated with Measurement Devices (MDs) and convey control signals to Programmable Logic Controllers (PLC) and Intelligent Electronic Devices (IEDs) for operating the system. Nevertheless, traditional SCADA systems are not sufficient for a proper monitoring of modern power systems for various reasons. Among these: the collection of measurement values is every 2 to 5 s; only the RMS values are collected; the measurements are not synchronized in time [18].

Phasor Measurement Units (PMUs) allow providing the WAMS with new capabilities in terms of power grid monitoring. PMUs are measurement devices designed to measure positive, negative and zero sequence phasors of voltages and currents. These signals are sampled at a rate of 50 to 60 times per second, and all the measurements are time-stamped using a clock synchronized to the Global Positioning System (GPS) [18]. Compared with traditional SCADA systems based on conventional RTUs, the integration of a large number of PMUs throughout the grid will result in some benefits. First, it will result in better monitoring due to the higher accuracy of PMU measurement; second, there will be faster control actions due to the higher sampling rate of voltage and current waveforms. Furthermore, due to availability of time-stamped data, there will be better handling with disturbances, potential cascade effects and postmortem analysis [19], [20]. Conventional PMUs are used in transmission systems, and are characterized by an accuracy of $\pm 1^\circ$. However, a higher accuracy is needed for distribution systems as they are characterized by smaller angle difference between buses due to smaller X/R ratios. To meet this requirement, μPMUs have recently been developed. They are able to discern angle differences with an accuracy of $\pm 0.01^\circ$ [21], [22].

In Fig. 1 a typical representation of a modern Wide Area Monitoring Control and Protection system is shown. Substation 1 represents a traditional substation, where measurements from traditional metering devices are merged in a RTU and sent to the Distribution System Operator (DSO) control center, where the information is elaborated by the SCADA system. A modern configuration of substation is represented by Substation 2. Metering devices are substituted by IEDs, that individually communicate with the DSO control center. These substations are also provided with PMUs/μPMUs, whose signals may be aggregated by local or remote Phasor Data Concentrators (PDC) and sent to the DSO control center, where this information is stored in databases and/or processed for real time monitoring by Distribution Management System (DMS) algorithms.

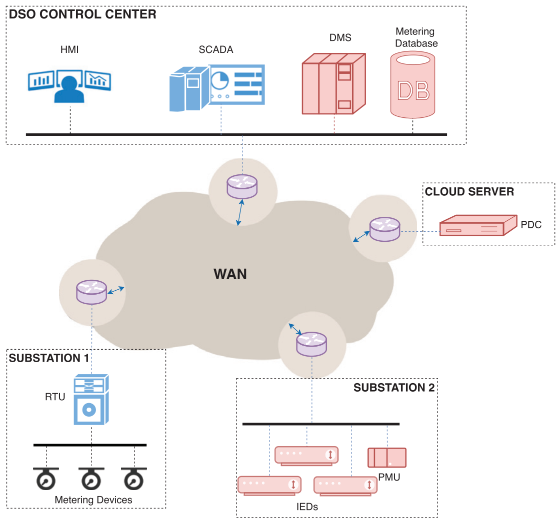


FIGURE 1. Schematic representation of a WAMS: blue blocks represent components of traditional SCADA-based monitoring system; red blocks represent components of modern DMS-based monitoring system.

B. COMMUNICATION ARCHITECTURE

In general, two main levels in the power grid monitoring communication infrastructure can be identified [23]:

- Field Area Network (FAN), that includes the communication of measurement data that is transmitted within the substation, typically between the measurement devices and the RTU.
- Wide Area Network (WAN), that includes the communication of measurement data aggregated at substation level to the central controller, SCADA Master or DMS.

The internal substation communication infrastructure facilitates the communication between the measurement devices and the RTU for substation automation within the same FAN. The RTU collects measurements, alarms, and other information and forwards it to the SCADA system. The most common networking technology within substations FANs is serial communication based on Fieldbus RS-485, that communicate through Modbus, DNP3 or IEC 60870-5-103 communication protocols [24]. The modernization process of substations goes towards replacing these traditional protocols with the newer standard IEC 61850 and introducing a set of abstract models that allow mapping the data objects and services to any other protocol that can meet the data and service requirements. Moreover, conventional RTUs and measurement devices are being replaced with microprocessor-based Intelligent Electronic Devices (IEDs), that support functions formerly supported by multiple conventional devices in the substations. This reduces the cost associated with substation automation and SCADA operation [25]. Compared with previous protocols, IEC 61850 switches from the traditional master-slave communication to a peer-to-peer communication, where all substation devices are IED based and internally communicate through Ethernet LAN. This enables distributed functions as well as data rates up to 100 Mb/s.

The external substation communication infrastructure enables the communication between RTU/IEDs and the SCADA master through the WAN. The state-of-the-art in external substation communication is deployed through Ethernet or Fieldbus RS232, using IEC 60870-5-101, IEC 60870-5-104 and DNP3 protocols. In 2010 the Technical committee TC57 of the International Electromechanical Commission has further extended the standard IEC 61850 to support communication between substations and to support communication between substations and generation sources (IEC 61850-90). With IEC 61850, all substation devices are IED based. Each IED supports one or more functions including switchgears, measurement devices, bay controller and relay. In this stage of modernization of substation automation, each IED will communicate directly with IEC 61850 with the SCADA master over protocols like DNP3, allowing RTUs to be removed. With the advent of IP for SCADA communication, DNP3 has added a Data Connection Management layer, that allows running DNP3 over a TCP/IP or UDP/IP connection. For consistency with IEC 61850 standards, DNP3 will need to support the object models defined in the IEC 61850 standards [18].

Requirements for wide area monitoring communication vary according to the specific application. For example, local voltage stability monitoring, based on conventional metering devices or IEDs, require a typical data sampling with a period of 0.5 to 5 seconds; on the other hand, applications such as real time state estimation or monitoring for supporting power system protection requires data sampling with a period of few milliseconds [26]. IP enabled DNP protocol allow exploiting internet based communication technologies, such as Fiber Optic and broadband wireless technologies (4G and 5G), which are able to meet the low latencies and high reliability required for these monitoring applications [23].

C. 5G COMMUNICATION FOR WAMS

Wireless technologies have already been integrated to SCADA systems for monitoring and remotely accessing the parameters of controlling the substations [27]. Compared with fiber optics, wireless data communication offer significant benefits, such as low cost installations, rapid deployment, easy user access and mobility [28].

Since the 2nd Generation of mobile communication technologies (2G), wireless communication has been successfully tested for monitoring and accessing the performance of remotely situated devices [28], [29]. Nowadays, vendors develop and implement 4G-LTE SCADA connectivity devices, designed to provide several security features like uniquely addressed devices, cryptographic capability, in addition to communication speed [30].

The 5th Generation (5G) of mobile communication technologies represents not only an enhancement of 4G-LTE, but entails a complete redesign of the architecture that supports wireless cellular communication. The 5G, whose first release has been made available since 2020, is designed to meet the growing demand to the mobile communication infrastructure in terms of number of connected devices, mobile data volumes, latency, reliability and security. Moreover, a wide scope of different use cases will rely on the 5G infrastructure, like enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC), and Ultra Reliable and Low Latency Communication (URLLC) for Mission Critical Services (MCS), each of which with different and specific requirements [31]. Being able to provide a wide range of use cases and services cost-efficiently requires a high flexibility and a high scalability of the network, that in the 5G vision is obtained through the softwarization of the network, and the concept of network slicing. A network slice consists of a set of virtual network functions that run on the same physical infrastructure, that can be orchestrated and configured according to the specific requirements requested by the network tenant [32]. The key technologies that allow implementing the concept of network slicing are [33], [34]:

- Software Defined Networking (SDN): it separates the control plane and data plane of the current network, promoting flexibility and customization of the network.
- Network Function Virtualization (NFV): it replaces the conventional device bound network functions, such as firewalls, load balancers, etc., with conventional off the shelf servers, enhancing flexibility, convergence of heterogeneous appliances, and allowing reduction of operating and capital expenditures.
- Mobile Edge Computing (MEC): it locates cloud-based architectures at the edge of the mobile network, within the Radio Access Network (RAN) and in proximity of the mobile subscribers, allowing low latency, location awareness, more efficient network and service operations, reduced network congestion and minimized data transmission costs.

In the 21st meeting of Working Party 5A of ITU a preliminary draft of document on utility communication system requirements was reported [35]. Different power network applications are classified in terms of coverage, reliability, latency time, bandwidth, security, priority and backup power. A synthesis of the Working Party results related to the WAMS communication are reported on Table 1.

TABLE 1. Network requirements for monitoring communication.

Application	Coverage	Bandwidth	Reliability	Latency
SCADA WAN	Medium	10 - 100 kbps/node	99 - 99.99 %	2-15 sec
SCADA FAN	High	9.6 - 100 kbps/device	99 - 99.99 %	20 ms - several minutes
PMU for situation awareness	High	600 - 1500 kbps/node	99.999 - 99.9999 %	20 ms - 200 ms

5G technologies promise to meet these requirements. Network Function Virtualization and Mobile Edge Computing allow moving virtual machines with Smart Grid applications and computation capabilities into the edge cloud, reducing the computation delays and enhancing the flexibility and scalability of the system. Ultra Reliable and Low Latency Communication (URLLC) allow meeting requirements, bandwidth and reliability requested for real time state estimation and situational awareness supported by the expected massive deployment of PMUs in distribution grids. Finally, network slicing promises to meet the requirements in terms of security through slice isolation and data encryption.

D. WAMS STATE ESTIMATION

In the Smart Grid (SG) paradigm, measurement systems play an important role. The unpredictability of the power flow, mainly due to the high number of distributed generation units from renewable energy sources (RES) that will be connected to the grid, implies an increasing difficulty in monitoring the state of the network and, based on that, optimally dispatching the resources.

Nevertheless, measurements are prone to errors, due to the precision and accuracy of the measurement devices. State estimation consists in a statistical approach for the calculation of the state variables of the system, given a limited number of measured values characterized by a given uncertainty. Typical measured quantities are the active and reactive power flows on network branches, active and reactive power injections on the buses and voltages on the buses. Recently, the spreading of PMUs and μPMUs enhances the potential of state estimation algorithms with new capabilities, such as prediction of disturbances and potential cascading events, through the measurement of voltage and current phasors and global time stamps [20].

Distribution systems are traditionally a power grid level that is scarcely monitored. A relatively small number of measurement devices is currently deployed along the network compared with the high number of buses. For this reason, pseudo-measurements, i.e. non-real-time measurements obtained from historical data, play an important role for reaching the observability of the system.

The first studies on state estimation algorithms applied to power grids date back to early 70s [36]. In the following years state estimation, due to the evolution of the algorithms, has become a fundamental tool for Transmission System Operators (TSO), and in recent years even for Distribution System Operators (DSO), allowing a continuous monitoring of the power grid and supporting network management interventions.

Several algorithms have been elaborated that allow obtaining an estimation of the state of electrical power systems. The Weighted Least Squares (WLS) is the most commonly used algorithm for obtaining an accurate estimation of the network starting from a set of measures and pseudo-measures [37].

Given a measurement model of a system described by (1):

$$z = h(x) + e \tag{1}$$

where z is a vector containing measurements (and pseudo-measurements) on the electrical system, $h(x)$ is the function that relates the network state variables x to the measurements on the system, and e is the measurement error vector.

The WLS approach consists in minimizing the following objective function:

$$J(x) = \sum_{i=1}^{M} w_i \left(z - h(x)\right)^2 \tag{2}$$

where w_i is the weight associated to the i_{th} measurement related to the correspondent variance σ_i (if, as commonly assumed, the measurement errors are independent, $w_i = 1/\sigma_i^2$), and M is the total number of measures and pseudo-measures.

Equation (2) can be formulated in matrix form with the following expression (3):

$$\mathbf{J}(\mathbf{x}) = [\mathbf{z} - \mathbf{h}(\mathbf{x})]^T \, \mathbf{W} \, [\mathbf{z} - \mathbf{h}(\mathbf{x})] \tag{3}$$

The non-linear problem can be solved thought iterative methods, like Gauss-Newton methods, with the following formulation (4)

$$\mathbf{G}(\mathbf{x_k})\Delta\mathbf{x_k} = \mathbf{H_k^T}\mathbf{W}\,[\mathbf{z} - \mathbf{h}(\mathbf{x_k})] \tag{4}$$

where

$\mathbf{G}(\mathbf{x_k}) = \mathbf{H_k^T W H_k}$ is the Gain Matrix;

$\mathbf{H_k} = \mathbf{H}(\mathbf{x_k}) = \dfrac{\partial h(x_k)}{\partial x}$ is the Jacobian matrix of the measurement function $\mathbf{h}(\mathbf{x})$;

$\Delta\mathbf{x_k}$ is the updating state vector from the k_{th} to the $(k+1)_{th}$ iteration.

1) PMU-BASED STATE ESTIMATION

In general it is possible to integrate the measurements from PMUs (and/or μPMUs) in the traditional WLS-based state estimation algorithms with two approaches [38]. The first approach consists in appending the voltage and current measurements from PMUs as additional measurements to the conventional measurements vector. Equation (1) is rewritten in the following form (5):

$$\begin{bmatrix} \mathbf{z_1} \\ \mathbf{z_2} \end{bmatrix} = \begin{bmatrix} \mathbf{h_1}(\mathbf{x}) \\ \mathbf{h_2}(\mathbf{x}) \end{bmatrix} + \begin{bmatrix} \mathbf{e_1} \\ \mathbf{e_2} \end{bmatrix} \tag{5}$$

where $\mathbf{z_1}$ is the vector containing the measurements from traditional measurement devices, $\mathbf{z_2}$ is the vector that contains real and imaginary parts of the voltage and current phasor measurements from PMUs, $\mathbf{h_2}(\mathbf{x})$ is the set of non-linear equations that relate the measurements with the state vector $\mathbf{x}$, and $\mathbf{e_2}$ is the vector of PMU measurement errors. With this approach, both conventional and PMU measurements are processed together, with an iterative approach as in the traditional WLS method.

The second approach is based on a two stages method, which consists in first processing the measurements set from the standard measurement devices with the WLS method, according to (4), and in a second stage post-processing the result of the WLS state estimation with the data based on the measures from PMUs. One example of this approach is proposed in [38], where the PMU measurement vectors is augmented by the estimated state from the WLS:

$$\mathbf{z_2} = \begin{bmatrix} \mathbf{V_{1r}} & \mathbf{V_{1i}} & \mathbf{V_{2r}} & \mathbf{V_{2i}} & \mathbf{I_{2r}} & \mathbf{I_{2i}} \end{bmatrix}^T \tag{6}$$

where $(\mathbf{V_{1r}}, \mathbf{V_{1i}})$ is the solution from the WLS state estimation, and $(\mathbf{V_{2r}}, \mathbf{V_{2i}})$ and $(\mathbf{I_{2r}}, \mathbf{I_{2i}})$ are the voltage and current measurement vectors from PMUs, expressed in rectangular coordinates. Being $\mathbf{x} = [\mathbf{x_r}\ \mathbf{x_i}]^T$ the solution vector that represents the state of the system (real and imaginary part of the vector in the buses), the authors in [38] show that the solution of the state estimation is a linear problem (7):

$$\mathbf{z_2} = \mathbf{H} \cdot \mathbf{x} + \mathbf{e_2} \tag{7}$$

therefore it can be solved in algebraic form. This approach has the main advantage of not requiring the redefinition of already existing state estimation algorithms in SCADA systems. Moreover, being a linear problem, an algebraic solution is obtained without recurring to iterative solvers. For this reason, this approach has also been adopted in the implementation of the state estimation in the dependability platform developed.

III. MODELING

This section presents the 5G based WAMS architecture proposed in Subsection III-A, and the methodological approach adopted for modeling the smart grid monitoring as a Cyber physical system in Subsection III-B. Then, a top level description of the method along with the characteristics of the tool is presented in Subsection III-C. The details on the components model are described in Subsection III-D.

A. PROPOSED 5G BASED WAMS ARCHITECTURE

Based on the technological evolution discussed in Section II-C, a 5G based WAMS architecture is proposed. The monitoring and control logic are virtualized and moved into an edge cloud in a 5G communication infrastructure. IED and PMU functions (such as conversion of analog measurements to digital) are kept near to field devices while PDC data processing functions and Distribution System Operator (DSO) functions are moved into the edge cloud. A completely isolated end to end network slice is considered, which brings multiple benefits such as improved performance due to interference avoidance from the rest of the network.

The 5G based architecture proposed is shown in Fig. 2. IEDs and μPMUs are assumed to communicate with the base station (eNB) through a radio link where ultra reliable and low latency communications (URLLC) service category in 5G is used. The edge computing cloud provides the virtualized application environment, where virtual machines (VM) are used to host monitoring functions of DSO controllers. A Hypervisor is used to manage and orchestrate multiple virtual machines that run concurrently on the host edge cloud server, while a Software Defined Network (SDN) controller is used to manage the front- and back-haul network.

The timing requirement of a real time monitoring applications, as described in Section II-B, is in the range of few

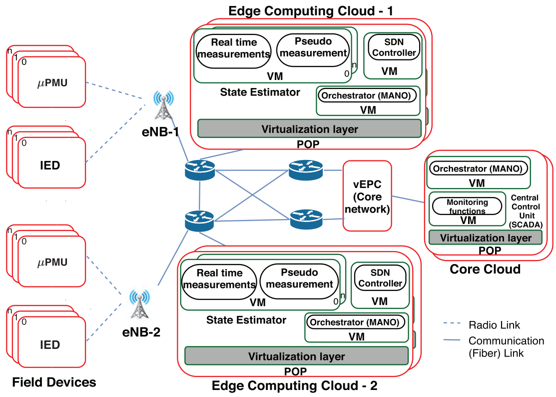


FIGURE 2. 5G based architecture for WAMS.

milliseconds. 5G, by using URLLC radio links and moving the control servers close to the base station (access point), is expected to meet this requirements, with round trip latencies of 1 ms [39].

B. METHODOLOGICAL CHALLENGES IN MODELING SMART GRID

The main issue in studying smart grids as CPS is to allow the two main components of the smart grid, power system and ICT, to be studied comprehensively, despite being two systems with their own peculiar characteristics. More specifically, the power system is traditionally described by mathematical models in the continuous domain. On the other hand, ICT system is typically described with discrete event simulation: the evolution of the ICT system is defined by the sequence of occurring events. In order to properly characterize the smart grid as a CPS, proper attention should be focused on the design of the simulation tool, that must be able to merge these two systems and describe the interdependencies among the elements that compose the complex system (see Fig. 3). This issue brings a methodological

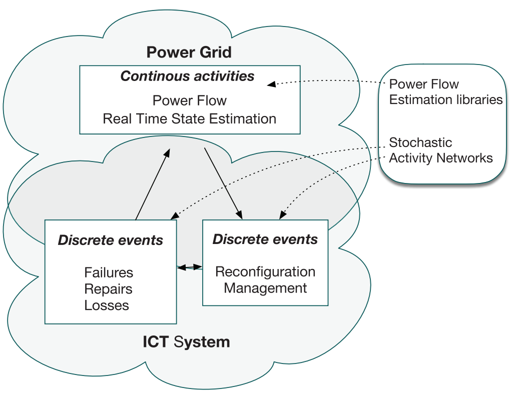


FIGURE 3. Top level methodology description.

challenge, since different exigencies must coexist: on one hand, the necessity of reproducing the operation of the system accurately, on the other hand the need of simplifying the system according to the detail of interest.

C. METHOD AND TOOL

The proposed method follows the principles outlined in Fig. 3. Major events such as failure and repair within power system and ICT systems are modeled along with the ICT infrastructure management (MANO system, VM redundancy, etc.) with the Stochastic Activity Network (SAN) formalism [40]. The power flow and state estimation calculations are performed with numerical solvers.

The SAN models are defined in the Möbius tool [41]. The use of SAN and the tool are extended to allow dealing with continuous phenomena. The main novelty of this extension of Möbius is the inclusion of power system analysis functions by exploiting external C++ libraries purposely developed. In Fig. 4, a schematic representation of the software tool is illustrated.

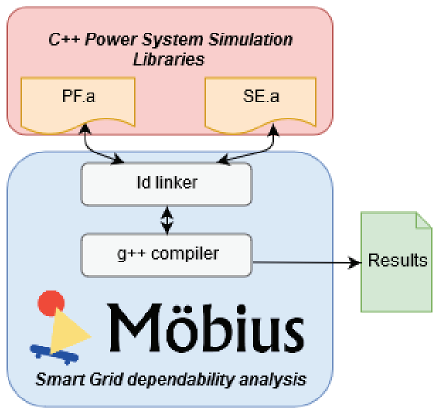


FIGURE 4. Schematic representation of the software architecture of the tool.

The C++ libraries developed for this study are:

- *PF.a*, which provides the tool with the capability of performing power flows;
- *SE.a*, which provides the tool with the capability of performing state estimation calculations.

The simulation is carried out as ordinary discrete event simulation in the Möbius tool, with a modification at the events that may change the power flow. A high level description of the handling procedure of the events is presented in Algorithm 1. Whenever a failure or repair event is generated by the simulation in Möbius, power flow and state estimation calculations are performed. The extensions to Möbius provide the power system analysis functions, defined within the C++ libraries, with the working state of each system component. Based on this information, the power system functions process the data and perform the calculations. Then, the results are collected and recorded as values in the

Algorithm 1 Procedure at Discrete Events in the Simulation

```
1:  Event in the Discrete Event Simulation of the SAN
2:  Execute actions in the SAN
3:  if The event affects the wide area measurements then
4:      Power flow analysis of new state            ▷ PF.a library
5:      Store new flow in extended place                ▷ Figure 7,
                    ▷ Places: P_fr, VA_fr, P_bus, VA_bus
6:      Perform State Estimation                    ▷ SE.a library
7:      if PMU-based State Estimation then
8:          Perform PMU-based post processing
9:      end if
10:     Accumulate state estimation statistics
11: end if
12: Update the event list
13: Next event in the simulation, i.e. goto line 1
```

extended places in Möbius, and might be acted upon in further simulations. Extended places are special elements in the SAN formalism of Möbius that allows the model to handle the representation of structures and arrays of primitive data-types (places).

The tool implemented exploits and enhances the inherent advantages of Stochastic Activity Networks formalism:

- *Efficient simulation*: during the simulation, power flow and state estimation calculations carried out only after events change the ICT system topology and/or the power flows. Results for a given configuration are cached to avoid repetitive calculations of normal conditions, shortening the simulation time;
- *Structured modeling*: each type of component of relevance in the power grid and ICT system is modeled with an atomic model. The interconnection between components is embedded in the input/output gates and extended places. This approach simplifies the description of the system and the interdependencies that exist between the system components;
- *Modularity and flexibility*: the model is easily extendable with new features; the introduction of new atomic models and refinement of existing allow upgrading the smart grid definition with an enhanced level of details. Furthermore, the exploitation of external libraries allows modeling the dynamics of the system such as introducing power system analysis capabilities and other active management functionalities (network operation strategies, transient simulation analysis, etc.).

D. MODEL DESCRIPTION

Based on the 5G based architecture proposed in Section III-A. The model is based on the principles of object orientation. First, a Möbius atomic model is developed for all types of components of the architecture describing their generic behavior. Next, these types are instantiated, i.e. given parameters and variables, to represent the specific individual components of that type in the system. The instances and the system topology are represented using an indexed extended place in the atomic models. Then, the overall system is modelled by connecting the atomic sub-models. The reward model functionality in Möbius is used to collect statistics of interest for each state transition of the system (failures and repairs). Below, some important atomic model types for the 5G architecture are presented. For a more detailed description of the atomic models, refer to [42].

1) EDGE INFRASTRUCTURE

Figure 5 shows the atomic model of an edge server. It has four extended places: hardware failure (`Server_Failed`), working state (`Server_Ok`), Operating system/Software failure (`Soft_Failed`) and No Power states (`No_Power`). The states of the servers are modeled by markings of the respective extended places. The atomic model for virtual machine is shown in Fig. 6. A virtual machine may have a software failure (`VM_Sf_Fail`) or a failure in the underneath edge server may change its state into a hardware failure state in `VM_Hr_Fail`. The unconnected extended places at the top are shared places, which are used to share states with other atomic models.

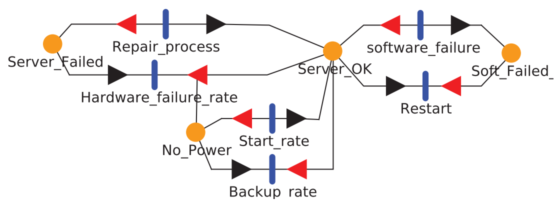


FIGURE 5. Atomic model of the server.

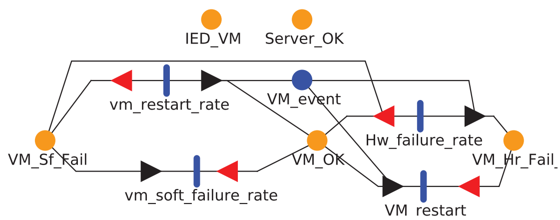


FIGURE 6. Atomic model of virtual machine.

2) ESTIMATOR APPLICATION MODEL

The estimator application atomic model, shown in Fig. 7, contains the core setup for the exchange of information between the ICT system and power system models as discussed in Subsection III-C. It consists of three places: `OK_Initial`, `Estimation` and `Failed`. The global variables, defined as extended places, are exploited for storing the power system variables from both the power flow analysis and state estimation. A power flow analysis is made on the initial state prior to estimation so that the ideal case values are known.

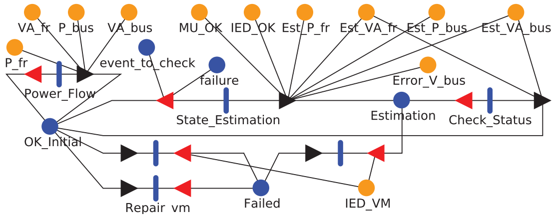


FIGURE 7. Atomic model of estimator application.

The remaining places `failure` and `event_to_check` are shared with other monitoring system components such as the measurement devices. According to discrete event simulation paradigm, these shared states are used to trigger the state estimation calculation. Both the power flow and estimation libraries are called in this atomic model and the results are stored in the respective global power system variables. The estimator application may turn from working states (`OK_Initial` and `Estimation`) to a failure state (`Failed`) if the underlying virtual machine fails to provide service (through `IED_VM`).

3) FIELD MEASUREMENT DEVICES

The atomic model for field measurement devices, such as μPMUs or IEDs, is shown in Fig. 8. It consists three extended places: hardware failure (`Sensor_Failed`), working state (`Sensor_OK`) and loss of communication `Sensor_No_Comm`. A field measurement device will be unavailable if it either has a hardware failure or if the radio communication to the eNB is lost. The state of the radio communication is monitored through the shared extended place `Com_OK`. The state of the field device measurement will finally be communicated to the estimator through the shared place `event_to_check` and `failure`.

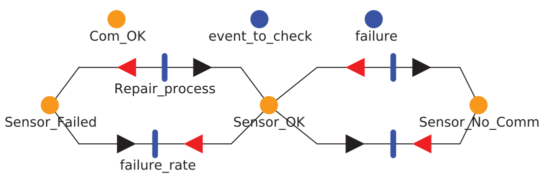


FIGURE 8. Atomic model of field measurement device.

4) RADIO COMMUNICATION

The radio communication represents the most vulnerable part of WAMS. For this reason, a detailed model of the radio communication subsystem is developed. In addition to conventional component failures, a special focus is put on environmental factors such as signal fading and rain effect. The model assumes that each field component (SCADA measurement device or μPMUs) is connected to the eNB through a single homed radio communication channel. It is also assumed that each radio communication channel consists of multiple paths (n radio signals).

The radio subsystem model is structured in three stages, which will be discussed separately. First, an atomic model for reliability of the wireless channel modeling the multi-path fading on the n redundant signals of a single radio communication channel. Next, the atomic model of the radio communication that includes the radio channel together with hardware equipment is introduced. Lastly, the modeling of rain effect on the radio channel reliability is discussed.

a: RADIO CHANNEL MODEL

The radio channel is typically characterized by either a large-scale fading or a small scale fading. The large scale fading is due to the path loss and shadowing while the small scale fading is due to the constructive and destructive interference of the multiple signal paths [43], [44]. Though the model developed is exploitable to analyze both properties, the model proposed ignores path loss and shadowing, assuming a compensation is performed by controlling the transmission power. Considering urban areas where there can be many moving objects that may scatter the n radio signals on their way to the receiver, a Rayleigh model is assumed for capturing the effect of small-scale fading.

For reliability studies, the fading behavior of the radio transmission can be considered as an alternating renewal process with failure (λ) and recovery (μ) rates where the failure of the transmission is attributed to the fading. The average fading and non-fading duration of a Rayleigh-faded signal can be determined by level crossing analysis as discussed in [43], [44]. Their reciprocals characterize the transition rates between a working state and a failure state, which is denoted as failure rate λ and recovery rate μ as shown in (8):

$$\lambda = \sqrt{\frac{2\pi}{F}} f_{\mathrm{D}}, \quad \mu = \frac{\sqrt{\frac{2\pi}{F}} f_{\mathrm{D}}}{\exp\frac{1}{F} - 1} \tag{8}$$

where $F = p_{\mathrm{avg}}/p_{\mathrm{min}}$ represents the fading margin with the average receive power p_{avg}. The maximum Doppler frequency is characterized by $f_D = vf/c$, where f is the carrier frequency of the signal and c is the speed of light. The relative velocity between transmitter, receiver, and scatterers is denoted by v. In smart grid environment, the transmitter and receiver are stationary. Nevertheless, there can be a minor effect from scatters especially in urban areas. Hence, the model assumes a small fraction of the failure due to fading (r) where $f_D = (vf/c) \cdot r$.

The first stage atomic model in Fig. 9 is used to study the wireless channel property (i.e. the short term fading behavior). It consists two extended places; working (`Radio_signal_Ok`) and failure due to fading (`Radio_signal_Failed`). The markings in the two extended places represent how many of the n radio signals are (not-)working. A radio channel is assumed to be viable as long as one out of the n redundant signals is operational. The radio channel is said to be failed if all n tokens are present

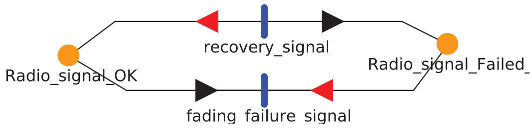


FIGURE 9. Atomic model of a fading radio channel.

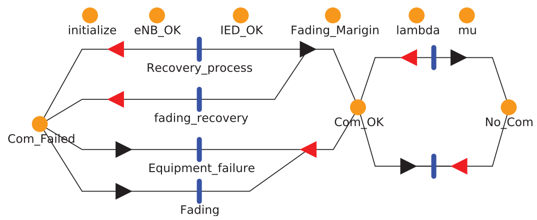


FIGURE 10. Atomic model of the radio communication.

in `Radio_signal_Failed`. The rates of transitions, `fading_failure_signal` and `recovery_signal`, are obtained from the λ and μ of (8). The model measures the rate at which the radio channel fails (all signals are down) due to fading and get recovered by tracking the number of visits to the failure state.

b: RADIO COMMUNICATION

The second stage radio communication model, shown in Fig. 10, is used to model the radio communication as a single entity, including the radio channel together with hardware equipment. This model is suited for studying the availability of communication between sensors and the radio tower. It consists of three extended places: Working (`Com_Ok`), No communication due to failure on ICT components (`No_Com`) and link failure (`Com_Failed`). The failure of a communication link has different states represented by different marking of the extended place. It could be due to hardware failure on the receiver and transmitters which need maintenance by a recovery crew, or due to fading with a failure rate obtained from the first stage model.

c: RAIN EFFECT MODEL

In addition to the small-scale fading, the attenuation due to rain precipitation is considered. In fact, similar to small-scale fading, rain precipitation is an event that rapidly changes the attenuation between base station and user equipment. Therefore, no compensation from the base station can occur and the rain may cause communication failure. The effect may be pronounced in areas where the rainfall intensity reaches high values in large parts of the year.

In this study Norway has been considered. According to ITU recommendations, Norway is described by four rain regions that differ in terms of distribution of rainfall intensity over the year [45], [46]. The four regions considered (C, E, G, J) are reported in Table 2 with the corresponding rainfall distribution.

TABLE 2. ITU-R rain rates for map regions of Norway.

% of year exceeded	Rainfall rate exceeded (mm/h) C	E	G	J
0.001	42	70	65	55
0.003	26	41	45	45
0.01	15	22	30	35
0.03	9	12	20	28
0.1	5	6	12	20
0.3	2.8	2.4	7	13
1	0.7	0.6	3	8

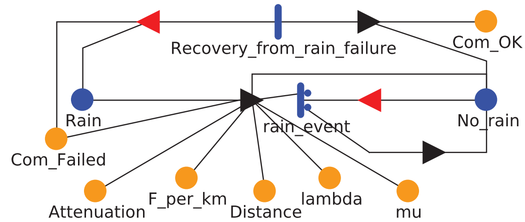


FIGURE 11. Atomic model of rain effect.

The attenuation Γ_R (dB) is obtained from the rain rate R (mm/h) using (9):

$$\Gamma_R = k \cdot R^{\alpha} \cdot d \tag{9}$$

where k and α are two coefficients that depend on polarization and frequency, and d is the distance between the considered node and the nearest base station.

The attenuation Γ_R reduces the fading margin available for the small-term fading F in (8). Given F^* as the maximum fading margin in the radio link, the actual fading margin value will be given by (10):

$$F = F^* - \Gamma_R \tag{10}$$

A Möbius atomic model for modeling the rain effect is presented in Fig. 11. It has two places: Rain (`Rain`) and No rain (`No_rain`). The markings in the two places represent the condition when the rainfall results in a significant attenuation or if it results in a negligible attenuation that does not affect the signal transmission. A rainfall rate of 3 mm/h has been considered as threshold for the transition between these two states. When a rain event exceeding the threshold occurs, the resulting attenuation for each radio channel is calculated according to (9) and stored in `Attenuation`. Then, the remaining fading margin is calculated according to (10), and the failure and recovery rates (`lambda` and `mu`) of the radio channel model (Fig. 10) are updated accordingly. For those radio channels with attenuation exceeding the fading margin, the radio channel is considered failed (through `Com_Failed`). When the rainfall ends, all the radio channel states are restored to their default state.

IV. DEPENDABILITY ANALYSIS

The study investigates the dependability of the proposed 5G communication infrastructure of WAMS in distribution grid.

A comparative analysis, that considers different assumptions and configurations of the 5G infrastructure, is conducted with the simulation tool introduced in Subsection III-C.

A. CASE STUDY

A simulation study of a distribution network is carried out, focusing on measuring the impact of ICT failures on the state estimation of the grid.

1) POWER GRID

The analysis is performed on the IEEE 33-bus standard distribution network (Fig. 12). It is a 12.66 kV radial network that feeds approximately 3.6 MW of peak active power load and 2.2 MVAR of peak reactive power load [47]. The IEEE 33-bus standard network considers normally open emergency ties that allow reconfiguring the network when failures occur. In the future distribution networks, with a high penetration of distributed generation, will increasingly be operated in weakly meshed topology [48]. Therefore, in this study, the disconnectors that maneuver the emergency ties (dotted lines) are considered normally closed, i.e. the distribution network operates in a meshed configuration. The bus 1 is assumed as the slack bus, with reference voltage 1 *pu*. Power flow calculations return the voltage profile over the 33 buses, which are within the normal operation range for distribution networks of $0.95 \div 1.05\,pu$ [49].

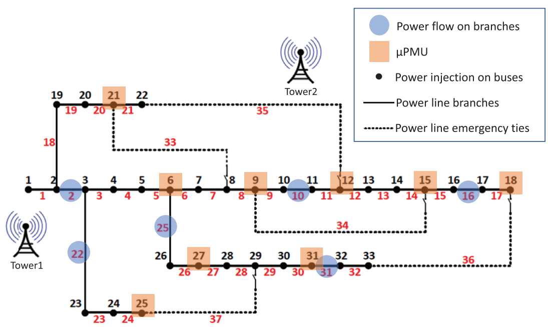


FIGURE 12. IEEE 33-bus standard distribution network.

A mix of bus power injection measurements, branch power flow measurements and μPMU measurements are deployed along the network. The Wide Area Measurement System is implemented with IEDs or μPMUs, that communicate directly to the SCADA master and DMS located at the DSO control center, according to a centralized architecture. The IEDs and μPMUs placement is done ensuring that the power system is fully observable whenever any measurement unit is interested by a failure (N-1 approach).

The IEDs transmit the measurements of bus power injections and branch power flows to the SCADA master every 2 seconds, and then a robust SCADA+PMU state estimation calculation is performed. μPMUs transmit voltage and current phasor measurements every 100 ms to the DMS. The DMS post-processes the previous state estimation with the updated μPMUs measurements, exploiting the two-stages linear state estimation approach explained in subsection II-D1. An example of the approach followed is represented in Fig. 13.

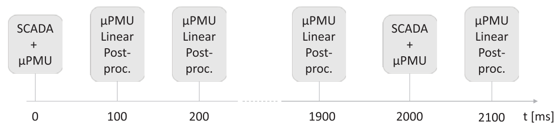


FIGURE 13. State estimation SCADA + PMU processing synchronization.

2) ICT SYSTEM

The 5G architecture proposed in subsection III-A is studied, which assumes that the measurement points are connected to the estimator application on the edge cloud through a radio access network, see Fig. 2. Two radio towers are located in the proximity of the power grid and each sensor is provided with a 5G User Equipment which is connected to the nearest tower. To each of these components (IEDs, μPMUs, UE, Base Station) an instantiation of the correspondent atomic models (ref. III-D) is associated. For a description of the instantiation process, see Subsection III-D. An atomic model is also instantiated for each communication link between UEs and nearest base station. Finally, an atomic model is instantiated for each component of the 5G Edge Computing Cloud and Core Cloud (Fig. 2), namely the server, the virtual machine, the estimator application. For a complete list of 5G architecture model, see Subsection III-D. All these atomic models are merged with the Join feature of the Möbius tool. For the sake of brevity, the authors refer the reader to [50], [51] as example of application of SAN atomic models for ICT system modeling in different distribution systems.

All the transitions (i.e., Failure events, repair events, rain occurrence, etc.) in each atomic model are assumed with a constant failure rate, yielding negative exponentially distributed firing times T_x, i.e. $P(T_x > t) = e^{-\lambda_x t}$, for transition x. The usage of negative exponential distribution for repair and recovery times is due to the lack of empirical information about the distribution of these events, combined with the lack of sensitivity in the results to their distribution. This is considered a fair assumption, as long as the repair and recovery times are short compared to the time between failures. Table 3 presents the failure rates and repair times used in the numerical evaluation. For edge computing server components these are based on [52] and [53], while the parameters used for the field devices are from [54].

3) METRICS

The following metrics are used to quantify the impact of communication failures on the accuracy of the state estimation of the power grid:

- Mean Estimation Error (MER) – $\bar{E}(x)$: measures the difference between the estimated power system state

TABLE 3. Failure rates and recovery times of the system components.

Component type	Failure rate [days^{-1}]	Mean recovery time [hr]
RTU / μPMU	$2.6 \cdot 10^{-3}$	2
Fiber Line	$6 \cdot 10^{-6}$	6
Router/Switches	$5 \cdot 10^{-3}$	3
Host server (permanent failures)	$4.9 \cdot 10^{-3}$	2
Host OS (Software failures)	$1.667 \cdot 10^{-2}$	1 (repair) $1.667 \cdot 10^{-1}$ (reboot)
Virtual Machine Monitor	$8.3 \cdot 10^{-3}$	1 (repair) $1.667 \cdot 10^{-1}$ (reboot)
Virtual machines	$1.1 \cdot 10^{-2}$	1
eNB	$2 \cdot 10^{-4}$	10
Power supply failure	$1.9 \cdot 10^{-3}$	3
Radio Link	$8.64 \cdot (10^0–10^1)$	$2.77 \cdot 10^{-4}$ (=100ms)

variable x using WAMS and the ideal/actual values obtained with power flow calculation. In the following study cases, the state variable x considered is the bus voltage magnitude. The mean estimation error is measured for each bus in the power grid network. The mean of the estimator error for all buses is also considered as metric.

- Safety – $\bar{S}(x)$: represents the probability that the estimation error is greater than a certain critical threshold value, *TR*. It gives information about the probability that the estimation error triggers a decisive and critical action by the control unit.

4) STUDY CASES

The study aims at assessing the dependability of the two different state estimation algorithms introduced in Subsection II-D. The study investigates first the degree of vulnerability of the different subsystems of the WAMS architecture, then the impact of component failures over the state estimation accuracy is analyzed in detail. The study is divided in the following cases:

A: The influence of the different 5G-based WAMS subsystems (Sensors, Radio access, eNBs and Edge cloud) on the reliability of state estimation calculations is analyzed.

B: The 5G configuration with a SCADA based state estimation (SCADA-SE) is studied and compared with a WAMS setup with ideal communication. Two sub-cases are considered:
B.1: The SCADA-SE with a closer look at the radio subsystem (the environmental impact due to rain) is considered. The effect of failure in communication due to rain on the state estimation performances is investigated. Four map regions (C, E, G and J) of the ITU-standard (2) that fall into the area of Norway are considered.
B.2: The SCADA-SE with a focus on the sensor subsystem is considered. The effect of different recovery strategy for sensors is studied. The following three strategies are considered; immediate repair, differing recovery until two sensors are failed, and differing recovery until three sensors are failed.

C: The impact of communication failures on state estimation MER and safety is analyzed in the WAMS setup with PMU-based linear post-processing of SCADA measurements.

In all case studies, the safety metric has been considered associated with a voltage threshold $TR = 0.02\, pu$. Therefore, it has been assumed as critical state the condition when the estimation error exceeds $\pm 2\%$ of the actual voltage value. Moreover, in the case of losing information due to failures, the estimator algorithm uses pseudo-measurements taken from the historical data. Except for the case in which the four rain-regions are specifically compared, we assume region G as default region in all cases, corresponding to the most severe scenario (details are provided in the discussion of case B.2 in subsection IV-B).

All cases are simulated for 1 year of calendar time, each replicated 15 to 20 times to achieve a sufficient statistical confidence level of the simulation results. In the result presented below, the ratio between the 95% confidence interval of the estimates and the estimate are 3% to 8%.

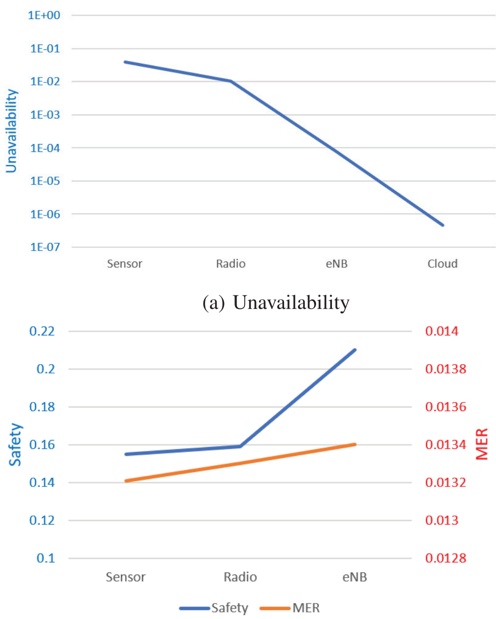
B. EVALUATION AND DISCUSSION

For all cases mentioned in Section IV-A4, a simulation of the operations of the network, including failures, repairs, transmission problems, etc., is run with WLS State Estimation (4) calculated every 2 seconds with SCADA-based WAMS. For the case where μPMUs are considered, every 100 ms the results are refined with the PMU-based linear state estimation algorithm (7).

Case A: The effect of failures on the different subsystems is first analyzed by measuring the unavailability of each subsystem. A subsystem is considered unavailable if one or more component in the subsystem fail, assuming it may affect the estimation process. In this analysis, measurements are taken provided that a failure occurs in the considered subsystem.

Fig. 14a shows the unavailability measure of the four major subsystems of the 5G based WAMS architecture: set of sensors, radio channel, radio towers (eNBs) and edge cloud. It can be observed that the measurement devices (sensors) introduce the highest contribution to the total unavailability, followed by the radio access subsystem. The eNBs and the edge cloud have a very small contribution to the system unavailability, 10^{-4} and 10^{-7} respectively.

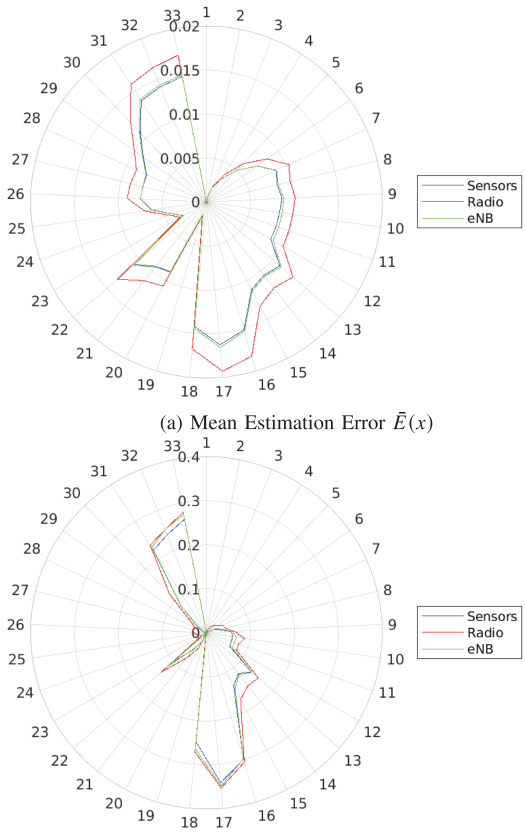
Fig. 14b shows the impact of the different subsystems on the WAMS dependability in terms of MER and safety metrics. The radio subsystem, although characterized by a lower unavailability figure compared with the sensor subsystem, results in slightly higher mean estimation error and safety values. Failures in the radio access are frequent and characterized by short duration that results in a higher number of simultaneous failures. They therefore affect the performance of state estimator algorithm that results in higher MER.



(a) Unavailability

(b) Safety and mean estimation error

FIGURE 14. **Comparison of different subsystems in 5G architecture.**



(a) Mean Estimation Error $\bar{E}(x)$

(b) Safety $\bar{S}(x)$

FIGURE 15. **Effect of failure in the different subsystems in 5G architecture.**

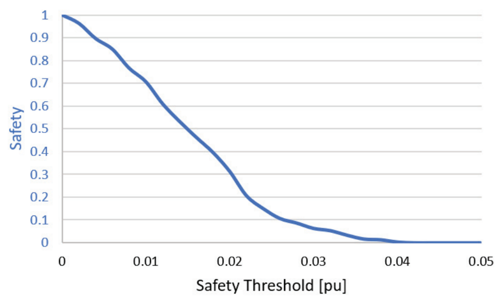


FIGURE 16. **Safety $\bar{S}(x)$ on bus 33 for different threshold values.**

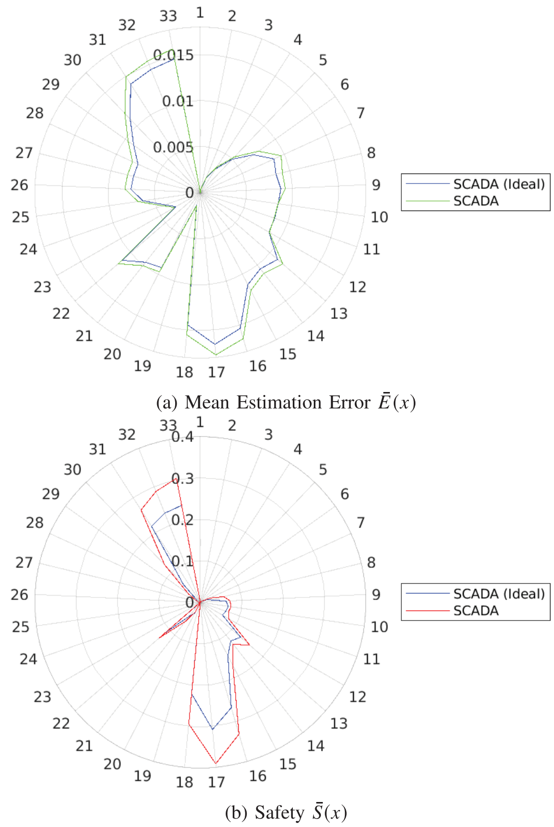
Failures in eNBs result in the highest MER. The main reason is the wide impact of failures in eNBs, which result in loss of coverage for a high number of sensors, and therefore a higher uncertainty in the state estimation calculation. Nevertheless, the exploitation of pseudo-measurements mitigate this effect allowing to produce a reasonable estimation. For the same reason, even the safety does not increase consistently compared with the other cases. In Fig. 14b the metrics related to failure on the edge cloud are not reported since failure of the edge cloud would leave the system unobservable.

The following polar diagrams report the analysis of the state estimation accuracy at a bus level. The results of the state estimation are compared with the actual value calculated with the power flow library, and the metrics MER and Safety are calculated for each bus.

In Fig. 15 the impact of failures on the different WAMS subsystems in terms of MER (Fig. 15a) and safety (Fig. 15b) is evaluated on each bus.

Figure 15a shows that the radio channel is the most critical source of mean estimation error compared to sensors and eNBs. Although each failure in the eNBs results in a high MER, the effect seen over a ten-year simulation is small. On the other hand, failures on the radio channel, although singularly characterized by a lower MER impact than the eNBs, result in a higher MER on a longer time scale, due mainly to the higher failure rate. A similar behavior is observed for the safety metrics, but with failures in radio access subsystem resulting in slightly higher safety values only on some buses, such as from bus 9 to bus 16.

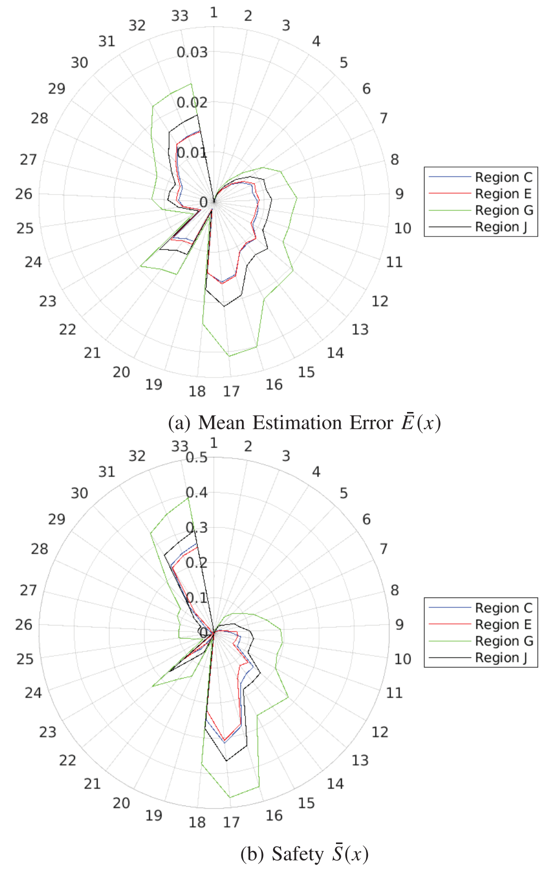
It can be observed that some critical buses (for example, buses from 16 to 18, and from 31 to 33) are characterized by a high value of the safety metrics. Based on the presented definition of Safety (cfr. IV-A3), it means that these buses have a high probability of estimation error. The safety values are dependent both on the location of the measurement devices, and on the strict threshold adopted (0.02 *pu*). On Fig. 16 the



(a) Mean Estimation Error $\bar{E}(x)$

(b) Safety $\bar{S}(x)$

FIGURE 17. **Comparison of SCADA-SE vs Ideal case.**



(a) Mean Estimation Error $\bar{E}(x)$

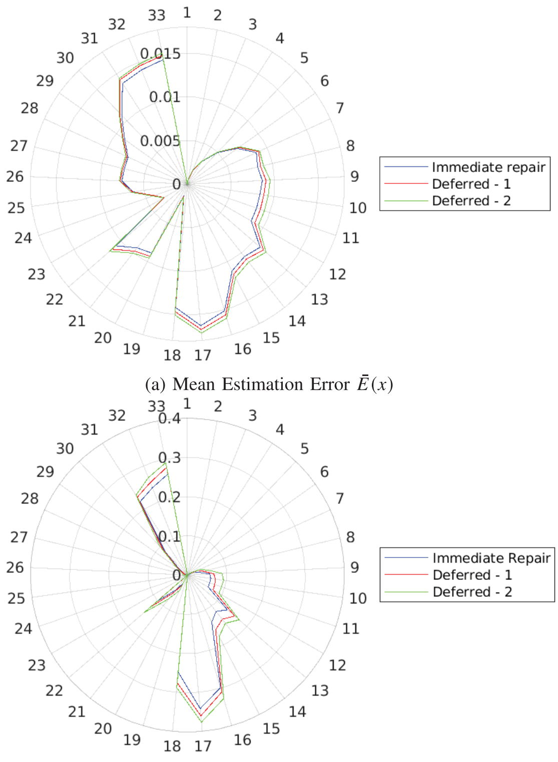
(b) Safety $\bar{S}(x)$

FIGURE 18. **Comparison of the four rain regions of Norway.**

safety metric is analyzed for different threshold values on bus 33. It can be observed that the safety decreases significantly for threshold values over 0.03 *pu*, becoming negligible for thresholds bigger than 0.04 *pu*.

Case B: This case focuses on analyzing the reliability of a 5G-based WAMS with traditional SCADA measurement installation. Figure 17a shows the comparison between the 5G-based WAMS with an ideal communication based (no failure) WAMS in terms of mean estimation error. It is observed that the mean estimation error, with the use of SCADA sensors, gives an error in the range of 0.5% to 1.5% in most of the buses. The results are close to the ideal case, where the errors are mainly due to uncertainty in the sensors data and the intrinsic accuracy of the estimator algorithm. Figure 17b shows the comparison among these two scenarios in terms of safety metrics. It can be observed that the probability of occurrence of critical state increases significantly in the 5G-based WAMS on buses 31 to 33, and 16 to 18, meanwhile on the other buses the safety metrics presents values similar to the ideal case.

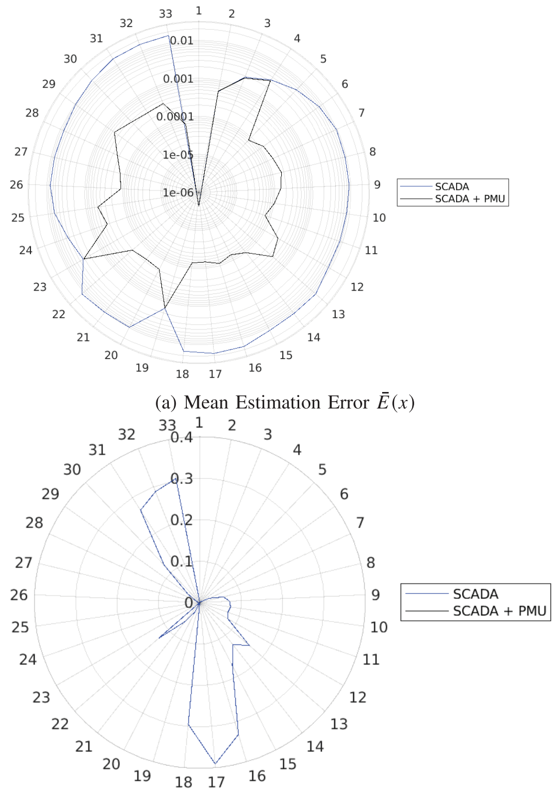
Case B.1: The effect of rain on state estimation is studied for the four rain regions that intersect the Norway area (Table 2). On these cases, the state estimation calculation is based on a 5G-based SCADA system with traditional measurement devices. Figure 18a shows the mean estimation error metrics when there is rainfall. The simulation demonstrates the significance of rainfall rates on the accuracy of the state estimation. The rain region G has a significantly higher MER than other rain regions on all buses. The mean error ranges between 1.5% to 3% on a notable portion of the network (buses 31 to 33, 13 to 18) which might bring to major problems on power system operations. Even though, according to Table 2, region J presents a higher probability of rainfall, the mean estimation error for region J is lower than region G. This is due to the fact that region G has longer intense rainy periods, resulting in a significant attenuation. For most of the buses, the MER in region J ranges between 1% to 2%. For the other two areas which cover most of Norway, C and E, the introduced mean estimation error is relatively small, and the probability that rain introduces a significant attenuation is rare. The safety measures (Fig. 18b) show that all the regions considered have a significant probability of mean error greater than the threshold during rainy periods.



(a) Mean Estimation Error $\bar{E}(x)$

(b) Safety $\bar{S}(x)$

FIGURE 19. Comparison of repair strategies.



(a) Mean Estimation Error $\bar{E}(x)$

(b) Safety $\bar{S}(x)$

FIGURE 20. Comparison of SCADA-SE and (SCADA + PMU)-SE.

The region G appears to be the most critical in terms of probability of having a decisive action by the DMS due to the high mean estimation error.

Case B.2: A closer look at the impact of sensors failures with the use of different recovery strategies is shown in Fig. 19a and Fig. 19b. Figure 19a shows the polar plot of the mean estimation error for three scenarios: immediate repair; deferred repair until one other component fails; deferred repair until two other components fail. It can be seen that the effect of deferring the repair up to three components is small. This is mainly due to the use of pseudo measurements when measurement devices data are not received by the SCADA system: when the power load variations are relatively slow compared with the repair rates, the impact of sensors failures is in this context negligible.

Case C: The benefit in the adoption of a PMU-based state estimation is investigated in this case by comparing its performances with a traditional SCADA-based WLS state estimation. Figure 20a shows the mean estimation error comparison of the two 5G state estimation approaches: (SCADA + PMU)-SE and SCADA-SE. The results show a significant improvement in terms of MER with the PMU-based state estimation, compared with the traditional WLS state estimation. Note that in Fig. 20a the scale of magnitudes is logarithmic, hence the gain in MER reduction is more than two decades in a significant part of the network.

For some buses (such as bus 2-4, bus 19, bus 23), the two approaches give the same mean error, i.e. the use of μPMUs does not yield a significant improvement of the mean estimation error for these. This is mainly due to the placement of μPMUs on the topography considered.

The safety of the WAMS is also compared for the two state estimation approaches, and the results are shown in Fig. 20b. The estimations with μPMUs are seen as a dot in the origo. State estimation with standard measurement devices shows a significant probability that the MER can be higher than the 2 % threshold. Buses such as 16 to 18 and 31 to 33 have a relatively high probability of causing critical actions by the DMS (safety > 0.2), some buses such as 9 to 15 show safety metrics in the range of 0.1, and all the rest of the buses present an almost negligible probability. On the other hand, state estimation with μPMUs shows a very small probability that the error causes a wrong decision by the DMS. The (SCADA + PMU)-SE approach proves to be extremely accurate: the 10-year simulations reveal only one event where the mean estimation error exceeded the 2% threshold on one bus.

V. CONCLUSION

This paper has presented a novel methodological approach for analyzing the impact of 5G internal and external sources of interference to the ability of WAMS to provide measurement data to a Smart Grid state estimator. Different state estimator algorithms are compared, namely traditional WLS state estimator and PMU-based state estimator. The performance of these algorithms are compared in terms of Mean Estimation Error and Safety metrics.

The results obtained with the methodology proposed highlight the necessity of studying smart grids as cyber-physical systems to model and analyze the power system and the ICT system comprehensively. They also show how the failures in the ICT system may increase the intrinsic level of inaccuracy of measurement devices and state estimation algorithms.

The radio channel may be considerably affected by external factors such as fading and rain conditions. The outcome of the study indicates that this is the major cause of estimation error, affecting both state estimation MER and safety.

In the 5G-based WAMS scenario with traditional measurement devices, the mean estimation error along the grid buses is close to the ideal case, although there is a critical increase of probability that the estimation error may bring to wrong decisions by the DMS on some buses. The adoption of μPMUs measurement in the distribution network shows a significant improvement in the accuracy of the voltage estimation: the mean estimation error is reduced by more than two decades. The occurrence of wrong decisions by the DMS due to a high mean estimation error becomes negligible. The close-to-ideal behavior of 5G-URLLC observed in the dependability analysis enforces the prospect of a future adoption of 5G technologies for smart grid monitoring application, both for traditional SCADA- and PMU-based monitoring systems.

Tentative extension of this study as future work includes the analysis of the 5G technology as a service provider for power system monitoring and control. The study will focus on the effect of communication failures in the efficiency of a voltage regulation algorithm for distribution grids.

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