NTNU – Trondheim
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Performance Evaluation of V2V and V2I Messages in C-ITS

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Master of Telematics - Communication Networks and Networked Services (2
Submission date: June 2015
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Problem description:

Norwegian Public Roads Administration (NPRA. no: Statens vegvesen) is interested in exploring the concept of communication to, from and between vehicles to improve road safety and efficiency. In C-ITS, the IEEE 802.11p running in the 5,9 GHz band is so far the most likely link level communication protocol, both for V2V and V2I messages. There are multiple proposed protocols. Among these are GeoNetworking, standardized in ETSI EN 302 636-4-1. NPRA is interested in exploring the performance of the GeoNetworking protocol in different usage scenarios, ranging from crowded highways to more rural areas.

So far the research focus for the GeoNetworking protocol has been on the CAMs. There has been substantially less focus on the dynamic propagated warning messages (DENMs). The DENMs requires multi-hop communication and are forwarded both on the fly and through a store-cache-forward paradigm. This can cause problems with flooding and duplicated messages and local overloads. The overall task will be to evaluate the performance of the GeoNetworking protocol in different scenarios with CAM and DENM messages. A possible and likely approach will be to simulate the protocol in specific, challenging scenarios.

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Abstract

The Cooperative Intelligent Transport System (C-ITS), a system where vehicles cooperate in order to improve traffic safety and efficiency, have recently received a lot of attention. There are several standardization initiatives for the C-ITS, including ETSI TC ITS in Europe and their GeoNetworking protocol. The two primary standardized messages for V2V/V2I (Vehicle-to-Vehicle/Infrastructure) communication are the periodic beacons called Cooperative Awareness Messages (CAM) and the event-triggered warning messages, Decentralized Environment Notification Messages (DENM). A 10 MHz channel is allocated for exchange of these messages in the 5.9 GHz band, referred to as ETSI G5 in Europe. The utilized access technology is the IEEE 802.11p.

The frequency of the CAMs are determined by an adaptive algorithm that adjusts the frequency based on the current surroundings. Unlike CAMs, are the dynamic DENMs forwarded by surrounding vehicles through a multi-hop paradigm. This feature extends the communication range for the DENMs, but may also cause a lot of additional overhead and duplicate traffic in the already limited capacity network. The ability to achieve sufficient delivery-rates at a low cost is a major concern for the DENMs. Several forwarding algorithms with various characteristics are standardized for the purpose of efficiently disseminate DENMs. The challenge for these algorithms is to ensure good performance for a variety of situations, including difficult road topologies, varying vehicle-densities and decreased transmission conditions.

This thesis examines the performance of these messages in various situations through simulations and an analytic study. The advantages as well as the challenges of the different features are discussed and evaluated. The results of the simulations clearly indicates how the achievement of high delivery-rates is determined by the choice of forwarding algorithm. This decision should be carefully considered based on the specific characteristics of the event. The report emphasises how the ability to chose optimal DENM parameter-values are essential for the performance. The paper also includes a thorough description of the necessary technical details of the V2V/V2I messages, in addition to an evaluation of several proposed enhancement techniques.

Keywords: ITS, Intelligent Transport System, C-ITS, ETSI, The GeoNetworking protocol, GeoNetworking, CBF, VANET, ad hoc networks, DENM, CAM, traffic safety, IEEE 802.11p

Sammendrag

Det kooperative Intelligente Transport Systemet (C-ITS), et system der kjøretøy samarbeider for å bedre trafikk sikkerheten og effektiviteten, har nylig motatt mye oppmerksomhet. Flere standardiserings initiativ eksisterer for C-ITS, deriblant ETSI TC ITS i Europa og deres GeoNetworking protokoll. De to primære standardiserte meldingene for V2V/V2I (Kjøretøy-til-Kjøretøy/Infratruktur) kommunikasjon er den periodisk sendte Cooperative Awareness Messages (CAM) og den hendelsebaserte Decentralized Environment Notification Messages (DENM). En 10 MHz kanal allokert i 5.9 GHz båndet er dedikert til dette formålet. Den brukte aksess teknologien er IEEE 802.11p.

Frekvensen av CAM er bestemt av en adaptiv algoritme som justerer frekvensen basert på de gjeldene omgivelsene. I motsetning til CAM, er DENM videresendt av andre nærliggende kjøretøy gjennom et såkalt multi-hop paragime. Denne funksjonen øker rekkevidden til DENM, men samtidig kan nettopp denne funksjonaliteten skape utfordringer med tanke på ekstra duplikat trafikk i et nettverk med allerede begrenset kapasitet. Den store utfordingen for DENM er å oppnå tilstrekkelige leveringsrater til en lav kostnad. Flere forskjellige algoritmer med ulike egenskaper er standarisert for dette formålet. Utfordringene for disse algoritmene er å sikre god ytelse i en mengde ulike situasjoner. Dette kan omhandle blant annet vanskelige vei-topologier, varierende tetthet av kjøretøy og reduserte transmisjonsforhold.

Denne avhandlingen undersøker ytelsen til de nevnte meldingene i en rekke ulike situasjoner gjennom både simuleringer og et litteraturstudie. Fordelene, samt utfordringene med de ulike funksjonalitetene er diskutert og evaluert. De presenterte resultatene indikerer hvordan valg av vidersendings-algoritme, basert på tetthet og situasjonens natur er avgjørende for ytelsen. Rapporten understreker også viktigheten av å velge optimale verdier for DENM parameterene for å oppnå best mulig ytelse. Avhandlingen inneholder også en grundig beskrivelse av de tekninske detaljene til meldingene, i tilegg til en evaluering av flere mulige teknikker for å bedre ytelsen.

Nøkkelord: ITS, Det Intelligente Transport System, C-ITS, ETSI, GeoNetworking protokollen, CBF, VANET, ad hoc nettverk, DENM, CAM, trafikk sikkerhet, IEEE 802.11p

Preface

This paper serves as the master thesis in fulfillment of the authors Master of Science degree in Telematics - Communication networks and networked services at the Norwegian University of Science and Technology.

First, I must acknowledge my responsible professor Øivind Kure for his invaluable feedback and advices that helped me writing this thesis. Further I must thank my supervisor Ola Martin Lykkja at Q-Free ASA for taking time out of his busy schedule to give excellent feedback on several topics. I would also like to thank Statens Vegvesen/NPRA and especially Erik Olsen for their support and freedom to specify the thesis.

I dedicate this thesis to my parents, who have given my plenty support and motivation to write this master thesis. I must also thank my friends and fellow students for valid input and support throughout the semester.

Contents

List of Figures

List of Tables

List of Algorithms

List of Acronyms

AC Access Class.

AIFS Arbitration Inter-Frame Space.

BF Beacon Frequency.

BSA Basic Set of Applications.

CAM Cooperative Awareness Message.

CBF Contention Based Forwarding.

CCH Control Channel.

C-ITS Cooperative Intelligent Transport System.

CW Contention Window.

DCC Decentralized Congestion Control.

DENM Decentralized Environment Notification Message.

ETSI European Telecommunications Standard Institute.

IEEE Institute of Electrical and Electronics Engineers.

ITS Intelligent Transport System.

ITS-S ITS Station.

KAF KeepAlive Forwarding.

LDM Local Dynamic Map.

NTNU Norwegian University of Science and Technology.

PCF Packet Centric Forwarding.

PRNG Pseudo-Random Number Generator.

RSU Road Side Unit.

UD Update Delay.

V2I Vehicle-to-Infrastructure.

V2V Vehicle-to-Vehicle.

VANET Vehicular Ad Hoc Network.

Chapter 1

Introduction

1.1 Background

Cooperative Intelligent Transport Systems (C-ITS), designed to improve traffic safety and efficiency have over the last years become a popular research topic. These systems have great potential and could help reducing the number of accidents and injuries in traffic. In these Vehicular Ad hoc Networks (VANET), the vehicles and the roadside infrastructure exchanges information through both Vehicles-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication. The IEEE 802.11p technology, which is an amendment to the IEEE 802.11 standard known as Wi-Fi, is one of the technologies used for this purpose.

There are several standardization initiatives for the ITS, one of these is ETSI TC ITS in Europe. Information involving the different standardization initiatives, as well as a detailed overview of ETSI TC ITS can be studied in [Tub14]. The two primary standardized messages for the V2V and V2I communications are the Cooperative Awareness Messages (CAM) and the Decentralized Environment Notification Messages (DENM). The CAMs are periodically broadcasted beacons used to maintain awareness of the surrounding vehicles. These are single-hop messages sent with an adaptive frequency of 1-10 Hz. The CAMs include information such as position, type and direction. The DENMs are event-triggered multi-hop warning messages which are generated by the ITS applications in order to alert neighboring vehicles about potential hazards.

A 10 MHz control channel in the 5,9 GHz band is dedicated for both of these messages. The DENMs are given higher priority (higher Access Class (AC)) than the CAMs at the access layer. The advantage of the higher AC is a shorter Contention Window (CW) and Arbitration Inter-Frame Space (AIFS) when transmitting a message. The data rate for the utilized control channel (CCH) is 6 Mbps. The limited capacity might cause decreased delivery-rates and add additional delay, which are unfortunate for the safety applications performance. It is therefore essential to minimize any overhead traffic in the network. High mobility, high speed and varying transmission conditions are all challenging characteristics of VANETs that should be taken into account when discussing the system's performance. The serious consequences of imperfect message dissemination in the C-ITS makes the job of implementing the ITS applications a demanding task.

The GeoNetworking protocol is the chosen network layer protocol. It forwards messages based on geographical position. Unlike most of the other standardization initiatives network layer protocols, does ETSI's GeoNetworking protocol supports multi-hop communication. This feature makes it possible to forward the DENMs outside of the originating vehicle's single-hop communication range (up to 500 m in Line of Sight (LOS) conditions).

A major concern for the DENMs is the likelihood of duplicate traffic caused by several vehicles broadcasting DENMs for the same hazard. The flooding characteristics for different forwarding algorithms might also cause a lot of overhead traffic. This could be a problem in crowded areas with a high density of vehicles. As the DENMs may be forwarded by intermediate vehicles through a store-cache-forward approach, is it probable that several of the one-hop neighbors will re-broadcasts the same original DENM. This additional traffic might interfere with the dissemination of the CAMs and could cause problems maintaining awareness of the surrounding vehicles. DENM aggregation and optimized forwarding techniques could potentially help prevent these issues.

1.2 Problem Description

Norwegian Public Roads Administration (NPRA. no: Statens vegvesen) is interested in exploring the concept of communication to, from and between vehicles to improve road safety and efficiency. In C-ITS, the IEEE 802.11p running in the 5,9 GHz band is so far the most likely link level communication protocol, both for V2V and V2I messages. There are multiple proposed protocols. Among these are GeoNetworking, standardized in [Eur14e]. NPRA is interested in exploring the performance of the GeoNetworking protocol in different usage scenarios, ranging from crowded highways to more rural areas.

So far the research focus for the GeoNetworking protocol has been on the CAMs. There has been substantially less focus on the dynamic propagated warning messages (DENMs). The DENMs requires multi-hop communication and are forwarded both on the fly and through a store-cache-forward paradigm. This can cause problems with flooding and duplicated messages and local overloads. The overall task will be to evaluate the performance of the GeoNetworking protocol in different scenarios with CAM and DENM messages. A possible and likely approach will be to simulate the protocol in specific, challenging scenarios.

1.3 Related Work

Most of the published research related to the V2V/V2I messages in C-ITS revolves around the CAM frequency and the implications of its different frequencies. Examples of such research papers are [KSRdPM11] and [BJU11]. The authors of [BBM14] use both simulation and analytic estimations to study several aspects of CAM dissemination. This includes the rate of received CAMs which a vehicle needs to handle per second. Whereas the CAMs are only broadcasted to all single-hop neighbors, is the dissemination of DENMs on the other hand much more complex. An efficient broadcasting strategy is therefore essential in order to achieve sufficient delivery-rates. The authors of [TMJH04] proposes an broadcasting strategy which relies on giving higher priority to ITS stations which are transmitting time-critical messages. This approach will not reduce the overhead traffic nor decrease the channel load, but might help increasing the throughput for specific time-critical DENMs. The authors of [VCMD14] presents an comprehensive solution to the problems that occurs when the vehicle-density gets high. This scalable data dissemination solution combines several techniques at different layers, in order to effectively solve the scalability issue of these scenarios. Some of these combined techniques are transmit power control, adaptive beaconing, a new frame structure and a variation of proposed forwarding algorithms.

The ability to store-cache-forward DENMs has the potential to increase the transmission range of a DENM, but could also very easily create broadcast storms. In [WTP$^+$07] are several broadcast storm mitigation techniques proposed. All of which are computationally efficient and only requires minor computations. As both the CAM and DENMs are sent on the same channel, is it important to take both of them into account when evaluating them individually. A paper by Anette Bohm et al. [BJU13] focuses on the co-existing of both these types of messages. The paper thoroughly emphasizes the importance of keeping any unnecessary overhead traffic at a absolute minimum. It also discusses how the choice of priority classes influences the performance for both messages in a simulated platooning scenario. A experimental evaluation of CAM and DENM messaging services using real-world hardware is presented by José Santa et al. in [SPMS14]. The presented results clearly indicates how surrounding buildings, which are blocking the line of sight, may impact the delivery rate for the messages.

1.4 Methodology

This thesis consists of two main parts, a literature study and a simulation part. The literature study includes discussing the technical details, as well as the ability to understand the related works and the status of the standardization process. The studied literature includes research papers, ETSI standards and a selection of state-of-the art articles. Interaction with companies and persons involved in ITS research has also been an essential aspect.

The utilized simulation methodology is inspired by the presented methodology in [Ulg94]. The article describes and defines eight major phases for the simulation methodology. These are phases concerning building, verifying and validating simulation models, as well as documenting and presenting the results. The main phases of this thesis have been the following:

1. Identify and define the thesis's objectives and scope.
2. Understand the related work and the state-of-the-art.
3. Describe the necessary technical background information relevant for the evaluation.
4. Gain knowledge of network and VANET simulations and chose a simulation framework.
5. Understand the simulation framework and perform necessary modifications.
6. Test the simulations models and validate the utilized models and results. Make necessary enhancements.
7. Conduct the different simulations and present the results
8. Evaluate the simulated results and discuss the various features.

1.5 Scope

The objective of this paper is to provide an introduction to ETSI TC ITS standardization and evaluate the performance of the two standardized V2V/V2I messages. The evaluation covers both the advantages and disadvantages of the various components, as well as their implications and possible improvements. The analysis is based both on simulations of different scenarios and simple observations. A discussion of results made by others is also included. Privacy and security concerns of the messages are not part of the scope of this thesis.

1.6 Outline

This thesis is structured as follows:

- Chapter 2 contains background information of the ETSI TC ITS architecture as well as detailed information for the two standardized V2V/V2I messages. It also contains a variety of possible enhancements proposals.
- Chapter 3 involves the parameter-values used for disseminating DENMs. The chapter includes a step-by-step review and discussion for a few DENM scenarios.
- The performance of the messages is evaluated in chapter 4. The first part includes an overview of the system requirements and simulation tools. The rest of the chapter contains the simulation, its results and a discussion of the various features.
- Chapter 5 contains the conclusion of the thesis and potential future work is proposed.

Chapter 2

V2V and V2I Messages

2.1 Introduction

In this chapter we first present a brief overview of ETSI and the GeoNetworking protocol. The two primary types of V2V and V2I messages will then be described in detail. Finally, we look at some proposed enhancement techniques.

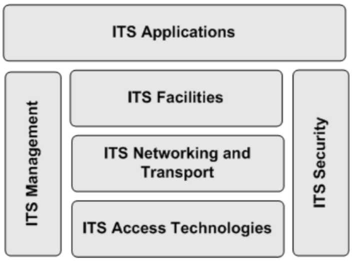


Figure 2.1: The reference protocol stack for an ITS station [Eur14d].

2.1.1 ETSI Protocol Stack

The general protocol stack for an ITS station (ITS-S) is shown in Figure 2.1. The two vertical protocol layers are the ITS Management and ITS Security layers. These layers are responsible for exchanging information utilized for configuration and security tasks across vertical layers. The ITS Access Technologies layer covers the related protocols for the physical and data link layer. The ITS Networking and Transport layer consist of among others the GeoNetworking protocol and the Basic Transport Protocol (BTP). These are thoroughly described in [Eur14e] and [Eur14f]. The ITS Facilities layer provides several sub-functions for the surrounding layers, including message generation which will described in depth in section 2.2.2 and 2.3.2. On top of the reference stack are the ITS Applications. These are the traffic safety, traffic efficiency and infotainment applications that utilizes the information from the underlying layers.

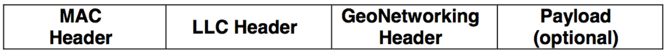


Figure 2.2: An ETSI GeoNetworking packet seen by MAC protocol [Eur14e].

Figure 2.3: The GeoNetworking header structure [Eur14e].

2.1.2 ETSI GeoNetworking Packet

Figure 2.2 shows an unsecured ETSI GeoNetworking packet seen by the MAC protocol. The payload is denoted as optional due to the beacons, which does not contain a payload. The GeoNetworking header (Figure 2.3) consists of a Basic, Common and optional Extended header. The Basic and Common header includes fields used for forwarding decisions, e.g. hop limit and traffic class. The information in the Extended header depends on the type of packet. A variation of headers are defined for the GeoNetworking protocol, such as the Beacon header (32 bytes) and the GeoUnicast header (60 bytes). The header utilized for CAM is the Single-Hop Broadcast (SHB), shown in Figure 2.4. While DENM uses the GeoBroadcast header (Figure 2.5). All the specified GeoNetworking headers can be studied in detail in [Eur14e].

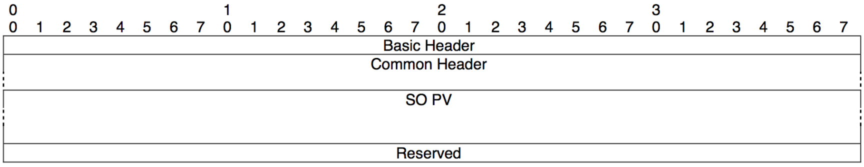


Figure 2.4: The format of the SHB header (32 bytes) [Eur14e].

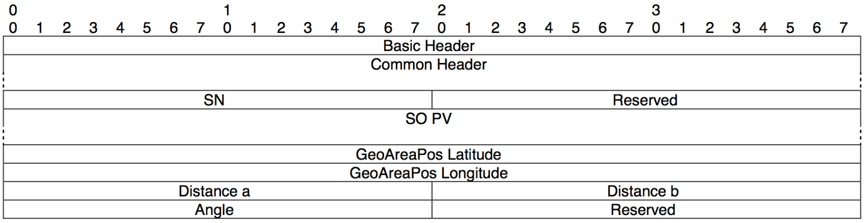


Figure 2.5: The format of the GeoBroadcast header (60 bytes) [Eur14e].

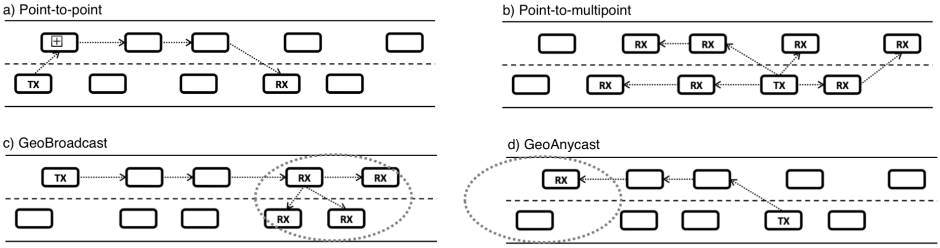


Figure 2.6: The specified ETSI TC ITS communication scenarios [Sjo13].

2.1.3 Communication Scenarios

The different communications scenarios defined for ETSI TC ITS are illustrated in Figure 2.6. GeoUnicast (Point-to-Point) allows an ITS-S to send messages to another specific ITS-S based on the GeoNetworking address. This feature requires a flooded location service request in order to get the requested ITS-S's geographical location. This feature is further discussed in [Tub14]. A GeoBroadcast will broadcast messages to all ITS-Ss in a defined area, whereas GeoAnycast packets will only be sent to one arbitrary ITS-S in the area. No specific applications are specified for GeoAnycast, and it is not discussed any further in this thesis. The two primary standardized messages (CAM and DENM) are only specified for V2V, V2I and I2V communication. The communication between the roadside stations (RSUs) and other ITS infrastructure, I2I/R2R, is outside of the scope of this evaluation. A more detailed overview of the GeoNetworking protocol and the ITS reference protocol stack is presented in [Tub14].

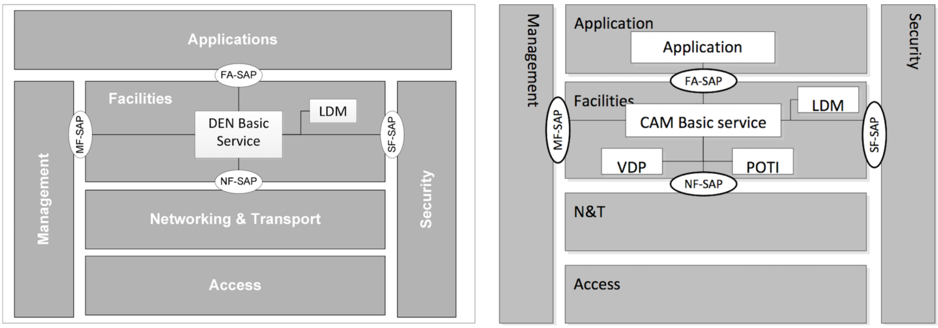


Figure 2.7: The DEN and CAM basic service at the facility layer [Eur14a] [Eur14b].

2.2 Cooperative Awareness Message (CAM)

The two V2V/V2I messages are handled and maintained by two basic services, referred to as the Cooperative Awareness basic service and the Decentralized Environment Notification basic service. These are located in the facility layer and are available for the ITS applications through the FA-SAP interface, as illustrated in Figure 2.7.

A CAM is periodically transmitted from every ITS-S to all single-hop neighbors with a specific frequency. The CAMs are utilized to ensure awareness of the surrounding ITS-Ss and maintaining the neighboring tables. The ITS neighbors geographical location, movement and direction are some of the information that is disseminated in these periodic messages.

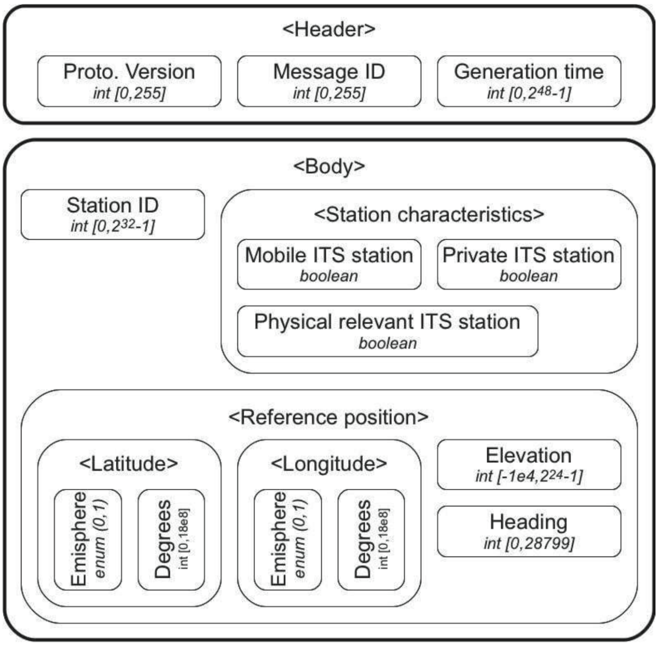


Figure 2.8: A simplified CAM message structure [SPMS13].

2.2.1 Format

A simplified message structure of the CAM is shown in Figure 2.8. Information concerning the latitude, longitude and GeoNetworking address of the source ITS-S are all located in the SO PV (Source ITS-S Position Vector) in the header. The header information is used to update the neighbor location table, called the LocT. The LocT contains detailed information about the surrounding ITS-Ss, and is used for routing purposes. It requires frequent maintenance to ensure connectivity between the different ITS-Ss. The LocT can be further studied in [Eur14e].

The CAM payload consist of a Basic Container, High Frequency (HF) Container and several optional containers. The information in Basic Container is similar to the information stored in SO PV. The HF container contains highly dynamic information, such as heading and speed of the originating ITS-S. The information displayed in the payload (<body>) of Figure 2.8 is a combination of fields from both the Basic Container and the HF container.

Algorithm 2.1 Simplified version of the CAM message generation algorithm.

```
void CamGeneration {
    //The variables declaration and
    //updates are not shown in this example.
    //
    //T_GenCamMin = 100 ms (10 Hz).
    //T_GenCamMax = 1000 ms (1 Hz).
    //T_GenCam_dcc (Minimum time interval set by DCC).
    //N_GenCam = 3 (Default and maximum value of the "dynamics").
    //D_Threshold = 4 meters.
    //H_Threshold = 4 degrees.
    //S_Threshold = 0,5 m/s.

    T_GenCam_dcc = dccAlgorithm(T_GenCamMin,T_GenCamMax)
    if (time - lastCamTime >= T_GenCam_dcc) then
        if  (distance(pos,lastPos) >= D_Threeshold) or
            (heading(head,lastHead) >= H_Threeshold) or
            (speed(spe,lastSpeed) >= S_Threeshold) then
                sendCam(time,pos,head,spe)
        if  (time - lastCamTime >= T_GenCamMax) then
                for (int i = 0; i < N_GenCam; i++)
                    sendCam(time,pos,head,spe)
}
```

2.2.2 Dissemination

The CAMs are as mentioned generated and maintained by the CAM Basic Service at the facility layer. Every CAM is transmitted with a time-stamp and an unique identifier. The identifier makes it easy to maintain the unique CAM entry for each of the neighboring ITS-Ss in the LDM. The upper and lower CAM generation limits are 10 and 1 Hz respectively. Within these limits and dependent of the originating ITS-Ss dynamics and channel congestion status, should the CAM be generated. Algorithm 2.1 shows a simplified version of the CAM message generation algorithm based on the ETSI standard [Eur14a]. The algorithm displays the required conditions that must be fulfilled in order to trigger a CAM message. The Decentralized Congestion Control (DCC) algorithm described in [Eur12], determines the minimum time interval between two subsequent CAM generations based on the channel conditions. The dynamics parameter is used to increase the probability of CAM reception. This is ensured by triggering a certain number of repetitive CAMs, based on the dynamical environmental conditions. The fact that the rate of CAMs are dynamically determined based on the surroundings will ensure a better overall performance than a static approach would. Exactly how much the improvement will be is difficult to quantify, as it will much depend on the efficiency of the DCC algorithm and the defined thresholds.

2.3 Decentralized Environmental Notification Messages (DENM)

The DENMs are asynchronous event-triggered messages that are broadcasted with the objective of alerting surrounding ITS-Ss about occurring hazards. DENMs requires multi-hop communication and may thus be forwarded outside the originating ITS-S's single-hop transmission range. The content of a DENM is defined as "information related to an event that has potential impact on road safety and traffic condition". An event is described by attributes such as event type, location, detection time and the duration of the event. The ITS-S which detect the event and triggers the DENM, is referred to as the originating ITS-S. The DENMs are triggered by the ITS applications in the vehicles. The ITS applications may utilize information from the Local Dynamic Map (LDM) to detect an event, or information retrieved directly from the vehicle's sensors. The LDM is described in Section 2.4.

2.3.1 Format

A simplified version of the DENM message structure is illustrated in Figure 2.9. The payload of the DENM typically contains three containers plus an additional ala-carte container. These are the Management, Situation and Location containers. These are respectively referred to as the Decentralized situation management, Decentralized situation and Decentralized situation location containers in Figure 2.9. The last two are optional while the Management container is mandatory. The ala-carte container contains additional information related to specific events and is not discussed further in this document. The Management container contains information concerning the DENM management of the triggered DENM. Parameters such as *actionID*, *relevanceDistance*, *relevanceTrafficDirection* and *detectionTime* are some of the key elements in this container. These are important parameters which are used to optimize the DENM dissemination. The Situation container specifies the type of the detected event. A list of the event-types described by cause and sub cause codes are

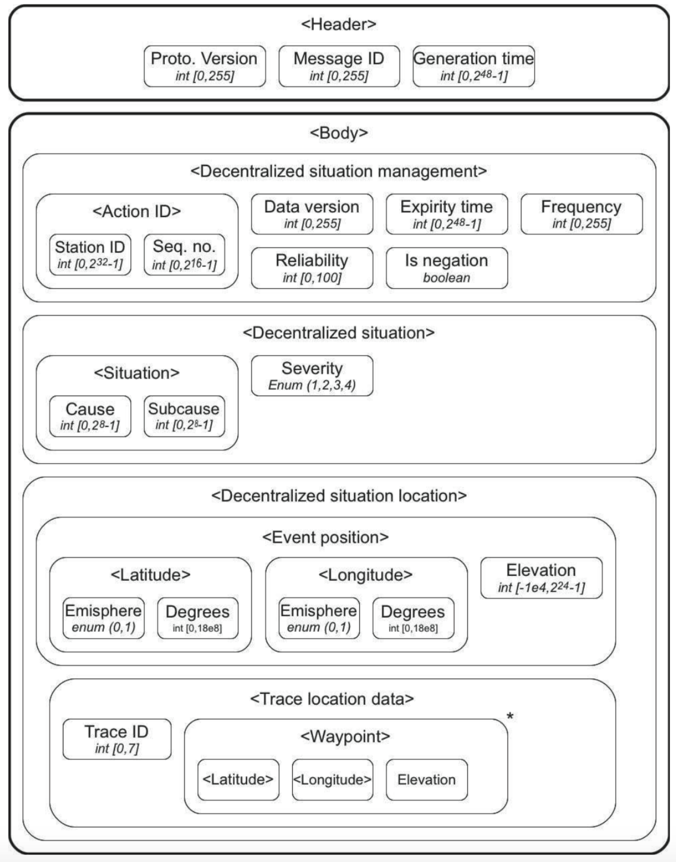


Figure 2.9: The DENM message structure [SPMS13].

given in [TIS]. The container also describes the information quality of the DENM, the event history plus the severity of the event. The Location container on the other hand, describes the location and relevant trace information for the detected event.

2.3.2 Dissemination

In this section we will the explain the different components and procedures for DENM dissemination.

Event Identification

Unlike a CAM, refers a DENM to an event rather than an unique ITS-S identifier. The *actionID* is the parameter used to identify and distinguish the different events. Every time a new DENM is triggered by an ITS application, a new unique *actionID* is assigned to the event. The *actionID* is a combination of the originating ITS-S's ID and a sequence number, as shown in Figure 2.9. This method ensures that DENMs, which are triggered by different ITS-Ss for the same event, will get different *actionIDs*. Every received DENM with an unique *actionID* will thereby get a separate entry in the LDM. The ITS-S's ID is assigned on a temporal basis due to privacy services [Eur14b]. A valid and up-to-date station ID is therefore required whenever a new *actionID* is generated.

In situations where several ITS-Ss detects the same event, might the LDM's contain several entries for the same events. This duplicate information decreases the efficiency of the LDM and could affect the overall performance. Performance issues and possible solutions involving DENM duplication are discussed in Section 4.4.4.

DENM Life Cycle

DENM trigger A DENM trigger is denoted as the generation and transmission process of a new DENM. When the DEN basic service receives an *AppDENM_trigger* from one of its ITS applications, it triggers a DENM of type New DENM. This New DENM contains the *actionID*, event type, time and other attributes describing the event.

DENM update If the originating ITS-S notices a change in the event after the DENM trigger, the ITS application may send an *AppDENM_update* to the FA-SAP interface with updated information. This will trigger a DENM of type Update DENM from the DEN basic service. The *referenceTime* parameter is utilized to identify the different Update DENMs for an identical *actionID*. The parameter refers to the time when the DEN basic service triggered the Update DENM. The *referenceTime* is updated for every DENM update, while the *actionID* remains unchanged.

DENM Repetition To ensure that every new ITS-S which is entering a DENM's destination area after the first DENM is triggered, also receives the DENM, may a DENM be repeated by the originating ITS-S. The repetition functionality only applies to the originating ITS-S. The repetition feature also increases the probability that an ITS-S within communication range will receive the DENM. The repetition interval is pre-defined and is managed by the DEN basic service. Both the *repetitionInterval* and *repetitionDuration* parameters are set by the ITS application which triggered the DENM. If none of these parameters are set, the DENM should not be repeated. Only the most recent updated DENM for a specific *actionID* should be repeated.

DENM Termination The DENMs can be terminated by the originator, but also by other ITS-Ss. Based on the *repetitionDuration* or *validityDuration* parameters, may the originator requests the termination of an event, and thereby trigger a DENM

Cancellation message. The *validityDuration* parameter indicates the validity time for a DENM, starting from the *detectionTime*. The *validityDuration* is set by the ITS application triggering the DENM. The default value of 600 seconds is utilized when the parameter is not set. The *validityDuration* should not be confused with the validity for the cached DENMs in Keepalive Forwarding (KAF), which is referred to as *T_F_Validity*. The *T_F_Validity* only indicates how long the DENM should be cached with the purpose of forwarding.

The *actionID* for the DENM shall be identical as long as the ITS-S's ID is unchanged. In situations where an arbitrary ITS-S passes the location of an indicated event during its validity period, and detects that the event no longer is relevant, may the ITS application trigger an *AppDENM_termination*. This request is received at the DEN basic service which then generates a negation DENM with the same *actionID*. If one of these DENM types are received and verified as trustworthy, will the DEN basic service notify the ITS applications of the event's termination.

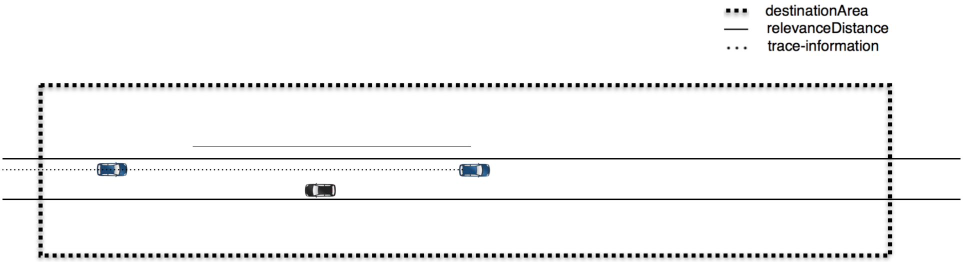


Figure 2.10: An illustration of the various components used for DENM location referencing.

Location Referencing

The ITS applications that detects and triggers the DENMs must precisely describe the events in an effective manner. The description of the geographical location of the event is one important element. The geographical areas defined for the DENMs are referred to as the *destinationArea* and the relevance area. Figure 2.10 illustrates the various components used for location referencing. These are further explained in the next paragraphs.

The *destinationArea*, located in the GeoNetworking header, is utilized for DENM dissemination purposes by the network & transport (N & T) layer. A completed DENM ready for transmission is passed from the DEN basic service at the facility layer to the N & T layer. The *destinationArea* is utilized by the recipients N & T layer, to determine what action to take upon reception. Recipients being part of the *destinationArea*, will pass the packet along to the facility layer. The ITS application will then perform a relevance check of the event, and possible decide to alert the driver. If the recipient is not part of the *destinationArea*, the packet will be forwarded towards the target area as a GeoUnicast packet. This forwarding paradigm is referred to as line forwarding.

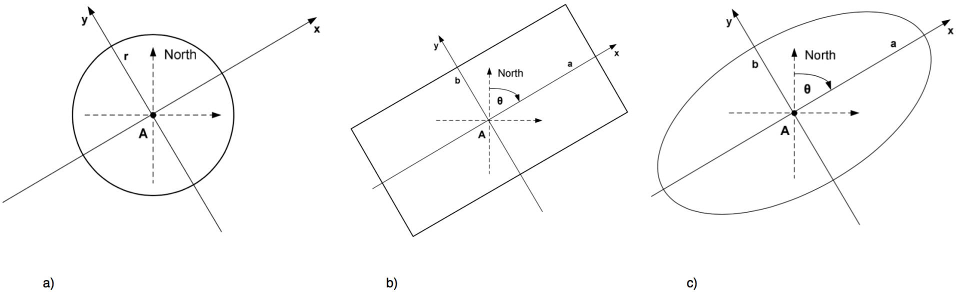


Figure 2.11: Overview of the geometric shapes that defines the *destinationArea* [Eur14b]. a) Circular area. b) Rectangular area. c) Elliptical area.

The *destinationArea* is described by geographical points and distances which constitutes the shape of the destination area. Figure 2.11 shows the defined geographical shapes which specifies the *destinationArea*. A circular area is described by the centre point A and the radius r of the circle. If the specific area is rectangular or elliptical shaped, it is described by a centre point A, the distance from A to the short side a, the distance from A to the long side b and the azimuth angle of the long side of the rectangle.

The DENMs should ideally be propagated to as many ITS-Ss as possible within the relevance area of the event. This includes every vehicle entering the relevance area as long as the DENM is valid, also those entering the relevance area after the originator is outside of communication range. The relevance area is determined by the ITS-S applications, and is unlike the *destinationArea* not used for forwarding purposes. Instead, it is utilized by the vehicles ITS applications to determine whether a DENM passed from the N & T layer is relevant or not. The relevance area and *destinationArea* are not necessary identical, though they have strong dependencies of each other. It is essential that *destinationArea* at a minimum covers the entire defined relevance area of the event, to ensure that the DENM is passed to the facility layer.

The *relevanceDistance* and the *relevanceTrafficDirection* parameters, together with the events geographical location (latitude and longitude) are used to describe the relevance area for the event. The value of the *relevanceTrafficDirection* should depend on the surroundings and standard of the road. In more rural areas with narrow roads and low vehicle-density, should the traffic direction be set to both directions. Arguments for this statement are both the "extra" idle capacity of the network in such scenarios, in addition to the likelihood that these events will affect both driving directions. For typical high-way scenarios with high vehicle-densities and physically separated lanes in each directions, should the *relevanceTrafficDirection* be utilized in order to reduce the amount of overhead traffic.

In addition to the relevance area, does the DENM also provide location referencing information called traces. These traces represents the directions towards the applicable event. The level of detail in the traces depends on the ITS applications, and the number of described intersections and trace lengths will differ. These traces might be helpful to e.g. redirect traffic if various road-blocking events are detected.

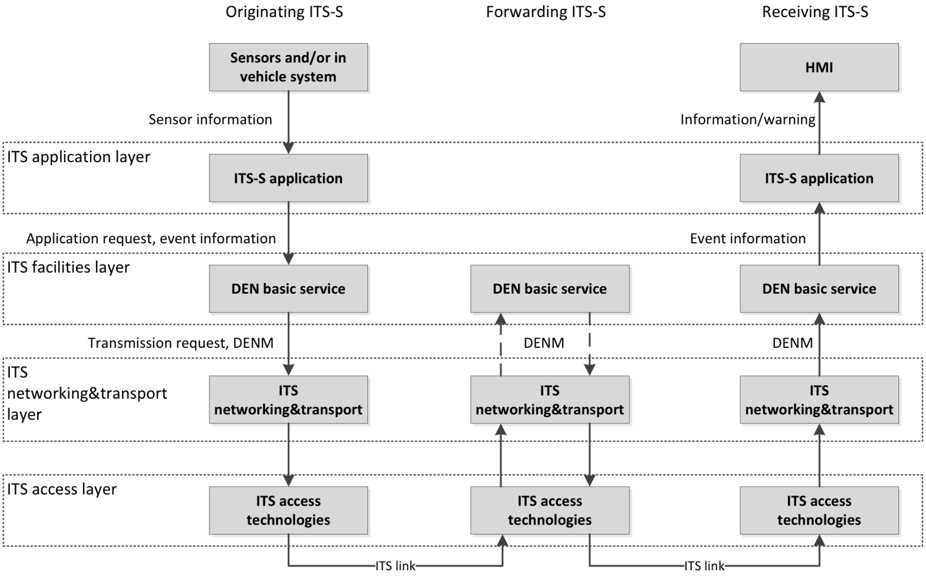


Figure 2.12: The data flow for a DENM being forwarded by an intermediate ITS-S. [Eur14b].

2.3.3 DENM Forwarding

The DENMs require multi-hop communication and may be forwarded by intermediate ITS-Ss. Two types of forwarding are defined for DENM forwarding, Packet Centric Forwarding (PCF) and KeepAlive Forwarding (KAF). Figure 2.12 shows the data flow for a multi-hop DENM forwarding scenario. Both forwarding schemes are performed at the network & transport layer. If the ITS-S's network & transport layer doesn't support the GeoNetworking protocol, may the forwarding be conducted at the facility layer. This is illustrated by the dotted lines in the figure.

PCF or on-the-fly forwarding, is utilized unless KAF is triggered by the ITS application or the DEN basic service. KAF, also referred to as Store-Cache-Forwarding (SCF), is another forwarding paradigm where the received DENMs are cached with the purpose of repetitive or deferred re-transmissions. KAF allows ITS-Ss to store DENMs in situations where no other ITS-Ss are within communication range at the time the original DENM was broadcasted. To be able to store the desired DENM, must the ITS-S be within the received DENM's *destinationArea*. It is also required that the DENM is valid, e.g. not cancelled nor negated by any ITS-S.

Since the enabling of KAF is dependent on the ITS applications implementation, is it difficult to predict the average rate of applications which will enable KAF. For some events such as emergency brake light or other quickly passing hazards, is it fair to assume that KAF will not be enabled. In situations where KAF is enabled for a DENM, might the DEN basic service deactivate the functionality itself. This could be to ease the load on the network to avoid congestion. The characteristics and implications of KAF are further discussed Chapter 3 & 4.

DENM Forwarding Algorithms

Three different GeoBroadcasting/DENM forwarding algorithms are defined in [Eur14e]. The value of the GeoNetworking protocol constant *itsGnGeoBroadcastForwardingAlgorithm*, decides the specific algorithm. The algorithms returns the link layer (LL) address of the next hop node. In this section we will examine the properties and pros and cons of these algorithms. The main focus will be the CBF algorithm.

Simple GeoBroadcast forwarding algorithm with line forwarding
A simplified version of the algorithm is shown in Algorithm 2.2. The algorithm will re-broadcast a successfully received DENM if the receiver is located in the *destinationArea* for the DENM. This process will continue until the receiver is outside the *destinationArea*, or until the packet is no longer considered valid (exceeded maximum hop count). If the ITS-S is not part of the *destinationArea* for the DENM, it uses the Greedy Forwarding (GF) algorithm to return the LL address of the next-hop node towards the destination. The GF algorithm is practicing the so-called Most Forward within Radius (MFR) policy. This involves selecting the neighbor with the shortest geographical distance to the destination, also referred to as the neighbor with the maximum forwarding progress. The algorithm compares the packet's destination position vector with each of the position vectors of the ITS-S's neighbors. This position vector information is stored in the neighboring table (LocT). This procedure is repeated until the neighbor with the most forwarding progress is chosen as the forwarder. If the GF algorithm fails, the packet is buffered. This might occur if

Algorithm 2.2 Simplified version of the Simple GeoBroadcast forwarding algorithm with line forwarding.

```
simpleAlgorithm {
    //The simpleAlgorithm returns the next-hop link
    //layer address used to forward the DENM.
    //greedy() is the algorithm used to return the next
    //hop address towards the target area when the ITS-S
    //is not part of the destination Area.

    Packet packet = listen()

    if (insideDestinationArea(packet))
        nexthop_linklayer_address = broadcast_address
        return nexthop_linklayer_address
    else
        nexthop_linklayer_address = greedy(targetArea)
        return nexthop_linklayer_address

}
```

the selected forwarder is no longer within communication range. The algorithm might also select non-optimal forwarding nodes due to asymmetric properties of the communication medium. This behaviour is also a concern for the algorithms presented next. The GF algorithm is further explained in [Eur14e].

The information that is transmitted in the ITS should have high reliability and the delay of the messages should be kept at a minimum. The flooding architecture of the Simple GeoBroadcast forwarding algorithm has proven efficient for these objectives for networks with a relatively low node-density. However, for networks with a higher node-density, the flooding and duplicate traffic may lead to major problems which could decrease the overall performance substantially. Precisely because of this scalability issue should preferably other forwarding algorithms be utilized in these situations. The algorithm is simulated and further discussed in Chapter 4.

Contention-based forwarding (CBF) algorithm for GeoBroadcast

The Contention-based forwarding (CBF) algorithm is a receiver-based approach, which allows the recipients to independently take part in the forwarding selection procedure. For a transmitted DENM utilizing the CBF algorithm, will every neighbor which receives the DENM, process and buffer it in their own CBF buffer. Simultaneously will the node start a timer for the packet with a specific timeout value, which is proportional to the distance between its local position and the position of the sender

Algorithm 2.3 Simplified version of the Contention-based forwarding (CBF) algorithm.

```
cbfAlgorithm {
    //The CBF algorithm return the link layer
    //address of the next-hop forwarder.
    //return value of -1 indicates that the packet is discarded.
    //return value of 0 indicates that the packet is buffered.

    Packet packet = listen()

    if (packetInBuffer(packet))     //indicates a duplicate packet
        removeFromBuffer(packet)    //meaning that another node has
        stopTimer(packet)           //already re-broadcasted.
        discard(packet)
        return -1
    else
        if (insideDetinationArea(packet))
            addToBuffer(packet)
            startTimer(packet)
            return 0
        else
            nexthop_linklayer_address = greedy(targetArea)
            return nexthop_linklayer_address

    if (timerExpired(packet))       //timer expires if no other
        fetchFromBuffer(packet)     //has re-broadcasted the message
        nexthop_linklayer_address = broadcast_address
        return nexthop_linklayer_address
}
```

or previous forwarder. This ensures that the node with the maximum forwarding process (closest to the destination) will get the smallest timeout value. This will be the node within single-hop communication range with the longest distance from the source or previous forwarder. As the node's timer expires it will re-broadcast the DENM and then at the same time implicit inform the neighboring nodes to not forward the same DENM. The neighboring nodes which receives this duplicate DENM will then stop their timers and remove the DENM from their CBF buffer. If KAF is enabled will the DENM remain in the ITS-S's cache regardless of the outcome of the CBF forwarder election. Algorithm 2.3 shows a simplified version of the algorithm.

The main benefit of this algorithm is the good performance achieved at much lower cost than the simple flooding technique. The algorithm greatly reduces the amount of duplicate traffic compared to simple flooding. The algorithm does however require a certain optimal node-density to perform well. This will be described in next paragraphs. The additional latency caused by usage of the CBF timer is one of the other main drawbacks of the algorithm. The design of the CBF is based on three assumptions which explains some of the fundamental weaknesses of the forwarding algorithm. These assumptions are uniform vehicular topology, non-fading transmission channels and homogeneous communication capabilities [HBHF13]. Real-life traffic topologies does not comply well these simplifications, causing non-optimal strategies in specific topologies. We will now have a look at some of these scenarios.

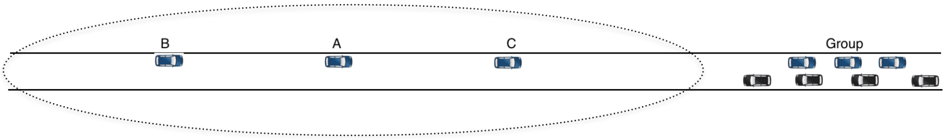


Figure 2.13: Country road with varying vehicle-density.

Country road with varying vehicle-density

In this example we examine the topology sketched in Figure 2.13. The dotted ellipse indicates vehicle A's single-hop communication range. The distances between the vehicles in the sketches are only used for visualization purposes and does not reflected the intended scenario. Both vehicle B and vehicle C are within single-hop communication range of vehicle A, but none of the vehicles referred to as "Group".

Vehicle A detects an event and broadcasts a DENM using the CBF algorithm. We assume a *destinationArea* that covers all vehicles in the sketch. Due to nature of the event is neither KAF nor any repetition triggered by the ITS application. Vehicle B and C receives the DENM and starts the CBF procedure as described in Algorithm 2.3. Due to the fact that vehicle B has a slightly longer relative distance to vehicle A than vehicle C has, will vehicle B's CBF timer expire first. When the timer expires, vehicle B re-broadcasts the DENM. The re-broadcasted DENM from vehicle B is successfully delivered to vehicle A and C. When vehicle C receives this duplicate DENM, it stops its timer and removes it from its CBF buffer according to the CBF procedure. The consequence of this unfortunate forwarding is that none of the vehicles which are referred to as "Group" will receive the DENM. These will then potentially be exposed to the event detected by vehicle A. However, if vehicle C had become the CBF forwarder would most likely all of the vehicles in the group received the DENM. This example underlines some of the fundamental weaknesses of the algorithm, caused by the assumption of uniform vehicular topology. For instance, if the inter-vehicle spacing in the scenario had been constant, is it fair to assume that all vehicles would have received the DENM.

Figure 2.14: Intersection with varying vehicle-density.

Urban intersection

The discussed scenario is an urban intersection with different node-densities, as sketched in Figure 2.14. The intersection is located within an area with tall buildings that blocks the line of sight for the vehicles transmitters. The velocity of the vehicles are approximately 40 km/h. The main road with the highest vehicle-density is the horizontal road. Vehicle A detects a hazard and triggers a DENM. CBF is chosen by the ITS application as the forwarding algorithm and the *destinationArea* covers the entire sketched area. Neither KAF nor any repetition is enabled for the DENM. Due to the tall surrounding buildings is the DENM only received by a few of the vehicles located near the intersection. This is only the 6 vehicles including vehicle B, which are located straight north for vehicle A. Vehicle B is the one with the most forwarding potential and therefore start a CBF timer with the shortest timeout-value. As the timer expires it re-broadcasts the DENM and implicitly informs the other 5 vehicles to cancel their own re-broadcasting procedure. No new vehicles in the horizontal road receives the re-broadcasted DENM from vehicle B. This means that the DENM will only continue to "live" in the northern direction while none of the vehicles in the other directions are informed about the hazard. This unfavorable forwarding eliminates some of the important benefits of the multi-hop feature, e.g.

relay messages around buildings. In contrast, if a probabilistic forwarding algorithm was utilized instead, would the DENM in all probability be successfully delivered in all directions. The CBF algorithm will be further discussed in Section 4.4.4.

Advanced GeoBroadcast forwarding algorithm

The Advanced forwarding algorithm for GeoBroadcast contains mechanisms from both the GF and CBF algorithm. The CBF algorithm is also modified in order to the improve its efficiency. The Advanced forwarding algorithm for GeoBroadcast is designed based on the following mechanisms:

- CBF's ability to deal with varying failure rates caused by vehicle mobility, fading and collisions on the wireless medium.
- Choose a specific next-hop forwarder already at the sender, to reduce the additional delay of the CBF algorithm. This causes the next-hop forwarder to immediately forward the packet upon reception.
- Increase the CBF efficiency by only picking forwarders from within a defined sector of the forwarding area. The sector is described by an angle and the maximum transmission range.
- A controlled packet retransmission scheme within the target area, to improve the reliability of the forwarding.

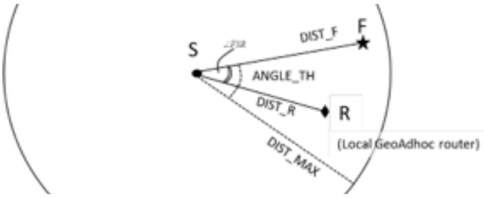


Figure 2.15: The sectoral contention area [Eur14e].

In the Advanced forwarding algorithm for GeoBroadcast, the source node selects the forwarder with the shortest distance to the destination from its location table. It also enters CBF mode, by storing the packet in the CBF buffer and starting a timer. As the chosen node receives the packet, it checks whether it is consider as part of the destination area of the packet. If this is the case, it picks a forwarder in the same manner as the source node. Otherwise will the node check whether the packet is already stored in the CBF buffer. The packet will be discarded if the recipient is part of the sectoral area or if the packet is received more times than a defined threshold value (MAX_COUNTER). A simplified version of the algorithm is shown

Algorithm 2.4 Simplified version of the Advanced GeoBroadcast forwarding algorithm.

```
advancedForwardingAlgorithm {
    //The advanced algorithm return the link layer
    //address of the next-hop forwarder.
    //return value of -1 indicates that the packet is discarded.
    //return value of 0 indicates that the packet is buffered.

    Packet packet = listen()

    if (insideDestinationArea(packet))
        if (packetInBuffer(packet))                     //old packet
            if (inBufferCounter(packet) > MAX_COUNTER)
                removeFromBuffer(packet)
                stopTimer(packet)
                discard(packet)
                return -1
            else
                if (insideSectorialArea(packet))
                    removeFromBuffer(packet)
                    stopTimer(packet)
                    discard(packet)
                    return -1
                else
                    increaseCounter(packet)
                    startTimer(packet)
                    return 0
        else                                            //new packet
            addToBuffer(packet)
            packet.Counter(1)
            nexthop_linklayer_address = greedy(targetArea)
            startTimer(packet)
            return nexthop_linklayer_address
    else
        nexthop_linklayer_address = greedy(targetArea)
        return nexthop_linklayer_address


    if (timerExpired(packet))       //timer expires if no other
        fetchFromBuffer(packet)     //has re-broadcasted the message
        nexthop_linklayer_address = broadcast_address
        return nexthop_linklayer_address
}
```

in Algorithm 2.4. To determine whether or not the receiver is considered as part of the sectoral area, are the following parameters utilized; the distance between the local node's position and the sender's position (DIST_R), distance between the forwarder position and the sender's position (DIST_F), theoretical maximum communication range (DIST_MAX) and the angle FSR between the forwarder, sender and the local node. Figure 2.15 shows the definition of the sectoral area. The disadvantages of this relatively complex algorithm is the extra computational effort required to calculate all the necessary parameters. Some additional delay is also introduced by the timers. The advantages of the algorithm are stated in the design objectives.

2.4 Local Dynamic Map (LDM)

The information from the CAMs and DENMs are also used to update the Local Dynamic Map (LDM). The LDM is located at the facility layer, shown in Figure 2.7. The LDM contains information received by on-board sensors, other vehicles, traffic centres and other ITS infrastructure entities. This could be transient information such as speed limits and weather information, but also highly dynamic information from CAMs or DENMs. The information in the LDM is accessible for the ITS applications, and is used to potentially trigger DENMs. A detailed description of the LDM is given in [Eur11].

2.5 Performance Enhancements Proposals

In this section we discuss several enhancement techniques with the objective of improving the performance of the V2V/V2I messages. These proposals will require implementation at different layers of the ETSI protocol stack. The specific details concerning the implementation of the suggested enhancements is outside the scope of this thesis.

2.5.1 Alternative DENM Forwarding Strategies

First we describe and evaluate several broadcasting algorithms proposed by various research papers, applicable for DENM forwarding. These are both new algorithms designed for VANETs as well as other well-established broadcasting algorithms such as probabilistic forwarding.

Two-mode Opportunistic Dissemination

The authors of [ALRK$^+$10] introduces a broadcasting algorithm designed to allow messages to remain alive in the relevance area, as long as it is relevant for new vehicles approaching. This is performed by combining the two explained forwarding schemes, PCF and KAF. The denotation used by the authors is Periodical mode

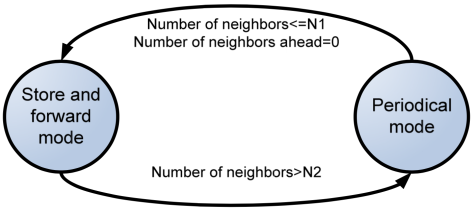
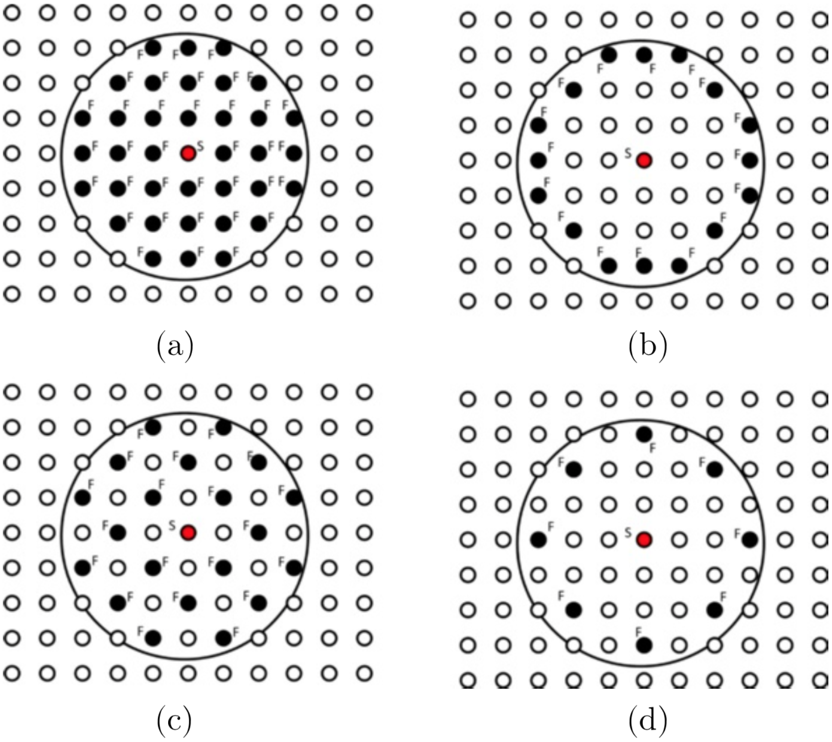


Figure 2.16: The two-mode Opportunistic dissemination [ALRK+10].

and Store and Forward mode. The idea is that the vehicles will switch between the two modes based on the number of neighbors. This is illustrated in Figure 2.16. The vehicles start in periodical mode and switches to store and forward mode if the number of neighbors drops below a specified threshold N1. If the number of neighbors increases and reaches another threshold named N2, the vehicle switches back to periodical mode. The number of neighbors is easily available through the neighboring tables, which lists all one-hop neighbors learned through exchanging CAMs. The opportunistic forwarding used for both modes is relatively similar to the CBF algorithm explained in Section 2.3.3, as it chooses forwarding nodes with the maximum forwarding progress. Figure 2.17(b) shows a typical opportunistic forwarding behaviour. The paper presents results where the store and forward mode outperforms several other forwarding schemes. However, for situations with relatively high vehicle-density, does the periodical mode perform better. The explanation is the increased packet loss caused by the high number of triggered re-transmissions when cached-and-forwarded. The presented results gives reason to believe that these two algorithms combined might give an increased performance, as both their individual advantages could be utilized.

Irresponsible

Forwarding based on probabilistic re-broadcasting is well-known and is utilized for large amount of different applications. The idea is that when a node receives a broadcast packet it retransmit it with a certain probability. The probability can be static, but also dynamically dependent of for instance the neighbor-density or relative distance from the previous sender [VCMD14]. Figure 2.17(c) illustrates a irresponsible forwarding scenario with a probability p = 0.5. A problem for these algorithms is the probability that none of the neighboring nodes will re-broadcast in networks with a low node-density. However, for scenarios with a medium node-density does this forwarding scheme perform reasonably well. For very high densities will the large amount of accompanying duplicate traffic decrease the performance.



(a) (b) (c) (d)

Figure 2.17: Illustration of the proposed forwarding strategies. (a) Simple Flooding. (b) Opportunistic forwarding. (c) Irresponsible forwarding. (d) Density-based Gossiping. [VCMD14].

Density-based Gossiping

The authors of [ALRK$^+$10] also introduces a broadcasting algorithm named Density-based Gossiping which re-broadcasts a packet with a certain probability P. The element that separates this particular algorithm from the regular probabilistic broadcasting algorithm is the calculation of the probability. The idea of the proposed algorithm is to handle both very dense and sparse situations by setting the probability dependent of the density surrounding the re-broadcasting node. The number of neighbors is similarly as the previous proposals available through CAMs. The defined thresholds and best probabilities are learned through simulations.

The algorithm is also utilizing the geographical aspect to optimize the broadcasting. As the nodes with the maximum forwarding process gets a higher probability, as illustrated in Figure 2.17d). The Density-Based Gossiping algorithm combines both these aspects and calculates the probability according to Figure 2.18. Figure 2.19

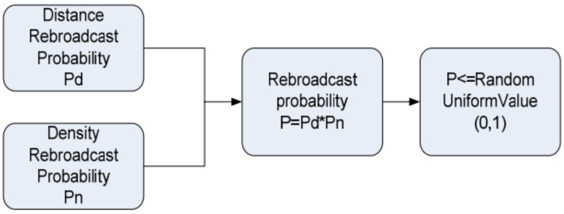


Figure 2.18: The re-broadcasting probability based on both density and distance information [ALRK+10].

illustrates the probability of reception for three broadcasting strategies in a simulated freeway scenario with a ranging number of vehicles. The results confirms that "Flooding" ensures a good performance for low/medium vehicle-densities. However as the density gets higher, is the performance of the flooding algorithm substantially decreased. Gossip 0.6, which re-broadcasts with a constant probability of 0.6, has poor performance for low vehicle-densities, but the performance quickly increases as the number of vehicles gets higher. The Density-based Gossiping algorithm on the other hand, has a probability of reception very close to 100%, regardless of the number of vehicles.

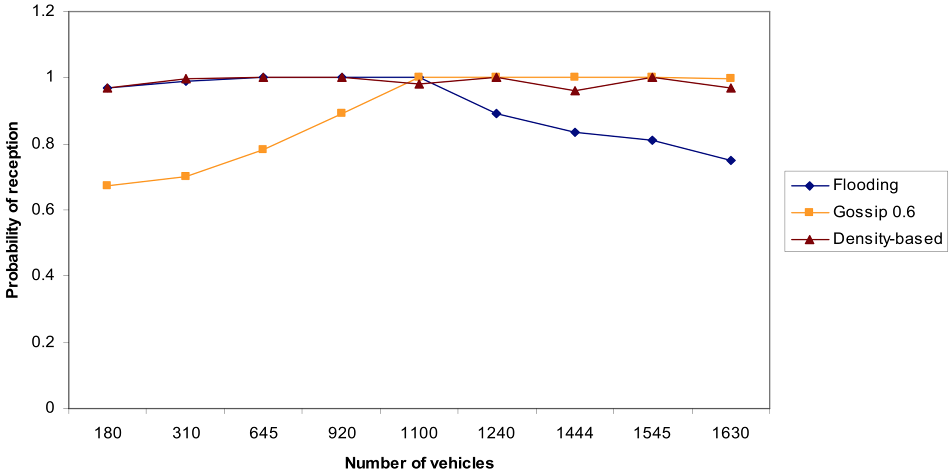
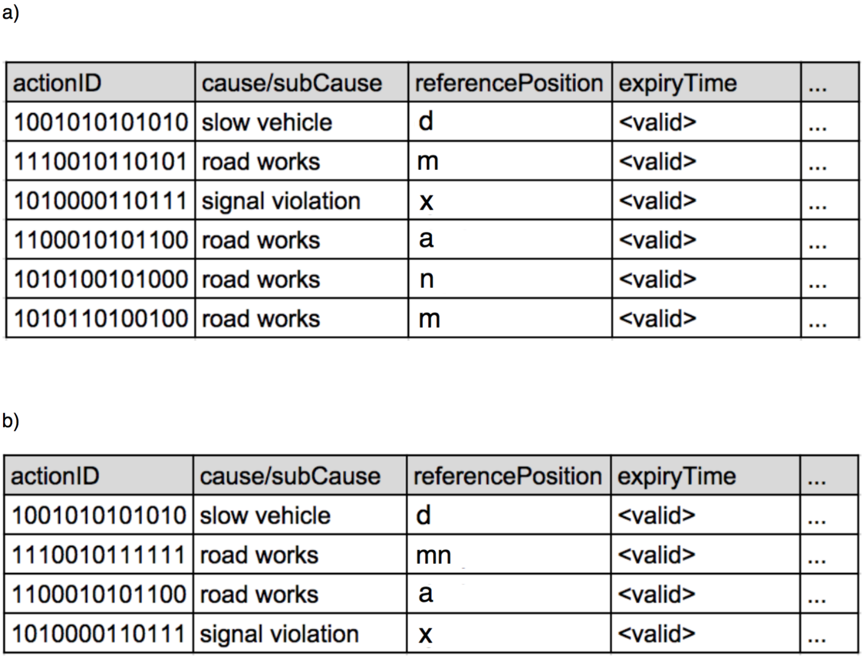


Figure 2.19: The probability of reception for the various forwarding algorithms [ALRK+10].

2.5.2 DENM Aggregation in LDM

In scenarios where several vehicles detects the same event, will each of these vehicle trigger their own DENM with an unique *actionID*. All of these unique DENMs (for the same event) will be stored separately with an own entry in each of the receiving ITS-S's LDM. This leads to a lot of duplicate information in the LDM which decreases the efficiency of the system. Events such as black ice or oil spills, are situations where a large percentage of the passing vehicle, most likely will detect the same event and trigger a DENM. Dependent of the vehicle-density, could this quickly result in hundreds of stored DENMs for the same event. To overcome this DENM duplication and inefficiency, would it be desirable to merge all the DENMs for the same events, into one separate LDM entry. The idea of this enhancement is described in depth in [MFAD11]. This type of aggregation requires intelligence which is beyond what is provided at the network & transport layer, and must be performed at the facility layer. In terms of utilizing the benefits of the aggregation with the purpose of reducing the amount of re-broadcast traffic, would it also be required that the forwarding is performed at the facility layer.



a)

actionID	cause/subCause	referencePosition	expiryTime	...
1001010101010	slow vehicle	d	<valid>	...
1110010110101	road works	m	<valid>	...
1010000110111	signal violation	x	<valid>	...
1100010101100	road works	a	<valid>	...
1010100101000	road works	n	<valid>	...
1010110100100	road works	m	<valid>	...

b)

actionID	cause/subCause	referencePosition	expiryTime	...
1001010101010	slow vehicle	d	<valid>	...
1110010111111	road works	mn	<valid>	...
1100010101100	road works	a	<valid>	...
1010000110111	signal violation	x	<valid>	...

Figure 2.20: a) A schematic of the LDM without aggregation. b) A schematic of the LDM after location and event aggregation.

Since the *actionID* in the Management container is unique due to combination of stations ID and sequence number, is it impossible to recognize duplicate events by just examining the *actionIDs*. In addition to the Management container is the DENM also described by a Situation and Location container. Two of the bytes in the Situation container referred to as the *cause* and *subCause*, describes the event-type. The possible values of these bytes are defined in [TIS]. This means that the most common events will have specific values which could be used to recognize similar events. Since there might occur several similar events within a relatively limited geographical area, could possibly an aggregation only based on the event-type lead to a removal of separate events in the LDM. In order to prevent this from happening, one may take the location information in the Location container into consideration. This will be location information such as *longitude* and *latitude*. The *heading* parameter may also be utilized to aggregate the entries. Although this could help improve the efficiency further, could this also make it harder to distinguish the events where the heading or direction is irrelevant. Example of these scenarios could be events referred to as "human problem" or "stationary vehicle", which could potentially affect both driving directions.

Parameters such as the *validityDuration*, *T_F_Validity* and trace-information, are all parameters which will deviate for the various entries. These parameters should also be considered when evaluating the proposal, as these will make the aggregation process more complex. The proposed new merged *actionIDs* will also require proper handling, as it plays an important part of the DENM life cycle described in Section 2.3.2. Due to the nature of the vehicles sensors will the different vehicles that detects an event at the same location, most probably describe the location of the event by slightly different coordinates. To distinguish between these situations and other similar events at different locations, is it necessary to have a specific threshold which applies for the events geographical location. To optimize the proposed aggregation should the threshold be dynamically dependent of the velocity and the surroundings. Proposed threshold-values or potential threshold algorithms are not discussed in this document.

Figure 2.20 shows a simplified version of LDM aggregation proposal. The illustrated parameter values are only for simplification purposes and are not according to the standard. Several other important parameters such as the *heading*, *severity* and *reliability* are left out of this simplification. In this example the entries are first sorted after event-type before they are aggregated based on location. The entries with slightly different *referencePosition* ("m", "n") are now merged into one entry ("mn") based on a threshold described in the previous paragraph. The new, merged entry will consequently get a new unique *actionID* and *referencePosition*, in addition to some other parameters. The generation of these values, as well as the possible compatibility concerns of the standardization, are not described further in this proposal.

2.5.3 CAM Size Reduction

The packet size of the CAM will most likely be in the area of 750 bytes. Omitting the trace and security information of every CAM, could reduce the CAM size to roughly 200 bytes for a proportion of the disseminated CAMs. The proposed schemes are 1/5 and 1/10. This means that only one out of every fifth or tenth CAM, contains the trace and security information. Consequently will eight or nine out of ten CAMs, have a packet size of 200 bytes. This reduction will ease some of the load on the network and possible make the conditions for DENM dissemination better. The omitted information could however affect the reliability of the messages. For instance may the reduced amount of trace-information possibly decrease the quality of the described relevance area for an upcoming event. Dependent of the CAM frequency, could also the reduction of security information lead to periods of several seconds without certificates being exchanged. This window of vulnerability could potentially be exploited, which substantially weakens the credibility of the system. This proposal is further explained and examined in Section 4.2.2.

2.5.4 Discussion

The idea of combining PCF and KAF is unquestionably a very interesting idea. This could help reducing the problems that might occur in both very spare and dense situations. In very spare scenarios will the number of neighbors in all likelihood be well below the threshold and vice versa for very dense situations. The challenges of this proposal might be the scenarios with a density close to the threshold. The defined thresholds and their efficiency will in these situations be the key factor. Situations with very dissimilar density in different directions, may potentially suffer from the proposed algorithm. This could especially be a concern for DENMs triggered by events only applicable for one traffic direction. In this situation will the algorithm most likely stay in the Periodic mode due to the large number of neighbors (in both directions). This could potentially affect the delivery rate for the vehicles in the relevant direction. The definition of the DENM's *destinationArea* and relevance area will have a large impact on the performance in these challenging situations.

The LDM aggregation will require a robust implementation in order to perform well for events with similar characteristics. Situations where several similar events occur relatively close to one another, makes it difficult to determine an aggregation threshold for the event-location. However if assume an implementation that takes the safe approach, and only aggregates the DENMs that are fairly certain, will the proposal still help reduce the amount of overhead traffic. The idea of reducing the CAM size will ease some of the load on the network. However, the removal of the security and trace-information could have consequences for the ITS applications performance or safety. This, and several of the presented enhancement proposals are simulated and further evaluated in chapter 4.

Chapter 3

DENM Dissemination Scenarios

3.1 Introduction

In this chapter we will study three different scenarios and observe how optimized parameter values could help increase the efficiency of the DENM dissemination. The parameters we will focus on in this chapter are among others the relevance area, the lifetime of the DENMs and the caching feature for the DENMs. A few simple scenarios will be explained in depth and we will examine how certain parameter values should depend on specific details of the situations. The objective of this chapter is to emphasize the importance of choosing optimal DENM parameters. We will for instance discuss how serious phenomenon such as broadcast storms will be more probable if KAF or a simple flooding algorithm is utilized in areas with very high vehicle-density. These minor non-optimal decisions could affect the delivery greatly and have severe consequences for the persons in the relevant vehicles.

The chosen parameter values are not specified in the standardization, as these will depend on the implementation of the different ITS applications. The values used in these examples are values chosen by best effort for educational purposes and may not reflect the implementation and behaviour of the ITS applications. In addition, are some of the discussed parameter values simply chosen to highlight the major influence of specific parameters.

Figure 3.1: The three presented scenarios. 1) Tyre puncture. 2) Black Ice. 3) Fallen trees.

3.2 DENM Scenarios

3.2.1 Scenario 1 - "Tyre puncture"

The imagined scenario is a freeway with three straight lanes in each direction, physically separated from the opposite direction by a concrete wall. The average speed is 100 km/h and we assume an average inter-vehicle spacing of about 2 seconds (approximately 55 meters) in each lane in both directions. The 500m transmission range radius makes approximately 110 vehicles be within single-hop communication range for an arbitrary vehicle in the scenario.

All of the sudden one of the tyres explodes for a vehicle driving in the northern direction. This is detected by the vehicle's sensors which triggers the "Tyre-puncture" ITS application. The results is a triggered DENM passed along to the network & transport layer with the suggested parameter values displayed in Table 3.1. The presented parameters are a selection of parameters from different DENM containers, described in Section 2.3.1. These are examined by the network & transport layer or by the ITS applications. The CAM frequency is decided by Algorithm 2.1. In this example we do some simplification and assume an average CAM frequency of 2 Hz.

Table 3.1: Scenario 1 - "Tyre puncture" - Alternative 1

Parameter	**Value**
destinationArea	Rectangular (a = 400m, b = 100m)
relevanceDistance	300m
relevanceTrafficDirection	North
validityDuration	30s
repetitionInterval	0
repetitionDuration	0
keepAliveForwarding	No
itsGnGeoBroadcastForwardingAlgorithm	0 (Simple)

The chosen *destinationArea* entails that approximately 87 of the 110 vehicles within single-hop communication range, will be considered as part of the *destinationArea*. These vehicles will upon reception pass the DENM along to the facility layer, as well as forward it to other surrounding ITS-Ss using the simple GeoBroadcast forwarding algorithm. The remaining 23 vehicles within communication range will trigger the explained Greedy Forwarding algorithm. The values of *relevanceDistance* and *relevanceTrafficDirection* will make roughly 16 of the 87 vehicles to consider themselves as part of the relevance area for the DENM. These 16 vehicles will store the DENM in their LDM with an own separate entry. Whether or not the driver of these vehicles are alerted, depends on the implementation details of the relevant ITS application.

The simplicity of the Simple GeoBroadcast forwarding algorithm ensures that all the 87 vehicles in the *destinationArea* will re-broadcast the DENM as long as the hop count is valid. The value of the GeoNetworking Hop limit is not part of the standardization. A vehicle which is within communication range of several vehicles which are considered part of a DENM's destination area, will due to the simple flooding receive a lot of duplicates. This leads to both unnecessary computational usage and waste of bandwidth. The decision to not enable KAF nor any repetition for the DENM, reduces any potential extra overhead traffic.

Table 3.2: Scenario 1 - "Tyre puncture" - Alternative 2

Parameter	**Value**
destinationArea	Rectangular (a = 400m, b = 100m)
relevanceDistance	400m
relevanceTrafficDirection	North
validityDuration	30s
repetitionInterval	0.1s (10 Hz)
repetitionDuration	5s
Keep-Alive Forwarding	No
itsGnGeoBroadcastForwardingAlgorithm	0 (Simple)

In Table 3.2 we have changed some of the parameter values. The major differences between the two alternatives is the repetition feature. This feature increases the probability for a hazard-exposed vehicle to receive the DENM. As the vehicles are moving, may also additional vehicles enter both the destination and relevance area. The repetition feature may ensure that also these vehicles are able to receive the DENM. This causes the originating ITS-S to transmit 50 DENMs instead of one, all of which are forwarded in the same manner as the first. Consequently will the DENM traffic load in this scenario be 50 times as large as the scenario without repetition.

3.2.2 Scenario 2 - "Black ice"

In this scenario, black ice is detected on a very crowded freeway. The freeway is the same as the previous studied scenario. Due to the weather conditions and the vehicle density is the average speed 30 km/h. The inter-vehicle spacing in each lane is 10m, which makes approximately 600 vehicles be within single-hop communication range for a arbitrary vehicle.

Situations where black ice, oil spills or similar is detected on the road, have fairly different characteristics than the previous described event. Especially considering the duration of such an event and the large probability that several vehicles will detect the same hazard. This expected behaviour should be reflected in the parameter values for the DENM. The triggered DENM for this hazard is according to [TIS], referred to as cause code 6 - "Adverse weather condition - adhesion" with "blackIceOnRoad(6): in case the low road adhesion is due to black ice on the road". The suggested parameter values are shown in Table 3.3. We assume a CAM frequency of 1 Hz.

Table 3.3: Scenario 2 - "Black ice" - Alternative 1

Parameter	**Value**
destinationArea	Rectangular (a = 2000m, b = 100m)
relevanceDistance	1000m
relevanceTrafficDirection	Both
validityDuration	600s
repetitionInterval	1s (1 Hz)
repetitionDuration	600s
keepAliveForwarding	Yes
itsGnGeoBroadcastForwardingAlgorithm	0 (Simple)

The values of *destinationArea* defines a destination area which is larger than what is within single-hop communication range for a vehicle in the scenario. As many as 1200 vehicles will be considered part of the DENM's destination area at the moment when the DENM is triggered. If we make the assumption that every vehicle in the area detects the black ice, will there exist as many DENMs (with unique *actionId*) in the network, as there are vehicles. Each and every unique successfully received DENM will thereby be stored at the receiving ITS-Ss' LDM, even though the entries concern the same hazard. A proposal to optimize the performance in similar situations is explained in Section 2.5.2.

The relevance area for the DENM is set to 1000m in each direction. This makes the *destinationArea* the same as the relevance area. The validity is set to the default value of 600s. This parameter is listed for every DENM entry in the LDM, and is utilized by the ITS applications to be able to discard outdated hazards. Unlike the previous scenario, is KAF enabled for this DENM. KAF relies on two timers, *T_F_Validity* and *T_Forwarding*. These are respectively utilized to schedule the termination and forwarding-interval for the repeated DENM. Since both KAF and repetition by the originating ITS-S is enabled, will this cause one arbitrary DENM to be repeated both by the originator and the receiving ITS-Ss. As every repeated DENMs from the originator will have the same *actionId*, will only the newest DENM be cached at the receiving ITS-Ss. Similar to the first scenario is the chosen forwarding algorithm the Simple GeoBroadcast forwarding algorithm. This means that every triggered (and stored DENM) will be forwarded as long as the hop count and DENM validity is valid. This behaviour could cause high level contention and multiple collisions at the link layers, which are often referred to as broadcast storms.

Table 3.4: Scenario 2 - "Black ice" - Alternative 2

Parameter	**Value**
destinationArea	Rectangular (a = 2000m, b = 100m)
relevanceDistance	1000m
relevanceTrafficDirection	Both
validityDuration	600s
repetitionInterval	1s (1 Hz)
repetitionDuration	600s
Keep-Alive Forwarding	Yes
itsGnGeoBroadcastForwardingAlgorithm	2 (CBF)

The alternative parameter values are displayed in Table 3.4. Even though the two suggestions are very similar, is there one small, but important difference. The chosen forwarding algorithm is now the Contention-Based Forwarding (CBF) algorithm which causes considerably less re-broadcasts and duplicates than the Simple GeoBroadcast forwarding algorithm used in the first alternative. The ramifications of these forwarding algorithms will be further discussed in Section 4.4.4.

3.2.3 Scenario 3 - "Fallen trees"

The third and last scenario is a single-lane country road with a sparse vehicle-density. The curvy road is located within a relative dense forest, which is affecting the transmission conditions. The average inter-vehicle spacing is 1000m in each direction and the vehicles velocity is approximately 70km/h. During a windy afternoon a few of the trees close to the road falls down and blocks most of the lane in the southern direction. After some time a vehicle passes by, detects the trees and triggers a DENM. The specifics of the DENM is shown in Table 3.5. The utilized CAM frequency is 10 Hz.

Due to the surroundings of the country road and the low vehicle-density, is it reasonable that a large area will be considered as part of both the *destinationArea* and relevance area for the event. The validity and repetition duration for the DENM are both set to 10 minutes. The DENM is repeated from the originating ITS-S ever 4 seconds. The CBF algorithm is chosen as the forwarding algorithm. The CBF algorithm is an cost-effective algorithm, however it does require a certain node-density to ensure sufficient results. The delivery-rate in this example will consequently

Table 3.5: Scenario 3 - "Fallen trees" - Alternative 1

Parameter	**Value**
destinationArea	Rectangular (a = 3000m, b = 200m)
relevanceDistance	1500m
relevanceTrafficDirection	Both
validityDuration	600s
repetitionInterval	0.25 Hz
repetitionDuration	600s
keepAliveForwarding	No
itsGnGeoBroadcastForwardingAlgorithm	2 (CBF)

depend on the outcome of the CBF forwarder election. If a similar situation occurs as described in Section 2.3.3, could the DENM dissemination completely stop in one direction.

Table 3.6: Scenario 3 - "Fallen trees" - Alternative 2

Parameter	**Value**
destinationArea	Rectangular (a = 3000m, b = 200m)
relevanceDistance	1500m
relevanceTrafficDirection	Both
validityDuration	600s
repetitionInterval	0.25 Hz
repetitionDuration	600s
keepAliveForwarding	Yes
itsGnGeoBroadcastForwardingAlgorithm	0 (Simple)

Table 3.6 shows the alternative parameter values for scenario 3. The only two differences between the two suggestions are the KAF enabling and selection of forwarding algorithm. Both these amendments greatly increases the probability of receiving the DENM for a random vehicle in the area. Situations with as low vehicle-density as in this presented scenario, should preferably use the simple forwarding algorithm due to the available network capacity. The enabling of KAF allows the intermediate vehicles to cache the DENM when there are no relaying vehicles within communication range.

3.3 Discussion

These three different scenarios illustrates a couple of the many challenging situations in the C-ITS. Each situation requires situation-specific decisions in order to perform optimally, and should therefore be managed independently from each other. The parameter values are selected to highlight certain characteristics, consequently will not the demonstrated performance reflect the performance of the actual deployed ITS applications. Each of the presented parameters have a very dissimilar impact on the performance, as some of them are more important than others. The *destinationArea* is without a doubt an important setting, however slightly unfortunate values will most likely not have crucial consequences. The *relevanceArea* does not affect the network performance as long as the forwarding decision is executed at the network & transport layer. One of the least complex parameters to determine is the *relevanceTrafficDirection*. Hazards which possibly could influence the traffic in both directions should be set to "both". While in less crucial events, or events occurring on highways with physically separated lanes in each direction, should only the current direction be selected.

The *validityDuration* should be set to an sufficient time-period, that ensures validity for the vehicles within immediately vicinity. Instead, may the DENMs preferably be terminated by other ITS-S as described in Section 2.3.2. The repetition feature is enabled by the *repetitionInterval* and *repetitionDuration*, and is likely utilized for events which are considered very important or situations with very low vehicle-density. Whether or not a repeated DENMs may decrease the performance, is much dependent of the chosen forwarding scheme. If for instance both repetition and the Simple GeoBroadcast forwarding algorithm are selected in a dense scenario, will the flooded duplicates most likely create problems in the network. In a scenario with a long repetition duration and high repetition frequency, might one originating vehicle broadcast hundreds or even thousands duplicate DENMs for the same detected event. This situation itself could be challenging enough, but might be significantly worse if several or all vehicles in the area does the same. These are just some of the many challenging situations which requires optimal parameter-values. Vehicle-density, detection-likelihood, event-seriousness and the surroundings are just some of the many aspects that should be thoroughly examined whenever triggering a DENM. As stated will both *keepAliveForwarding* and *itsGnGeoBroadcastForwardingAlgorithm* have a large impact on the performance of the messages in ETSI TC ITS. These will be further discussed in Section 4.4.3 and 4.4.4.

Chapter 4
Performance Evaluation

4.1 Introduction

In this chapter we will first discuss the performance requirements for the protocol, as well as introduce the metrics used for the evaluation. Next, the simulation approach and simulation framework is presented in Section 4.1.3 and 4.2.1. The rest of Section 4.2 contains both a description of simulated scenario and the results of the simulations. The results from the state-of-the-art research papers are discussed in Section 4.3. Finally, in Section 4.4 we discuss and look at the implications of the different features of the ETSI TC ITS standardization.

4.1.1 Requirements

Reference [Eur14c] specifies the following performance requirements which are expected by the ITS network and transport layer:

- provide low-latency communications
- provide reliable communications with the highest reliability for safety messages
- keep signalling, routing and packet forwarding overhead low
- be fair among different nodes with respect to bandwidth usage considering the type of messages
- be robust against security attack and malfunction in ITS stations
- be able to work in scenarios with low and high density of GeoNetworking-enabled nodes.

The C-ITS is designed to help increase traffic safety in a global perspective. In order to achieve this objective must the system provide satisfactory performance in a wide range of different situations and topologies. This involves everything from rural roads in the middle of nowhere to multiple-lane intersections during rush-hour. These varying topologies and different vehicle-densities makes the system design very complex and comprehensive. To achieve awareness of the surrounding vehicles or for instance utilize CAM information to predict collisions, is it essential that CAMs are frequently received without large delays.

The DENMs are as mentioned given higher priority than the CAMs at the ITS-S's access layer, due to severity of these warning messages. The information in the DENMs might be crucial, and consequently could incomplete broadcasting have major consequences for the affected vehicles. Optimizing DENM broadcasting by choosing efficient forwarding algorithms and consequently reduce overhead traffic is therefore an important factor.

As the CAMs and DENMs co-exists in the same channel, is it essential to mention the latter when discussing the former, and the other way around. Proposed DENM forwarding and optimization techniques relies on properly maintained neighboring tables through CAM exchange. Unsuccessful CAM dissemination may thereby cause problems for the DENM, and the different rates and parameters for the two messages should be set accordingly.

4.1.2 Performance Metrics

The following performance parameters are used to evaluate the dissemination of the V2V/V2I messages:

- **Update Delay (UD)**: The average time between each successfully received CAM from a specific ITS-S.
- **Number of received CAMs**: The average amount of received CAMs for a arbitrary ITS-S.
- **Percentage of receptions**: The average percentage of the vehicles in the destination area which received a specific DENM.
- **Duplicate DENMs received**: The average amount of duplicate DENMs received among the vehicles which received the specific DENM.
- **Sent DENMs**: The total amount of broadcasted/re-broadcasted DENMs for a specific DENM scenario.
- **Received DENMs**: The total amount of received DENMs (including duplicates).
- **Total lost**: The total amount of CAM/DENMs lost due to bit errors.

The delivery-delay of the DENMs are unquestionably an essential parameter when discussing the performance. Nevertheless, is the parameter excluded from the presented simulation results. The justification is the very small delay-values which were experienced for the simulated scenarios. These values, in the very low end of the milliseconds, are considered far less crucial for the overall performance than the ability to achieve a high DENM-receiving percentage among the relevant vehicles. The focus of the simulations will mostly involve the number of duplicates messages, overhead traffic and the probability of reception for the relevant vehicles.

4.1.3 Approach

The first step of the simulation process was to determine which simulation framework to use. Due to limited experience with network simulation tools, VANET simulation in particular, was several articles and web-forums on the subject studied in detail. After studying several papers, including [MM11] and [KGB12], the decision landed on the iTETRIS framework [iPC10].

The iTETRIS framework is an open-source, EU-funded simulation platform, triggered by the lack of large-scale scenario simulation platforms with high modelling accuracy. iTETRIS integrates and extends SUMO and ns-3, two well-established platforms for vehicular mobility and wireless communications simulations. It also supports the implementation of C-ITS applications in several different programming languages.

After a long period of struggling with the lack of documentation and a not very active community, a decision was made to switch framework. The decision fell on the VEINS framework, which is further described in the next sections. The VEINS framework is less ETSI TC ITS specific than the iTETRIS framework, which entailed that the level of detail for the simulations was somewhat reduced. This change restricted for instance the ability to easily set parameters such as *destinationArea*, *validityDuration* and *repetitionInterval*. In order to save time, the starting point became the single-hop example included in the framework. The example involved a Road Side Unit (RSU) which sent messages to passing vehicles. After studying the documentation and the source code of the example, the modification-process started. Some of the necessary modifications were enabling multi-hop communication by implementing different forwarding algorithms, adjusting the parameters of the access technology and creating new road topologies. The details of the forwarding algorithms are presented together with the simulated situations in Section 4.2.

The source code for the simulation is written in C++, which often entailed modifications in both the class code files (.cc) and header files (.h). Details such as header size, payload, address and hop limit had to be implemented and modified in order to define messages-types similar to CAM and DENM. The implementation of the multi-hop features required necessary changes in several different layers of the supplied simulation-example. These layers are comparable to the data link, network and application layers of the OSI reference model. The source code required quite a few modifications, but these were often relatively small tasks. This could for instance be creating a DENM recognition algorithm, store DENM-information in arrays, implementing the probability methods used for probabilistic forwarding or designing methods which kept track of the remaining hop limits.

Most of the required modifications were in the "BaseWaveAppLayer.cc", "TraCIDemo11p.cc" and "Mac1609_4.cc" files. These are located under "veins/src/-modules/application". The forwarding algorithms were implemented in the "onData()" method in "TraCIDemo11p.cc", which is triggered by every successfully received DENM. The implementation of the reduced CAM size proposal required modifications in the "handleSelfMsg()" method in "BaseWaveAppLayer.cc". This method is triggered by the application layer at the rate of the determined CAM frequency. In addition, in order to obtain the desired performance metrics, was further modification of the source code necessary. This was performed in "Mac1609_4.cc" class, which represents the data link (access) layer of the protocol stack.

The job of successfully implementing and verifying the various multi-hop forwarding algorithms was completed within a couple of weeks. The verifying process consisted of running the simulations multiple times, examining the rate of (re)-broadcasted DENMs, perform the necessary changes and repeat the process until the expected behaviour was indicated in the results. The expected behaviour was based on simple calculations and reasonable thinking.

The different road topologies and vehicle-movement were generated using SUMO tools such as "netconvert" and "randomTrips.py" together with OpenStreetMap, as described in [Pra15].

The various simulations were each run 10 times and it was utilized a 95% confidence interval. This decision was based on research papers such as [JDW11], at the same time was also the limited time frame of the thesis taken into account. As the calculated confidence intervals amounted no more than approximately 4% of all the presented values in the graphs, are the intervals not displayed in the graphs. This was determined on the basis of both aesthetic reasons and the considered lack of importance of these minor deviations.

4.2 Simulation

4.2.1 Simulation Environment - VEINS

The chosen framework for performing the simulations is the open source framework called VEINS, short for Vehicles In Network Simulation [Som15]. The VEINS framework is a result of a completed research project also named VEINS, which focused on performance evaluation of vehicular networks. The VEINS framework

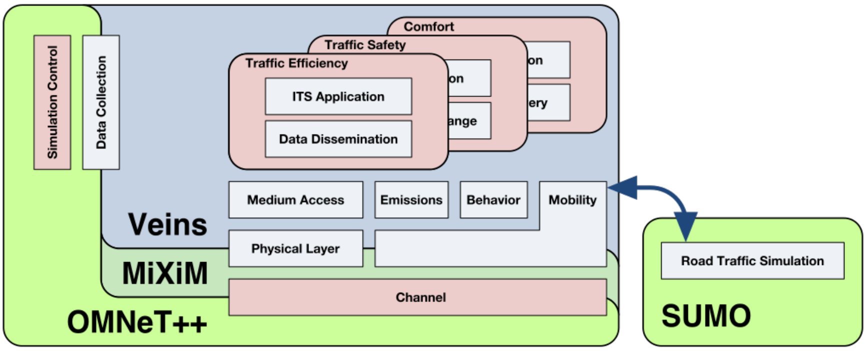
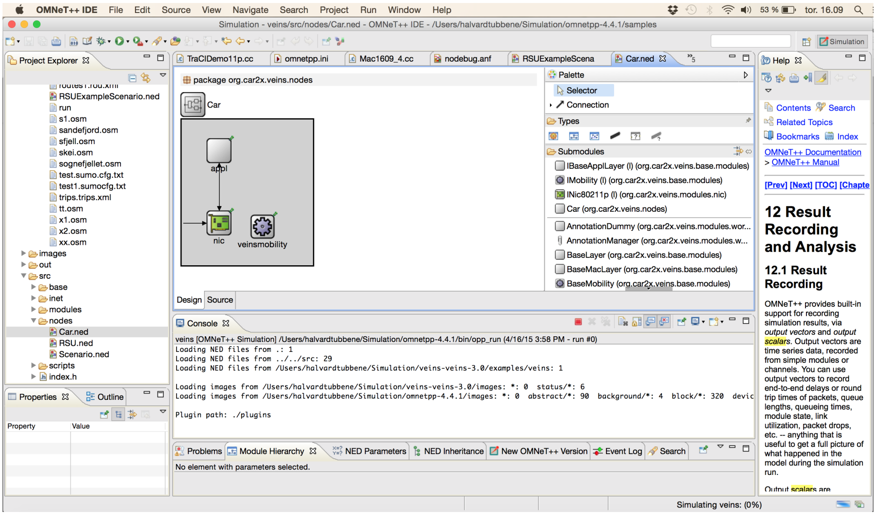


Figure 4.1: The building blocks in the VEINS framework [Som15].

is still under active development. It is used by a variety of users all over the world, ranging from governmental bodies and universities to major vehicle manufacturers.

It is based on OMNeT++ and SUMO, which are two well established network and road traffic simulators respectively. Both these simulators are bi-directional connected and are running in parallel through a TCP socket. The Traffic Control Interface (TraCI) protocol is standardized for this purpose. This bi-directional connection ensures that any mobility of the vehicles in SUMO is reflected via node mobility in OMNeT++. The VEINS framework contains an extensive amount of different models to make the VANET simulations as realistic as possible. The architecture of the VEINS framework is illustrated in Figure 4.1.



```
veins [OMNeT++ Simulation] /Users/halvardtubbene/Simulation/omnetpp-4.4.1/bin/opp_run (4/16/15 3:58 PM - run #0)
Loading NED files from .: 1
Loading NED files from ../../src: 29
Loading NED files from /Users/halvardtubbene/Simulation/veins-veins-3.0/examples/veins: 1

Loading images from /Users/halvardtubbene/Simulation/veins-veins-3.0/images: *: 0  status/*: 6
Loading images from /Users/halvardtubbene/Simulation/omnetpp-4.4.1/images: *: 0  abstract/*: 90  background/*: 4  block/*: 320  devic

Plugin path: ./plugins
```

No element with parameters selected.

12 Result Recording and Analysis

12.1 Result Recording

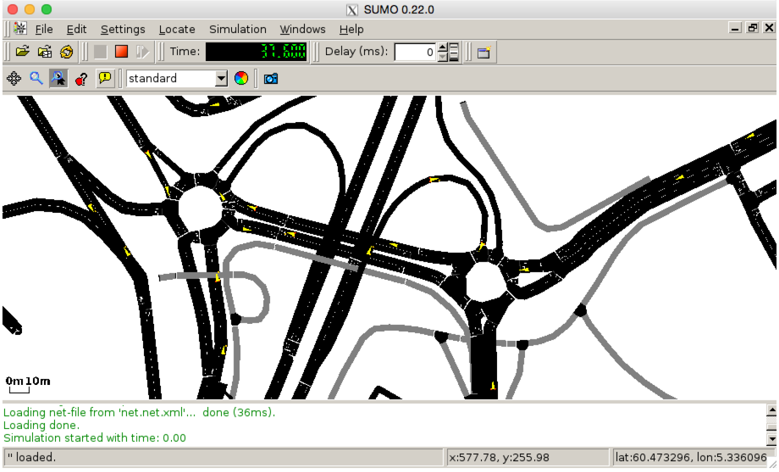
OMNeT++ provides built-in support for recording simulation results, via *output vectors* and *output scalars*. Output vectors are time series data, recorded from simple modules or channels. You can use output vectors to record end-to-end delays or round trip times of packets, queue lengths, queueing times, module state, link utilization, packet drops, etc. -- anything that is useful to get a full picture of what happened in the model during the simulation run.

Output scalars are

Figure 4.2: A capture of the OMNeT++ IDE.

OMNeT++ is an open-source component-based C++ simulation library and framework, designed for building network simulators [Ltd15]. OMNeT++ runs on the most popular operating systems such as Windows, Linux, Mac OS X and a variation of Unix systems. It has become a popular platform both in the scientific and industrial communities. Along with a physical layer modelling toolkit called MiXiM, is it possible to employ accurate models for radio interference, obstacles and other transmission challenges.

It was designed to enable large-scale simulations, relying on a hierarchical structure with reuse of components. The components which represents the building blocks in the system architecture are programmed in C++ and later assembled into larger components by using a high-level language referred to as NED. The OMNeT++ IDE is based on the Eclipse platform. A capture of the IDE is shown in Figure 4.2.



```
Loading net-file from 'net.net.xml'...  done (36ms).
Loading done.
Simulation started with time: 0.00
" loaded.
x:577.78, y:255.98
lat:60.473296, lon:5.336096
```

Figure 4.3: A capture of the SUMO GUI. The yellow arrows represents the moving vehicles.

SUMO (Simulation of Urban MObility) is a free traffic simulator which supports modelling of complex traffic systems [Hil15]. SUMO offers multiple features such as time scheduled traffic lights and modelling of pedestrians. The simulator has for instance been used to provide traffic forecast before large events such as the World Cup or presidential visits. Performance testing of traffic light control algorithms before deployment is another important application.

SUMO communicates with OMNeT++ via the mentioned TraCI protocol. It offers large scale simulations as there are no limitations in network size nor number of vehicles. The SUMO package is equipped with several tools supporting tasks as route-planning, visualization and emission calculation. Figure 4.3 shows a capture of the SUMO GUI during a simulation.

4.2.2 Simulation Scenario 1 - Country Road

Table 4.1: Simulation Parameters - Situation 1,2,3

Parameter	**Value**
Simulation time	600s
Access technology	IEEE 802.11p
Frequency band	5.9 GHz
Channel	CCH
Channel width	10 MHz
Data rate	6 Mbps
Radio sensitivity	-89dBm
EDCA Priority CAM	AC_BE
EDCA Priority DENM	AC_VI
Length of road	10 km
No. of lanes per direction	1
Number of vehicles	20, 40, 100, 200
Average inter-vehicle spacing	45m, 90m, 220m, 440m
Vehicle speed	80 km/h
Loss model	Simple path loss model (k=2)
CAM size	750 Bytes (200 Bytes)
CAM frequency	1 Hz, 5 Hz, 10 Hz
DENM size	550 Bytes

The simulated topology utilized for the first part of the simulation is a 10 km Norwegian country-road with one lane in each direction. The road section does not contain any sharp turns and the surrounding landscape is flat without any tall obstacles. In this section we will study a four different situations with various characteristics. The utilized parameter values for the first part of the simulation are listed in Table 4.1.

Situation 1 - Vehicle Density & CAM Frequency

In the first scenario we evaluate a pure CAM dissemination scenario without any DENMs being triggered. The examined variables in this scenario are the CAM frequency and the vehicle density. The CAM frequency for the ETSI standardization is adaptive and is optimized based on the surroundings, as described in Section 2.2.2. This algorithm is however not implemented in this thesis due to the limited time frame and limitations in the simulation framework. Instead, is the upper and lower limit of the algorithm (10 Hz and 1 Hz) tested, in addition to 5 Hz. The vehicles are generated by SUMO as described in Section 4.2.1. Every other vehicle is located in the opposite ends of the road, driving in opposite directions of each other.

The results of the simulations indicated a very small difference in Update Delay (UD) for the different inter-vehicle spacings. A decision was made to not present the graph of these results in this thesis, due to the small performance differences compared to the values of the confidence interval. The small differences did however indicate a small tendency for the different CAM frequencies. For a CAM frequency of 1 Hz, gave the shortest inter-vehicle spacing (45m) the best UD. For a 10 Hz CAM frequency however, was the tendency reversed. The longest inter-vehicle spacing (440m) now gave the lowest average UD. The cause of this shift is the increasing packet loss which is experienced for the vehicles within an area with a relatively high vehicle-density.

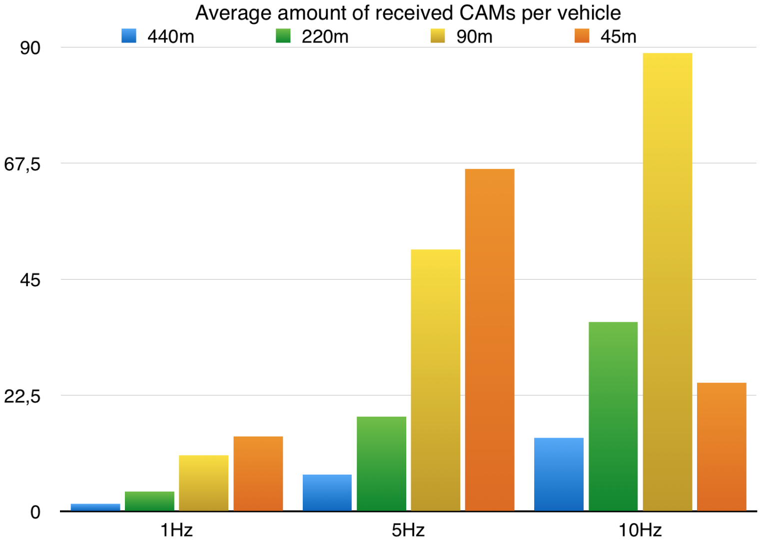


Figure 4.4: The average amount of received CAMs per second for various inter-vehicle spacings and CAM frequencies.

The same is also applicable when evaluating the results shown in Figure 4.4. The bars for the 10 Hz CAM frequency clearly shows the sudden reduction of received CAMs for the highest density (45m). Whilst the bar for the 90m inter-vehicle spacing almost doubles from 5 Hz to 10 Hz, is the bar for the 45m spacing more than halved in the same interval. This is a results of the increased packet loss caused by the high vehicle-density and the fact that twice as many CAMs are generated per vehicle.

Situation 2 - CAM Size

It has been discussed whether or not every triggered CAM should contain a certificate and trace-information. By only including this information in every fifth or tenth broadcasted CAM, could the load on the network be significantly reduced. This reduction could lead to a CAM size of 200 bytes instead of 750 bytes, for every 4/5 or 9/10 triggered CAM. This proposal is also mentioned in Section 2.5.3. The same topology is used for the examining the performance of this proposal. The proposal is only simulated for a 10 Hz CAM frequency, as this will indicate the largest possible differences. No DENMs are broadcasted in this simulation.

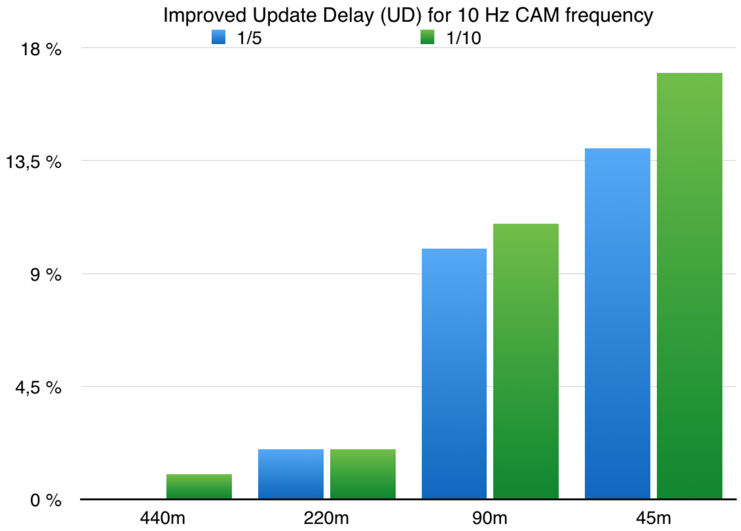


Figure 4.5: The improved UD for the 1/5 and 1/10 proposal for a 10 Hz CAM frequency.

Figure 4.5 illustrates the UD improvement for the 1/5 and 1/10 proposals compared to the 1/1 scheme. The results are quite unambiguous and does not indicate any surprising implications. For the sparse vehicle-densities are the experienced improvement relatively small. An inter-vehicle spacing of 220m provides an improvement of approximately 2% for both the proposals. This has a low impact on the performance, as it only decreases the average UD from 118 ms to approximately 115ms for the inter-vehicle spacing. The implications are much more clear for the inter-vehicle spacings of 90m and 45m. The results shows an improvement of 10% and 14% for the 1/5 scheme, and 11% and 17% for the proposed 1/10 scheme. This represents an improvement in the range of 13-24ms for the UD. Despite the relatively modest improvement, is it reasonable to believe that the proposal could have larger implications in more complex scenarios. This may for instance apply to situations where several DENMs are triggered in topologies with high vehicle-densities.

Situation 3 - One Vehicle Trigger DENM

The third simulated situation is a DENM dissemination scenario. The road topology and the varying inter-vehicles spacings are similar to the previous situations. In this situation, one vehicle detects an arbitrary event which triggers a DENM by one of the ITS safety applications. To ensure optimal results, are the DENMs triggered by several different vehicles at different times during the simulation. Only one vehicle is triggering the DENM each simulation-run. As mentioned in Section 4.1.3, did the VEINS-example only support single-hop communication. In order to examine the performance of different multi-hop forwarding algorithms for DENM, was some modification of the example required. First was a simple flooding algorithm implemented. This algorithm re-broadcasts a DENM automatically upon reception. The Remaining Hop Limit (RHL), often referred to as Time To Live (TTL), determines the number of allowed re-broadcasts for a GeoNetworking packet. This parameter is part of the Basic Header. However, the value of this field is not specified in the standardization. A maximum hop count of 10 hops was decided for the implementation of the algorithm, which is referred to as the "Simple Flooding Algorithm" in the following paragraphs.

Algorithm 4.1 Pseudo-code for an self-implemented CBF inspired algorithm.

```
cbfInspiredAlgorithm {

    if (timerExpired(packet))       //timer expires if no other
        sendDenm(packet)            //has re-broadcasted the message
                                    //sends the DENM

    Packet packet = listen()

    if (packetInBuffer(packet))     //indicates a duplicate DENM
        stopTimer(packet)           //meaning that another node has
        discard(packet)             //already re-broadcasted.
                                    //discards the DENM
    else
        addToBuffer(packet)         //timer dependent on the
        startTimer(packet)          //distance from sender.

}
```

An algorithm inspired by the standardized CBF algorithm was also implemented. The pseudo-code for the implementation is shown in Algorithm 4.1. The timer-values are based on a variation of defined distances. Due to the simplicity of the implementation and lack of sufficient defined intervals, will vehicles within in the similar distance get the same timer-value. This might cause neighboring vehicles to re-broadcast the same DENM. This behaviour will be less likely for the standardized algorithm. The described situation is simulated for both the Single-hop, Simple Flooding and the CBF inspired algorithm. To simplify the simulation, is every vehicle considered to be part of the *destinationArea* for the event. The CAM frequency is statically set to 1 Hz.

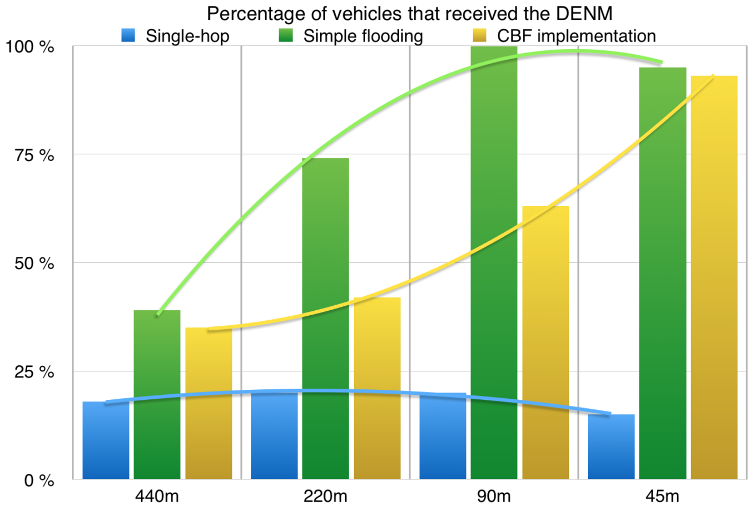


Figure 4.6: The total percentage of the vehicles within the *destinationArea* that received the DENM.

Figure 4.6 shows the percentage of the vehicles which received one or several DENMs for the detected event. The result of the three forwarding algorithms shows clear inequalities as they behave and alters differently. The Single-hop DENM algorithm only accomplishes a receiving-percentages of approximately 15-20%, which is about as modest as expected. The performance slightly improves from 440m to 220 due to increasing number of vehicles within communication range. However, from 220m to 45m, is the receiving-percentage steadily decreased. This is caused by the increased packet loss.

The Simple Flooding forwarding algorithm provides much better results than Single-hop. At the most sparse situation is 42% of the vehicles able to receive the DENM. This is slightly more than double the recipient-percentage of single-hop for the corresponding density. For the other vehicle-densities, the differences are even bigger. An inter-vehicle spacing of 90m ensures 100% DENM delivery for the simulated vehicles. The green curve, which illustrates the trend-curve for the Simple flooding bars, indicates a negative trend when the density gets higher than a 90m inter-vehicle spacing. For 45m, the delivery rate has fallen to 95%. The increase of duplicate traffic and consequently increased packet loss is the reason behind this unfortunate development. It is therefore grounds to suspect that similar scenarios with even higher densities might experience a similar negative behaviour.

The implemented CBF-inspired algorithm shows a totally different development than the Simple flooding algorithm. For a 440m vehicle-density, can the algorithm almost compete with the performance of the Simple flooding algorithm. However, for 220m inter-vehicle spacing, is the difference between the two bars much larger. Whereas the Simple flooding algorithm had a 25% increase at this interval, is the corresponding increase for the CBF-inspired algorithm only 7%. The delivery-rate of the algorithm starts to increase more rapidly for the next inter-vehicle spacings. At 45m inter-vehicle spacing, only 2% separates the two multi-hop forwarding algorithms. The algorithm's yellow trend-curve clearly indicates a positive development as the density increases. This corresponds well with the discussed characteristics of the standardized CBF algorithm in Section 2.3.3. In short, is a certain node-density required for the CBF algorithm in order to ensure good performance. This gives reason to believe that the CBF algorithm would surpass the performance of the Simple flooding algorithm for higher vehicle-densities, and at the same time at a much lower cost.

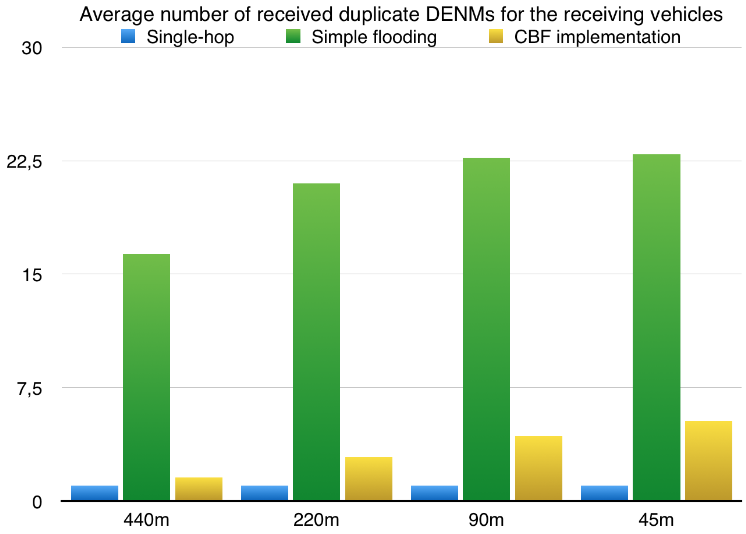


Figure 4.7: The amount of received DENMs for the same event for each of the receiving vehicles.

The simplicity of the simple flooding causes a lot of duplicates and overhead traffic. Figure 4.7 clearly demonstrates the wasted capacity that is caused by the Simple flooding algorithm. The diagram shows the average amount of received duplicate

DENMs for each of the receiving vehicles. For single-hop is obviously only one DENM received per vehicle, as the DENM is only broadcasted once by the triggering vehicle. The Simple flooding algorithm ensures that as many as 16-23 DENM is being received and processed at the each of the recipients. All of which contains identical details concerning the one detected event. This large amount of duplicates are unfortunate for the system's capacity. The duplicates which are received using the CBF-inspired algorithm on the other hand, is caused by the mentioned simplicity of the implementation. The standardized CBF algorithm will most likely keep the amount of duplicate traffic at a very low level. Some duplicates will regardless be received for the vehicles that are located within communication range of multiple CBF-elected forwarders.

Table 4.2: Simulation Parameters - Situation 4

Parameters	**Value**
Number of vehicles	200
Average inter-vehicle spacing	45m
CAM frequency	1 Hz
CAM size	750 bytes
DENM size	550 bytes

Situation 4 - Every Vehicle Detects Hole in Road

In this situation is every vehicle detecting the same hole in the road and thereby triggering their own DENM. The road topology is still the same, while the inter-vehicle spacing is now constant at 45m. Table 4.2 shows a selection of the parameter values for the simulated situation.

The vehicles triggers their own unique DENM as they pass the location of the hole. The presented results are based on the average of 10 simulation runs. The confidence interval is not shown in the tables. This was determined due to the fact that it is the magnitude of the numbers which are considered important, and not the small deviations between each of the simulation-runs. Details and results from three different forwarding algorithms will be presented in the next paragraphs.

Table 4.3: Results for the simple flooding forwarding algorithm

Results	**Value**
Total (re)broadcasted DENMs	1 336 714
(re)Broadcasted DENMs per vehicle	6 684
Average received DENMs per vehicle	19 514
Total lost CAM/DENMs due to SNIR	37 553 528
Average UD	1.35s
Highest average UD	1.50s

1. Simple flooding

Table 4.3 displays the results for the previously described Simple flooding algorithm. Since every vehicle triggered its own DENM, in addition to the re-broadcasting of every valid received DENM, was the total amount of (re)broadcasts per vehicle as high as 6 684. As a result were 19 514 DENMs received on average for each vehicle. This means 19 514 DENMs which all describes the same event. In total was 553 528 CAM and DENMs lost due bit errors. The average UD was 1.35 seconds for a CAM frequency of 1 Hz.

Algorithm 4.2 Pseudo-code for 0.25 - Probabilistic Forwarding with DENM recognition.

```
ProbabilisticForwardingAlgorithm_DENM {
    DENM denm = listen()
    if (denmInDatabase(denm))       //If already received,
        return 0                    //does nothing.
    else
        store(denm)                                 //Stores DENM in DB.
        Boolean rebroadcast = drawRandom(0.25)  //Gets true with 0.25
        if (rebroadcast)                            //probability.
            broadcastDENM(denm)                     //if true,
}                                                   //re-broadcasts.
```

Table 4.4: Results for 0.25 - Probabilistic Forwarding with DENM recognition

Results	Value
Total (re)broadcasted DENMs	6 625
(re)Broadcasted DENMs per vehicle	33
Average received DENMs per vehicle	731
Total lost CAM/DENMs due to SNIR	188 033
Average UD	1.14s
Highest average UD	1.22s

2. 0.25 - Probabilistic Forwarding with DENM recognition algorithm

The second forwarding algorithm simulated is a probabilistic forwarding algorithm that recognizes duplicate DENMs and re-broadcasts with a probability of 0.25. The pseudo-code for the algorithm is shown in Algorithm 4.2. A pseudo random number generator (PRNG) is utilized to generate the probability. This algorithm manages to recognize DENMs triggered by the same ITS-S. However, it does not recognize if the received DENMs is triggered by the same event. Table 4.4 illustrates the results, which are in a entirely different magnitude than the Simple flooding algorithm. The results are further discussed in later paragraphs.

Algorithm 4.3 Pseudo-code for 0.25 - Probabilistic Forwarding with event recognition algorithm.

```
ProbabilisticForwardingAlgorithm_EVENT {
    DENM denm = listen()
    event = getEventInfo(denm)
    if (eventInDatabase(event))     //If already received a DENM for
        return 0                    //the same event, does nothing.
    else
        store(event)                            //Stores event-info.
        Boolean rebroadcast = drawRandom(0.25)  //Gets true with 0.25
        if (rebroadcast)                        //probability.
            broadcastDENM(denm)                 //if true,
}                                               //re-broadcasts.
```

Table 4.5: Results for 0.25 - Probabilistic Forwarding with event recognition

Results	Value
Total (re)broadcasted DENMs	246
(re)Broadcasted DENMs per vehicles	1.23
Average received DENMs per vehicle	53
Total lost CAM/DENMs due to SNIR	76 480
Average UD	1.14s
Highest average UD	1.22s

3. 0.25 - Probabilistic Forwarding with event recognition

The third and last forwarding algorithm tested in this scenario is a probabilistic forwarding algorithm that recognizes events. The pseudo-code for the algorithm is shown in Algorithm 4.3. This algorithm is able to recognize DENMs triggered by the same event, thus reducing re-broadcasting of DENMs for the same events.

The results for the algorithm are presented in Table 4.5. The presented results are similar to the previous algorithm, in a entirely different magnitude than the Simple flooding algorithm. The results also indicated a small improvement compared to the second algorithm.

Comparison

A comparison of the results of the three algorithms are presented in Table 4.6. The objective of this particular situation was to illustrate the total amount of DENMs transmitted and received for the same event. The delivery-rate for all the 200 unique DENMs are consequently not presented in the results. 100% of the vehicles did however receive one or several DENMs. The variation of the different results are enormous, as the amount of overhead traffic significantly decreases for the more intelligent forwarding algorithms.

Table 4.6: A comparison of the results for situation 4

Results	**1**	**2**	**3**
Total (re)broadcasted DENMs	1 336 714	6 625	246
(re)Broadcasted DENMs per vehicle	6 684	33	1.23
Percentage of vehicles which received one or more DENM	100%	100%	100%
Average received DENMs per vehicle	19 514	731	53
Total lost CAM/DENMs due to SNIR	37 553 528	188 033	76 480
Average UD	1.35s	1.14s	1.14s
Highest average UD	1.50s	1.22s	1.22s

The results indicates that amount of overhead traffic for the Simple flooding algorithm, does not have severe consequences for the CAM dissemination. Its average UD was no worse than 1.35s, which is only 18% worse than corresponding results for the more intelligent algorithms. Implementation of similar recognition algorithms as the ones implemented, will however require forwarding decisions at a higher layer than the simple flooding. Whereas simple flooding can be performed at the network & transport layer, is more intelligent forwarding required to take place at the facility layer. Details on how to implement DENM/event recognition for the ETSI TC ITS standard is not discussed any further.

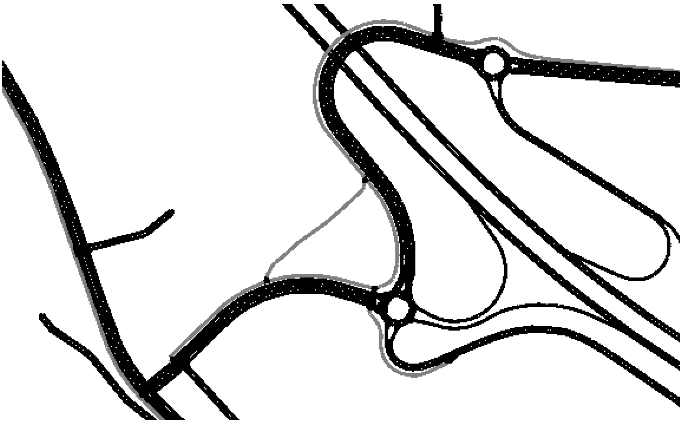


Figure 4.8: The simulated complex intersection (capture from SUMO).

4.2.3 Simulation Scenario 2 - Complex Intersection

The simulated topology in this section is a complex intersection with two roundabouts and several crossing lanes with varying standard. A sketch of the topology is shown in Figure 4.8. The simulated 150 vehicles are placed randomly in the topology based on the quality of the roads. The parameter values used for the simulation is listed in Table 4.7.

Table 4.7: Simulation Parameters - Situation 5

Parameter	Value
Simulation time	900s
Access technology	IEEE 802.11p
Frequency band	5.9 GHz
Channel	CCH
Channel width	10 MHz
Data rate	6 Mbps
Radio sensitivity	-89dBm
EDCA Priority CAM	AC_BE
EDCA Priority DENM	AC_VI
Number of vehicles	150
Vehicle speed	80 km/h
Percentage of vehicles detecting hazard	7.5%, 15%, 30%
Loss model	Simple path loss model (k=2)
Forwarding algorithm	Probabilistic (p = 0.25, 0.5, 0.75)
CAM size	750 Bytes
CAM frequency	1 Hz
DENM size	550 Bytes

Situation 5 - Probabilistic Forwarding for Several Detecting Vehicles

In the previous evaluated scenarios is the events detected either by only one vehicle or all vehicles. This might be a realistic for some real-world situations, but definitely not for all. In this section, we study the performance of a scenario where 7.5%, 15% and 30% of all the vehicles trigger a DENM. The results are based on several simulation-runs where different vehicles trigger the DENMs. The utilized forwarding algorithm is a simple probabilistic forwarding algorithm that re-broadcasts a (valid) received DENMs with a probability P equal to 0.25, 0.5 or 0.75. The probability is generated by a PRNG.

Figure 4.9a) shows the total number of broadcasts and re-broadcasts in the simulated scenario. The results confirms the expected behaviour of the algorithm, with a steadily increasing number of (re)broadcasts. The behaviour shown in the diagram in Figure 4.9b) is on the other hand somewhat interesting. Despite the number of broadcasted DENMs being much higher for the higher probability-values, the number of successfully received is decreasing. This trend is applicable for all trigger-rates, although it is most noticeable for a 30% trigger-rate. Again, this is caused by the packet loss which increases in parallel with the data-traffic, illustrated in Figure 4.10a).

The delivery-rate of the DENMs is presented in Figure 4.10b). All p-values ensures a 100% delivery-rate for the situations where 15% or 30% of the vehicles detects

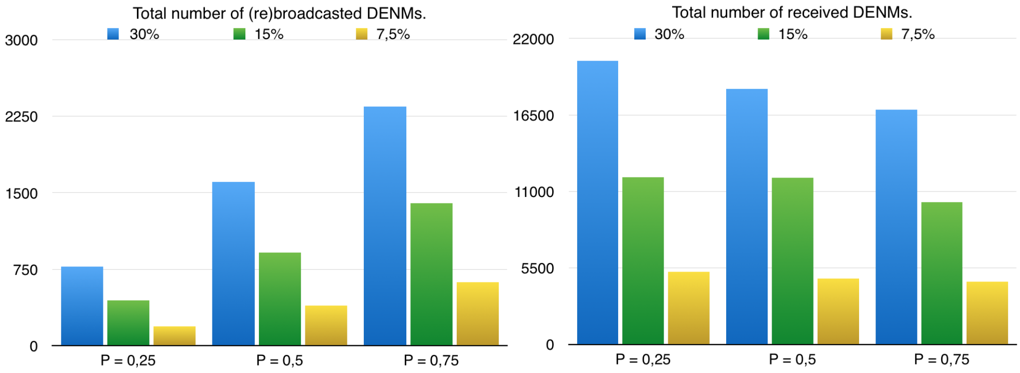


Figure 4.9: a) The total amount of (re)broadcasted DENMs. b) The total amount of received DENMs for each of the receiving vehicles.

the event. For a 7.5% rate the different probabilistic forwarding algorithm ensures a delivery-rate of 94.7% to 96%. This small variance is basically insignificant as it might be caused by unfortunate transmission conditions in the simulated scenario. In other word is the delivery-rate equal, despite that twice and thrice as many DENMs are broadcasted (Figure 4.9a). These results indicates that the most cost-effective approach, which is 0.25 probability forwarding, might be equally efficient in scenarios with similar characteristics.

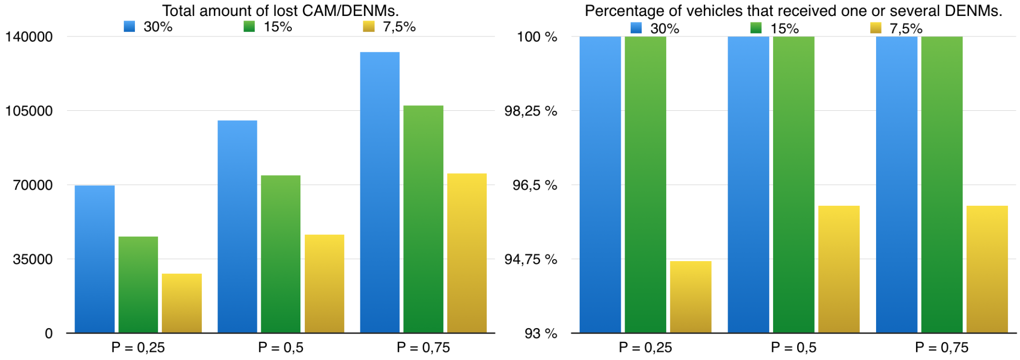


Figure 4.10: a) The total amount of lost CAM/DENMs. b) The delivery-rate for the DENMs.

4.3 State-of-the-art Results

In addition to these simulation-results, have several available research papers which are evaluating the performance of VANET, ITS and CAM/DENMs, been studied in detail. A few of these are mentioned in Section 1.3 - "Related Work". As discussed in the beginning of this thesis are both VANET and ITS in particular, relatively new research topics. This is clearly reflected in the small amount of relevant research papers which are available as of today. Most of these are based on other standardizations, and consequently only discusses single-hop communication. Some are however based on the ETSI standardization, but only studies the performance of one of the two standardized messages and not the co-existing of both of them. As the CAM and DENM are highly affected by each others presence, will the results from these types of papers not be further analyzed. Papers that actually considers all these specifics such as [BJU13], emphasizes the importance of the keeping DENM overhead traffic at a minimum, by proposing enhanced dissemination strategies similar to the ones presented in section 2.5.

4.4 Discussion

In this section we will discuss some of the key elements and features of the V2V/V2I messages for the ETSI TC ITS standardization.

4.4.1 Adaptive CAM Frequency

Proper CAM dissemination is one of the key elements enabling good overall performance for the V2V and V2I messages. The CAMs, also often referred to as beacons, are periodically sent, and consequently constitutes the majority of the total amount of messages. Unnecessary frequent transmission of CAMs could in specific scenarios occupy the entire dedicated capacity and prevent DENMs from being successfully delivered. On the other hand could too rare CAM transmission lead to impaired performance for the ITS applications, or problems maintaining neighboring tables.

The standardized adaptive CAM frequency algorithm discussed in Section 2.2.2, will in all likelihood help optimizing the CAM dissemination. This could prevent unfortunate situations as the ones described the previous paragraph. Due to the limited scope of this thesis has the algorithm not been implemented. The efficiency of the algorithm (shown in Algorithm 2.1) is difficult to predict, as it greatly depends on the defined thresholds and the efficiency of the DCC algorithm.

4.4.2 Multi-hop vs. Single-hop

Unlike most of the other C-ITS standardization initiatives, does the ETSI TC ITS standardization support multi-hop communication for the DENMs. This feature allows vehicles outside of single-hop communication range, to exchange information. This feature significantly improves the DENM delivery-rate in situations where one or just a few vehicles detects and triggers a DENM. A similar situation was simulated in Section 4.2.2 - Situation 3. Here, the single-hop DENM dissemination only achieved a delivery-rate of approximately 20%, whereas multi-hop ensured a 100% delivery-rate for some of the corresponding vehicle-densities. It is worth mentioning that single-hop might perform as well as multi-hop in situations where a large percentage of the vehicles detects and triggers DENMs for the same events. Perhaps even better if one is considering the delivery-costs.

Although the advantage of the multi-hop feature is easy understand, is it also important to be aware of the disadvantages of the multi-hop feature. The consequences of irresponsible forwarding might affect the CAM delivery-rate thus potentially decreasing the performance of the ITS applications. Enabling multi-hop might also cause decreased delivery-rates and increased delay for the single-hop neighbors which would be within communication range regardless of this feature. The additional computational effort required because of the complex forwarding algorithms and the duplicate traffic, might also be a concern for the ITS vehicles.

4.4.3 KeepAlive Forwarding (KAF)

The ability to cache DENMs and later forward is without a doubt a very useful feature, as long as it is utilized properly. Forwarding at sparse situations without immediately relaying vehicles within communication range are no longer a hopeless situation if KAF is enabled. This allows vehicles within a DENM's *destinationArea*, which never reaches the single-hop communication range of the originator, to still be able to receive the DENM. Simply by the help of forwarding vehicles caching DENMs. The KAF feature is quite similar to the repetition feature. The difference however, is that KAF also allows the forwarding vehicles to repetitively re-broadcast the DENMs, not just the DENM's originator.

Although KAF can be useful, may it also cause additional overhead traffic that potentially could impact the delivery-rate. If several DENMs triggered by the same event are cached, will most likely all of the cached DENMs (for the same event) be re-broadcasted. The re-broadcasting will either occur at a specific frequency, or whenever a new vehicle enters the communication range of the forwarder. This will lead to a lot of duplicate traffic that will continue to propagate at the neighboring vehicles. Because of this pitfall should there be some sort of event recognition implemented, to ensure that just one stored DENM per event is re-broadcasted. A proposal that reduces the number of duplicate DENM entries is proposed in Section 2.5.2.

4.4.4 DENM Forwarding Algorithms

Another part of this evaluation concerns the impact that the proposed forwarding algorithms have on the system's performance. As described in Section 2.3.3, are three algorithms standardized for DENM dissemination in the ETSI TC ITS. These have very different characteristics and are best suited for various uses. The Simple GeoBroadcast forwarding algorithm with line forwarding (described in Algorithm 2.2) is a fairly simple algorithm that re-broadcasts a valid packet as long as the forwarder is considered as part of the DENM's *destinationArea*. If the forwarder is outside this area, it will trigger the GF algorithm to find another suitable forwarder closer to the destination. The advantage of the Simple GeoBroadcast forwarding algorithm is the good performance achieved at relatively low density scenarios. By letting every vehicle re-broadcasts the received DENMs, one prevents messages from dying out in certain directions (as described for CBF). The simplicity of the forwarding decisions makes also sure that no extra delay is added. The major disadvantage is however the decreasing performance due to duplicate traffic and packet loss when the vehicle-density gets high.

The Contention Based Forwarding (CBF) algorithm discussed in Section 2.3.3, overcomes some of the disadvantages of the simple forwarding, but at the same time it introduces some new ones. The presented trend-curves for the two algorithms in Figure 4.6 clearly demonstrates their different characteristics. Whereas CBF requires a certain vehicle-density to perform well, is the performance of simple flooding decreasing for the corresponding density. The objective and the main advantage of the algorithm is the accomplished delivery-rate at a much lower cost than the simple flooding. The important reduction of overhead traffic and duplicates might be essential in dense situations in order to be able to achieve sufficient delivery-rates. Unfortunate forwarder-election as a consequences of the mentioned assumptions the algorithm relies on, is one of the fundamental weaknesses for the CBF algorithm. The scenarios presented in Section 2.3.3 are just some of the many possible scenarios where the CBF may perform poorly. In addition, is also additional delay introduced by the use of the CBF timers.

The Advanced GeoBroadcast forwarding algorithm (Algorithm 2.4) is as stated designed to improve the efficiency of the CBF algorithm. The performance of the algorithm is however not simulated in this paper due to the scope of the thesis, and the limitations of the VEINS framework. Several other algorithms have also been discussed and implemented in this thesis, such as probabilistic forwarding, with or without DENM or event recognition. These algorithms have shown promising results and might prove effective in a number of situations. The implementation of the discussed algorithms might require intelligence from the higher layers than the network & transport layer of the protocol stack. The details concerning the implementations are outside the scope of this thesis.

4.4.5 Varying Topologies

The very wide range of existing road topologies makes C-ITS a very challenging system. The aim of the system is to ensure good performance in all possible topologies and situations, ranging from very deserted areas to the most crowded intersections imaginable. The adaptivity of the CAM frequency algorithm, the different standardized forwarding algorithms and the opportunity to cache messages (KAF) are all key elements of ensuring the system's objectives.

An C-ITS implementation with for instance a static CAM frequency of 10 Hz and DENM forwarding using simple flooding, could possibly perform well in certain scenarios with an ideal vehicle-density. However, if the scenario is a crowded intersection with a very high density, could the usability of the implementation be very limited. In other words, are the different topologies not necessary crucial for the system's performance, although they might cause some extra challenges. The performance in these situations will instead depend on the robustness and detail-level of the implementation for the ITS applications. In very challenging scenarios involving difficult transmission conditions, high vehicle-density and several events occurring simultaneously will it be difficult to give any performance guarantees. Regardless, is a robust and comprehensive implementation a good starting point.

4.4.6 Proposed Strategy

As clearly illustrated in chapter 4, may unsuitable parameter values cause very unfortunate transmission conditions and strongly affect the system's performance. This especially applies for the decisions concerning the election of forwarding algorithm and various types of repetition. These are both potential pitfalls that requires carefully informed decisions.

An essential part of the ability to chose optimal parameters and dissemination strategies, is the information that is learned through the exchange of CAMs. This information is sometimes directly utilized by the safety applications to avoid collisions etc, but is it also absolutely crucial when the objective is to gain knowledge of the current surroundings. Information concerning the vehicle-density for instance, is easily accessible through the neighbor table (LocT) learned through CAMs. Available details such as the CAM freshness could for instance also be used to calculate the probability of successful dissemination. This could make it easier to determine whether or not a DENM should be repeated or which forwarding algorithm to use. In addition could the cached information from the recently received DENMs be utilized to decide whether or not an ITS should refrain from broadcasting a DENM even though an event is detected. Classifications of events may also be an important part of optimizing DENM forwarding. This could be performed by giving different priority to the various possible events thus increasing the probability of reception for these events, by utilizing the available functionalities in the standardization.

In short, is the key to sufficient dissemination and good performance, the ability to utilize all the available information.

Chapter

5

Conclusion & Future Work

This thesis has conducted a performance evaluation of the V2V/V2I messages for the ETSI TC ITS standardization. The evaluation is based on simulations of several challenging situation containing various features of the standardization. The two simulated topologies are a typical country road as well as a complex urban intersection with crossing lanes and several roundabouts. The situations range from a pure CAM dissemination scenario to more challenging situations where CAMs co-exists together with DENMs, broadcasted by a variety of forwarding algorithms. This thesis also gives a thoroughly description of the background information as well as the necessary technical details for the CAM and the DENM message. Three specific situations containing detailed information of the necessary DENM parameters are carefully reviewed and discussed.

The challenge of the C-ITS is the ability to ensure sufficient CAM delivery-rates, combined with high DENM receiving-percentage at a low-cost. Several forwarding algorithms are standardized for DENM dissemination purposes. These have fairly different characteristics and their performance highly depends on the surroundings and the current vehicle-density. The objective of maintaining duplicate traffic at a minimal level while still ensuring high DENM delivery-rates, is difficult to fulfill. The presented results clearly indicates the correlation of these two factors, and creates a distinct picture of the large differences in terms of the amount of duplicate traffic for the algorithms. The responsibility to handle these challenges and efficiently ensure sufficient results, are mainly based on the robustness and efficiency of the ITS applications implementation. Several enhancement techniques are also presented in this thesis. DENM forwarding based on probabilistic forwarding algorithms with or without event or DENM recognition, are some of the proposals that shows promising results. A suggestion that optimizes the packet size for a varying rate of CAMs are also discussed and simulated. This amendment shows a noticeable improvement for CAM's update delay as the vehicle-density increases.

The ability to cache the DENMs is especially important in rural scenarios with a limited amount of vehicles within communication range. Without this feature, would in all likelihood the DENM delivery fail. The thesis also discusses the consequences irresponsible caching might have on the network due to the increasing amount of duplicate traffic. The proposal of aggregating LDM entries might help reduce some of these concerns.

The C-ITS has the potential to achieve good results and sufficient performance for a large variety of possible situations and topologies. The decisive factor will be the system's ability to adapt and chose optimal parameter values for the situations that may arise.

Even though the VEINS framework is a robust and well-documented framework, could it be interesting to perform simulations utilizing other frameworks, especially the iTETRIS framework. This framework is more ETSI specific and could allow more complex and comprehensive simulations. Due to limitations of this thesis, was only a handful of situations simulated and discussed. Implementing and testing the standardized forwarding algorithms as well as the other performance enhancement proposals could potentially be very useful. In the future could it also be interesting to simulate several of the ITS applications and observe their behaviour.

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