Achieving Guaranteed Performance for Protection Traffic in Smart Grid Wide-Area Networks

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***Abstract*—Recent years, tele-protection applications in utility grids have been deployed using Ethernet. However, Ethernet without Time Sensitive Network (TSN) mechanisms is non-deterministic. Hence, challenges of the queuing delays occurring on multi-hop paths result in Packet Delay Variations (PDV) and may even result in packet losses due to buffer overflows. There have been recommendations to use Priority Scheduling (PS) to lower the latency of tele-protection messages. However, for PS, maximum PDV occurs on higher priority packets when contending with lower priority packets, needing to wait until a lower priority packet with maximum length have exited a switch. In this paper, we explore through a performance simulation study the suitability of applying FUSION in smart grid tele-protection applications. FUSION is a packet switched principle applying Ethernet, offering circuit-switched quality of service with deterministic latency, zero packet loss and ultra-low PDV for high priority packets. We demonstrate FUSION performance in tele-protection for power system networks, and compare it with Strict Priority Queuing (SPQ), which is recommended for real-time industrial applications. Our results show that by applying FUSION, we are able to guarantee a fixed delay, zero PDV and packet loss through the network. Furthermore, we show that through proper network dimensioning, lower priority traffic can additionally be added with delays within acceptable limits.**

Keywords-communications; packet scheduling; power system protection; tele-protection; ethernet networks; wide area networks

I. Introduction

Ethernet is the most widely used local area network technology. Despite originally not being designed for industrial communication, some of its properties, such as easy integration with Internet, inherent compatibility with the management networks used at higher levels in hierarchical industrial systems, and low price make its use in industrial context very attractive [1].

In the power system industry, there has been a clear trend to move utility network services such as tele-protection, control and automation, voice and video and other applications to Ethernet-based communications systems. The goal is to reduce capital costs, standardize common interfaces, simplify the network design, and move away from legacy equipment when implementing system upgrades. For Ethernet without TSN mechanisms, latency and throughput are non-deterministic because of the shared medium. However, Ethernet supports Virtual Local-Area Networks (VLANs), priority queuing and class of service to reduce latency on high priority traffic [2].

Tele-protection communications service is one of the most critical services that supports electric power system operations, with strict requirements for communication latency, packet delay variations and packet losses. Current differential protection typically requires symmetrical communications channels with equal latency in each direction for correct operation [3]. Current differential line protections requires synchronization between substations to a normal accuracy less than $0.1\,\mathrm{msec}$, and even less than $0.01\,\mathrm{msec}$ if high fault current sensitivity is required [4]. In addition, the influence of delay on protection algorithms is acceptable if it is constant and does not lead to the protection application exceeding its operating time. However, deploying tele-protection in Ethernet faces challenges of non-deterministic latency and asymmetric latency due to packet delay variations from variable queuing latency [2].

One method addressing latency and asymmetry requirements for tele-protection communications is high priority provisioning using Quality of Service (QoS) prioritization [5]. This ensures that tele-protection traffic packets do not incur additional latency due to queuing which is caused by waiting for larger, lower priority packets to be processed. This feature helps to guarantee that tele-protection traffic will be left untouched on congested circuits. Whereas traffic with lower priority may suffer from data loss, the tele-protection traffic should remain unaffected even during a network congestion scenario.

However, these techniques do not give absolute hard QoS guarantees offering deterministic latency. High priority tele-protection traffic may still have to wait when low priority packets are being processed. As stated in [6], the queuing delay encountered at a given hop due to a single packet from one of the other low priority or best effort queues that has already started to transmit, is unavoidable. An aggregation of this behaviour assuming several nodes in a wide area network results in high Packet Delay Variation (PDV) of tele-protection traffic. In extreme network congestion scenarios in a node, losses may even occur.

There has been research efforts and standardization on Time Sensitive Networking (TSN) which makes it possible to carry data traffic of time or mission critical applications with bounded delay over a bridged Ethernet network shared by various kinds of applications having different QoS requirements [7]. Fusion networking, a novel contribution to TSN, offers fixed latency and ultra low PDV properties and has been proposed as a solution to transport time critical tele-protection traffic over Ethernet wide area networks [8]. In this paper, we explore by simulation the performance of Fusion Scheduling and Queuing (FSQ), as a differentiated service queuing method for supporting time critical tele-protection traffic in Ethernet networks. We first implement and validate the FSQ algorithm using an ns-3 simulator, with the aim to achieve deterministic delays and zero PDV for tele-protection traffic. We then deploy FSQ on the communication network of a 4-bus power system, where we compare the performance of FSQ with Strict Priority Queuing (SPQ), a well-known scheduling technique used in industrial Ethernet networks to support real-time traffic.

The structure of the rest of the paper is as follows: In section II, we provide the background of fusion networking and related work on guaranteed performance for critical data in Ethernet networks. In Section III, we show details of the design and implementation of FSQ in ns-3. Section IV presents the validation of the FSQ implementation. In Section V, we evaluate the performance of tele-protection traffic in a network deploying FSQ and SPQ. Finally, our conclusions are presented in Section VI.

II. Background and Related Work

This section describes the fusion networking fundamentals and relevant research on guaranteed performance for critical traffic in industrial and smart grid protection applications.

A. Overview of Fusion Networking

Fusion is a technology bringing the advantages of circuit-switched networks to packet-switched networks [9]. The technology is built on the architecture of Integrated Hybrid Optical Networks (IHON). IHON is a concept bringing packet and circuit network domains together. IHON distinguishes between two types of traffic, a circuit-service class referred to as Guaranteed Service Transport (GST), and a packet-service class, referred to as Statistically Multiplexed (SM) class. The two classes of service share the same physical wavelength resource. The GST traffic offers hard QoS including: zero packet delay variations, zero packet loss, and low deterministic delay while the SM traffic is statistically multiplexed, accepting lower priority QoS.

Provisioning circuits of wavelength granularity leads to the well-known issue of low resource utilization in optical circuit switching and Wavelength Routed Optical Networks (WRONs) [10] because statistical multiplexing is not available. Therefore, to optimize the wavelength capacity, IHON first establishes GST wavelengths for the guaranteed traffic and then applies the wavelengths for transport of SM traffic whenever there is an idle time gap between GST packets. The GST traffic is not affected by this technique since the SM traffic is only added in the vacant gaps that are unused by the GST packets.

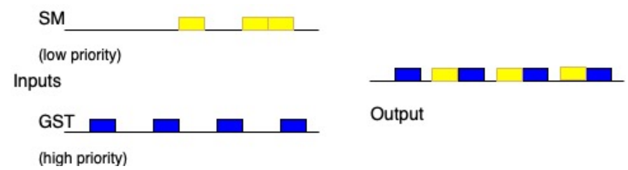

Figure 1. Fusion queuing and scheduling.

In FSQ shown in Fig 1, low priority SM packets are inserted only if there is a vacant gap between the high-priority GST packets. As such, PDV and packet loss are avoided on GST packets.

B. Related Work

Fodero et al. [11], proposed a deterministic packet transport method for transporting tele-protection channels across packet-based WANs while achieving the same performance as that of TDM-based systems. The method involves packetizing SONET signals of critical protection data to be streamed over an Ethernet network. These are transported deterministically through low-latency tunnels using "strict priority" queue schedulers to provide almost the same performance as conventional SONET/SDH networks. However, the approach only gives guarantee of the worse case PDV for each network egress port, that is the time for a lower-priority packet to complete an already started egress. For example 1.2us delay for a 1518-byte lower-priority packet at 10GE.

Standardization efforts for TSN, IEEE 802.1 mechanisms for minimizing delay and PDV have been in progress. One variant IEEE 802.1Qbu [12] defines a class of service for time-critical frames that requests the transmitter in a bridged Local Area Network to suspend the transmission of a non-time-critical frame and allow for one or more time-critical frames to be transmitted. When the time-critical frames have been transmitted, the transmission of the preempted frame is resumed. The technique allows non-time-critical frame to be preempted multiple times. This preemption mechanism enables the minimum delay on time-critical frames when mixed with non-time-critical frames. Some PDV might be experienced on high priority packets because preemption is only performed if at least 60 bytes of the preemptable frame have been transmitted and at least 64 bytes (including the frame CRC) remain to be transmitted. Adding the Ethernet mandatory inter-frame gap, preamble and delimiter, this results in a worst-case of 1240 bit (155 bytes) of delay, and a best case of zero delay.

Another variant, the IEEE 802.1Qbv [13], specified as enhancement for scheduled traffic, allows transmission to be switched on and off on a timed basis for each traffic class that is implemented on a port. The switching mechanism is achieved through individual on/off transmission gates associated with each traffic class queue with a list of defined gate operations that control each gate. The sequence of gate operations provides a repeating cycle of gate state changes. However, the duration and start of the time-slots may vary, hence, some PDV might occur. In addition, the timing of the gate operations assumes a time-synchronization protocol such as IEEE 1588 Precision Time Protocol (PTP) is operating. Hence, there is a challenge whenever PTP communication is interrupted.

End-to-end delays and upper bound delays, for switched Ethernet architectures in industrial applications have been evaluated using formal methods [14], [15], [16]. These works involved using priority-enabled switches, non-preemptive priority queuing models, and weighted fair queuing scheduling based on weighted round robin, or SPQ for time critical applications. Although these results found upper-bounded delays, hard QoS with fixed latency was not shown.

From the works reviewed, none of the approaches offer solutions of fixed latency and ultra-low PDV. This is primarily because the QoS prioritization techniques employed to manage high priority traffic will still be affected by lower priority packets at some point in the network. Our proposed approach of FSQ ensures fixed latency and zero PDV, by eliminating the influence of lower priority traffic on high priority traffic in the network.

III. Implementation of the Proposed Technique

A. ns-3 and Traffic Control

ns-3 [17] is an open-source discrete event simulator that provides support for network protocol simulations.

The traffic control layer in ns-3 attempts to give an identical implementation of the Linux Traffic Control infrastructure. The layer lies in between the network devices and network protocols like IP. It takes on the role of processing packets and performing various operations like scheduling, dropping, marking, and policing the packets. Outgoing packets from the network layer to the network device are intercepted by the traffic control layer, which are then en-queued into various queuing disciplines and allowed to perform various actions.

B. Fusion Scheduling and Queuing

1) Design: Fusion scheduling has two internal queues namely, GST and SM. Packets of critical traffic are placed in GST queue, with SM queue set as default queue for non-critical traffic. A VLAN-ID, port or IP address can be used to match traffic that is sorted into the GST queue, while other traffic are sorted in the SM queue.

In the GST queue, there is an application of deterministic delay, which is chosen as a function of the maximum size of an SM packet and data rate of the output network. This ensures that we can deterministically ensure the amount of delay incurred by each GST packet in a node.

2) Implementation: In our implementation in ns-3, a *DoEnqueue()* function operation first categorizes a packet as either GST or SM, and inserts it into first-in-first-out (FIFO) GST or SM queue respectively. At the time the GST packet enters its queue, the predetermined deterministic delay value is set for the packet to be scheduled out of the queue.

A *DoDequeue()* function call dequeues a packet from the GST queue when the current time matches its time-stamp plus the deterministic delay set.

IV. Validation

We validate the correctness of our FSQ implementation by testing it under various network load conditions. We compare the performance to another scheduling discipline called "Pfifo" in ns-3, which emulates SPQ. SPQ has been recommended as a solution to guarantee deterministic communication for industrial Ethernet communications [18], as well as protection applications over packet-based wide-area networks [11]. In SPQ, priority packets and regular packets are filtered into separate FIFO queues, where the priority queue must be completely empty before the regular queue is served [19].

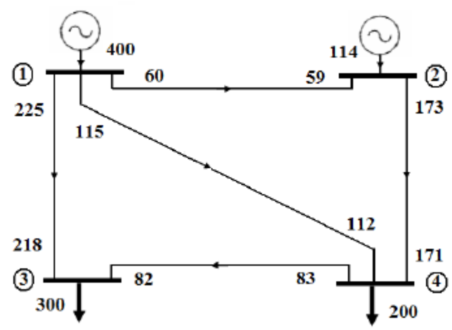

Figure 2. 4-bus test system.

A modified 4-bus power system network is illustrated in Figure 2, which we assume to be used in wide area protection and control operations. A ring networking topology is designed for the power network, involving four edge routers as shown in Figure 3, connecting the substations. The links are connected by point-to-point protocol over a $100\,\mathrm{Mbps}$ channel capacity. The two scheduling disciplines are installed on each router, and we measure network performance between substation 1 as source and substation 4 as the sink.

The performance metrics of average delay, packet delivery ratio and packet delay variation are used in the evaluations and are explained below:

- Average Delay: The average time difference between a packet being generated at a source node and its arrival at the destination node.
- Packet Delivery Ratio (PDR): The percentage of successful packets received with respect to the total number of packets transmitted.
- Packet Delay Variation (PDV): The absolute difference of delays between successive received packets divided by the total number of packets received.

In our simulation, we allocated sufficient and equal queuing buffer in the nodes, such that losses experienced in the network are due to the scheduling behaviours of the scheduling algorithms. The simulations were run for a $100\,\mathrm{seconds}$ duration, with 10 consecutive runs using different seeds for each simulation scenario.

We label critical traffic and non-critical traffic deployed using FSQ as GST and SM respectively, while critical and non-critical traffic deployed using SPQ as high priority (H-P) and low priority (L-P) respectively.

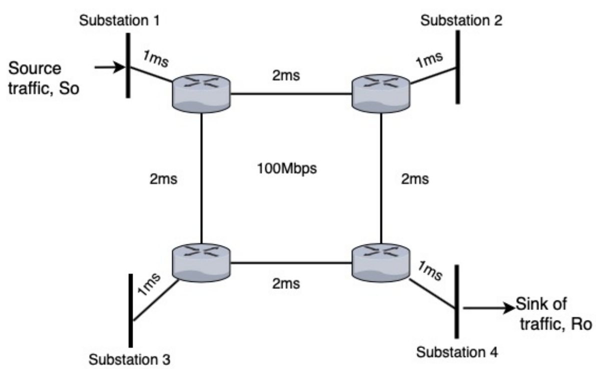

Figure 3. Ring topology for a 4-bus power network.

We test the network using three levels of critical traffic, (i.e. GST/H-P) of 10, 25 and $50\,\mathrm{Mbps}$ against increasing non-critical traffic from $10-100\,\mathrm{Mbps}$. We measure the PDR for both the critical and non-critical traffic in our network. The traffic patterns used in these tests scenarios were modelled as constant bit rate traffic sources and are enumerated as follows;

- Light load : $r_{\mathtt{c}} = 10\,\mathrm{Mbps}$, $r_{\mathtt{nc}} = \{10\,,...,100\,\}\mathrm{Mbps}$
- Medium load: $r_{\mathtt{c}} = 25\,\mathrm{Mbps}$, $r_{\mathtt{nc}} = \{10\,,...,100\,\}\mathrm{Mbps}$
- Heavy load : $r_{\mathtt{c}} = 50\,\mathrm{Mbps}$, $r_{\mathtt{nc}} = \{10\,,...,100\,\}\mathrm{Mbps}$

where $r_{\mathtt{c}}$ is critical traffic load, and $r_{\mathtt{nc}}$ is the non-critical traffic load.

A. Results and Discussion: Packet Delivery Ratio

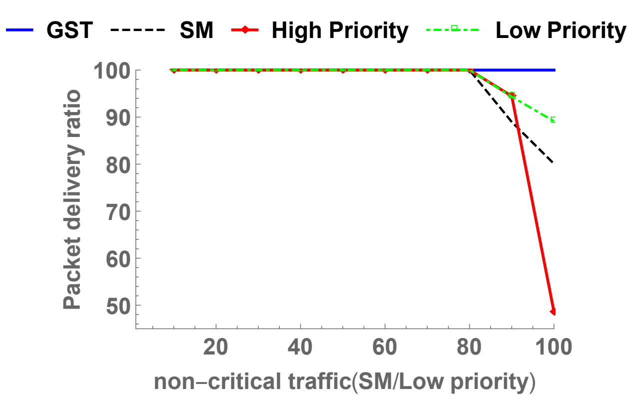

Figure 4. Light load, $r_{\mathtt{C}}$ = 10Mbps.

We first measure the PDR for critical and non-critical traffic in our network, when deployed with FSQ and SPQ.

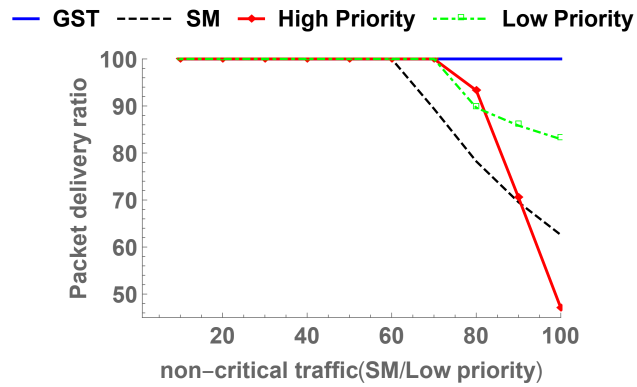

Figure 5. Medium load,$r_{\mathtt{C}}$ = 25Mbps.

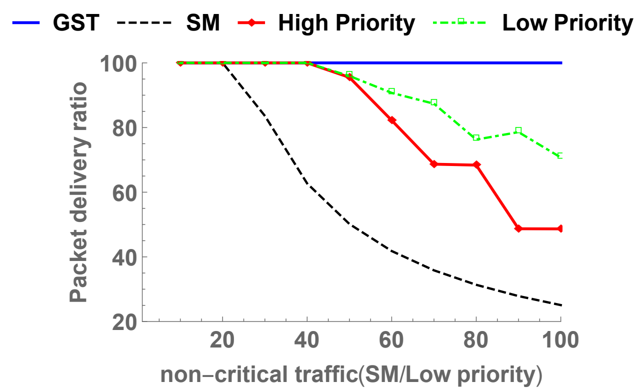

Figure 6. Heavy load, $r_{\mathtt{C}}$ = 50Mbps.

Figures 4, 5, and 6 show the PDR for light, medium and heavy loads of critical traffic explained earlier.

As can be observed the GST load, using FSQ achieved a 100% PDR in all three scenarios. No packet losses were experienced in the network because of the determinism of the scheduling and control throughout the network. The GST load will theoretically experience losses only if its capacity exceeds the network load capacity.

For light load ($r_{\mathtt{c}} = 10\,\mathrm{Mbps}$), the SM load experienced losses at SM = $80\,\mathrm{Mbps}$ and 90% of total load capacity of the network. Using the SPQ, both the high and low priority loads experienced packet losses after L-P = $80\,\mathrm{Mbps}$ and 90% of total load capacity of the network.

For medium load ($r_{\mathtt{c}} = 25\,\mathrm{Mbps}$), the critical traffic load occupies 25% of entire network capacity. The SM load started experiencing losses from SM = $60\,\mathrm{Mbps}$. Both the high and low priority loads experienced losses from L-P = $75\,\mathrm{Mbps}$. At L-P = $100\,\mathrm{Mbps}$, high priority load had a PDR of 47.1%.

For heavy load ($r_{\mathtt{c}} = 50\,\mathrm{Mbps}$), critical traffic load is 50% of the network capacity. The SM load experiences losses very early on from SM = $20\,\mathrm{Mbps}$ and declines rapidly to a low of 25% PDR at full SM load. The high and low priority loads experienced losses from SM = $40\,\mathrm{Mbps}$, with PDR of the high priority at 48.7% when L-P = $100\,\mathrm{Mbps}$.

The results above show that using FSQ enabled critical traffic to pass through the network without experiencing any packet losses, notwithstanding the increased non-critical traffic. On the other hand, using SPQ resulted in losses on the critical traffic as the non-critical traffic increased. The extreme packet losses experienced on high priority traffic when the network was overloaded, were due to losses in the queuing buffer.

The strict zero packet loss guarantee with FSQ results in significantly more losses being incurred on SM load, hence a good trade-off between acceptable losses on non-critical traffic should be considered during network dimensioning.

V. Performance of Protection Traffic

We test the network to see how protection traffic as critical traffic will behave using the two different scheduling approaches deployed on the nodes. The critical traffic can be modelled from two tele-protection traffic sources namely; Generic Object Oriented Substation Event (GOOSE) and Sample Values (SV) [20].

GOOSE messages are event driven and triggered by change of data-set values. SV are sampled measurements of current and voltage generated from devices called merging units, which are continuously sent. Assuming $50\,\mathrm{Hz}$ and a sampling rate of $80\,\mathrm{samples/cycles}$, SV generated will be $4000\,\mathrm{packets/second}$. We choose SV traffic as the critical traffic in our simulation which is modelled as a constant bit rate traffic source with packet sizes varying based on the data rate used, in order to ensure the property of $4000\,\mathrm{packets/second}$ being generated is maintained.

The non-critical traffic is modelled with the following traffic patterns (TP);

TP-1 constant bit rate traffic source, $p_{\mathtt{size}} = 1000$

TP-2 Traffic source with mean packet interval normal distribution ($\mu = (8 \cdot p_{\mathtt{size}})/d_{\mathtt{rate}}$, variance = 0), $p_{\mathtt{size}}$ uniformly distributed $(min, max = 500, 1400)$.

TP-3 Traffic source with mean packet interval exponential distribution ($\mu = (8 \cdot p_{\mathtt{size}})/d_{\mathtt{rate}}$, upper bound= $+10\%$ of μ), $p_{\mathtt{size}}$ uniformly distributed $(min, max = 500, 1400)$.

where $p_{\mathtt{size}}$ is packet size in bytes, $d_{\mathtt{rate}}$ is data rate of channel, μ is mean.

The aim of these tests are to evaluate the performance of SV as critical traffic, with different traffic patterns of non-critical traffic in the network. The following scenarios were tested on the network shown in Figure 3.

- Case 1 ($r_{\mathtt{c}}$(SV) = $10\,\mathrm{Mbps}$, $p_{\mathtt{size}}$ = 313) : $r_{\mathtt{nc}}(\textbf{TP-1}) = \{10, ..., 100\}Mbps$
- Case 2 ($r_{\mathtt{c}}$(SV) = $25\,\mathrm{Mbps}$, $p_{\mathtt{size}}$ = 781) : $r_{\mathtt{nc}}(\textbf{TP-2}) = \{10, ..., 100\}Mbps$
- Case 3 ($r_{\mathtt{c}}$(SV) = $25\,\mathrm{Mbps}$, $p_{\mathtt{size}}$ = 781) : $r_{\mathtt{nc}}(\textbf{TP-3}) = \{10, ..., 100\}Mbps$

A. Results and Discussions: Average Delay and PDV

In Figure 7, 8, and 9, we have plotted the average delays obtained for critical and non-critical traffic for the three scenarios. As can be seen, the GST load in all three scenarios measured a constant average delay, notwithstanding the increasing non-critical load in the network. On the other hand, in all three scenarios, the average delay of high priority load varied as the non-critical load increased in the network.

TABLE I: Packet Delay Variation (μsec)

	Case 1			Case2			Case 3		
$r_{\mathtt{nc}}$	SM	H-P	L-P	SM	H-P	L-P	SM	H-P	L-P
10	78.3	46.2	3.0	147.4	17.5	79.8	142.6	40.8	80.0
20	120.2	87.8	3.0	181.4	32.9	84.1	113.6	64.7	74.2
30	30.2	22.5	2.5	112.7	30.1	75.1	93.4	56.3	67.5
40	60.2	75.1	3.0	97.8	51.4	68.4	93.8	37.8	62.9
50	56.0	78.6	3.0	76.9	54.6	56.5	95.5	37.8	57.7
60	47.6	28.6	3.0	59.5	45.9	46.8	96.6	37.8	54.7
70	51.8	35.3	3.0	67.1	45.3	38.9	96.9	37.4	52.6
80	65.9	50.0	9.1	72.9	37.1	34.1	96.8	36.5	51.3
90	76.8	34.2	14.3	77.6	37.0	36.6	96.5	35.0	50.4
100	85.7	33.4	16.4	81.7	37.2	37.6	94.5	34.4	48.2

In Case 1, with non-critical traffic as a constant bit rate source (Figure 7), the SM traffic recorded stable delays until $60\,\mathrm{Mbps}$ load, beyond which the SM traffic had high delays. The high priority traffic varied by about $0.2\,\mathrm{msec}$, from the minimum to maximum load. Low priority traffic was observed with fairly constant delays to about $80\,\mathrm{Mbps}$, beyond which high delays were observed.

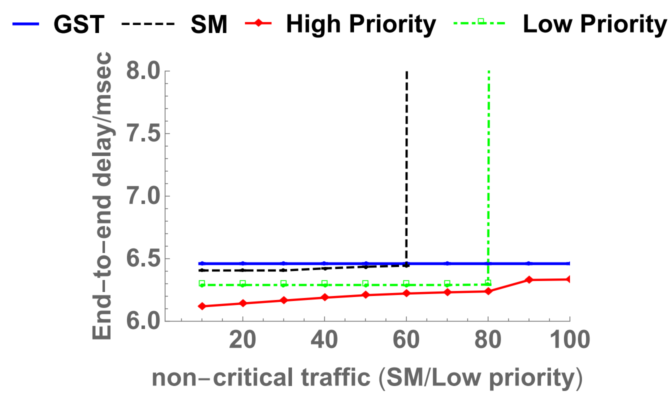

Figure 7. Case 1 ($r_{\mathtt{c}}$(SV) = $10\,\mathrm{Mbps}$, $p_{\mathtt{size}}$= 313, $r_{\mathtt{nc}}$(**TP-1**)).

With non-critical traffic as normal distribution in Case 2 (Figure 8), the high priority traffic varied in the network by about $0.2\,\mathrm{msec}$. Up to about $70\,\mathrm{Mbps}$ of low priority traffic was observed with stable delays, beyond this extremely high delays were recorded with packet losses. The SM traffic of up to $50\,\mathrm{Mbps}$ was measured with relatively stable delays.

In Case 3, where exponential load distribution was used as a non-critical traffic source, the worst mean delays for non-critical traffic were observed. The mean delay for GST load was constant while the variation of delays in high priority traffic observed with increasing load in the network was $0.2\,\mathrm{msec}$. Beyond $20\,\mathrm{Mbps}$ SM and $30\,\mathrm{Mbps}$ low priority loads respectively, very high delays were observed of the non-critical traffic.

Table I shows the PDV calculated for each of the scenarios. The PDV of GST traffic measured in all three scenarios was

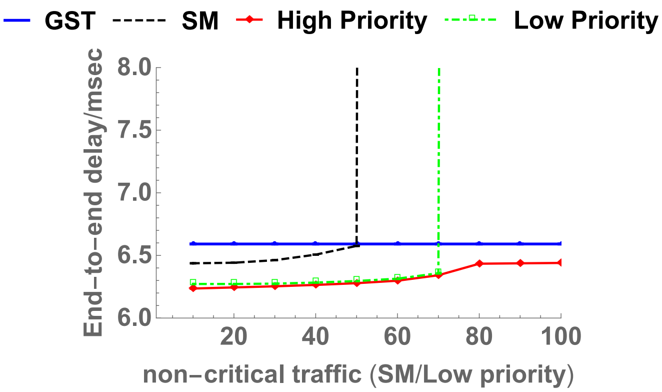

Figure 8. Case 2 (r_c(SV) = 25 Mbps , p_{size}= 781, r_{nd}(**TP-2**)).

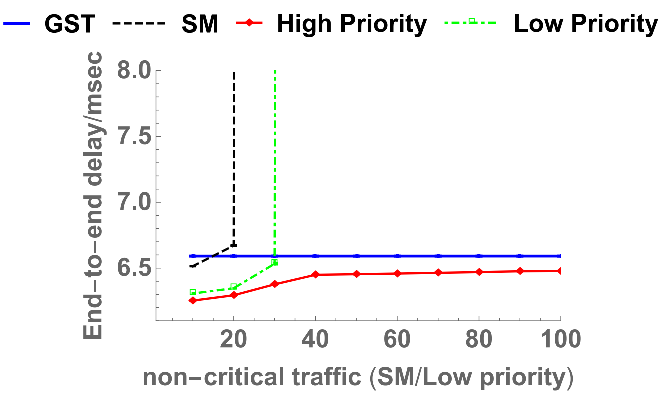

Figure 9. Case 3 (r_c(SV) = 25 Mbps, p_{size}= 781, r_{nd}(**TP-3**)).

zero. This shows that FSQ ensured the guarantee of zero PDV across the network. For the high priority traffic, the PDV varied based on increasing low priority load in all three cases.

VI. Conclusion

Simulation results show that deterministic end-to-end delays, zero packet loss and PDV can be achieved for tele-protection traffic (GST packets) by applying fusion queuing and scheduling in switched Ethernet networks. In addition, the delay of GST packets is independent of the system load and experiences a zero packet delay variation in a node. Utilization of network bandwidth is assured by inserting suitable lower priority (SM) traffic in available gaps between the GST packets.

For smart grid communication networks deploying VLAN, IP, and MPLS solutions for routing tele-protection traffic between substations, it is feasible to implement this scheduling mechanism on nodes in the network. For example, tele-protection data can be assigned unique VLAN-ID's which allow for marking the traffic as GST and placing it in GST queues in the node. When dimensioning the network with a given delay budget for critical protection applications, network performance can be guaranteed by varying the number of nodes and link distances between end points.

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