Analysis of End-to-End Delay Characteristics among Various Packet Sizes in Modern Substation Communication Systems based on IEC 61850

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Abstract*— Substation plays an important part for electricity generation, transmission and distribution systems, where voltage is stepped up/down or vice versa. The substation serves as a center point of all kind of connection between various power system networks, such as distribution line from electricity generation to household or industrial consumers. Hence, the performance of the substation should be maintained at all times with proper implementation of substation communication systems. A reliable substation communication system relies on the performance of data transmission's end-to-end delay characteristics in the substation communication systems. In this paper, we modelled, simulated and compared the end-to-end delay characteristics among different data packet sizes as well as different types of substation network topologies using IEC 61850. The simulation results confirmed that the larger packet sizes have higher amount of delays compare to the smaller packet sizes. Besides that, communication network topology with higher number of components obtained the results with a higher amount of end-to-end delays. Therefore, based on the simulated results, it is recommended to reduce the end-to-end delay of substation communication's data flow for a sustainable and reliable modern power system.

***Index Terms*— End-to-End delay, IEC 61850, IEDs, Riverbed Modeler, Communication Topologies, Substation Automation System.**

I. INTRODUCTION

The success of a substation automation system (SAS) relies on high reliable technology, standard and communication systems. Communication system has been an important role in real time operation of power systems. The application of data acquisition systems (DAS) in the communication systems assist to collect the measurement of data from a substation for monitoring, control and analysis. However, due to the limitation of bandwidth, the DAS communication protocols were optimized to operate over a low-bandwidth communication. As the system is moving towards the digital age, large amount of analog and digital data points are available in a single Intelligent Electronic Device (IED) and the communication bandwidth is no longer a limiting factor [1-3].

However, the data transmission time and control commands within the substation should be less than 4-ms as stated in the IEC 61850 standard [4]. Therefore, this pose a great challenge for substation designer as real time data transfer has becomes the key element of substation data communication. This challenge also applied to various design of communication network architectures in a substation system [4-5].

The main objective of this paper is to model, simulate and compare the end-to-end delay characteristics among different data packet sizes as well as different types of network topologies using IEC 61850. Based on the simulation results, propose an optimized design for the modern substation communication systems for protection, control and automation. For simulation, Optimized Network Engineering Tools (OPNET) or Riverbed Modeler is used to obtain the proposed model simulation results and compare them.

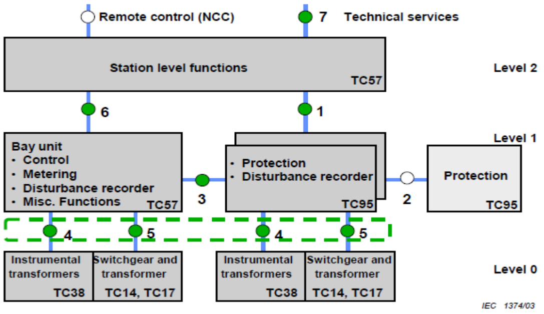
This paper is organized as follows: Introduction is in section I, network architecture simulation model of IEC 61850 based SAS is in section II, networks end-to-end delay characteristics are presented in section III. Section IV presents the simulation results and discussion. Finally, the conclusion is in section V.

II. NETWORK ARCHITECTURE SIMULATION MODEL OF IEC 61850 BASED SAS

A) Substation Level Construction

There are three basic level functional hierarchies in the SAS of an IEC 61850 based substation as shown in Fig. 1. These are as follows:

i) Process level '**0**': This level includes switchyard equipment's, such as CTs/VTs, Remote I/O, actuators, etc.
ii) Bay level '**1**': Bay level includes protection and control IEDs of different bays.
iii) Station level '**2**': The functions requiring data from more than one bay are implemented at this level.



NOTE Logical interface 2 (teleprotection) and the interface to the remote control centre (NCC) are beyond the scope of the IEC 61850 series.

Figure 1: Three level functional hierarchy proposed in an IEC 61850 [7].

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The basic Ethernet switched architectures or topologies are considered in this research. The topologies are; (1) cascaded (2) ring, (3) star, (4) star-ring and (5) redundant ring topology. The proposed simulation model is a D2-1 type medium size distribution substation as stated in IEC 61850-5 [6]. The Riverbed modeler software is capable to design and simulate the real-time performances of substation level network based on the IEC 61850. The IEDs at bay level are connected together through a switch then towards to the station level where the controller and the human machine interface are located for control command and monitoring. The simulation model consists of 12 bay level IEDs with the connection of Ethernet communication network by 10-BaseT UTP to each network node as shown in following Figs. 2-6.

A) Cascaded Topology

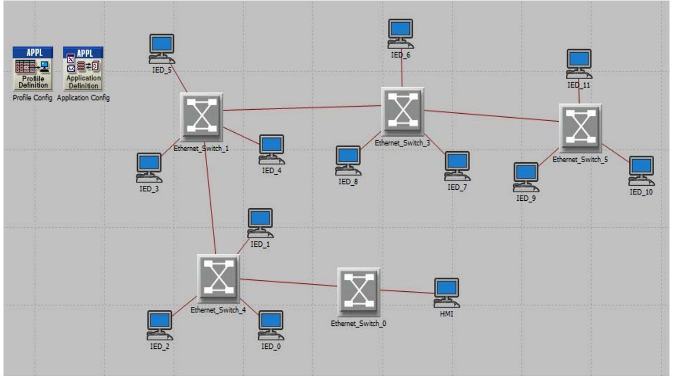

Figure 2: A typical diagram of cascaded network architecture.

A typical diagram of a cascaded architecture is shown in Fig. 2. Each Ethernet switch is connected with the previous switch and/or next switch in the cascade via one of its ports. The maximum number of switches which can be cascaded depends on the worst case of delay that can be tolerated by the system [9]. This topology may provide allowable time delays and it is cost effective due to its capability for shorter wiring connection to the central network point. However, no redundancy is achieved with this topology.

B) Ring Topology

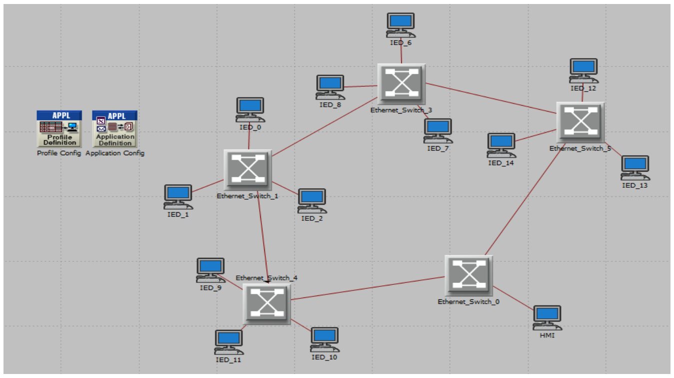

Figure 3: A typical diagram of ring network architecture.

A typical diagram of ring network architecture is a closed loop from the last switch to the first switch as shown in Fig. 3. However, the Ethernet switches don't support the looping. Therefore, it is required to employ managed switches with the Rapid Spanning Tree Protocol (RSTP). This protocol allows switches to detect loops and internally block messages from circulating in the loop and also allows reconfiguration of the network during communication network fault within sub-second. This architecture has potential to offer a better reliability, because it facilitates ***n-1*** redundancy i.e., IEDs can still communicate even if any one of the ring connection fails, where ***n*** is the number of switches. However, this architecture is costly and a bit complex [1, 4, 5, 8].

C) Star topology

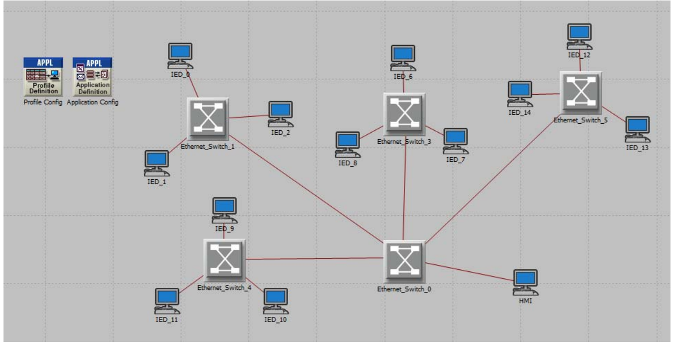

Figure 4: A typical diagram of star network architecture.

Fig. 4 shows a typical diagram of a star network architecture, where each station is connected directly to a common Ethernet switch***_0*** ('***0'*** is the center switch). The message transmission time delay for Ethernet switch based on star topology has the capability to comply with the IEC 61850 standard requirements. However, this topology has less reliability, because all the IEDs are connected to a single central Ethernet switch which is highly susceptible to environmental and electromagnetic interference conditions of the substation [1, 4, 5, 8].

D) Star-ring Topology

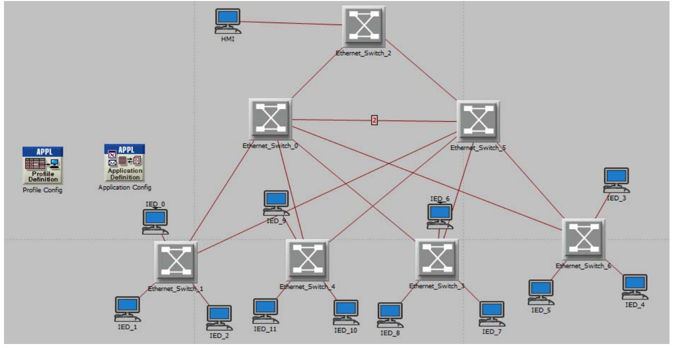

Figure 5: A typical diagram of star-ring network architecture.

Fig. 5 shows a typical diagram of a star-ring architecture, each bay level Ethernet switch is connected directly to two redundant main Ethernet switches. Both the main Ethernet switches are connected as a ring. This architecture provides higher redundancy but it requires two additional switches to arrange the star-ring network configuration [1, 4, 5, 8].

E) Redundant-Ring Topology

Fig. 6 shows a typical diagram of redundant-ring network architecture, which provides two completely redundant rings. Furthermore, both the rings are connected again with a ring of four main Ethernet switches. This type of architecture provides complete redundant ring network with medium latency or delay. However, this architecture requires many managed Ethernet switches with RSTP (i.e., IEEE 802.1w). Hence, this network provides highest reliability, on the other hand, suffers from high cost and the complexity [1, 4, 5, 8].

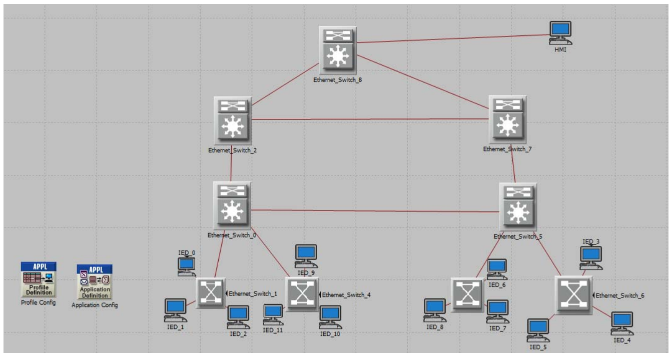

Figure 6: A typical diagram of redundant ring network architecture.

III. NETWORKS END-TO-END DELAY CHARACTERISTICS

The end-to-end delay characteristic for networks is the time measure, when a data packet is sent out from the source application layer to the time, when it is completely received by the application layer in the destination node. During this data transfer, delays may occur at any phase as listed below [2].

- Processing delay of the source node for transmission $= t_{sa} + t_{st} + t_{se}$ (1)
- Processing delay of the destination node for receiving $= t_{ra} + t_{rt} + t_{re}$ (2)
- The delay of other digital equipment's (switch) $= t_s$ (3)
- Link delay $= t_l$ (4)

The digital network of this analysis adopts the Ethernet as the bottom protocol, TCP/IP as the network layer and transfer layer protocols, respectively. The end-to-end delay model of the network is shown in Fig. 7.

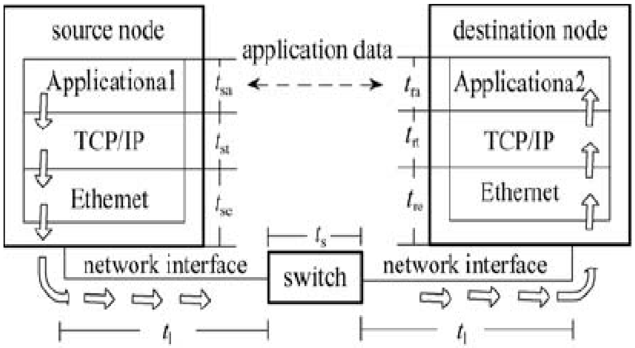

Figure 7: End to end delay of messages flow diagram [2].

A) Processing delay of the source node for transmission

The processing delay of the source node is ($t_{sa} + t_{st} + t_{se}$), where, t_{sa} means the time required by the application of the source node when the message is partitioned. t_{sa} is related to the length of original data frames from the source node and the maximum limitation of the data packets in the application layer. t_{st} refers to the time during a message head for TCP/IP is appended. t_{se} denotes the time during media access control (MAC) message head is appended [2].

B) Processing delay of the destination node for receiving

The processing delay of the receiving or destination node is ($t_{ra} + t_{rt} + t_{re}$), where t_{re} represents the time required when the MAC message head is removed, t_{rt} represents to the time required for removing TCP/IP message head, and t_{ra} represents the time required, when the application of the source node assembles a new messages [2].

C) Delay of other digital equipment (Switches)

The processing delay of other digital equipment is t_s. It is measured from the time, when the message is received to the time, when the message is transmitted by that switch, and it is related to the transfer strategy and exchanging rate of data [2].

D) Link delay

The transfer delay of the links t_l is measured from the time when the message arrives at the network interface of the source node to the time, when the message arrives at the network interface of the destination node (the switch delay is not included here). It includes queuing delay t_{que}, transmitting delay t_{tra}, and spreading or propagation delay t_{pro} as given below [2].

$$t_l = t_{que} + t_{tra} + t_{pro} \tag{5}$$

t_{que} is measured from the time, when the message queues to the time it is transmitted. It depends on accessing and controlling methods of the communication network medium. t_{tra} is measured from the time, when the source node begins to send the first bit of the message to the time when the last bit is sent. It depends on the length of the message and the transfer rate of data. Let the length of the message is λ, the transfer rate of data is μ bit/s, and consequently the transmitting delay t_{tra} is given as follows [2]:

$$t_{tra} = \frac{8\lambda}{\mu} \tag{6}$$

t_{pro} is measured from the time, when the source node begins to send the first bit to the time when the last bit is sent. It depends on the transfer distance and propagation as well. Suppose the transfer distance is l m, and the transmitting rate is v m/s, the propagation delay t_{pro} can be represented as below [2]:

$$t_{pro} = l/v \tag{7}$$

The total delay time T is given by the following equation [2]:

$$T = t_{sa} + t_{st} + t_{se} + t_l + t_s + t_{ra} + t_{rt} + t_{re} \tag{8}$$

IV. SIMULATION RESULTS AND DISCUSSION

A) Simulation Contents and Objectives

The simulation results are carried out between the station level and the bay level. By using the video conferencing service for signal transmission, such as analog values, status information and control command packets.

The main objectives of these modelling and simulation are:

i) To analyse end-to-end delay characteristics that causes by different packet sizes of signal in the SAS.
ii) To analyse end-to-end delay characteristics that causes by different network topologies in the SAS.

B) Simulation Results and Discussion

In this section, the simulation results of various packet sizes on substation network topologies and various substation topologies with same packet size are analyzed and discussed in detail.

Fig. 8 shows the average delay of packet data transfer rate per second for a cascaded topology. The packet sizes from bottom to top are 128, 256, 512, and 1024 bytes, respectively. All the 4 cases reach their steady state at ~125 seconds. The system with a higher bytes of packet data show a higher rate of average delay packet data transfer rate per second. When the packet size is 1024, the end-to-end delay exceeds 4-ms towards 5.25-ms. However, when the packet sizes of 512, 256 and 128 are under save operating zone of 4-ms.

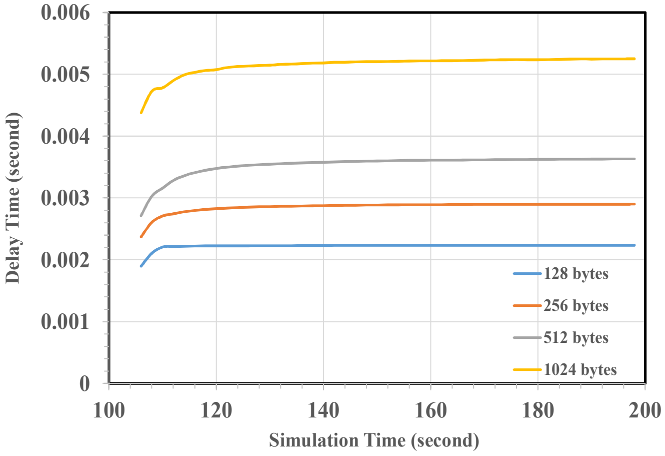

Figure 8: End-to-end delay characteristics in cascaded topology.

Fig. 9 shows that the average delay of packet data transfer rate per second for a ring topology, the packet sizes from bottom to top are 128, 256, 512, and 1024 bytes, respectively. All the 4 cases reach their steady state at ~2-minutes and 25 seconds. The system with a higher bytes of packet data show a higher rate of average delay packet data transfer rate per second. When the packet size is 1024 bytes, the end-to-end delay exceed 4-ms towards 4.8-ms. However, if the packet sizes of 512, 256 and 128 bytes are under save operating zone of 4ms end-to-end delay.

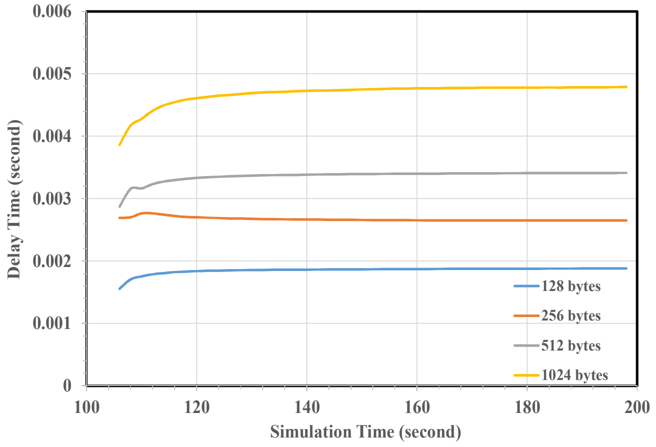

Figure 9: End-to-end delay characteristics in ring topology.

Fig. 10 shows the simulation result of star topology, from bottom to top are the packet sizes are 128, 256, 512 and 1024 bytes. The average delay packet data transfer rate per second occurs around 2 minutes and 20 seconds. The system with higher bytes of packet data result with a higher average delay packet data transfer rate per second. When the packet size is 1024 bytes, a huge delay variation is observed compare to packet sizes of 128, 256 and 512 as shown Fig. 10. Besides that, the average end-to-end delay is ~5.4-ms which exceeds 4-ms. On the other hand, the packet size of 128, 256 and 512's end-to-end delay are lower than 4-ms.

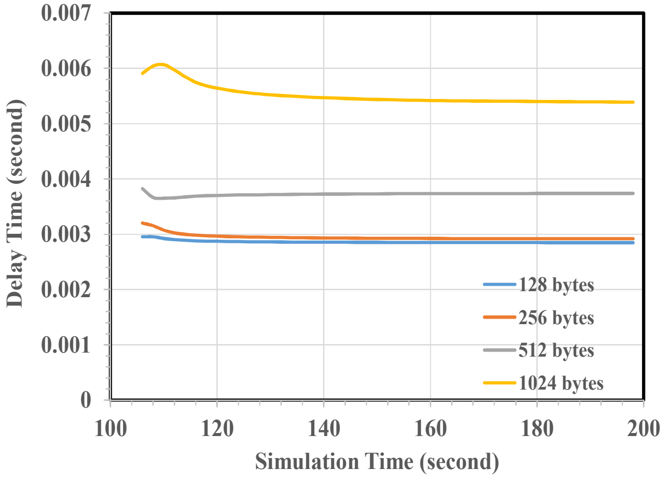

Figure 10: End-to-end delay characteristics in star topology.

Fig. 11 shows simulation results of star-ring topology, from bottom to top are the packet sizes of 128, 256, 512, and 1024 bytes. The average delay of packet data transfer rate per second reaches to their steady state at ~2-minutes. The system with a higher bytes of packet data show a higher rate of average delay packet data transfer rate per second. The end-to-end delay for all 4 cases of packet sizes have exceeded within 4-ms of 5.8-ms, 7-ms, 7.5-ms, and 9.6-ms. This result occured due to extra Ethernet switches and connection presence in the network for the redundancy consideration for the system.

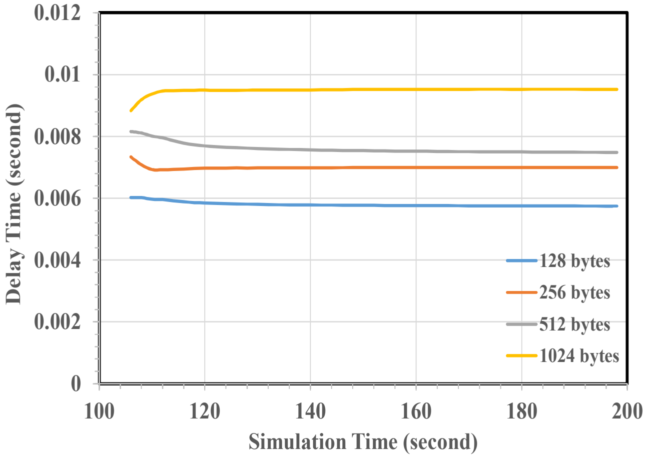

Figure 11: End-to-end delay characteristics of a star-ring topology.

Fig. 12 shows the simulation result of redundant ring topology, from bottom to top are the packet size of 128, 256, 512 and 1024 bytes, respectively. The average delay of packet data transfer rate per second reaches to their steady state at around 2 minutes and 55 seconds. The system with a higher bytes of packet data show a higher rate of average delay packet data transfer rate per second. The end-to-end delays for all 4 cases of packet sizes have exceeded 4-ms of 5-ms, 6-ms, 6.6-ms and 8.5-ms. This result occurred due to extra Ethernet switches and connection presence in the network for the redundancy consideration for the system.

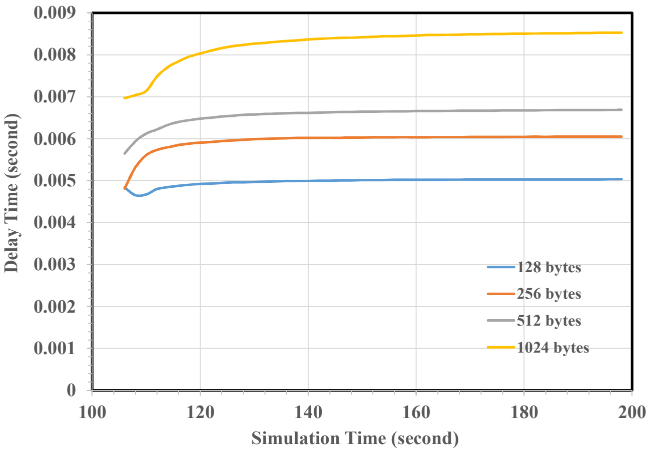

Figure 12: End-to-end delay characteristics of a redundant ring topology.

From Fig. 13, it shows clearly that the average end-to-end delay characteristics for different topologies, such as, cascaded, ring, star, star-ring and redundant-ring topologies with the same packet size of 256 bytes. The redundant ring architecture shows a higher end-to-end delay of 6-ms compare to other 4 network architectures. This result occurred due to extra Ethernet switches required for redundancy which contributes to a higher delay of packet data transfer rate per second. The star-ring topology shows a result of slightly lower that redundant ring topology but still this result in a higher delay per second of 5-ms which due to extra IEDs introduced into the system.

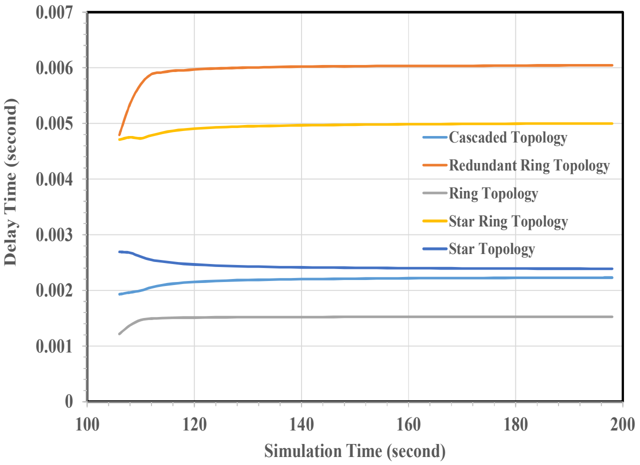

Figure 13: Comparison of End-to-end delay characteristics of ring, star, star-ring and redundant-ring topologies.

The redundant ring and star-ring topologies both exceed the end-to-end delay of 4-ms which stated by the IEC 61850 [6]. The ring topology shows a better result of the lowest delay average packet data transfer rate per second among the five topologies with the end-to-end delay of 1.5-ms. The star topology show a slightly higher delay per second due to all the IEDs are connected to a single Ethernet switch with the end-to end delay of 2.4-ms. In addition, the cascaded topology has a bit slightly lower end-to-end delay compare to the star topology of 2.2-ms.

V. CONCLUSION

In conclusion, the higher number of bytes of a message transfer in most network architectures will result a higher amount of end-to-end delay. Besides that the redundant ring shows a higher end-to-end delay with constant message size of bytes compare to other 4 network architectures, such as, cascaded, star, ring, and star-ring topologies. Additional IEDs and Ethernet switches will contribute to the delay of data transfer rate per second in a network.

We simulated different network architectures, such as, cascaded, star, ring, star-ring, and redundant ring topologies using the OPNET simulator. We obtained different types of end-to-end delay characteristics for different packet sizes. Hence, these results confirmed that the larger packet sizes result with higher amount of delays compare to the smaller packet sizes. Therefore, the recommendations for future improvement on reducing the end-to-end delay in substation communication networks are listed as below:

1) It is recommended not to send higher order packets for safe and reliable power systems.
2) The layout design of the network should be reasonable.
3) Bandwidth of network should be distributed accordingly to the level of data flow.

REFERENCES

[1] T. S. Sidhu, M. G. Kanabar, and P. P. Parikh, “Implementation Issues with IEC 61850 Based Substation Automation Systems,” *in proc. of the Fifteenth National Power Systems Conference (NPSC),* IIT Bombay, India, December 2008. pp. 473-478.

[2] H. Gao, W. Jin, and G. Liu, “Simulation study on delay of end-to-end data communication for protective relaying in substations,” Front. Electr. Electron. Eng., China 2008, vol. 3(2), pp. 246–250.

[3] H. Ali and D. Dasgupta, “Effects of time delays in the electric power grid,” J. Butts and S. Shenoi (Eds.), Critical Infrastructure Protection VI IFIP (International Federation for Information Processing), AICT (Advances in Information and Communication Technology), vol. 390, 2012, pp. 139-154.

[4] J. C. Sailor, R. Patel, S. U. Kulkarni, “IEC 61850: Substation Automation Protocol & Implementation Issues for Distinctive Substation Automation,” All India Seminar on Intelligent Motion control of Electrical Drives, The Institution of Engineers (India), Udaipur, December 2010.

[5] M. G. Kanabar and T. S. Sidhu, “Reliability and availability analysis of IEC 61850 based substation communication architectures,” *in proc. of the IEEE Power & Energy Society General Meeting 2009 (IEEE PES GM 2009), 26-30 July 2009,* Calgary, AB, Canada.

[6] IEC-TC 57, “Communication networks and systems in substations - Part 5: Communication Requirements for Functions and Device Models,” IEC Standard IEC/TR 61850-5, Edition 1.0, Geneva, Switzerland, 2003.

[7] IEC-TC 57, “Communication networks and systems in substations - Part 1: Introduction and overview,” IEC Standard IEC/TR 61850-1, Edition 1.0, Geneva, Switzerland, 2003.

[8] M. P. Pozzuoli, “Ethernet in Substation Automation Applications – Issues and Requirements,” RuggedCom Inc., Energy Central, July 2007**.**

[9] S. Coppel, T. Tibbals, and A. Silgardo, “Practical Considerations for Ethernet Networking within Substations,” Schweitzer Engineering Laboratories, Inc. (SEL), Energy Central, February 2008.