Comparison Study of Various Factors Affecting End-to-End Delay in IEC 61850 Substation Communications Using OPNET

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***Abstract*— The use of IEC 61850 communication protocol has more widely applied in electrical engineering, it presents new challenges to real-time performance simulation and testing of protective relays. In this paper, the OPNET Modeler simulation software has been used for the modeling of intelligent electronic device (IED) in substation level network. Based on simulations, different types of data stream have been discussed, such as, periodic data stream, random data stream and burst data steam. The specific studies using these models to construct substation automation system (SAS) network on OPNET modeler was made to reveal the influence of each factor to the real-time performance, which is also included in this report.**

***Index Terms*— IEC 61850, substation automation system (SAS), Real-time, Power system simulation, OPNET Modeler, Transmission delay.**

I. Introduction

Substation intelligent electronic devices (IEDs) are transmitted through the data communications network, once the data packets transfer has been delayed, and has not arrived target devices within the predetermined period of time, which may lead to extremely serious consequences, and endanger the substation and even the entire grid [1-8]. The use of communication in substations has been in vogue for more than two decades nowadays. Over the years, communication system has evolved from offline data collection to the more real-time functions realization [1, 7]. Substation communication network transmission packets have strict delay requirements, real-time study for the underlying communication network, in particular, the media access control (MAC) layer protocol, while ignoring the real-time upper-layer protocols [2]. The transmission protocol, network load and networking mode are the main factors affecting the real-time performance of the substation automation system (SAS) network [3-4]. Among the transmission delay constitution factors, message packaging and parsing take up most of the time, which relates to the transmission model and protocol [5].

According to the IEC61850-5, the messages transmission time requirements for the SAS network must be ensured under any operating conditions and contingencies inside the substation. Also, the dynamic performance of the SAS network must be studied during the planning stage in order to catch the network performance problems ahead of the deployment stage [6]. The modeling of communication requires the definition of objects (for example, data objects, data sets, report control, and log control) and services provided by objects (for example, get, set, report, create, and delete).

However, the real-time data transmission of underlying network is only laid the basis for real-time performance of substation communication network, packets end-to-end real-time truly reflect the real-time performance of substation communication. Substation communications network usually use TCP/IP protocol stack as a network layer and transport layer protocol, in order to ensure openness and interoperability of systems [9]. The OPNET model is used to simulate various SAS network under different scenarios, allowing user to set the raw sample rate, fault time, number of faults, background traffic and other configuration parameters [6, 10]. As part of IEC 61850 standard special messages are also planned for a quick exchange of information between the IEDs, so called GOOSE (Generic Object-Oriented Substation Event) [4, 11]. The network topology is critical when using the GOOSE messaging. Since the message may include protective signals, redundancy of the Ethernet LAN may be required [4, 12-15]. For the star architecture, a single point of failure causes communication failure and network recovery times are approximately 5-6 ms per Ethernet switch [7, 12-15].

In this paper, star network architectures have been used for the modeling of IEC 61850 and analyzing the simulated results. Such as, (i) According to substation communication network performance requirements, substation communication network architecture solutions based on IEC 61850 standard have been analyzed. The feasibility of the Ethernet substation communication network has also been analyzed. (ii) Substation messages transmission delay and its impact factors using several methods that can improve the real-time performances are discussed. A comprehensive study of substation communication network packet transmission delay of the composition and the impact of this delay are considered. There are several ways to improve Ethernet real-time effective measures are also included. (iii) It has proposed to characterize the data stream for transmission substation communication network, create a data flow model. Using OPNET network simulation, established the IEC 61850 based substation-level network simulation model, analyzed the real-time performances in substation level network with different bandwidths and different types of networks.

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This paper is organized as follows: Introduction is in section I, model of substation automation system (SAS) is in section II, simulation setup is in section III. Section IV presents results and discussion. Finally, the conclusion is in section V.

II. Model of Substation Automation System (SAS)

A) Substation Level Construction

There are three basic functions of a SAS, such as, control, monitoring and protection. Substation based on IEC 61850 logically can be divided into three sections, such as, i) Substation level, ii) Bay level and, iii) Process level, as shown in Fig. 1. The station level device has database computers, operator workstations, remote communication interfaces; the process level device has typical I/O's, smart sensors and actuators; and the bay level device has control protection or monitoring units, etc.

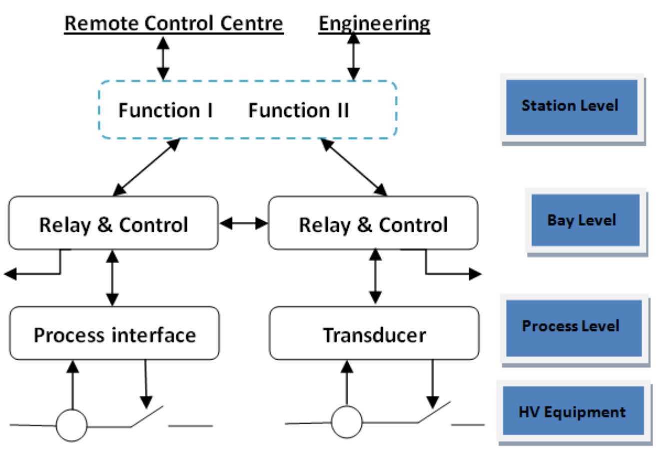

Fig. 1. SAS hierarchy and logical interfaces.

B) Substation Data Flow Analysis

There are several types of data flow within a substation. Based on IEC 61850 protocols, the characteristics of the packet can be divided into seven different categories of messages, as shown in Table 1.

From the perspective of time domain view, substation communication network data stream can be summarized in three types. These are: i) periodic data stream, ii) random data stream, and iii) burst data stream. The periodic data stream means the regular transmission of switch state information and analogue data from bay level IEDs to station level monitoring devices during normal operation. There are huge amount of this type of data, it requires high level real-time performance, the data variation is very small, having good stability. The random data, including some short length and high real-time data packets, such as: switch operation commands, time synchronization, also include some long length and low real-time packets, such as relay protection setting value modification, wave record data transmission. The burst data stream, including data transmission of protection action and switch position changing from bay level IEDs to station level monitoring under frequent node failures and multi-faults situations. It combines large amount of data, also require a high level real-time performance.

Table 1. Message type and performance requirement in SAS network [8]

Message Type	Example Messages In PICOM	Transfer Time Range (ms)
1. Fast Message	Trigger	10 - 100
	Complex Block or Release,	10 - 100
	Fast Broadcast Message	1
	Process State Changed	10 - 100
	Trip	1
2. Medium Speed Message	Process Value in r.m.s.	50 - 1000
	Request for synchrocheck, interlocking	10 - 100
	Process State	1 - 100
	External State	1 - 100
3. Low Speed Message	Measured Value or Meter Value such as Energy	100–1000
	Non-electrical Process Value (temperature)	1000 -5000
	Fault Value e.g. fault distance	0.1 - 5000
	Event/Alarm	100 - 1000
	Mode of Operation	10 - 100
	Set Point	100 - 1000
	Acknowledgement by Operator or auto.	10 - 1000
	Date and Time	100 - 1000
4. Raw Data Message	Process Value (sample voltage & current)	0.1 -10
5. File Transfer	Report such as Calculated Energy List	1000 -5000
	Mixed Fault Information	1000 -5000
	Mixed Fault Data such as Disturbance Recording	5000
	Event/Alarm List	100 - 1000
	ID Data, Setting	1000 -5000
	Diagnostic Data	5000
6. Time Syn-chronization Message	Synchronization Pulse	0.1 - 10
7. Command Message with Access Control	Command	1 – 1000

III. Simulation Set Up

A) Simulation Model

IEC 61850 uses different stacks for different kinds of traffic. A star topology has been used in a substation bus level network, the IEDs between bay level and substation level are connected together through a switch. In this model, a D2 type medium-sized distribution substation is defined as an IEC61850. According to the data flow characteristics of the substation communication network, the OPNET modeller software is used to analysis the real-time performances of the substation level network based on IEC 61850. Fig. 2 shows the station level network which is consists of 18 bay level IEDs, a substation monitoring host and a server. Each network node is connected with the Ethernet communication network by 10-BaseT UTP. In order to increase the reliability of the network, the substation bus is required to build a dual network redundancy. Due to the independence of the physical network and the logic network, only one network simulation is required, so only the internal network communication has been simulated, to the exclusion of the remote communication part.

As, each logical node (LN) message mapping includes TCP/IP protocol layer, all objects and services are the base of the function model, directly use the ethernet_wkstn_adv LN model in OPNET to simulate the data communication between station level and bay level. The data model including its services is mapped to a mainstream communication stack consisting of manufacturing message specification (MMS), TCP/IP, and Ethernet; time critical messages directly to the link layer of the Ethernet.

By using the video conference service to simulate the periodic data stream and the random data stream, using the file transfer protocol (FTP) service to simulate the Bay level protection and control (P&C) IEDs to send fault recorder, protection action information and unexpected stream to substation level.

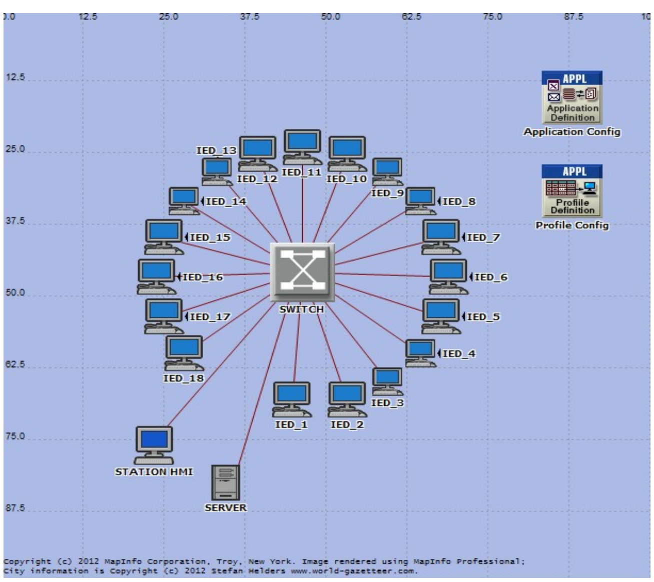

Fig. 2 Station-level network simulation model.

Application Config and profile Config have been used to configure the global parameters of the simulation model. The application Config set with application parameters, which describe the action of applications, including the size of a packet or the data sending interval e.g., profile Config is used to describe the applications involved in the same user group, also used for describing the specification of each application, such as when the simulation starts and how long it will last. During a simulation, packets sent from IEDs are received by the hub receiver object (hub_rx_0_0) and processed up the protocol stack to the application module. After processing, they are sent down the stack to the transmitter (hub_tx_0_0), then back to the IEDs [10, 15].

B) Simulation Parameters Configuration

The worst case of the load bus has been set as the simulation conditions, including the periodic data flow, random data flow and burst data flow. These data flows are discussed in previous section. The specific configurations are as follows:

(1) *Periodic data stream:* the bay level LNs using the user datagram protocol (UDP), to send all the telesignalisation and telemetering to the host by 20 ms cycle, such as, analog values and status information etc., and the data length is 256 bytes [10, 15].

The main configuration parameters of the video conference are as follows:

Incoming Stream Interarrival Time (second): constant (0.02)
Outcoming Stream Interarrival Time (second): constant (0.02)
Incoming Stream, Frame Time (bytes): constant (256)
Outcoming Stream Frame Time (bytes): constant (256)

(2) *Random data stream:* The host send control command packets to bay level notes IDE1 and IED2, the message length is 128 bytes, and the arrived packets obey the exponential distribution of $\lambda = 0.01$ [10, 15].

The main configuration parameters of the video conference are as follows:

Incoming Stream Interarrival Time (second): exponential (0.01)
Outcoming Stream Interarrival Time (second): exponential (0.01)
Incoming Stream, Frame Time (Bytes): constant (128)
Outcoming Stream Frame Time (Bytes): constant (128)

(3) *Burst data stream:* Server nodes send the burst data stream packets to the host nodes via FTP, the arrived messages obey the Pareto distribution by the ON duration parameters [10, 15], k = 0.512 ms, $\alpha = 1.1$, and the OFF duration subject to the negative exponential distribution of $1/\lambda$, the length of the data is subject to a constant distribution with 1024-byte mean value. The configuration parameters of the FTP are as follows:

Command Mix (Get / Total): 50%
Inter-request Time (seconds): Pareto (0.000512, 1.1)
File Size (Bytes): constant (1024)

IV. Results and Discussion

This section analysed the overall performance of the star topology network, the sending packet size, sending interval and the CPU utilization has been simulated, and the impact to end to end data caused by high-level protocol. By changing a single variable in the simulation, simply it is possible to analyse the real-time performance of the transmission [11, 15].

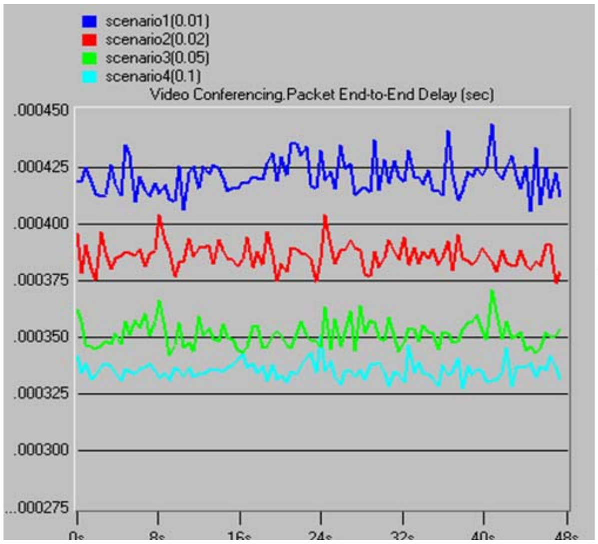

Fig. 3. End-to-end *transmission delay* messages in different packet interval.

The end to end delay of packet interval is shown in Fig. 3, from top to bottom, the packet interval from top to bottom are 0.01 s, 0.02 s, 0.05 s, and 0.1 s, respectively. The rest of the configurations remain same. The end-to-end real-time performance of the relay protection data stream is impacted by the interval of the periodic data stream. Fig. 3 shows clearly, when the packet interval is 0.01 s, the end-to-end delay in 0.425 ms fluctuation, compared when packet interval is 0.1 s, the delay fluctuation is down to 0.337 ms. Obviously the data stream interval is smaller, the end-to-end delay time is greater and more undulate.

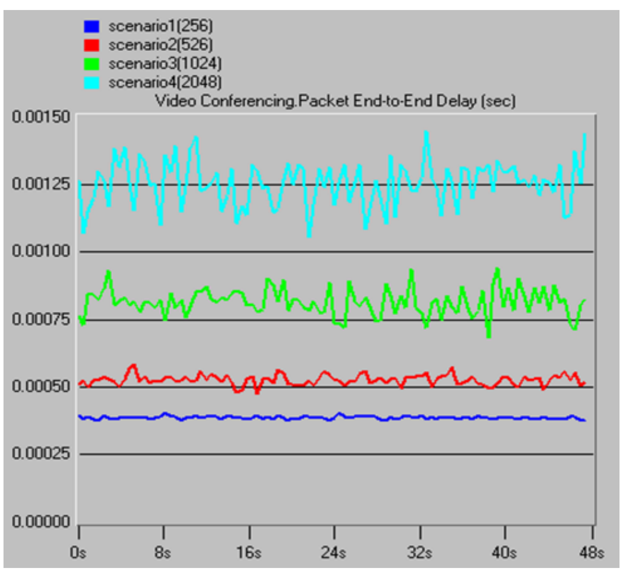

Fig. 4. End-to-end *transmission delay* message in different packet sizes.

The end-to-end delay of message in different packet size is shown in Fig. 4. The packet sizes from top to bottom are 256, 528, 1024, and 2048, respectively. It shows clearly that with the increase of packet sizes, the end-to-end delay time increases. When data packet size is 256, the end-to-end delay is about 0.4 ms and the delay variation is not much fluctuating (i.e., like a smooth variation or a steady condition), but when the packet size is 2048, the end-to-end delay significantly increases with huge variations. For this reason, in the actual configuration, it should avoid to send a variety of data streams at the same time, as well as avoid to send too large packets to meet the real-time requirements [11, 15].

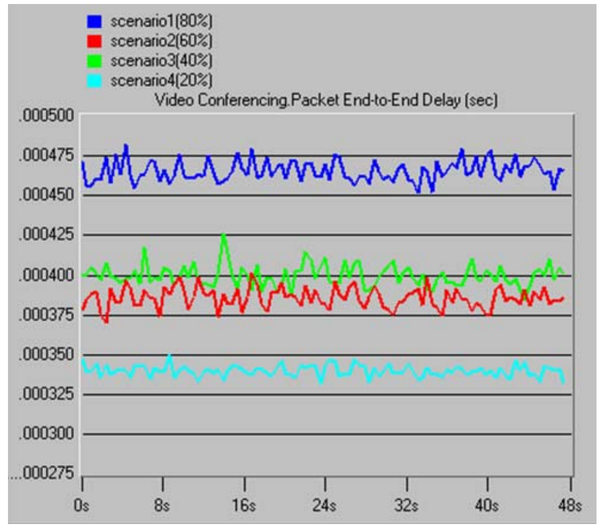

Fig. 5. End-to-end *transmission delay* in different CPU background utilization.

The end to end delay of message in different CPU background utilization is shown in Fig. 5. The CPU background utilization from top to bottom is 80%, 60%, 40%, and 20%, respectively. Fig. 5 shows clearly that when the CPU background utilization is increasing, the delay of the protective relaying data stream is increasing. However, when the CPU background utilization is increasing the station bus traffic is increasing, the possible conflicts to reduce real-time performances of the protective relaying end-to-end data stream, which can be solved by reducing the link background utilization or increasing the Ethernet bandwidth.

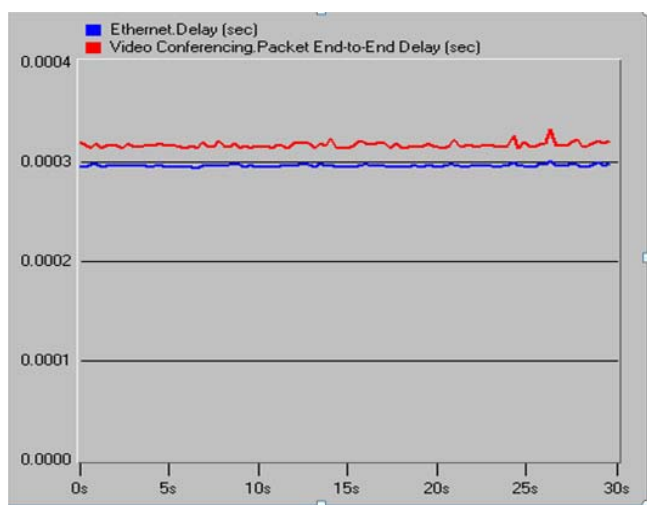

Fig. 6. Comparison of control command messages end-to-end delay and Ethernet delay.

The comparison of control command message end-to-end delay and the Ethernet delay is shown in Fig. 6. Simulation result shows that the end-to-end delay fluctuation of the control command is about 0.32 ms, up and down, 0.30 ms higher than the Ethernet link delay 0.02 ms. This is mainly caused by the encapsulation and separation of high-level protocol, before it reaches to the destination node application, the messages need restructuring. That will consume a certain amount of time, apply to high-level protocol decoding algorithm, reflecting the high-level protocol end-to-end real-time data streams that have a significant impact. Therefore, it is required to select the end-to-end delay and the Ethernet delay carefully for bay level control IEDs [11, 15].

V. CONCLUSION

This paper presented the performance of IEC 61850 based on simulation results and suggested that the practical applications should optimize the size of the packet, select small packets and avoid too large packets, avoid to send a variety of data streams at the same time to ensure real-time and reliable data transmission. The transmission data stream should be set at high-level of protocols, high real-time requirement of the selected UDP/IP, and high reliability requirement of the selected TCP/IP for different levels. To meet the high real-time requirements for substation protection relay data stream, with modelling of communication between bay level protection & control IEDs and station level local monitoring. The main factors affecting delay have been concluded, such as, packet interval transmission, packet sizes, the utilization of CPU background and high level protocols. Therefore, for practical applications, it is recommended to consider reasonable configuration of parameters, then the real-time data transmission will improve and ensure the normal operation of substation.

ACKNOWLEDGEMENT

This research is supported by the Centre for Smart Grid and Sustainable Power Systems (Coperative Research Centre for Infrastructure and Engineering Asset Management (CIEAM) grant), the Faculty of Science and Enginering, Curtin University, Australia.

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