Gigabit Ethernet Based Substation under IEC61850 standard

Ali Raza*, Khalil Ullah**, Saleem Ahmed**, Salman Ahmed[1], Hyuk-Soo Jang* and Hyo-Sik Yang[2]

Abstract**-- Communication architecture for substation automation is one of the challenging and subtle tasks to address in order to visualize the substation into digital world under the umbrella of IEC61850. Communication paradigm for substation automation demands critical importance because of two reasons; as communication arena is changing day by day so it is convenient to opt for something that is simple to deploy and incur a less cost in terms of time and asset when migration is to be considered since data-intensive applications drive the incremental demand for bandwidth as per growing need with the expansion of concerned network and last but not least the interoperability as it is one of the core constrained put by IEC61850 for substation automation. So it is viable to consider Ethernet as the most promising solution for the communication architecture of substation automation as Ethernet technology has changed the trend of communication network because of its availability, efficiency, and cost effectiveness on the other hand interoperability is assured based on the proven and highly deployed industrial Ethernet. This paper presents analysis and the crucial need for the deployment of Gigabit Ethernet in the substation and also presents how Ethernet technology can help in the substation automation as a long run solution in the changing arena of communication as Ethernet is one of the most pervasive communication technologies. In the end we have performed simulations in NS-2 to prove that our suggested communication paradigm is optimal in various regards by keeping into consideration the constraints imposed by IEC61850**.

Index Terms**-- Communication architecture, Gigabit Ethernet, IEC61850, Substation Automation**.

I. Introduction

IN this digital age, where everyone is talking about information highway as witnessed by the pervasive use of digital technology in every walk of life, IEC61850 is also playing a vital role in this regard by digitizing the traditional substation automation (SA) system. The significant impact of IEC61850 standard could be observed in the shape of efficient and cost-effective architecture for power systems. By imposing the IEC61850 standards, substation will not only boost performance but also provide a universal platform to maintain and upgrade substation assets with cost-effective approaches.

The objective of IEC61850 is to track the way for a global standard that would achieve interoperability between different vendors and also would be able to accommodate future technological development in this regard, i.e., future-proof. In IEC61850, functional and performance requirements are imposed on intelligent electronic devices (IEDs) to achieve interoperability for automation process as a whole. Functional requirements are supposed to address required capabilities for IEDs and on the other hand performance requirements are oriented towards end to end operational or execution response time. To achieve functional requirements for IEDs, a modular approach is addressed by IEC61850 standard which is object- oriented. By contrast, the objectives to achieve performance requirements are changing dramatically as communication technology is getting smarter day by day.

Communication infrastructure obviously has the potential to virtualize the physical world of substation but when it comes to efficient and reliable architecture for SA then there are many challenges for various economic and standardization reasons those need to overcome for the complete realization of SA and also to cope with the recent development in the communication technology [1]. Ethernet has been the flavor of choice for SA because of its availability, efficiency, cost-effectiveness, and proven interoperability. The widespread use of Ethernet technology provides a huge base of vendor support and also now Ethernet is not only used for local communication but also providing support for long haul communication as a high speed communication backbone thereby providing support to transmit local packets on access technology without incurring the cost of protocol conversion seamlessly. So goal here is to use Ethernet as a standard networking protocol to achieve the performance requirements as specified by IEC61850 for SA and build efficient and reliable communication architecture in this regard.

In this paper, it is investigated that whether Ethernet is the viable solution to address the performance requirements of IEC61850 and how sufficient its performance characteristics are to meet the real-time demands of SA and then later the effectiveness of our proposed claim is proved with the help of simulated graphs by taking Gigabit Ethernet and GOOSE (Generic Object Oriented Substation Event) message (UPD/IP packet) into consideration.

The rest of this paper is structured as follows. In section II, the suggested communication architecture for substation automation is analyzed theoretically. Section III presents simulation results obtained for the evaluation of different

*Ali Raza and H. Jang are with the Department of Computer Software, Myongji University, Yongin, Korea (email:jang-h andaliraza@mju.ac.kr)

**Khalil Ullah and Saleem Ahmed are with the Department of Electronics and Communication Engineering, Myongji University, Yongin, Korea (email: khalil_dirvi@yahoo.com and saleem@mju.ac.kr

[2]H. Yang is with the Department of Computer Engineering, Sejong University, Seoul, South Korea (email: hsyang@sejong.ac.kr)

[1]Salman Ahmed is with the Department of Computer Systems Engineering, Mehran University, Jamshoro, Pakistan (email: salman.ahmed@muet.edu.pk)

attributes of GOOSE message in Gigabit Ethernet environment. Finally some concluding remarks are presented in section IV.

II. Gigabit Ethernet In Substation

Efficient and reliable communication architecture is one of the crucial tasks in the automation process of the substation. In order to meet the performance requirements of IEC61850 and to ensure future-proof technological development to be adjusted by the communication architecture for substation, there are various constraints related to performance, economy, and standardization that need to be addressed in this regard. This section presents suggested communication paradigm for SA, theoretical analysis for the effectiveness of suggested architecture and the most important challenges in this regard. Before proceeding towards suggested communication architecture, it is important to mention that communication paradigm needs to address the various aspects such as capacity, performance, reliability, accuracy, coverage, security, availability, and interoperability for substation automation [1]. By ensuring these communication attributes, robust communication architecture can be designed which revolutionize the power systems for many years as per specification of IEC61850.

A. Ethernet in substation

The significant advancement in Ethernet technology evolves it from traditional Local Area Network (LAN) to Wide Area Network (WAN) so now Ethernet technology is driven by high speed data rate as well as with the dominance of local area communication thereby making Ethernet as one of the feasible communication technology choice for SA [2]. Indeed, Ethernet is the most appropriate communication technology for the SA as it can operate at all the three levels specified by IEC61850, i.e., station, bay, and at process level seamlessly and can also used to interconnect different substations for the long-haul communication.

Ethernet technology supports very high data rate. 10GB Ethernet switches are available in the market and the landmark of 100GB Ethernet switches will be achieved in near future as it is claimed by several computing labs. With such a high speed data rate, Ethernet technology has maintained its performance throughout its upgrading generation. As electronics industry is progressing day by day, so Ethernet will keep its momentum towards high speed data rate and efficient performance.

Ethernet technology is cost-effective due to the reduced device count and can also carry power as specified by IEEE 802.3af standard thereby offering an economical and safe route to rapid flexible deployment of computing devices. The economical and flexible Ethernet technology can also provide the facility of fault tolerant Ethernet route thereby minimizing the downtime of substation communication in case when any failure occurs at the operational network. Ethernet technology also provides the support of traffic class prioritization and dynamic multicast filtering as specified by IEEE 802.1p [3]. By making use of this attribute, it is possible to prioritize mission-critical data within the substation over noncritical data and also provides the mechanism of efficient multicasting in Ethernet environment via layer-2 protocols. It is one of the significant developments towards the realization of deterministic Ethernet [4]. Hence real-time control of substation can be optimized by making use of deterministic Ethernet.

Availability of Ethernet technology can be witnessed by its huge industrial deployment which is supported by many vendors thereby assuring interoperability over different access network solutions. Because of Ethernet pervasive usage, it is the most scalable transmission technology having granularity of bandwidth, reliability, and coverage. Security is one of the main concerns when it comes to Ethernet; it has been augmented over the years to improve security but it seems to be compromised at the expense of its technological complexity. So in order to deploy secure communication network under Ethernet technology, some other corporate network security solutions need to be addressed such as firewalls, VPNs, and use of encryption schemes for mitigating Ethernet security risks.

According to IEC61850, Ethernet packet is the packet of choice to transmit the substation message within the substation because of its performance and also most of the proprietary communication solutions are available with Ethernet support [1], beside that when it comes to interconnect different substations, same Ethernet packet specified by IEC61850 can be transmitted through long-haul communication to other substations without incurring the cost of protocol conversion unlike ATM. In this way, Ethernet provides migration to a single and all-encompassing network concept to monitor and configure different substations across the region by making use of EPON which is a communication trend shipped with the two most demanding communication technologies, i.e., Ethernet as a communication protocol and fiber optical communication system as a communication medium [6]. Hence Ethernet is the most demanding communication trend for substation to build up an efficient communication infrastructure.

In this paper, we are examining the potential of Gigabit Ethernet switch to meet the communication needs of substation by imposing performance constraints specified by IEC61850. To our knowledge so far not much research has done to examine the performance of Gigabit Ethernet within the substation. LAN congestion scenarios for Ethernet based substation is analyzed [7] by Tengdin but it differs from our work in several key aspects such as no consideration for shared process bus, absence of industrial protocols (such as TCP/IP and UDP) specified by Internet Engineering Task Force (IETF) over Ethernet, and also there is no consideration given to background traffic load for accurate result. Brunner [2] examined role of Ethernet in the SA. However our work differs from [2] as we are deploying Gigabit Ethernet because it is cost-effective and can also be utilized at the access network to take full advantage of inherent local substation messages when different substations are inter-network and also we are considering that Ethernet packets are encrypted using hybrid encryption scheme [8] as Ethernet security is also one of the crucial concerns and we have divided communication infrastructure at two levels i.e. Bay level and station level.

B. Suggested Communication Paradigm

In the previous section, theoretical analysis of Ethernet is presented to show how feasible the choice of Ethernet technology for SA is when there is lot of other communication trends available in the market. In this section, models for the suggested communication architecture are presented, i.e., deployment of Gigabit Ethernet within the substation.

According to IEC61850, the functionality of SA has been logically allocated at three distinct levels: station level, process level, and bay level [2]. Station level devices consist of the station computer with a database such as HMI (Human Machine Interface) device, the operator's workplace, control center, interfaces for remote communication, etc (at this level these devices provide functions to control and protect the entire substation). Bay level devices consist of control, protection, or monitoring units per bay such devices actually relate to the different subparts of substation. Process level devices are typically remote I/Os, intelligent sensors and actuators or in other words such devices which are responsible for providing interface to primary equipments of substation [9]. So accordingly, we have built Gigabit Ethernet model at different logical levels of substation because of standardization, simplicity, and maintenance purposes.

Gigabit Ethernet communication model at station level for SA is illustrated in Fig. 1. In this communication model bays are depicted as another level of communication where Ethernet switch provides interface between bay level and process level. Gigabit Ethernet at station level is providing interface between bays and station level devices such as HMI, engineering, control center, backup control center and to the access network. Gigabit Ethernet switches are installed at two levels, i.e., at bay level to connect different bays and at substation level to connect all the bays to the station level devices. Fault tolerance switch is also installed to provide the connectivity in case when primary operational switch goes down as a result of failure. In order to connect substation to the outside world for remote monitoring or to connect with other substations as in the case of SACDA (Supervisory Control and Data Acquisition) system, these switches are further connected to a router which routes the traffic for the substation and then via firewall communication is made to the access network. When connectivity to the access network goes down or there is some other problem then wireless communication is used to transmit the substation data to the outside world and also provides connectivity for the remote monitoring. Technically optical fiber communication system is one of the most attractive communication medium. Therefore, it is used as a communication medium in the substation because of its high capacity, efficiency, coverage, and last but not the least the security.

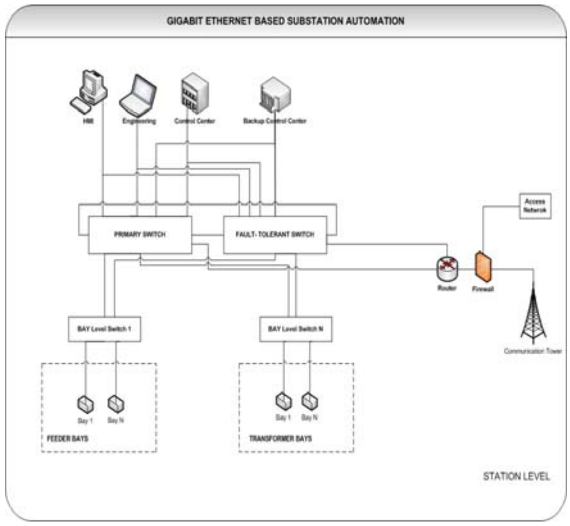

Fig. 1. Gigabit Ethernet based Substation Automation

In Fig. 2, communication model at bay level for substation automation is shown as the lowest communication level within the substation. In this communication model, Ethernet switch is deployed between bay level devices such as different IEDs and process level devices such as CT/VTs (Current Transformer / Voltage Transformers), CB (Circuit Breaker), switch gear, and etc as specified by IEC61850 9-2 .

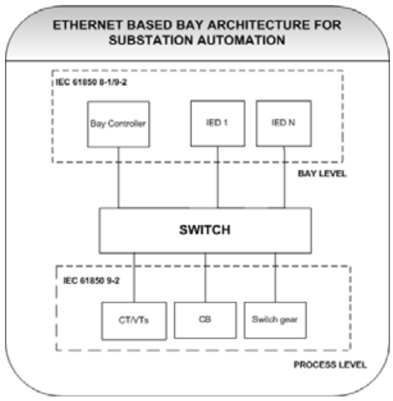

Fig. 2. Ethernet based Bay architecture for substation

Indeed Ethernet technology is the most pressing need for the functionality of bay level devices and process level devices since traditionally process level devices were supported by multiple vendors thereby raising concerns related to incompatibility, poor performance, and some other economical reasons. To mitigate all these concerns, Ethernet technology is modeled here between bay level and process level to fulfill the natural desire of standardization, performance, and cost effectiveness. On the other hand proliferation of Ethernet capable IEDs used for SA has increased markedly in the past several years.

The environmental conditions found in the substations can straddle the extremes of the surrounding climatic conditions, so it is one of the challenges for the Ethernet technology to operate in such an extreme environment where various kinds of electromagnetic disturbances in a wide frequency range can exist that may be conducted through power supply lines, control lines, or directly radiated by the equipment [9]. Ethernet switches for the substation need to operate in the same temperature range as IEDs and should also fulfill the requirements of general environment and electromagnetic interference (EMI) immunity for network equipment used in substations as specified in the IEC61850-3 [9].

In the next section, performance evaluation related to our suggested communication architecture for SA is presented to show the significant impact of using Ethernet technology within the substation. It is not possible to test Ethernet switches in the real substation because of mission critical and high-voltage substation components, so the alternative is to simulate the whole network with some powerful simulator.

III. Performance Evaluation

In this section, performance evaluation of Gigabit Ethernet within substation is presented with the help of simulation. By keeping into consideration, the real parameters of substation, network modeling of nodes and background traffic for normal conditions and abnormal conditions, we decided to use NS2 (Network Simulator 2) for simulation [11].

A. Simulation Framework

According to IEC61850, the transmission of sampled values from the process level to the bay level or to the protection devices should be completed with a maximum delay of about 4ms and same delay is specified for the trip signals which are actually mission critical data packet. In this respect, two types of messages are specified by IEC61850 draft, i.e., GOOSE and GSSE (Generic Substation State Event). GOOSE message contains information that allows the receiving device to know that a status has changed and the time of the last status change. GSSE model is the same like GOOSE except the kind of information exchanged. GOOSE provides a flexible means to specify which information is to be exchanged whereas GSSE provides a simple list of status information [9]. Therefore, we selected GOOSE message to simulate in NS2 for evaluating the performance of Gigabit Ethernet for the SA. So in order to get most accurate results, we maintain the size of GOOSE message such that it can also support encryption to cope with malicious attacks. The ability to trade-off the reliability for delivering greater determinism is crucial for multicasting GOOSE state change messages. Sending the most recent GOOSE is much more important than resending old updates that were previously dropped by the network, which will probably be out-of-date when they are delivered anyway.

In NS2, GOOSE message is modeled as UDP packet. UDP as a real-time protocol is able to meet the critical time requirement of GOOSE message since the normal response requirement for SA is 4 ms. Most of the simulation packages are tend to emphasize client-server or publisher-subscriber paradigms. In simulation, we have maintained the model such as to allow different IEDs to subscribe for the multicast group of GOOSE message or to cancel the subscription for GOOSE message. For simulating Gigabit Ethernet at station level within substation, we have modeled MAC layer at two levels, i.e., one where different bays are going to interconnect with each other and other at substation level where different bay level switches are interfaced with the station level devices such as HMI, engineering, control center, backup control center, and finally connectivity to the access network for remote communication control via router and corporate firewall.

Network parameters for simulation setup are derived by keeping into consideration administrative overhead and measured data from IEC61850 specification. The size of the GOOSE packet in simulation is 123 byte which is evaluated as per GOOSE message requirement specified in IEC61850 with parameters such as Ethernet frame, priority tagging, PDU, dataset, encryption bits and etc [9] while the packet sending rate is 140,000 packets per second as a gross estimate from the real substation requirement [2], thus having data rate of about 137.76 Mbps by adding 10% reserve bandwidth, for optimizing data rate in real practical scenario as above data rate is solely derived on theoretical basis, final data rate will be 151.53 Mbps. Strict limit of 4ms is set for the expiration of GOOSE message to analyze packet lost ratio. As security in Ethernet is one of the growing concerns, so in order to ensure secure transmission, powerful encryption techniques can be used to encrypt GOOSE messages for the substation so adding another 176 byte in the Ethernet frame for RSA algorithm. By using these network parameters, simulation is run for 200 seconds to analyze different network characteristics shown in the next section.

B. Simulation Result

Here we present simulation result obtained from NS2 related to the simulation of Gigabit Ethernet based substation at station level. In order to evaluate the performance of Gigabit Ethernet model for the SA, we have selected following three communication characteristics for the GOOSE message:

- Average packets end to end delay
- Packet drop rate
- Bandwidth consumption

For simulation in NS2, we have selected four bays from two isolated parts of substation, and then we examined those four bays over these communication characteristics. In this way, we come to know that how much time a GOOSE message takes from process level to all the members of the multicast group during all this communication how many GOOSE packets are dropped since a GOOSE message can last for only 4ms and finally how much bandwidth is consumed by these bays.

Fig. 3a and 3b show average packets end-to-end delay for the GOOSE message for a selected bay at station level for normal GOOSE message and encrypted GOOSE message respectively. It is clearly shown in the graph that normal GOOSE packets are transmitted with the maximum delay of 7.3 µs for the bay while the minimum delay is about 7 µs. While for encrypted GOOSE message maximum delay is about 17.8 µs and minimum delay is 17.1 µs.

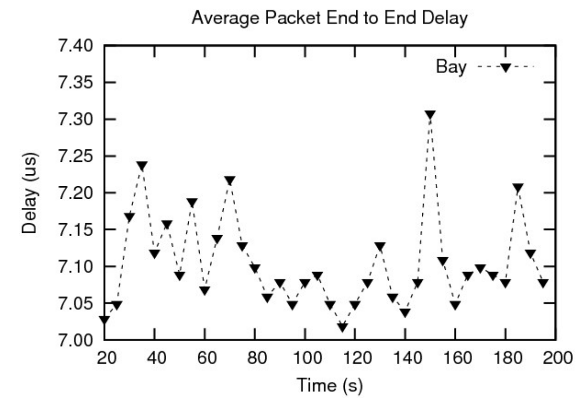

Fig. 3a. Average packets end-to-end delay at station level

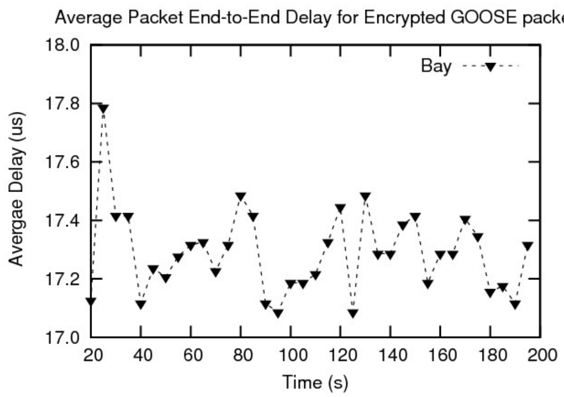

Fig. 3b. Average packets end-to-end delay at station level for encrypted GOOSE packets

Fig. 4 shows packet drop rate for the GOOSE messages. As it can be observed clearly from the graph that the packet drop rate for all the bays that we have selected for the simulation is zero. At bay level similar result is obtained so due to space limitation packet loss ratio at station level is shown only. It means during the transmission of GOOSE message not a single packet is lost all packets are delivered to the destination.

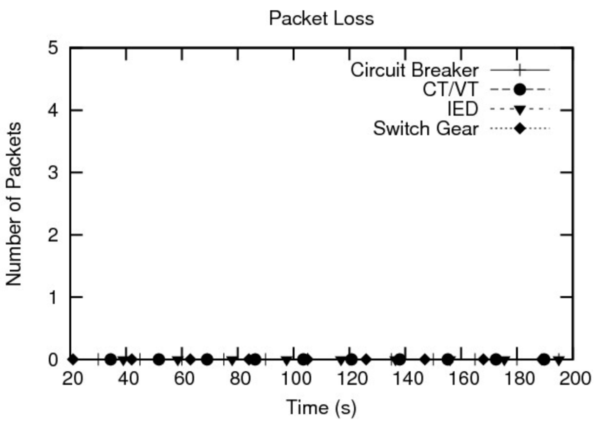

Fig. 4. Packet drop rate

Fig. 5 shows bandwidth consumption for IED selected at station level during the transmission of GOOSE messages. It can be seen clearly in the graph where the bandwidth consumption for this IED lies in the range of 140-141.5 Mbps for GOOSE messages. While the bandwidth consumption for IED at Bay level is reported as 140 Mbps as shown in Fig. 6.

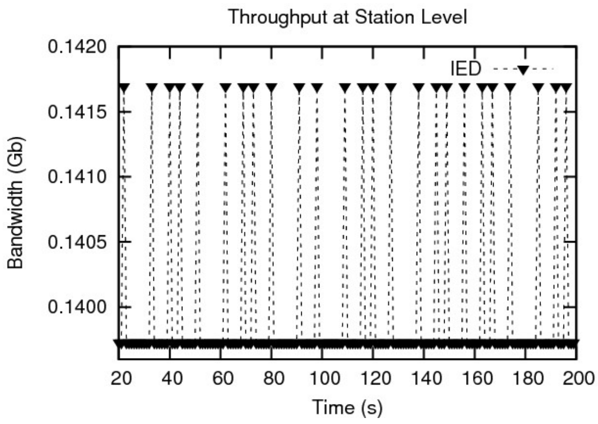

Fig.5. Bandwidth consumption for IED at station Level

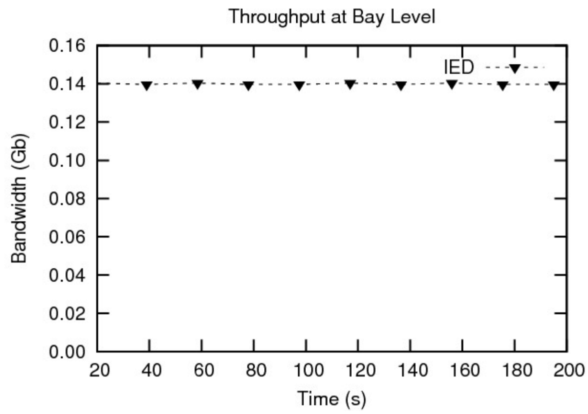

Fig.6. Bandwidth consumption for IED at Bay Level

Fig. 7 shows average delay for the IED at bay level. According to graph, IED takes 17µs delay during initiation in the presence of other IEDs which are transmitting GOOSE messages on the network and then an average delay of about 7.05 - 7.1 µs for the rest of simulation.

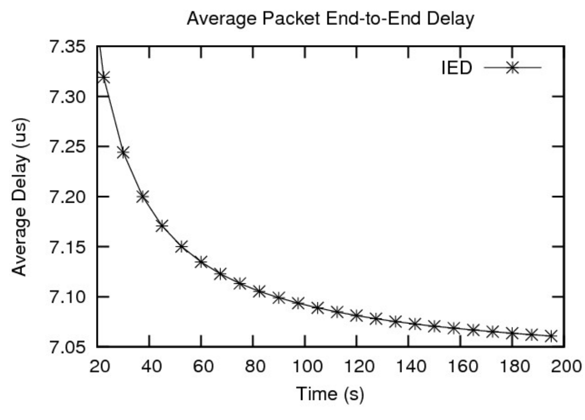

Fig. 7. Average end-to-end delay at bay level

While average packets end-to-end delay for encrypted GOOSE message if encryption technique is employed for GOOSE message to ensure security at bay level is reported 17.5 µs.

C. *Performance Impact*

If a GOOSE message is transmitted for the bay which is located at the different region of substation then the total round trip delay during initiation phase will be 1.9ms and about average 28.65 µs in steady delay condition. If GOOSE message is encrypted then the round trip delay during initiation phase will be 2ms and about 70.6 µs in the steady state. After observing simulation result we can conclude that GOOSE message along with encryption scheme to combat with security risks is still managed to transmit under the transmission range limit which is specified by IEC61850, i.e., 4ms when Gigabit Ethernet is deployed for SA.

IV. Conclusion

In this paper, we addressed one of the crucial aspects of SA with respect to communication architecture, i.e., deployment of Gigabit Ethernet in the substation. Due to Cost-effectiveness, high availability and interoperability, Ethernet technology evolved as one of the viable solution for substation. As power industry is becoming mature day by day, so there is no doubt about widespread use of Ethernet not only for local communication but also for long-haul communication in near future. On the other hand Ethernet networks can migrate seamlessly from 10 to 100 Mbps to 1 Gbps by maintaining the packet format and protocol of most of today's network thereby saving the cost of protocol conversion. Our proposed communication paradigm is not only optimized for the current IEC61850 constraints but can also support future considerations smoothly as it is one of the most adaptive and pervasive communication trends available in the communication arena. In the end, we used simulated experiments to validate the effectiveness of our proposed communication paradigm and prove the performance impact of Ethernet technology for SA.

V. References

[1] M. Qureshi, A. Raza, D. Kumar, S. Kim, U. Song, M. Park, H. Jang, H. Yang, and B. Park, “A survey of communication network paradigms for substation automation”, *Proc. of IEEE ISPLC 2008*, pp. 310-315 .

[2] Tor Skiei, Svien Johannessen and Christoph Brunner, “Ethernet in Substation Automation,” *In IEEE Control Systems Magazine*, June 2002, pp 43-51.

[3] IEEE 802.1D, ”Local and Metropolitan Area Networks – Common Specification”, 1998.

[4] Holmeide and T. Skieie, ”VoIP drives real-time Ethernet”, In Industrial Ethernet book, vol. 5, Mar.2001, pp. 26.29.

[6] M. Qureshi, A. Raza, D. Kumar, S. Kim, U. Song, M. Park, H. Jang and H. Yang, “A Communication Architecture for Inter-substation Communication”, *Proc. of IEEE CIT 2008*, pp. 577-582.

[7] J. Tengdin, M.S. Simon and C.R. Sufana, “LAN congestion scenario and performance evaluation”, *in Proc. IEEE Power Engineering Society Winter Meeting*, 1999, pp. 919-924.

[8] M.T. El-Hadidi, N.H. Hegazi and H.K. Aslan, “Implementation of a hybrid encryption scheme for Ethernet”, *In IEEE symposium on Computers and Communications (ISCC’ 95)* .

[9] IEC61850, “Communication networks and systems in substations”.

[10] Marzio P. Pozzuoli, “The need for “Substation Hardened” Ethernet switches”. *White Paper*, Available: http://www.ruggedcom.com

[11] NS2 [Online]. Available: http://www.isi.edu/nsnam/ns/