An Improved High-availability Seamless Redundancy (HSR) for dependable Substation Automation System

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Abstract— **High-availability Seamless Redundancy (HSR) is an emerging standard that is suitable for mission-critical communication of IEC 61850 based Substation Automation System in smart grid, where the dependability is very important. This redundancy protocol provides zero recovery time by offering duplicated frames for separate physical paths, but it generates and circulates unnecessary traffic inside the network that will degrade the performance of the network and may cause the congestion, delay, or frame loss. To improve the HSR network performance, the main drawback of generating extra traffic should be considered and eliminated. This paper demonstrates comprehensive performance analysis of IEC 61850 based substation automation networks and applies the quick removing (QR) algorithm to improve the performance of the HSR network to overcome the major drawback. The performance analysis includes the HSR modules, i.e., Doubly Attached Node for HSR (DANH), Redundancy Box (RedBox), and Quadruple Box (QuadBox), and IEC 61850 services, i.e., Generic Object Oriented Substation Events (GOOSE), Sampled Measurement Values (SMV), and report service. Performance analysis was conducted to verify the timing constraints described in IEC 61850 as a reference for designing proper HSR network topology. The numerical results show that the frame loss, restricted in mission-critical network, occurs due to large amount of traffic volume, which is the main drawback of HSR. The QR algorithm improves the traffic performance of HSR by reducing the unnecessary traffic along with the decrease of packet loss significantly.**

Keywords— **Smart grid, IEC 61850, Substation Automation System, High-availability Seamless Redundancy, network performance**

I. Introduction

A scalable and pervasive communication infrastructure is essential part for smart grid to enhance efficiency and reliability for a modern electric power grid infrastructure in both construction and operation [1], [2]. The communication network of the Substation Automation System (SAS), defined by IEC 61850 standard, is used to transfer information for monitoring and protecting the primary equipment of inside the substation and its associated feeders [3].

High-availability Seamless Redundancy (HSR), described in IEC 62439-3 clause 5 [4], seamlessly fail-over by applying the principle of frame duplication using ring topology, is an emerging standard that is suitable for mission-critical communication of IEC 61850 based substation automation system in smart grid [5]. The main drawback of HSR is the extra traffic generated due to the redundant frame copies that generated and circulated inside the network that will degrade the network performance and may cause network congestion, delay, or frame drop. Especially with stringent real-time messages such as Generic Object Oriented Substation Events (GOOSE) or Sampled Measurement Values (SMV) which require a large volume of traffic in SAS network, the extra throughput of HSR may lead the network to dropping, restricted in mission-critical network.

Inspired by [6] that the bandwidth of the designed network should meet the requirement and the network traffic should be minimized for efficient use of network bandwidth, and encouraged from a proposed approach at [7] that removes the redundant frame copies to reduce the HSR network traffic, this paper considers the main drawback of generating extra throughput carefully and proposes a concreted solution for improving HSR through a comprehensive performance analysis for IEC 61850 based substation networks. The solution includes abilities to distinguish a frame whether duplicate or not at each HSR node and to remove the unnecessary-duplicated frames. In this paper, performance analysis includes HSR modules such as Doubly Attached Node for HSR (DANH), Redundancy Box (RedBox), Quadruple Box (QuadBox), IEC 61850 services such as GOOSE, SMV, and report service. The numerical results show that the frame loss and the decrease in packet dropping of the proposed solution due to the reducing significantly of unnecessary traffic.

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This paper is structured as follows: The related works are reviewed in Section 2, followed by the HSR implementation in Section 3. Section 4 analysed the simulation results, while Section 5 explained the proposed solution for HSR. Finally, conclusions and future work are given in Section 6.

II. Related Works

A generic modeling technique of intelligent electronic device (IED) and the setup of a research platform using the OPNET Modeler were introduced in [8]. It explained about how to create and setup a platform for the performance study of an IEC 61850-based substation communication system by modeling devices with the specific protocol stack. According to this modeling, Thomas and Ali [9] proposed a network architecture for IEC 61850 substation automation system and demonstrated that it is reliable, fast, and deterministic.

The performance evaluation of the IEC 61850-9-2 process bus for a typical 345 kV/230 kV substation by studying the time-critical sampled value messages delay and loss using OPNET simulation tool was presented in [10]. The process bus parameters influenced on the sampled value packet loss and maximum delay. It also proposed the sampled value estimation algorithm for any digital substation relaying and examined it for various power system scenarios with the help of PSCAD/EMTDC and MATLAB simulation tools.

Communication networks and performance analysis were designed and conducted on an IEC 61850 based substation station bus and process bus in [11]. Some network components of IEC 61850 were implemented by adding module for IEC 61850 using NS-2. This module includes the GOOSE, SMV, report, and SNTP time synchronization services, a new trace method to get results and a graphic user interface to make faster and more effective simulation. Three experiments were simulated using this new module on NS-2 including station bus, process bus for transmission line and process bus for distribution line of Poong-Dong digital substation. The performance analysis concluded that the proposed simulation network satisfies the timing requirement of IEC 61850.

A new IEC 61850 simulation platform based on OMMeT++ was also presented at [12]. It does not only allow to conduct a network performance analysis, but also to carry out hardware-in-the-loop simulations before implementing them in to a real device. This platform developed simulation core, which uses two processes working in parallel manner and the implementation of the real IEC 61850 protocol stack.

The generic architecture of IEC 61850 and modelling approach for evaluating high performance and real-time capability of communication technologies in smart grid application are introduced in [13]. The modeling approach was demonstrated and a simulation model was developed along with an analytical approach on the basis of Network Calculus. The results show the applicability of Network Calculus for real-time constrained smart grid communication.

A sequential Monte Carlo method is used to simulate the reliability and probability of failure in [14]. The analytical and simulation solutions show that the redundant ring architecture has increased the reliability compared with the cascaded architecture.

III. Substation Automation Network

In this paper, the HSR components such as DANH, RedBox and QuadBox and IEC 61850 services such as GOOSE, SMV, and report service for simulating HSR networks has been implemented using NS-2. A GUI tool based on Java is also implemented to make IEC 61850 based network simulation easier and a result analyser is used to get results efficiently.

A. HSR Components

HSR uses Doubly Attached Node for HSR (DANH) nodes with two ports, one for clockwise and the other for counter-clockwise, to forward frames within HSR network. The Redundancy box (RedBox) is required to attach the HSR network with non-HSR nodes; two Quadboxes are required to connect HSR rings for preventing single point of failure.

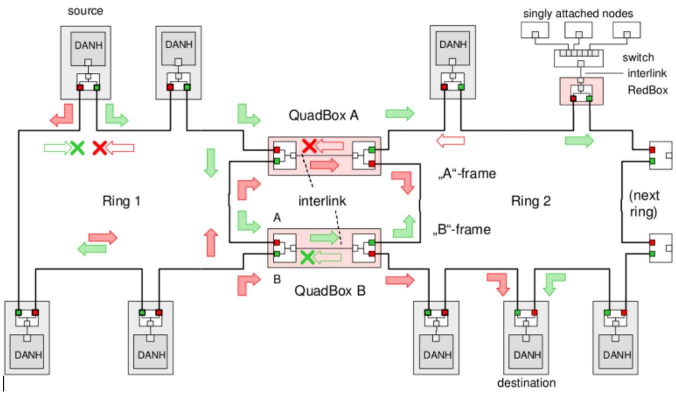

Figure 1. An example of HSR network

Fig. 1 shows an example of a HSR network, consists of DANH, QuadBox, RedBox, and Singly Attached Node (SAN) nodes. Each source DANH inserts a HSR tag to identify frame, duplicates and sends them over its two ports. At destination, DANH receives two identical frames from each port, removes the HSR tag of the first frame, passes it to its upper layer, and forward any duplicate frame to next hop. The SAN nodes cannot be inserted directly into the HSR ring since they have only one port and cannot interpret the HSR tag in the HSR frames. SANs communicate with HSR ring through a RedBox that acts as a proxy for the SANs attached to it. Two HSR rings can be connected using QuadBoxes that forwards frames over each ring as any HSR nodes and pass frames to another ring.

B. IEC 61850 Services and Structure of the Simulator

GOOSE, SMV, and report services are implemented as applications for generating traffic at HSR components. The GOOSE and SMV services mapped directly to ISO/IEC 8802-3 Ethernet type with IEEE 802.1 Q priority tagging which reduce the queuing delay generated by passing LLC (Link Layer Control) and ISO transport layer. GOOSE and SMV services are used to deliver time and mission critical messages e.g., trip or acquisition messages. These are peer to peer service based multicast services and can be delivered faster than other traffic i.e., MMS (Manufacturing Message Specification) because of priority tagging. MMS using client-server model, on top of TCP/IP, is used to exchange report, reading and writing variable, and control the device.

The structure of simulator is shown in Fig. 2. There is a GUI based on Java for making simulations easier and generating TCL script automatically. The new module implemented in NS-2 runs the script file from GUI and extracts the simulation result in the new format of trace file. Finally, the trace file can be used to analyse at GUI efficiently.

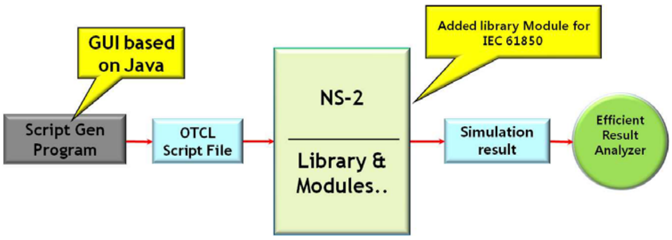

Figure 2. Structure of the simulator

IV. NETWORK SIMULATION

Various HSR network topologies are considered and the simulation results are analysed in this section. The HSR single ring topology includes Merging Units (MUs) and IED connected into a ring, while the HSR ring of rings topology includes QuadBoxes separating HSR ring into two rings. The worst case of the network, failure of link, is also considered.

A. The HSR Single Ring

The process bus of the substation is related to gathering measured information, such as voltage, current, and status information from the transformers and transducers connected to the primary power system equipment. Signals from voltage and current transformers are input into a Merging Unit (MU). MUs transmit SMV messages on a multicast mode from one publisher to multiple subscribers. IEDs in same VLAN setup will receive SMV from multiple MUs and automatically align and process the data.

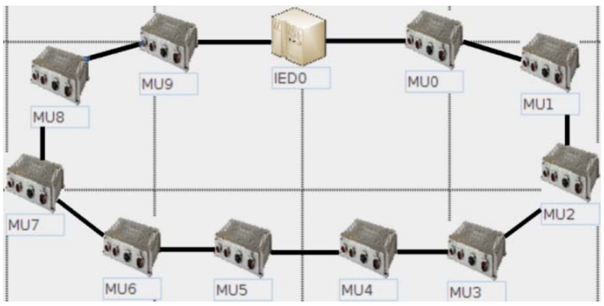

Figure 3. HSR single ring

A HSR ring topology is considered as shown in Figure 3. SMV traffic is generated at a base sample rate of 80 samples per power system cycle for protection and monitoring and at a high rate of 256 samples per power system cycle for high-frequency applications. There are one IED and a number of MUs connected into a HSR ring topology. IED and MUs nodes are applied as DANH nodes in HSR module. The bandwidth of links in Mbps and the number of MUs are varied. SMV message is set to 180 bytes and the interval is varied depending on the rates of sample. The maximum delays in microseconds and the number of frame loss are summarised in Table 1 for both the base and high sample rates.

The maximum delay increases along with the increase of the number of MUs and the decrease of the bandwidth of links. Packet loss occurs under 80 samples/cycle and many loss at 256 samples/cycle. This drop is caused from the main drawback of HSR, extra traffic generated due to the redundant frame copies, making big traffic volume in HSR ring.

TABLE 1. MAXIMUM DELAY AND NUMBER OF DROPS ON HSR SINGLE RING

Samples /cycle	Num. of MUs	Links (Mbps)									
		100	200	300	400	500	600	700	800	900	1000
Maximum delay in microsecond											
80	10	73	37	25	19	15	13	11	10	9	8
	15	66132	58	39	30	24	20	17	15	14	12
	20	478098	73	49	37	30	25	22	19	17	15
	25	685964	95	64	48	39	32	28	25	22	20
256	10	806157	169482	25	19	15	13	11	10	9	8
	15	941364	643324	17445	30	24	20	17	15	14	12
	20	977842	825761	545628	177032	30	25	22	19	17	15
	25	987784	908740	730541	481722	178641	32	28	25	22	20
Number of dropping frames											
80	10	0	0	0	0	0	0	0	0	0	0
	15	2187	0	0	0	0	0	0	0	0	0
	20	26164	0	0	0	0	0	0	0	0	0
	25	50098	0	0	0	0	0	0	0	0	0
256	10	84083	14540	0	0	0	0	0	0	0	0
	15	160945	91425	21893	0	0	0	0	0	0	0
	20	237941	168431	98952	29166	0	0	0	0	0	0
	25	314822	245390	176082	106539	36469	0	0	0	0	0

The packet loss is not acceptable in mission critical network and partly caused from the extra traffic of HSR. These simulation results is used for referencing to design HSR ring with suitable number of MUs and the bandwidth of links that satisfying the time constraints. A proposal for HSR, will be introduced in the following subsection, for reducing the traffic, was implemented in the new HSR module and restricted the drop situations significantly.

B. The HSR Ring of Rings

QuadBox, composed of two Redboxes, is used to connect two HSR rings forming the HSR ring of rings topology. To connect HSR rings redundantly without a single point of failure, two QuadBoxes are installed as shown on Figure 4. Simulations of the HSR ring of rings are the same setup with the HSR single ring simulations but two QuadBoxes are added to separate a HSR single ring into two rings.

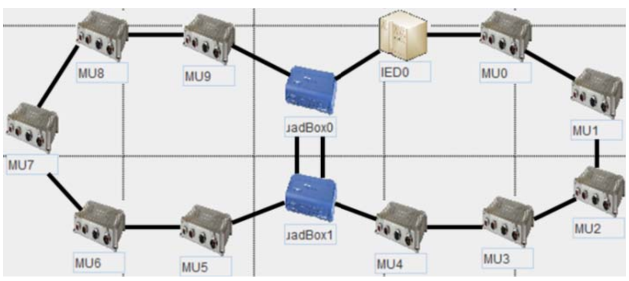

Figure 4. HSR ring of rings

The maximum delay in micro seconds and the number of dropping frames of HSR ring of rings are shown on Table 2 in two samples rates with the various numbers of MUs and bandwidth of links. The maximum delay at the HSR ring of rings is slightly increased at none frame loss situations comparing to the HSR single ring topology due to the increase of number of nodes and links. Frame loss is the same as HSR single ring topology at some simulations.

TABLE 2. MAXIMUM DELAY AND NUMBER OF DROPS ON HSR RING OF RINGS

Samples /cycle	Num. of MUs	Links (Mbps) 100	200	300	400	500	600	700	800	900	1000
Maximum delay in microsecond											
80	10	116	58	39	29	24	20	17	15	13	12
	15	66938	87	58	44	35	29	25	22	20	18
	20	453924	116	78	58	47	39	34	30	26	24
	25	558299	167	97	73	58	49	42	37	33	30
256	10	755187	161083	44	30	24	20	17	15	13	12
	15	910997	599994	172378	51	35	29	25	22	20	18
	20	955687	778725	481314	181772	56	39	34	30	27	24
	25	982425	874783	647449	375066	166511	58	42	37	33	30
Number of dropping frames											
80	10	0	0	0	0	0	0	0	0	0	0
	15	5220	0	0	0	0	0	0	0	0	0
	20	59095	0	0	0	0	0	0	0	0	0
	25	125882	0	0	0	0	0	0	0	0	0
256	10	201344	36667	0	0	0	0	0	0	0	0
	15	336627	268849	58426	0	0	0	0	0	0	0
	20	442310	481594	421015	81231	0	0	0	0	0	0
	25	535746	618729	702450	425233	147340	0	0	0	0	0

C. The Worst Case

The same simulations as HSR ring above with various number of MUs and bandwidth of links in two sample rates are conducted but in the worst case that there is a link failure on HSR ring as shown on Fig. 5. This link failure cause the maximum hops between source and destination increase.

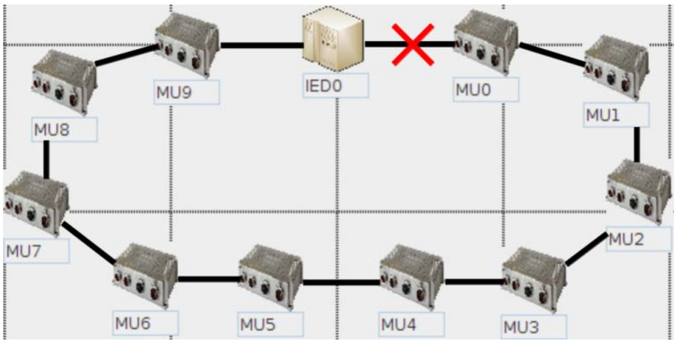

Figure 5. The worst case of HSR single ring

TABLE 3. SIMULATION RESULTS AT THE WORST CASE

Samples /cycle	Num. of MUs	Links (Mbps) 100	200	300	400	500	600	700	800	900	1000
Maximum delay in microsecond											
80	10	145	73	49	37	30	25	21	19	17	15
	15	35698	109	73	55	44	37	32	28	25	23
	20	39686	145	97	73	59	49	42	37	33	30
	25	50715	188	126	92	74	62	53	47	42	38
256	10	667051	95842	49	37	30	25	22	19	17	15
	15	877216	464889	9778	55	44	37	32	28	25	23
	20	953768	683320	367821	98125	59	49	43	37	33	30
	25	980384	812581	557062	310935	9872	62	53	47	42	38
Number of dropping frames											
80	10	0	0	0	0	0	0	0	0	0	0
	15	0	0	0	0	0	0	0	0	0	0
	20	21511	0	0	0	0	0	0	0	0	0
	25	45266	0	0	0	0	0	0	0	0	0
256	10	68547	0	0	0	0	0	0	0	0	0
	15	145097	75902	6658	0	0	0	0	0	0	0
	20	221647	152452	83208	14013	0	0	0	0	0	0
	25	298197	229002	159758	90563	21319	0	0	0	0	0

The maximum delay in micro seconds and the drop problem of HSR single ring simulations at worst case are shown on Table 3. On average, the maximum delay at the worst case is approximately double the maximum delay at normal case on Table 1 since the maximum number of hops between a source and a destination is increased obviously. The frame loss at worst case (Table 3) are sightly reduce comparing with the normal case (Table 1) since the lack of one link cause frames cannot circulate the entire ring.

V. QUICK REMOVING ALGORITHM

HSR nodes such as DANH and QuadBox using Quick Removing algorithms are considered to eliminate the wasted traffic in HSR. Simulation analysis for the HSR is also conducted and compared to the standard ones to show the improving of HSR traffic performance.

A. HSR nodes with Quick Removing Algorithm

Each source HSR node generates two frames of packet, A-frame and B-frame, into two opposite directions of the HSR ring topology. Whenever a destination or an intermediate node has received the first frame from one direction, every node on that direction has received the first frame explicitly. The forwarding of the duplicated frame from opposite direction is not necessary and making wasted traffic.

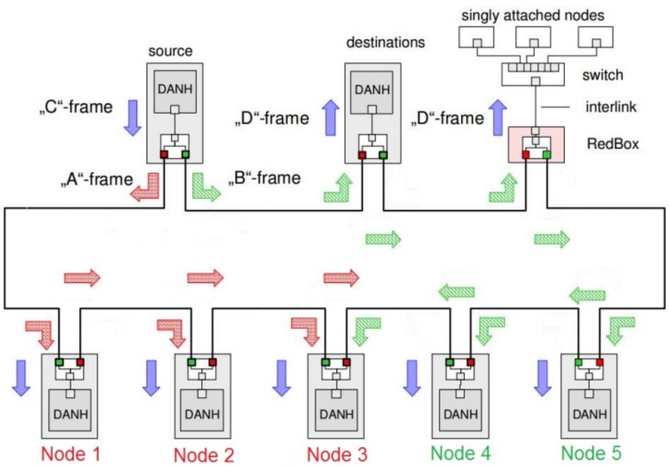

Figure 6. The proposed HSR nodes

As the example on Figure 6, A-frame and B-frame are generated from the source into two directions on the HSR ring. Assuming that A-frame is the first one coming to Node 3 and B-frame is the duplicated one. Whenever Node 3 has received A-frame, Node 1 and Node 2 received A-frame explicitly on that direction, the forwarding of the duplicated B-frame from Node 3 to Node 2 and Node 1 is not necessary.

To eliminate this wasted traffic, the QR HSR nodes adds an ability for stopping to forward the duplicated frame into the direction that has gone through by the first frame. There is a forwarding table at each HSR node that traces packet information for distinguishing whether a coming frame is the first or the duplicate. This table essentially includes the source address and the sequence number of the frame. A frame could be realized as the first or the duplicate by comparing the source address and the sequence number information between the frame and the forwarding table.

The forwarding table is updated at the time HSR node receives a frame and its size will be increased along with the increase of the number of received frames. To prevent this increasing, which may lead to a lot of memory and long time of comparing process, the algorithm limit the size of the forwarding table. Each entry of the forwarding table has a tracing time and will be deleted automatically after a certain time-to-live. The number of entries is also limited to a certain value for each source address. Whenever the number of entries of a source address exceed to this value, the oldest one with the smallest sequence number is deleted.

B. Theoretical traffic volume of the HSR network

The total SMV traffic volume in one second can be expressed as following:

$$V_{SMV} = F_{SMV} \,.\, N_{Frames} \,.\, S_{Frame} \text{ (bps)}$$

Where F_{SMV} is the frequency of SMV traffic, $F_{SMV} = R_S \cdot F_P$ (Hertz), with R_S is the rate of samples and F_P is the frequency of power cycle; N_{Frames} is the number of frames, $N_{Frames} = 2\cdot$ *Number of MUs*, since each MU generates two copies of frames; and S_{Frame} is the size of frame in bit.

On standard HSR ring, two copies of an original frame circulate full ring on two opposite directions as illustrated on Fig. 7. The number of hop that a frame traverse is the double of number of links. As frames generated into two directions, each direction just load a half of SMV traffic volume, then we have the overall throughput at all links on standard HSR ring by the equation (1), where N_{link} is number of links.

$$Thr\_{HSR} = 2 \,.\, N_{link} \,.\, V_{SMV} / 2 \text{ (bps)} \tag{1}$$

On QR HSR ring, each frame of two copies is transmitted on an opposite direction but not the full ring, since it will be removed any time a frame become duplicated at intermediate nodes. There is one common link that two copies of frame are transmitted as illustrated on Fig. 7. So that, the total number of hops that frames are transmitted is $N_{link} + 1$. Then we have the overall throughput at all link on proposed HSR ring by the equation (2).

$$Thr\_{QR\_HSR} = (N_{link} + 1) .\, V_{SMV} / 2 \text{ (bps)} \tag{2}$$

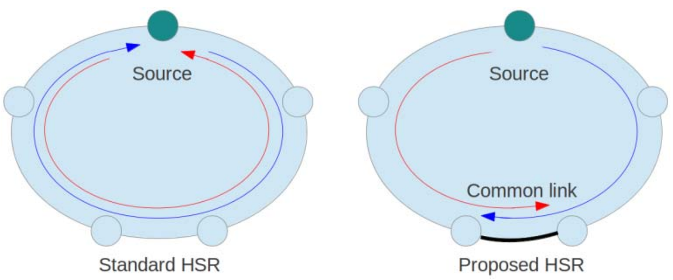

Figure 7. The standard and proposed HSR

From (1) and (2), the overall throughput at the proposed HSR is reduced obviously.

C. HSR Single Ring using the QR DANH

Making the same simulations as the HSR single ring at process bus above, but using the DANH with QR algorithm, the maximum delay results in micro second and the number of frame loss are summarized in Table 4. The maximum delay is not different with the HSR single ring that uses standard DANH, but the number of dropping situations is reduced significantly at both sample rates.

TABLE 4. HSR SINGLE RING USING THE DANH WITH QR ALGORITHM

Samples /cycle	Num. of MUs	Links (Mbps)									
		100	200	300	400	500	600	700	800	900	1000
Maximum delay in microsecond											
80	10	73	37	25	19	15	13	11	10	9	8
	15	116	58	39	30	24	20	17	15	14	12
	20	145	73	49	37	30	25	22	19	17	15
	25	188	95	64	48	39	32	28	25	22	20
256	10	805072	37	25	19	15	13	11	10	9	8
	15	940362	58	39	30	24	20	17	15	14	12
	20	979134	822963	49	37	30	25	22	19	17	15
	25	990678	906377	718988	48	39	32	28	25	22	20
Number of dropping frames											
80	10	0	0	0	0	0	0	0	0	0	0
	15	0	0	0	0	0	0	0	0	0	0
	20	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
256	10	88383	0	0	0	0	0	0	0	0	0
	15	160854	0	0	0	0	0	0	0	0	0
	20	237895	172520	0	0	0	0	0	0	0	0
	25	314689	245273	228434	0	0	0	0	0	0	0

The average link throughput in Mbps of the HSR ring using the DANH with QR algorithm and the standard DANH is shown on Fig. 8. The average link throughput of the HSR ring using the DANH with QR algorithm accounted for 54.5% of the ring using standard DANHs at 10 MUs, 53.1% at 15MUs 52.4% at 20MUs and 51.9% at 25MUs simulations. This is the reason of the decrease on the number of frames loss using the DANH with QR algorithm.

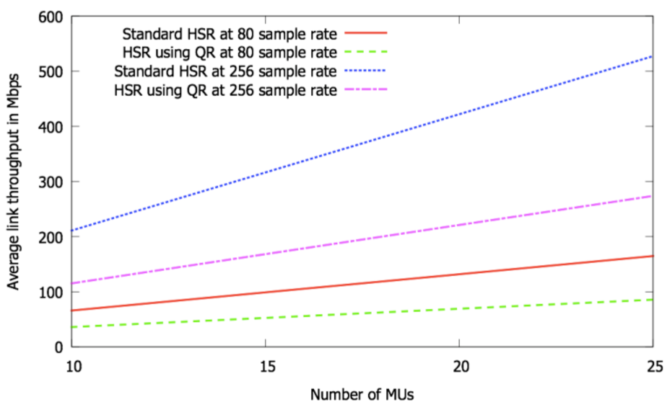

Figure 8. The average link throughput of the HSR single ring using QR algorithm and standard DANH

D. HSR ring of rings topology

The same simulation results of HSR ring of rings with QR algorithm are summarized in Table 5 with the maximum delay and the number of frame loss. Maximum delay at none dropping situations is same but the number of drop is reduced at Table 5 comparing to Table 2 at the HSR ring of rings topology using the standard HSR nodes.

Fig. 9 shows the average link throughput of the HSR ring of rings topology using HSR with QR algorithm and the standard ones. The average link throughput of the HSR ring of rings topology using the HSR with QR nodes accounted for 57.1% of the ring using standard ones at 10 MUs, 55.3% at 15 MUs, 54.2% at 20MUs, and 53.4% at 25MUs simulations.

TABLE 5. HSR RING OF RINGS USING THE PROPOSED HSR NODES

Samples /cycle	Num. of MUs	Links (Mbps) 100	200	300	400	500	600	700	800	900	1000
Maximum delay in microsecond											
80	10	116	58	39	29	24	20	17	15	13	12
	15	173	87	58	44	35	29	25	22	20	18
	20	281	116	78	58	47	39	34	30	26	20
	25	540023	145	97	73	58	49	42	37	33	30
256	10	779640	58	39	30	24	20	17	15	14	12
	15	909521	562718	58	44	35	30	26	22	20	18
	20	958744	732828	495093	59	47	39	34	30	27	24
	25	983207	876660	648647	80	58	49	42	37	33	30
Number of dropping frames											
80	10	0	0	0	0	0	0	0	0	0	0
	15	0	0	0	0	0	0	0	0	0	0
	20	0	0	0	0	0	0	0	0	0	0
	25	125613	0	0	0	0	0	0	0	0	0
256	10	212356	0	0	0	0	0	0	0	0	0
	15	336229	269681	0	0	0	0	0	0	0	0
	20	435636	468440	357492	0	0	0	0	0	0	0
	25	536052	619419	709136	0	0	0	0	0	0	0

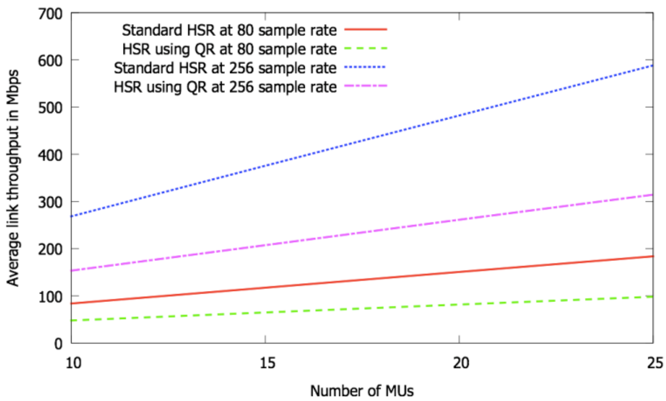

Figure 9. The average link throughput with and without QR algorithm

VI. CONCLUSION

HSR is a novel redundancy technology that allows multiple paths from communication source to sink at the same time, enables seamless redundant communication, and prevents looping frames. The main drawback of HSR is, however, the extra traffic since it generates and circulates unnecessary traffic inside the network. This reduces the available usage of bandwidth and influences the HSR network performance.

This paper implemented HSR components such as DANH, QuadBox, RedBox, IEC 61850 services and showed the main drawback of HSR through frame loss. We used Quick Removing algorithm to improve the availability of HSR. We conducted performance analysis to evaluate whether the network topology meets the timing constraints described in the IEC 61850 and provided a reference for designing suitable HSR network topology. The proposed solution improved the traffic performance of HSR, reduced the throughput along with the decrease of packet drop significantly. Based on these initial results, further work includes completed substation automation system performance analysis using HSR and the HSR with QR algorithm in both IEC 61850 based process bus and station bus.

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