High-Availability Seamless Redundancy (HSR)의 Unicast 트래픽 성능 향상을 위한 QRPL 알고리즘

이브라힘 알타하*, 이종명** 종신회원

Improvement to High-Availability Seamless Redundancy (HSR) Unicast Traffic Performance Using a Hybrid Approach, QRPL

Ibraheem Raed Altaha* and Jong Myung Rhee** *Lifelong Member*

요 약

High-availability seamless redundancy (HSR) 은 두 개의 복제된 프레임을 각각의 경로로 전송하여 거의'0'시간에 고장을 복구하는 실시간 고장 허용 프로토콜이다. 그러므로 HSR은 스마트 그리드 통신과 같은 첨단 실시간 네트워크에 사용이 가능하다. 그러나 HSR 프로토콜은 고장 복구를 위해 생성되는 불필요한 트래픽이 목적지 노드가 포함되지 않은 하부 네트워크에도 지속적으로 순환하는 주요 단점이 있으며, 이는 네트워크의 트래픽 성능을 저하시키고, 네트워크의 활용 자원을 감소시키는 원인이 된다. 이러한 단점을 보완하기 위해, 효율적인 두 가지 알고리즘, Quick Removing (QR) 과 Port Locking (PL) 이 발표된 바 있다. 본 논문은 QR과 PL을 결합한 새로운 알고리즘, QRPL의 구현 가능성 및 그 성능을 수학적으로 해석 제시하고 시뮬레이션으로 확인하였다. 그 결과 다수의 하위 ring이 연결된 HSR 네트워크에서 유니캐스트 트래픽을 적용시, 표준 HSR, QR, 또는 PL 알고리즘을 개별로 사용하는 것보다, QRPL 알고리즘을 사용하는 경우 성능이 크게 향상됨을 확인하였다.

Key Words : HSR, QR, PL, QRPL, Hybrid approach

ABSTRACT

High-availability seamless redundancy (HSR) is a fault-tolerant protocol for Ethernet networks that provides two frame copies for each frame sent. Each copy is forwarded on a separate physical path. HSR is a potential candidate for several fault-tolerant Ethernet applications, including smart-grid communications. However, the major drawback of the HSR protocol is that it generates and circulates unnecessary frames within connected rings regardless of the presence of a destination node in the ring. This downside degrades network performance and can deplete network resources. Two simple but efficient approaches have previously been proposed to solve the above problem: quick removing (QR) and port locking (PL). In this paper, we will present a hybrid approach, QRPL, by combining QR with PL, resulting in further traffic reductions. Our analysis showed that network traffic is significantly reduced for a large-sized HSR connected ring network compared to the standard HSR protocol, QR, and PL.

Ⅰ. Introduction

The high-availability seamless redundancy (HSR) protocol was standardized by the International Electrotechnical Commission (IEC) as IEC 62439-3 Clause 5 [1], and is mostly used for ring topologies, including connected rings. The HSR principle and application is described in [1-5]. The main drawback of HSR is the extra traffic due to the generation and circulation of redundant frame copies inside the network, especially when unicast traffic applications such as video or audio streaming are used. This downside degrades network performance and can cause network congestion or delays.

Several studies have been conducted to improve HSR

※ 본 연구는 한국연구재단 (과제번호: NRF-2015R1D1A1A02059506) 지원으로 수행된 연구 결과임.
*명지대학교 정보통신공학과 U&C 연구실 및 엠피스연구단 소속 (ibrahimgate@gmail.com),
**명지대학교 부총장/정보통신공학과 교수 및 엠피스연구단 소속 (jmr77@mju.ac.kr), 교신저자
접수일자 : 2016년 5월 31일, 최종게재확정일자 : 2016년 6월 21일

networks by reducing unnecessary traffic. Nsaif and Rhee [5], presented an approach to enhance HSR-based network performance called quick removing (QR), which is suitable for ring or connected-ring topologies. The idea is to remove the duplicated frame copies from the network when all the nodes have received one copy of the sent frame and are starting to receive the second copy. Therefore, the forwarding of these frame copies until they reach the source node, as occurs in standard HSR, is not needed in QR. Hong and Joe [6], introduced a packet transmission scheme with different periods based on an HSR ring topology for reducing the network traffic load. Shin and Joe [7], proposed an algorithm to reduce network traffic and maintain HSR network availability using traffic control intelligent electronic devices (IEDs) in a smart grid. Our prior work on port locking (PL) [8], aimed to enhance HSR traffic performance, which is highly efficient for the connected-rings configuration popular in substation automation systems.

In this paper, we present a hybrid approach, QRPL, which combines quick removing and port locking to result in further traffic reductions. First, an analytical expression of the network performance for the QRPL approach is derived. Then we look into the impact of various parameters, such as the number of doubly attached node for HSR (DANH) rings and the number of QuadBox rings, on traffic reduction performance. The rest of the paper is organized as follows: in Section 2, we briefly review the PL and QR approaches in terms of network traffic performance. Then we present our QRPL approach and explain its operational concept in section 3. Detailed analytical derivation and traffic performance analysis for the network under standard HSR, QR, PL, and QRPL have been made in section 4. Section 5 presents the simulation results that validate our mathematical analyses. Finally, in Section 6, we provide our conclusions.

Ⅱ. PL and QR Approaches

In this section, we review how the PL and QR approaches are used to improve HSR unicast traffic performance. In general, the HSR a node forwards a frame inside a network ring using an interface. After a while, it may receive the same frame from the same interface that was originally used to send it. The node then raises a flag indicating that there is no destination inside the ring and prevents the interface from sending any further frames to that destination. (Figures 1 and 2) show a typical HSR connected rings network that applies standard HSR and PL, respectively.

(Figure 1) depicts unicast frame distribution under the standard HSR protocol. The arrows refer to the instances of traffic generation and circulation inside each ring. All the rings participate in flooding the network with frames, even the rings that do not contain a destination node. (Figure 2) shows the traffic distribution under the PL approach. The lock symbol means that the ring has been pruned from the network for traffic currently being sent because it does not contain the destination node.

The PL approach also reduces traffic by dividing the QuadBox node into two sides. One side is connected to a DANH ring and the other to a QuadBox ring, as shown in (Figure 3). The PL works on the DANH ring side only. However, the QuadBox used to connect the two QuadBox rings is not divided [8]. The dividing method helps prevent the network from locking the QuadBox rings when the PL approach is applied.

The QR has a different working concept since it depends on disallowing the path to pass a frame through it twice [5]. To understand the operational concept of the QR approach, let us assume that node C in (Figure 4) has sent copies A and B to all the ring nodes as duplicates for a non-HSR frame generated in the upper layer of node C.

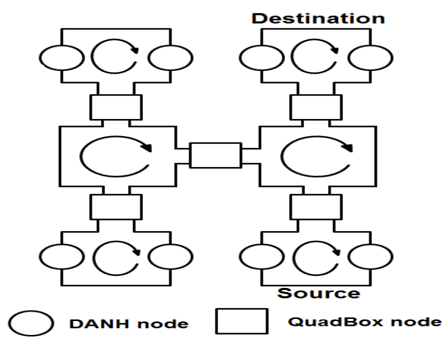

Figure1. An HSR network with four DANH rings and two QuadBox rings.

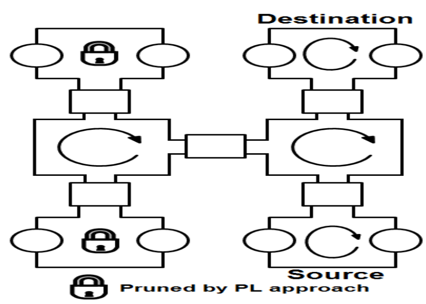

Figure 2. HSR network after the PL approach has been applied.

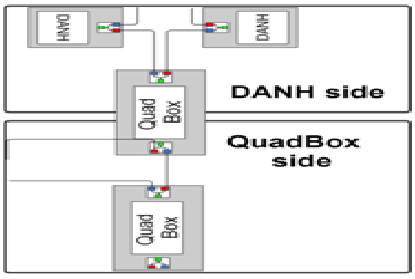

Figure 3. PL approach designation for QuadBox operation.

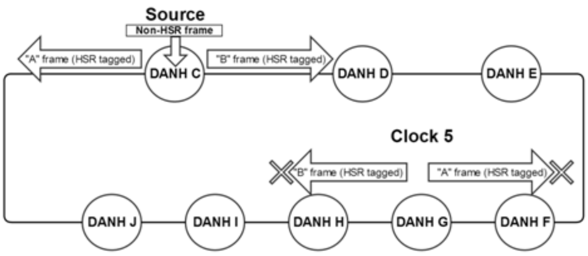

Figure 4. Clock5, removing duplicated copies under the QR approach.

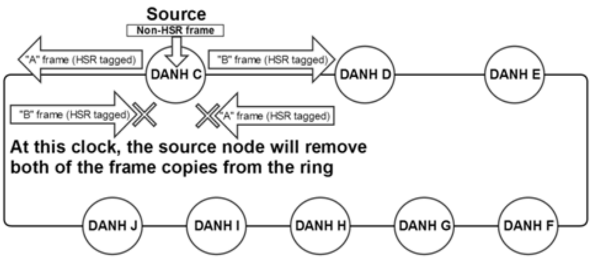

Figure 5. Clock8, removing duplicated copies under standard HSR.

Therefore, within five clocks, each of the frame copies, A and B, will pass each other at node G with a certain delay between them, and then travel toward nodes F and H. At that moment, each HSR node will take the following actions:

if both frame copies are error-free, all the nodes on the left and right sides of node G will have already received a copy of the sent frame. Node F will have also received copy B from the right side and copy A from the left side. The same is true for node H; it will have received copy A from the left side and copy B from the right side.

Now, if it is assumed that node G received copy A first and then received copy B, then nodes H, I, and J will have also received copy A and there would be no need for copy B. The same is true for nodes F, E, and D; if they received copy B, there would be no need for copy A.

Hence in the worst-case scenario, node H would remove copy B from the ring that is, if node G could not do so because the delay between the arrivals of copy A and copy B would be so small that node G would not be able to recognize that copy B is a duplicated frame of copy A. If this were the case, it would not remove it from the ring. Otherwise, it would. Node F would also remove copy A. They would have done so because all the nodes would have each received one copy of the sent frame.

Note that during the healthy case of the QR approach, both copies of the sent frame will be removed from the ring in the fifth clock. In contrast, in the standard HSR protocol, both copies of the sent frame will be removed from the ring at the eighth clock, as shown in (Figure 5). In other words, they will be removed when they reach the source node.

Ⅲ. QRPL Approach

In this section, we present our new approach, QRPL, which combines QR and PL. Again, the HSR ring network consists of two types of rings, the QuadBox rings and the DANH rings. To ensure the maximum performance of traffic reduction, the QR approach will be applied in the QuadBox rings only, and the PL will be applied in the DANH rings only. To do that, each QuadBox node will be assigned to two sides, as shown in (Figure 6); a side that is connected to the DANH ring with PL applied, and the other side to the QuadBox ring with QR applied.

The PL approach works by locking any DANH ring that does not contain the destination, while QR works by preventing the frames from traveling forward and backward in any link belonging to the QuadBox rings. QRPL results in greater traffic reductions due to the combination of the traffic reduction of the QR and PL approaches. (Figure 7) shows a connected ring network where standard HSR, PL, QR, and QRPL has been applied. Each case shows a different traffic generation percentage due to the node activity inside each ring.

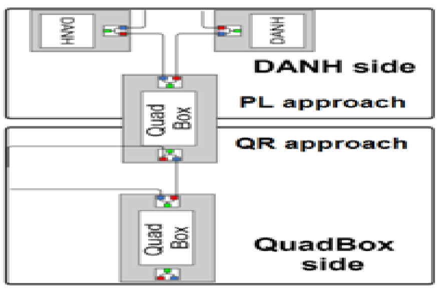

Figure 6. QRPL approach designation for QuadBox

operation.

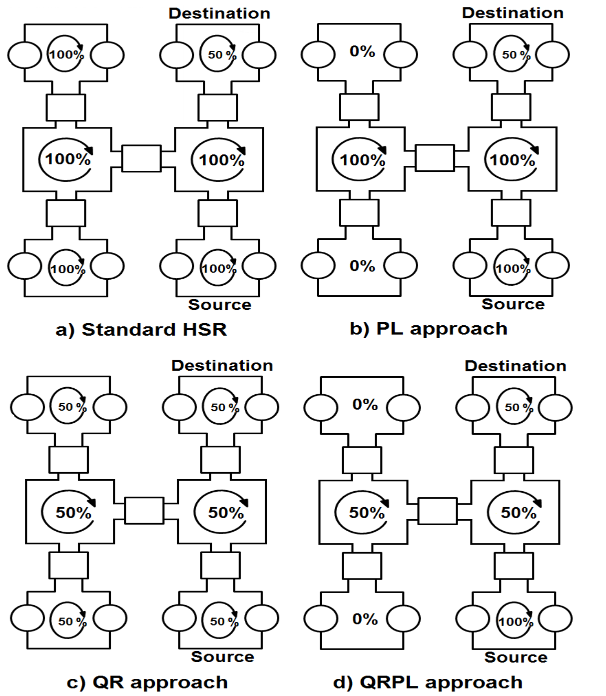

Figure 7. Comparison of HSR, PL, QR, and QRPL traffic generation.

The 100% traffic generation in (Figure 7) means that each node in that ring forwards each frame at least two times. The 50% traffic generation in the figure means that each node in that ring forwards each frame only once, while 0% means the forwarding process has been stopped. (Figures 7 a, b, c, and d) show 50% traffic generation at the destination ring because the destination consumes the frame instead of forwarding it. When the PL approach is applied, traffic generation in the non-existent source or destination DANH rings will be reduced to 0%, as shown in (Figure 7b). When the QR approach is applied, traffic generation will be reduced to 50% in all the network rings, as shown in (Figure 7c). When the QRPL approach is applied, traffic generation in the QuadBox rings will be reduced to 50%, and the non-existent source or destination DANH rings will show 0% traffic generation, as shown in (Figure 7d). The traffic reduction performance will vary according to the number of connected rings.

The QRPL approach can work side by side with any HSR DANH node in the ring network because only the standard QuadBox nodes need to be configured with the QRPL approach; the DANH nodes do not need to adopt any of the QR, PL, or QRPL approaches in their configurations.

Ⅳ. Traffic Performance Comparison between Standard HSR, QR, PL, and QRPL

In this paper, the amount of network traffic is used as a metric to compare standard HSR, QR, PL, and QRPL. We will show a mathematical expression to represent the network traffic generation after adopting the QRPL approach.

The QR approach works by disallowing the frame from traveling a round trip in the HSR network ring. Equation 1 shows the traffic generation under the QR approach:

$$T_{QR} = \sum_{i=1}^{N} [Round\,up(\frac{N}{2}) + 1] \times F_i \times D_F \qquad (1)$$

where (N) is the number of nodes inside the ring, (F) is the number of frames sent per node, (D) is the number of duplicated copies and (TQR) is the traffic generation under the QR approach. Note that for TQR, ([Roundup(N/2)+1]) is used instead of N because within QR the duplicated frame copies will be removed from the ring after they have passed a length of [Roundup(L/2)+1] in a worst-case scenario, i.e., after they have passed the midway node N/2 and reached the adjacent node. If N is an odd number, then the roundup function will take the larger number of the N/2 result, i.e., if N=7, then [Roundup(7/2)]=4[5].

The PL approach works by pruning the unused rings. To find network traffic generation after applying PL, we need to subtract the activities of the pruned nodes (Nt), which are equal to (Nt × 2NFrame), from the total network traffic as follows[8]:

$$T_{PL} = T_{SH} - (N_t \times 2N_{Frame}) \qquad (2)$$

where (TSH) is the traffic generation of standard HSR, and (NFrame) is the number of sent frames. (TSH) can be found by multiplying the number of links in the network by the number of frames sends per node as shown in Equation 3 [5]

$$T_{SH} = L \times F \times D_F \qquad (3)$$

where L is the total number of links in the network.

Since the QRPL approach is based on combining QR and PL, then substituting TSH in Equation 2 by TQR from Equation1 reveals the traffic generation TQRPL.

$$T_{QRPL} = T_{QR} - (N_t \times N_{Frame}) \qquad (4)$$

In Equation 4, the term (Nt×NFrame) is used instead of (Nt×2NFrame) as in Equation 2 because the term

([Roundup(N/2)+1]) of the QR approach in Equation 1 limited the frame forwarding of each node inside the network to one frame instead of two.

The working condition of PL depends on two stages: the learning stage and the working stage. To meet the condition of PL, Equation 4 must accumulate the traffic generation for the first frame sending as standard HSR with the traffic generation for the rest of the frames as QRPL. Equation 5 shows the total traffic generation under the QRPL approach:

$$T_{QRPL} = \lim_{N_{Frame} \to 1} T_{SH} + \left(\sum_{i=2}^{i=TN_{Frame}} T_{RQR} - 2N_t i \right) \tag{5}$$

where (TNFrame) is the total number of sent frames. Equation 5 shows a sequential working steps; the network will work as standard HSR for the first frame, which will allow the PL to fulfill its learning stage. After that and for further frames sending, the network will prune the unused DANH rings due to the PL working stage effect. Meanwhile, the QR approach is already working on removing the extra traffic from any QuadBox ring in the network.

In the case of a faulty free ring network, a unicast frame being sent from a source to a destination will generate frame duplications; the number of generated frames will be directly proportional to the number of nodes in the ring network. To compare HSR, QR, PL, and QRPL, we apply them to a network comprising of three QuadBox rings, as shown in (Figure 8). Here, each QuadBox ring contains two DANH rings, and each DANH ring contains four DANH nodes. By applying Equations 1 to 4, we can compare the traffic between TQR, TSH, TPL, and TQRPL, as shown in (Figure 9).

If TSH is considered to be the reference for purposes of comparison with TQRPL, then the reduction percentage (R) in the network traffic will be equal to

$$R_{QRPL} = [1 - (\frac{T_{QRPL}}{T_{SH}})] \times 100\% \tag{6}$$

$$R_{QR} = [1 - (\frac{T_{QR}}{T_{SH}})] \times 100\% \tag{7}$$

$$R_{PL} = [1 - (\frac{T_{PL}}{T_{SH}})] \times 100\% \tag{8}$$

By using Equations 6, 7, and 8 for the network shown in (Figure 8), we can compare the traffic reduction between TSH, TPL, TQR, and TQRPL, as shown in Table 1.

Based on the results of the analysis, it is shown that QRPL provides a significant traffic reduction of 62%, while PL and QR provide traffic reductions of 52% and 41%, respectively.

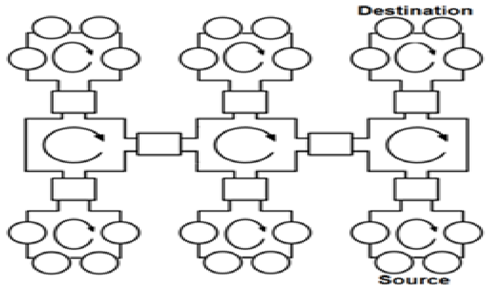

Figure 8. HSR connected ring network of three QuadBox rings; each QuadBox ring contains two DANH rings, and each DANH ring contains three DANH nodes.

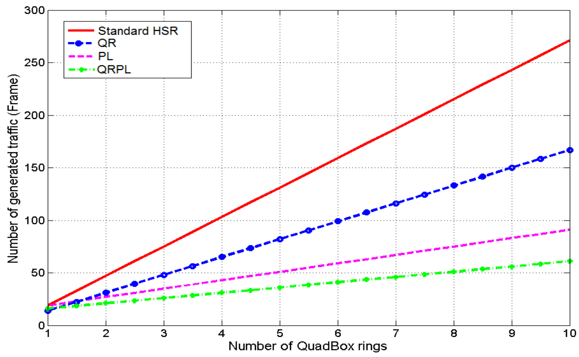

Figure 9. TSH, TQR, TPL, and TQRPL values with respect to the number of QuadBox rings.

Table 1. Traffic reduction comparison between standard HSR, PL, QR, and QRPL.

	Traffic generation	Traffic reduction
Standard HSR	73	0%
PL	35	52%
QR	43	41%
QRPL	28	62%

V. Simulation Results

In this section, we present the simulation results that validate our mathematical analyses. The QRPL algorithm has been implemented within an HSR network using OMNET++ [9]. The simulation steps included the creation of an HSR source and destination, multiple unicast frames sent from the source to the destination, and lastly, a calculation by the software of each node's traffic generation based on the embedded algorithm in each one. For comparison purposes, the simulation results covered the HSR, PL, QR, and QRPL. (Figure 10) shows the network topology representation under the simulation environment. It contains three connected QuadBox rings, with each ring containing two DANH rings, and each DANH ring containing four DANHs. The simulation result in (Figure 11) shows the total network traffic for our simulation scenario.

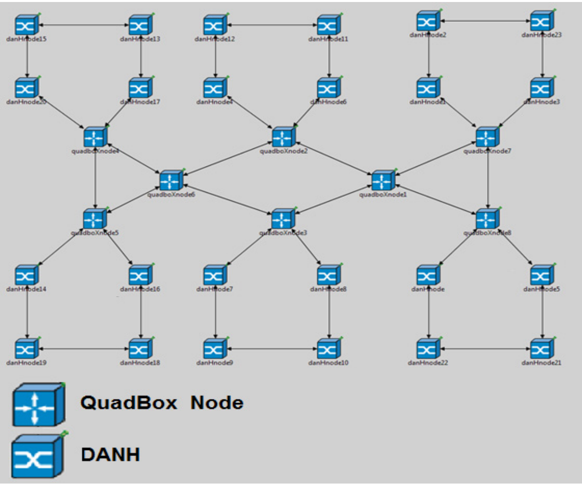

Figure 10. HSR network topology screenshot from the OMNET++ simulation [9].

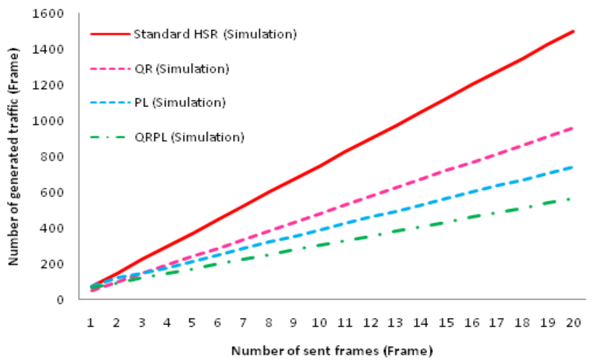

Figure 11. TSH, TQR, TPL, and TQRPL results with respect to the number of sent frames.

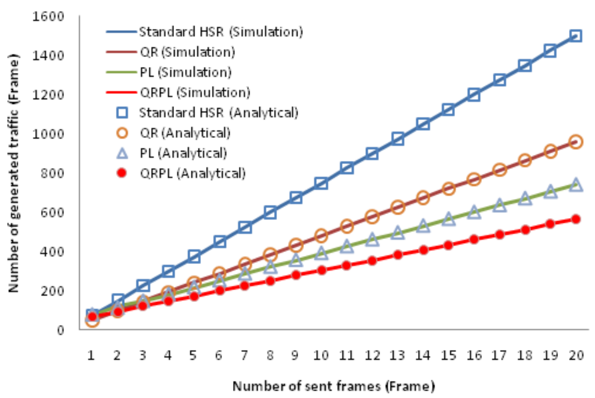

Figure 12. TSH, TQR, TPL, and TQRPL simulation and analytical comparison with respect to the number of sent frames.

To compare the simulation results with the analytical results, Equations 1, 2, and 5 were used to calculate the traffic generation of the network topology as shown in (Figure 10). A comparison between the simulation and analytical results for all our simulation cases revealed no differences, as shown in (Figure 12). The standard HSR traffic shown in the results was considered the highest since all the network rings were participating in the forwarding process. In the counter of the QR and PL, the QR showed less traffic generation due to the path cutting for unnecessary forwarding. And the PL approach showed greater traffic reduction since all the DANH rings that did not contain a destination were pruned. The QRPL showed the highest traffic reduction among all the other approaches, due to the combination of stopping the unnecessary traffic forwarding and pruning the DANH rings that did not contain a destination.

Ⅵ. Conclusion

In this paper, we proposed a new approach, QRPL, to solve the issue of unnecessary network traffic from the standard HSR protocol by combining the two approaches QR and PL. Our detailed analysis shows that QRPL gives a significantly better network performance than either QL or PL. We also noted that:

(i) The traffic reduction percentage is proportional to the number of DANH rings in the network: increasing the number of DANH rings increases the number of links, eventually resulting in a huge number of unnecessary frames occupying the network. However, by using the QRPL approach, the frames will stop circulating due to the DANH ring pruning process of the QRPL.

(ii) Increases in the QuadBox rings degrade network performance in standard HSR due to the increasing number of links. Eventually the path segments will become longer and make the frames travel forward and backward over greater distances. Therefore, by using the QRPL approach, these frames will stop circulating as soon as they reach, in the worst-case scenario, node number [Roundup(N/2)+1]. Almost half the traffic will be removed from the QuadBox rings instead of traveling through the remaining links (2×{N-[Roundup(N/2)+1]}) in both directions. Note that this number will increase if Nisincreased.

References

[1] IEC 62439-3 International Electrotechnical Commission. Industrial Communication Networks - High-available Automation Networks, Part: 3 Parallel Redundancy Protocol and High-availability Seamless Redundancy (HSR), 2010.

[2] Araujo, J. A.; Lazaro, J.; Astarloa, A.; Zuloaga, A.; Garcia, A. High availability automation networks: PRP and HSR ring implementations. In Industrial Electronics (ISIE), 2012 IEEE International Symposium on, IEEE, 2012; pp. 1197-1202.

[3] Kirrmann,; H. HSR - High Availability Seamless Redundancy, Fault-tolerance in Ethernet networks IEC 62439, Presentation slides, ABB Switzerland Ltd, Corporate Research, Baden, 2010.

[4] IEC 61850-90-4, Network Engineering Guideline for Communication Networks and System in Substation, 2013.

[5] Nsaif, S.A.; Rhee, J. M. Improvement of high-availability seamless redundancy (HSR) traffic performance for smart grid communications. Journal of Communications and Networks 14, pp. 653-661, 2012.

[6] Hong, S.; Joe, I. A novel packet transmission scheme with different periods according to the HSR ring direction in smart grid. 4th International Conference-FGIT, Dec. 2012; pp. 95 - 102.

[7] Shin, M.; Joe, I. Performance improvement for the HSR ring protocol with traffic control in smart grid. 4th International Conference-FGIT, Dec. 2012; pp. 48 - 55.

[8] Abdulsalam, I. R.; Rhee, J. M. Improvement of High-availability Seamless Redundancy (HSR) Unicast Traffic Performance Using Port Locking, Hong Kong, China. WCSE 2013, CPS, 2013; pp. 246-250.

[9] OMNET++ v.4.2.2 Simulator. Available online: http://www.omnetpp.org/ (accessed on 1 August 2013).

Authors

Ibraheem Read ABDULSAM

· 2006년 6월 : Nahrain Univ., Iraq B.Sc in Laser and Optoelectronics Eng.
· 2010년 6월 : Nahrain Univ., Iraq M.Sc in Laser and Optoelectronics Eng Eng.
· 2010년~2012년 : Network Enginee in IDN(Iraqi Defense Network) for MOD(Ministry of Defense)
· 2012년 3월~현재 : 명지대학교 정보통신공학과 박사과정

<관심분야> : Military communications, ubiquitous networks and smart grid communications.

이 종 명(Jong Myung Rhee) **정회원**

· 1976년 2월 : 서울대학교 전자공학과 (공학사)
· 1978년 2월 : 서울대학교 전자공학과 (공학석사)
· 1987년 12월 : North Carolina State Univ. ECE Dept. (공학박사)
· 1978년~1997년 : 국방과학연구소 책임연구원
· 1997년~1999년 : 데이콤 연구소 부소장
· 1999년~2005년 : 하나로텔레콤 CTO (부사장)
· 2006년 9월~현재 : 명지대학교 정보통신공학과 교수
· 2016년 2월~현재 : 명지대학교 부총장

<주 관심분야> : Military Communication, Fault Tolerant System, Ad-hoc, Data Link, Convergence, Smart Grid Communications