

Improvement of High-availability Seamless Redundancy (HSR) Traffic Performance

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Abstract—High-availability Seamless Redundancy (HSR) is a redundancy protocol for Ethernet (IEEE802.3) networks that provides duplicated frames for separate physical paths with zero recovery time. This means that even in the case of a node or a link failure, there is no stoppage of network operations whatsoever. HSR is suitable for mission critical Ethernet applications, but its main drawback is the extra traffic created due to the redundant frame copies that are generated and circulated inside the network, especially when using multi-broadcast applications, such as video or audio streaming. This downside will degrade the network performance and may cause network congestion or delays.

We propose two approaches to solve the abovementioned problem.

The first approach is called Quick Removing (QR) and is suited to a ring or connected ring topologies. The idea behind this approach is to remove the redundant frame copies from the network when all the nodes have received one copy from the sent frame and begin to receive a redundant copy. Therefore, the forwarding of the redundant frame copies until they reach the source node (in order to remove them) is not needed in HSR. Instead, removing them at a proper time will reduce the network traffic and retain the HSR network's availability. For a network illustrated in this paper, a 37.5% reduction in network traffic is achieved with reference to standard HSR.

The second approach is called the Virtual Ring (VRing), which is similar to the Virtual Local Area Network (VLAN). The idea is to divide an HSR network (any closed-loop network) into several VRings. Each of them will circulate (isolate) the traffic (frames) of a certain group of nodes within it. Therefore, the traffic of that group will not affect all the other network links or nodes, and this will result in an enhancement of traffic or network security. For the sample network in this paper, the VRing approach shows a 53% reduction of network traffic under the healthy network case and a 42.8-60% reduction under the faulty case in comparison with the standard HSR.

Keywords—HSR, HSR Unicast and Multi-Broadcast, Network Traffic Improvement, Redundancy, Quick Removing, Virtual Rings.

I. INTRODUCTION

The HSR protocol is standardized by the International Electrotechnical Commission (IEC) as IEC 62439-3 Clause 5, [1] and it is mostly used for ring topologies. However, redundant connections to other networks are also possible (e.g., connected rings or mesh topologies). As a redundancy protocol for the Ethernet (IEEE802.3) network, the HSR

provides duplicated (or copied) frames on separate physical paths with zero recovery time. This means that even in the case of a node or a link failure, there is no stoppage of network operations. Therefore, HSR is suited for applications that require high availability and zero recovery time because the conventional protocol, such as the Rapid Spanning Tree Protocol (RSTP), cannot provide this. Typical HSR applications are as follow:

- *Smart Grid Electrical Substation Automation*
- *Protection and Monitoring Systems for Nuclear Stations*
- *Military Communication Systems for Operations Centres and Command Headquarters*
- *Motion Control*
- *Industrial Automation*

The HSR principle and its implementation can be found in [2-4]. The main drawback of HSR is the extra traffic due to the redundant frame copies that are generated and circulated inside the network, especially when using multi-broadcast applications, such as the video or audio streaming. This downside will degrade the network performance and may cause network congestion or delay. No previous work has been performed regarding the HSR traffic issue or the reduction techniques.

In this paper, we introduce two approaches to reduce the extra traffic in HSR. Also, a performance comparison has been made between the proposed schemes and standard HSR.

II. BACKGROUND

In this section, the HSR traffic issues will be covered. In general, the HSR has four types of nodes, but the DANH (Doubly Attached Node for HSR) is enough to handle the traffic issues. It is an HSR node that has two Ethernet ports (HSR ports) that share the same MAC address and IP set address. This allows network management protocols, such as ARP, to operate as usual (unmodified) and simplifies engineering [3]. Each DANH node will duplicate a non-HSR frame that is generated in its upper layer into two copies (Copy A and B). It will then append an HSR tag to each copy and send them out through its ports (one in a clockwise direction and the other in a counter-clockwise direction), as shown in Figure 1.

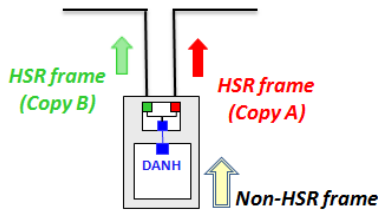


Figure 1. DANH node functionality

A. Unicast Traffic Issues

Actually, HSR has no issues with unicast traffic inside a ring topology, but with closed-loop networks, the duplicated copies of the sent frames will be spread out across all the network links and nodes due to the duplication concept of the HSR process. Therefore, many duplicated frame copies will be generated, but eventually they will be removed from the network, and just one copy will be used by the destination node.

B. Multi-Broadcast Traffic Issues

1) Ring Topology: In this type of topology, the duplicated frame copies will be circulated inside the ring until they reach the source node, which will remove them from the ring, as shown in Figure 2.

The advantage of the duplicated frames is to ensure that each node will receive at least one copy of the sent frame, especially if there is a fault in one of the network components, but if the network is healthy (fault-free), then each node will receive two copies of the sent frame (one from each direction), accept the first one that reaches it, and discard the second. In this case, half of the network bandwidth will be wasted due to the redundant frame copies, which will account for about 50% of the total frames. Note that these are useless frames, which will later be removed from the network.

2) Other Closed-loop Networks: The situation here is similar to that of unicast traffic within closed-loop networks, but it is more complicated because many duplicated frame copies will be generated, spread out, and then removed, which means more network bandwidth will be consumed.

C. HSR Node Action with Bad Frames

1) One Bad Frame: if one of the received frame copies is bad (has an error), then it does not matter. There is another copy that will be delivered from the other direction.

2) Two Bad Frames: If both directions did not deliver an error-free copy, the transport layer (such as the TCP) will resend the information because this is the task of the transport layer [5].

III. TWO PROPOSED APPROACHES

Our approaches for improving HSR traffic performance within a ring or any other closed-loop network topology are introduced in this section.

The first approach is called **Quick Removing (QR)** and is suited for ring or connected ring topologies with multi-

broadcast traffic. This approach aims to remove all the redundant frame copies from the network when all the nodes have received one copy of the sent frame and begin to receive a redundant copy.

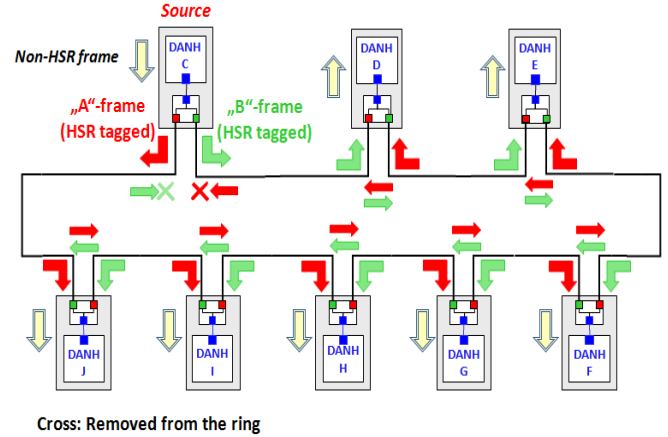


Figure 2. HSR broadcast process

The second approach is called the **Virtual Ring (VRing)**. In this approach, the HSR network will be divided into several VRings in order to separate the traffic (frames) of a nodes group from the other traffics in the network. It will increase the network performance, reduce the effect of the multi-broadcast traffic, improve manageability, and even enhance traffic security. This approach is suited to any closed-loop network.

A. Operational Concepts for the QR Approach

The HSR is dependent on clock synchronization that relies on IEEE 1588 V2 [6], and the preferred method that is used for HSR is the one step clock [7], which means that within each clock, the frames will move from one node to its adjacent node. In this paper, we adopt the same clock operation concept.

To understand the operational concepts for the QR approach, let us assume that node C in Figure 3 has sent duplicated copies (copy A and B) of a frame to all the network nodes. 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 travel toward nodes F and H. At this moment, each HSR node will take the following actions:

1) If Both Copies are Error-Free

- All the nodes on the left and right sides of node G have already received copy A.
- Node F received copy B from the right side and received copy A from the left side. The same is true for node H; it received copy A from the left side and received copy B from the right side.
- If node G received copy A first and then received copy B, this means that nodes H, I, and J have also received copy A and that there is no need for copy B.
- The same is true for nodes F, E, and D; they received copy B, and there is no need for copy A.

Node Action: Node H will remove copy B from the ring, and node F will also remove copy A. They will do so because all the nodes have received one copy of the sent frame.

2) If a Copy is Bad

Let us assume that copy A received an error during transmission from the source node (C) to J. In this case:

- Node J will remove the bad copy from the ring as soon as the node receives it.
- All the nodes in the network (except the source) will wait for copy B because copy A has been removed from the ring.

Node Action: Each node will take a copy and forward it to the next node on its left side until it reaches the source node. The same steps will occur if copy B is bad.

3) If a Copy became Bad during Transmission

Let us assume that copy A became bad during transmission, for example, between nodes J and I. In that case:

- Node I will remove copy A from the ring.
- Node H will not receive copy A.

Node Action: Node H will forward copy B as soon as it receives copy B from the right side because it realizes that all the other nodes located on the left side did not get copy A, or at least, the node next to it did not get it. If it had, node H would have gotten copy A. Node I will also forward copy B to node J, but node J has already received copy A, so it will discard copy B and remove it from the ring. The same steps will be applied if a link or a node in the middle of the network is down.

Note that in the QR approach, in the best case scenario (in the 5th clock), both copies of the sent frame will be removed from the network, but if one side still needs a copy, while on the other side, all nodes received an error-free copy, then one copy of the sent frame will be removed, and the other will be forwarded to that side. In contrast, in the standard HSR process, in the best case scenario, both copies of the sent frame will be removed from the ring at the 8th clock, as shown in Figure 4. In other words, they will be removed when they reach the source node.

B. Traffic Performance Comparison between Standard HSR and our QR Approach

In this paper, the amount of network traffic will be used as a metric to compare standard HSR and our approaches. This metric is a good candidate because the aim of our approaches is to reduce the redundant traffic in the network.

First, let us denote the following parameters as:

- Network traffic under standard HSR = T_{SH}
- Network traffic under the QR approach = T_{QR}
- Network traffic under standard HSR with a faulty link = T_{SHLF}
- Network traffic under the QR approach with a faulty link = T_{QRLF}
- Network traffic under standard HSR with a faulty node = T_{SHNF}
- Number of duplicated frame copies = D_F

- Network traffic under the QR approach with a faulty node = T_{QRNF}
- Number of frames sent per node = F
- Number of clocks that are required to complete one transmission process per sent frame = C
- Total number of nodes = N
- Total number of links = L

Note that, C is always equal to L and is equal to N in a ring topology.

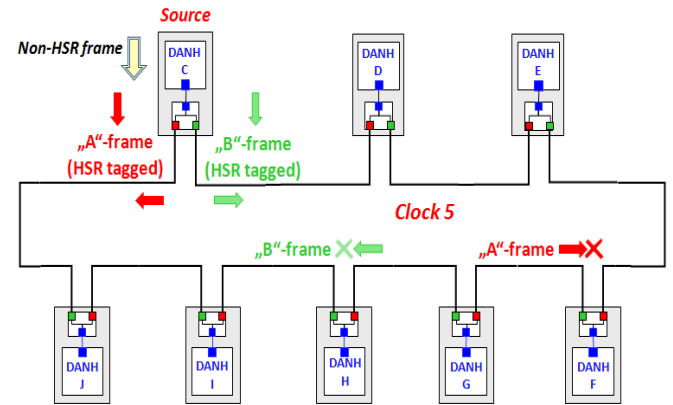


Figure 3. Clock 5, removing redundant copies under the QR approach

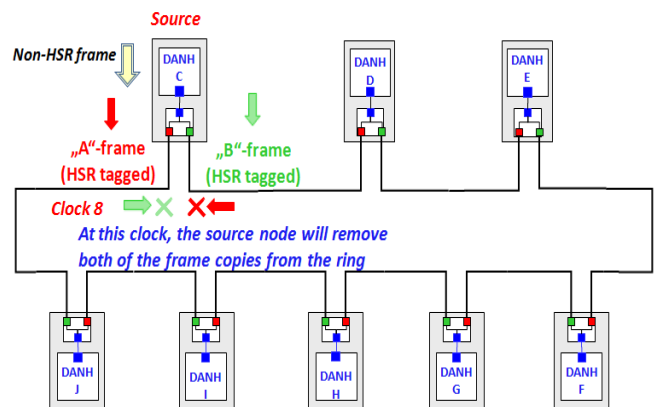


Figure 4. Clock 8, removing redundant copies under standard HSR

It is obvious that for each frame sending process, under each clock time, two links of the network are busy with carrying the redundant frame copies, but if one of the redundant copies is removed (maybe a bad copy), then only one link will be busy.

Now let us compare the network traffics for a ring under the standard HSR process and the QR approach in different cases.

1) Healthy Network (Error-Free): As a simple example, the network traffic under the standard HSR process for one node transmitting with one transmission process (send and receive period) is equal to:

$$T_{SH} = L * F * D_F \dots\dots\dots (1)$$

Since $L=N$, then (1) can be written as

$$T_{SH} = N * F * D_F \dots\dots\dots (2)$$

For more than one simultaneous transmitting node, T_{SH} will be

$$T_{SH} = \sum_{i=1}^N \{N * F_i * D_F\} \dots\dots\dots(3)$$

Where i = the number of nodes that are transmitting simultaneously.

Also

$$T_{QR} = [\text{Roundup}(N/2) + 1] * F * D_F \dots\dots\dots(4)$$

Note that for T_{QR} , $[\text{Roundup}(N/2) + 1]$ is used here instead of N in T_{SH} because within the QR , the redundant frame copies will be removed from the ring after they pass a length of $[\text{Roundup}(L/2) + 1]$, or in other words, after they pass the midway node ($N/2$) and reach the adjacent node.

If N is an odd number, then the *Roundup* function will take the larger number of the $N/2$ result, e.g., if $N=7$, then *roundup* ($7/2$) = 4

For more than one simultaneous transmitting node, T_{QR} will be

$$T_{QR} = \sum_{i=1}^N \{[\text{Roundup}(\frac{N}{2}) + 1] * F_i * D_F\} \dots\dots\dots(5)$$

If T_{SH} is considered to be the reference for purposes of comparison with T_{QR} , then the reduction percentage (R) in network traffic will be equal to

$$R = [1 - (\frac{T_{QR}}{T_{SH}})] * 100 \dots\dots\dots(6)$$

Substituting equations (2) and (4) into (6) yields

$$R = [1 - (\frac{[\text{Roundup}(N/2) + 1] * F * D_F}{N * F * D_F})] * 100\% \dots\dots\dots(7)$$

For the network shown in Figure 3, if it is assumed that node C broadcasted one frame, then

$T_{SH}=16$ frames, $T_{QR}=10$ frames, and $R=37.5\%$

Therefore, it is clear that the QR approach reduces the network traffic by 37.5% in this case.

For a general case, equation (7) can be modified as

$$R = [1 - (\frac{\sum_{i=1}^N \{[\text{Roundup}(\frac{N}{2}) + 1] * F_i * D_F\}}{\sum_{i=1}^N \{N * F_i * D_F\}})] * 100\% \dots\dots\dots(8)$$

If a limit function with a large number of nodes ($N \rightarrow \infty$) is applied to the above equation, it yields:

$$R = \lim_{N \rightarrow \infty} [1 - (\frac{\sum_{i=1}^N \{[\text{Roundup}(\frac{N}{2}) + 1] * F_i * D_F\}}{\sum_{i=1}^N \{N * F_i * D_F\}})] * 100\% = 50\%$$

For a practical case, it is capable of producing an R value close to 49.5% with $N=200$ nodes.

Note that the R percentage and T_{SH} are proportional to the number of the nodes N in the ring network, while T_{QR} is proportional to $N/2$, as shown in Figures 5 and 6.

The number of clocks that is required to complete the transmission process will also be reduced by the same percentage R , so the network shown in Figure 3 will only need 5 clocks, instead of 8 clocks, after applying the QR approach. The reduction percentage in clock number = $(1 - (5/8)) * 100\% = 37.5\%$

2) Faulty Network with Link Failure: In this case, the duplicated copies will not circulate in the ring. They will only travel until they reach the faulty link, which means that only $N-1$ links will be available to carry the frames. Then

$$T_{SHLF} = T_{QRLF} = (N - 1) * F \dots\dots\dots(9)$$

In addition, for a general case,

$$T_{SHLF} = T_{QRLF} = \sum_{i=1}^N \{(N - 1) * F_i\} \dots\dots\dots(10)$$

3) Faulty Network with Node Failure: Under a node failure, two links will be lost, so

$$T_{SHNF} = T_{QRNF} = \sum_{i=1}^N \{(N - 2) * F_i\} \dots\dots\dots(11)$$

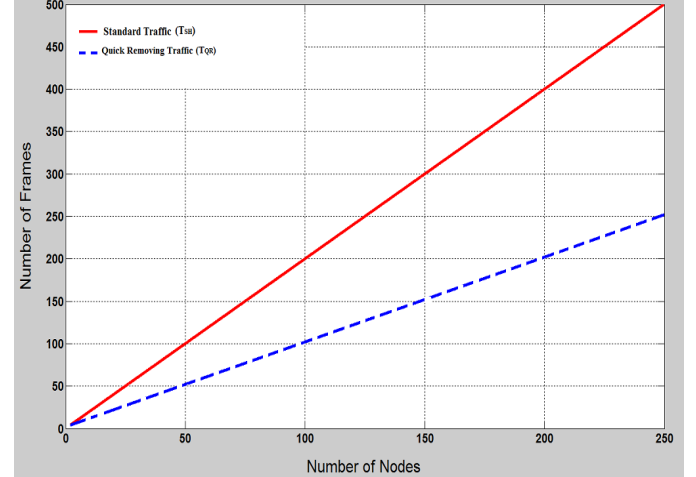


Figure 5. T_{SH} and T_{QR} values with respect to the number of network nodes

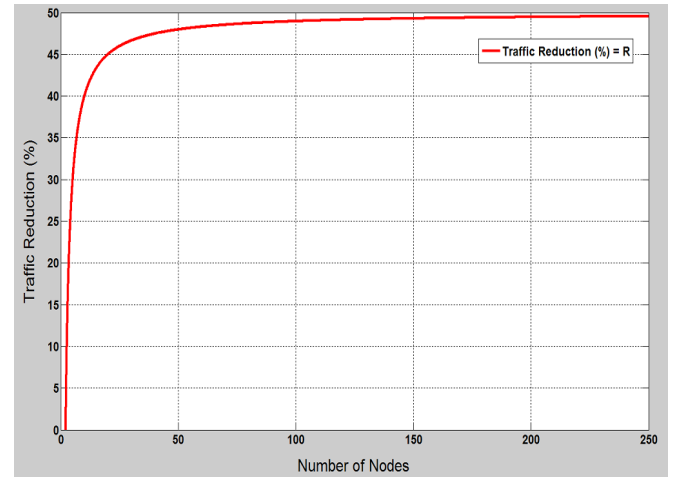


Figure 6. R percentage with respect to the number of network nodes

C. Operational Concepts for the VRing Approach

The VRing is similar to the Virtual Local Area Network (VLAN) technique [8], and it is especially useful with multi-broadcast applications because the traffic of a certain group of nodes that are using those applications can be isolated from other traffics. In this way, heavy traffic, such as video or audio streaming, will not affect all the network nodes and links because it will not spread out across the entire network, as it does in the standard HSR process. Eventually, this will improve network performance by increasing the network traffic reduction percentage and also increase the security of the different traffics. In addition, the administrator of the network will know through which path each group's traffic

will pass, because he or she will draw or identify the paths for each VRing traffic according to the customer requirements as well as the network performance and security limitations.

1) Healthy Network (Error-Free): This approach can be implemented in any closed-loop network except for a ring, where it would be useless. Therefore, let us adopt the matrix-type topology shown in Figure 7 as a typical example.

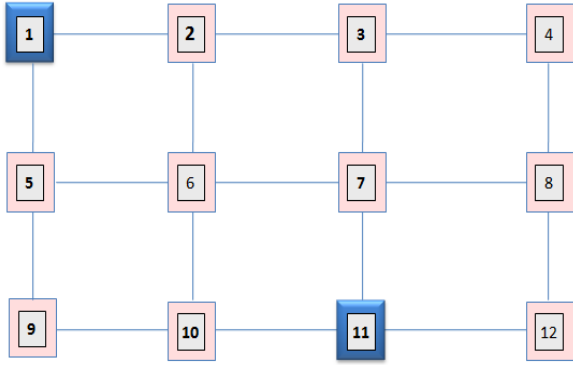


Figure 7. Matrix HSR Network

Let us assume that node 1 is sending information to node 11 in a continuous manner. By using a standard HSR frame distribution process, node 1 will send two copies from each frame to nodes 2 and 5, which nodes 2 and 5 will duplicate and send out to the adjacent nodes and so on. The transmission process will take 6 clocks since node 12 will also forward the frames to node 11, and the frames will pass through all the network links (17 links). The traffic distribution in this case will affect network performance, especially when several nodes are sending a continuous stream of frames (multi-broadcast or even unicast traffic).

However, if a VRing is established between nodes 1 and 11, then the frames will be circulating within that VRing and will not affect the other links and nodes.

Let us assume that the VRing will be established among the following nodes group: [1, 2, 3, 7, 11, 10, 9, and 5] as shown in Figure 8. Note that nodes 3 and 7 will not forward any traffic (frames) related with that VRing to the adjacent nodes 4 and 8, but they can receive or forward other traffic that is related to other VRings. Nodes 2, 7, 10, and 5 will also do likewise regarding node 6 because it is not a member in the VRing.

It is clear from Figure 8 that just 8 links (or 8 frames that will pass through the whole transmission process) will be used during one transmission process under this approach (each link will carry just one frame at a time), instead of using all the network links (17 links, most of them will carry more than one frame a time) during the standard HSR process.

Therefore, the R percentage here can be calculated as follows:

$$R \cong 1 - (8/17) * 100\% = 53\%$$

In this case, the traffic is reduced at least by 53% because it is assumed that only one frame per link will pass, note that the same assumption will be use for the next cases.

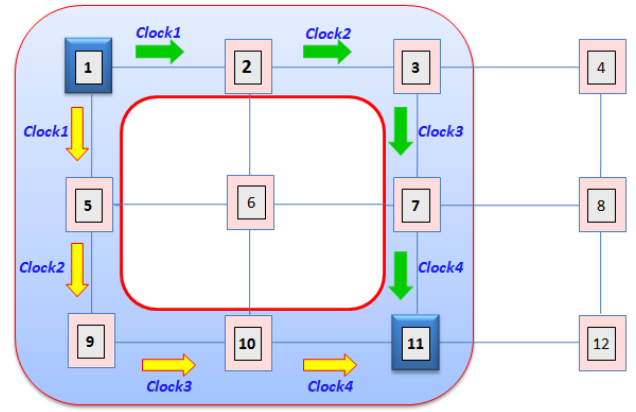


Figure 8. VRing members for the connection between nodes 1 and 11

In general, R will be increased if the matrix or mesh networks are larger. R is proportional to the number of network links.

2) Faulty Network with Link Failure (Outside the VRing)

$$T_{SHLF} \cong 17 - 1 = 16 \text{ frames}$$

$$T_{VRLF} = 8 \text{ frames}$$

where T_{VRLF} is the network traffic under the VRing approach with a faulty link

$$R \cong 1 - (8/16) * 100\% = 50\%$$

3) Faulty Network with Node Failure (Outside the VRing)

If node 8 is assumed down, that means 3 links will be lost, so

$$T_{SHNF} \cong 17 - 3 = 14 \text{ frames}$$

$$T_{VRNF} = T_{VRLF} = 8 \text{ frames}$$

where T_{VRNF} is the network traffic under the VRing approach with a faulty node

$$R \cong 1 - (8/14) * 100\% = 42.8\%$$

4) Faulty Network with Link Failure (Inside the VRing)

The traffic of the network under standard HSR will equal to $T_{SHLF} \cong 16$ frames

The traffic for the VRing approach inside the VRing with a link failure will be equal to $T_{QRLF} = 7$ frames. Then

$$R \cong 1 - (7/16) * 100\% = 56.2\%$$

5) Faulty Network with Node Failure (Inside the VRing)

The traffic of the network under standard HSR will equal to $(T_{SHLF} - 1) = 15$ frames

For the VRing approach, the traffic inside the VRing with a node failure will equal to $T_{QRNF} = 6$ frames

$$R \cong 1 - (6/15) * 100\% = 60\%$$

IV. CONCLUSIONS

In this paper, we proposed two approaches to solve the extra traffic issues of the standard HSR protocol. Through a comparison of the traffic performances of each approach with respect to the standard HSR process, it has been shown that both QR and VRing provided better performances than standard HSR. We can also note the following points related to each approach

For the QR approach, it is shown that the R percentage is proportional to the number of nodes in the ring, which means that increasing the number of nodes will increase the number of links, and eventually, the path segments will become longer and make frames travel forward and backward greater distances. Therefore, during the QR approach, those frames will stop circulating as soon as they reach (in the best case scenario) node number $\lceil N/2 \rceil + 1$. Almost half of the traffic will be removed, instead of travelling through the remaining links $(2 * \{N - \lceil N/2 \rceil + 1\})$ in both directions. Note that this number will increase if N is increased. Therefore, it seems that QR performance will be better in the wide rings that have tens of nodes as well as in a connected-rings topology.

As a future work for improving the QR approach, it would be beneficial if it could be modified so as to be applicable to any closed-loop network (such as matrices or meshes) because the amount of redundant traffic within those types of networks is too high due to their many links.

The VRing approach seems to be the better approach and can be applied to any closed-loop network except for the ring topology. Applying the VRing approach will give the administrator wide flexibility to use HSR with this approach, because with this approach, he or she will be free to use any topology with a closed-loop, so it is more resilient and gives better performance as compared with standard HSR. This approach also will reduce and organize the random broadcasting inside closed-loop networks and make the traffic travel through clear and identified paths.

The performance of the VRing will be further improved if the QR is applied inside each VRing during multi-broadcasting traffic.

As a future project regarding the VRing, the procedures for all the steps of implementing and configuring it on the HSR nodes should be established. Also, explicit and general mathematical equations for network traffic under the different cases that are discussed within this paper should be developed.

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