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, one of the drawbacks 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 will degrade network performance and may deplete network resources. Previously, we proposed a simple but efficient approach to solving the above problem, namely, port locking (PL), which is based on the media access control address. The PL approach enables the network to learn the locations of the source and destination nodes gradually for each connection pair without using network control frames; the PL then prunes all the rings that do not contain the destination node by locking the corresponding ring’s entrance ports at its QuadBox node. In this paper, we present an enhanced port-locking (EPL) approach that increases the number of pruned unused HSR rings. The analysis and corresponding simulation results show that the network traffic volume is significantly reduced for a large-sized HSR connected-rings network and consequently, network performance is greatly improved compared to the standard HSR protocol, and even PL.

**key words:** HSR, EPL, traffic performance, port locking, enhanced port locking

### 1. 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. As a fault redundancy protocol for Ethernet networks, the HSR protocol provides duplicated frames on separate physical paths with zero fault recovery time. This means that even in the case of node or link failure, there is no stoppage in network operations. Therefore, the HSR protocol is useful for applications that require high availability and zero fault recovery time, which a conventional protocol such as the rapid spanning tree protocol cannot provide. Typical HSR protocol applications are as follows:

- Substation automation system networks [2]
- Military communication systems for operation centers and command headquarters [3]
- Vehicular backbone networks [4]

The HSR principle is described in [1], [5]–[8]. 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. The HSR protocol works on forwarding frame copies to all the network nodes. This process is considered essential in broadcast sending, but in unicast sending, it is considered unnecessary since the destination is one node only. This downside will degrade network performance and may cause network congestion or delay.

Several studies have been carried out on how to improve HSR networks by reducing unnecessary traffic. Naif and Rhee presented an approach to enhancing HSR-based network performance called quick removing (QR) [8], and it is suitable for ring or connected-rings 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 those frame copies until they reach the source node, as occurs in standard HSR, is not needed in QR. Hong and Joe introduced a packet transmission scheme with different periods based on an HSR ring topology for reducing the network traffic load [9]. Shin and Joe proposed an algorithm to reduce network traffic and maintain the HSR network’s availability by using traffic control IEDs in a smart grid [10]. Other research on the HSR protocol has been dedicated to HSR implementation [5], [11]–[13]. Our preliminary work on port locking (PL) was aimed at enhancing HSR traffic performance [14] and is very efficient for the connected-rings configuration popular in substation automation systems.

In general, the HSR protocol has four types of nodes [1]. However, in the PL approach, the doubly attached node for the HSR (DANH) and QuadBox nodes are sufficient to handle HSR traffic. Connected-ring topologies...
usually consist of two kinds of rings: the DANH ring and the QuadBox ring. The ring that mainly contains DANHs is called the DANH ring, and the ring that contains mainly QuadBox nodes is called the QuadBox ring. The PL approach can only be adopted inside the QuadBox node type and it works without the need for control frames. However, this approach only prevents the DANH rings that do not contain the destination node from generating extra frames; the QuadBox rings will keep generating extra frames even if they do not lead to the required destination. Therefore, we propose a new approach to handle this issue, namely, the enhanced port locking (EPL) approach, which works to prune the QuadBox rings together with the DANH rings that do not lead to a destination, rather than pruning the DANH rings only as is the case with PL. In this paper, we first derive an analytical network performance for the HSR protocol, as well as the PL and EPL approaches. Then we look into the impact of various parameters, such as the number of DANH rings and the number of QuadBox rings, on traffic reduction performance. Finally, various simulations are made to validate the derived analytical results.

The rest of this paper is organized as follows. In Sect. 2, we briefly describe the PL approach, including an example showing the effect of the PL approach on network performance. In Sect. 3, we present our EPL approach and explain its concept of operation. Section 4 is an analysis showing the superiority of EPL’s performance over the HSR protocol and the PL approach. The simulation results are then presented in Sect. 5. Finally, in Sect. 6, we explain our conclusions and suggestions for future work.

2. PL Approach

In this section, we describe how the PL approach can be used to improve HSR unicast traffic performance and explain the issues that the PL approach still does not solve. The PL approach is based on the creation of a media access control (MAC) address table that locks the interface facing the DANH ring side in case the destination node does not exist [14].

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 those not containing a destination node. Figure 2 shows the same topology depicted in Fig. 1, but using 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 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 Fig. 3. The PL works on the DANH ring side only. How-
ever, the QuadBox used to connect the two QuadBox rings is not divided [14]. The dividing method helps to prevent the network from locking the QuadBox rings when the PL approach is applied.

3. EPL Approach

3.1 Concept of Operation

In this section, we describe our EPL approach to improving the PL approach for HSR unicast traffic performance in a connected-rings topology. EPL works with the same locking concept that is used in the PL approach. This helps to expand the locking of unused rings inside the HSR network by including the QuadBox rings, in other words, by locking the QuadBox rings that do not lead to a destination.

The EPL function works on the basis of the following two required conditions for the QuadBoxes used to connect the QuadBox rings to the DANH rings:

- If the QuadBox receives a unicast frame tagged with a sequence of 1, then it will obey the standard HSR forwarding mechanism through all the interfaces.
- Any frame tagged with a sequence larger than 1 will not be forwarded from all interfaces. It will either be forwarded inside the DANH ring or inside the QuadBox ring when the destination MAC address does exist in the PL locking table.

Figure 4 is a flowchart showing the processing steps involved in the PL approach according to the EPL principles. When a frame is received on an interface, the QuadBox will forward the frame inside the DANH ring based on the existence of the destination. The destination’s existence can be determined using the PL approach [14]. The PL approach helps to create a table that stores the MAC addresses for the non-existent destinations inside the DANH rings. EPL will allow all QuadBoxes to benefit from the PL locking table indirectly based on that table. The QuadBox decides which side the frame will be forwarded to. Since the QuadBox will stop forwarding any frame inside the DANH ring that does not contain the destination, as shown in Fig. 4, the frame will dwell inside the QuadBox ring instead of the DANH ring, indicating that the destination does not exist within any DANH ring. The process of locating the destination is carried out in two learning stages. The first is the registration of the non-existent MAC addresses in the PL locking table of the QuadBoxes that connect QuadBox rings with DANH rings [14]. The second is the registration of the non-existent MAC addresses in the EPL locking table in the QuadBoxes that connect two QuadBox rings.

Figure 5 is a simple demonstration of the two learning stages in the PL and EPL approaches. The arrows represent a unicast frame sending from a source to a ring that does not contain a destination. Figure 5(a) represents the first learning stage in the PL approach, and Fig. 5(b) represents the second learning stage in the EPL, which contributes to more traffic reduction.

Figure 6 shows the steps in the EPL approach inside each QuadBox that connects two QuadBox rings. These steps aim to lock the interface based on a comparison between a sent frame and a received one. A similarity will occur if the received frame has been sent before to a ring by the same interface; the HSR node will figure out that the destination does not exist in the corresponding ring.

The second learning stage will not be defined after a single similarity occurs; rather, a few similar instances need to occur before the decision to lock the interface is made. Eventually, if the destination does not exist in any DANH ring, the QuadBox that connects two QuadBox rings will have many similarities between the frames sent and the received frames from a specific interface, and will block its interface from forwarding frames to the corresponding ring.

Parameter $\psi$ in Fig. 6 is used as a counter for the number of frames required to activate the learning stages. It can also be defined as the number of similarities that may occur when the destination does not exist in any DANH ring. The increment of $\psi$ will be discussed in Sect. 4.

Consequently, a single path of rings from the source to the destination will be active during the sending process. The number of active QuadBox rings between the source and the destination depends on the destination’s location in the network.

Figure 7 shows an HSR ring network after EPL has been applied. The arrows identify the data path between the source and the destination. The small lock
Fig. 5  The learning stage effects of the PL and EPL approaches on the HSR network rings.

refers to the PL activity of locking the DANH rings, while the large shaded lock refers to the activity of the EPL.

The EPL approach works in three sequential stages as follows:

- First learning stage (DANH rings locking stage)
- Second learning stage (QuadBox rings locking stage)
- Working stage.

In the first learning stage, the network will work as standard HSR during the sending of the first frame, and all the DANH rings that contain no destination will be pruned. At this stage, QuadBoxes that connect DANH rings with QuadBox rings will build their locking tables based on the concepts of the PL approach. In the second learning stage, the QuadBoxes that connect QuadBox rings to DANH rings will lock all the interfaces that do not lead to pruned DANH rings. At this stage, QuadBoxes that connect two QuadBox rings will build their own locking tables based on the same concept used in the PL approach, but with regard to parameter $\psi$. In the final stage, a unique ring path will remain active while the rest of the unused rings will be pruned.

3.2 Case Study Scenario

A case study scenario involving the sending and receiving of a unicast message will illustrate the work of EPL in detail. Figure 8 shows the topology of two QuadBox rings and four DANH rings. For demonstration purposes, the QuadBoxes involved in our case study scenario are labeled from A to D. Each side of a QuadBox is labeled based on the ring type connected to it, e.g., AD means that QuadBox A’s side is
The learning stages are sequentially related to each other, so that the second learning stage cannot start until the first learning stage is completed. The stages start and end according to parameter $\psi$, which acts as a counter that triggers the second learning stage. A stream of frames sent from the source to the destination will generate two scenarios that cover all cases. The first learning stage starts with the first frame that reaches QuadBox A on AQ. QuadBox A will forward the frame inside the DANH ring using AD and inside the QuadBox ring using AQ at the same time. The first frame will never be forwarded back to AD because the destination exists. QuadBox A will never lock AD according to the PL approach. Later, any frame that reaches the destination will only be forwarded inside the DANH ring of QuadBox A according to the EPL approach. Meanwhile QuadBox D receives a frame forwarded by AQ. However, since it is in the first learning stage, DQ will never be locked unless it receives a number of returned frames that equal $\psi$. As a result, during the overall unicast sending process, QuadBox A will keep forwarding frames to its DANH ring only, due to the EPL effect; in addition, QuadBox D will never receive returned frames to reach a count of $\psi$ and thus will never be locked for that destination address. QuadBox B will forward the first frame through BQ to CQ. QuadBox C is connected to a DANH ring that does not contain a destination. Since this is the first frame, QuadBox C will forward it from all interfaces. Because there is no destination, the frame will be forwarded back to CD, and the PL approach will be triggered in QuadBox C to register the destination MAC address in the PL table. When a second frame travels from QuadBox B to C, it will be forwarded only in the QuadBox ring through CQ based on the steps in the EPL approach. Since no other QuadBox leads to a destination, any frame traveling from QuadBox B using BQ will be forwarded back to BQ itself.

After receiving $\psi$ number of returned frames, the second learning stage will be triggered, and the EPL approach will decide to lock that interface by registering the destination MAC address in the EPL table inside QuadBox B. Putting a MAC address inside the EPL table means that the QuadBox will stop forwarding in that direction any frame tagged with that MAC address as a destination.

The previous scenario represents an ideal example of a unicast between a source and a destination in the ring network. The time lag between the frames sent in the real-time sending process will add more complications, so $\psi$ must be calculated based on two aspects: the network topology and the time period between the frames in the sending process.

4. Traffic Performance Analysis

In this section, we derive the analytical traffic performance of our EPL approach, and compare it to the PL approach. In a small-sized HSR network that contains only a few rings, there will be little enhancement in traffic performance using the EPL approach.

However, for a large connected-rings network, there will be a significant performance enhancement. Applying the EPL approach to any number of connected rings will reduce the number of used rings, which will result in significant traffic reduction.

Certain conditions are shared between the PL and EPL approaches. For example, if the source and destination are located in the same ring, applying the EPL approach will result in only one active DANH ring. Conversely, if the source and destination are not located in the same ring, then our approach results in two active DANH rings in addition to the QuadBox rings that lie in between.

To evaluate HSR network traffic performance, analyt-
Table 1: Parameters for performance analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{QR}$</td>
<td>Number of QuadBox rings</td>
</tr>
<tr>
<td>$N_{DN}$</td>
<td>Number of DANH rings</td>
</tr>
<tr>
<td>$N_{PR}$</td>
<td>Number of pruned QuadBox rings</td>
</tr>
<tr>
<td>$N_{DN}^i$</td>
<td>Number of DANH rings in the $i^{th}$ QuadBox ring</td>
</tr>
<tr>
<td>$N_{DN}^j$</td>
<td>Number of nodes in the $j^{th}$ DANH ring</td>
</tr>
<tr>
<td>$N_{ADN}$</td>
<td>Number of active DANHs</td>
</tr>
<tr>
<td>$N_{AQN}$</td>
<td>Number of active QuadBox nodes</td>
</tr>
<tr>
<td>$N_t$</td>
<td>Total number of network active nodes</td>
</tr>
<tr>
<td>$N_i$</td>
<td>Number of pruned nodes</td>
</tr>
<tr>
<td>$N_{Frame}$</td>
<td>Number of frames sent</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Number of frames required to activate the learning stages</td>
</tr>
</tbody>
</table>


critical expressions of the network traffic will be derived for various cases using the parameters shown in Table 1.

4.1 Definition of $\psi$

Parameter $\psi$ is an integer number that represents the number of frames required to activate the second learning stage, namely, the allowance to receive more returned frames until the interface is locked. Statistically, when 100 frames are sent from the source to the destination, $\psi$ will take place between 1 and 100. So from the first frame only, the network will work as a standard HSR. From the second frame to the $\psi^{th}$ frame, the network will work under the PL effect; from the $(\psi^{th} + 1)$ frame to frame number 100; the network will work under the EPL effect.

From the device perspective, the $\psi$ value can either be generated as a counter for each frame received and forwarded or as a fixed value taken from the HSR frame structure, which is the sequence number. $\psi$ is determined by the network topology. If the network contains 10 QuadBox rings, then $\psi$ should be around that number. In addition, $\psi$ can take a typical value, such as 50 frames, to cover all medium/large network topologies. Picking $\psi = 50$ frames gives a linear enhancement, whether the network contains 50 QuadBox rings or not. Leading with an example of $\psi = 50$ frames, if we send 1000 frames in a network that contains 10 QuadBox rings, the HSR network will work under the PL effect for 50 frames only, and the EPL will take control of the traffic for the remaining 950 frames. For optimal traffic reduction, however, $\psi$ must be around 10 frames.

4.2 Performance Evaluation

In each unicast process in standard HSR, the frame will be forwarded and dispersed among all the network rings. Each DANH will forward the frame twice, because the frames will reach each node from both directions. As a simple example, the predicted network traffic can be approximated as follows:

$$T_{sh} = N_a \times 2N_{Frame} \times F$$

(1)

The transmission activity function for each node $F$ can be substituted with network node activities such as traffic generation or power consumption for each node. In the case of estimating traffic generation, we simply assume $F$ is equal to one, since any interface will generate one frame for each forwarding process.

The traffic generation prediction in Eq. (1) above is described as the total traffic generation by each node, but not all the nodes will contribute to forwarding from two directions, because the destination node receives only without forwarding. In this case, the destination will not generate any frames, and all the nodes inside the destination’s ring will then forward the frames in one direction. Thus, we need to subtract the halfway traffic of one DANH ring node from the total generated traffic, which is one frame from each node in the destination’s DANH ring. So the more accurate HSR network traffic expression will be as follows:

$$T_{SH} = (N_a \times 2N_{Frame} - (N_{DN} + 1)) \times F$$

(2)

Applying the PL approach will prune the traffic of the unused rings, and to calculate traffic generation after applying the PL approach, we need to subtract the activities of the pruned nodes $N_t$, which is equal to $(N_t \times 2N_{frame} \times F)$, from the total network traffic as follows:

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

(3)

The total number of active nodes is the sum of all the nodes that contribute to traffic generation, i.e., $N_a = N_{ADN} + N_{AQN}$. The number of active DANHs $N_{ADN}$ is the sum of all DANHs in each DANH ring, multiplied by the number of DANH rings in each QuadBox ring, and finally multiplied by the number of QuadBox rings. Thus, $N_{ADN}$ can be calculated as follows:

$$N_{ADN} = \sum_{i=1}^{N_{QR}} \sum_{j=1}^{N_{PR}} \sum_{k=1}^{\psi} c$$

(4)

In Eq. (4), $c$ is the constant that equals 1, and the reason behind using the summation notation instead of the simple product is to cover the symmetrical and the asymmetrical HSR network topologies. Using the simple product presupposes that all the rings have the same number of nodes inside them. The sum, on the other hand, enables us to accumulate each ring’s specific number of nodes.

To ascertain total traffic generation, we also need to
identify the number of active QuadBoxes in the network. There are two kinds of QuadBoxes:

- QuadBoxes that connect two QuadBox rings,
- QuadBoxes that connect QuadBox rings to DANH rings.

Since QuadBox rings use one QuadBox to connect to any DANH ring, we can say that we have \( n \) number of QuadBoxes in a network of connected rings that contains \( n \) number of DANH rings. Moreover, since the QuadBox rings use one QuadBox to connect to any other QuadBox ring, then we can say that \( n \) number of QuadBox rings can be connected together using \( n - 1 \) QuadBoxes. Thus, the number of active QuadBoxes can be ascertained as follows:

\[
N_{AQN} = (N_{QR} - 1) + N_{DR} = (N_{QR} + N_{DR} - 1)
\]  

Equation (5) is valid for estimating traffic generation accurately, let us assume that the source in the network shown in Fig. 8 will send one frame to the destination. According to the standard HSR principle, each DANH will forward the frame twice, and the QuadBox nodes will forward the frame four times based on each node’s number of interfaces. Sixteen frames will be forwarded by the DANHs, since there are eight of them in the topology. Twenty frames will be forwarded by the QuadBox nodes, since there are five of them. Thus, the total frame generation will be \( 20 + 16 = 36 \) frames. Since the destination will take the frames without forwarding them, three frames must be subtracted from the total generated frames, and the total traffic generated in that case will be \( 36 - 3 = 33 \). To represent the topology in Fig. 8 using Eq. (4), we first need to define the parameters. If we have two nodes in each DANH ring, then \( N_{DN} = 2 \); if we have \( 2 \) DANH rings in each QuadBox ring, then \( N_{DR} = 4 \). The number of QuadBox rings is \( N_{QR} = 2 \), which also equals the number of active QuadBox rings \( N_{AQR} \); the number of active DANH rings \( N_{ADR} = 6 \), and since we are sending one frame, then \( N_{frame} = 1 \). Since we are calculating the traffic, then \( F = 1 \), with the following result:

\[
T_{SH} = \left[ 2(2 + 4 - 1) + \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{1} 1 \right] \times 2 - (2 + 1) = 33
\]

Equation (7) gives the same results as the conventional calculation, so this can be considered a valid way of ascertaining traffic generation in further scenarios.

The total traffic generated under the PL approach can be calculated fractionally by accumulating the total generated traffic in the learning stage and the working stage. The traffic generated in the learning stage can be found by taking a limit of \( N \) equals 1 for Eq. (7), because the learning stage of the PL approach only happens during the sending of the first frame. The traffic generated in the working stage can be considered the PL contribution to total traffic generation, and the PL contribution can be calculated by using Eq. (7) after changing two parameters according to the effects of the PL approach. First, the number of participating frames \( N_{frame} \) will start at the second frame and continue to the last, since the first frame already participated in the learning stage. Second, according to the PL approach, the number of DANH rings will be limited either by one or two rings depending on the topology, so \( N_{DR} \) will equal one ring if the source and the destination are in the same ring and two rings if the source and destination are in separate rings. The total traffic generated under the PL approach can then be calculated as follows:

\[
\lim_{N_{frame} \rightarrow 1} T_{SH} + N_{AQN} \sum_{p=2}^{N_{AQN}} \left[ 2(2N_{QR} + N_{DR} - 1) + \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{1} c - N_{PQR} \right] \times (N_{DN}^{i} + 1)F
\]

Equation (8) is valid for estimating traffic generation accurately, let us assume that the source in the network shown in Fig. 8 will send one frame to the destination. According to the standard HSR principle, each DANH will forward the frame twice, and the QuadBox nodes will forward the frame four times based on each node’s number of interfaces. Sixteen frames will be forwarded by the DANHs, since there are eight of them in the topology. Twenty frames will be forwarded by the QuadBox nodes, since there are five of them. Thus, the total frame generation will be \( 20 + 16 = 36 \) frames. Since the destination will take the frames without forwarding them, three frames must be subtracted from the total generated frames, and the total traffic generated in that case will be \( 36 - 3 = 33 \). To represent the topology in Fig. 8 using Eq. (4), we first need to define the parameters. If we have two nodes in each DANH ring, then \( N_{DN}^{i} = 2 \); if we have \( 2 \) DANH rings in each QuadBox ring, then \( N_{DR} = 4 \). The number of QuadBox rings is \( N_{QR} = 2 \), which also equals the number of active QuadBox rings \( N_{AQR} \); the number of active DANH rings \( N_{ADR} = 6 \), and since we are sending one frame, then \( N_{frame} = 1 \). Since we are calculating the traffic, then \( F = 1 \), with the following result:

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\[
\lim_{N_{frame} \rightarrow 1} T_{SH} + N_{AQN} \sum_{p=2}^{N_{AQN}} \left[ 2(2N_{QR} + N_{DR} - 1) + \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{1} c - N_{PQR} \right] \times (N_{DN}^{i} + 1)F
\]
Figures show analytical network traffic generation during the working stage.

* Number of QuadBox rings between the source location and the destination location

Figure 9 shows a theoretical evaluation of network behavior at the working stage, according to the network traffic generated per single frame from Eqs. (7), (8), and (9).

The network topology consists of a variable number of QuadBox rings. Each QuadBox ring contains 2 DANH rings, and each DANH ring contains 4 DANHs. Similarities can be seen between the PL and EPL approaches. Traffic reduction increases as the network topology grows bigger, because the increasing number of nodes in the network rings lead to more nodes becoming inactive after the pruning process happens. Another aspect relating to the number of nodes that can affect traffic performance under the EPL approach is the number of QuadBox rings between the source and the destination. In this paper, all DANH rings are being connected through QuadBox rings, as shown in Fig. 8. If the source and the destination lie in separated DANH rings that are connected together through a QuadBox ring, then, there is only one QuadBox ring between the source location and the destination location. In the same fashion, we can increase the number of QuadBox rings between the source location and the destination location by adding more QuadBox rings to the network. Figure 9 also shows an increase in the traffic generated when there are more QuadBox rings between the source and the destination. The source and destination locations in the network topology can decide the number of QuadBoxes in between. Table 2 shows the analytical results for the network topology shown in Fig. 10.

### Table 2: Analytical traffic results for HSR, PL, and EPL

<table>
<thead>
<tr>
<th>Sent frame(s)</th>
<th>HSR</th>
<th>PL</th>
<th>EPL Case A</th>
<th>EPL Case B</th>
<th>EPL Case C</th>
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<tr>
<td>1</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>75</td>
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<tr>
<td>2</td>
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<td>110</td>
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<tr>
<td>3</td>
<td>225</td>
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</tr>
<tr>
<td>4</td>
<td>300</td>
<td>180</td>
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<tr>
<td>8</td>
<td>600</td>
<td>320</td>
<td>220</td>
<td>250</td>
<td>280</td>
</tr>
</tbody>
</table>

Figure 10: HSR network topology screenshot from the OMNET++ simulation for the three scenarios.
which will be used for comparison purposes with the simulation results.

5. Simulation Results

In this section, we present the simulation results that validate our mathematical analyses. The EPL processing steps depicted in Figs. 4 and 6 have been implemented within an HSR network using OMNET++ [15]. 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. The simulation results cover the HSR, PL, and EPL for comparison purposes. Parameter $\psi$ is optimized to 3, depending on the number of QuadBox rings. Figure 10 shows the network topology representation for all of our simulation cases. It contains three connected QuadBox rings, each ring containing two DANH rings, and each DANH ring containing four DANHs. Different scenarios have been taken into consideration based on the location of the source. The simulation results in Table 3 and Fig. 11 show the total network traffic for all our simulation cases. Comparisons between the simulation and analytical results for all our simulation cases are depicted in Fig. 12. The standard HSR traffic shown in Fig. 12 (a) is the highest, since all the network rings participate in the forwarding operation. Figure 12 (b) shows the PL approach; the results show less traffic generation since all the DANH rings that do not contain a destination are pruned. In the case of Figs. 12 (a) and (b), changing the source location will not affect the results. The EPL results displayed in Figs. 12 (c), (d), and (e) show different traffic generation for three cases A, B, and C according to the sender’s location. Case A is considered the lowest traffic load on the network, because there is only one QuadBox ring between the source’s ring and the destination’s ring; the EPL approach recognizes 66% of the network rings as unused nodes. Case B indicates that there are two QuadBox rings between the source’s ring and the destination’s ring instead of one, so the EPL approach recognizes 57% of the network rings as unused nodes. Case C shows three active QuadBox rings between the source’s ring and the destination’s ring, so it is considered the highest traffic generation scenario of all EPL scenarios, since the EPL recognizes only 50% of the networks as unused nodes.

The differences between the simulation results and the analytical results can be spotted in Fig. 12 and are based on the following reasons:

- Equations (7) (8), and (9) give a total traffic estimation based on each ring’s activity
- In practice, the EPL approach controls the traffic flow gradually based on the frame count $\psi$, leading some nodes to forward the frames either inside the DANH ring or outside of it. In Figs. 12(c), (d), and (e), the analytical results after the third frame sending show a sudden decrease in the slope, as the analytical model does not work gradually. The traffic generation calculation depends directly on $\psi$. When $\psi$ is chosen to be 3, then the mathematical model gives a zero traffic generation by the pruned QuadBox rings after the third frame sending. In the practical model, the process of pruning will take a few more frames forwarding to fulfill the learning stage until it prunes these QuadBox rings. However, Fig. 12 (c) shows the traffic generation for Case A. Since Case A shows the highest number of pruned rings between all cases, then the analytical results becomes lower than the simulation results after the 3rd frame.

Despite different traffic generation in the cases of A, B, and C, the EPL approach in each case individually shows less traffic generation compared to the standard HSR with or without the PL approach.

6. Conclusions

In this paper, we have presented a new approach called the EPL approach, which is based on our previous PL approach that was used to prune the extra unicast traffic inherent in the standard HSR protocol for a connected-ring network type. The PL approach is a method for reducing any number of DANH rings used in a network to one or at most two rings
while keeping all the QuadBox rings active. The EPL approach is an enhancement of the PL approach that reduces any ring whether it is a DANH ring or QuadBox ring as long as it is not been used. This contributes to significant bandwidth savings and less congestion.

We analytically compared network traffic for HSR, PL, and EPL and expressed the results in Eqs. (7), (8), and (9), respectively. The results in Fig. 9 clearly show the advantage of the EPL over the PL approach. We then validated our analytical results using various simulations, as depicted in Fig. 12, which clearly indicate that network traffic reduction increases in line with expansion of the network topology. An enhancement in traffic reduction performance is recorded for the EPL approach to a level of around 61%,
References


