A NOVEL FILTERING TECHNIQUE FOR REDUCING REDUNDANT UNICAST TRAFFIC IN HSR NETWORKS

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ABSTRACT

High-availability seamless redundancy (HSR) is one of the seamless redundancy protocols providing fault-tolerance for Ethernet networks. HSR is very useful for applications that demand high availability with fault-tolerance. However, redundant unicast traffic is excessively generated in HSR networks. This drawback causes high consumption of network bandwidth and may degrade network performance in HSR networks. In this paper, we propose a novel single-filtering technique called FQR that filters unicast frames for unused QuadBox rings in HSR networks. The FQR technique reduces duplicated unicast frames in an HSR network by filtering the frames for passive QuadBox rings that are not used to forward the unicast frames for a communication session between a source and a destination in the network. The FQR uses a simple mechanism to discover passive QuadBox rings and then prevent QuadBoxes from forwarding unicast frames into the passive QuadBox rings. By pruning unicast frames for passive QuadBox rings, the proposed technique dramatically decreases duplicated unicast frames in HSR networks compared to the standard HSR protocol. Traffic performance of FQR is analyzed and several simulations were carried out to validate the analysis. Numerical results showed that, for the sample network used in this paper, network unicast traffic under the proposed technique was reduced by 37% compared to that under the standard HSR protocol, resulting in the save of network bandwidth and the improvement of network traffic performance. The proposed single-filtering technique can be combined with other single-filtering techniques to propose a very effective combined-filtering technique for HSR networks.

Keywords: *High-availability Seamless Redundancy (HSR) Protocol, Filtering Unicast Frames for Passive QuadBox Rings, Traffic Reduction Technique, Fault-tolerant Communications, Smart Grids*

1. INTRODUCTION

High-availability seamless redundancy (HSR) is a seamless redundancy protocol standardized in IEC 62439-3 [1] that provides the fault-tolerant capability for Ethernet networks. HSR is mainly designed for use in ring topologies, namely single-ring and connected-ring topologies. The operation of HSR is based on the duplication of every frame sent in a ring topology. A single-ring HSR network consists of doubly attached nodes for HSR protocol (DANHs); each DANH has two HSR ports. When a source DANH sends a unicast frame to a destination DANH in the ring, the source adds an HSR tag into the frame that is passed from its upper layers and

sends the tagged frame over two its port. When a DANH in the ring receives the HSR frame from one port, it forwards the frame to the other port without any changes. In the failure-free case, the destination receives two identical copies of the frame, removes the HSR tag of the first received frame before passing the frame to its upper layers, and discards any duplicate. If one of the network components fails, such as a link failure or a node failure, only one copy of the frame is lost. The destination still receives the other copy of the frame [2-3]. Therefore, even if a link failure or a node failure occurs, the communication between the source and the destination is not interrupted.

Singly-attached nodes (SANs), such as maintenance laptops or printers, cannot be inserted directly into HSR rings. SANs communicate with HSR ring devices through a redundancy box (RedBox) that acts as a proxy for the SANs attached to it. In HSR connected-ring networks, DANH rings are connected to each other by using quadruple port devices (QuadBoxes). HSR is very suitable for systems demanding high availability with fault-tolerance, such as substation automation systems (SASs) and automation networks. HSR is one of the redundancy protocols used in SASs [4].

The main drawback of HSR is that it generates a lot of redundant unicast traffic in HSR connected-ring networks. The drawback is caused by the following issues:

1) *Issue 1*: Unicast frames are duplicated and circulated in all rings, except the destination ring.

2) *Issue 2*: Unicast frames are forwarded into all DANH rings.

3) *Issue 3*: Unicast frames are forwarded into all QuadBox rings.

This drawback results in the high consumption of network bandwidth and the degradation of network performance. Several techniques have been proposed to reduce the redundant unicast traffic in HSR connected-ring networks, including traffic filtering techniques and dual paths techniques [5]. Traffic filtering techniques consist of single-filtering techniques, such as quick removing (QR) [6] and pork locking (PL) [7], and combined-filtering techniques, such as filtering HSR traffic (FHT) [8] and enhanced PL (EPL) [9]. Dual paths techniques include optimal dual paths (ODP) [10], dual virtual paths (DVP) [11], ring-based dual paths (RDP) [12], and dual separate paths (DSP) [13].

Single-filtering techniques deal with one of the abovementioned HSR issues. The QR technique [6] prevents unicast frames from being circulated in rings, whereas the PL technique [7] filters unicast traffic frames for unused DANH rings. Most of existing single-filtering techniques solve HSR issues 1 and 2. However, there is no work that addresses HSR issue 3. In this paper, we propose a novel single-filtering technique called FQR to solve HSR issue 3. The proposed technique filters unicast frames for unused QuadBox rings called passive QuadBox rings in HSR networks. Therefore, the proposed FQR technique reduces redundant unicast frames in HSR networks.

The remainder of this paper is organized as follows. In Section 2, we briefly introduce existing single-filtering techniques. Next, in Section 3, we describe the proposed technique to filter unicast frames for passive QuadBox rings. Traffic performance of FQR is analyzed in Section 4, and several simulations and their results are described Section 5. The discussions are provided in Section 6. Finally, we conclude the paper and give our future work in Section 7.

2.   RELATED WORK

We consider an HSR connected-ring network that consists of eight DANH rings, each having four DANHs, as shown in Figure 1. In this sample network, QuadBoxes are used to interconnect DANH rings. Source DANH 1 in DANH ring 1 sends unicast frames to destination DANH 10 in DANH ring 3.
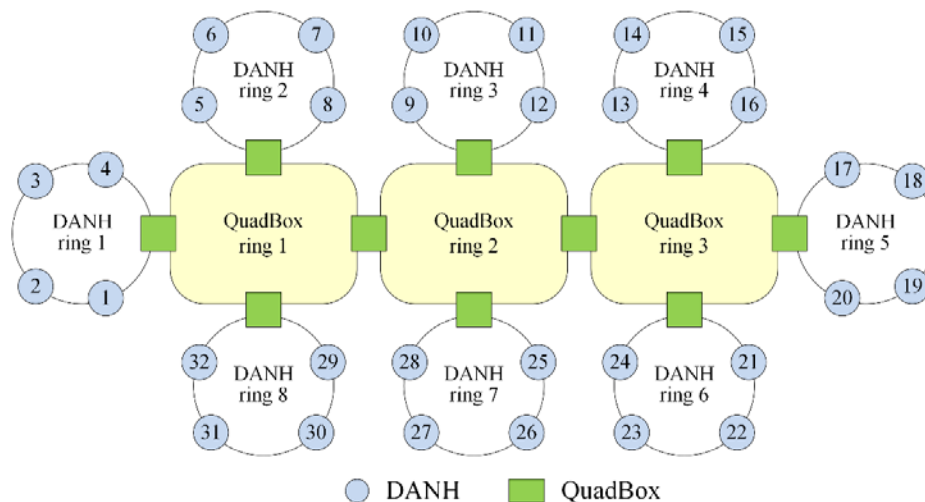

Figure 1: The sample HSR connected-ring network

Under the standard HSR protocol, when unicast frames are sent from the source DANH to the destination DANH, the frames are duplicated and circulated in all rings of the network, except the destination ring. The frames are not circulated in the destination ring because the destination does not forward the frames. The process of forwarding unicast frames under the standard HSR protocol is shown in Figure 2. It is clear that there is a lot of unicast traffic generated by the standard HSR protocol in the connected-ring network.

Several filtering techniques have been proposed to reduce the redundant unicast frames in HSR connected-ring networks. Filtering techniques can be sub-classified into two categories, including single-filtering techniques and combined-filtering techniques. The former are simple techniques that solve one of the HSR issues, whereas the latter usually combine some single-filtering techniques to address some or all of the HSR issues. There are two existing single-filtering techniques, namely the quick removing (QR) technique [6] and the port locking (PL) technique [7].

2.1   QR

QR is one of the simplest single-filtering approaches for reducing redundant traffic in HSR networks. QR reduces the redundant traffic by preventing traffic frames from being circulated in rings, including DANH rings and QuadBox rings. QR can be used in any topology and applied for any traffic.

The key idea of QR is that each HSR node forwards a unicast frame once, at most. When an HSR node receives an HSR frame, the node checks if the unicast frame is received for the first time. If not, the node floods the HSR frame. If so, it discards the duplicated frame.

Figure 3 shows the process of forwarding a unicast frame under the QR technique.

2.2   PL

PL is a single-filtering technique that solves HSR issue 2 to reduce redundant unicast traffic in HSR networks. The PL technique does not forward HSR unicast frames into non-destination DANH rings that do not contain the destination DANH. PL is implemented on access QuadBoxes that connect to DANH rings. Each access QuadBox connects to two rings: a DANH ring and a QuadBox ring. PL divides each access QuadBox into two sides: the DANH side that connects to a DANH ring and the QuadBox side that connects to a QuadBox ring.

When a source DANH sends a unicast frame to a destination DANH in an HSR network, the frame is forwarded into all DANH rings of the network. The frame is not circulated in the destination DANH ring because the destination DANH does not forward the frame. Otherwise, the frame is circulated in all non-destination DANH rings. The PL technique uses this mechanism to check and lock non-destination DANH rings. When an access QuadBox forwards a unicast frame into its DANH ring over one port and receives the sent frame through the other port connected to the same DANH ring, it means that the DANH ring is a non-destination DANH ring. The PL then locks DANH sides connecting to non-destination DANH rings in order to prevent the sides from forwarding unicast frames into the non-destination DANH rings.
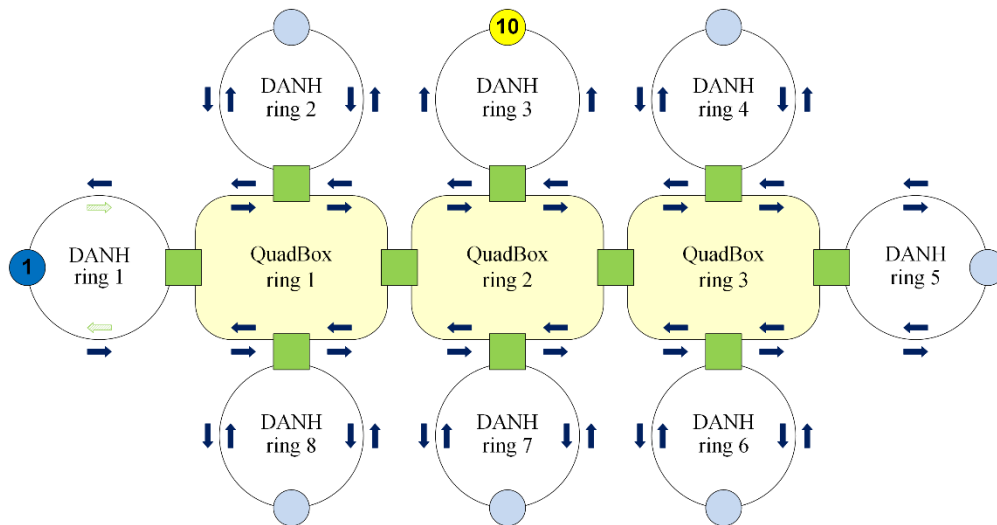

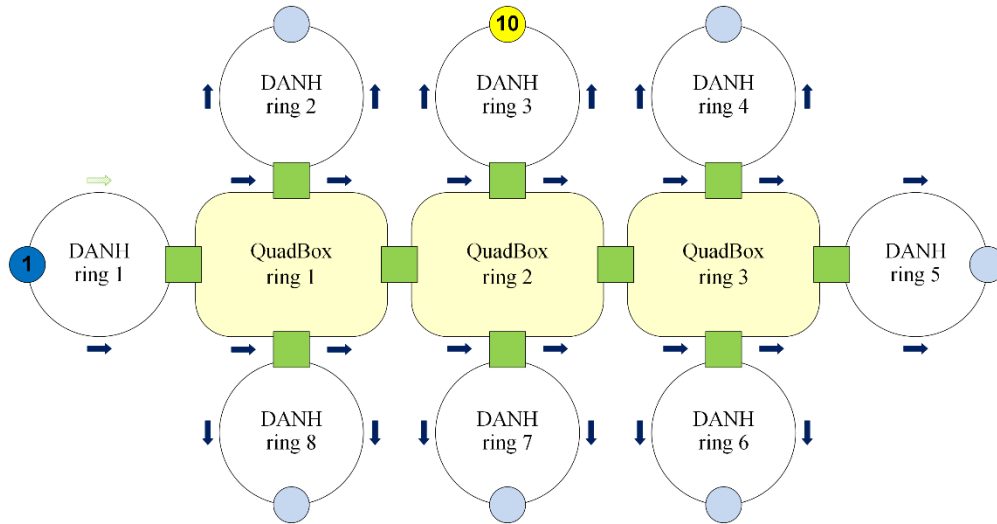*Figure 2: Forwarding a unicast frame under the standard HSR protocol*

Figure 3: Forwarding a unicast frame under the QR technique

Figure 4 shows the process of forwarding a unicast frame under the PL technique.

As described above, the QR technique solves HSR issue 1, whereas the PL technique solves HSR issue 2. There is, however, no any single-filtering technique that is proposed to solve HSR issue 3. In this paper, the novel FQR technique is proposed to solve HSR issue 3.

3. THE PROPOSED FQR TECHNIQUE

The main idea of the proposed FQR technique is to prevent QuadBoxes from forwarding unicast frames into passive QuadBox rings that are not used to deliver the frames from the source to the destination.

3.1 Concepts

There are two types of QuadBox used in the FQR technique, including access QuadBoxes and trunk QuadBoxes.

- An access QuadBox is a QuadBox that connects to one DANH ring and one QuadBox ring.
- A trunk QuadBox is a QuadBox that connects two QuadBox rings.

There are two types of DANH rings defined for a certain communication session, including a
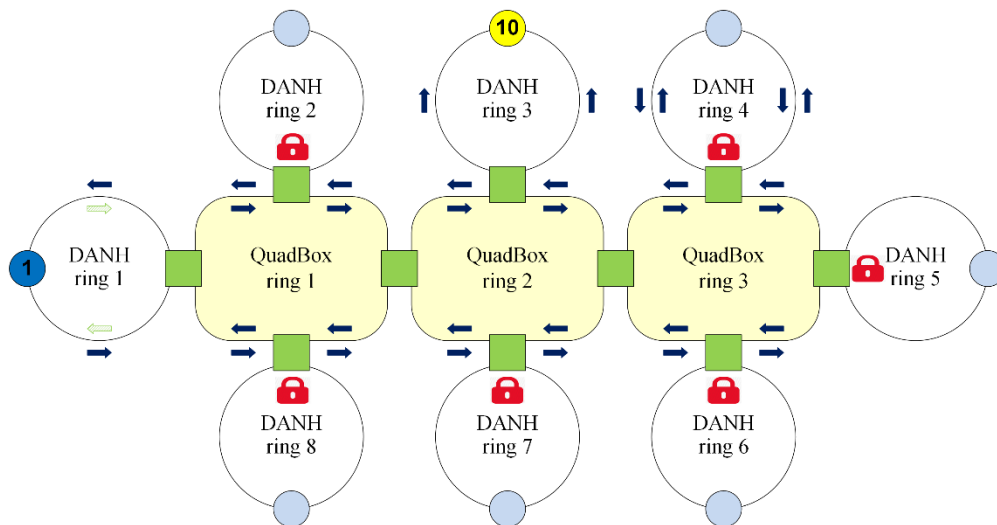

Figure 4: Forwarding a unicast frame under the PL technique

destination DANH ring and non-destination DANH rings.

- The destination DANH ring contains the destination DANH.
- Non-destination DANH rings are DANH rings that do not contain the destination DANH.

There are two types of QuadBox rings defined for a communication session, including active QuadBox rings and passive QuadBox rings.

- Active QuadBox rings are used to deliver unicast frames from the source DANH to the destination DANH during the communication session.
- Passive QuadBox rings are not used to deliver the frames during the communication session.

The FQR technique is implemented at trunk QuadBoxes that used to connect two QuadBox rings. In the FQR technique, for a communication session, each trunk QuadBox is divided into two sides: the source side and the destination side, as shown in Figure 5.

- The source side is the side that is closer to the source DANH.
- The destination side is the side that is closer to the destination DANH.

The side types of trunk QuadBoxes are locally significant in each communication session.

3.2 Operations

The operation of the proposed FQR technique includes the following two phases: the side setting phase and the side locking phase.

3.2.1 Side Setting Phase

During the side setting phase, each trunk QuadBox checks and sets its sides to source side and destination side. This step is initiated when the source DANH starts to send the first unicast frame to the destination DANH. The first frame is forwarded into all rings of the network.

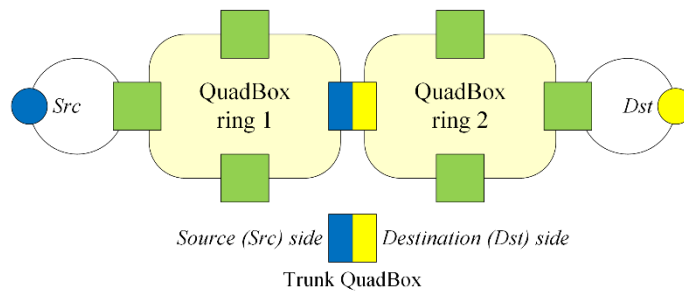Upon receiving the first frame, each trunk QuadBox sets the receiving side to the source side

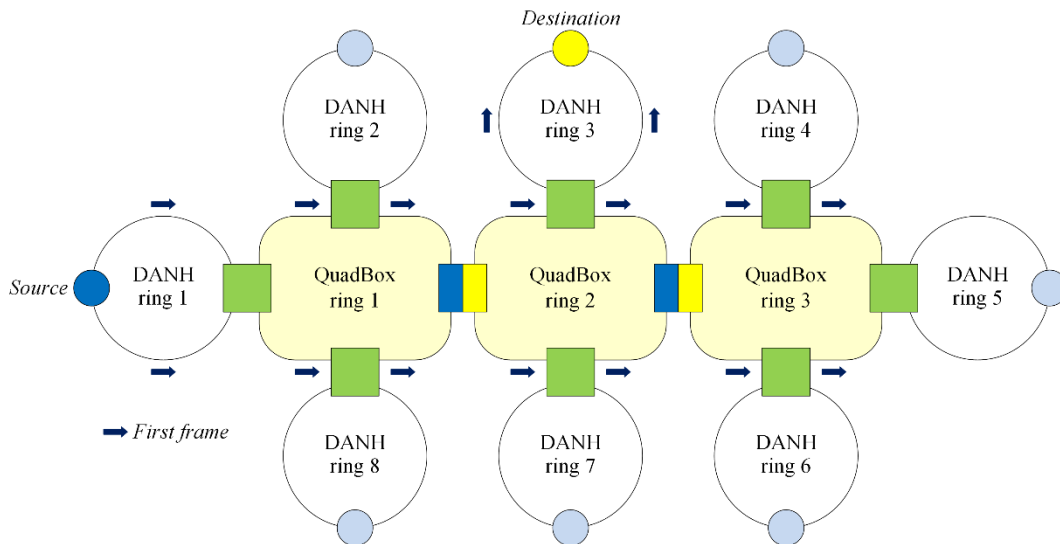*Figure 5: Source side and destination side of a trunk QuadBox*

Figure 6: The side setting phase

and the other side to the destination side for the communication session, as shown in Figure 6.

3.2.2   Side Locking Phase

The process of discovering and locking passive QuadBox rings is performed in the side locking phase. When the destination DANH receives the first unicast frame, the destination DANH sends a control message called Locking message back to the source DANH. The control message is used to discover passive QuadBox rings.

Upon receiving the control message, each trunk QuadBox checks what type its receiving side is and then discovers the type of its QuadBox ring.

- If the receiving side is the destination side, the QuadBox ring that the destination side connects to is an active QuadBox ring.
- If the receiving side is the source side, the QuadBox ring that the destination side connects to is a passive QuadBox ring.

The Locking message is forwarded until it reaches the source. The control message, however, is not forwarded into passive QuadBox rings.

Finally, trunk QuadBoxes lock their destination sides that connect to passive QuadBox rings.

The process of discovering passive QuadBox rings is shown in Figure 7.

3.3   Forwarding Unicast Traffic

Under the FQR technique, when the first unicast frame sent by the source DANH is flooded into the entire network just as it is in the standard HSR

protocol. As from the second unicast frame, trunk QuadBoxes do not forward unicast frames into passive QuadBox rings.

The process of forwarding a unicast frame under the FQR technique is shown in Figure 8. In this case, QuadBox rings 1 and 2 are active QuadBox rings, whereas QuadBox ring 3 is a passive QuadBox ring for the communication session. Therefore, unicast frames of the communication session are not forwarded into QuadBox ring 3.

4.   PERFORMANCE ANALYSIS

In this section, traffic performance of the proposed FQR technique is analyzed, evaluated, and compared with that of standard HSR protocols and two existing single-filtering techniques, including the QR technique and the PL technique.

The sample HSR connected-ring network shown in Figure 1 is used for the purpose of the network traffic performance analysis. We consider the communication session in that source DANH 1 in DANH ring 1 sends unicast frames to destination DANH 10 in DANH ring 3. In this case, DANH ring 3 is the destination DANH ring and the other DANH rings are non-destination DANH rings.

In this paper, network traffic was chosen as a performance metric to analyze, evaluate, and compare the network traffic performance. Network traffic is defined as the total number of frame copies that travel on links and that are received by nodes in the network. When a unicast frame is sent from a source to a destination in a network, the network
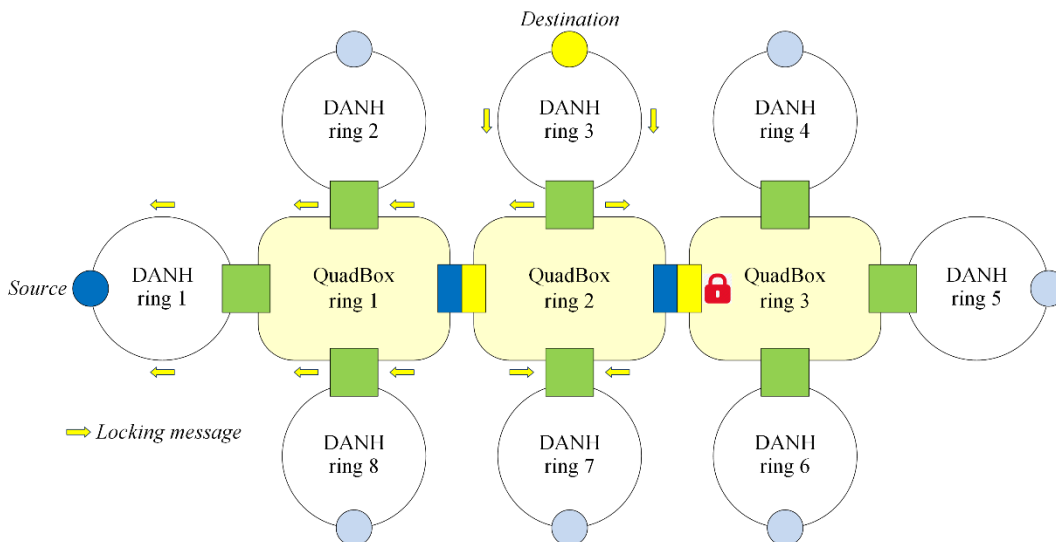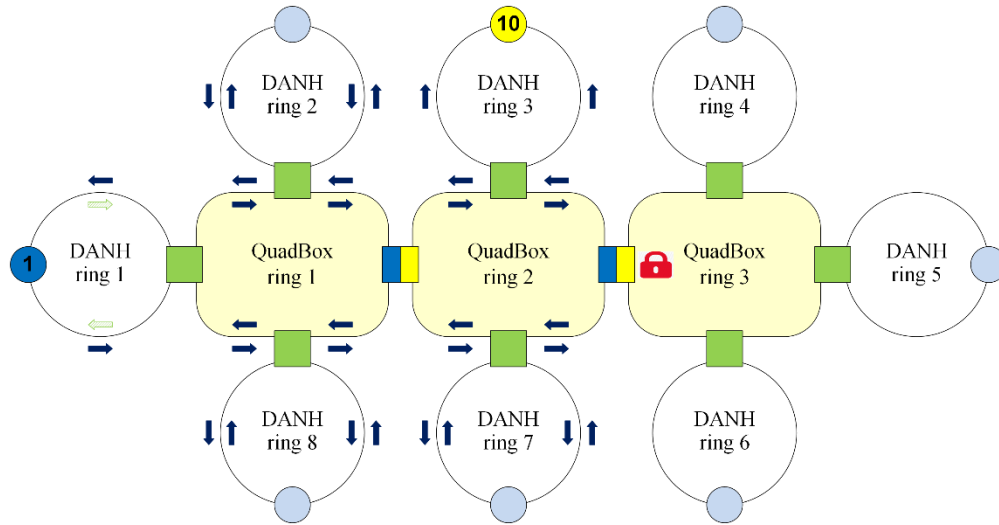

Figure 7: The side locking phase

Figure 8: Forwarding a unicast frame under the FQR technique

traffic is the total number of the frame's copies that are delivered and received in the network.

4.1 Standard HSR

When the source DANH sends a unicast frame to the destination DANH, the frame is circulated in all rings, except the destination DANH ring, as shown in Figure 2.

Network traffic when the source DANH sends a unicast frame to the destination DANH under the standard HSR protocol, denoted by nt_{hsr}^1, is calculated as follows:

$$nt_{hsr}^1 = \sum_{i \in NR} 2n_i - n_d \qquad (1)$$

where n_d is the number of nodes in the destination DANH ring, n_i is the number of nodes in the ith ring, and NR is the collection of all rings, including DANH rings and QuadBox rings.

Generally, network traffic when a source sends N unicast frames to a destination, denoted by nt_{hsr}, is determined by:

$$nt_{hsr} = N \left(\sum_{i \in NR} 2n_i - n_d \right) \qquad (2)$$

4.2 QR

When the source DANH sends a unicast frame to the destination DANH, the QR forwards the frame into all rings and prevents the frame from being circulated in the rings, as shown in Figure 3.

Network traffic when the source DANH sends a unicast frame to the destination DANH under the QR technique, denoted by nt_{qr}^1, is calculated as follows:

$$nt_{qr}^1 = \sum_{i \in NR} (n_i + 1) \qquad (3)$$

Generally, network traffic when a source sends N unicast frames to a destination in an HSR network, denoted by nt_{qr}, is determined by:

$$nt_{qr} = N \sum_{i \in NR} (n_i + 1) \qquad (4)$$

4.3 PL

When the source DANH sends the first unicast frame, the frame is circulated in all rings, except the destination ring.

Network traffic when the source DANH sends the first unicast frame to the destination DANH under the PL technique, denoted by nt_{pl}^1, is calculated as follows:

$$nt_{pl}^1 = \sum_{i \in NR} 2n_i - n_d \qquad (5)$$

When the source DANH sends the kth ($k \geq 2$) unicast frame to the destination DANH, PL does not forward the frame into non-destination DANH rings. However, the frame is still forwarded and circulated in all QuadBox rings, as shown in Figure 4.

Network traffic when the source DANH sends the kth ($k \geq 2$) unicast frame to the destination

DANH under the PL technique, denoted by nt_{pl}^{k}, is calculated as follows:

$$nt_{pl}^{k} = 2n_s + \sum_{i \in QR} 2n_i + n_d \qquad (6)$$

where n_s is the number of nodes in the source ring and QR is the set of all QuadBox rings.

Generally, network traffic when a source DANH sends N unicast frames to a destination DANH under the PL technique, denoted by nt_{pl}, is determined by:

$$nt_{pl} = \sum_{i \in NR} 2n_i$$
$$+(N-1)\left(2n_s + \sum_{i \in QR} 2n_i\right) + (N-2)n_d \qquad (7)$$

4.4 FQR

Under the FQR technique, when the source DANH sends the first unicast frame, the frame is forwarded and circulated in all rings, except the destination DANH ring.

Network traffic when the source DANH sends the first unicast frame to the destination DANH under the FQR technique, denoted by nt_{fqr}^{1}, is calculated as follows:

$$nt_{fqr}^{1} = \sum_{i \in NR} 2n_i - n_d \qquad (8)$$

When the source DANH sends the kth ($k \geq 2$) unicast frame to the destination DANH, FQR does not forward the frame into passive QuadBox rings, as shown in Figure 8. In this communication session, QuadBox rings 1 and 2 are active QuadBox rings, whereas QuadBox rings 3 is a passive QuadBox ring.

Network traffic when the source DANH sends the kth ($k \geq 2$) unicast frame to the destination DANH under the FQR technique, denoted by nt_{fqr}^{k}, is calculated as follows:

$$nt_{fqr}^{k} = \sum_{i \in AQR} 2n_i + \sum_{i \in ADR} 2n_i - n_d \qquad (9)$$

where AQR is the set of active QuadBox rings and ADR is the set of active DANH rings that connect to active QuadBox rings.

Generally, network traffic when a source DANH sends N unicast frames to a destination DANH under the FQR technique, denoted by nt_{fqr}, is determined by:

$$nt_{fqr} = \sum_{i \in NR} 2n_i - n_d$$
$$+(N-1)\left(\sum_{i \in AQR} 2n_i + \sum_{i \in ADR} 2n_i - n_d\right) \qquad (10)$$

5.   SIMULATIONS AND RESULTS

To evaluate and validate the traffic performance analysis of the proposed FQR technique, several simulations were conducted using the OMNeT++ network simulator [14].

5.1   Simulation Description

We considered the sample HSR connected-ring network consisting of eight DANH rings and three QuadBox rings, as shown in Figure 1. Each HSR ring included four DANH nodes. QuadBoxes were used to connect DANH rings.

In the simulations, source DANH 1 in DANH ring 1 sent N (N = 10, 20, …, 100) unicast frames to destination DANH 10 in DANH ring 3. The network traffic frames were recorded under the standard HSR protocol and single-filtering techniques to evaluate and compare the network traffic performance.

5.2   Simulation Results

Figure 9 shows a comparison of the network traffic performance between the FQR technique, the standard HSR protocol, and these existing single-filtering techniques.

The line graph in this figure illustrates the number of network traffic frames generated in the simulation network when the source DANH sent unicast frames to the destination DANH under the standard HSR protocol and single-filtering techniques, including the QR, PL, and FQR techniques. Overall, it can be seen from the graph that these single-filtering techniques significantly reduce network traffic in comparison to the standard HSR protocol. While the QR technique prevents unicast frames from being circulated in DANH and QuadBox rings, the PL and FQR techniques filter the unicast frames for non-destination DANH rings and passive QuadBox rings, respectively.

Numerically, for the sample network, the FQR technique decreased the network frames by 37% compared to the standard HSR protocol, resulting in
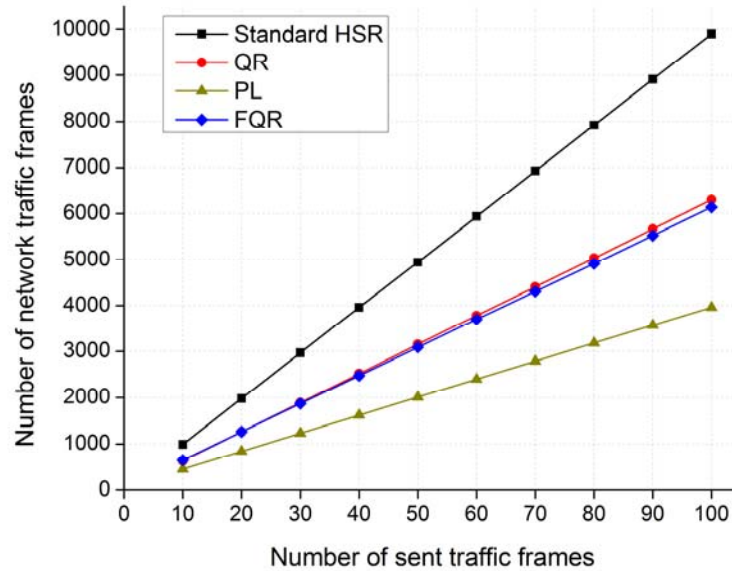
Figure 9: A comparison of network traffic performance

the save of network bandwidth and the improvement of network performance.

6. DISCUSSIONS

As mentioned in Section 1, the main drawback of HSR is the redundant unicast traffic in HSR networks that is caused by the three HSR issues. Several single-filtering techniques have been proposed to solve one of these HSR issues. Most of the existing single-filtering techniques focus on solving HSR issue 1 (the QR technique) and HSR issue 2 (the PL technique). However, there is no single-filtering technique that was proposed to solve HSR issue 3. In other words, there is no single-filtering technique that can filter redundant unicast traffic for passive QuadBox rings. In this paper, we proposed a novel single-filtering technique called FQR to address HSR issue 3.

While the existing single-filtering techniques including QR and PL focus on removing circulated traffic in rings and filtering unicast traffic for non-destination DANH rings, the FQR technique filters unicast traffic for passive QuadBox rings. The network traffic performance of these single-filtering techniques depends on the topology of HSR networks.

The proposed single-filtering technique (FQR) can be combined with the existing single-filtering techniques (QL and PL) to propose a very efficiently combined-filtering approach that solves all issues of the standard HSR protocol and dramatically reduces the redundant unicast traffic in HSR networks.

7. CONCLUSIONS

In this paper, we proposed a novel single-filtering technique called FQR for filtering network unicast frames for passive QuadBox rings. The proposed FQR technique filters unicast frames for unused QuadBox rings based on discovering and locking destination sides of trunk QuadBoxes that connect to passive QuadBox rings in the communication session. By preventing unicast frames from being forwarded into passive QuadBox rings, FQR significantly decreases unicast traffic frames in HSR networks compared to the standard HSR protocol. Numerical results showed that, for the sample simulation network, the FQR technique reduced network unicast frames by 37% in comparison to the standard HSR protocol.

Our future work is to propose a combined-filtering approach that combines the newly proposed technique with other single-filtering techniques in order to solve all the HSR issues and effectively improving the network traffic performance for HSR networks.

ACKNOWLEDGMENTS

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