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Enhanced Effective Filtering Approach (eEFA) for Improving HSR Network Performance in Smart Grids

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Abstract: The effective filtering approach (EFA) is one of the most effective approaches for improving the network traffic performance of high-availability seamless redundancy (HSR) networks. However, because EFA uses port locking (PL) for detecting nondestination doubly-attached nodes with HSR protocol (DANH) rings in HSR networks, it forwards the first sent frame to all DANH rings in the network. In addition, it uses a control message for discovering passive QuadBox rings in both unidirectional and bidirectional communications. In this study, we propose an enhanced version of EFA called enhanced-EFA (eEFA) that does not forward unicast frames to nondestination DANH rings. eEFA does not use any control message to discover passive QuadBox rings in bidirectional communications. eEFA thus reduces the network traffic in HSR networks compared with EFA. Analytical and simulation results for a sample network show that the traffic reduction of eEFA was 4–26% and 2–20% for unidirectional and bidirectional communications, respectively, compared to EFA. eEFA, thus, clearly saves network bandwidth and improves the network performance.

Keywords: smart grid; high-availability seamless redundancy (HSR); effective filtering approach (EFA); enhanced EFA (eEFA); substation automation system (SAS)

1. Introduction

A smart grid is an evolving grid that uses advanced automation, control, information technology (IT), and Internet of things (IoT) systems to enable real-time monitoring and control of power flow from generation to end users. The smart grid is a new kind of electrical grid where the power system and the IT system are tightly coupled with each other [1]. It is a next-generation power distribution grid. To realize smart grid technology, substation automation systems (SASs) have been designed and used to improve the efficiency of control and communication schemes [2]. Redundancy protocols are used to provide fault-tolerant communications for SASs and, thereby, ensure their operation [3]. High-availability seamless redundancy (HSR) is one type of redundancy protocol used for providing seamless and fault-tolerant communication for SASs [4].

HSR is standardized under IEC 62439-3 [5]. It provides fault-tolerant communications for ring-based Ethernet networks by forwarding and circulating frames in all network rings. End nodes in HSR networks, called doubly-attached nodes with HSR protocol (DANH), have two HSR-enabled ports. A single-ring HSR network consists of DANHs interconnected by full-duplex links. To forward a unicast frame to a destination DANH in a single-ring network, a source DANH inserts an HSR tag into an Ethernet frame passed from its upper layers and sends the tagged frame over two of its ports. Two copies of the frame are forwarded to the destination DANH through two directions of the ring. In other words, the frame is delivered from the source to the destination through two separate paths in the ring. The destination receives two identical copies of the frame, removes the HSR tag from the first received copy before passing the copy to its upper layers, and discards the duplicate. If a failure (e.g., link failure or node failure) occurs, only one path between the source and the destination is interrupted and the other path can still be used to deliver the frame to the destination. Therefore, HSR can provide seamless communications with zero recovery time for Ethernet rings. For more complex ring topologies, quadruple port devices (QuadBoxes) are used to interconnect DANH rings. A connected-ring HSR network consists of DANH rings and QuadBox rings. HSR works very well in single-ring HSR networks; however, it generates a lot of redundant traffic in connected-ring HSR networks. This drawback is caused by the following issues:

1. Issue 1: Duplicating and circulating frames in all the rings, except the destination DANH ring;
2. Issue 2: Forwarding unicast frames into all DANH rings; and
3. Issue 3: Forwarding unicast frames into all QuadBox rings.

This problem causes high consumption of network bandwidth and may degrade the network traffic performance in HSR networks. Several approaches have been proposed to solve this problem that is faced in the standard HSR protocol. Two main types of traffic reduction approaches are available: the traffic filtering-based approach and the dual paths-based approach [6]. In the former, redundant unicast traffic in HSR networks is reduced by filtering the traffic for rings and/or by preventing the traffic from being duplicated and circulated in rings. In the latter, unicast frames are forwarded from a source to a destination through two separate paths that are pre-established between the source and the destination. Traffic filtering-based techniques can be classified into single-filtering techniques, including the quick removing (QR) technique [7], the traffic control (TC) technique [8], the port locking (PL) technique [9], and combined-filtering techniques, including the hybrid QR and PL approach (QRPL) [10], the enhanced port locking (EPL) technique [11], the filtering HSR traffic (FHT) technique [12], and the effectively filtering approach (EFA) [13]. Most of the filtering-based techniques (QR, TC, PL, QRPL, and EPL) do not solve all the HSR issues. FHT and EFA are techniques that solve all the issues. However, FHT generates additional control overhead in HSR networks, whereas EFA still forwards the first sent frame to all DANH rings, including nondestination DANH rings.

Several dual paths-based techniques have been proposed to reduce redundant unicast traffic in HSR networks based on pre-established paths. These techniques discover and establish dual paths between a source and a destination in an HSR network before forwarding unicast traffic frames from the source to the destination through the dual paths. Dual paths-based techniques include the dual virtual paths (DVP) [14] technique, which was then extended as extended dual virtual paths (EDVP) [15], the ring-based dual paths (RDP) [16] technique, and the dual separate paths (DSP) [17] technique. These dual paths-based techniques significantly reduce redundant unicast traffic in HSR networks. The main drawback of the techniques, however, is to generate additional control overhead in the networks because they exchange control messages to discover and establish dual paths. In addition, there are other techniques for reducing redundant traffic in HSR networks, including the HSR SwitchBox technique [18], the integration of HSR and OpenFlow (HSE + OF) [19], the reducing multicast traffic (RMT) [20], the cost-effective topology design for HSR resilient mesh networks [21], and the latency and traffic reduction technique for process-level network [22]. The HSR SwitchBox technique defines a new switching node in HSR networks that forwards HSR frames based on looking up of media access control (MAC) tables instead of flooding the frames. The HSE + OF approach aims to manage HSR networks by means of the software-defined networking (SDN) paradigm. The approach defines new HSE + OF nodes whose control plane is managed by an OpenFlow controller. In other words, this approach is an implementation of HSR in SDN. The RMT technique was proposed to reduce multicast traffic in HSR networks by limiting the spreading of the multicast traffic to only the rings that have members associated with that traffic instead of spreading the traffic into all the network parts. The study of traffic reduction for process-level networks [22] presented two enhanced solutions and fully implemented QR to HSR for improving the latency and reducing the traffic volume in a process-level network. The main idea of these two enhanced solutions is to reduce the minimum number of hops required for the delivery of messages to destinations for reducing the maximum end-to-end latency.

EFA is one of the most effective filtering techniques. EFA reduces redundant unicast traffic in HSR networks by solving all issues faced in HSR [13]. EFA uses the PL and FQR techniques for filtering unicast traffic for nondestination DANH rings and passive QuadBox rings, respectively. In addition, EFA uses QR in HSR networks to prevent traffic frames from being duplicated and circulated in rings. However, EFA has to forward the first sent frame to all DANH rings to check nondestination DANH rings. Additionally, EFA uses FQR to discover passive QuadBox rings by broadcasting a control message. In this paper, we propose an enhanced version of EFA, called enhanced-EFA (eEFA), to overcome these two issues. The main purpose of eEFA is to reduce more redundant unicast traffic compared to EFA by filtering the first sent frame for nondestination DANH rings and by avoiding using a control message to discover passive QuadBox rings for bidirectional communications, thus saving network bandwidth and improving the network performance.

The remainder of this paper is organized as follows: In Section 2, we briefly introduce EFA. In Section 3, we describe eEFA. The traffic performance of eEFA is analyzed in Section 4. Several simulations are conducted, and their results are presented in Section 5. Finally, Section 6 presents the conclusions of this study.

2. Effective Filtering Approach (EFA)

To significantly reduce redundant unicast traffic in HSR networks, EFA performs traffic filtering for all unused rings, including nondestination DANH rings and passive QuadBox rings.

1. Filter traffic for nondestination DANH rings by using PL; and
2. Filter traffic for passive QuadBox rings by using FQR.

In this study, for the purposes of operational descriptions, performance analysis, and simulations, we consider a sample HSR network that consists of eight DANH rings interconnected by QuadBoxes, as shown in Figure 1. In communication scenarios, source DANH 1 sends unicast frames to destination DANH 10.

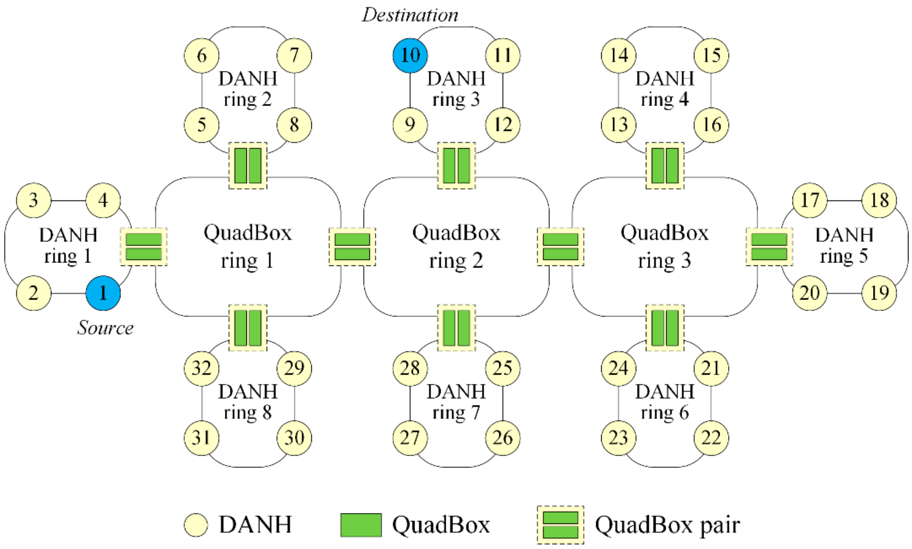


Figure 1. Sample HSR network. HSR: high-availability seamless redundancy; DANH: doubly-attached nodes with HSR protocol.

2.1. Filtering Unicast Traffic in DANH Rings

EFA uses PL for filtering unicast frames for nondestination DANH rings. Nondestination DANH rings are those DANH rings that do not contain the destination DANH. In the sample network shown in Figure 1, DANH ring 3 is the destination DANH ring, whereas the other DANH rings are nondestination DANH rings.

PL uses the first frame sent by the source DANH to detect nondestination DANH rings. When the source DANH sends the first frame to the destination DANH in an HSR network, the frame is forwarded to all DANH rings of the network. The frame is then circulated in all DANH rings except the destination DANH ring, as shown in Figure 2. By checking the circulation of the first frame, PL discovers nondestination DANH rings. PL then locks nondestination DANH rings to prevent the next frames from being forwarded to the DANH rings. From the second frame onward, EFA does not forward the unicast frame to nondestination DANH rings [13].

2.2. Filtering Unicast Traffic for QuadBox Rings

EFA uses PL for filtering unicast frames for nondestination DANH rings. Nondestination DANH rings are those DANH rings that do not contain the destination DANH. In the sample network shown in Figure 1, DANH ring 3 is the destination DANH ring, whereas the other DANH rings are nondestination DANH rings.

PL uses the first frame sent by the source DANH to detect nondestination DANH rings. When the source DANH sends the first frame to the destination DANH in an HSR network, the frame is forwarded to all DANH rings of the network. The frame is then circulated in all DANH rings except the destination DANH ring, as shown in Figure 2. By checking the circulation of the first frame, PL discovers nondestination DANH rings. PL then locks the nondestination DANH rings to prevent the next frames from being forwarded to the DANH rings. From the second frame onward, EFA does not forward the unicast frame to nondestination DANH rings [13].

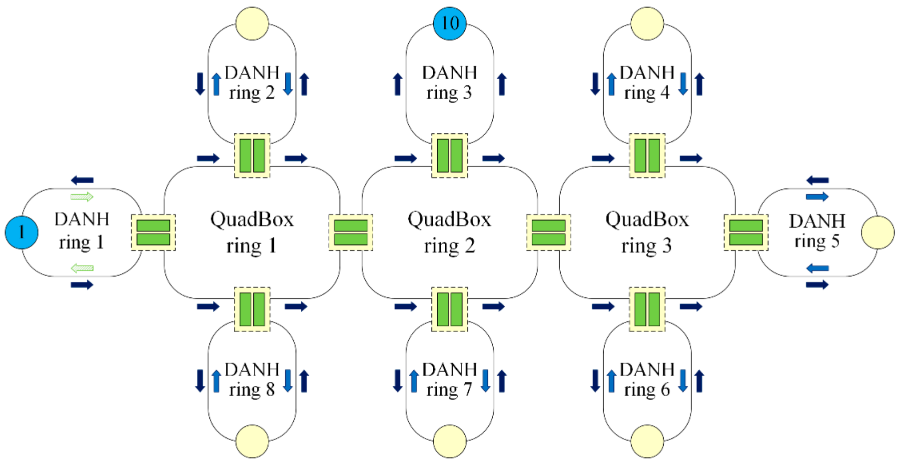


Figure 2. Flooding the first frame to discover nondestination DANH rings in EFA. EFA: effectively filtering approach.

2.3. Forwarding Unicast Frames

1. First frame

When the first frame is sent from the source DANH to the destination DANH, it is forwarded and circulated in all rings except the destination DANH ring, as shown in Figure 2.

When the destination DANH receives the first sent frame, it sends a control message called the locking message back to the source DANH, as shown in Figure 3. Upon receiving the control message, trunk QuadBoxes check whether the QuadBox rings to which they are connecting are passive QuadBox rings. For the communication session between source DANH 1 and destination DANH 10, QuadBox ring 3 is a passive QuadBox ring, whereas QuadBox rings 1 and 2 are active QuadBox rings.

2. kth frame ($k \geq 2$)

From the second unicast frame of the communication session, EFA does not forward the frame to nondestination DANH rings and passive QuadBox rings, as shown in Figure 4. In addition, EFA uses QR for removing the circulated traffic from the rings.

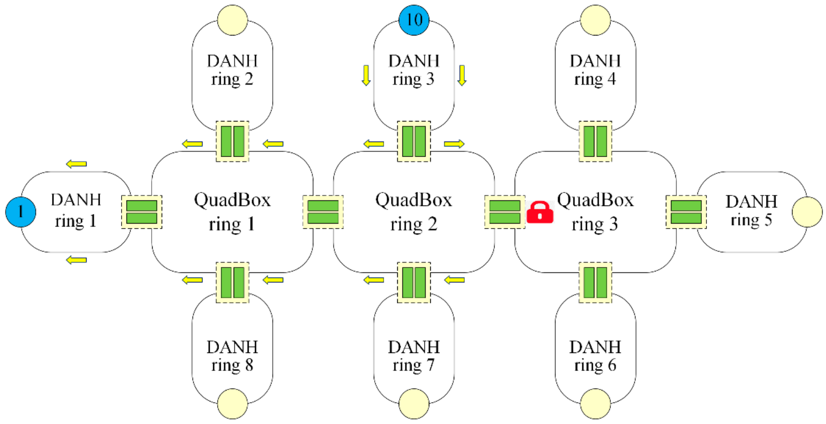


Figure 3. Using the locking message to discover passive QuadBox rings in EFA.

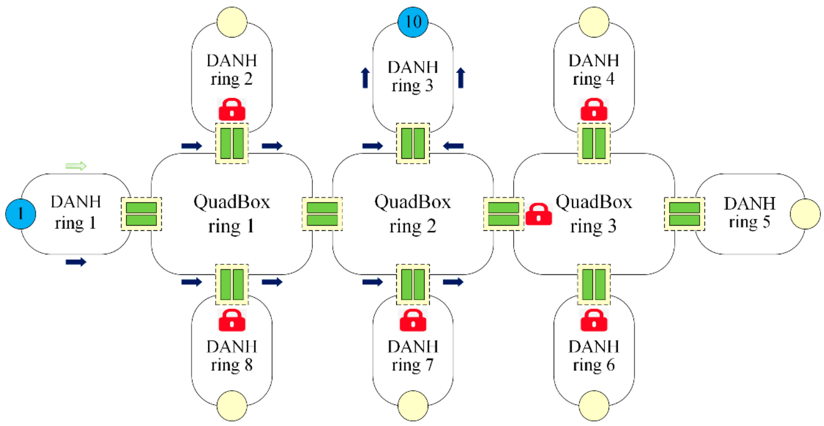


Figure 4. Forwarding a unicast frame in EFA.

2.4. Issues in EFA

EFA is one of the best traffic reduction techniques for HSR networks. However, it has the following drawbacks:

1. It still forwards the first frame to all DANH rings; and
2. It uses a control message to discover passive QuadBox rings in both unidirectional and bidirectional communications.

These drawbacks cause additional redundant traffic and control overheads in HSR networks. In this study, eEFA is proposed to solve these two problems, thereby improving the network traffic performance of HSR networks.

3. Proposed eEFA Approach

We propose eEFA to solve the following issues of EFA networks:

1. eEFA does not forward unicast frames, including the first sent frame, to nondestination DANH rings; and

2. eEFA does not use any control message to detect passive QuadBox rings for bidirectional communications.

3.1. Filtering Unicast Frames in DANH Rings

As specified in the standard HSR protocol, each DANH periodically multicasts a supervision frame called HSR_Supervision with an interval called LifeCheckInterval [5]. Upon receiving an HSR_Supervision frame, each access QuadBox learns the MAC addresses of DANHs in its DANH ring and stores these in a MAC table called NodesTable. Supervision frames allow the NodesTable of access QuadBoxes to keep track of the presence of DANH nodes in their DANH rings. When a DANH does not send an HSR_Supervision frame within a given timeout called NodeForgetTime, its address is removed from NodesTable.

Instead of using PL for filtering traffic for nondestination DANH rings, eEFA looks-up NodesTable to make forwarding decisions. When an access QuadBox receives an HSR unicast frame, it looks up its NodesTable and checks whether there is an entry matching the destination MAC address of the frame. If so, it means that the DANH ring of the QuadBox contains the destination DANH; the QuadBox then forwards the frame to its DANH rings. If not, the access QuadBox sends the frame over the other port connecting to its QuadBox ring and does not send the frame to its DANH ring. Figure 5 shows the process of forwarding a unicast frame at access QuadBoxes in eEFA.

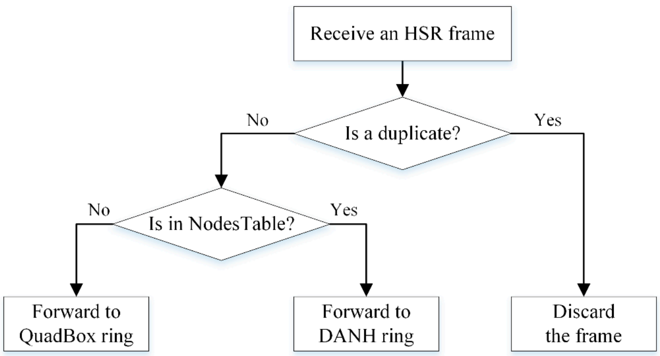


Figure 5. Process of forwarding a unicast frame in access QuadBoxes in eEFA. eEFA: Enhanced effectively filtering approach.

By looking up the NodesTable, eEFA avoids forwarding HSR frames, including the first sent frame, to nondestination DANH rings, as shown in Figure 6.

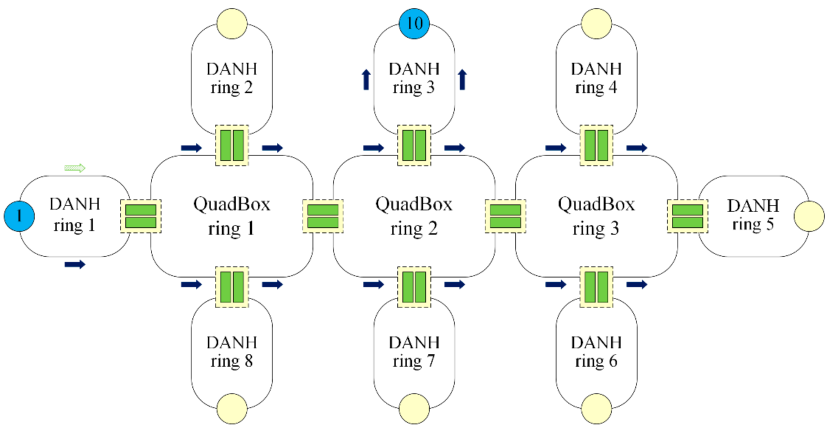


Figure 6. Forwarding the first sent frame in eEFA.

3.2. Discovering Passive QuadBox Rings

In eEFA, communications are classified into two types: unidirectional and bidirectional. In a unidirectional communication, unicast frames are propagated in only one direction from a source to a destination. In a bidirectional communication, unicast frames are exchanged between the source and the destination. In other words, in bidirectional communication, if the destination receives a frame sent by the source, it will reply by sending a frame back to the source.

3.2.1. Unidirectional Communication

For unidirectional communications, eEFA uses the same process for discovering passive QuadBox rings as EFA. In other words, eEFA uses the locking message sent by the destination DANH to discover and lock passive QuadBox rings, as shown in Figure 3.

3.2.2. Bidirectional Communications

In bidirectional communications, unlike in the case of EFA, eEFA does not use any control message to detect and lock passive QuadBox rings. Instead, eEFA uses the first replied frame sent by the destination DANH to discover passive QuadBox rings.

When the destination DANH receives the first sent frame, it replies by sending a unicast frame back to the source. Upon receiving the first replied frame, trunk QuadBoxes detect passive QuadBox rings, as shown in Figure 7.

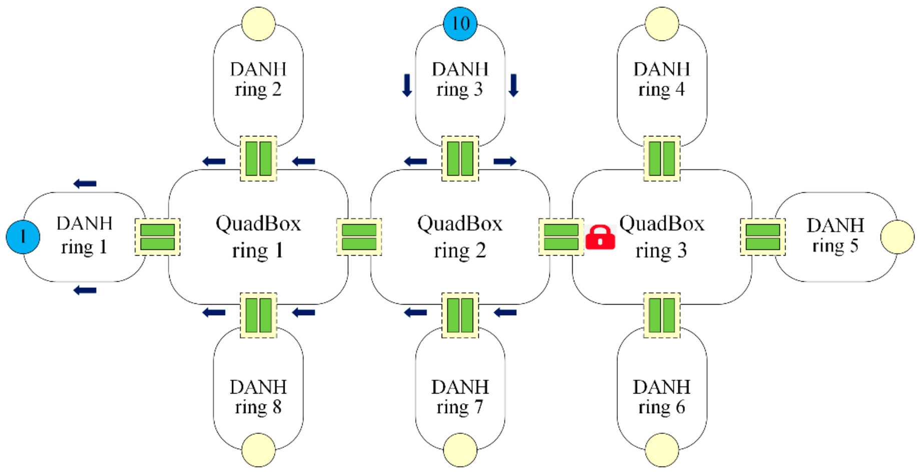
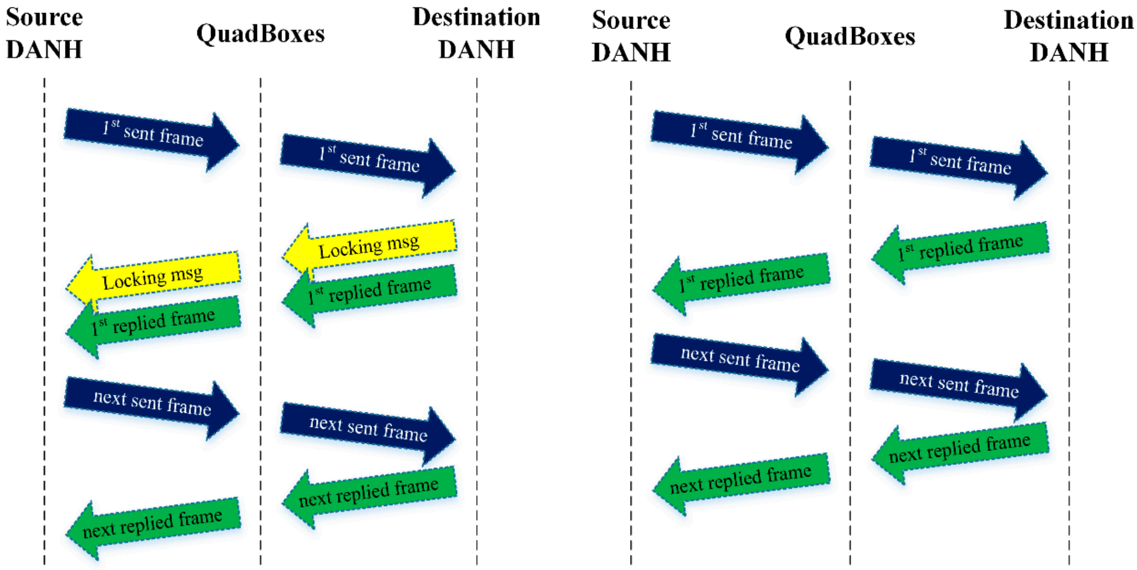


Figure 7. Using the first replied frame to discover passive QuadBox rings in eEFA.

Figure 8a,b show the processes of forwarding unicast frames between the source DANH and the destination DANH in EFA and eEFA, respectively.

3.3. Forwarding Unicast Frames

Unlike EFA, which forwards the first sent frame to all DANH rings, eEFA does not send the first sent frame and other traffic frames to nondestination DANH rings by looking up the NodesTable. Like EFA, eEFA does not forward the kth $(k \geq 2)$ frame to passive QuadBox rings. Figure 9 shows the process of forwarding the kth $(k \geq 2)$ traffic frame in eEFA.



(**a**) In EFA (**b**) In eEFA

Figure 8. Process of forwarding frames between the source and the destination.

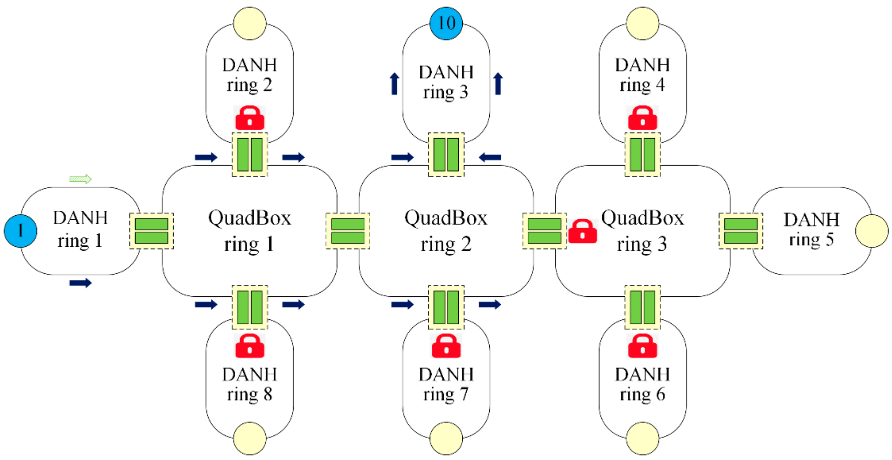


Figure 9. Forwarding the kth ($k \geq 2$) frame in eEFA.

4. Traffic Performance Analysis

This section analyzes, evaluates, and compares the network traffic performance of EFA and eEFA. We consider the sample HSR network with data communication sessions between source DANH 1 and destination DANH 10, as shown in Figure 1.

The following two scenarios are considered:

- Unidirectional communication between the source and the destination; and
- Bidirectional communication between the source and the destination.

4.1. Unidirectional Communication

4.1.1. In EFA

In EFA, the first sent frame is forwarded and circulated in all DANH and QuadBox rings except the destination DANH ring. The number of network frames generated in the network upon delivering the sent first frame, denoted by nf^1_{EFA}, is calculated as:

$$nf^1_{EFA} = \sum_{i \in NR} 2n_i - n_d \tag{1}$$

where NR is the set of all rings in the network; n_d, the number of nodes in the destination DANH ring; and n_i, the number of nodes in the ith ring.

When the destination receives the first sent frame, it sends a Locking message back to the source to discover passive QuadBox rings in the network. The Locking message is forwarded to the destination DANH ring and active QuadBox rings. The number of network frames generated by the locking message, denoted by nf^{lock}_{EFA}, is calculated as:

$$nf^{lock}_{EFA} = n_d + \sum_{i \in AQR} n_i \tag{2}$$

where AQR is the set of all active QuadBox rings.

For the kth$(k \geq 2)$ frame, EFA does not forward the frame to nondestination DANH ring and passive QuadBox rings. The number of network frames generated by the kth frame ($k \geq 2$), denoted by nf^k_{EFA}, is calculated as:

$$nf^k_{EFA} = n_s + n_d + \sum_{i \in AQR} n_i \tag{3}$$

where n_s is the number of nodes in the source DANH ring.

Generally, the number of network frames when the source sends N unicast frames to the destination in unidirectional communication in EFA, denoted by nf^{uni}_{EFA}, is calculated as:

$$nf^{uni}_{EFA} = nf^1_{EFA} + nf^{lock}_{EFA} + (N-1)nf^k_{EFA} \tag{4}$$

By substituting nf^1_{EFA}, nf^{lock}_{EFA}, and nf^k_{EFA}, nf^{uni}_{EFA} can be calculated as:

$$nf^{uni}_{EFA} = \sum_{i \in NR} 2n_i + (N-1)(n_s + n_d) + N \sum_{i \in AQR} n_i \tag{5}$$

4.1.2. In eEFA

In eEFA, the first sent frame is not forwarded to nondestination DANH rings. Instead, it is forwarded to the destination DANH ring and all QuadBox rings. The number of network frames generated by the first sent frame, denoted by nf^1_{eEFA}, is calculated as:

$$nf^1_{eEFA} = n_d + \sum_{i \in QR} n_i \tag{6}$$

where QR is the set of all QuadBox rings in the network.

For unidirectional communication, eEFA also uses the Locking message to discover passive QuadBox rings. The number of network frames generated by the Locking message, denoted by nf^{lock}_{eEFA}, is calculated as:

$$nf^{lock}_{eEFA} = n_d + \sum_{i \in AQR} n_i \tag{7}$$

Like EFA, eEFA does not forward the kth$(k \geq 2)$ frame to nondestination DANH ring and passive QuadBox rings. The number of network frames generated by the kth frame ($k \geq 2$), denoted by nf^{k}_{eEFA}, is calculated as:

$$nf^{k}_{eEFA} = n_s + n_d + \sum_{i \in AQR} n_i \tag{8}$$

Generally, the number of network frames generated in the network when the source sends N unicast frames to the destination in unidirectional communication in eEFA, denoted by nf^{uni}_{eEFA}, is calculated as:

$$nf^{uni}_{eEFA} = nf^{1}_{eEFA} + nf^{lock}_{eEFA} + (N-1)nf^{k}_{eEFA} \tag{9}$$

By substituting nf^{1}_{eEFA}, nf^{lock}_{eEFA}, and nf^{k}_{eEFA}, nf^{uni}_{eEFA} can be calculated as:

$$nf^{uni}_{eEFA} = \sum_{i \in QR} n_i + 2n_d + (N-1)(n_s + n_d) + N \sum_{i \in AQR} n_i \tag{10}$$

4.2. Bidirectional Communication

4.2.1. In EFA

The number of network frames generated in the network when the source sends the first frame to the destination, denoted by $nf^{1,send}_{EFA}$, is calculated as:

$$nf^{1,send}_{EFA} = \sum_{i \in NR} 2n_i - n_d \tag{11}$$

The number of network frames generated in the network by the Locking message, denoted by nf^{lock}_{EFA}, is calculated as:

$$nf^{lock}_{EFA} = n_d + \sum_{i \in AQR} n_i \tag{12}$$

After sending the Locking message, the destination DANH sends the first replied frame to the source DANH. The number of network frames generated in the network when the destination sends the first replied frame, denoted by $nf^{1,reply}_{EFA}$, is calculated as:

$$nf^{1,reply}_{EFA} = n_d + \sum_{i \in AQR} n_i + n_s \tag{13}$$

The number of network frames generated in the network by sending the kth frame ($k \geq 2$), denoted by $nf^{k,\ send}_{EFA}$, is calculated as:

$$nf^{k,\ send}_{EFA} = n_s + \sum_{i \in AQR} n_i + n_d \tag{14}$$

The number of network frames generated in the network by replying to the kth frame ($k \geq 2$), denoted by $nf^{k,\ reply}_{EFA}$, is calculated as:

$$nf^{k,\ reply}_{EFA} = n_d + \sum_{i \in AQR} n_i + n_s \tag{15}$$

Generally, the number of network frames generated in the network when the source sends N unicast frames to the destination in bidirectional communication in EFA, denoted by nf^{bi}_{EFA}, is calculated as:

$$nf^{bi}_{EFA} = nf^{1,send}_{EFA} + nf^{lock}_{EFA} + nf^{1,reply}_{EFA} + (N-1)\left(nf^{k,\ send}_{EFA} + nf^{k,\ reply}_{EFA}\right) \tag{16}$$

Therefore, nf_{EFA}^{bi} is calculated as:

$$nf_{EFA}^{bi} = \left(\sum_{i \in NR} 2n_i + n_s + n_d\right) + 2(N-1)(n_s + n_d) + 2N \sum_{i \in AQR} n_i \tag{17}$$

4.2.2. In eEFA

The number of network frames generated in the network by the first sent frame, denoted by $nf_{eEFA}^{1,send}$, is calculated as:

$$nf_{eEFA}^{1,send} = n_d + \sum_{i \in QR} n_i \tag{18}$$

When the destination receives the first sent frame, it sends the first replied frame back to the source. The number of network frames generated in the network by the first replied frame, denoted by $nf_{eEFA}^{1,reply}$, is calculated as:

$$nf_{eEFA}^{1,reply} = n_d + \sum_{i \in AQR} n_i \tag{19}$$

The number of network frames generated in the network by sending the kth frame ($k \geq 2$), denoted by $nf_{eEFA}^{k,\, send}$, is calculated as:

$$nf_{eEFA}^{k,\, send} = n_S + \sum_{i \in AQR} n_i + n_d \tag{20}$$

The number of network frames generated in the network by replying to the kth frame ($k \geq 2$), denoted by $nf_{eEFA}^{k,\, reply}$, is calculated as:

$$nf_{eEFA}^{k,\, reply} = n_d + \sum_{i \in AR} n_i + n_s \tag{21}$$

Generally, the number of network frames generated in the network when the source sends N unicast frames to the destination in bidirectional communication in eEFA, denoted by nf_{eEFA}^{bi}, is calculated as:

$$nf_{eEFA}^{bi} = nt_{eEFA}^{1,send} + nt_{eEFA}^{1,reply} + (N-1)\left(nt_{eEFA}^{k,\, send} + nt_{eEFA}^{k,\, reply}\right) \tag{22}$$

Therefore, nf_{eEFA}^{bi} is calculated as:

$$nf_{eEFA}^{bi} = \left(\sum_{i \in QR} n_i + 2n_d + \sum_{i \in AQR} n_i\right) + 2(N-1)\left(n_s + n_d + \sum_{i \in AQR} n_i\right) \tag{23}$$

5. Simulations and Discussion

Several simulations have been conducted to validate the performance analysis performed in Section 4. The network simulator OMNeT++ (Version 4.6, Andras Varga, https://www.omnetpp.org/andras/, Budapest, Hungary, 2014) [23] was used to conduct these simulations.

5.1. Simulation Description

In the simulations, we considered the sample HSR network shown in Figure 1. Two simulations were conducted to validate, evaluate, and compare the network performance for both unidirectional and bidirectional communication. In both types of communication, the source and destination DANH are DANH 1 and DANH 10, respectively.

5.1.1. Simulation 1: Unidirectional Communication

In this simulation, the communication between the source and destination DANH was unidirectional. The source DANH sent N ($N = 10, 20, \ldots, 100$) unicast frames to the destination DANH. Network frames (including network traffic frames and control frames) were recorded to validate and compare the network performance.

5.1.2. Simulation 2: Bidirectional Communication

In this simulation, the communication between the source and destination DANH was bidirectional. When the destination DANH receives a unicast frame sent by the source DANH, it replies by sending a unicast frame back to the source DANH. The source DANH sent N ($N = 10, 20, \ldots, 100$) unicast frames to the destination DANH. Network frames (including network traffic frames and control frames) were recorded to validate and compare the network performance.

5.2. Results and Discussion

Figures 10 and 11 show the results of simulations 1 and 2, respectively. The line graphs in Figures 10 and 11 show comparisons of the number of network frames generated in the network when the source DANH sent unicast frames to the destination DANH in EFA and eEFA.

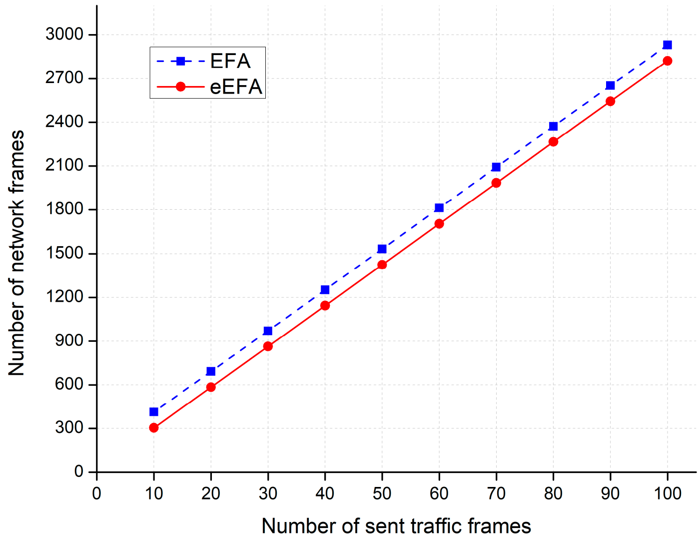


Figure 10. Result of Simulation 1.

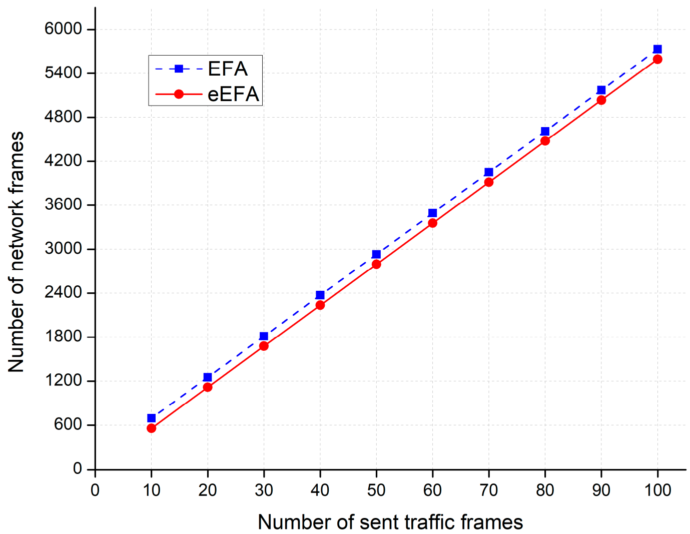


Figure 11. Result of Simulation 2.

Overall, it can be seen from the graphs above that eEFA reduced the number of network frames compared with EFA in both unidirectional and bidirectional communication. While EFA still forwards the first sent frame to all DANH rings, eEFA filters the first sent frame for nondestination DANH rings. In addition, unlike EFA that uses the Locking message to discover passive QuadBox rings for both unidirectional and bidirectional communications, eEFA does not use any control message to detect the passive QuadBox rings for bidirectional communications. Therefore, eEFA saves the network bandwidth and improves the network performance.

Figure 12 shows the percentage traffic reduction of eEFA compared to EFA. This graph clearly shows that the amount of traffic reduction decreased with an increase in the number of traffic frames sent in the communication. When the source DANH sent 10 frames to the destination DANH, the traffic reduction for unidirectional and bidirectional communication showed the maximum value of 26.21% and 19.65%, respectively. The traffic reduction rate decreased with a further increase in the number of sent frames, ultimately reaching values of 3.68% and 2.37% for unidirectional and bidirectional communication, respectively.

The main contributions of the proposed eEFA approach are as follows:

- eEFA filters all HSR frames for nondestination DANH rings, even the first sent frame.
- eEFA does not use any control message to discover passive QuadBox rings for bidirectional communications.

By solving these issues, eEFA reduces more redundant unicast traffic than EFA, thus saving the network bandwidth and improving the network performance in HSR networks.

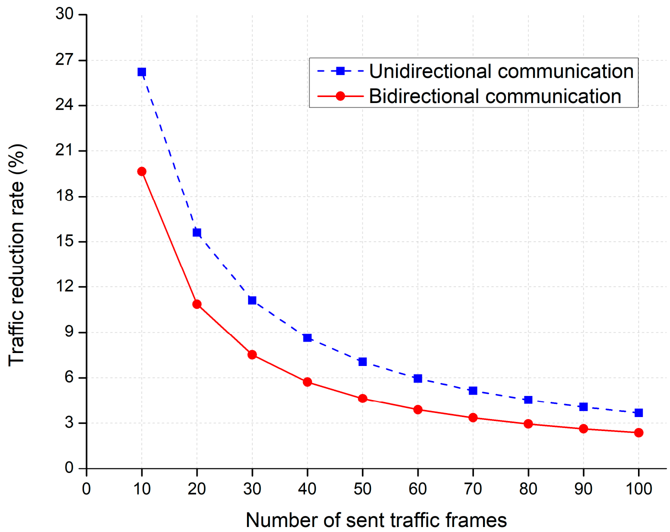


Figure 12. Traffic reduction (%) of eEFA compared to EFA for both bidirectional and unidirectional communications.

6. Conclusions

In this study, we proposed an enhanced version of EFA called enhanced-EFA (eEFA). eEFA uses existing MAC tables called NodesTable to forward HSR unicast frames to DANH rings instead of using PL, as in the case of EFA. By looking up NodesTable, eEFA avoids forwarding any HSR unicast frames, including the first sent frame, to nondestination DANH rings. In addition, eEFA does not use any control message to discover and lock passive QuadBox rings for bidirectional communications. Therefore, eEFA reduces the number of network frames sent in both unidirectional and bidirectional communications compared to EFA. For the sample HSR network considered in this study, the traffic reduction of eEFA was 4–26% and 2–20% for unidirectional and bidirectional communication, respectively, compared to EFA. eEFA thus clearly improved the network traffic performance of HSR networks. Our future work will develop and implement the proposed approach in hardware devices.

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