

Quick Removing (QR) Approach using Cut-Through Switching Mode

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Abstract— We previously introduced a quick removing (QR) approach to improve the high-availability seamless redundancy (HSR) protocol's traffic performance. The idea of the QR approach is to remove the duplicated frame copies from the network when all the nodes have received one copy of the sent frame and begin 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. In our earlier paper, we adopted the store and forward switching mode, whereas in this paper, we present the HSR node's behavior and the QR approach performance using a cut-through switching mode. The performance analysis shows a reduction percentage in frame latency that reaches about 49% compared to the store and forward switching mode. Consequently, this will improve network performance, free more bandwidth, and deliver sent frames quickly to their required destinations, which is a firm condition in many industrial and automation applications.

Keywords— HSR protocol, QR approach, HSR traffic performance, cut-through, seamless redundancy, IEC 62439-3- Clause 5.

I. INTRODUCTION

Modern control and time-critical systems typically require seamless communication networks. This means that some form of fault tolerance in such a communications network is required in order to achieve satisfactory system availability. High availability, achieved through redundancy and fault tolerance, can prevent a system from momentary interruptions that may be considered inconvenient and may cause critical stoppage in some industrial applications.

Generally, seamless communication with fault tolerance is one of the key requirements for Ethernet-based mission-critical systems such as substation automation system (SAS) networks. A fault-tolerant Ethernet (FTE) eliminates the single point of failure and therefore improves overall system availability [1]. Since the standard Ethernet does not provide a fault-tolerance capability, various FTE protocols for power applications have been developed [2]. Among these, only two protocols, the parallel redundancy protocol (PRP) and the high-availability seamless redundancy (HSR) protocol, standardized as IEC 62439-3, are suitable for seamless communication [2-4]. Both HSR and PRP are based upon the same principle of active redundancy by duplicating the information frames, therefore resulting in a zero-delay reconfiguration in the event of a switch or link failure.

However, this paper only addresses the HSR protocol, because it is generally accepted as the developed version of the PRP. The HSR protocol is a redundancy protocol for Ethernet-based networks, and it provides duplicated frame copies for each frame sent. In other words, the HSR protocol provides two frame copies for the destination node, one from each side, enabling zero-fault recovery time in case one of the frame copies is lost. This means that even in the case of a node failure or a link failure, there is no stoppage of network operations. If both sent copies reach the destination node, the node will take the fastest copy and discard the other copy. This feature of the HSR protocol makes it very useful for time-critical and mission-critical systems.

However, the main drawback of the HSR protocol is the unnecessary traffic due to the duplicated frames that are generated and circulated inside the network. If typical HSR is applied, traffic will be doubled at each QuadBox node type. The situation becomes worse when the HSR is used for generic object-oriented substation event (GOOSE) and sampled values (SV) messages' transmissions, which generate huge amounts of traffic. This downside will degrade network performance and may cause network congestion or even stoppage. Therefore, data traffic control for maximizing network operational performance is essential [5]. However, for the potential advantages of HSR, several works have also been dedicated to implementing the HSR [6-8] and improving its performance by reducing its unnecessary redundant traffic [9-14]. For the above mentioned issue, we have proposed an HSR approach called quick removing (QR) [9] to remove the unnecessary redundant traffic from the network instead of keeping it circulating inside the network and consuming its bandwidth. The idea of the QR approach was to remove the duplicated frame copies from the network when all the nodes had received one copy of the sent frame and began to receive the second copy. However, in [9] we only considered the store and forward switching mode, in which the entire frame needs to be stored in the ingress of the node before the node can forward it. Obviously, the node will take more time to forward the frame because it has to calculate the CRC code and compare it with the one appended to the frame to ensure that the received frame is error-free before sending it to the upper layers or forwarding it to the next nodes. But the other type of switching mode is called the cut-through switching mode, in which the node starts to send the frame forward as soon as the destination is learned, normally at the first 6 bytes, long before

the entire frame is read into the node. Obviously, under this type, the node will take less time to forward the frame compared to the time used for the store and forward type. In other words, the cut-through mode will be much faster than the store and forward mode [15].

In this paper, we discuss the HSR node's behaviour under the QR approach using the cut-through switching mode. We also show the performance of the QR approach under this type of switching mode.

The rest of the paper is organized as follows. In Section II, we introduce our QR approach and the HSR node behaviour and actions when the cut-through switching mode is applied under this approach. In Section III, we present the performance analysis of the QR approach under the cut-through switching mode. Finally, in Section IV, we summarize our work and describe our conclusions.

II. QR APPROACH UNDER CUT-THROUGH SWITCHING MODE

As mentioned in Section I, the QR approach aims to remove duplicated frame copies from the network when all the nodes have received one copy of the sent frame and begin to receive the second copy. The QR approach can be applied to any network topology type. It is also suitable for removing all types of unnecessary redundant traffic regardless of whether it was a unicast, multicast, or broadcast type. The QR approach also does not need to use any special control frames. However, in [9], we discussed our QR approach using the store and forward switching mode only. In this paper, the cut-through switching mode will be adopted in the QR approach to provide faster transmission and to free more bandwidth.

Under the store and forward switching mode, the QR nodes wait to receive all the frame's bytes and calculate the CRC code to make sure the received frame is error-free before deciding to send it to the upper layers or forward it to the next nodes. However, under the cut-through switching mode, when a node receives a frame, it reads the first 6 bytes of it, or we can say it reads the destination MAC address, and thereafter, the node takes the following actions according to the type of destination MAC address:

A. Unicast MAC Type (The Receiving Node is the Destination Node for The Received Frame)

In this case, the receiving node will wait to receive and read the source MAC address of the received frame. Then the node will check its received frames table to see whether it has already received a copy from that frame. If the node does not find that source MAC address inside its table, then it will:

- Buffer all the received bytes until the reception of all of them is complete, and then,
- Calculate the CRC code and compare it to the frame's CRC. If they are equal, the node will send that frame to the upper layers and update its received frames table or else delete it.

However, if the node does find that the received source MAC address exists inside its received frames table, then it will:

- Read the HSR frame's header to check whether the sequence number exists inside the received frames table and then repeat the above steps in a case where the received sequence number does not exist; otherwise, the node will delete the bytes that have been received thus far and all the remaining bytes that will be received sequentially.

B. Unicast MAC Type (The Received Frame is Heading to other Node)

If the received frame is a unicast type and heading to other node than the receiving node, or in other words, the frame is passing through the receiving frame and going to other node. In this case, the receiving node will:

- Read the destination MAC address of the frame and look for that address inside its forwarded frames table. If the address does not exist inside the table, then the node will sequentially forward all the received bytes into the other node's ports and then update its forwarded frames table.
- If the destination MAC address exists inside the table, the node will read the source MAC address of the received frame and look up the table again for that pair of addresses. If the address pair does not exist, then the node will sequentially forward all the received bytes into the other node's ports, and then update its forwarded frames table.
- If that addresses pair exists inside the table, the node will read the HSR header of the frame to see whether it has already forwarded the same frame. If the node finds that it has forwarded a frame with the same destination, source MAC address, and HSR header, then the node will delete the received bytes and all the remaining bytes of that frame as soon as they reach the node. Otherwise, the node will sequentially forward all the received bytes into the other node's ports and then update its forwarded frames table.

C. Multi/broadcast MAC Type

The receiving node will wait to receive and read the source MAC address to see whether the node has already received a copy of that frame. If the source node of that frame does not exist in the received frames table, then the node will:

- Take a copy of each received byte, buffer it, and then forward the original bytes into the other ports.
- When all the bytes of that frame are received, the node will calculate the CRC code and compare it to the frame's CRC code. If they are equal, the node will send that frame to the upper layers and update its received frames table or else delete it.

However, if the source MAC address is shown in the received frames table, the node will read the HSR frame's header. If the node shows that it has already received a copy of that frame, then the node will delete the received bytes and all the remaining bytes of that frame as soon as they reach the node; otherwise, it will execute all the steps mentioned above.

Figure 1 illustrates a flow chart that summarizes the QR steps under the cut-through switching mode.

III. PERFORMANCE ANALYSIS

In this section, we will demonstrate the performance of the QR approach under the cut-through switching mode compared to the store and forward mode from the point view of frame latency. Let us consider the network shown in Figure 2 as an example for our performance analysis. However, assume that node C has sent a unicast frame to node G. The following

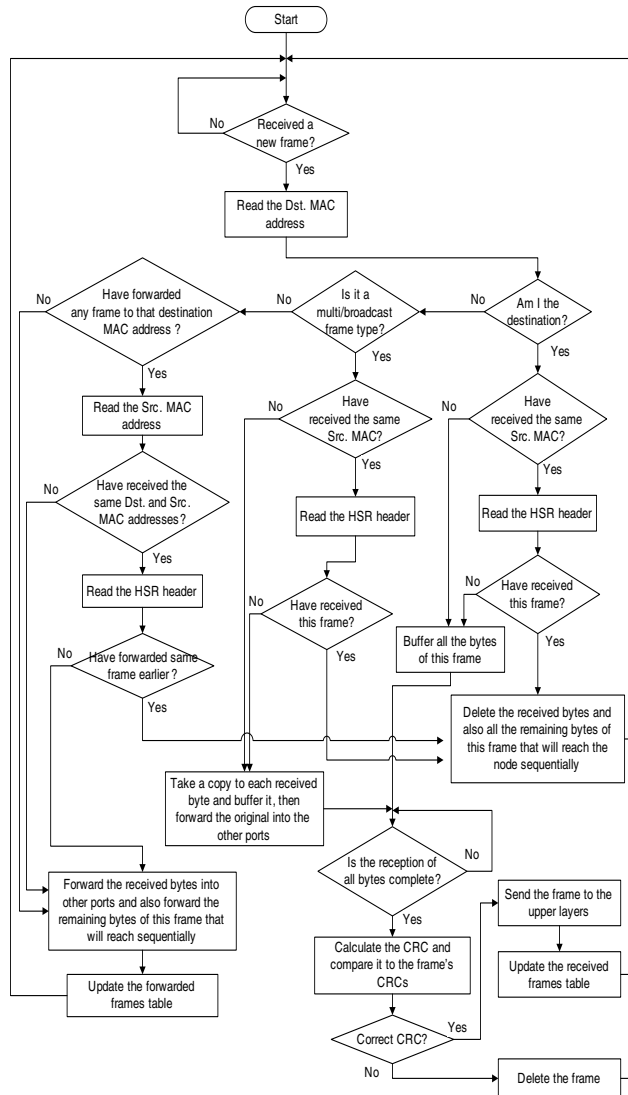


Figure 1. Flow chart of the HSR node under the operation of QR approach using cut-through switching mode.

expression represents the latency of the frame from the time at which the sending node sent its bits until the destination node has received all of them:

$$t_c = \tau_r + \tau_p + \tau_n$$

where t_c is the frame latency under the cut-through switching mode, τ_r is the transmission delay time, τ_p is the propagation delay time, assumed to be zero since the network example has short link lengths, and τ_n is the node delay time. Assume the queuing delay time is zero.

The above expression can be written as below:

$$t_c = l \left(\frac{f}{\beta} \right) + \left[(n-2) \left(\frac{h}{\rho} \right) + \left(\frac{f}{\rho} \right) \right] \quad (1)$$

where l is the number of network links, f is the frame size in bits, β is link capacity in bits per second, n is the number of nodes in the path of the sent frame, h is the frame header size in bits, and ρ is the node processing rate. h might be 48 bits when the received node only reads the destination MAC address of the received frame, or it might be 96 bits or even 144 bits if the destination MAC, the source MAC, and the HSR frame header are read.

The term $(n-2)$ represents the exclusion of the source and destination nodes from the calculation of the delay time on the path of the sent frame, whereas $\left(\frac{f}{\rho} \right)$ represents the delay time of the destination node.

From the other side, the latency under the store and forward switching mode can be determined as follows:

$$t_{sf} = l \left(\frac{f}{\beta} \right) + \left[(n-1) \left(\frac{f}{\rho} \right) \right] \quad (2)$$

$(n-2)$ represents the exclusion of the source node from the calculation of the delay time on the path of the sent frame.

Assume the frame size that node C has sent is 1522 bytes, each of the network links' capacity is 100Mb/s, and the node processing rate is 100Mb/s. Thereafter, the latency under both the cut-through and store and forward switching modes will be

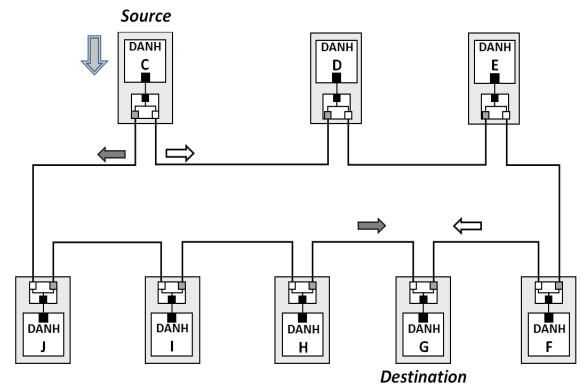


Figure 2. An HSR example network.

determined using (1) and (2) as follows:

$$t_c = 4 \left(\frac{1522 \times 8}{100 \times 10^6} \right) + \left[(5-2) \left(\frac{48}{100 \times 10^6} \right) + \left(\frac{1522 \times 8}{100 \times 10^6} \right) \right] = 0.610 \text{ ms}$$

Note that $h=48$ bits, which is the size of the destination MAC address of the sent frame, because each node can recognize that the frame is a unicast frame and is sent to a unique address. Therefore, the nodes do not need to read more bits from the frame.

$$t_{sf} = 4 \left(\frac{1522 \times 8}{100 \times 10^6} \right) + \left[(5-1) \left(\frac{1522 \times 8}{100 \times 10^6} \right) \right] = 0.947 \text{ ms}$$

However, let us find the latency reduction percentage with respect to the network size, or in other words, with respect to the number of network nodes. This can be represented in the following expression:

$$\lim_{n \rightarrow \infty} \varepsilon = \lim_{n \rightarrow \infty} \left(1 - \frac{t_c}{t_{sf}} \right) \times 100\%$$

where ε is the latency reduction percentage of the cut-through mode compared to the store and forward mode.

$$\lim_{n \rightarrow \infty} \varepsilon = \lim_{n \rightarrow \infty} \left(1 - \frac{l \left(\frac{f}{\rho} \right) + \left[(n-2) \left(\frac{h}{\rho} \right) + \left(\frac{f}{\rho} \right) \right]}{l \left(\frac{f}{\rho} \right) + \left[(n-1) \left(\frac{f}{\rho} \right) \right]} \right) \times 100\%$$

Assume that $\beta = \rho$. In Figure 2, the path from nodes C to G has a number of links equal to the number of nodes $\square l$, or we can say that $l = n - 1$.

Thus, we can rewrite the above expression as follows:

$$\lim_{n \rightarrow \infty} \varepsilon = \lim_{n \rightarrow \infty} \left(1 - \frac{n \left(\frac{f}{\rho} \right) - \left(\frac{f}{\rho} \right) + \left[(n-2) \left(\frac{h}{\rho} \right) + \left(\frac{f}{\rho} \right) \right]}{n \left(\frac{f}{\rho} \right) - \left(\frac{f}{\rho} \right) + \left[(n-1) \left(\frac{f}{\rho} \right) \right]} \right) \times 100\%$$

$$\lim_{n \rightarrow \infty} \varepsilon = \lim_{n \rightarrow \infty} \left(1 - \frac{n f + n h - 2 h}{2 n f - 2 f} \right) \times 100\%$$

$$\lim_{n \rightarrow \infty} \varepsilon = \left(\lim_{n \rightarrow \infty} 1 - \lim_{n \rightarrow \infty} \left(\frac{n \left(f + h - 2 \frac{h}{n} \right)}{2 n \left(f - \frac{f}{n} \right)} \right) \right) \times 100\%$$

$$\lim_{n \rightarrow \infty} \varepsilon = \lim_{n \rightarrow \infty} \left(1 - \frac{f + h}{2 f} \right) \times 100\%$$

$$\lim_{n \rightarrow \infty} \varepsilon = \lim_{n \rightarrow \infty} \left(0.5 - \frac{h}{2 f} \right) \times 100\% \quad (3)$$

It is obvious from (3) that ε is not affected by the number of nodes when this number becomes large; to the contrary, it varies inversely with respect to the frame size. Figure 3 shows

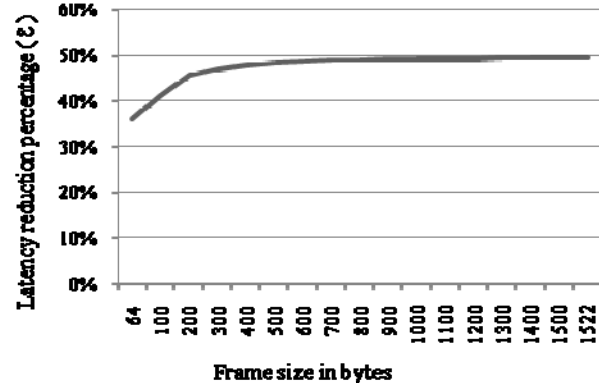


Figure 3. Latency reduction percentage versus frame size.

that ε increases when the frame size increases, and the maximum reduction percentage that can be achieved is 49.4% when $h=144$ and $f=1522$ bytes. However, the lowest ε value is about 35% when the frame size is 64 bytes.

It is also shown from Figure 4 that the cut-through mode offers less latency than the store and forward mode, which in turn improves network performance and delivers the sent frames quickly.

IV. CONCLUSIONS

In this paper, we present HSR node behaviour when it receives a frame under the QR approach using the cut-through switching mode and what actions it will take to receive or forward the received frame depending on the destination MAC, source MAC, and HSR header. We also present the QR performance from the point view of frame latency, since the cut-through and the store and forward switching modes will not differ from the traffic reduction aspect. Under the cut-through mode, the QR shows a reduction percentage in frame latency reached of more than 49% compared to the store and forward mode. The performance analysis also showed a reduction of the percentage range of from 35% to 49%.

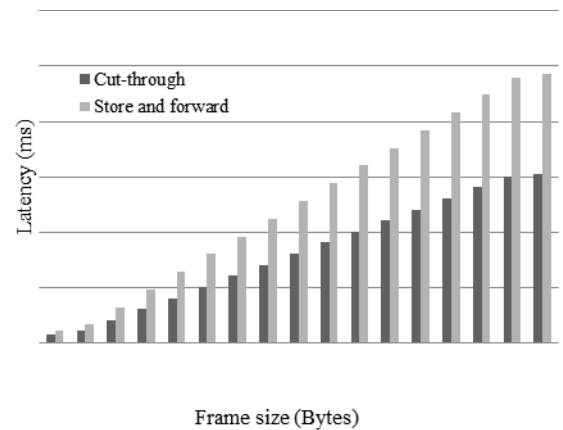


Figure 4. Frame latency under cut-through and store and forward switching modes using QR approach.

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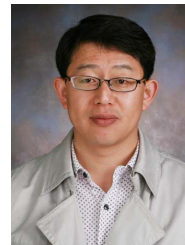
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