A Novel Optical High-Availability Seamless Redundancy (OHSR) Design Based on Beam Splitting / Combining Techniques

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The standard high-availability seamless redundancy (HSR) protocol utilizes duplicated frame copies of each sent frame for zero fail over time. This means that even in cases of a node or link failure, the destination node will receive at least one copy of the sent frame, resulting in no network downtime. However, the standard HSR is mostly based on the electrical signal connection inside the node, which leads to the production of considerable latency at each node due to frame processing. Therefore, in a large scale HSR ring network, the accumulated latencies become significant and can often restrict the mission-critical real-time application of HSR. In this paper, we present a novel design for optical HSR (OHSR) that uses beam splitting/combining techniques. The proposed OHSR passes the frames directly to adjacent nodes without frame processing at each node, thereby theoretically generating no latency in any node. Various simulations for network samples, made to validate the OHSR design and its performance, show that the OHSR outperforms the standard HSR.

Keywords: Optical HSR, Beam splitting/combining, Optical communications, Optical networks

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I. INTRODUCTION

The major driving force behind the widespread use of fiber optic communication is the increasing demand by consumer telecommunications and internet services. Technological advances have enabled the conveyance of huge amounts of data through a single optical fiber. However, this high data trafficking has increased the risks associated with network failure. This has made network reliability and protection the most important issues concerning data transport across high-speed connections [1].

The occurrence of a link failure absolutely demands real-time link recovery. One potential candidate for assuring zero fault-recovery time is the high-availability seamless redundancy (HSR) protocol. This protocol was standardized by the International Electrotechnical Commission (IEC) as IEC 62439-3 Clause 5 [2] and is mostly used for ring topologies. It is a fault redundancy protocol for Ethernet networks, and provides duplicated frames on separate physical paths with zero fault-recovery time. Consequently, even in the event of a node or link failure, no stoppage occurs in network operations. Therefore, the HSR protocol is useful for applications that require high availability and zero fault-recovery time, which cannot be provided by a conventional protocol like the rapid spanning tree protocol (RSTP). Typical HSR protocol applications are as follows:

- Substation automation systems [3];
- Military communication systems for command operation centers [4];
- Vehicular backbone networks [5]

The HSR principle is described in [6-9]. The standard HSR protocol utilizes duplicated frame copies of each sent
frame for zero fail-over time. However, the standard HSR is mostly based on the electrical signal connection inside the node, which consequently produces considerable latency in each node due to frame processing. Therefore, the accumulated latencies from each node become significant in large scale HSR ring networks, which then can restrict the mission critical real time application for HSR. In this paper, we present a novel optical HSR ring network (OHSR) that works by distributing the frames using a beam splitting/combing technique instead of receiving and forwarding from one node to another. Therefore, it enhances the network performance without altering the standard HSR protocol mission. This is the first study to report an enhancement of the HSR network utilizing all-optical techniques. The analysis and simulation demonstrate the superiority of the OHSR model over conventional HSR in terms of traffic generation and network latency.

The rest of this paper is organized as follows. In Section II, we briefly describe the HSR protocol for network traffic generation. In Section III, we present our OHSR model and its concept of operation. Section IV presents analysis demonstrating the superiority of the OHSR performance over the conventional HSR protocol. Section V then shows the simulation results to validate the analysis. Finally, Section VI presents conclusions and suggestions for future work.

II. HSR FRAME TRAFFIC AND LATENCY

This section describes the handling of HSR traffic and latency. In general, the HSR protocol has four types of nodes [2]. However, the doubly attached node for HSR (DANH) and the two rings connecting the QUAD box node are sufficient to handle HSR traffic in this study. The DANH is an HSR node with two Ethernet ports that share the same media access control (MAC) and internet protocol (IP) addresses. It allows network management protocols, like the address resolution protocol (ARP), to operate without modification, and it simplifies engineering [6].

2.1. Frame Traffic

Each DANH duplicates a non-HSR frame that is generated in its upper layer into two copies (copy A and copy B). It then appends an HSR tag to each copy and sends the copies out through its ports. Figure 1 shows how the DANH sends frames. The first frame (Copy A) is sent in a counter-clockwise direction and the other frame (Copy B) is sent clockwise. Basically, each DANH is connected by two links. If one of these links carries a bad frame, the HSR node will discard that frame and wait for the duplicate to arrive at the other link. If both links carry bad frames, a higher layer, like the transmission control protocol (TCP), will interact to resend the information.

The HSR protocol unicasting process is summarized as duplicated frame copies (Copies A and B) that travel via different paths to the destination node as shown in Fig. 1.

FIG. 1. Single ring HSR unicast process.

The receiver accepts the first (fastest) copy to arrive and then discards the other. For multicast and broadcast traffic, the duplicated frame copies are circulated inside the ring until they reach the source node, and they are eventually removed from the network ring by the source node as shown in Fig. 2. The advantage of duplicated frames is that they ensure that each node will receive at least one copy of the transmitted frame. Thus, the network resumes its work even when a fault or error occurs at a network component.

2.2. Latency

In general, the frame checking and forwarding processes at each node increase the time required for the sent frame to reach the destination. For the single ring HSR network shown in Fig. 2, the total latency for a single ring $T_{HSR, single ring}$ can be estimated as

$$T_{HSR, single ring} = T_w + T_{cp} + T_{fp}$$

where $T_w$ is the physical medium links delay; the terms $T_{cp}$...
and $T_{fp}$ represent the required time for checking and forwarding of a single node, respectively; and $n$ is the total number of nodes in the network. Note that node latency depends on the frame size [10]. Therefore, the present analysis relies on an estimated latency that is fixed for each node.

III. THE PROPOSED OHSR

Enhancing HSR network performance by upgrading the node-to-node connections from a copper medium to optical fiber is valid as a conventional solution. The HSR nodes may use an optical interface that increases link speed and bandwidth. However, the HSR node delay will still remain due to the process of checking and forwarding the frames.

3.1. OHSR Design

Further enhancement of network performance is made possible by reducing the impact of $T_{cp}$ and $T_{fp}$ in Eq. (1). This can be done by decreasing the number of nodes that participate in the checking and forwarding processes. Therefore, application the OHSR design concept shown in Fig. 3, significantly reduces the checking and forwarding latencies, since the links have not been terminated at each node but instead travel past all nodes. Each node is connected to the network ring by an optical coupler (the red circle in Fig. 3). In this design, each DANH node works passively to receive frames only, without the need to forward them (unlike standard HSR nodes). However, the coupler contains two Y-branch splitter waveguides [11] that are connected back to back. The reasons for this are:

- to split the signal into node carriers and a main carrier, where the node carriers go to the HSR node and the main carrier keeps travelling in the optical ring network.
- to enable the nodes to send frames inside the ring as a main carrier.

A Y-branch or fiber coupler is made using two or more fibers that are thermally tapered and fused. Amplitude distribution in a fiber coupler can be seen in Fig. 4; light distribution oscillates between the two fiber cores, and ultimately the larger part of the power remains in the original (upper) fiber [11].

3.2. OHSR Design Issues

Accommodating OHSR will generate three issues that must be taken into consideration in the network design.

- In large network rings, due to the splitting effect, the network traffic signal is attenuated after passing each node and will eventually disappear.
- Conversely, small network rings will suffer from continuous frame travelling due to the low attenuation factor, with the result that the nodes will receive the same frame more than once.
- As the medium is shared, collisions might occur when multiple nodes send frames simultaneously.

3.2.1. The Signal Attenuation Issue

The first issue, signal attenuation in a large network ring, can be resolved by allowing each HSR node to retransmit only a weak signal in the network ring. However, although this solution reduces costs, it requires a redesign of the HSR node. An alternative solution is to use a passive amplifier that compensates for the signal attenuation, and that should be located after splitting the wave, as shown in Fig. 5. Inline optical amplifiers, for example, an erbium-doped fiber Amplifier (EDFA), are widely used in the field of optical communication [12]. An EDFA is capable of amplifying a signal while imposing only a very short time delay, which can be neglected [13].

3.2.2. The Issue of Broadcasting in a Small Network Ring

The second issue can be resolved by adding a link-terminating node in each ring, as shown in Fig. 6. At least one node should not be connected to the optical ring by a coupler; this node is called the optical path terminator (OPT). Following the HSR protocol steps, if the OPT node receives a new frame, then it will forward it. However, if that frame has
be received previously by this node, then it will be discarded as a duplicate. The main reason for using an OPT node is to terminate the link and prevent the signal from persisting within the ring network.

3.2.3. Frame Collisions and Timing Issues

The final issue can be resolved using time division multiplexing (TDM) or wavelength division multiplexing (WDM) [15], and can be considered as a subject for future work.

IV. PERFORMANCE ANALYSIS OF THE CONNECTED RING NETWORK

4.1. Frame Traffic

The number of generated frames depends on the number of nodes in the ring network. Each node receives and forwards a minimum of two frames in any broadcasting process. Therefore, the amount of frame traffic generated in an HSR connected ring network can be expressed as

\[ FT_{HSR} = \sum_{i} N_i \times 2N_{Frame} \]  

(2)

where \( FT_{HSR} \) is the network generated traffic in a standard HSR network; \( r \) is the number of rings; \( N_i \) is the number of nodes in the \( i^{th} \) ring; and \( N_{Frame} \) is the number of frames sent by the source node. In Fig. 2, if the source broadcasts one frame, then \( FT_{HSR} = 8 \times 2 = 16 \) frame copies.

In the OHSR network shown in Fig. 6, if the source transmits a frame then the generated traffic in the optical HSR network \( FT_{OHSR} \) can be estimated as

\[ FT_{OHSR} = \sum_{i} 2N_{Frame} \]  

(3)

4.2. Latency

Generally, the signal traveling speed in the medium approaches the speed of light, so the propagation delay \( T_m \) between nodes inside the medium equals the distance (in meters) between nodes / \( 3 \times 10^8 \). For example, if the distance between each two nodes is around 100 meters [16], then \( T_m \approx 0.3 \) \( \mu \)sec. The total frame latency of a single node in a typical condition is larger than 200 \( \mu \)sec [17], therefore, \( T_m \) can be neglected. Eq. (1) can then be rewritten as

\[ T_{HSR, single \ ring} = \sum_{i} T_{cp} + \sum_{i} T_{fp} \]  

(4)

In a single OHSR ring, changing the number of nodes in the ring does not affect latency, because the nodes will not retransmit any frames. The total time delay of a single OHSR ring can then be estimated as

\[ T_{OHSR, single \ ring} = T_{cp} + T_{fp} \]  

(5)

Transmission time \( T_{fp} \) depends on node speed and the frame size of the HSR protocol. Therefore, the transmission time can be calculated based on the technology (e.g., Ethernet) employed. In cut-through technologies, the processing time is ignored; therefore, \( T_{fp} \) will be considered as the receiving time of each frame, from the first bit to the last bit. For the sake of simplicity, if we assume that the HSR node...
imposes only a very short time delay when checking each frame, then the frames will be received and forwarded at the same speed, i.e., $T_{cp} = T_{fp}$. The analysis presented here is based on using Ethernet transmission speed of 100Mbit/s for each HSR node. The HSR maximum frame size equals 1522 octets [8], so the maximum transmission time of a single frame equals $(1522 \times 8) \text{ bits} / (100 \times 10^6 \text{ bit/s}) \approx 121 \mu s \ (T_{fp} = 121 \mu s = T_{cp})$. Therefore, the HSR frame delay inside a single HSR node is calculated as $T_t = T_{cp} + T_{fp} = 242 \mu s$, where $T_t$ is the receiving and transmission latency of a single HSR node.

In a multiple connected ring network, the frame travelling time delay between a source and destination can be found by estimating the delay inside each ring separately. Figure 7(a) shows a symmetrical standard HSR network consisting of three rings, each containing eight HSR nodes. When the source broadcasts a frame in the first ring, the latency that exists until the frame is removed from that ring supposedly equals $T_{HSR}$. However, in practice, the frame will travel four nodes until it gets forwarded in the second ring. The true latency of a single ring can be found based on the number of nodes the frame passes until it get transmitted into another ring until it ultimately reaches the last ring. The frame will then spend a full delay equal to $T_{HSR}$ for the last ring only until it is removed from the network. Thus, the connected ring HSR latency can be estimated as

$$T_{CR,HSR} = \sum_{k=1}^{r} \left[ \sum_{m(k)=1}^{m(k)} T_{cp} + \sum_{m(k)=1}^{m(k)} T_{fp} \right] + \sum_{k=1}^{L} T_t,$$

where $m(k)$ is the least number of nodes the frame needs to pass in the $k^{th}$ ring until it is retransmitted to the $(k+1)^{th}$ ring and $L$ is the number of HSR nodes in the last ring. For example, applying Eq. (6) to the network shown in Fig. 7(a), the total delay is computed as

$$T_{CR,HSR} = 16 \times 242 \mu s = 3.872 \text{ m sec}$$

FIG. 7. (a) Standard HSR connected ring network (maximum duration = 16 time delays), (b) OHSR connected rings network (maximum duration = 3 time delays).
Figure 7(b) represents the OHSR design for the network topology depicted in Fig. 7(a). The total network latency can be estimated as

\[ T_{\text{CR.OHSR}} = \sum T_i \]  

(7)

For the sample network shown in Fig. 7(b), the total time delay \( T_{\text{OHSR}} \) will be equal to \( 3T_i = 726 \mu s \). The OHSR therefore shows a significantly shorter time delay when compared to the standard HSR.

V. SIMULATION RESULTS

In this section, we present the simulation results that validate our analysis. The standard HSR and OHSR network topologies shown in Fig. 7 were implemented using the OMNET++ [18] network simulator.

The following parameter values are used in the our simulations:

- \( T_{cp} \) for each node = 121 \( \mu s \)
- \( T_{fp} \) for each node = 121 \( \mu s \)
- Frame transmission rate = 100Mbps
- Number of sending frame, \( N_{\text{Frame}} \) = 1
- Number of rings, \( r \) = 3.

The network shown in Fig. 7(a) generates 16 frames in each ring; so that total number of frames reaches 48 as a consequence of a single frame-transmission process. By contrast, in the OHSR design shown in Fig. 7(b), the same process generates only six frames. Figure 8 provides a larger-scale comparison between the standard HSR and OHSR latencies. In Fig. 8(a), the standard HSR shows a direct relationship between the number of nodes in each ring and the total latency, due to the checking and forwarding process in each node.

In comparison, the OHSR is independent of the number of nodes in the ring, and shows a fixed value of 726 \( \mu s \) because only two retransmissions occur across all the network rings. Fixing each ring as eight nodes and varying the number of rings lead to increased latency for both the standard and the optical HSR techniques. Figure 8(b) shows around 75% reduction in latency between the OHSR and the standard HSR.

Figure 9 shows a larger-scale comparison of frame generation, between the standard HSR and OHSR. With the number of rings fixed at three, the traffic generated in the standard HSR network shows a direct relationship with the increasing number of nodes inside each ring. However, similarities can be seen between the analytical results shown in Figs. 8 and 9. The number of frames generated is fixed to six in the OHSR; because it depends on how many times the frame is being retransmitted from ring to ring. A significant decline in generated traffic can be seen in Fig. 9(b), when changing the number of rings and fixing each to eight nodes. Using the OHSR, the traffic generated by broadcasting a single frame was reduced by 85.8%.

The simulation included the creation of HSR nodes based on the standard HSR protocol. Simulation results for the networks in Fig. 10 show a perfect match with the analytical results shown in Figs. 8 and 9.

Exact match between calculation and simulation occurs for the following reasons:

- The network case in our paper has been made on symmetrical topology. The sender node and destination node have a fixed location in all cases. So, the time delay does not alter the case studies. In the real application, nodes are supposed to be randomly distributed, and that will give a difference between simulation and analysis results.
FIG. 9. Traffic frame comparison between standard HSR and OHSR (a) Number of rings is fixed as 3, (b) Number of nodes in each ring is fixed as 8.

FIG. 10. Screen shot showing OMNET++ simulation for both OHSR and standard HSR.

The case study is focused on finding the traffic generation and time delay based on a healthy network exclusively. In other words, the simulation has been made under a semi-ideal environment (no packet drops or bit error rate).

The results show total latencies of 3,872 $\mu$s and 726 $\mu$s for the networks shown in Fig. 10(a) and (b), respectively. The scenario of single frame broadcasting using the network shown in Fig. 10(a) leads to a total traffic generation of 48 frames until the frame reaches all nodes in the network. However, repeating the same scenario for the network shown in Fig. 10(b) generates only six frames. A slight mismatch might appear between the simulation results and the analytical estimation in the case of changing the source location. If
the source node is located two nodes closer to the QUAD box, the broadcast frame will pass two nodes instead of three until it is retransmitted in the next ring, thereby invoking a time delay of $2T_f$ instead of $3T_f$.

The network topology in the analysis and simulation was selected as a general example to give a converged result for the latency and traffic generation.

VI. CONCLUSIONS

In this paper, we have presented a new OHSR model that works by distributing the frames inside an HSR ring network without the need for frame checking and forwarding in each node. This model employs a beam splitting/combining optical coupler to connect the nodes to the main signal path.

The model reduces the time delay for checking and forwarding frames when compared to the standard HSR. It also helps to reduce the total number of frames that are generated inside the network. We analytically compared the network traffic and latency between the HSR and OHSR; the analysis results show the significant advantages in latency and traffic generation of the OHSR model over the standard HSR protocol for different network topologies. The analytical results were then validated by various simulations. For a case study sending a single frame from source to destination, the standard HSR finishes the task after 3.87 ms while generating 48 frames across the network. The OHSR shows a better performance for the same study case by finishing the task after 726 µs while generating only six frames across the network. When compared with the standard HSR protocol, the OHSR model achieves around 85.8% traffic reduction and 75% latency reduction.

Future work can examine the model’s capability for simultaneous sending and receiving by multi-nodes and the possibility of employing the TDM method for sending and receiving between nodes. Another sphere of research would investigate how to implement the OHSR in different network topologies like mesh networks.

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