Comparative Analysis of IEC 62439-3 (HSR) and IEEE 802.1CB (FRER) Standards

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***Abstract*—Because more and more on-board electronics devices are being used inside such complicated systems as cars or spacecraft, Ethernet-based protocol with high bandwidth capability might be an alternative to legacy low-speed protocols. Many efforts have been made to improve the reliability of Ethernet for safety-critical networks, including the IEC 62439-3 (High-availability Seamless Redundancy) and IEEE 802.1CB (Frame Replication and Elimination for Reliability) standards. This paper is a comparative study of the two aforementioned protocols. Although both achieve seamless redundancy by replicating and sending multiple copies of the same frame over disjointed paths, their characteristics might be suited for different network configurations.**

***Index Terms*—IEEE 802.1CB; IEC 62439-3; safety-critical network**

I. Introduction

In recent times, advancements in technology have led to the growing number of electronics devices being integrated into sophisticated systems such as automobiles or spacecraft. However, conventional network protocols such as Control Area Network (CAN) and Modbus lack the increasing bandwidth demand for communication between numerous onboard devices. For this reason, Ethernet is achieving popularity with leading industries as one of the appealing alternatives.

However, standard Ethernet is not an ideal solution for real-time and mission-critical applications since it does not provide a redundancy mechanism for critical data paths. Although User Datagram Protocol (UDP) might be suited for real-time voice and video streaming as occasional packet loss is preferable to large delays due to retransmission, it is not a good option for hard real-time systems since a delayed control signal would result in engine failure or damage. Another candidate might be the Rapid Spanning Tree Protocol (RSTP) which builds logical topology for Ethernet networks and includes redundant links in the case of failure of the current active one. However, the amount of recovery time must be zero in time-critical networks and RSTP is not able to guarantee this.

Therefore, there is a need for a protocol providing redundancy capability with zero recovery time. For this reason, the Time-Sensitive Networking (TSN) group was founded to improve the reliability of Ethernet for safety-critical networks. Among various standards introduced by TSN, a redundancy approach named Frame Replication and Elimination (FRER) is published as IEEE 802.1CB standard [1] by TSN in 2017. IEEE 802.1CB-2017 realizes redundancy by making copies of the same frame and sending them over separate paths. Meanwhile, the same concept is also used by High-availability Seamless Redundancy (HSR) [2], which is standardized in the IEC 62439-3:2016. Hereafter, the two standards will be abbreviated as FRER and HSR respectively.

In this paper, we firstly study and explain the details of the two standards in many aspects, including their operation and potential challenges. Then, relevant comparisons are presented to examine their similarities and differences in characteristics. We believe that with this comparison, the readers are able to understand the fundamentals of the two standards and thus find it easier to choose the right protocol for their specific network configurations. The rest of this paper is structured as follows: Section II provides an overview of HSR protocol. In section III, the details of FRER are presented. Section IV provides a comparative analysis between the two seamless redundancy approaches while section V concludes the paper.

II. High-availability seamless redundancy

High-availability seamless redundancy (HSR) is standardized by the International Electrotechnical Commission in the IEC 62439-3:2016 [2]. It is a redundancy protocol in switch Ethernet networks, especially for time-critical systems that demand zero switchover time in cases of network failure. It is worth noting that HSR realizes redundancy at the data link or layer 2 in the OSI model and since HSR serves as an Ethernet interface for the upper layers, it is compatible with protocols using the IEEE 802 link layer [3].

A. Operation

Unlike Parallel Redundancy Protocol (PRP) [2] that requires a duplication of the entire network to achieve redundancy, HSR only uses a single network. In detail, instead of using another network to create a second physical path from source to destination, HSR mainly uses a ring topology where there are two paths between every pair of nodes. For every frame sent by a node, two duplicated copies are simultaneously injected into the ring through two separate Ethernet ports in both clockwise and counterclockwise directions. Therefore, HSR is theoretically able to provide zero recovery time even when there is either a node or a link failure provided that one path is still functional. Since every node in the ring has the bridge function, there is no dedicated switch in an HSR network.

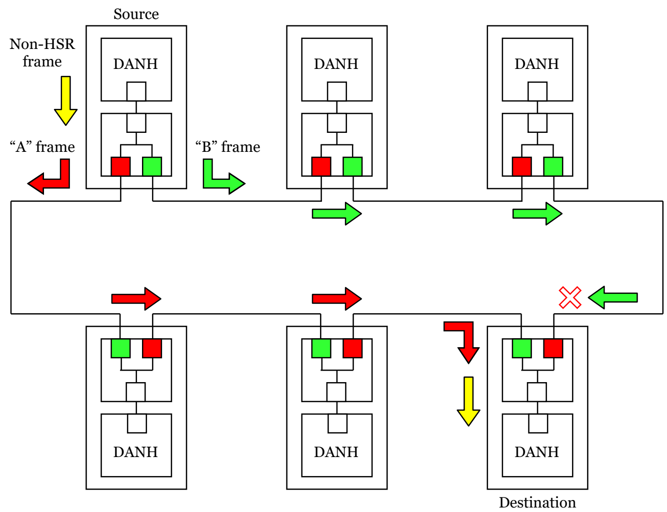

Fig. 1. HSR example of unicast traffic in single-ring topology.

An illustration of HSR operation can be found in Fig. 1. In this example, each node in the network is serially connected to the two neighboring nodes next to it, consequently forming a ring topology. To send a frame, the "Source" node inserts two copies ("A" and "B" frames) of it through two Ethernet ports into the ring. Upon receiving a frame, if a node is neither its source nor its only destination, it forwards the frame to the other port, except that it has already forwarded that frame in the same direction. MeanCOMPARATIVEANALYSISwhile, the "Destination" node of a unicast frame does not forward the frame even if it receives the frame for the first time ("A" frame). Instead, the frame is passed to the upper layer after its HSR tag has been removed. And as the second copy of that frame ("B" frame) arrives at the "Destination" node, it will be simply discarded. In cases of multicast or broadcast, except for the node that injects the frame into the ring, every node will forward the frame.

B. Frame Format

Before a node sends any frames to the HSR network, it has to encapsulate what is passed from the upper layer inside an HSR frame, as depicted in Fig. 2. Compared to the original Ethernet frame, an HSR tag is inserted between the link-layer header (MAC addresses and VLAN tag if used) and the payload. The HSR tag is used to detect duplication and includes four fields:

- "PT" denotes the HSR EtherType and is used to identify an HSR frame;
- "Path" is 4-bit long and reserved for testing purposes;
- "LSDU size" is the size of LSDU;
- "Sequence number" is used for sequencing the frames.

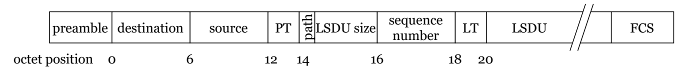

Fig. 2. HSR frame format.

Since a node is responsible for incrementing its sequence number each time it sends a frame, the combination of the source address and a sequence number is used to identify copies of the same frame.

C. Network Components

In Fig. 1, the basic ring topology of an HSR network is constructed by a set of Doubly Attached Nodes with HSR or DANHs and each DANH has two Ethernet ports with the same MAC address. However, higher-level layers in the protocol stack still see the same interface as a single Ethernet port presents. More details regarding the structure of DANH can be found in [4].

For popular devices with traditional Ethernet interfaces offering no support for HSR tag, they must be attached through a RedBox (Redundancy Box). Many devices can connect to a single RedBox to join an HSR network, which makes the structure of a RedBox more complicated than a DANH. Besides, HSR can be extended to multi-ring topology in addition to the single-ring topology. For the connection between rings in the network, a device called QuadBox is introduced. Each QuadBox has four ports and is connected to two HSR rings to prevent a single point of failure [5].

Moreover, the authors in [6] propose a concept of Switch-Box - a switching node with numerous ports and able to perform packet switching in HSR networks. HSR SwitchBoxes have two types of port, namely access and trunk port types. While access ports connect to terminal nodes (e.g., DANHs and RedBox nodes), a trunk port is used for connection between two SwitchBoxes. This enables HSR to be applied to numerous topologies, such as ring, mesh, or star topologies.

D. Challenges

Although HSR might benefit networks with low latency requirements thanks to its redundancy capability, it faces manifold major challenges. For example, as HSR is mainly designed for ring configurations, there are possibly a large number of nodes in every ring. Therefore, the amount of forwarding time in every node must be as short as possible to make sure that latency requirements are satisfied when frames are transmitted through a high hop count. One feasible solution is to make use of Field-Programmable Gate Array (FPGA) circuits to realize hardware implementation of switching functionality in HSR nodes [7], [8]. With the development of technology, more affordable FPGAs are being used inside HSR nodes to achieve minimal forwarding delays.

Another major limitation of HSR is excessive redundant traffic being generated. For instance, network performance is impaired in a typical HSR ring when all frames are duplicated and sent twice even there is no network fault. For that reason, only approximately half of the bandwidth is actually available to applications in terms of multicast traffic. Therefore, several traffic-reduction techniques have been introduced to cut down the amount of unnecessary traffic in the network. For example, quick removing (QR) [9], port locking (PL) [10], and enhanced port locking (EPL) [11] are "traffic filtering-based" techniques; while "predefined path-based" techniques include, for instance, optimal dual paths (ODP) [12] and ring-based dual paths (RDP) [13]. A comprehensive comparison of popular approaches used to reduce traffic in HSR networks can be found in [14].

III. Frame Replication and Elimination for Reliability

IEEE 802.1CB is one of the standards proposed by the Time Sensitive Networking (TSN) group, aiming at making the popular Ethernet-based system robust and reliable for safety-critical traffic. In detail, this standard defines Frame Replication and Elimination for Reliability (FRER) approach. FRER transmits both a frame and its replicated one through multiple paths to overcome the recovery delay of ARQ or RSTP protocols. However, unlike HSR which is mainly used in a ring topology, FRER manages multiple paths between nodes in the network by using a service introduced in IEEE 802.1Qca standard [15].

A. Operation

In an Ethernet network that is compatible with the new set of IEEE 802.1 standards, especially IEEE 802.1CB; in the fault-free state, there must exist at least two separate physical routes between a *talker* (sender) and a *listener* (receiver). Then, each replication of the same frame travels along a different path to the destination node. While the first arriving frame is accepted, the later replicas are discarded. Similar to HSR, the activity of this redundancy functionality is transparent to the upper layers.

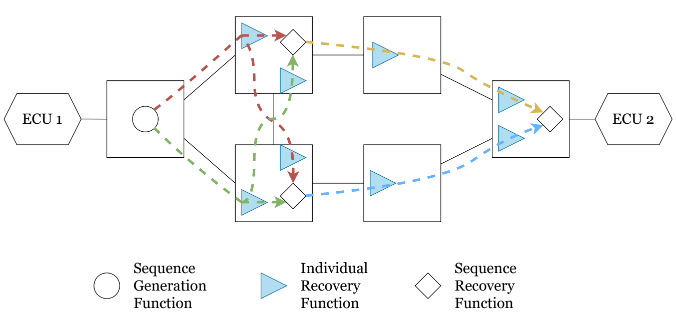

Fig. 3. Example of network with two redundant paths between talker and listener.

Fig. 3 depicts a simple network configured with a redundancy mechanism. In detail, the same *sequence number* is assigned to each replication of the frame sent by node ECU 1, and this task is handled by a *sequence generation function* in the bridge that initially inserts the frame into the network. Subsequently, each of these two copies travels to node ECU 2 via a different route. The bridge connected to node ECU 2, as well as all bridges in the network, implements the replication and elimination mechanism so they are able to identify and discard replicas.

B. Frame elimination

FRER introduces a variety of functions for redundancy operation. In fact, the frame elimination is carried out by both *individual* and *sequence recovery functions* (IRF and SRF respectively). Both IRF and SRF are used to detect and remove duplications of the same frame (copies of a frame with a repeating *sequence number*). Nevertheless, IRF is only applied to single paths while SRF works on a merged set of many paths.

There are two different algorithms for a recovery function (i.e., either IRF or SRF) for duplication detection: *match recovery algorithm* (MRA) and *vector recovery algorithm* (VRA). MRA simply keeps a counter of the last accepted *sequence number* and if the next arriving frames match this value, they will be discarded, otherwise forwarded. In contrast, VRA uses a predefined interval from the most recently seen frame and only accepts frames that are within that interval value.

For duplication identification, the sending node defines a Redundancy Tag inside a link-layer frame, which includes the following fields:

- "EtherType" with the value 0xF1C1;
- "Reserved" reserved for future usage;
- "Sequence Number" as explained above.

The frame format of the Redundancy Tag can be seen Fig. 4.

EtherType (2 bytes)	Reserved (2 bytes)	Sequence Number (2 bytes)

Fig. 4. Frame format of Redundancy Tag.

C. Challenges

Several limitations and challenges of FRER are pointed out in [16]. For instance, as mentioned above, an interval value is used by VRA to accept an incoming frame. If this value is too small, the valid frames that arrive late will be rejected. However, there is no provided instruction in the standard to choose a proper value. Interval value is just one example out of many protocol configurations. Apparently, those advanced settings might be helpful for network engineers to comprehensively maneuver the entire network system. However, it is necessary to employ FRER safely with proper configurations since any misconfigurations could downgrade the system's robustness and reliability [16].

Analogous to HSR, FRER also implements redundancy using physical redundant paths between nodes in the network. Consequently, excessive traffic might be generated for sending replicas of the same frame, the actual bandwidth available to applications is thus limited.

IV. Comparative Analysis of HSR and FRER

In this section, we present a comparative study of HSR and FRER, mostly based on their operation fundamentals. The reason is that this work aims to provide a technical overview when it comes to network construction practice.

Although sharing some similarities in making use of physical redundant paths to achieve seamless redundancy in a network system, HSR and FRER do have several differences. Although both protocols are applicable to a variety of network topologies, the main structure for HSR is a ring or connected rings. Besides, despite HSR being globally standardized as a seamless redundancy standard, both important and non-critical data frames have to be used for the whole network's redundancy capability. Meanwhile, seamless redundancy in FRER can be applied only to specific critical data streams created and managed by IEEE 802.1Qca [17], thus vastly reducing the overhead of administration activities. However, this reliance prevents FRER from being able to operate independently.

While both standards require dedicated network devices to operate, switches compatible with FRER may offer more services such as calculable and guaranteed latencies. This is because FRER is just a part of the TSN standard set, which implements many other functions besides seamless redundancy. For this reason, networking devices supporting TSN standards may be more functional for modern heterogeneous industrial networks.

However, the number of Time Sensitive Networking-Ready Ethernet switches is not large yet and industrial Ethernet organizations are just beginning to adopt TSN technology. Therefore, HSR is still a reliable protocol when it comes to seamless recovery. And as both protocols can make use of FPGA-based architecture, switching performance can be markedly improved. However, FRER together with TSN standard set requires network designers to fully understand its advanced protocol settings to be safely deployed. In conclusion, a summary comparison table between the two standards can be found in Table I.

TABLE I
Comparison between HSR and FRER

	HSR	FRER
Seamless redundancy	Yes	Yes
Support for various network topologies	Yes	Yes
Minimal protocol administation cost	No	Yes
Independent operation	Yes	No
Dedicated switching devices required	Yes	Yes
Expandability for other functions	No	Yes
Hardware support (e.g., FPGA)	Yes	Yes
Proper configuration requirement	No	Yes

V. Conclusion

In this paper, we present a comparative analysis of two standards providing seamless redundancy for industrial networks: IEC 62439-3, Clause 5 (HSR), and IEEE 802.1CB-2017 (FRER). Both approaches utilize redundant physical paths to transmit replicas of the same frame over the network. In the fault-free state of the network, the receiver node should accept the first arriving frame while discarding the later ones. Despite sharing the same operation concept, FRER seems to be more functional and efficient than HSR, especially when it is normally accompanied by other TSN standards.

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