A novel ring-based dual paths approach for reducing redundant traffic in HSR networks

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ARTICLE INFO

ABSTRACT

In this paper, we propose a novel dual paths-based approach, called ring-based dual paths (RDP), to significantly reduce redundant unicast traffic in high-availability seamless redundancy (HSR) networks. RDP establishes dual paths for forwarding unicast frames between nodes in HSR networks. Unlike existing dual paths-based approaches, such as dual virtual paths (DVP) that establish dual paths for each connection pair of HSR terminal nodes, RDP sets up dual paths for each connection pair of HSR rings. Therefore, RDP significantly reduces the number of established dual paths, which, in turn, reduces the overhead in discovering and establishing dual paths, as well as the memory space required to store these paths compared with the existing dual paths-based approaches. The performance of RDP has been analyzed, evaluated, and compared to that of the standard HSR protocol and the DVP approach. Various simulations were conducted to validate the traffic performance analysis. Analytical and simulation results showed that for the sample networks RDP reduced network unicast traffic by 80–88% compared with the standard HSR protocol, thus freeing up network bandwidth and improving network traffic performance.

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1. Introduction

High seamless communication with fault tolerance is one of the key requirements for Ethernet-based, time-critical and mission-critical systems such as substation automation systems (SAS), automation networks and other industrial Ethernet networks. Since the Ethernet standardized by the Institute of Electrical and Electronics Engineers (IEEE) in IEEE 802.3 [1] is not capable of supporting fault-tolerant networks at all, the high availability of Ethernet networks can be increased by using redundancy protocols. Various redundancy protocols for Ethernet have been developed and standardized, such as rapid spanning tree protocol (RSTP) [2], media redundancy protocol (MRP) [3], shortest path bridging (SPB) [4], rapid ring recovery (RRR) [5], time-sensitive network (TSN) [6,7], parallel redundancy protocol (PRP) [8], high-availability seamless redundancy (HSR) [8] and others. RSTP and MRP provide redundancy in networks. Both the RSTP and the MRP have a switchover delay disadvantage: the RSTP suffers from a recovery time ranging from several hundred milliseconds to 2 s [9], whereas the MRP's switchover delay is about a few milliseconds [10]. SPB is the replacement for the older spanning tree protocols. SPB allows all paths to be active with multiple equal cost paths and provides much larger layer 2 topologies. SPB also provides fast connectivity restoration after failure. RRR is an approach for swift failure detection and recovery in Ethernet ring topologies, which can re-converge after a failure within a few hundred microseconds [5]. TSN is a set of standards developed by the Time-Sensitive Networking Task Group (IEEE 802.1) [6]. The TSN is the second generation Audio and Video Bridging (AVB) standards [11] that are being developed to address the requirements of industrial automation and control networks, and automotive in-vehicle networks. The TSN will enable IEEE 802 Ethernet to be used in industrial applications with stringent end-to-end latency and fault-tolerance requirements, replacing vendor specific real-time solutions in many application areas [7]. The TSN is currently being developed. PRP and HSR, which provide end-node redundancy, provide seamless redundancy with zero recovery time. In other words, the PRP and HSR protocols are suitable for seamless communications. Both the HSR and the PRP are based upon the principle of providing duplicated frames for separate physical paths with zero recovery time [8,12]. HSR provides zero-time recovery using a single network, whereas PRP provides zero-time recovery using two independent networks.

HSR was standardized by International Electrotechnical Commission (IEC) as IEC62439-3 Clause 5 [8] and as one of the redundancy protocols selected for substation automation in the IEC61850 standard [13]. HSR is a redundancy protocol for Ethernet. HSR provides zero recovery time in case of failure of one component. HSR is based on the duplication of every frame sent in a ring topology. Each copy of the frame is injected in a different direction of the ring. In the fault-free state of the network, the

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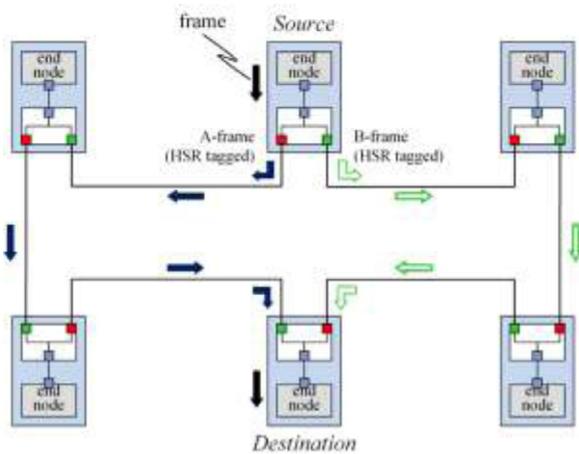
Fig. 1. An HSR example of single-ring topology for unicast traffic.

destination node receives two identical frames, passes the first frame to its upper layers, and discards the duplicate. In the case of failure of one component such as link failure or node failure, only one frame is lost. The application on the destination node operates with the remaining frame undisturbed. Therefore, even in the case of a node or link failure, there is no communication interruption in the network. This feature of the HSR protocol makes it very useful for time- and mission-critical applications, such as substation automation systems and automation networks. The HSR principles are described and discussed in [8,12–15].

The major drawback of HSR is that it generates too much unnecessary, redundant unicast traffic in connected-ring HSR networks. This drawback degrades network performance and may cause congestion and delay.

In this paper, we propose a novel dual paths-based approach, called ring-based dual paths (RDP), to solve that problem in connected-ring HSR networks. RDP forwards unicast frames through two separate predefined paths, called dual paths, instead of duplicating and flooding the traffic as in the standard HSR protocol. Therefore, RDP significantly reduces redundant unicast traffic in connected-ring HSR networks. Additionally, RDP establishes dual paths for connection pairs of HSR rings instead of HSR terminal nodes. Therefore, RDP significantly reduces the number of dual paths established in connected-ring HSR networks, which in turn reduces the overhead required to discover and establish dual paths, as well as the memory space needed to store these dual paths.

The rest of this paper is organized as follows: Section 2 briefly introduces the standard HSR protocol. Related work is described in Section 3. Next, in Section 4, we describe the proposed RDP approach. In Section 5, the performance of RDP is analyzed, evaluated, and compared to that of the standard HSR protocol and the DVP approach. Section 6 describes several simulations and their results to evaluate and validate the traffic performance analysis of RDP. Finally, we provide our conclusions and suggestions for future work in Section 7.

2. Background

2.1. HSR nodes

The HSR protocol defines the following node types [8].

- *Doubly attached node for HSR (DANH)*: A DANH node is an HSR-capable switching end node that has two HSR ports sharing the same MAC address. These two ports form a single interface. The source DANH inserts the HSR tag into the frame received from upper layers, duplicates the frame into two frame copies and sends the two copies over both ports. The destination DANH receives two copies of the same frame, one from each port

- *Redundancy Box (RedBox)*: Singly attached nodes (SAN), such as servers, maintenance laptops or printers cannot be directly connected to an HSR ring, since they have no HSR forwarding capability and do not support the HSR tag. A RedBox is used to connect SANs to the HSR ring. RedBoxes forward the frames over the ring like DANH nodes and act as proxies for all SANs that access them.

- *Quadruple port device (QuadBox)*: QuadBox nodes are used to connect HSR rings together. A QuadBox has four HSR ports that are divided into two pairs connected by an interlink; each pair shares the same MAC. QuadBoxes operate as HSR nodes toward both rings simultaneously. Although one QuadBox is sufficient to conduct the traffic in a fault-free network, two QuadBoxes are used to prevent a single point of failure [8].

2.2. HSR operations

HSR is usually applied for any ring topology, in particular single rings and rings of rings (connected-rings). DANH and RedBox nodes are terminal nodes in HSR rings, whereas QuadBox nodes are intermediate nodes that are used to connect HSR rings.

2.2.1. Single-ring networks

In a single-ring HSR network, HSR uses the two HSR ports of each HSR terminal node such as DANH node to interconnect all HSR nodes to the network, as shown in Fig. 1. There is no QuadBox used in single-ring networks.

The source node sends two copies of the same frame simultaneously through each port in both directions in the ring. The two frame copies travel in opposite directions. If an HSR node receives the frame but is neither its source nor its only destination, the node forwards the frame to its other port, except if it has already forwarded the same frame. The destination node of a unicast frame does not forward a frame for which it is the only destination. Frames forwarded in the ring carry the HSR tag inserted by the source node, which contains a sequence number. The doublet of the source MAC address and the sequence number uniquely identifies copies of the same frame. In the fault-free case of the network, the destination node receives two identical frames, passes the first frame to upper layers and discards the duplicate. If a single fault on the ring occurs, only one of the two frames travelling on the two network paths through the ring will experience a communication interruption. The second frame will still reach the destination node.

2.2.2. Connected-ring networks

To allow more complex network topologies, HSR rings can be connected through the use of QuadBox nodes. A QuadBox node forwards frames over each ring, passing the frames to another ring without changes. Fig. 2 shows an example of a connected-ring network that consists of four pairs of QuadBoxes used to connect four HSR rings.

A source node in HSR ring 1 transmits a unicast frame to a destination node in HSR ring 4. The source node sends two copies of the frame simultaneously through each port in both directions in the source HSR ring. QuadBox nodes receive the frame's copies and forward them to other HSR rings. In the HSR rings except the destination HSR ring, the frame's copies are delivered and doubled. In the destination HSR ring, the destination node receives two identical copies of the frame, passes the first copy to upper layers and discards the duplicate.

2.3. HSR issues

The forwarding rule of the standard HSR protocol is that nodes forward unicast frames from one port to other ports, unless they
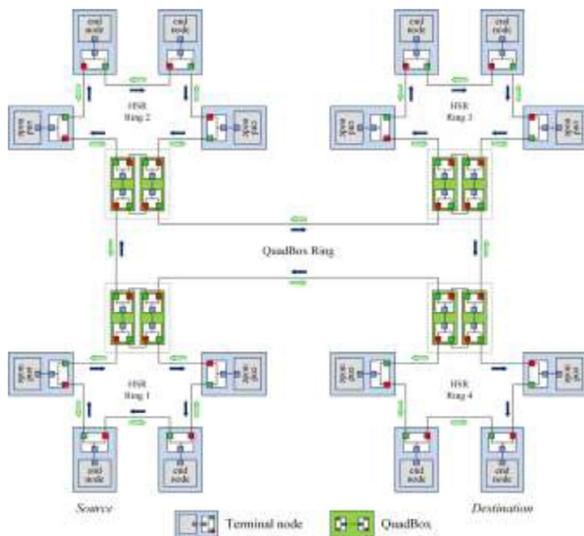
Fig. 2. An HSR example of the connected-ring topology for unicast traffic.

already sent the same frame in that direction. A node will not forward a frame that it injected into the ring [8].

HSR protocol has no issues with unicast frames inside single-ring HSR networks. However, the standard HSR protocol generates too much redundant unicast traffic in connected-ring HSR networks. In a connected-ring network, unicast frames are forwarded and doubled in all rings, except the destination ring, as shown in Fig. 2. In other words, there are two frame copies delivered to each link of all rings in the network, one in each direction, except the destination ring. This problem degrades the network performance and may cause network congestion and delay.

3. Related work

Several approaches have been proposed to reduce unnecessary unicast traffic in connected-ring HSR networks. These approaches can be classified into two categories: traffic filtering-based methods and dual paths-based methods.

Traffic filtering-based methods mainly focus on filtering unicast traffic for rings in HSR networks, and preventing the traffic from circulating in the rings. Nsaif and Rhee [16] proposed an approach called quick removing (QR) to prevent traffic from circulating in the rings of HSR networks. QR removes the redundant frame copies from the network when all nodes have received one copy of the sent frame and begun to receive a redundant copy. Ngo et al. [17] implemented the QR algorithm for HSR components to improve the availability of HSR. Shin and Joe [18] proposed a traffic control (TC) method to remove duplicated and circulated frames from a ring by selecting one of nodes within the ring as the traffic control node. The traffic control node will make decision of discarding duplicated frames. The TC is applied for single rings. Abdulsalam and Rhee [19] proposed a method called port locking (PL) to filter unicast traffic for the Doubly attached node for HSR (DANH) rings of HSR networks. The PL approach identifies the locations of the source and destination nodes for each connection pair, and then prunes the DANH rings that do not contain the destination node by locking the corresponding ports of the related Quadruple port device (QuadBox) node. Hong and Joe [20] introduced a packet transmission scheme with different periods based on a single-ring topology to reduce the HSR network-traffic load. Tien and Rhee [21] proposed a method of filtering HSR traffic (FHT) that filters unicast traffic for not only DANH rings, but also for QuadBox rings. FHT removes duplicated and circulated traffic in the rings. Additionally, Tien and Rhee [22] developed a new

switching node for the HSR protocol, called SwitchBox, which is used in HSR networks to support any network topology and significantly reduce redundant network traffic.

Dual paths-based methods set up two separate paths, called dual paths, for each connection pair of HSR terminal nodes before transmitting traffic in HSR networks. These dual paths are called node-based dual paths. The node-based dual paths are then used to forward unicast frames between each connection pair of nodes, instead of duplicating and forwarding frames to all parts of the networks. Tien, Nsaif, and Rhee [23] proposed an optimal dual paths (ODP) approach that establishes optimal dual paths for each connection pair of terminal nodes in an HSR network, based on the network topology. The dual paths are determined based on the optimal metrics of the links and have no common nodes between them. Nsaif and Rhee [24] proposed a dual virtual paths (DVP) algorithm, which automatically sets up dual paths between each connection pair of terminal nodes to send unicast traffic only, instead of duplicating and forwarding copies at random in all directions. The DVP establishes node-based dual paths by sending control messages from each DANH node to all of the other DANH nodes. However, since these existing dual paths-based methods set up dual paths for each connection pair of terminal nodes, there are too many node-based dual paths to be discovered and established in HSR networks. This drawback results in high overhead for the discovery and construction of paths, as well as requiring large memory space to store these paths.

In this paper, we propose a novel dual paths-based approach, called ring-based dual paths (RDP), to reduce unicast traffic in connected-ring HSR networks. Unlike existing dual paths-based methods, such as ODP [23] and DVP [24], that discover and establish node-based dual paths for each connection pair of HSR terminal nodes, RDP discovers and sets up dual paths for each connection pair of HSR rings. These dual paths are called ring-based dual paths. All nodes in an HSR ring have the same ring-based dual paths to all nodes in another HSR ring. Therefore, RDP significantly reduces the number of dual paths established in connected-ring HSR networks, which in turn reduces the overhead required to discover and establish dual paths, as well as the memory space needed to store these dual paths. Like other dual paths-based approaches, RDP significantly reduces redundant unicast traffic in connected-ring HSR networks and thus improves network performance.

4. The proposed RDP approach

In this section, we describe the proposed RDP approach for reducing unicast traffic and improving network performance in HSR connected-ring networks.

4.1. RDP concepts

4.1.1. Definitions
The purpose of RDP is to establish ring-based dual paths for each connection pair of HSR rings in connected-ring networks. RDP forwards a unicast frame from a source node to a destination node through dual paths pre-established between the source ring and the destination ring.

Definition 1 (HSR ring). An HSR ring is a ring in an HSR connected-ring network that consists of HSR terminal nodes, including DANH and RedBox nodes, and Quad-Box nodes. QuadBox nodes in a connected-ring network are used to connect HSR rings of the network together.

Definition 2 (source ring). The source ring of a unicast frame is an HSR ring that contains the source node of the frame.

Definition 3 (destination ring). The destination ring of a unicast frame is an HSR ring that contains the destination node of the frame.

Definition 4 (QuadBox ring). A QuadBox ring is a ring in an HSR connected-ring network that consists of only QuadBox nodes. In other words, QuadBox rings are used to connect HSR rings in a connected-ring network.

In this paper, the term "ring" refers to an HSR ring. In the RDP approach, the functions of discovering and establishing dual paths are performed only at QuadBox nodes, not terminal nodes. RDP defines two types of QuadBox nodes: access QuadBox nodes and trunk QuadBox nodes.

Definition 5 (access QuadBox node). An access QuadBox is a QuadBox that is connected to at least one HSR ring.

Definition 6 (trunk QuadBox node). A trunk QuadBox is a Quad-Box that is used to connect two QuadBox rings. In other words, trunk QuadBox does not connect to any HSR ring.

Although one QuadBox is sufficient to conduct the traffic in a fault-free network, two paired QuadBox nodes are used to prevent a single point of failure in HSR networks.

Definition 7 (paired QuadBox nodes). Paired QuadBox nodes are two QuadBox nodes that are used in a pair to connect two rings to prevent a single point of failure.

During the discovery and establishment of dual paths between HSR rings, RDP establishes and maintains several tables, including a MAC table, a ring table, and a forwarding table.

Definition 8 (MAC table). A MAC table is established and maintained at each access QuadBox node and contains the MAC addresses of all terminal nodes in the HSR ring of the access QuadBox node.

Definition 9 (ring table). A ring table is established and maintained at each trunk QuadBox node and includes the MAC addresses of all terminal nodes associated with their HSR ring identity (ID).

Definition 10 (forwarding table). A forwarding table is established and maintained at each trunk QuadBox node and contains route entries between HSR rings in a connected-ring network.

4.1.2. Control messages

RDP uses control messages to discover and set up ring-based dual paths between HSR rings.

- *HSR_Supervision frame*: HSR_Supervision is the supervision frame defined by the standard HSR protocol. Each HSR terminal node shall periodically multicast an HSR_Supervision frame over both its ports [8]. Each access QuadBox node learns the MAC addresses of the terminal nodes that connect to its HSR ring and builds its MAC table, based on receiving the HSR_Supervision frames sent by the terminal nodes.
- *Path_Request (PREQ) and Path_Reply (PREP) messages*: PREQ and PREP messages are used to find dual paths between HSR rings and build ring and forwarding tables at each trunk Quad-Box node. PREQ and PREP messages are sent only by access QuadBox nodes. PREQ and PREP messages contain a sequence number to prevent the circulation in HSR networks

4.2. RDP description

The functions of discovering and establishing dual paths between rings are implemented at QuadBox nodes in HSR networks. The mechanisms underlying the RDP approach are shown in Fig. 3.
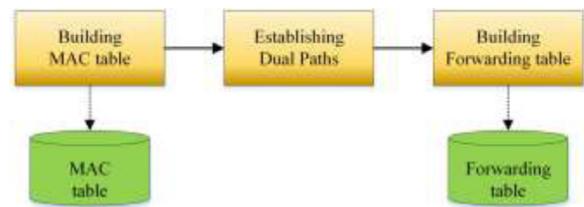
Fig. 3. The process of establishing ring-based dual paths in HSR networks.
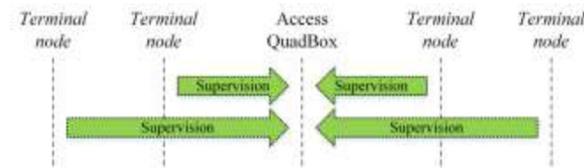
Fig. 4. The process of sending Supervision frames.

RDP first builds a MAC table for each access QuadBox node, then discovers and establishes dual paths for each connection pair of HSR rings, and, finally, sets up ring-based dual paths by building a forwarding table for each trunk QuadBox node. The dual paths are then used to forward unicast frames from a source node to a destination node in a network instead of flooding the frames in the network as in the standard HSR protocol.

4.2.1. Building the MAC table

Each access QuadBox node learns the MAC addresses of the HSR terminal nodes connected to the QuadBox's HSR ring based on the HSR_Supervision frames sent by the terminal nodes. Each HSR terminal node multicasts an HSR_Supervision frame over both ports at every LifeCheckInterval [8], as shown in Fig. 4. When an access QuadBox node receives an HSR_Supervision frame sent by a terminal node, the access QuadBox node checks whether its MAC table contains the source MAC address of the HSR_Supervision frame. If not, the access QuadBox node adds the source MAC address into its MAC table. If so, the QuadBox node updates the corresponding entry of the source MAC address.

By learning the MAC addresses of terminal nodes, each access QuadBox builds its MAC table that contains MAC addresses of all the terminal nodes connected to the access QuadBox's HSR ring. Based on the MAC table, an access QuadBox node will not forward an HSR unicast traffic frame into its HSR ring if the ring does not contain the destination node of the frame.

RDP also uses the LifeCheckInterval to monitor the reachability of the connected HSR terminal nodes. If an access QuadBox node no longer receives an HSR_Supervision frame from a connected HSR terminal node, then the access QuadBox node considers the HSR terminal node to have failed and removes it from the MAC table.

By default, each HSR terminal node sends an HSR_Supervision frame over both ports every 2 seconds. The interval can be adjusted by the network operators. However, adjusting the supervision frame interval affects RDP operations. If the interval is long, the update process for the MAC table will slow, resulting in RDP malfunction. For example, if the LifeCheckInterval is set to 300 seconds, when an HSR terminal node disconnects from an access QuadBox node and it has not updated its MAC table due to the long interval, the access QuadBox node will continue forwarding unicast frames sent to the HSR terminal node over the corresponding port. Additionally, if an HSR terminal node connects to an access QuadBox node and it has not updated its MAC table, the access QuadBox node will flood unicast frames sent to the HSR terminal node instead of forwarding to the connected port. To optimize the MAC table update, network operators could reduce
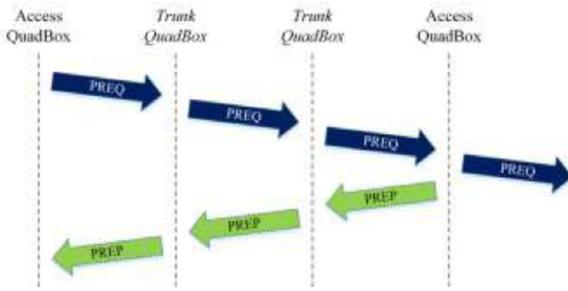
Fig. 5. The process of the two-way handshake.

the interval, which leads to insignificant additional overhead in return for shorter update times.

4.2.2. Establishing ring-based dual paths

The functions of discovering and establishing dual paths between rings are performed at access QuadBoxes through a two-way handshake process, path request and path reply, as shown in Fig. 5.

4.2.2.1. Path request
To discover and establish ring-based dual paths for each connection pair of HSR rings, each access QuadBox node sends a path request to all of the other access QuadBox nodes by broadcasting a PREQ message. The PREQ message contains the following information:

- *Sequence number*: the sequence number of the message.
- *Source ring ID*: the ID of the sending QuadBox's ring.
- *MAC list*: the list of MAC addresses contained in the sending QuadBox's MAC table.
- *Node list*: the list of QuadBox nodes' ID through which the PREQ message has been passed.

When a trunk QuadBox node receives a PREQ message, the trunk QuadBox node updates its ring table based on the MAC list of the PREQ message. A ring table's entry consists of a MAC address of a terminal node and a ring ID of an HSR ring to which the terminal node is being connected. After updating the ring table, the trunk QuadBox node adds its node ID to the node list of the PREQ message and then sends the updated PREQ messages over all of its ports, except the received port.

When an access QuadBox node receives a PREQ message, the access QuadBox node replies to the path request by sending a path reply (PREP) message, and then adds its node ID to the node list of the PREQ message and forwards the updated PREQ messages to another QuadBox node.

4.2.2.2. Path reply
When an access QuadBox node has received a PREQ message sent by another access QuadBox node for the first time, the access QuadBox node builds a path between the sending and receiving access QuadBox nodes, based on the node list of the PREQ message. The path is also a ring-based path between the source ring to which the sending QuadBox is connecting and the destination ring to which the receiving QuadBox is connecting. The receiving QuadBox then responds to the path request by sending a PREP message to the sending QuadBox. The PREP message is generated based on information in the received PREQ message. The ring-based path is built from the node list of the received PREQ message. The PREP message contains the following information:

- *Sequence number*: the sequence number.
- *Source ring ID*: the ring ID of the source ring.
- *Destination ring ID*: the ring ID of the destination ring.

- *Path*: the ring-based path between the source and destination rings built based on the node list of the received PREQ message.

To reduce path setup overhead for each connection pair of HSR rings, only the access QuadBox node that is connected to the HSR ring with a lower ring ID sends the PREP message.

4.2.3. Building the forwarding table.
Based on received PREQ and PREP messages, trunk QuadBox nodes in between ring-based paths build their forwarding table. Each entry of the forwarding table consists of a source ring, a destination ring, and an output port. When a trunk QuadBox node receives a PREQ of an access QuadBox node, the trunk QuadBox node notes the received port associated with the source ring ID of the PREQ message. When a trunk QuadBox receives a PREP message, the trunk QuadBox node immediately adds the following two route entries to its forwarding table:

- One entry consists of the source ring that is the source ring ID of the PREP message, the destination that is the destination ID of the PREP message, and the output port that is the port that trunk QuadBox noted when it received the corresponding PREQ message.
- The other entry consists of the source ring that is the destination ring ID of the PREP message, the destination that is the source ID of the PREP message, and the output port that is the port on which the PREP message is received.

Since two paired access QuadBox nodes connect to each HSR ring, there are two ring-based paths, called ring-based dual paths, established for each connection pair of HSR rings.

4.2.4. Single point of failure and synchronization problems
To avoid a single point of failure in HSR networks, the ring-based dual paths for each connection pair of HSR rings must not have any common nodes. RDP performs the following procedure to solve the single point of failure problem as well as synchronize dual paths between paired QuadBoxes.

When one of two paired QuadBox nodes connected to a DANH ring receives the first PREQ message, the discovered ring-based path is the fastest ring-based path between the source ring and the destination ring. This path is set to the first path. The access QuadBox that found the first path sends a PREP message to set up the path and then shares the path with its paired QuadBox node. When the paired QuadBox receives a PREQ message for the same source ring ID, the paired QuadBox checks if its path has any common nodes with its paired node's path. If not, that means the dual paths have no common nodes, and the paired QuadBox node then sends a PREP to set up the second path. If so, the paired QuadBox then sends a PREQ message associated with the first path to discover and set up the second path that has no common nodes with the first path. Any QuadBox nodes receiving the PREQ message will discard the PREQ message if they see their node ID in the first path, and forward the message otherwise.

4.3. RDP forwarding principle

Fig. 6 shows the RDP process of forwarding a unicast frame from node 1 - ring 1 to node 10 - ring 3 in a connected-ring HSR network.

In this case, RDP discovered and established ring-based dual paths without any common nodes for the connection pair of HSR rings 1 and 3. The dual path consists of the following two paths:

- *The first path*: QuadBox 2 - QuadBox 3 - QuadBox 4 - QuadBox 17 - QuadBox 5.
- *The second path*: QuadBox 1 - QuadBox 16 - QuadBox 15 - QuadBox 18 - QuadBox 14 - QuadBox 13 - QuadBox 20 - QuadBox 19 - QuadBox 6.
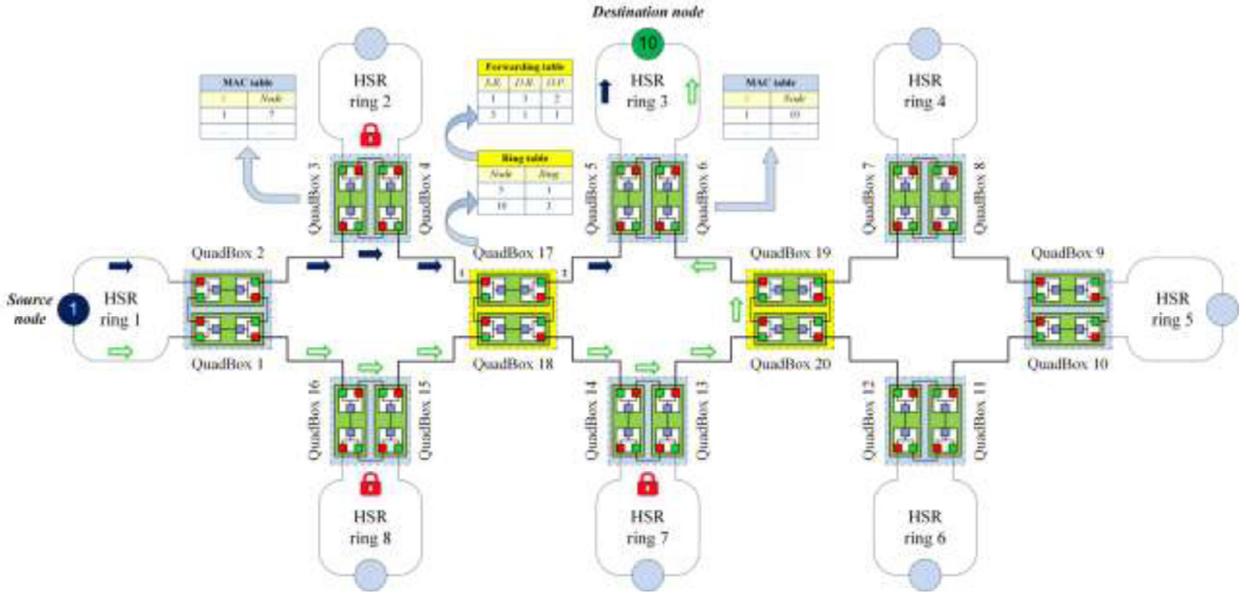
Fig. 6. The process of forwarding a unicast frame using the RDP approach.

The source node 1 sends two copies of the frame simultaneously through each port in both directions in HSR ring 1. Access QuadBox 2 passes the frame to QuadBox 3. Access QuadBox 3 looks up its MAC table and does not forward the frame to HSR ring 2 since this DANH ring does not contain the destination node of the frame. Access QuadBox 3 then forwards the frame to access QuadBox 4. Access QuadBox 4 forwards the frame to trunk QuadBox 17. Trunk QuadBox 17 looks up its ring table and forwarding table to find a route entry that matches the connection pair of the two HSR rings and then forwards the frame to access QuadBox 5 through the output port 2. Finally, by looking up the MAC table, QuadBox 5 forwards the frame into its ring 3 because its MAC table contains destination node 10 of the frame.

Similarly, QuadBox 1 receives a copy of the frame sent by source node 1 and forwards it to destination node 10 through the second ring-based path. Destination node 10 receives two copies of the frame from both directions of HSR ring 3, passes the first frame to its upper layers, and discards the duplicate.

4.4. Monitoring and repairing path failures

As soon as access QuadBox nodes complete the establishment of dual paths, they start monitoring status of the dual paths continuously by sending Path_Check (PCHK) messages periodically, every path_check interval. A PCHK message contains ring IDs of the source and destination rings and is forwarded through dual paths established between the source and destination rings.

If an access QuadBox node ceases to receive a PCHK message of a ring through a path in three subsequent path_check intervals, it is certain that the problem is contained on the path.

When an access QuadBox detects a path failure, the QuadBox and its paired QuadBox will re-establish dual paths for the corresponding ring by sending PREQ messages for the ring.

5. Performance analysis

This section first describes overhead performance analysis of RDP compared with the DVP approach, and then describes traffic performance analysis of RDP compared with standard HSR protocol and the DVP approach.

We consider a sample HSR network consisting of eight HSR rings, as shown in Fig. 7. Each HSR ring includes four HSR terminal nodes and two paired QuadBox nodes.

5.1. Control overhead performance

In this section, we analyze and evaluate the control overhead for discovering and setting up dual paths with DVP and RDP. Both RDP and DVP use control messages to discover and establish dual paths in HSR networks.

In this paper, the number of dual paths is used to analyze and evaluate the overhead performance. The number of dual paths in an HSR network is the total number of dual paths that must be discovered and set up in the HSR network. The large number of dual paths results in high control overhead during the discovery and establishment of dual paths, as well as requiring significant memory space to store the route entries of these dual paths.

We consider the case in which dual paths are established between nodes in ring 1 and nodes in 3 of the sample network in Fig. 7. DVP discovers and establishes node-based dual paths for each connection pair of HSR terminal nodes. There is one connection pair between each node in ring 1 and each node in ring 3. Therefore, there are a total of 16 connections pairs of nodes between ring 1 and ring 3, as shown in Fig. 8a. RDP discovers and establishes ring-based dual paths for each connection pair of HSR rings. Therefore, there is only one connection pair between nodes in ring 1 and nodes in ring 3, as shown in Fig. 8b.

5.1.1. Under the DVP approach

The DVP approach discovers and establishes dual paths for each connection pair of HSR terminal nodes.

Let n be the number of HSR rings and m be the number of terminal nodes per a ring in an HSR network.

The number of terminal nodes in the HSR network, denoted by N_{tnode}, is calculated as follows:

$$N_{tnode} = nm \tag{1}$$

The number of connection pairs between the terminal nodes, denoted by N_{dvp}^{cp}, can be determined as follows:

$$N_{dvp}^{cp} = \frac{N_{tnode} \times (N_{tnode} - 1)}{2} = \frac{nm(nm - 1)}{2} \tag{2}$$
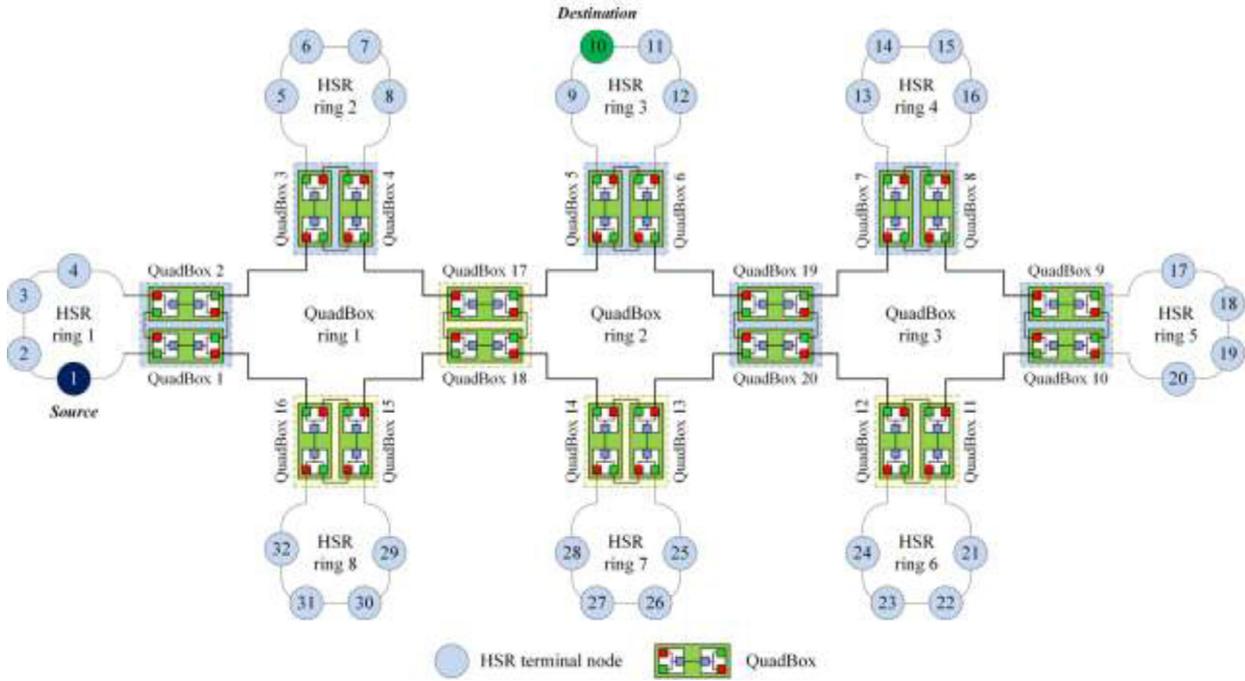
Fig. 7. A sample connected-ring HSR network with eight HSR rings.
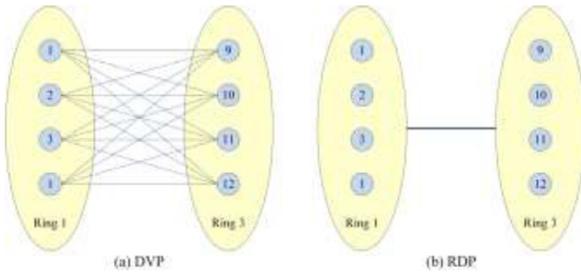
Fig. 8. Number of connection pairs between rings 1 and 3.

The number of node-based dual paths under the DVP approach in the HSR network, denoted by N_{dvp}^{dp}, is determined as follows:

$$N_{dvp}^{dp} = 2 \times N_{dvp}^{cp} = nm(nm - 1) \tag{3}$$

For the sample network with eight rings in Fig. 7, the total number of dual paths is $N_{dvp}^{dp} = 992$ paths.

5.1.2. Under the RDP approach

Unlike the DVP approach that discovers and establishes dual paths for each connection pair of HSR terminal nodes, the RDP discovers and establishes dual paths for each connection pair of HSR rings.

The number of connection pairs between n rings, denoted by N_{rdp}^{cp}, can be calculated as follows:

$$N_{rdp}^{cp} = \frac{n(n - 1)}{2} \tag{4}$$

The number of ring-based dual paths under the RDP in the HSR network, denoted by N_{rdp}^{dp}, is determined as follows:

$$N_{rdp}^{dp} = 2 \times N_{rdp}^{cp} = n(n - 1) \tag{5}$$

For the sample network in Fig. 7, the total number of dual paths is $N_{rdp}^{dp} = 56$ paths.

The analytical results show that the RDP has about m^2 times less the number of dual paths than the DVP approach, where m is the number of HSR terminal nodes in a ring.
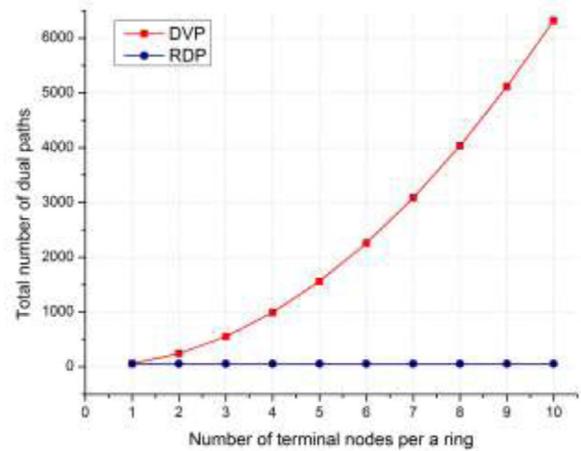
Fig. 9. Comparison of overhead performance between DVP and RDP.

Table 1
Number of dual paths.

Number of terminal nodes per a ring	DVP	RDP
1	56	56
2	240	56
3	552	56
4	992	56
5	1560	56
6	2256	56
7	3080	56
8	4032	56
9	5112	56
10	6320	56

Table 1 and Fig. 9 show a comparison of the total number of dual paths for RDP, compared with the DVP approach for the sample network with eight rings shown in Fig. 7.

Additionally, unlike the DVP under which each terminal node broadcasts an announcement frame (Ann. frame) in order to learn MAC addresses and build a neighbor table, the RDP learns
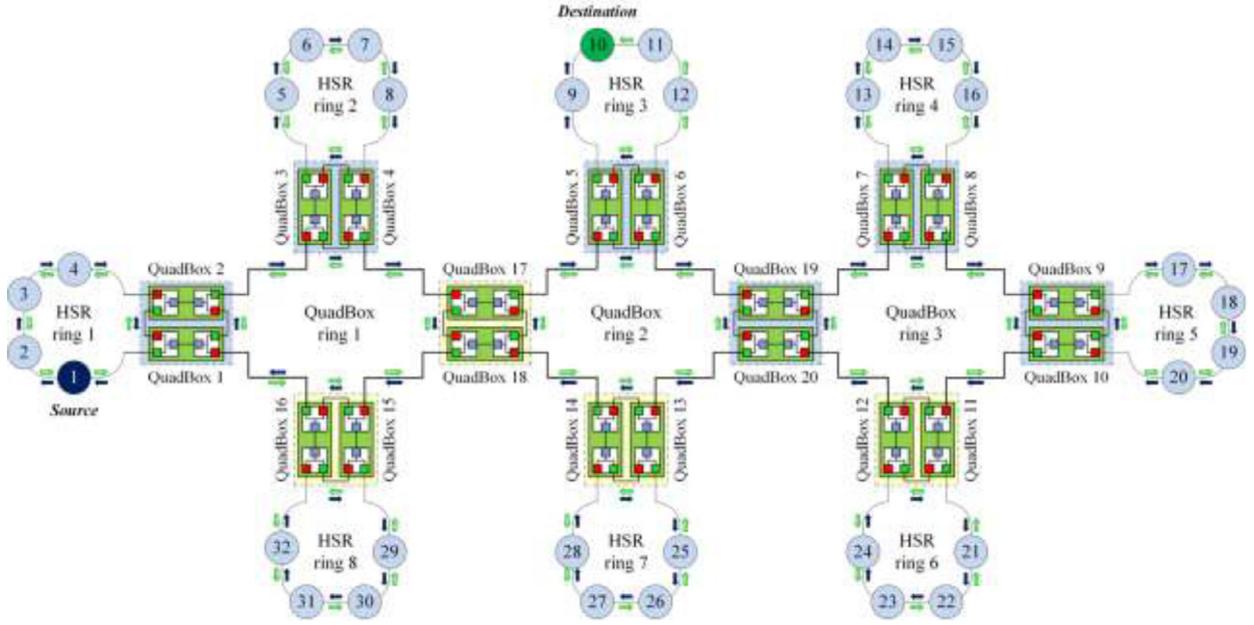
Fig. 10. The process of forwarding a unicast frame in the sample network under the standard HSR protocol.

and builds the MAC table based on the existing HSR_Supervision frames sent periodically by the terminal nodes. In other words, the RDP learns and builds the MAC table without sending additional control frames. Therefore, the RDP significantly reduces control overhead compared with the DVP approach.

5.2. Traffic performance analysis

This section describes the traffic performance analysis of RDP compared to the standard HSR and the DVP approach.

To analyze and evaluate traffic performance, network unicast traffic was chosen as a performance metric. Network unicast traffic in an HSR network is defined as the total number of unicast frame copies that are delivered on links and received by nodes when a source node sends unicast frames to a destination node in the network. In this paper, "network traffic" refers to network unicast traffic.

We consider a sample network consisting of eight rings; each ring includes four terminal nodes, as shown in Fig. 7. Source node 1 in ring 1 sends unicast frames to destination node 10 in ring 3.

5.2.1. Under the standard HSR protocol

When source node 1 sends a unicast frame to destination node 10, standard HSR protocol forwards and duplicates the frame in all rings, except the destination DANH ring; two copies of the frame are delivered on each link, one in each direction. The destination DANH ring does not circulate and double the frame since the destination node does not forward the frame.

Fig. 10 shows the process of forwarding a unicast frame from the source node to the destination node under standard HSR protocol.

Clearly, if a frame is duplicated and doubled in a ring, the number of copies of the frame delivered in the ring is equal to twice the total number of links in the ring. Otherwise, the number of frame copies is equal to the total number of links in the ring.

Network unicast traffic when the source node sends a unicast frame to the destination node under standard HSR protocol,

denoted by nt_{hsr}^1, is calculated as follows:

$$nt_{hsr}^1 = n_{link}^D + \sum_{i \in TR^{-D}} 2n_{link}^i + \sum_{i \in QR} 2n_{link}^i \qquad (6)$$

where n_{link}^D is the number of links in the destination ring, n_{link}^i is the number of links in the ith ring, TR^{-D} is a set of all HSR rings except the destination ring, and QR is a set of all QuadBox rings.

$$\sum_{i \in TR^{-D}} 2n_{link}^i = \sum_{i \in TR} 2n_{link}^i - 2n_{link}^D \qquad (7)$$

where TR is a set of all HSR rings.

$$\sum_{i \in TR} 2n_{link}^i + \sum_{i \in QR} 2n_{link}^i = 2n_{link} \qquad (8)$$

where n_{link} is the total number of links in the HSR network.

Therefore, nt_{hsr}^1 can be re-calculated as follows:

$$nt_{hsr}^1 = 2n_{link} - n_{link}^D \qquad (9)$$

The following equation can be used to determine network unicast traffic under standard HSR protocol when a source node sends N unicast frames to a destination node:

$$nt_{hsr} = N\left(2n_{link} - n_{link}^D\right) \qquad (10)$$

For the sample network in Fig. 7, network unicast traffic when the source node sends N unicast frames to the destination node is $nt_{hsr} = 138N$ frames.

5.2.2. Under the DVP approach

Based on connection pairs of HSR terminal nodes, DVP discovers and establishes node-based dual paths. The node-based dual paths for the connection pair between two nodes 1 and 10, established by DVP are as follows:

- *Node-based path 1*: Node 2 - Node 3 - Node 4 - QuadBox 2 - QuadBox 3 - QuadBox 4 - QuadBox 17 - QuadBox 5 - Node 9.
- *Node-based path 2*: QuadBox 1 - QuadBox 16 - QuadBox 15 - QuadBox 18 - QuadBox 14 - QuadBox 13 - QuadBox 20 - QuadBox 19 - QuadBox 6 - Node 12 - Node 11.

Intuitively, the node-based dual paths are the end-to-end dual paths between the two nodes. When source node 1 sends a
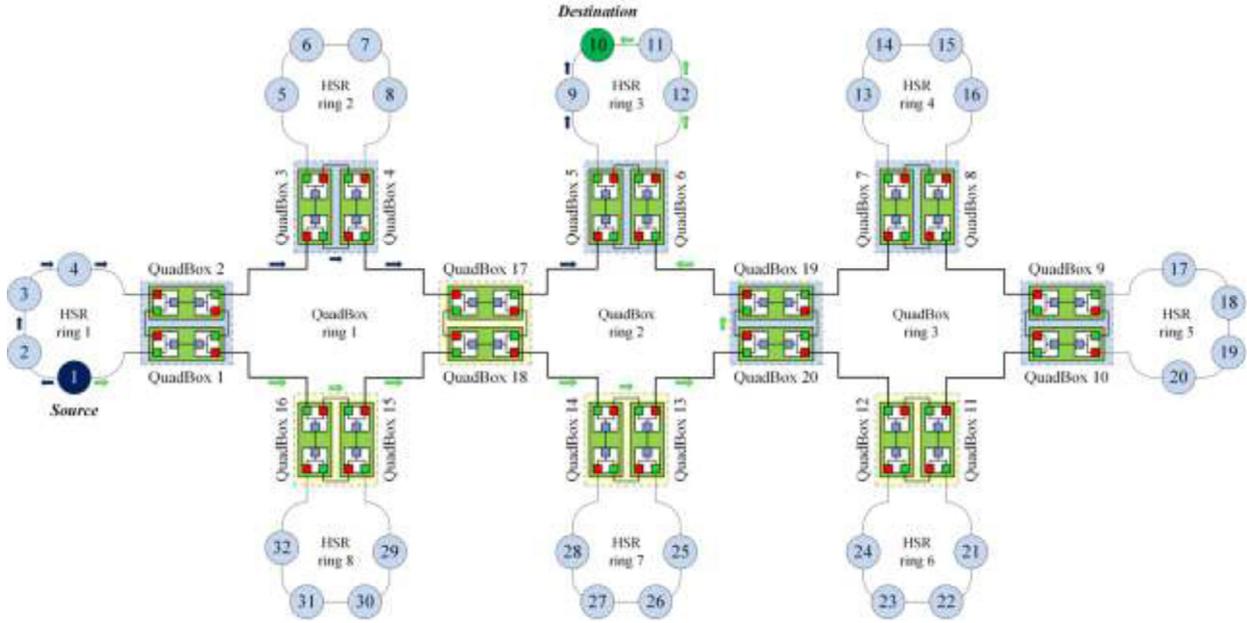
Fig. 11. The process of forwarding a unicast frame in the sample network under the DVP and RDP approaches.

unicast frame to destination node 10, the DVP approach forwards the frame from the source node to the destination node through the node-based dual paths predefined for the connection pair of the two source and destination nodes.

Fig. 11 shows the process of forwarding a unicast frame from the source node to the destination node under the DVP approach.

Network unicast traffic when the source node sends a unicast frame to the destination node under the DVP approach, denoted by nt_{dvp}^1, is calculated as follows:

$$nt_{dvp}^1 = n_{link}^{p1} + n_{link}^{p2} \tag{11}$$

where n_{link}^{p1} and n_{link}^{p2} are the number of links in the first and second end-to-end paths between the source and destination nodes, respectively.

The following equation can be used to determine network unicast traffic under the DVP approach when a source node sends N unicast frames to a destination node:

$$nt_{dvp} = N\left(n_{link}^{p1} + n_{link}^{p2}\right) \tag{12}$$

For the sample network in Fig. 7, $n_{link}^{p1} = 10$, $n_{link}^{p2} = 12$, therefore network unicast traffic when the source node sends N unicast frames to the destination node under the DVP approach is $nt_{dvp} = 22N$ frames.

5.2.3. Under the RDP approach

Based on connection pairs of HSR rings, RDP discovers and establishes ring-based dual paths. The ring-based dual paths for the connection pair between two rings 1 and 3 established by RDP are as follows.

- *Ring-based path 1*: QuadBox 2 - QuadBox 3 - QuadBox 4 - QuadBox 17 - QuadBox 5.
- *Ring-based path 2*: QuadBox 1 - QuadBox 16 - QuadBox 15 - QuadBox 18 - QuadBox 14 - QuadBox 13 - QuadBox 20 - QuadBox 19 - QuadBox 6.

All nodes in ring 1 have the same ring-based dual paths to all nodes in ring 3. However, the ring-based dual paths are not end-to-end paths. End-to-end paths between two nodes consist of the ring-based dual paths and links in the source ring and the destination ring. The end-to-end paths between two nodes 1 and 10 are as follows:

- *End-to-end path 1*: Node 2 - Node 3 - Node 4 - QuadBox 2 - QuadBox 3 - QuadBox 4 - QuadBox 17 - QuadBox 5 - Node 9.
- *End-to-end path 2*: QuadBox 1 - QuadBox 16 - QuadBox 15 - QuadBox 18 - QuadBox 14 - QuadBox 13 - QuadBox 20 - QuadBox 19 - QuadBox 6 - Node 12 - Node 11.

The RDP end-to-end paths are the same as DVP. When source node 1 sends a unicast frame to destination node 10, RDP forwards the frame from the source node to the destination node through ring-based dual paths pre-established for the connection pair of the two corresponding rings: ring 1 and ring 3. Fig. 11 shows the process of forwarding a unicast frame from the source node to the destination node under the RDP approach.

Network unicast traffic when the source node sends a unicast frame to the destination node under the RDP approach, denoted by nt_{rdp}^1, is calculated as follows:

$$nt_{rdp}^1 = n_{link}^{p1} + n_{link}^{p2} \tag{13}$$

where n_{link}^{p1} and n_{link}^{p2} are the number of links in the first and second end-to-end paths, respectively.

The following equation can be used to determine network unicast traffic under the RDP approach when a source node sends N unicast frames to a destination node:

$$nt_{rdp} = N\left(n_{link}^{p1} + n_{link}^{p2}\right) \tag{14}$$

For the sample network in Fig. 7, $n_{link}^{p1} = 10$, $n_{link}^{p2} = 12$, therefore network unicast traffic when the source node sends N unicast frames to the destination node under the RDP is $nt_{rdp} = 22N$ frames.

Clearly, network traffic of the RDP is the same as that of the DVP. The RDP and DVP significantly reduce redundant unicast traffic compared with the standard HSR protocol.

6. Simulations

To validate the analyzed performance and evaluate network performance of the proposed RDP, various simulations were carried out using the OMNeT++ simulation tool [25].
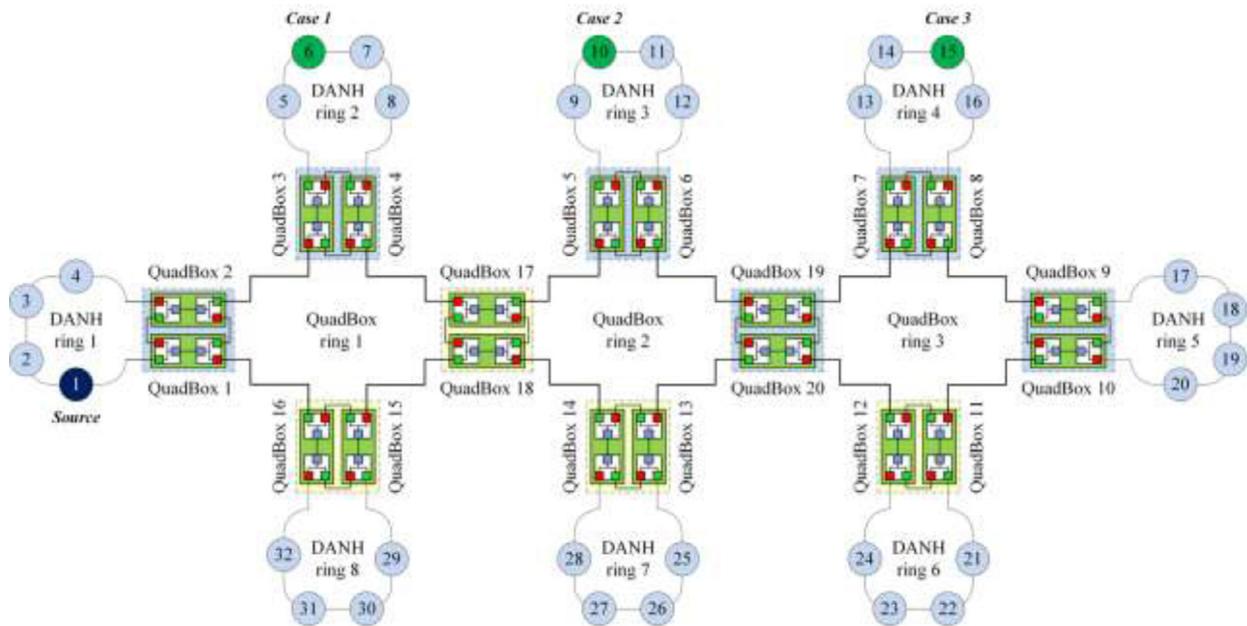
Fig. 12. The simulation network used in three simulation cases.

Table 2
Network traffic frames in Case 1.

Number of sent frames	Case 1		
	HSR	DVP	RDP
10	1390	160	160
20	2780	320	320
30	4170	480	480
40	5560	640	640
50	6950	800	800
60	8340	960	960
70	9730	1120	1120
80	11,120	1280	1280
90	12,510	1440	1440
100	13,900	1600	1600

Fig. 13. Comparison of network traffic performance in Case 1.

6.1. Simulation description

We conducted several simulations to evaluate our RDP approach. The objective of the simulations was to evaluate and compare the traffic performance of RDP to that of standard HSR protocol and the DVP approach. We considered the sample HSR network, consisting of eight HSR rings and three QuadBox rings, as shown in Fig. 7. Each HSR ring included four HSR terminal nodes and two paired QuadBox nodes.

Simulations were conducted for the following three cases as shown in Fig. 12:

- *Case 1*: Source node 1 in ring 1 sends unicast frames to destination 6 in ring 2. In that case, the source and destination rings connect to the same QuadBox ring.
- *Case 2*: Source node 1 in ring 1 sends unicast frames to destination 10 in ring 3. In that case, the source and destination rings connect to different QuadBox rings.
- *Case 3*: Source node 1 in ring 1 sends unicast frames to destination node 15 in ring 4. The distance between the source and destination nodes in that case is greater than the distance in Case 2.

6.2. Simulation results

Table 2 shows network unicast traffic recorded from simulations in Case 1 under standard HSR protocol, the DVP approach, and the RDP approach. As analyzed in Section 5, the network traffic of RDP is the same as that of DVP. Fig. 13 shows comparisons of analytical and simulated traffic performance, respectively for the RDP approach, the standard HSR protocol, and the DVP approach in Case 1. In this case, the analytical and simulation results show that RDP and DVP approaches reduce network unicast traffic by up to 88% compared with standard HSR protocol.

Table 3 shows network unicast traffic recorded from simulations in Case 2 under standard HSR protocol, the DVP approach, and the RDP approach. As analyzed in Section 5, the network traffic of RDP is the same as that of DVP. Fig. 14 shows comparisons of analytical and simulated traffic performance, respectively for the RDP approach, the standard HSR protocol, and the DVP approach in Case 2. In this case, the analytical and simulation results show that RDP and DVP approaches reduce network unicast traffic by about 84% compared with standard HSR protocol.

Table 4 shows network unicast traffic recorded from simulations in Case 3 under standard HSR protocol, the DVP approach, and the RDP approach. As analyzed in Section 5, the network traffic of RDP is the same as that of DVP. Fig. 15 shows comparisons of

Table 3
Network traffic frames in Case 2.

Number of sent frames	Case 1		
	HSR	DVP	RDP
10	1390	220	220
20	2780	440	440
30	4170	660	660
40	5560	880	880
50	6950	1100	1100
60	8340	1320	1320
70	9730	1540	1540
80	11,120	1760	1760
90	12,510	1980	1980
100	13,900	2200	2200

Table 4
Network traffic frames in Case 3.

Number of sent frames	Case 1		
	HSR	DVP	RDP
10	1390	280	280
20	2780	560	560
30	4170	840	840
40	5560	1120	1120
50	6950	1400	1400
60	8340	1680	1680
70	9730	1960	1960
80	11,120	2240	2240
90	12,510	2520	2520
100	13,900	2800	2800
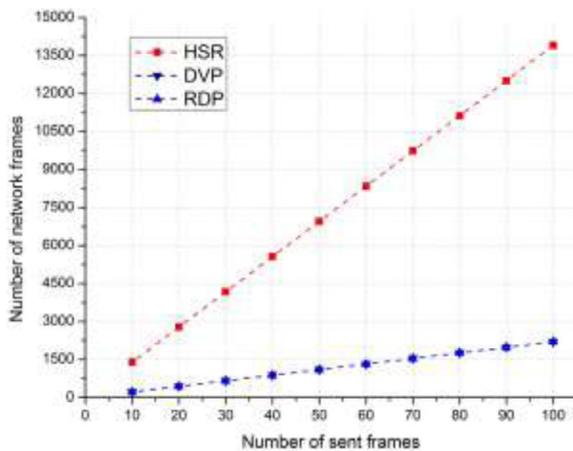
Fig. 14. Comparison of network traffic performance in Case 2.
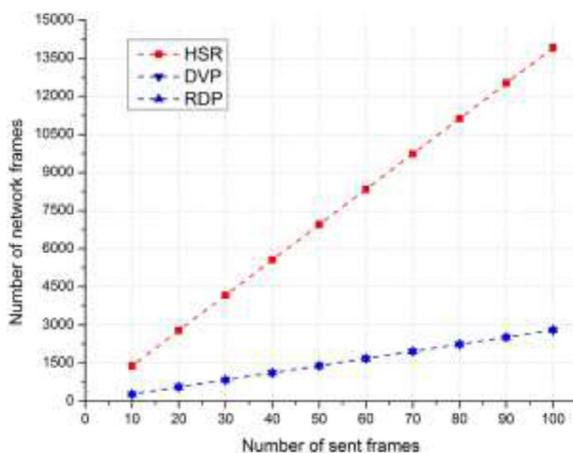
Fig. 15. Comparison of network traffic performance in Case 3.

analytical and simulated traffic performance, respectively for the RDP approach, the standard HSR protocol, and the DVP approach in Case 3. In this case, the analytical and simulation results show that RDP and DVP approaches reduce network unicast traffic by about 80% compared with standard HSR protocol.

6.3. Discussion

The simulation results demonstrate that the traffic performance of the proposed RDP approach and the DVP approach is the same. In addition, the traffic performance of the RDP and DVP approaches is much better than that of the standard HSR protocol. Unlike the standard HSR protocol, which duplicates and forwards unicast frames to all parts of HSR networks, the RDP approach forwards unicast traffic from the source node to the destination node through pre-defined dual paths. Therefore, RDP significantly reduces HSR unicast network traffic compared with the standard HSR protocol. Numerically, for the sample HSR network, RDP reduces unicast network traffic by 80–88% compared with the standard HSR protocol.

Additionally, RDP discovers and establishes dual paths for each connection pair of HSR terminal rings instead of the HSR terminal nodes. The analyzed and simulated results showed that the number of dual paths decreases hyperbolically compared with that of the DVP approach by increasing the number of HSR terminal nodes in an HSR terminal ring. Therefore, the proposed RDP approach significantly reduces the number of dual paths in HSR networks compared with the DVP approach, which, in turn, reduces the overhead required to discover and establish dual paths, as well as the memory space needed to store the dual paths.

However, because RDP uses control messages to discover and build dual paths, this approach requires additional control overhead to set up dual paths in HSR networks.

7. Conclusions

In this paper, we proposed a novel approach called RDP for reducing network unicast traffic in HSR networks. Unlike DVP, which establishes node-based dual paths for each connection pair of HSR terminal nodes, our RDP approach discovers and sets up ring-based dual paths for each connection pair of HSR rings. Additionally, unlike the DVP under which each terminal node broadcasts an additional frame to learn MAC addresses and build neighbor tables, the RDP learns and builds MAC tables based on the existing HSR_Supervision frames of the standard HSR protocol sent periodically by HSR terminal nodes. Therefore, RDP significantly reduces the control overhead for discovering and establishing dual paths, as well as the memory space required to store these dual paths in networks compared to existing dual paths-based methods, such as DVP.

RDP forwards unicast frames based on predefined dual paths, instead of duplicating and forwarding to all parts of HSR networks. Therefore, RDP significantly reduces unicast traffic compared with standard HSR protocol. Analytical and simulation results showed that, for our sample network, RDP reduced network unicast traffic by 80%−88% compared with the standard HSR protocol, thus saving network bandwidth and improving network traffic performance.

Our future work will involve developing and applying the RDP approach for all network traffic types: unicast as well as multi-broadcast.

Acknowledgment

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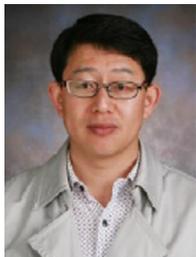
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