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Developing the Minimizing Re-Transmissions (MRT) Technique for Broadcasting in Wired Networks

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Abstract

Broadcasting is the simplest way to send a message from one node to all the other nodes in a network. Simple flooding is the simplest form of broadcasting that provides important control, route discovery, and network information update functionality for unicast and multicast protocols. However, simple flooding generates too many broadcast message duplications in networks. The Minimizing Re-Transmissions (MRT) approach has been developed to reduce broadcast duplication in ad hoc wireless networks by minimizing the number of retransmitting nodes based on the network topology information. While MRT is one of the most efficient broadcasting techniques for ad hoc wireless networks, when MRT is applied for wired networks, it still generates broadcast duplication in the networks. In this paper, we develop a variant of MRT for wired networks called MRT for wired networks (wMRT) to completely remove broadcast duplication in wired networks. In addition to minimizing the number of retransmitting nodes, wMRT also minimizes the number of retransmitting ports of each node in wired networks. This results in no broadcast duplication in wired networks. The traffic performance of wMRT is analyzed, evaluated, and compared to that of the simple flooding and MRT techniques. Simulations are conducted using the OMNeT++ simulation tool in order to validate the traffic performance analysis. The analyzed and simulated results show that the wMRT completely removes broadcast duplication in wired networks, thus saving a significant amount of network bandwidth, as well as improving network traffic performance.

***Keywords**: minimizing retransmissions (MRT), MRT for wired networks, efficient broadcasting, efficient flooding*

1. Introduction

Broadcasting is the process of sending a message from one node to every other node in a network. During broadcasting, the source node usually requires the assistance of its immediate neighbors to rebroadcast the message to their neighboring nodes. This process continues until all nodes in the network have received at least a copy of the message [1]. Broadcasting provides route establishment and control functionality for a number of unicast and multicast protocols. Many routing protocols, such as AODV [2], DSR [3], OSPF [4], and IS-IS [5], rely on broadcasting for failure notification, route discovery and maintenance, and network topology updating, or simply for sending control or maintenance messages. Broadcasting techniques are also used in Video-on-Demand (VOD) systems. Broadcasting protocols are proved to be efficient for transmitting most of the popular videos in VOD systems [6]. Additionally, broadcasting supports to maintain valuable global information of peer-to-peer (P2P) networks. In P2P networks,

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broadcasting disseminates a message to all peers; in the reverse direction, it can aggregate the responses from peers [7].

The most basic form of broadcasting is "simple flooding" (SP). In this form, every node rebroadcasts a broadcast message when it first receives the message [8-11]. In other words, each node retransmits the broadcast message once. When a node receives a broadcast message, it determines if it has transmitted the message before; if not, the node rebroadcasts the message. This process allows a broadcast message to be delivered throughout the network. Simple flooding ends when all nodes in the network have received and retransmitted the broadcast message at least once. This simple scheme guarantees that a broadcast message can reach all nodes if the network is connected. The main problem with simple flooding, however, is that too many retransmitting nodes in a network generate too many broadcast message duplications. Generally, when a broadcast message is sent in an *n*-node network, a total of n-1 retransmitting nodes rebroadcast the message once. The large number of retransmitting nodes causes significant broadcast message duplication. High broadcast message duplication can result in high bandwidth consumption in networks.

Several broadcasting techniques have been developed and proposed in order to reduce the number of retransmissions while attempting to ensure that a broadcast message is delivered to each node in the network. Many broadcasting methods have been proposed for mobile ad hoc networks (MANETs). The broadcasting methods can be broadly classified into the following categories: heuristic-based, area-based, neighbor cover-age-based, cluster-based, and tree-based broadcasting methods. Broadcasting methods for MANETs were reviewed and explored in [8-12]. Some efficient broadcasting protocols for VOD systems have been proposed. These broadcasting protocols can be subdivided in to three groups [6]. Protocols in the first group [14-15] are pyramid-based protocols that partition the video into increasing size of segments and transmit them in logical channels of the same bandwidth. Broadcasting protocols of the second group [16-18] called harmonic-based protocols divide the video into equal size segments and transmit them in logical channels of decreasing bandwidth. Protocols of the third group [19-20] are hybrid of pyramid-based protocols and harmonic-based protocols. They partition each video into fixed size segments and map them into a small number of data streams of equal bandwidth. Broadcasting techniques in P2P networks have been proposed in [21-23]. Broadcasting on a structured P2P network usually disseminates messages along the edges of a spanning tree [7]. Some broadcasting techniques [21-22] presented how a peer broadcast a message to peers within a range. These techniques implicitly construct a spanning tree in a top-down and on-demand fashion by selecting proper routing entries in their own routing tables. Another technique [23] proposed to build and maintain a spanning tree explicitly on a bottom-up fashion to support operations such as information aggregation. When a peer wants to broadcast a message, it first sends the message to the root of the spanning tree.

An effective broadcasting technique minimizes the number of nodes that are involved in re-broadcasting broadcast messages. Among the various broadcasting techniques, Minimizing Re-Transmissions (MRT) [12-13] is one of the most efficient. The MRT technique was developed to work with link state routing protocols in ad hoc wireless networks. MRT uses link state information obtained by the routing protocols to provide an efficient flooding technique in ad hoc wireless networks. The primary goal of MRT is to minimize the number of retransmitting nodes in a network; it thus significantly reduces broadcast message duplication in the network. The MRT technique works very efficiently when it is applied to ad hoc wireless networks. When MRT is used to send broadcast traffic in wired networks, however, it generates broadcast duplication in the networks.

In this paper, we develop a variant of MRT for wired networks called wMRT. The key idea of wMRT is to minimize not only the number of retransmitting nodes, but also the number of retransmitting nodes' ports in wired networks. Like MRT, the wMRT technique allows a minimum number of nodes in a wired network to retransmit broadcast messages. The rest of the nodes are not allowed to retransmit the broadcast messages. The wMRT approach also allows a minimum number of nodes' ports in the wired network to retransmit broadcast messages. By minimizing both the number of retransmitting nodes and the number of retransmitting ports, wMRT completely removes broadcast duplication in wired networks.

The remainder of this paper is organized as follows. In Section 2, we introduce the MRT technique. In Section 3, we present the proposed wMRT. Then, in Section 4, we analyze, evaluate, and compare the traffic performance of wMRT to that of both simple flooding and MRT. In Section 5, we present various simulations, and we describe their results in order to evaluate and validate the traffic performance analysis of wMRT. Finally, we provide our conclusions and suggestions for future work in Section 6.

2. The MRT Technique

The purpose of the MRT technique [12] is to minimize the number of retransmitting nodes in a network. Based on broadcast roles of nodes in the network, the MRT technique classifies them into two types of nodes: active-broadcast nodes and passive-broadcast nodes.

- *Active-broadcast nodes*: Active-broadcast nodes are nodes in a network that are allowed to retransmit a broadcast message when it receives the message for the first time in the network.
- *Passive-broadcast nodes*: Passive-broadcast nodes are nodes in a network that are not allowed to retransmit broadcast messages in the network.

When receiving a broadcast message, the active-broadcast nodes retransmit the message that is received for the first time, whereas the passive-broadcast nodes do not rebroadcast the message.

In order to classify and assign broadcast roles to nodes in a network, the MRT technique establishes and maintains a broadcast tree of the network; based on this broadcast tree, MRT assigns broadcast roles to network nodes. The processes of establishing the broadcast tree and assigning broadcast roles to nodes are described as follows.

2.1. Establishing the Broadcast Tree

Only one broadcast tree is established for the network in connected networks. The broadcast tree consists of one root, intermediate nodes and leaves. The MRT algorithm for establishing the broadcast tree is described as follows [12].

MRT Algorithm

$BT = \{\emptyset\}$ *// Broadcast Tree*
$Q = \{all\_nodes\}$
$r = ExtraxtMax\{Q\}$ *// Find node with the most neighbors*
$BT.root = r$
for each neighbor m of r
$BT.leaves \leftarrow \{m\}$
$Q = Q - \{m\}$
while $Q \neq \{\emptyset\}$
$n = ExtraxtMax\{BT.leaves\}$
$BT.nodes \leftarrow n$
for each neighbor m of n
$BT.leaves \leftarrow \{m\}$
$Q = Q - \{m\}$
end while

A sample network with 25 nodes is shown in Figure 1. Figure 2 shows the broadcast tree of the sample network that is constructed from the MRT technique.

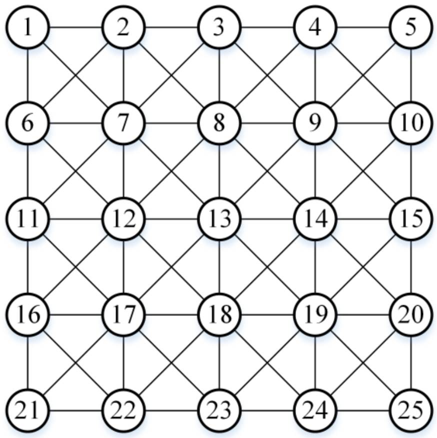


Figure 1. A Sample Network with 25 Nodes

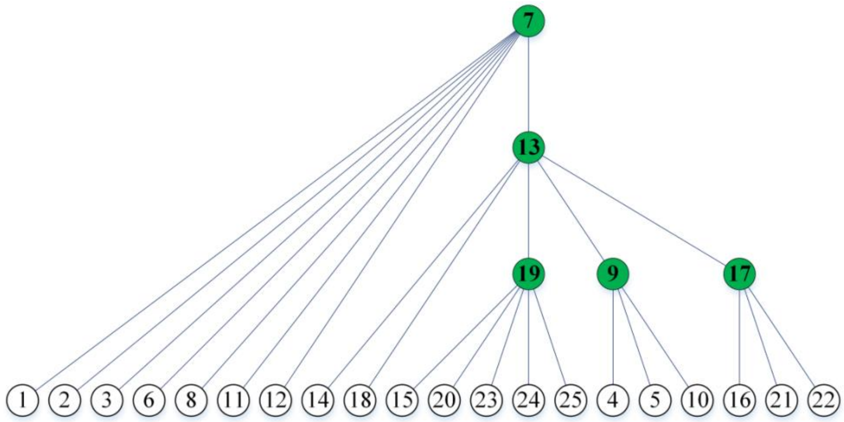


Figure 2. The Broadcast Tree of the Sample Network in Figure 1

2.2. Assigning Broadcast Roles

Once the broadcast tree is built, MRT assigns broadcast roles to nodes in the network. The root and the intermediate nodes of the broadcast tree are set to active-broadcast nodes, whereas the leaves are set to passive-broadcast nodes.

For the sample network in Figure 1, five active-broadcast nodes and twenty passive-broadcast nodes are assigned, based on the broadcast tree of the network, as shown in Figure 3.

2.2. MRT Issues

When a node sends a broadcast message, active-broadcast nodes will receive the broadcast message and flood it to all their ports, except the port in which the broadcast message is received. Passive-broadcast nodes will not retransmit the received message. Because all passive-broadcast nodes are connected to active-broadcast nodes, the broadcast message is delivered through the network.

In wired networks, a passive-broadcast node can connect to a few active-broadcast nodes. This causes broadcast duplications to be received at the passive-broadcast node.

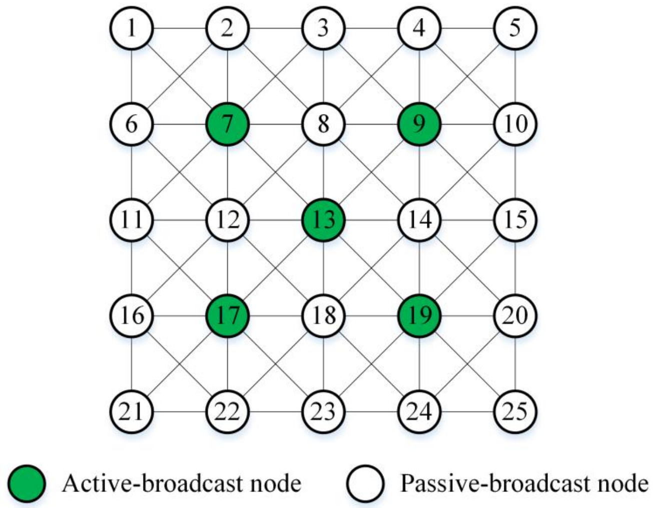


Figure 3. Broadcast Roles of Nodes in the Sample Network in Figure 1

For the sample network in Figure 3, when node 1 sends a broadcast message, it sends the broadcast message over all its ports. Active-broadcast node 7 receives and floods the broadcast message to all its ports, except the port connecting to node 1, in which the broadcast message is received. Active-broadcast node 13 receives and floods the message to all its ports, except the port connecting to node 7. Similarly, the other active-broadcast nodes 9, 17, and 19 receive and flood the message to all of their ports, except the port connecting to node 13. In that case, passive-broadcast node 8 will receive three copies of the broadcast messages that are retransmitted by active-broadcast nodes 7, 9, and 13. The same situation is true for passive-broadcast nodes 14 and 18. In other words, MRT generates broadcast duplication in wired networks.

3. The Proposed wMRT Technique

The proposed wMRT is a variant of MRT that was developed for efficiently broadcasting in wired networks. Like MRT, the wMRT approach works with link state protocols and uses link state information obtained by the routing protocols.

The primary goal of wMRT is to minimize not only the number of retransmitting nodes, but also the number of retransmitting ports of nodes in a wired network. Unlike MRT, which allows active-broadcast nodes to flood received broadcast messages to all of their ports, the wMRT approach allows the active-broadcast nodes to exclusively send the broadcast messages over their active-broadcast ports; wMRT thus completely removes broadcast message duplication in the wired network.

3.1. Definitions

As a variant of MRT, the wMRT technique uses all of the terms defined in MRT [12]. Along with the terms defined in MRT, wMRT defines a few of its own new terms.

In order to remove broadcast duplication in wired networks, the wMRT technique defines two types of node ports: active-broadcast ports and passive-broadcast ports.

Definition 1 (Active-broadcast port): An active-broadcast port is a port of a node that is used to retransmit broadcast messages.

Definition 2 (Passive-broadcast port): A passive-broadcast port is a port of a node that is not used to retransmit broadcast messages.

Each passive-broadcast node has only one active-broadcast port, whereas each active-broadcast node can have some active-broadcast ports. The port type is set based on the type of the link that the port is connected to. The wMRT approach also defines two types of links in a wired network: active-broadcast links and passive-broadcast links.

Definition 3 (Active-broadcast link): An active-broadcast link is a link in a wired network that is used to deliver broadcast messages in the wired network.

Definition 4 (Passive-broadcast port): A passive-broadcast link is a link in a wired network that is not used to deliver broadcast messages in the wired network.

3.2. The wMRT Operations

The proposed wMRT consists of three stages, as follows:

1) Building the broadcast tree of a network;
2) Assigning broadcast roles to nodes in the network;
3) Assigning broadcast roles to node ports in the network.

The first two stages of wMRT are similar to those of MRT [12]. The final stage is used to minimize the number of active-broadcast ports in the network. This stage is the main enhancement of the proposed wMRT compared with MRT for wired networks.

In the MRT technique, when an active-broadcast node receives a broadcast message, it floods the broadcast message to all of its ports, except for the port that receives the message. The drawback of this approach is that it causes broadcast duplications to be received at the passive-broadcast nodes. In order to remove the broadcast duplication from the passive-broadcast nodes as well as from the whole network, wMRT allows active-broadcast nodes to send received broadcast messages exclusively over their active-broadcast ports, instead of flooding all of their ports.

The process of assigning broadcast roles to nodes' ports consists of the following two steps: (1) assigning broadcast roles to links and (2) assigning broadcast roles to ports.

3.2.1. Assigning Broadcast Roles to Links: For the MRT technique, all links connected to active-broadcast nodes are active-broadcast links. The active-broadcast links of the sample network in Figure 1 under the MRT technique are shown in Figure 4.

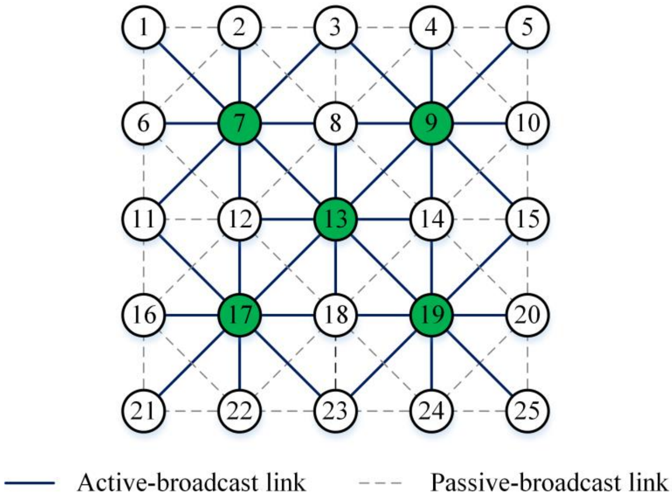


Figure 4. Active-Broadcast Links of the Sample Network under MRT

The wMRT technique assigns broadcast roles to links in a wired network based on the broadcast tree of the network. Links that form the edges of the broadcast tree are set to active-broadcast links; the rest of the links are passive-broadcast links. The active-broadcast links of the sample network in Figure 1 are shown in Figure 5.

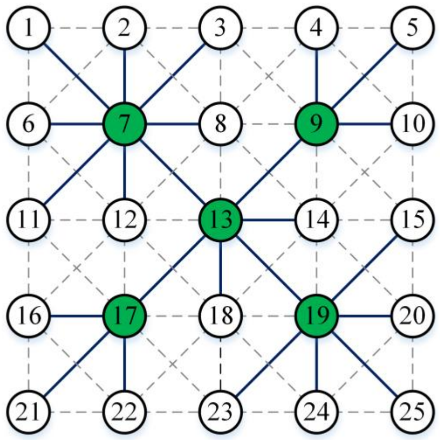


Figure 5. Active-Broadcast Links of the Sample Network under wMRT

Therefore, in the wMRT approach, each passive-broadcast node only has one active-broadcast link that connects to an active-broadcast node. For the same network, the number of active-broadcast links in the wMRT technique is much less than that in the MRT technique. Intuitively, there is no broadcast duplication at passive-broadcast nodes using the wMRT technique.

3.2.2. Assigning Broadcast Roles to Ports: Based on the active-broadcast links, each node in the wired network assigns broad-cast roles to its ports. Ports that are connected to active-broadcast links are set to active-broadcast ports, whereas ports that are connected to passive-broadcast links are set to passive-broadcast ports.

Under the wMRT approach, when an active-broadcast node receives a broadcast message, it exclusively sends the message over its active-broadcast ports.

The pseudocode of the wMRT algorithm is described as follows.

wMRT Algorithm

$BT = \{\emptyset\}$ *// Broadcast Tree*
$AL = \{\emptyset\}$ *// Active Links*
$Q = \{all\_nodes\}$
$r = ExtraxtMax\{Q\}$ *// Find node with the most neighbors*
$BT.root = r$
for each neighbor *m* of *r*
$BT.leaves \leftarrow \{m\}$
$AL \leftarrow \{r, m\}$
$Q = Q - \{m\}$
while $Q \neq \{\emptyset\}$
$n = ExtraxtMax\{BT.leaves\}$
$BT.nodes = n$
for each neighbor *m* of *n*
$BT.leaves \leftarrow \{m\}$
$AL \leftarrow \{n, m\}$
$Q = Q - \{m\}$
end while

3.2.2. Broadcasting Operations: Under wMRT, when a node sends a broadcast message, it only sends the broadcast message over its active-broadcast ports. When active-broadcast nodes receive the broadcast message, they only send it over their active-broadcast ports, and not all their ports (as in MRT) except for the port that receives the broadcast message. Passive-broadcast nodes will not retransmit the received message. Because all passive-broadcast nodes are connected to active-broadcast nodes via active-broadcast links, the broadcast message is delivered through the network.

For the sample network with the broadcast tree shown in Figure 5, when node 1 sends a broadcast message, it only sends the message over its active-broadcast port. Active-broadcast node 7 receives and sends the message only to its active-broadcast ports, except for the port connecting to node 1. Active-broadcast node 13 receives and sends the message only to its active-broadcast ports, except for the port connecting to node 7. Similarly, the other active-broadcast nodes (9, 17, and 19) receive and send the message only to their active-broadcast ports, except for the ports connecting to node 13. In that case, passive-broadcast node 8 receives only one copy of the broadcast messages that are retransmitted by active-broadcast node 7. Similarly, the other passive-broadcast nodes receive only one copy of the broadcast message. In other words, the wMRT approach completely removes broadcast duplication in the wired network.

3.3. Maintaining and Updating the Broadcast Tree

When any link state change occurs in a wired network, the link state routing protocol exchanges the link information messages and updates the link state table of the network.

Once the link table is updated, wMRT recalculates the broadcast tree of the network based on the latest updated link table and updates the broadcast roles for the nodes and ports of the nodes in the network.

4. Performance Analysis

This section describes an analysis of the broadcast traffic performance of the wMRT technique compared to the simple flooding and MRT techniques.

In this paper, the measures of broadcast traffic and broadcast duplication are used in order to analyze and evaluate the broadcast traffic performance of the broadcasting techniques.

- *Broadcast traffic*: Broadcast traffic in a network is defined as the total number of broadcast messages that are delivered in links and received by nodes in the network.
- *Broadcast duplications*: Broadcast duplications are the total number of broadcast messages that are received and discarded by all nodes due to duplication.

When a node sends a broadcast message to an n-node network, all of the other nodes expect to receive a copy of the broadcast message. In other words, n-1 copies of the broadcast message are expected to be received at n-1 nodes, except for the sender node. After receiving the first copy of the broadcast message, if the nodes continue to receive more copies of the message, the copies are considered to be broadcast duplications. Therefore, broadcast duplications are n-1 less than broadcast traffic.

The sample wired network consisting of 25 nodes as shown in Figure 1 is used to analyze and evaluate the broadcast traffic performance of the broadcasting techniques.

4.1. Under Simple Flooding

For the simple flooding technique, when a node sends a broadcast message, all of the nodes (except the sending node) retransmit the message when it is first received. Figure 6 shows a message being broadcast in the sample network under simple flooding.

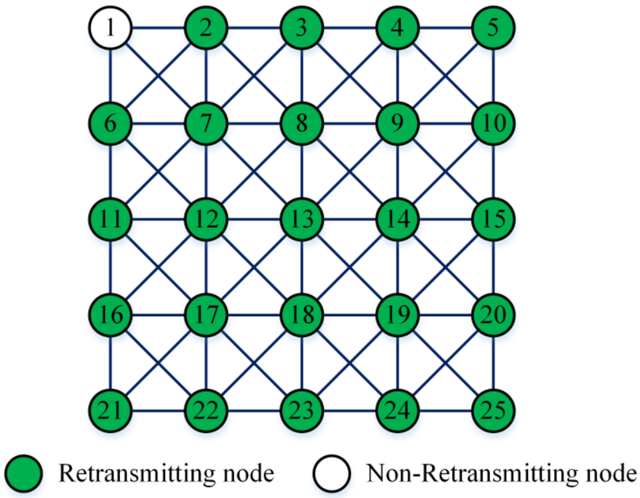


Figure 6. Broadcasting a Message under Simple Flooding

Under simple flooding, broadcast traffic when a node sends a broadcast message, denoted by tf_{sim}^{1}, is calculated as follows:

$$tf_{sim}^{1} = N_{link}^{S} + \sum_{i \in S_{sim}^{rtx}} \left(N_{link}^{i} - 1\right) \tag{1}$$

where N_{link}^{S} is the number of links of the sender node, S_{sim}^{rtx} is a set of retransmitting nodes, and N_{link}^{i} is the number of links of the i^{th} node.

The sum of the links of all retransmitting nodes is determined as follows:

$$\sum_{i \in S_{sim}^{rtx}} N_{link}^{i} = 2N_{link} - N_{link}^{S} \tag{2}$$

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

Equation (1) can be rewritten as follows:

$$tf_{sim}^{1} = 2N_{link} - N_{sim}^{rtx} = 2N_{link} - (N_{node} - 1) \tag{3}$$

where N_{node} is the total number of nodes in the network, and $N_{sim}^{rtx} = N_{node} - 1$ is the number of retransmitting nodes.

Broadcast duplications when a node sends a broadcast message, denoted by dup_{sim}^{1}, are determined as follows:

$$dup_{sim}^{1} = tf_{sim}^{1} - (N_{node} - 1) \tag{4}$$

By replacing (3) with (4), the broadcast duplications can be calculated as follows:

$$dup_{sim}^{1} = 2(N_{link} - N_{node} + 1) \tag{5}$$

In general, broadcast duplications when a node sends N broadcast messages, denoted by dup_{sim}, are calculated as follows:

$$dup_{sim} = 2N(N_{link} - N_{node} + 1) \tag{6}$$

For the sample network in Figure 1, broadcast duplications are calculated as follows:

$$dup_{sim} = 2N(72 - 25 + 1) = 96N$$

4.2. Under MRT

Under MRT flooding, when a node sends a broadcast message, it floods the message to all of its ports. When active-broadcast nodes receive the message, they flood the message to all of their ports, except for the received port. When passive-broadcast nodes receive the message, they do not retransmit it. Figure 4 shows a message being broadcast in the sample network under MRT. We consider the following scenarios:

- Broadcast messages are sent by a passive-broadcast node.
- Broadcast messages are sent by an active-broadcast node.

4.2.1. Sent by a Passive-broadcast Node: Broadcast traffic when a passive-broadcast node sends a broadcast message, denoted by tf_{MRT}^{1}, is calculated as follows:

$$tf_{MRT}^{1} = N_{link}^{S} + \sum_{i \in S_{MRT}^{act}} \left(N_{link}^{i} - 1\right) \tag{7}$$

where N_{link}^{S} is the number of links of the sender node and S_{MRT}^{act} is a set of active-broadcast nodes.

When a passive-broadcast node sends a broadcast message, broadcast duplications, denoted by dup_{MRT}^{1}, are determined as follows:

$$dup_{MRT}^{1} = N_{link}^{S} + \sum_{i \in S_{MRT}^{act}} \left(N_{link}^{i} - 1\right) - (N_{node} - 1) \tag{8}$$

In general, broadcast duplications when a passive-broadcast node sends N broadcast messages, denoted by dup_{MRT}, are calculated as follows:

$$dup_{MRT} = N\left(N_{link}^{S} + \sum_{i \in S_{MRT}^{act}} \left(N_{link}^{i} - 1\right) - (N_{node} - 1)\right) \tag{9}$$

For the sample network in Figure 1, when node 1 sends N broadcast messages, broadcast duplications are calculated as follows:

$$dup_{MRT} = N(3 + 5 \times 7 - 25 + 1) = 14N$$

4.2.2. Sent by an Active-broadcast Node: When an active-broadcast node sends a broadcast message, broadcast traffic, denoted by tf_{MRT}^{1}, is calculated as follows:

$$tf_{MRT}^{1} = N_{link}^{S} + \sum_{i \in S_{MRT}^{act,!S}} \left(N_{link}^{i} - 1\right) \tag{10}$$

where $S_{MRT}^{act,!S}$ is a set of active-broadcast nodes (except for the sending node).

$$\sum_{i \in S_{MRT}^{act}} N_{link}^{i} = N_{link}^{S} + \sum_{i \in S_{MRT}^{act,!S}} N_{link}^{i} \tag{11}$$

Equation (10) can be rewritten as follows:

$$tf_{MRT}^{1} = 1 + \sum_{i \in S_{MRT}^{act}} \left(N_{link}^{i} - 1\right) \tag{12}$$

When an active-broadcast node sends a broadcast message, broadcast duplications, denoted by dup_{MRT}^{1}, are determined as follows:

$$dup_{MRT}^{1} = \sum_{i \in S_{MRT}^{act}} \left(N_{link}^{i} - 1\right) - (N_{node} - 2) \tag{13}$$

In general, broadcast duplications when an active-broadcast node sends N broadcast messages, denoted by dup_{MRT}, are calculated as follows:

$$dup_{MRT} = N\left(\sum_{i \in S_{MRT}^{act}} \left(N_{link}^{i} - 1\right) - (N_{node} - 2)\right) \tag{14}$$

For the sample network in Figure 1, when node 7 sends N broadcast messages, broadcast duplications are calculated as follows:

$$dup_{MRT} = N(5 \times 7 - 25 + 2) = 12N$$

4.3. Under wMRT

Under wMRT, when a node sends a broadcast message, it only sends the message over its active-broadcast ports. When active-broadcast nodes receive the message, they only send the message to their active-broadcast ports, except for the receiving port. When passive-broadcast nodes receive the message, they discard it. Figure 5 shows a message being broadcast in the sample network under wMRT. We consider the following scenarios:

- Broadcast messages are sent by a passive-broadcast node (node 1).
- Broadcast messages are sent by an active-broadcast node (node 7).

4.3.1. Sent by a Passive-broadcast Node: Broadcast traffic when a passive-broadcast node sends a broadcast message, denoted by tf^1_{wMRT}, is calculated as follows:

$$tf^1_{wMRT} = N^S_{ap} + \sum_{i \in S^{act}_{wMRT}} \left(N^i_{ap} - 1\right) \tag{15}$$

where N^S_{ap} is the number of active-broadcast ports of the sender node ($N^S_{ap} = 1$ for passive-broadcast nodes), S^{act}_{wMRT} is a set of active-broadcast nodes, and $\mathrm{N}^{\mathrm{i}}_{\mathrm{ap}}$ is the number of active-broadcast ports of the i^{th} node.

Broadcast duplications when a passive-broadcast node sends a broadcast message, denoted by dup^1_{wMRT}, are determined as follows:

$$dup^1_{wMRT} = \sum_{i \in S^{act}_{wMRT}} \left(N^i_{ap} - 1\right) - (N_{node} - 2) \tag{16}$$

For the broadcast tree,

$$\sum_{i \in S^{act}_{wMRT}} \left(N^i_{ap} - 1\right) = N^{act}_{link} - 1 = N_{node} - 2 \tag{17}$$

where $\mathrm{N}^{\mathrm{act}}_{\mathrm{link}}$ is the number of active-broadcast links ($\mathrm{N}^{\mathrm{act}}_{\mathrm{link}} = \mathrm{N}_{\mathrm{node}} - 1$).

Therefore, broadcast duplications in (16) can be determined as:

$$dup^1_{wMRT} = N_{node} - 2 - (N_{node} - 2) = 0 \tag{18}$$

4.3.2. Sent by an Active-broadcast Node: Broadcast traffic when an active-broadcast node sends a broadcast message, denoted by $\mathrm{tf}^1_{\mathrm{wMRT}}$, is calculated as follows:

$$tf^1_{wMRT} = N^S_{ap} + \sum_{i \in S^{act,!S}_{wMRT}} \left(N^i_{ap} - 1\right) \tag{19}$$

where $\mathrm{S}^{\mathrm{act,!S}}_{\mathrm{wMRT}}$ is a set of active-broadcast nodes (except for the sender node).

$$\sum_{i \in S^{act}_{MRT}} N^i_{ap} = N^i_{ap} + \sum_{i \in S^{act,!S}_{wMRT}} N^i_{ap} \tag{20}$$

Equation (19) can be rewritten as follows:

$$tf^1_{wMRT} = 1 + \sum_{i \in S^{act}_{wMRT}} \left(N^i_{ap} - 1\right) = N_{node} - 1 \tag{21}$$

Broadcast duplications when an active-broadcast node sends a broadcast message, denoted by $\mathrm{dup}^1_{\mathrm{wMRT}}$, are determined as follows:

$$dup^1_{wMRT} = tf^1_{wMRT} - (N_{node} - 1) = 0 \tag{22}$$

Therefore, when an active-broadcast or passive-broadcast node sends broadcast messages, there is no broadcast duplication in the wired network under the wMRT approach.

5. Simulations

In order to validate the analytical results derived in Section 4, various simulations were carried out using a network simulation tool, OMNeT++v4.6 [24].

5.1 Simulation Model

The objective of the simulations is to validate the analytical results and compare the broadcast traffic performance of the proposed wMRT technique with that of the simple flooding and the original MRT technique in a wired network.

Networks used in the simulations were wired networks with network size of $m \times m$ nodes, as shown in Figure 7.

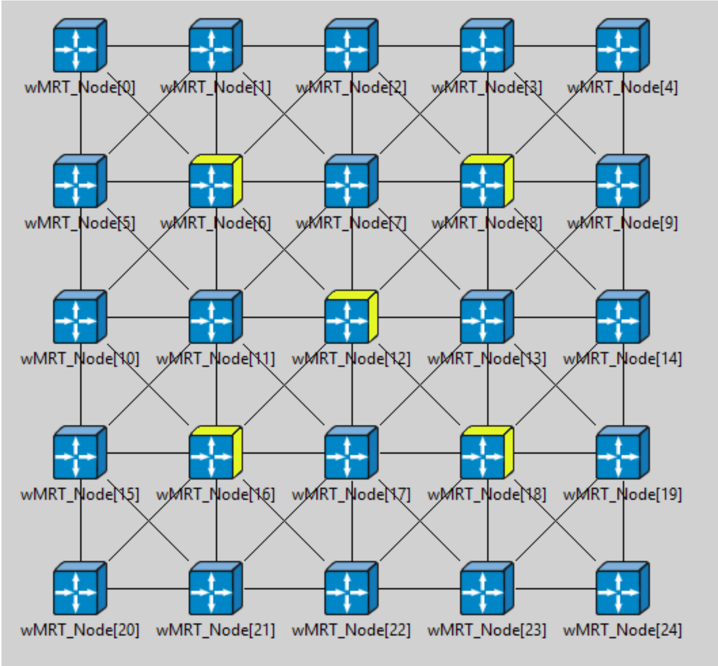


Figure 7. A Simulation Network with Network Size of 5×5 Nodes

Because both the MRT and wMRT techniques deliver broadcast messages based on the broadcast tree of a network that is constructed based on the network's link information, it is necessary to build a link table that describes a map of the connectivity to the network.

In the simulations, the link tables of simulation networks were built by using the BER-based routing protocol (BRP) [25]. The BRP's nodes first discover their neighboring nodes, then exchange their links' information, and finally build the link table based on the received link information.

The process of building a network link table in the BRP model is briefly described as follows.

- *Discovering neighbors*: First, every node discovers its available neighbors. A Hello message is used to discover neighbors. Each node receives the Hello messages from its neighbors and then builds its own neighbor table.
- *Exchanging BER information*: To build the link table, nodes first send their links' information to each other. Each node advertises its links' information by broadcasting a Link-metric message.
- *Building the link table*: Based on the received Link-metric messages, each node builds its own link table. For a connected network, all nodes in the network have the same link table.

Based on the link table built by the BRP, the MRT and wMRT algorithms create the broadcast tree of the network.

5.2. Simulation Description

Two simulations were conducted to validate and evaluate the broadcast traffic performance of the proposed wMRT technique.

5.2.1. Simulation 1: The first simulation was performed to validate the broadcast traffic performance analysis in Section 4. We considered the sample wired network with 25 nodes, as shown in Figure 1. The sender node sent N broadcast messages to the network (N = 10, 20, …, 100). The broadcast traffic and broadcast duplication under the flooding techniques were recorded for comparison with the traffic performance analyzed in Section 4.

We considered the following cases:

- *Case 1*: Broadcast messages were sent by a passive-broadcast node.
- *Case 2*: Broadcast messages were sent by an active-broadcast node.

5.2.2. Simulation 2: The second simulation was implemented in various simulated networks with different numbers of nodes. Each network had $m \times m$ nodes (m = 3, 4, …, 10). The simulation was performed under the simple flooding, MRT, and wMRT approaches. Sender node 1 sent 50 broadcast messages to the networks. The simulation results were recorded and used to evaluate and compare the broadcast traffic performance of the flooding techniques.

5.3 Simulation Results

5.3.1. Simulation 1: The results of the simulation 1 are shown in Table 1 and Table 2.

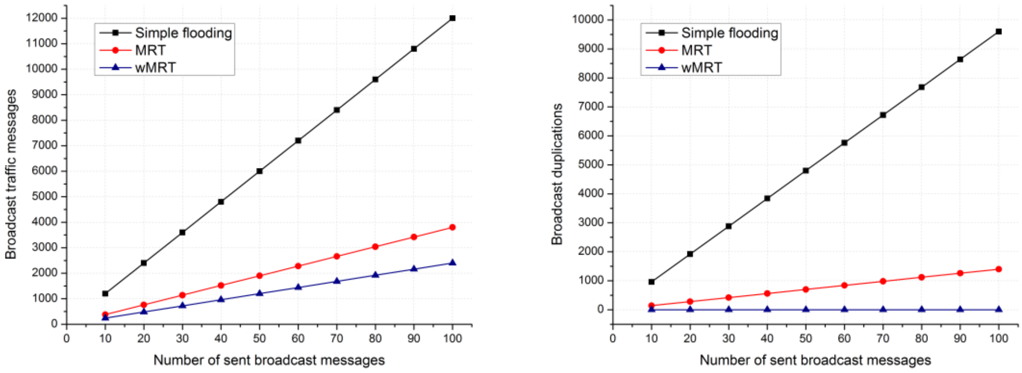
Table 1. Simulation Results of Case 1 in Simulation 1

Sent messages	Broadcast traffic			Broadcast duplications		
	SP	MRT	wMRT	SP	MRT	wMRT
10	1,200	380	240	960	140	0
20	2,400	760	480	1,920	280	0
30	3,600	1,140	720	2,880	420	0
40	4,800	1,520	960	3,840	560	0
50	6,000	1,900	1,200	4,800	700	0
60	7,200	2,280	1,440	5,760	840	0
70	8,400	2,660	1,680	6,720	980	0
80	9,600	3,040	1,920	7,680	1,120	0
90	10,800	3,420	2,160	8,640	1,260	0
100	12,000	3,800	2,400	9,600	1,400	0

Table 2. Simulation Results of Case 2 in Simulation 1

Sent messages	Broadcast traffic			Broadcast duplications		
	SP	MRT	wMRT	SP	MRT	wMRT
10	1,200	360	240	960	120	0
20	2,400	720	480	1,920	240	0
30	3,600	1080	720	2,880	360	0
40	4,800	1440	960	3,840	480	0
50	6,000	1800	1,200	4,800	600	0
60	7,200	2160	1,440	5,760	720	0
70	8,400	2520	1,680	6,720	840	0
80	9,600	2880	1,920	7,680	960	0
90	10,800	3240	2,160	8,640	1080	0
100	12,000	3600	2,400	9,600	1200	0

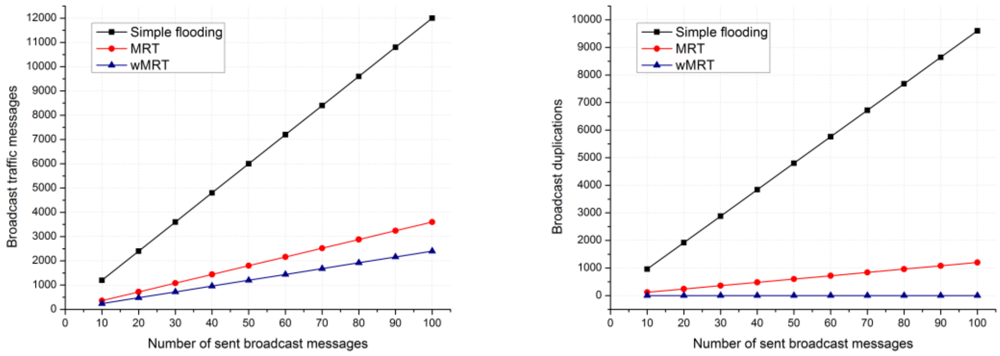
Figures 8a and 8b show comparisons of broadcast traffic and broadcast duplication, respectively, for the simple flooding, MRT, and wMRT approaches in Case 1.



(a) (b)

Figure 8. Comparisons of (a) Broadcast Traffic and (b) Broadcast Duplications in Simulation 1's Case 1

Figures 9a and 9b show comparisons of broadcast traffic and broadcast duplication, respectively, for these flooding techniques in Case 2.



(a) (b)

Figure 9. Comparisons of (a) Broadcast Traffic and (b) Broadcast Duplications in Simulation 1's Case 2

The simulation results showed that there was no broadcast duplication in the sample network under the wMRT. In other words, the wMRT completely removed broadcast duplication in wired networks. Therefore, the wMRT significantly reduced broadcast traffic compared with simple flooding and original MRT. For our sample network, the wMRT approach reduced broadcast traffic by 33% (in Case 2) to 37% (in Case 1) compared with MRT, and by about 80% compared with simple flooding.

5.3.2. Simulation 2: The recorded broadcast traffic and duplications of Simulation 2 are shown in Table 3. Figure 10a shows a comparison of broadcast traffic, and Figure 10b shows a comparison of broadcast duplication for the simple flooding, MRT, and wMRT techniques. As with Simulation 1's results, the simulation results also show that wMRT completely removed broadcast duplication in the sample wired networks. For our sample networks, wMRT reduced broadcast traffic by 20% to 45% compared with MRT, and by 75% to 83% compared with simple flooding.

Table 3. Simulation Results of Case 2

Network size	Broadcast traffic			Broadcast duplications		
	SP	MRT	wMRT	SP	MRT	wMRT
3 × 3	1,600	500	400	1,200	100	0
4 × 4	3,450	1,250	750	2,700	500	0
5 × 5	6,000	1,900	1,200	4,800	700	0
6 × 6	9,250	2,950	1,750	7,500	1,200	0
7 × 7	13,200	4,100	2,400	10,800	1,700	0
8 × 8	17,850	5,750	3,150	14,700	2,600	0
9 × 9	23,200	7,200	4,000	19,200	3,200	0
10 × 10	29,250	8,650	4,950	24,300	3,700	0

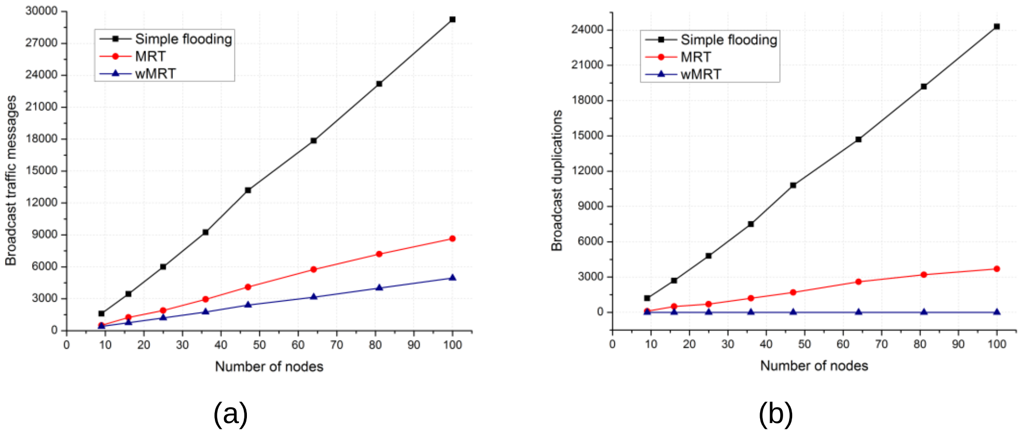


Figure 10. Comparisons of (a) Broadcast Traffic and (b) Broadcast Duplications in Simulation 2

5.4. Discussions

The simulation results demonstrate that the broadcast traffic performance of the proposed wMRT is much better than that of the simple flooding and original MRT approaches. As shown in Figures 8b, 9b, and 10b, while the number of broadcast duplications is too high under simple flooding and low under MRT, the number of broadcast duplications under wMRT is reduced to zero. In other words, the wMRT approach completely removes broadcast duplication from the network.

As a result of the minimization of both retransmitting nodes and retransmitting ports, MRT completely removes broadcast message duplication, and thus significantly reduces broadcast traffic messages compared to simple flooding and MRT, as shown in Figure 8a, 9a, and 10a. Numerically, for our sample networks, wMRT reduced broadcast traffic by 20% to 45% compared with MRT, and by 75% to 83% compared with simple flooding.

6. Conclusions

In this paper, we developed a variant of the MRT approach for broadcasting in wired networks, called wMRT. Unlike MRT, which allows active-broadcast nodes to flood a received broadcast message to all of their ports, the proposed wMRT allows the active-broadcast nodes to only retransmit the received broadcast message over their active-broadcast ports, instead of all ports. By minimizing both the number of active-broadcast nodes and the number of active-broadcast ports, the wMRT approach significantly reduces the number of broadcast traffic messages and completely prevents broadcast messages from being duplicated in wired networks, thus saving a significant amount of network bandwidth, as well as improving network traffic performance. The proposed wMRT is a broadcasting technique that is highly suitable for wired networks working with link state routing protocols.

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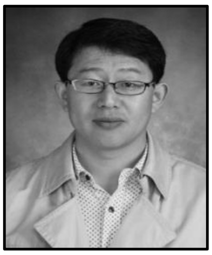

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