Efficient forwarding scheme for downlink broadcast messages in IEEE 802.16j multi-hop relay networks

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1. Introduction

Recently, a tree-based architecture with relay deployment has been broadly investigated for a cost-effective enhancement of the throughput, coverage, and system capacity of wireless broadband access networks [1–4]. The IEEE 802.16j task group also considered this architecture to extend the IEEE 802.16e standard and developed the so-called multi-hop relay (MR) network [5]. An IEEE 802.16j MR network consists of the base station (MR-BS), mobile station (MS), and relay station (RS), as shown in Fig. 1. The RS can provide a relaying service to its superordinate and subordinate stations for uplink and downlink data transmissions, respectively. The immediate superordinate station of an MS is called the access RS of that MS (e.g., RS1 and RS2 in Fig. 1). The data transmission between MR-BS and an MS is carried out on a unidirectional connection. This connection is identified by a unique connection identifier (CID) assigned by the MR-BS. Radio links originating from or terminating at an MS are called access links. Radio links between MR-BS and an RS or between a pair of RSs are called relay links.

In IEEE 802.16j, the MR-BS, based on the topology information, determines the path between itself and an access RS for bi-directional data transmission. The selection of a relay path, including a direct link or multi-hop path, has been discussed in the literature [6–9]. Ann et al. [7] considered a link’s available bandwidth, signal-to-noise ratio, and hop count for designing a metric to select a relay path. Numerical results validated that the use of the proposed metric in path selection could determine the lowest latency and a high throughput relay path. Liang et al. [8] considered the link bandwidth, path length,
channel condition as factors for the selection of a relay path. Numerical results revealed that the proposed mechanism significantly outperformed the other approaches in terms of the network utilization and average end-to-end path delay. Wang et al. [6] designed a metric, called radio resource utilization index (RRUI), and proposed an RRUI-based cost function to select the relay path. The RRUI was defined as the bandwidth unit required for transmitting a fixed amount of data. Simulation results revealed that the path determined by taking into the abovementioned consideration could increase the network throughput and reduce the MAP overhead, compared with the direct relay path and the multi-hop path. Based on previous research, Wang et al. [9] further took the traffic load into account to design a link spectral efficiency as a factor to determine the best relay path. The IEEE 802.16 standard [5] specifies that the path creation is carried out during the configuration stage. The MR-BS performs a three-way dynamic service addition (DSA) negotiation process to distribute the path information to all the RSs on the path. On the other hand, the MR-BS performs a two-way dynamic service deletion (DSD) negotiation process to remove all the information related to the path. Each intermediate RS retrieves the explicit path information from DSA or DSD management messages to maintain its forwarding table for data forwarding. Although each relay path is assigned a unique path ID and can bind the related service connections, forwarding the data between the MR-BS and an MS is carried out per CID, which identifies a transport connection or an uplink/downlink pair of the associated management connections.

The forwarding types of media access control protocol data units (MPDUs) in IEEE 802.16 are divided into four categories: broadcast, fragmentable broadcast, multicast, and unicast. Broadcast MPDUs are forwarded in every frame. Fragmentable broadcast MPDUs are transmitted by the MR-BS at a periodic interval. Multicast MPDUs are forwarded to multiple destinations, particularly for the scenario of RS grouping. Unicast MPDUs are forwarded to the specific destined station. In particular, broadcast MPDUs (e.g., DL-MAP management message and UL-MAP management message) and fragmentable broadcast MPDUs (e.g., downlink channel descriptor (DCD) management message and uplink channel descriptor (UCD) management message) are more important than multicast and unicast MPDUs because broadcast and fragmentable broadcast messages contain many system improvement parameters.

IEEE 802.16j proposes two data forwarding schemes: the tunnel-based forwarding scheme (TBFS) and the CID-based forwarding scheme (CBFS). The schemes depend on a forwarding table that contains the mapping between a CID and a given relay path as the basis for message forwarding. The TBFS uses DSA request (DSA-REQ) and DSA response (DSA-RSP) messages to establish a tunnel between the MR-BS and an access RS to accomplish message forwarding. Multiple MPDUs are constructed into a relay MPDU using an additional tunnel CID or management tunnel CID in the relay MAC header. When an access RS receives a relay MPDU, it removes the relay MAC header and forwards the remaining part of the received MPDU to the destined MS. In the CBFS, the individual CID instead of the tunnel CID is the main differentiated tag. The RS uses this CID as an entry to maintain a path-related forwarding table of all the subordinate stations in terms of every known destination and update the entries in its forwarding table as needed. In effect, the CBFS works like conventional table-driven routing protocols, such as DSDV [10] and WRP [11]. When an RS receives an MPDU, it looks for the entry with respect to the CID indication in the forwarding table to decide whether it must forward the received MPDU or not. If the entry is found, the RS forwards the received MPDU to its subordinate station. Although the IEEE 802.16j standard proposes the TBFS and the CBFS to achieve data forwarding, the TBFS renders a significant amount of overhead because it generates additional tunnel headers, thereby suffering a serious exhaustion of system resources. As for the CBFS, it only supports unicast MPDUs, and RSs require additional storage space and time to store the CID table and look up the desired CID up.

In this paper, we propose a basic CID-translated forwarding scheme, called B-CTFS, to forward broadcast messages. The main idea of the B-CTFS is that RSs perform a CID-translated strategy in which intermediate RSs (i.e., non-access RSs) and access RSs use distinct types of CIDs to forward the received MPDUs to the subordinate stations. Because fragmentable broadcast messages, unlike broadcast messages, comprise a common part and a PHY-specific part, in this paper, we propose an enhanced CID-translated forwarding scheme, called E-CTFS, to deal with the forwarding of fragmentable broadcast management messages. The MR-BS and the intermediate RSs in the E-CTFS transmit the common part, followed by the PHY-specific part of the messages. The common and PHY-specific parts are differentiated using the multicast management CID and the RS primary CID, respectively. When an access RS receives the common part and its own PHY-specific part of the MPDU, it uses the fragmentable broadcast CID rather than the CID in the received MPDU to transmit this message to the destined MSs. The main contribution of this study is that it proposes two efficient and effortless schemes to support the forwarding of downlink broadcast messages in IEEE 802.16j MR networks. Simulation results validate that the proposed CID-translated...
schemes outperform the TBFS in terms of the used resources. Moreover, because the proposed E-CTFS transmits the common part of messages one time only, it can save more system resources and transmission time while forwarding fragmentable broadcast management messages than the B-CTFS.

The rest of this paper is organized as follows. Section 2 introduces the TBFS and CBFS in IEEE 802.16j, aiming to provide the necessary background. Section 3 presents the proposed basic CID-translated and enhanced CID-translated forwarding schemes in detail. Section 4 presents the analysis of the forwarding overhead. Section 5 shows the performance evaluation results, and finally, Section 6 provides concluding remarks.

2. Preliminaries

This section gives a brief introduction to the CBFS and TBFS that IEEE 802.16j proposes. Fig. 2 shows the MPDU formats of CBFS and TBFS, and Table 1 provides the descriptions of all the abbreviations used in Fig. 2.

2.1. CID-based forwarding scheme (CBFS)

As a fundamental forwarding scheme, RSs in the CBFS use the original IEEE 802.16 generic MPDU to forward the received MPDUs. This generic MPDU consists of a MAC header field, a payload field, and a cyclic redundancy check (CRC) field. The CID in the MAC header is a tag for identifying a distinct destination station. Each RS on a specific path has to maintain a forwarding table including several CIDs as the entries. These CIDs are associated with the MSs directly attached to this RS. When receiving an MPDU, an RS depends on the CID in the MAC header of the received MPDU to either forward or discard the received MPDU. If the RS receives the MPDU whose CID can be found in the forwarding table, it forwards the received MPDU to the destined MS. Otherwise, the RS forwards the MPDU to the immediate subordinate RS if available.

Fig. 3 illustrates an example of the CBFS. Assume that the relay path has been created and two RSs, RS1 and RS2, are on this path. The immediate subordinate MS of the MR-BS is MS1. Further, the immediate subordinate MSs of the RS1 are MS2 and MS3, and those of RS2 are MS4 and MS5. For the sake of simplicity, assume that a single MS has only one connection. Let $x_i$ indicate the CIDs of MS$_i$, where $1 \leq i \leq 5$. Recall that the MR-BS and each RS on the path maintain their own forwarding tables, which contain the CIDs of all the subordinate MSs, as shown in Fig. 3(a). If RS1 receives the MPDU with CID $x_2$ or $x_3$, it broadcasts this MPDU to MS2 or MS3, respectively, by checking its forwarding table. On the other hand, if RS1 receives the MPDU whose corresponding CID is $x_4$ or $x_5$, it forwards the MPDU to RS2. RS2 then forwards the received MPDU to MS4 or MS5, as shown in Fig. 3(b).

![Fig. 2. MPDU formats for the CBFS and TBFS. (a) IEEE 802.16 generic MPDU (for the CBFS). (b) Relay MPDU (for the TBFS).](image-url)
### 2.2. Tunnel-based forwarding scheme (TBFS)

The IEEE 802.16j standard proposes the tunnel forwarding scheme as an alternative data forwarding scheme. The MR-BS in the TBFS establishes tunnels by using DSA-REQ and DSA-RSP management messages and encapsulates multiple generic MPDUs into a relay MPDU, which is forwarded in the tunnel. Fig. 2(b) shows the relay MPDU format in the TBFS. A relay MPDU consists of a relay MAC header field, a payload field, and an optional CRC field. In the relay MAC header, the CID field can be either a tunnel CID (T-CID) or a management tunnel CID (MT-CID), that the relay path binds. The T-CID and MT-CID identify the transport connection and the management tunnel connection, respectively. The payload is zero or that of many IEEE 802.16 generic MPDUs. The MR-BS in the TBFS uses the T-CID or the MT-CID as a tag to forward MPDUs through the established tunnel. RSs have to maintain a forwarding table with the T-CIDs as entries, each of which is associated with its next-hop RS. The main procedure for the TBFS is that the station at the ingress of a tunnel encapsulates multiple generic MPDUs and then places this encapsulated data into the tunnel. When the station at the egress of the tunnel receives MPDUs, it removes the relay MAC header to forward the remaining portion of the received MPDU to the destined MSs individually.

Fig. 4 illustrates an example of the TBFS. For the sake of simplicity, assume that a single tunnel carries the MPDU to be transmitted to a certain MS. There are four tunnels with different T-CIDs for all descendant MSs of the MR-BS. Let $y_i$, where $1 \leq i \leq 4$, denote the T-CIDs of the established tunnels. When receiving the encapsulated MPDUs from the tunnel with CID $y_1$ or $y_2$, RS1 decapsulates the MPDU and checks the T-CID information because the destined MS of the received MPDU is the immediate subordinate MSs of RS1. Then, it forwards the MPDU to MS2 or MS3 individually. On the other hand, if RS1 receives MPDU through the tunnels whose T-CID is $y_3$ or $y_4$, it immediately forwards the MPDU to RS2. Because RS2 is the egress of this tunnel, and the destined MS of the received MPDU is RS2’s immediate subordinate MS; RS2 only forwards the received MPDU to MS4 or MS5 individually.

### 3. Proposed forwarding schemes

By using the fundamental CBFS scheme, the MR-BS has to notify the destined RS of the reception of the scheduled broadcast and fragmentable broadcast messages in the DL relay zone. The MR-BS and RSs can use the CID indication in the MAC header of the received MPDU to unicast this MPDU to the destined MS. Unfortunately, the CBFS cannot support the forwarding of the broadcast MPDUs and the fragmentable broadcast MPDUs. While using the CBFS to forward the broadcast management messages, the MR-BS needs to unicast the message to all the access RSs of the destined MSs individually. This leads to a redundant transmission of a certain part of MPDUs, thereby using a significant amount of the system resources. Further, the use of the individual RS CID in the header cannot achieve MPDU forwarding on access links.

#### 3.1. Basic CID-translated forwarding scheme (B-CTFS)

To reduce the amount of used resources during the MPDU forwarding, in this paper, we propose a novel forwarding scheme, called the basic CID-translated forwarding scheme (B-CTFS), to relay the broadcast and the fragmentable broadcast MPDUs in IEEE 802.16j MR networks. The B-CTFS is motivated by the concept of simplicity and rapidity. The main idea of the B-CTFS is that it treats the broadcast and fragmentable broadcast messages as general data and uses different CIDs to identify the receiver (RS or MS) of the messages. The B-CTFS determines the CID based on the type of links that the messages pass through. The broadcast messages and the fragmentable broadcast messages on the relay links use the RS basic CID and the RS
primary CID, respectively. To guarantee the backward compatibility with the legacy IEEE 802.16 system, the B-CTFS does not modify any function of the MSs. That is, the broadcast messages and the fragmentable broadcast messages on access links uses the typical broadcast CID and the fragmentable broadcast CID, respectively.

Fig. 3 shows an example of the forwarding procedure for the B-CTFS. We use a two-hop MR network as an example, as illustrated in Fig. 5(a). In Fig. 5(b), we show that the broadcast management MPDU (e.g., DL-MAP or UL-MAP message) on the relay links uses the RS basic CID. When RS1 receives the broadcast MPDU, it translates the CID into the broadcast CID and forwards the message to MS1. Moreover, RS2 translates the CID into the broadcast CID and forwards the message to MS2 upon receiving the broadcast MPDU. On the other hand, while forwarding a fragmentable management message (e.g., DCD or UCD management message), the message on the relay links uses the RS primary CID, as shown in Fig. 5(c). Upon receiving a fragmentable broadcast MPDU, RS1 translates the CID into the fragmentable broadcast CID and forwards the message to MS1. RS2 performs a CID translation upon receiving the fragmentable broadcast MPDU from RS1. It translates the CID into the fragmentable broadcast CID and then forwards the message to its immediate subordinate MS, MS2.
3.2. Enhanced CID-translated forwarding scheme (E-CTFS)

IEEE 802.16 fragmentable broadcast management messages, such as DCD and UCD management messages, consist of a common part and a PHY-specific part, as shown in Fig. 6. The common part includes two mandatory and fixed-length parameters, management message type and configuration change count (CCC), and numbers of variable-length type-length-value (TLV) encoding information. Each TLV indicates the setting of one type of parameter. The fragmentable broadcast message uses the same parameters of the common part for RSs in an MR-BS service cell. The PHY-specific part is composed of burst profile encodings, which describe the PHY characteristics of the uplink or downlink channel.

![Fig. 4. Example of the TBFS. "MPDU (k)" and "Relay MPDU (k)" indicate that the connection whose CID is k is used for forwarding the MPDU and Relay MPDU, respectively. (a) Network topology, tunnel establishment, and forwarding tables. (b) Procedure for MPDU forwarding.](image-url)
Fig. 5. Example of B-CTFS operations. (a) Network topology. (b) Broadcast management message forwarding. (c) Fragmentable broadcast management message forwarding.

Fig. 6. DCD/UCD management message format in IEEE 802.16.
The B-CTFS is widely known for its simplicity because RSs only perform a CID translation to forward the broadcast and fragmentable broadcast management messages to their subordinate stations. Although the B-CTFS can reduce the transmission latency and the used resource overhead on the access links, it suffers the common part redundancy problem while forwarding the fragmentable broadcast management messages. In this study, we define the common part redundancy problem as a scenario in which a certain number of redundant transmissions of the common parameters of the fragmentable broadcast management messages appear. The problem is more likely to generate explicit resource wastage and limit the capacity of the overall system. As shown in Fig. 5(c), the MR-BS in the B-CTFS must unicast the fragmentable broadcast MPDU to RS1 and RS2 separately. The two fragmentable broadcast MPDUs are differentiated by using different RS primary CIDs on the relay links. Apparently, the common part of the MPDUs is transmitted twice, thereby causing unnecessary resource wastage.

To tackle the common part redundancy problem, in this study, we improve the B-CTFS and develop a resource-efficient forwarding scheme, called the enhanced CID-translated forwarding scheme (E-CTFS). The main concept of the E-CTFS is that it uses a multicast manner to forward the common part of the fragmentable broadcast management messages on the relay links to reduce resource wastage. Because the MR-BS in IEEE 802.16j MR networks is in charge of describing the DCD and UCD messages, it can sort out the common parameters and arrange each RS into the appropriate group by using the multicast management CID. The MR-BS uses the multicast management CID to forward the common part of messages on the relay links, while exhibited a broadcast behavior. They use the RS primary CID to forward the PHY-specific part of the fragmentable broadcast messages on the relay links. On the other hand, the MR-BS and non-access RSs forward the PHY-specific part of the fragmentable broadcast messages on the relay links, while exhibited a broadcast behavior. They use the RS primary CID to forward the PHY-specific part of the messages. Fig. 7 shows the format of the DCD and UCD management message in the E-CTFS. In addition to the original common and PHY-specific parts, the messages contain additional fields such as common header (CH), specific header (SH), type, reserved, and CCC. The CH is the common header with a multicast CID, and the SH is the specific header with an RS primary CID. To assist in forwarding the specific part, the proposed E-CTFS considers the newly added type, reserved, and CCC fields in the message; further, the value of CCC must be identical to that in the common part.

In this study, we use the network topology shown in Fig. 5(a) and consider the DCD management message forwarding as an example to illustrate the forwarding procedure for the fragmentable broadcast messages in the E-CTFS. As shown in Fig. 8, the MR-BS transmits the common parameters of the messages to RS1 and RS2 using the multicast management CID and then, transmits the corresponding PHY-specific parameters of the individual access RS (RS1 and RS2) by using its primary CID. If RS1 and RS2 successfully decode the common part of the received DCD management message, they are aware that they have to forward the received message to MS1 and MS2, respectively, because of the indication of the management message type field in the common part. RS1 and RS2 then wait for their own PHY-specific parts. Upon receiving the latest PHY-specific
parts, RS1 and RS2 reconstruct the common parameters that they have received and all the associated PHY-specific parameters to complete the DCD management messages. RS1 and RS2 set the CID of the new DCD management messages as the fragmentable broadcast CIDs instead of the original RS primary CIDs and then, forward the newly generated messages to MS1 and MS2, respectively.

4. Performance analysis

In this section, we present the analysis of the forwarding overhead of different forwarding schemes used for forwarding the fragmentable broadcast messages. The forwarding overhead that we consider in this study is defined as the total amount of system resources that the MR-BS and all RSs use for message forwarding. Assume that all the messages to each MS are identical in length, and the amount of available bandwidth is sufficient to support the total bandwidth request. The MR-BS and RSs are assumed to have a well-designed bandwidth allocation and scheduling approach to guarantee that one-hop message forwarding can be accomplished in a frame. In the E-CTFS, the common part ratio (CPR), defined as the ratio of the length occupied for transmitting the common part to the length occupied for the entire management message, significantly dominates the performance. In this study, we consider this ratio in the analysis. Table 2 lists all the notations used in the analysis.

The TBFS establishes a tunnel between the MR-BS and the access RSs and uses tunnel headers to forward messages on the relay links. This tunnel header apparently results in an additional forwarding overhead, which can be derived as

$$\text{OH}_{\text{TBFS-relay}} = L_T \cdot N_{RS}. \quad (1)$$

The TBFS also forwards messages to the corresponding MS on each access link. As a result, the forwarding overhead on the access links in the TBFS can be determined as follows:

$$\text{OH}_{\text{TBFS-access}} = L_C \cdot N_{RS} + L_C \cdot \sum_{i=1}^{N_{RS}} N_{MS}. \quad (2)$$

By using Eqs. (1) and (2), we obtain the total amount of forwarding overhead in the TBFS as follows:

$$\text{OH}_{\text{TBFS-total}} = \text{OH}_{\text{TBFS-relay}} + \text{OH}_{\text{TBFS-access}} = L_T \cdot N_{RS} + L_C \cdot N_{MS} + L_C \cdot \sum_{i=1}^{N_{RS}} N_{MS} = L_T \cdot N_{RS} + L_C \cdot \left( N_{MS} + \sum_{i=1}^{N_{RS}} N_{MS} \right). \quad (3)$$

The B-CTFS uses a CID-translated strategy to forward messages. It performs message forwarding on the relay links in a unicast manner. Thus, we derive the forwarding overhead on the relay links in the B-CTFS as follows:

$$\text{OH}_{\text{B-CTFS-relay}} = L_C \cdot N_{RS}. \quad (4)$$

In the B-CTFS, the forwarding overhead on the access links is twofold: the overhead on the links connecting the MR-BS and its immediate MSs and the overhead on the links connecting the RSs and their serving MSs. Therefore, we derive the forwarding overhead on the access links in the B-CTFS as follows:

$$\text{OH}_{\text{B-CTFS-access}} = L_C \cdot N_{MS} + L_C \cdot \sum_{i=1}^{N_{RS}} N_{MS}. \quad (5)$$

Table 2

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>( L_{MSDU} )</td>
<td>Length of MSDU of fragmentable management message</td>
</tr>
<tr>
<td>( L_{HDR} )</td>
<td>Length of generic MAC headers</td>
</tr>
<tr>
<td>( L_{CRC} )</td>
<td>Length of CRC of generic MPDUs</td>
</tr>
<tr>
<td>( L_C )</td>
<td>Length of MPDU in the connection</td>
</tr>
<tr>
<td>( L_{HDR} )</td>
<td>Length of relay MAC headers</td>
</tr>
<tr>
<td>( L_{CRC} )</td>
<td>Length of CRC of relay MPDUs</td>
</tr>
<tr>
<td>( L_T )</td>
<td>Length of MPDU in the tunnel</td>
</tr>
<tr>
<td>( N_{RS} )</td>
<td>Number of MSs directly served by the MR-BS</td>
</tr>
<tr>
<td>( N_{MS} )</td>
<td>Number of MSs directly served by ( R_S_i )</td>
</tr>
<tr>
<td>( N_{NT-RS} )</td>
<td>Number of access NT-RSs in the network</td>
</tr>
<tr>
<td>( R_S_i )</td>
<td>The ( i )th access NT-RS</td>
</tr>
<tr>
<td>( N_{MS} )</td>
<td>The ( j )th MS directly served by ( R_S_i )</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Ratio of the common part to the entire message</td>
</tr>
</tbody>
</table>
By using Eqs. (4) and (5), we obtain the total amount of forwarding overhead in the B-CTFS as follows:

\[
\begin{align*}
\text{OH}_{\text{total}}^{B-CTFS} &= \text{OH}_{\text{relay}}^{B-CTFS} + \text{OH}_{\text{access}}^{B-CTFS} \\
&= L_c \cdot (N_{RS} + L_c \cdot N_{BS} + L_c \cdot N_{MS} + \sum_{i=1}^{N_{MS}} N_{MS}^i) \\
&= (L_{HDR}^E + L_{MSDU}^E + L_{CRC}^E) \cdot \left( N_{RS} + N_{BS} + \sum_{i=1}^{N_{MS}} N_{MS}^i \right).
\end{align*}
\]  

(6)

The E-CTFS enables the MR-BS to transmit the common parameters prior to the PHY-specific parameters to access RSs. The forwarding overhead on the relay links in the E-CTFS can be derived from

\[
\begin{align*}
\text{OH}_{\text{relay}}^{E-CTFS} &= (L_{HDR}^E + \gamma \cdot L_{MSDU}^E + L_{CRC}^E) + \left( L_{HDR}^E + (1 - \gamma) \cdot L_{MSDU}^E + L_{CRC}^E \right) \cdot N_{RS}.
\end{align*}
\]  

(7)

The E-CTFS forwards messages to the corresponding MS on each access link. Therefore, the forwarding overhead on the access links in the E-CTFS can be obtained as follows:

\[
\begin{align*}
\text{OH}_{\text{access}}^{E-CTFS} &= L_c \cdot N_{BS}^E + L_c \cdot \sum_{i=1}^{N_{MS}} N_{MS}^i = (L_{HDR}^E + L_{MSDU}^E + L_{CRC}^E) \cdot \left( N_{BS}^E + \sum_{i=1}^{N_{MS}} N_{MS}^i \right).
\end{align*}
\]  

(8)

By using Eqs. (7) and (8), we obtain the total amount of forwarding overhead in the E-CTFS as follows:

\[
\begin{align*}
\text{OH}_{\text{total}}^{E-CTFS} &= \text{OH}_{\text{relay}}^{E-CTFS} + \text{OH}_{\text{access}}^{E-CTFS} \\
&= (L_{HDR}^E + \gamma \cdot L_{MSDU}^E + L_{CRC}^E) + \left( L_{HDR}^E + (1 - \gamma) \cdot L_{MSDU}^E + L_{CRC}^E \right) \cdot N_{RS} + L_c \cdot N_{BS}^E + L_c \cdot \sum_{i=1}^{N_{MS}} N_{MS}^i \\
&= (L_{HDR}^E + \gamma \cdot L_{MSDU}^E + L_{CRC}^E) + \left( L_{HDR}^E + (1 - \gamma) \cdot L_{MSDU}^E + L_{CRC}^E \right) \cdot N_{RS} + \left( L_{HDR}^E + L_{MSDU}^E + L_{CRC}^E \right) \cdot \left( N_{BS}^E + \sum_{i=1}^{N_{MS}} N_{MS}^i \right)
\end{align*}
\]

(9)

5. Performance evaluation

In this section, we describe the environment and parameters of the analysis, followed by the numerical results.

5.1. Environment and parameter setup

This study considers a two-hop MR network in typical urban environments [12] and adopts the in-band non-transparent frame structure defined in [13]. As shown in Fig. 9, an MR-BS cell is partitioned into three sectors to support the three-segment scenario. A three-sector MR-BS is located at the center of the cell, and six non-transparent RSs (NT-RSs) are deployed in a hexagonal lattice shape. Each NT-RS uses an omni-directional antenna to serve the attached MSs. The MR-BS and the two NT-RSs use different frequency segments, and assume that the frequency reuse factor is 3 and 1 on the access and the relay links, respectively. All MSs are randomly scattered within the coverage, and each MS can be served by the MR-BS directly or by a single NT-RS.

We use the 64-QAM modulation with a 3/4 coding rate scheme on the relay links and the QPSK modulation with a 1/2 coding rate and one repetition scheme on the access links. Without loss of generality, assume that the DCD and UCD management messages are fixed in size. This ensures that the radio resource used for forwarding these messages are also fixed at each NT-RS. The length of the MAC service data unit (MSDU) of every DCD management message forwarded on the access links is 400 bytes. The length of every UCD management message forwarded on the access links is 300 bytes. The other system parameters are based on [12,14] and are listed in Table 3.

Fig. 9. Two-hop three-sector MR cell, in which different colors represent the separate frequency segments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
5.2. Results

Because the CBFS in nature supports only unicast traffic forwarding, in this study, we do not consider the CBFS in the performance evaluation. Moreover, only the fragmentable management messages, such as the DCD message and the UCD message, are considered because the E-CTFS is specially designed for these types of messages. In this section, we first validate the used resource on the relay links of different schemes and then, compare the total amount of resource on the relay and the access links that different schemes use. In this study, we also investigate the transmission latency of different forwarding schemes.

5.2.1. Used resource on relay links

Fig. 10 shows the used resource on the relay links of the TBFS, B-CTFS, and E-CTFS for transmitting the DCD and UCD management messages. The TBFS and B-CTFS use the constantly used amounts of resources (approximately 2520 bytes and 2460 bytes, respectively) when the CPR increases. Note that the TBFS uses more resources than the B-CTFS does. This is because the TBFS needs additional resources to deal with the tunnel headers. The system resources that the E-CTFS uses decrease linearly with an increase in the CPR. The maximum and minimum used resources are 2473 and 473 bytes, respectively. The E-CTFS efficiently re-packs an MPDU for a common part and a PHY-specific part and transmits the common part on the relay links only once. Therefore, the higher the CPR is, the less is the system resource that the E-CTFS uses. This also leads to a reduction of the used resources compared with the B-CTFS.

**Table 3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame length</td>
<td>5 ms</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>11.2 MHz</td>
</tr>
<tr>
<td>FFT size (NFFT)</td>
<td>1024</td>
</tr>
<tr>
<td>Number of sub-channels</td>
<td>30 (DL), 35 (UL)</td>
</tr>
<tr>
<td>Sub-carrier frequency spacing</td>
<td>10.94 KHz</td>
</tr>
<tr>
<td>Useful symbol time ($T_u = 1/f$)</td>
<td>91.4 µs</td>
</tr>
<tr>
<td>Guard time ($T_g = T_u/8$)</td>
<td>11.4 µs</td>
</tr>
<tr>
<td>OFDMA symbol duration</td>
<td>102.9 µs</td>
</tr>
<tr>
<td>Number of OFDMA symbols</td>
<td>48</td>
</tr>
<tr>
<td>Ratio of used OFDMA symbols</td>
<td>23(DL):24(UL)</td>
</tr>
<tr>
<td>Radius of the cell coverage</td>
<td>500 m</td>
</tr>
<tr>
<td>Distance between MR-BS and each RS</td>
<td>300 m</td>
</tr>
<tr>
<td>Length of generic MPDU headers</td>
<td>6 bytes</td>
</tr>
<tr>
<td>Length of relay MAC MPDU headers</td>
<td>6 bytes</td>
</tr>
<tr>
<td>Length of CRC of generic MPDUs</td>
<td>4 bytes</td>
</tr>
<tr>
<td>Length of CRC of relay MAC MPDUs</td>
<td>4 bytes</td>
</tr>
<tr>
<td>Number of MSs in an MR-BS cell</td>
<td>100, 200, 300</td>
</tr>
</tbody>
</table>

**Fig. 10.** Used resource on the relay links of the TBFS, B-CTFS, and E-CTFS for forwarding the fragmentable broadcast messages. (a) DCD message forwarding. (b) UCD message forwarding.
As shown in Fig. 10(b), the TBFS and B-CTFS use approximately a constant amount of resources (1920 bytes and 1860 bytes, respectively) to forward the UCD management messages when the CPR increases. On the other hand, the amount of resources that the E-CTFS uses apparently decreases with an increase in the CPR. When the CPR is 1, the TBFS, B-CTFS, and E-CTFS require 1920 bytes, 1860 bytes, and 376 bytes, respectively. In fact, the CID-translated strategy used in the B-CTFS and E-CTFS reduces the amount of resources used in comparison with the TBFS. Moreover, the E-CTFS uses fewer resources than the B-CTFS because it uses a multicast strategy.

Fig. 10(a) and (b) present a similar trend in that the E-CTFS uses less system resources on the relay links than the TBFS and the B-CTFS do when forwarding the DCD and UCD messages, respectively. When forwarding the DCD management messages, the improvement of the E-CTFS in terms of the amount of resources used, compared with the TBFS and the B-CTFS is approximately from 1.87% to 81.23% and from 1.10% to 80.77%, respectively, with an increase in the CPR. When forwarding the UCD management messages, the improvement of the E-CTFS in terms of the amount of resources used, compared with the TBFS and the B-CTFS is approximately from 2.29% to 80.42% and from 0.75% to 79.78%, respectively, with an increase in the CPR. This can be validated in Fig. 11.

5.2.2. Total amount of resources used

In addition to forwarding on relay links, message forwarding on access links also requires the use of system resources. Apparently, the number of MSs influences the amount of resources used on the access links. In this study, we compare the total amount of resources used among different forwarding schemes, as shown in Figs. 12 and 13. Because message forwarding on access links is based on the unicast approach, the amount of resources used of access links increases with an increase in the number of MSs. Increasing the amount of resources used on the access links apparently leads to an increase in the total amount of resources used. Figs. 12 and 13 also show that the total amount of resources used by the TBFS, B-CTFS, and E-CTFS increases with an increase in the number of MSs. Moreover, the trends of increases in the amount of resources

Fig. 11. Improvement of the E-CTFS in terms of the amount of resources used as compared to the TBFS and B-CTFS. (a) DCD message forwarding. (b) UCD message forwarding.

Fig. 12. Total amount of resources used by the TBFS, B-CTFS, and E-CTFS to forward DCD messages with different numbers of MSs. (a) 100 MSs. (b) 200 MSs. (c) 300 MSs.
used for different numbers of MSs are identical. We derive that the number of MSs is almost unrelated to the forwarding performance of the TBFS, B-CTFS, and E-CTFS.

As shown in Figs. 12 and 13, the total amount of resources used by the TBFS and B-CTFS remains constant with an increase in the CPR, and the total amount of resources used by the E-CTFS decreases with an increase in the CPR. This is because the E-CTFS transmits the common part of messages in a multicast manner. Thus, the higher the common part ratio is, the more is the amount of used resources saved by the E-CTFS.

5.2.3. Transmission latency

In general, the higher the amount of resources a scheme uses, a longer will be the transmission latency of the scheme. On the basis of Figs. 10(a) and (b), we can derive that the TBFS generates a longer latency to transmit the DCD and UCD massages than the B-CTFS and E-CTFS, and the transmission time of the E-CTFS decreases with an increase in the CPR. This can be validated in Fig. 14.

6. Conclusions

In this paper, we have proposed two efficient schemes, called the basic CID-translated forwarding scheme (B-CTFS) and the enhanced CID-translated forwarding scheme (E-CTFS), to forward downlink broadcast messages in IEEE 802.16j multihop relay networks. The central idea of the proposed B-CTFS and E-CTFS is that these schemes exploit an efficient CID-translated strategy. Because this strategy does not require any additional resources, the B-CTFS and E-CTFS can significantly reduce the forwarding overhead, compared with the traditional CID-based forwarding scheme and the tunnel-based forwarding scheme. As an enhanced scheme, the E-CTFS uses the multicast CID to forward the common part of messages on relay links and uses the fragmentable broadcast CID to forward the PHY-specific part of messages on access links. Thus,
it can reduce the amount of resources used compared with the B-CTFS. The performance evaluation reveals that compared with the TBFS, the B-CTFS reduces the amount of the resources used slightly, and the E-CTFS can significantly reduce the amount of resources used because it does not involve the use of relay MAC headers. The results also show that the used resource is independent of the number of MSs. Further, in this study, we evaluated the transmission latency for forwarding DCD and UCD management messages. The result reveals that the E-CTFS uses fewer system resources than the TBFS and the B-CTFS, thereby generating a short transmission latency. Our on-going research focuses on investigating the data forwarding scheme without the aid of CID information. Future research should also explore the solution to other issues, such as multicast and unicast data forwarding.

References


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