

Relay Performance Analysis of TTR and STR Relay Modes in IEEE 802.16j MMR System

Si-O Seo, Se-Jin Kim, Seung-Yeon Kim, Young-Il Kim, Hyong-Woo Lee, Seungwan Ryu, and Choong-Ho Cho

The IEEE802.16j standard uses non-transparent relay stations to extend coverage. There are two types of non-transparent relay modes, that is, the time-division transmit and receive (TTR) relay mode which can operate with one of two types of frame structures, a single-frame and multiframe structure, and the simultaneous transmit and receive (STR) relay mode. In this paper, we analyze the relay performance of TTR and STR relay modes in IEEE 802.16j MMR system. We also propose a fair resource allocation scheme for the downlink relay frame. Numerical results show that relay performance of the TTR with a single-frame or a multiframe structure and that of the STR relay modes are almost the same in a two-hop system. However, in a three-hop system, the TTR mode with a single-frame structure outperforms other relay modes.

Keywords: IEEE802.16j, mobile multihop relay, TTR, STR.

I. Introduction

Numerous standardization activities have been made for an orthogonal frequency division multiple access (OFDMA) IEEE802.16e system supporting mobile users in metropolitan areas [1], [2]. Standardization activities of the 802.16e-2005 were completed in 2005, and currently, enhancements of the 802.16e standard are under discussion. One such enhancement effort is cell coverage extension and link throughput enhancement. This IEEE 802.16j standard was published by the 802.16j task group (TG) [3]. The major difference between 802.16e and 802.16j is the existence of relay stations (RSs) for data communication as shown in Fig. 1. In the 802.16e system, a base station (BS) communicates with mobile stations (MSs) through single-hop wireless links. Conversely, in the 802.16j system, a multihop relay BS (MR-BS) communicates with MSs through multihop wireless links by deploying RSs between the MR-BS and MSs. Thus, MSs may communicate with the MR-BS directly or with RSs through multihop wireless links without being aware of the existence of an intermediate RS. Another enhancement effort is discussed by 802.16 maintenance TG (802.16m). A key difference between the 802.16m and the 802.16j standards is that the former is not constrained by legacy issues and hence is at liberty to design an entirely new radio access system [2]-[4].

The 802.16j standard defines two separate types of RSs: a transparent RS and a non-transparent RS. The transparent RS is designed to increase the link capacity of the MR-BS by covering coverage holes. Therefore, the transparent RSs are located inside the coverage of the MR-BS. In contrast, the non-transparent RS is designed to extend the coverage area of an MR-BS by deploying RSs at the edge of the coverage in low traffic areas.

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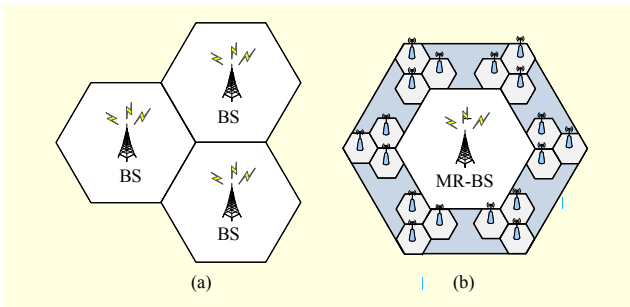


Fig. 1. (a) IEEE802.16e and (b) IEEE802.16j MMR system topologies.

The non-transparent RS may use two separate relay modes: a time-division transmit and receive (TTR) relay mode and a simultaneous transmit and receive (STR) relay mode. In this paper, we analyze the relay performance of the IEEE802.16j mobile multihop relay (MMR) system, focusing on two types of non-transparent relay modes.

The TTR and STR relay modes have recently been introduced in the 802.16j standard [5], but performance of those modes has not yet been actively studied. Many research issues related to TTR and STR relay modes were introduced in the Rewind Project [6]. This project presented many advantages and weaknesses of the two relay modes, without providing performance research results about the inter-cell interference effect and relay capacity analysis. Therefore, it is useful to analyze the relay performance of the two relay modes to estimate the coverage extension performance of the non-transparent relay-based MMR system.

In this paper, we analyze the downlink (DL) relay performance of the TTR and the STR relay modes of the non-transparent RS in the OFDMA and time-division-duplex (TDD)-based IEEE 802.16j. First, we analyze interference effects in the RSs. Next, we propose a fair resource allocation scheme for the DL relay frame. Finally, we present numerical analysis for maximum relay capacities of an MR-BS with the TTR and the STR relay modes, respectively.

The remainder of this paper is organized as follows. In section II, we briefly introduce the TTR and STR relay modes of 802.16j. In section III, after describing the system model, we analyze the system capacity by considering the interference effect and propose a fair DL frame resource allocation scheme. In section IV, we analyze the relay system performance for 2-hop and 3-hop relay systems. In section V, we discuss several open research issues with suggestions for improvement of the MMR system. In section VI, we conclude our paper.

II. TTR and STR Relay Modes in IEEE802.16j

The non-transparent RS of the IEEE802.16j system supports

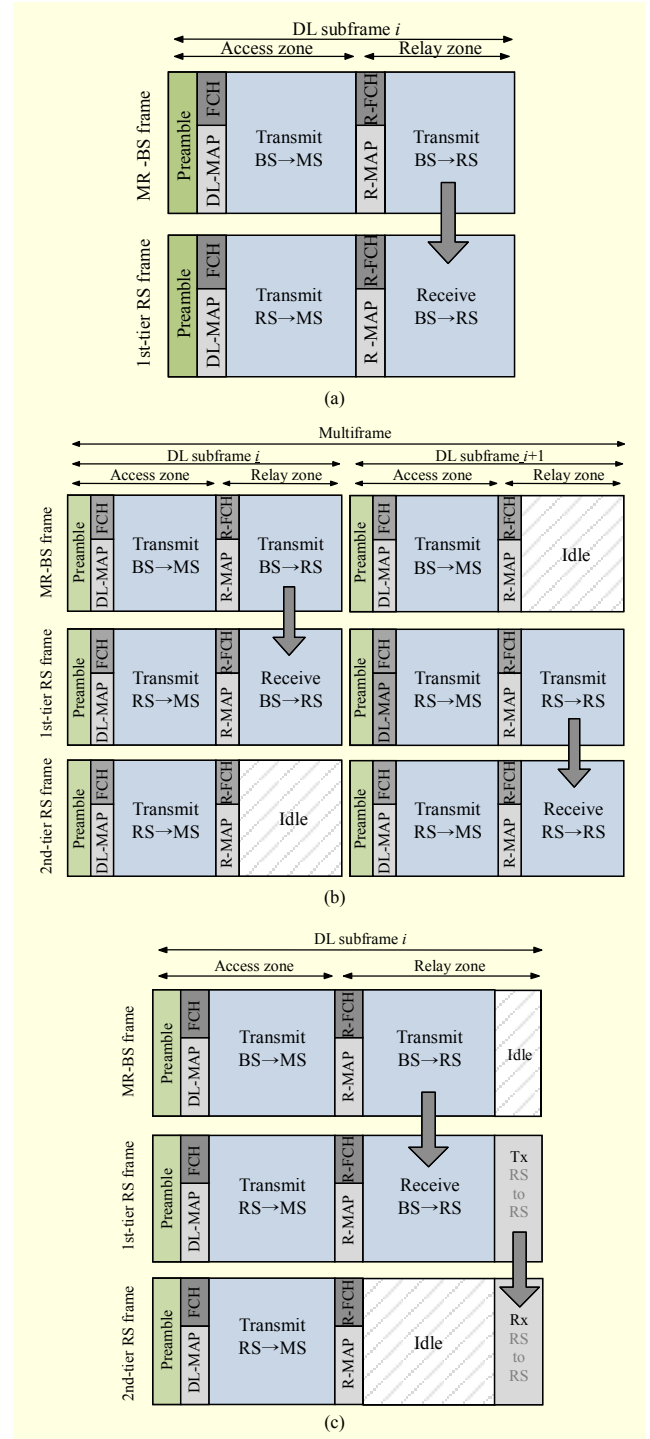


Fig. 2. DL frame structures for (a) 2-hop systems, (b) 3-hop systems with multiframe, and (c) 3-hop systems with single frame in TTR relay mode.

both single- and dual-radio RSs. The single-radio RS, also called the TTR relay mode RS, communicates with its superior and subordinates using the same radio frequency. The TTR relay mode RS also supports single-frame and multiframe structures.

Figure 2 shows the frame structures of the TTR relay mode for

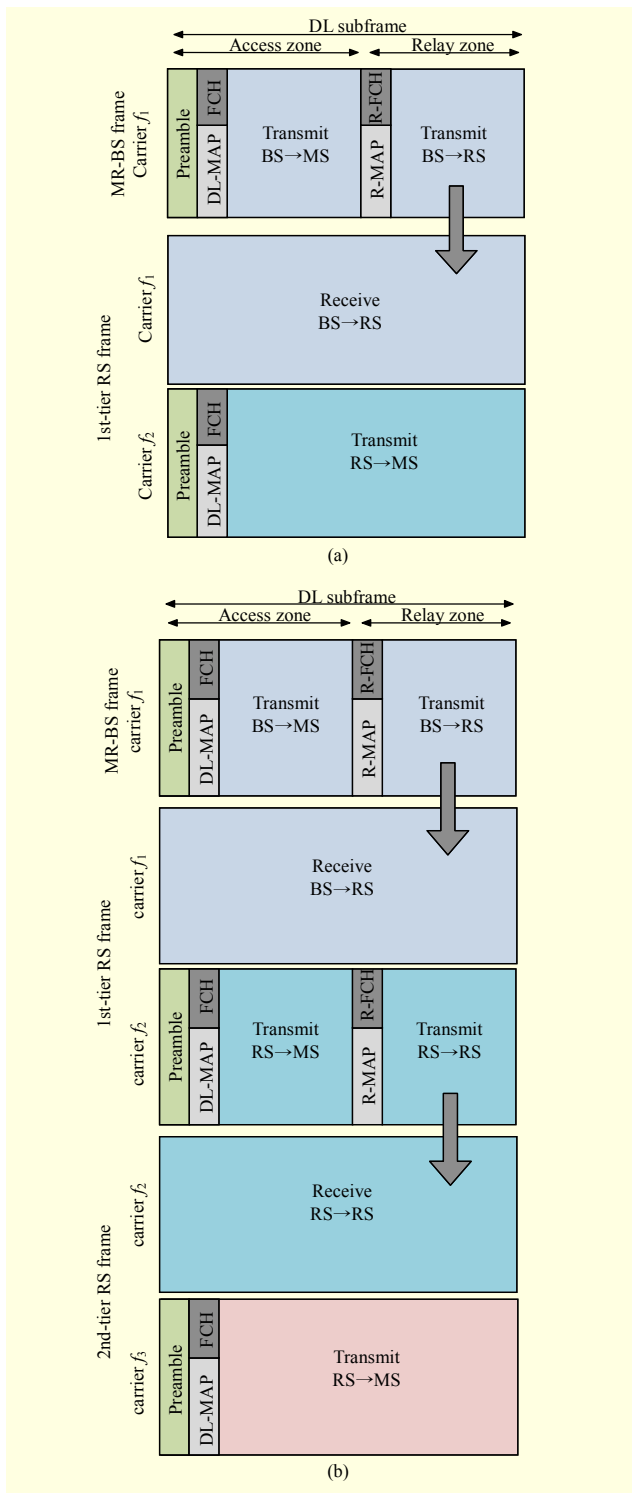


Fig. 3. DL frame structures for (a) 2-hop and (b) 3-hop systems in STR relay mode.

the 2-hop system (Fig. 2(a)) and the 3-hop system (Figs. 2(b) and (c)). In particular, for the 3-hop system, two types of frame structures, a single-frame and a multiframe structure, can be used in the TTR relay mode. The frame structure is divided into two

subframes: a DL subframe and an uplink (UL) subframe. As shown in Fig. 2, the DL subframe is divided into two zones: an access zone (AZ) and a relay zone (RZ). Figure 2(a) shows the DL subframe structure for the 2-hop relay system. The MR-BS and RSs communicate with their respective subordinate MSs separately using the AZ, and the MR-BS communicates with the subordinate RSs in the RZ. In the 2-hop system, since there is only the first-tier RSs, the same frame structure is used for the single-frame and multiframe structures as shown in Fig. 2(a).

The 3-hop system, shown in Fig. 2(b), operates similarly to the 2-hop system, except for the alternate operation of the RZ. In this case, the RZ is used for the first hop relay communication between the MR-BS and its subordinate RSs (that is, the first-tier RSs), and then used for the second hop relay communication between the first-tier RSs and the second-tier RSs. Figure 2(c) shows the DL subframe structure of the 3-hop TTR relay mode with a single-frame structure consisting of more than one RZ. The MR-BS and RSs are assigned to transmit, receive, or be idle in each RZ within the frame. As an example, the odd-hop RSs can be assigned to transmit in one DL RZ, while the MR-BS and even-hop RSs can be assigned to transmit in another DL RZ.

In contrast, the dual-radio RS, also called the STR relay mode RS, communicates with its superior stations and subordinate stations simultaneously using different radio frequencies. Therefore, the STR relay mode RS supports simultaneous communications with the MR-BS, RS, and MSs. The STR relay mode frame structures for 2-hop and 3-hop relay systems are described in Fig. 3. For example, suppose that the MR-BS is communicating with subordinate RSs using the radio frequency of f_1 in the 2-hop system. Then, the RS can receive data from the MR-BS using the radio frequency of f_1 while transmitting data to the subordinate stations using a different radio frequency of f_2 .

III. System models

1. Multihop Relay System Topologies

In this paper, we consider IEEE802.16j-based 2-hop and 3-hop multihop relay systems. Since the target area for non-transparent RS-based coverage extension is suburban or rural areas with a low or medium traffic density, we assume that each MR-BS and RS uses an omnidirectional antenna. Multiple-directional antennas can be used in the MR-BS and RSs. However, in this case, the relay performance will be highly dependent upon the location of each RS, and the optimal and fair frame resource allocation problem should be addressed at the same time. Therefore, in this paper, we consider a single omnidirectional-antenna-based relay system for the convenience of analytic modeling and analysis.

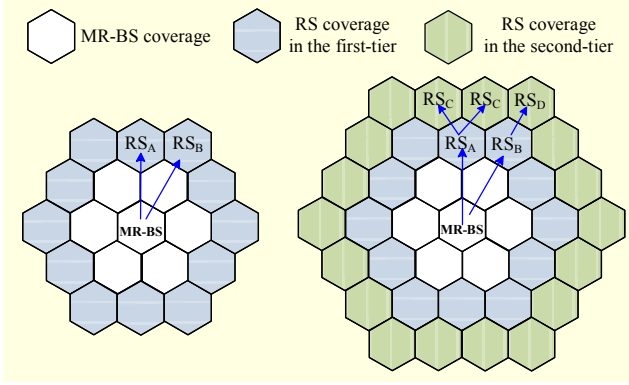


Fig. 4. 2-hop and 3-hop relay topology models.

Consequently, for the convenience of numerical modeling and analysis, we assume that each RS has single unit hexagonal cell coverage. By considering the difference of transmission power between an RS and the MR-BS, the MR-BS coverage is assumed to be seven hexagonal unit cells, and the tower is located in the center. Figure 4 shows hexagonal cell-based 2-hop and 3-hop multihop relay topologies. Then, the MR-BS has twelve surrounding first-tier subordinate RSs, and eighteen surrounding second-tier subordinate RSs in the case of the 3-hop relay topology. Therefore, users located within coverage of the MR-BS coverage, that is, within the 7 unit cells in the center of the topology, communicate directly with the MR-BS using a 1-hop link. However, users located within coverage of an RS communicate indirectly with the MR-BS through 2-hop or 3-hop links through the first-tier and the second-tier RSs respectively.

As shown in Figure 4, the first-tier RSs can be grouped into two types, type A (RS_A) and type B (RS_B), based on the distance between the MR-BS and the RS. In addition, the second-tier RSs also can be grouped into two types: type C (RS_C) and type D (RS_D). Then, a type A first-tier RS has two subordinate second-tier RSs of type C, while a type B first-tier RS has one type D subordinate RS.

2. Propagation Model

We assume that two relay links, between the MR-BS and RS (BS-RS) and between the first- and second-tier RSs (RS-RS), are reliable and in line-of-sight (LOS). The LOS assumption can be realized by placing RSs at a carefully selected location, such as the roof of a building. We use the IEEE 802.16 type D path loss model for the free space LOS path loss model [7] as follows:

$$PL(\text{dB}) = \begin{cases} 20 \log \left(\frac{4\pi d}{\lambda} \right) & \text{for } d < d'_0, \\ A + 10\gamma \log \left(\frac{d}{d_0} \right) + \Delta PL_f + \Delta PL_{h_t} & \text{for } d > d'_0, \end{cases} \quad (1)$$

where d is the geographic distance between the transmitter and the receiver and the reference distance (d_0) is set to 100 m. $A = 20 \cdot \log(4\pi d'_0 / \lambda)$, and λ is the wavelength in meters. $\gamma = a - b \cdot h_b + c/h_b$ and $d'_0 = d_0 \cdot 10^{-((\Delta PL_f + \Delta PL_{h_t})/10\gamma)}$. ΔPL_f is the correction factor for carrier frequency and ΔPL_{h_t} is the height of the receiving antenna. Then,

$$\Delta PL_f = 6 \log_2 \left(\frac{f(\text{MHz})}{2000} \right), \quad (2)$$

$$\Delta PL_{h_t} = \begin{cases} -10 \log \left(\frac{h_t}{3} \right) & \text{for } h_t \leq 3 \text{ m}, \\ -20 \log \left(\frac{h_t}{3} \right) & \text{for } h_t > 3 \text{ m}, \end{cases} \quad (3)$$

where f is the carrier frequency in MHz, h_b is the height of the transmitting MR-BS (or RS) antenna, which is a value between 10 m and 80 m, and h_t is the height of the receiving RS antenna. Finally, values for other parameters, a , b , and c are set to 3.6, 0.005, and 20, respectively.

3. Analyses of Interference and System Capacity

To analyze the system capacities of the multihop topologies shown in Fig. 4, the relationship of the signal to interference and noise ratio (SINR) is of great importance in estimating the system capacity. In our system model, there are three interference scenarios for the DL subframe in calculating the SINR of each link. The first scenario involves interferences to MSs, in that interferences from the reference cells and the neighboring MR-BSs and RSs cells could be considered. However, since our analysis aims to evaluate the DL relay performance of the MR-BS and RSs, these interferences are not considered in our analysis. The second scenario deals with the interference to the first-tier RSs from the neighboring MR-BSs. The third scenario deals with interference to the second-tier RSs from the first-tier RSs of the same and the neighboring relay systems. Figure 5 describes the second and the third interference scenarios. In this paper, the second and the third scenarios are considered in analyzing relay performance of the TTR and STR relay modes for the 2-hop and the 3-hop systems.

We calculated the relay capacities of both the MR-BS and RSs for the 2-hop and the 3-hop relay systems using Shannon's equation. The co-channel interference and receiver's thermal noise are considered together in calculating the SINR value:

$$C = B \cdot \log_2 \left(1 + \frac{S}{N + \sum_{n=1}^{n=i} I_n} \right), \quad (4)$$

where C is the maximum MR-BS capacity in bps, B is the bandwidth of the channel in hertz, S is the received signal

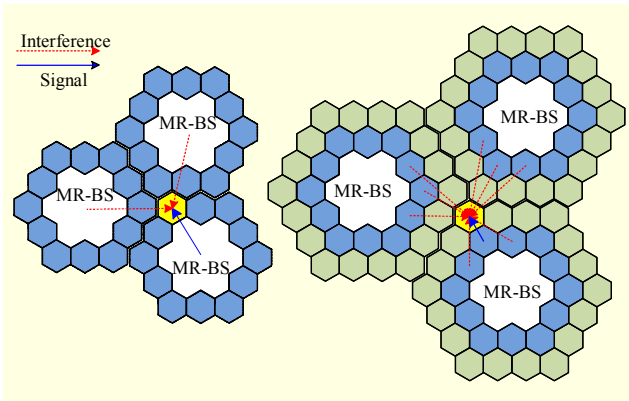


Fig. 5. Two interference scenarios to the first and the second RSs.

power, N is the thermal noise of the receiver, i is the number of interfering cells, and I_n is the co-channel interference from $n \geq 1$ neighboring MR-BSs and RSs.

4. Frequency Allocation Scheme

In our model, the SINR between the MR-BS and the first-tier RSs is calculated separately for each type of first-tier RS, type A (RS_A), and type B (RS_B). Interference to these RSs differs due to the different distances from the MR-BS to each type of first-tier RSs. Since the system capacity is proportional to the SINR, each type of first-tier RS has a different relay capacity. In the case of the 3-hop relay system, each type of first-tier RSs has a different number of subordinate second-tier RSs, two for type A and one for type B, as shown in Fig. 4. Thus, a sophisticated frame resource allocation scheme is required to provide relay capacity fairly to the last subordinate RSs that communicate with the MSs directly.

In this paper, we propose a fair resource allocation method that is capable to support the same relay capacity to the subordinate RSs in both of the 2-hop and the 3-hop relay system. In the proposed fair relay capacity allocation method, different SINR values of each type of RSs stem from the distance differences between an MS-BS and its subordinate RSs and between the first-tier and the second-tier RSs are considered in designing DL subframes resource allocation so as to allocate uniform relay capacity to all subordinate RSs.

Since the MR-BS frame is assumed to use the TDD mode, the problem becomes how to divide the DL subframe into AZ and RZ, and how to allocate RZ resource to each type of RS. With a fair frame resource allocation scheme, every RS is able to support the same DL relay capacity. In particular, with the STR relay mode, the frequency band must also be divided into subbands for MR-BS and for RS frames optimally. In this section, we first propose a fair frame resource allocation scheme focusing on the DL subframe. Then, we propose an

optimal frequency allocation scheme for the 2-hop and the 3-hop STR relay mode.

A. Fair Frame Resource Allocation Scheme

We assume that the relay frame is divided into DL and UL subframes at the rate of two to one. The DL subframe is divided into AZ and RZ at the ratio of the size of the MR-BS coverage to that of the total RS coverage. For regular topologies, the DL subframe of every relay system is divided into AZ and RZ at a fixed rate. For example, for 2-hop and 3-hop topologies, shown in Fig. 4, the DL subframe is divided in the ratios of 7 to 12 and 7 to 30, respectively. Note that these DL subframe division ratios are determined by the number of unit hexagonal cells covered by the MR-BS and RSs in each 2-hop and 3-hop relay topology as shown in Fig. 4. Frame overhead is not considered in designing a fair frame resource allocation scheme for the convenience of numerical modeling and analysis.

The relay traffic to an RS consists of the traffic to users who communicate with the RS directly and the relay traffic to the subordinate RSs (if there are any subordinate RSs). Since there are two types of RSs, RS_A and RS_B , the RZ resource in the MR-BS DL subframe must be allocated to each type of RSs separately, considering not only the relay capacity of each type RS but also the number of its subordinate RSs. The relay capacity of each type RS, $C(i)$, $i = A, B$ is estimated from Shannon's equation. Then, the amount of resource that should be allocated to each type RS is $C(i) * \varphi_i * E[r_i]$, where φ_i , $i = A, B$, is the number of RSs supported by the type i RS including itself and $E[r_i]$, $i = A, B$, is the expected amount of resource allocation for type i RS. Then, $\varphi_i = 1$ for the 2-hop system regardless of RS type, and $\varphi_A = 3$ and $\varphi_B = 3$ for a 3-hop system. Suppose that r_{AB} is the ratio of the expected resource allocation for type A RS to that of type B RS, it is given by equation (5):

$$r_{AB} = \frac{E[r_A]}{E[r_B]} = \frac{\varphi_B C(A)}{\varphi_A C(B)}. \quad (5)$$

The minimum required relay capacity for each type of RS, $C(R, i)$, $i = A, B$, is

$$C(R, i) = C(i) \times L_{DL} \times \frac{n(R, i)}{n(B) + n(R, k)} \times \frac{E[r_i]}{\sum_i \alpha_i E[r_i]}, \quad (6)$$

where L_{DL} is the ratio of the length of the DL subframe to that of the total frame, $n(B)$ and $n(R, k)$, $k = 2, 3$, are the number of unit cells covered by the MR-BS and the total number of RSs in the k -hop system, α_i , $i = A$ and B , is the number of type RSs at the first-tier. For example, $\alpha_A = \alpha_B = 6$ for the relay system topologies as shown in Fig. 4. Then, after estimating $C(A)$ and

$C(B)$ using Shannon's equation, $C(R, i)$ is obtained from (6) for each k -hop system, where $k=2$ or 3. For the 3-hop system, capacities of RS_C and RS_D , $C(j), j=C, D$, are given by

$$C(j) = \begin{cases} C(R, A) \frac{1}{\varphi_A}, j = C, \\ C(R, B) \frac{1}{\varphi_B}, j = D. \end{cases} \quad (7)$$

B. Frequency Allocation Scheme for the STR Relay Mode.

In the STR system, the frequency band is divided into two subbands, one for the MR-BS frame and the other for RSs. We propose a frequency allocation scheme for the STR relay mode that is able to provide a fair relay capacity to all RSs. As mentioned earlier, from the TDD, the DL subframe is divided into two zones, an AZ and an RZ, at the rate of $n(B)$ to $n(R, k)$, $k=2, 3$.

Frequency allocation for the 2-hop STR system.

We first propose a frequency allocation scheme for the 2-hop STR relay system.

As shown in Fig. 4, it is assumed that an MR-BS is serving n surrounding first-tier subordinate RSs. Then, as shown in Fig. 6, in the STR mode, the total amount of frequency, f_T , is divided into two subbands, f_1 and f_2 , for the MR-BS and each of the first-tier RS, respectively. With this relaying environment, the relay capacity of an MR-BS for its n subordinate RSs, C_{BS_RZ} , should be larger than the total access capacity of n first-tier RSs, $\sum_{i=1}^n C_{RS_AZi}$, as below:

$$C_{BS_RZ} \geq \sum_{i=1}^n C_{RS_AZi}, \quad (8)$$

where i is the number of first-tier RSs.

Meanwhile, a first-tier RS can support all the traffic relayed from the MR-BS to its subordinate MSs when its AZ resource is equivalent to the amount of RZ resource of an MR-BS allocated to a first-tier RS.

Suppose that FR_{BS} and FR_{RS} are the number of DL subframe

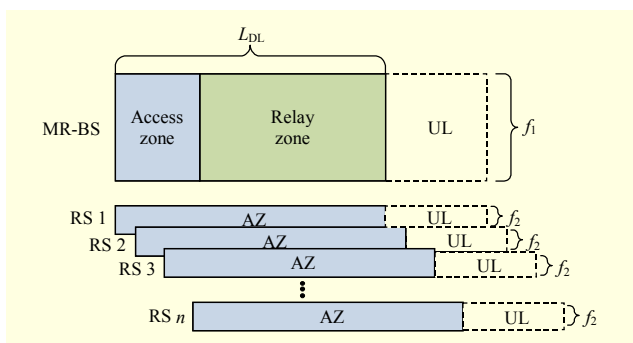


Fig. 6. DL subframe structure and frequency band allocation for MR-BS and each of the first-tier RSs.

resources allocated to the MR-BS and each first-tier RS, respectively. The length of the RZ of the MR-BS subframe is $L_{DL} \cdot n(R, k)/(n(B)+n(R, 2))$, and thus FR_{BS} is given by

$$FR_{BS} = f_1 \times L_{DL} \times \frac{n(R, 2)}{n(B) + n(R, 2)}. \quad (9)$$

Since there are $n(R, 2)$ RSs in the 2-hop system and each RS can use the whole portion of the DL frame length to communicate with MSs, $FR_{RS} = f_2 \times L_{DL}$. Note that the amount of resource for the RZ of the MR-BS should be sufficiently large to support all the relay traffic to its subordinate RSs. Consequently, we have the following equation:

$$FR_{BS} = f_1 \times L_{DL} \times \frac{n(R, 2)}{n(B) + n(R, 2)} \geq f_2 \times L_{DL}. \quad (10)$$

Finally, we can obtain the optimal amount of each subband, f_1 and f_2 , by setting the inequality equation (10) to an equality one. For example, $n(B)=7$ and $n(R, 2)=12$ for the 2-hop system as shown in Fig. 4. Then, $FR_{BS} = f_1 \times L_{DL} \times (12/19) = 12 \times (f_T - f_1) \times L_{DL}$, and thus $f_1 = (19/20)f_T$. In other words, at least 95% of the frequency band is allocated to the MR-BS, and at most 5% of the frequency band is allocated to each of the first tier RSs.

Frequency allocation for the 3-hop STR system.

Similar to the frequency allocation for the 2-hop STR system, we can obtain optimal frequency band allocation for the 3-hop relay system. In the 3-hop system, a first-tier RS should support up to m subordinate second-tier RSs as shown in Fig. 4. As shown in Fig. 7, in the STR mode, the total amount of frequency, f_T , is divided into three subbands, f_1 , f_2 , and f_3 for the MR-BS, each of the first-tier RS, and each of the second-tier RSs, respectively. Then, relay capacity of an MR-BS for its n subordinate RSs, C_{BS_RZ} , should be larger than the total amount

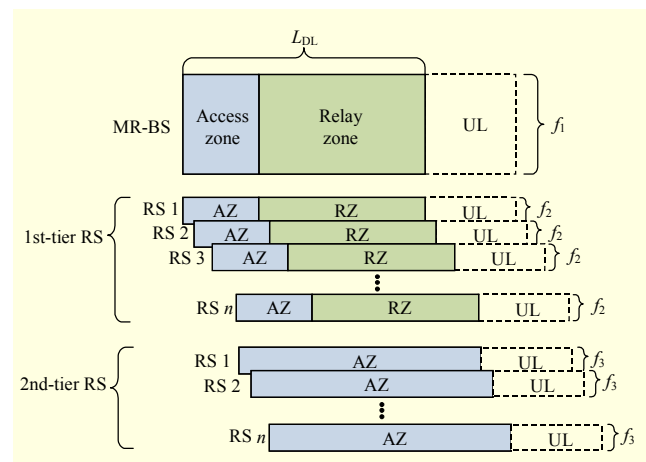


Fig. 7. DL subframe structure and frequency band allocation for MR-BS and each of the first- and the second-tier RSs.

of capacity of n first-tier RSs which should be able to support its subordinate MSs and subordinate second-tier RSs at the same time. The capacity of a first-tier RS consists of two parts, the relay capacity for its subordinate MSs, C_{RS1_AZi} , and the relay capacity for its subordinate up to m second-tier RSs, C_{RS1_RZi} . Therefore, we obtain the following capacity constraint:

$$C_{BS_RZ} \geq \sum_{i=1}^n (C_{RS1_AZi} + C_{RS1_RZi}). \quad (11)$$

In addition, the relay capacity of each first-tier RS should be larger than the total amount of relay capacity of its m subordinate second-tier RSs as

$$C_{RS1_RZi} \geq \sum_{j=1}^m C_{RS2_AZj}, \quad (12)$$

where C_{RZ2_RZj} is the relay capacity of a second-tier RS j , $j=1, 2$, which is supported by a first-tier RS. From the similar procedure presented in the 2-hop case, we can obtain the optimal amount of each subband, f_1 , f_2 , and f_3 . For example, $n(B)=7$, $n(R, 2)=12$, and $n(R, 3)=18$ for the 3-hop system as shown in Fig. 4. Then, $f_2 \geq (37/15)f_2$, $f_1 \geq (74/5)f_2 \geq (73/2)f_2$. Since $f_1+f_2+f_3=1$, we obtain that at least 92.6% of the frequency band is allocated to the MR-BS, and at most 5.6% and 1.8% of the frequency band is allocated to each of the first-tier and the second-tier RSs, respectively.

IV. Performance Evaluation

1. System Environments

We investigate the DL relay capacity of an MR-BS, a first-tier RSs, and a second-tier RSs for the 2-hop and the 3-hop TTR and STR relay systems. The radii of the MR-BS and RSs are assumed to be 1 km and 415 m.

As shown in Fig. 8, it is also assumed that there are 7 multihop relay clusters, one for the target reference system and the other six for the neighboring interfering systems. In each cluster, one MR-BS, located in the middle, is assumed to cover 7 unit cells, and 12 first-tier subordinate RSs are assumed to be located around the MR-BS coverage in the 2-hop system. In particular, in the 3-hop system, 18 second-tier RSs are assumed to be located around the first-tier RSs. Based on such 7 cluster-based MMR topology, we analyze relay capacity by considering inter-cell interference not only from the same cluster but also from the neighboring 6 clusters.

It is assumed that the traffic density is distributed uniformly over the whole service coverage area and the frequency band is 10 MHz. Then, in the TTR relay mode of 2-hop and 3-hop systems, the MR-BS and each RS use the same frequency band of 10 MHz. In the STR relay mode, by applying the frequency allocation scheme proposed in the previous

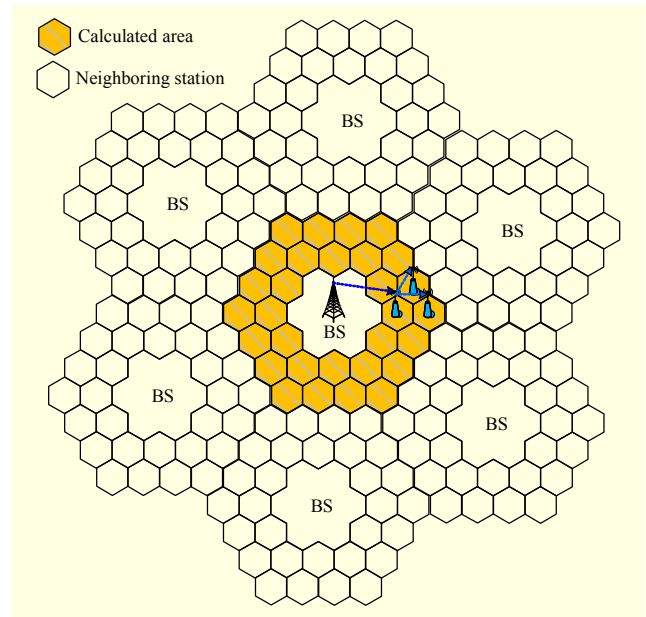


Fig. 8. Seven-cluster-based simulation topology.

Table 1. Simulation parameters.

Parameter	Value	
Cell layout	7 cells of multihop structure	
BS/RS radius	1 km /415 m	
No. of RS (per MMR system)	12 (1st-tier), 18 (2nd-tier)	
Duplex mode	TDD	
Carrier frequency	2.3 GHz	
Bandwidth	10 MHz	
TDD frame length	5 ms	
No. of frame/second	200	
Antenna type	Omnidirectional	
Antenna height	BS: 30 m, RS: 8 m	
Transmit power	BS: 20 W, RS: 5 W	
Ratio of DL and UL	2:1	
Radio resource allocation	TTR for 2&3-hop	Same channels (10 MHz)
	STR for 2-hop	MR-BS (f_1): 9.5 MHz RS _{1st} (f_2): 0.5 MHz
	STR for 3-hop	MR-BS (f_1): 9.26 MHz RS _{1st} (f_2): 0.56 MHz RS _{2nd} (f_3): 0.18 MHz

subsection, we obtain each frequency subband for the 2-hop and 3-hop relay systems. Frequency subbands for the MR-BS and each RS are 9.5 MHz and 0.5 MHz in the 2-hop system, and those for the MR-BS, the first-tier RS, and the second-tier RS are 8.54 MHz, 1.22 MHz, and 0.24 MHz in the 3-hop system. The transmission power of the MR-BS and RS are assumed to be 20 W and 5 W, respectively. Both shadow and

multipath fading are not considered due to the LOS assumption on the BS-RS and RS-RS links. The modulation and coding scheme (MCS) option is not considered. The key simulation parameters are defined based on the IEEE 802.16 standard, summarized in Table 1.

2. Performance Results

We analyzed the interferences and capacities of the MR-BS and RSs in 2-hop and 3-hop systems for the system environment given in Table 1.

Figure 9 shows interferences to each type of RSs for the TTR and STR relay modes. The interferences to the TTR and the STR relay mode are the same because the same system topology is used for both modes. However, the interference to the RSs in the 2-hop system is larger than for the 3-hop system

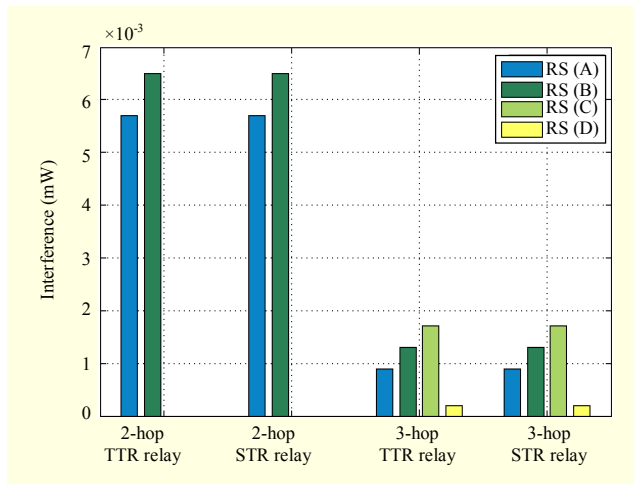


Fig. 9. Interferences to RSs of TTR and STR relay modes in 2-hop and 3-hop relay systems.

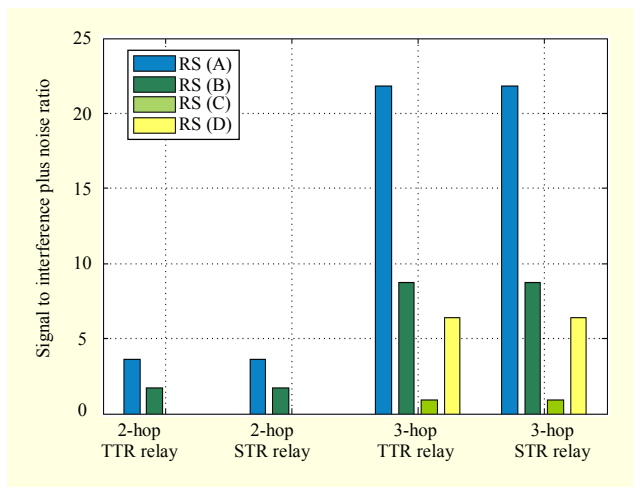


Fig. 10. SINR of each type RSs of TTR and STR relay modes in 2-hop and 3-hop relay systems.

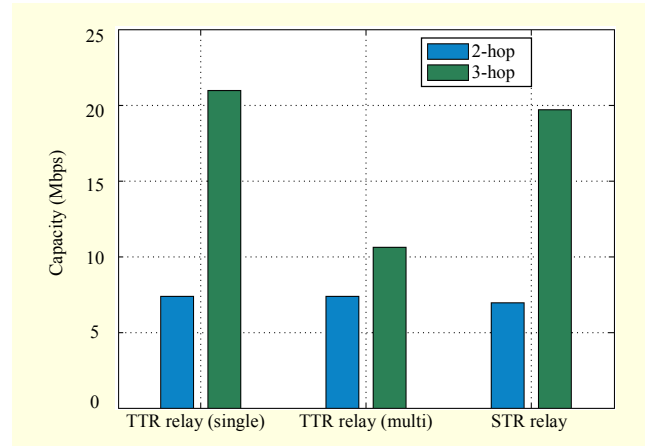


Fig. 11. Result of MR-BS relaying capacity.

since the interference signal strength from the neighboring MR-BSs is stronger in the 2-hop system. In particular, the type C RSs (RS_C) in the 3-hop system get more interference from neighboring RSs than the type D (RS_D). Figure 10 shows the resulting SINR values of the TTR and STR relay modes in the 2-hop and the 3-hop relay systems calculated from the interferences shown in Fig. 9.

Figure 11 shows the MR-BS relay capacities of the TTR and the STR relay modes in 2-hop and 3-hop systems. The MR-BS relay capacity of the TTR relay mode is slightly higher than that of the STR in the 2-hop system since the TTR mode uses 0.5 MHz more bandwidth than the STR mode to relay. Since the single-frame structure and the multiframe structure have the same structure, there is no difference between those two structures with the TTR relay mode.

In the 3-hop system, the relay capacity has shown in the order of TTR (single-frame), STR, and TTR (multiframe). The TTR single-frame shows the highest MR-BS relay capacity because the amount of idle period of the TTR mode is minimized with this structure and data is transmitted to the first-tier subordinate RSs using the whole available frequency band. The MR-BS relay capacity of the STR relay mode is shown to be higher than that of the TTR multiframe structure due to the idle periods of the TTR mode that occur in the frame structures of the MR-BS, the first-tier RSs, and the second-tier RSs.

Based upon our analysis of the TTR and the STR relay modes for 2-hop and 3-hop system, we can estimate the maximum number of users that can be supported in each relay system. For example, suppose that each user requires a minimum data rate of 64 kbps, 128 kbps, and 512 kbps, respectively. Then the maximum numbers of users that can be supported by the TTR relay mode with a single-frame structure in the 2-hop relay system are 114, 57, and 14 respectively. Table 2 summarizes the maximum number of users that can be

Table 2. Relay capacities and the maximum number of users supported in the relay of TTR and STR relay modes.

	TTR-single		TTR-multi		STR	
	2-hop	3-hop	2-hop	3-hop	2-hop	3-hop
Relay capacity	7.33 Mbps	20.9 Mbps	7.33 Mbps	10.6 Mbps	6.96 Mbps	19.7 Mbps
64 kbps users	114	326	114	166	108	307
128 kbps users	57	163	57	83	54	153
512 kbps users	14	40	14	21	13	38

supported for each relay mode for 2-hop and 3-hop relay systems with respect to different minimum required data rates per user.

V. Open Issues

There are many challenging open issues related to the TTR and STR relay modes in IEEE802.16j MMR system. One such challenging issue is in analyzing relay performance of the TTR and STR systems with regarding to MCS options. Investigation of the relay performance of the final-hop access link between MSs and the MR-BS or RSs is also challenging. Other issues are relay performance analysis of a multiple-antenna-based MMR system, cooperative relay performance for the TTR and the STR technologies, capacity analysis of a non-regular relay networking topology, and so on. We are planning to investigate these research issues not only to improve the IEEE802.16j MMR system but also to design next generation MMR-based systems.

We are developing new relay modes by adopting advantages of the TTR and STR relay modes. The major advantage of the STR relay mode is reduction of co-channel interference via allocation of different frequency bands to the MR-BS and its subordinate RSs within a relay cluster. However, since the same frequency band is used in every multihop relay cluster as shown in Fig. 8, inter-cluster interference is still unavoidable. Therefore, we propose one possible approach, a TTR-reuse relay mode, to mitigate the inter-cluster interference by combining advantages of the STR relay modes with the TTR mode. In this relay mode, the frame-structure of the TTR relay mode can be used without any change except the amount of allocated frequency band. As shown in Figs. 12(a) and (b), in the TTR-reuse mode, the whole frequency band (F) is divided into several subbands $f_i, i=1, 2, \dots, k$, where k is the number of

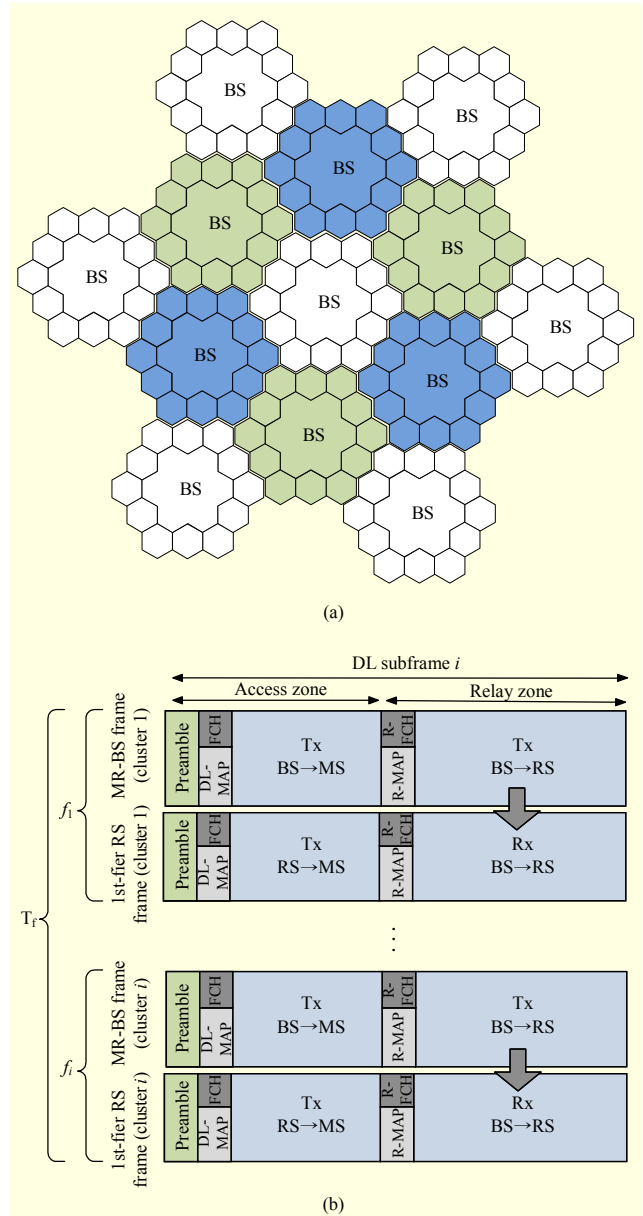


Fig. 12. Examples of 2-hop TTR-reuse relay (a) topology and (b) frame structure.

subbands and $\sum_{i=1}^k f_i = F$. Each subband is allocated to each cluster according to predefined frequency reuse factor (k) similar to the frequency reuse concept in the conventional cellular system. Then, each cluster operates the TTR relay mode using the allocated subband (f_i) instead of using the whole band. With the TTR-reuse relay, additional relay capacity improvement is expected by virtue of reduction of inter-cluster interference. However, such capacity improvement is obtained at the cost of reduction of frequency band used in each cluster. Therefore, currently we are designing an optimal frequency reuse factor for the TTR-reuse relay mode so that it can provide better relay performance than the TTR and the STR relay modes.

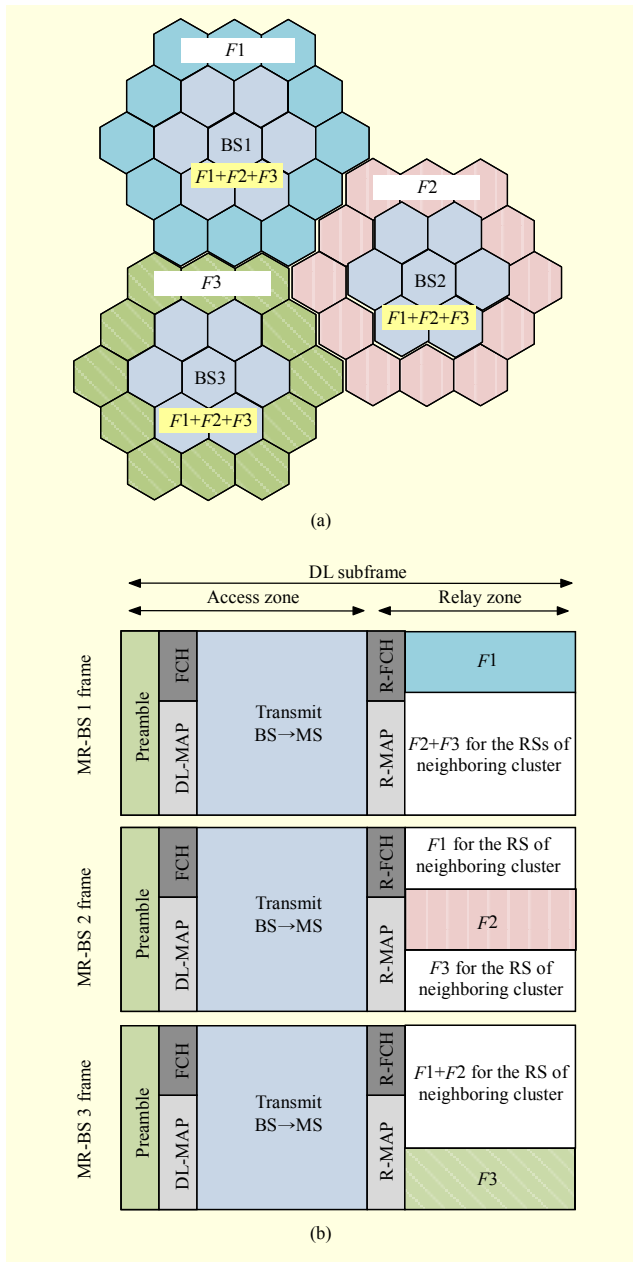


Fig. 13. Examples of 2-hop cluster-based FFR relay (a) topology and (b) frame structure.

Another possible approach is the cluster-based fractional frequency reuse (FFR) relay mode. In fact, in the TTR and the STR relay mode, there is interference from RSs of neighboring clusters because they use the same frequency band. Therefore, in this mode, in order to mitigate interference from RSs of the neighboring clusters, different frequency subbands are used in RSs whereas the whole band is used in every MR-BS. Figures 13(a) and (b) show examples of 2-hop relay topology of the proposed cluster-based FFR relay mode and its frame structure. In this example, the whole frequency band is divided into 3 subbands: $F = f_1 + f_2 + f_3$. Then, each subband is assigned to

RSs of each cluster. With this cluster-based FFR relay mode, it is expected that a great amount of inter-cluster co-channel interference mainly caused by the RSs of neighboring clusters could be reduced, and thus the system capacity could be improved. However, such capacity improvement is obtained at the cost of reduction of the frequency band used in RSs of each cluster. In addition, since the amount of frequency band used in the MR-BS and its subordinate RSs are different, the frame structure of the MR-BS and RSs must be redesigned to fit the cluster-based FFR relay mode. Therefore, currently we are trying to find the optimal frequency reuse factor and the frame structure for the cluster-based FFR relay mode.

We are also planning to compare performance of the various relay modes including the TTR, the STR, the TTR-reuse, and the cluster-based FFR relay mode while considering a number of challenging issues previously introduced.

VI. Conclusion

In this paper, we analyzed the performance of the TTR and the STR relay modes in OFDMA/TDD-based IEEE 802.16j MMR systems. We first introduced frame structures and multihop relay system topologies of the TTR and the STR relay modes. Then, we investigated the relay capacities of the MR-BS, the first-tier RSs, and the second-tier RSs via numerical modeling and analysis. Analysis results show that the MR-BS relay capacity of the TTR relay mode turns out to be slightly higher than that of the STR relay mode in the 2-hop relay system. In the 3-hop relay system, relay capacity of each system has shown in the order of the TTR relay with a single-frame structure, the STR relay, and the TTR relay with a multiframe structure. The TTR relay with a single-frame structure shows the highest MR-BS relay capacity because the idle period of the TTR mode is minimized with this structure, and data is transmitted to the first-tier subordinate RSs using the whole available frequency band. The TTR and the STR relay modes show similar performance in the 2-hop system in terms of the maximum number of supportable users. In particular, in the 3-hop system, performance of the TTR relay with a single-frame structure and the STR relay mode are shown to be similar and better than that of the TTR relay with a multiframe structure.

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