Computer Communications 32 (2009) 1298–1305

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Multiple frequency reuse schemes in the two-hop IEEE 802.16j wireless relay networks with asymmetrical topology ☆,☆☆

Weiwei Wang [a,*], Zihua Guo [b], Jun Cai [c], Xuemin(Sherman) Shen [d], Changjia Chen [a]

[a] School of Electronics and Information Engineering, Beijing Jiaotong University, Beijing, China
[b] Lenovo Cooperate Research, Beijing, China
[c] Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, Man., Canada
[d] Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ont., Canada

ARTICLE INFO

Article history:
Available online 12 February 2009

Keywords:
Frequency reuse
Relay network
Isolation band

ABSTRACT

In this paper, throughput performance of the access links (i.e., base station to mobile station and relay station to mobile station) is analyzed for the two-hop IEEE 802.16j wireless relay networks with asymmetrical topology. In specific, three frequency reuse schemes are proposed to improve the spectrum efficiency of the access links: (1) an isolation band based frequency reuse scheme (IBFRS) which introduces an isolation band surrounding each relay station (RS) cluster (i.e, a separate RS or several adjacent RSs) so that the throughput of the access link can be improved by allowing frequency reuse between RSs and the base station (BS); (2) the dynamic frequency power partition (DFPP) scheme for reusing the frequency among RSs; (3) the selective reuse (SR) scheme for the RSs to further selectively reuse the frequency in the isolation band according to the interference measurement. Comprehensive simulation shows that by applying the proposed IBFRS+DFPP+SR, the throughput of the access link can be significantly improved.

1. Introduction

With the increasing demand for ubiquitous multimedia data services, future wireless cellular networks are expected to provide services with wider coverage range and higher data packet throughput. To achieve these goals, wider bandwidth at higher carrier frequency above 2 GHz is foreseen to be used. Since the radio propagation in these frequency bands is more vulnerable to non-Line-of-Sight conditions, a new network node, called relay station (RS), is introduced in wireless networks, which could store and forward data packets received from base stations (BSs) to mobile stations (MSs), and vice versa [1–3]. There are generally two advantages brought by RS: first, instead of increasing the density of BSs, adding RS could overcome the coverage hole of BS and provide ubiquitous wireless services cost-efficiently; second, adding RSs could improve network throughput due to possible reuse of radio resources. As a result, relay networks have driven both industry and academia interests recently.

Relay-related function is being standardized as the extension to the basic standards, such as IEEE 802.16j [4,5]. Another standard, IEEE802.16m, which is deemed as a potential 4G standard, also supports the application of relay stations [6]. In the IST-WINNER project [7], integrating relay function has been considered as an inevitable part of the system design for cellular deployment. Furthermore, several studies on relay networks have also been reported. One of main focuses is on the resource reuse and scheduling, which could be divided into two categories based on different network topologies under consideration: (1) symmetrical topology where a BS is surrounded by several RSs evenly; and (2) asymmetrical topology where the RSs are established around BS randomly. For the first category, as shown in Fig. 1(a), two-hop network is considered, where the data could be transmitted to the destination by at most one RS. Li et al. [8] proposes a frequency partition scheme, which allocates orthogonal frequencies to three kinds of links, BS to MS, BS to RS and RS to MS; in [9], different frequency reuse factors (FRF), such as 1, 2, 3 and 6, are proposed among RSs; similarly, in [10], different FRFs are used for BSs and RSs, respectively. In [11], with FRF = 1, frequency hopping scheme among BS and RSs is introduced. For the second category, as shown in Fig. 1(b), multi-hop network is considered, where the data may be transmitted to the destination through at least two RSs. The area

☆ This work was supported in part by the Chinese NSFC under Grant 60672069 and 60772043, Chinese Ministry of Education under Grant 20050004033 and Beijing Jiaotong University under Grant 2005SM006.
☆☆ This work is partly presented at Qshine'08.
* Corresponding author. Tel.: +1 204 474 8923.
E-mail addresses: wwwang@ee.umanitoba.ca (W. Wang), guozh@lenovo.com (Z. Guo), jcai@ee.umanitoba.ca (J. Cai), xshen@bbcr.uwaterloo.ca (X. Shen), changjiachen@sina.com.cn (C. Chen).

0140-3664/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.comcom.2009.02.001

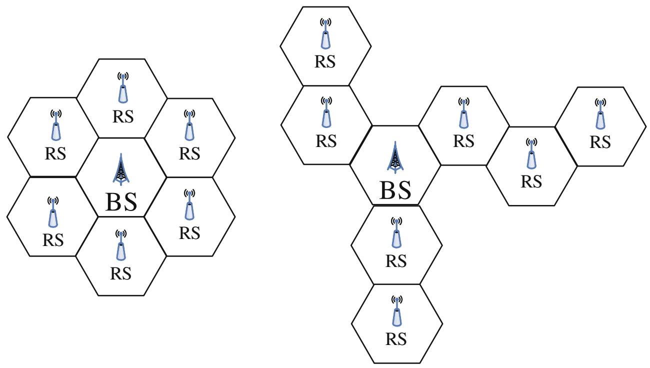

Fig. 1. The network topology under consideration.

covered by RSs is adjacent to that covered by BS. As a result, the serving area by each RS could be treated as the traditional cell, and the frequency reuse method used in the traditional cellular network could be used in the relay network with minor modifications [12], where a soft frequency scheme is proposed with adaptive scheduling among BS and RSs.

However, in the real world, these regular topologies do not always exist. According to the usage model defined in IEEE 802.16j [13], in order to overcome the coverage holes and the shadowing areas of the BS, the typical topology is that several RSs are deployed in the BS serving area irregularly, i.e., the areas covered by RSs are often surrounded by rather than adjacent to the area covered by BS.

In order to consider all these new characteristics, in this paper, the frequency reuse schemes are studied by taking into account the two-hop IEEE 802.16j network with an irregular deployment of RSs. First, the throughput of the access link (i.e., BS to MS, or RS to MS) is analyzed. Then, three frequency reuse schemes are proposed: (1) isolation band based frequency reuse scheme where an isolation band is defined to surround each RS cluster which includes a separate RS or several adjacent RSs in the BS serving area, and each RS cluster could reuse the frequency out of the isolation band, this scheme is partly presented in [14]; (2) dynamic frequency power partition (DFPP) scheme where the frequency could be reused among RSs in one RS cluster; (3) the selective reuse (SR) scheme where RSs could selectively reuse the frequency in the isolation band according to the interference measurement. Through the comprehensive simulation, the numerical results verify the significant throughput improvement from the proposed schemes.

The remainder of this paper is organized as follows. Section 2 provides an overview of IEEE 802.16j. Section 3 gives the throughput analysis of the relay network. Section 4 describes IBFRS and introduces an analytical method to determine the isolation band. Section 5 introduces the DFPP and SR schemes. Section 6 gives the implementation of the proposed frequency reuse schemes in IEEE 802.16j network. Section 7 presents the simulation results, followed by conclusions in Section 8.

2. Overview of IEEE 802.16j

As the extension of the current standards (IEEE802.16d and IEEE 802.16e), IEEE 802.16j aims at defining the multi-hop relay specification including the MAC and the physical (PHY) layers. According to the newest baseline document [4], two modes, non-transparent mode and transparent mode, are specified to support those application scenarios. The former one indicates that the RS has the scheduling function; while for the latter one, the RS just forwards data to and from MSs based on the frequency allocation information obtained from BS.

In Fig. 2, the frame structures of BS and RS are depicted for two modes, respectively [4]. For non-transparent mode, as in Fig. 2(a), each frame is divided into downlink (DL) and uplink (UL) sub-frames. Both DL and UL sub-frames consist of one access zone and one relay zone. The access zone is used for the communication between BS (or RS) and the corresponding MSs, while the relay zone is used for the communication between BS and RS or between RS and the subordinate RSs. Both access zones in BS frame and RS frame may share the same resource. For transparent mode, similar BS and RS frame structures are defined as shown in Fig. 2(b). In DL sub-frame, BS transmits data to the corresponding MSs and the subordinate RSs in the access zone. During this period, RSs are in the receiving state. In the optional transparent zone of the DL sub-frame, RS transmits data to the corresponding MSs or the subordinate RSs; while BS could be in silent state or provide the cooperative diversity for RS communicating with its subordinate RSs and MSs. In UL sub-frame, the access zone is used by MSs for transmitting data to the corresponding BS and RSs. However, the zones in BS frame and RS frame should use different frequency bands. In the relay zone, RSs deliver the data to BS or their superordinate RSs.

Through the comparison between the two modes, the major difference lies in that, for non-transparent mode, BS and RSs may communicate with the corresponding MSs in the access zone using the same frequency bands, while frequency reuse is not allowed in the transparent mode. In other words, in non-transparent mode, more resource could be used for improving the system performance in the access zone. Therefore, in this paper, we will focus on the resource allocation of the non-transparent mode.

In [13], from the perspective of the infrastructure, especially where the coverage is provided, four usage models are defined as the guideline of drafting IEEE 802.16j. They are fixed infrastructure, in-building coverage, temporary coverage and coverage on mobile vehicle. Therefore, a typical topology can be formed, as shown in Fig. 3, where several RSs are established asymmetrically in each cell to overcome the coverage holes or the shadowing areas where the BS could not serve. Obviously, with non-transparent mode, when RSs can use the same resource as the BS in the access zone, they could obtain the whole system bandwidth to serve the users in their coverage area with little interference from the BS. However, they may cause severe interference to the users currently

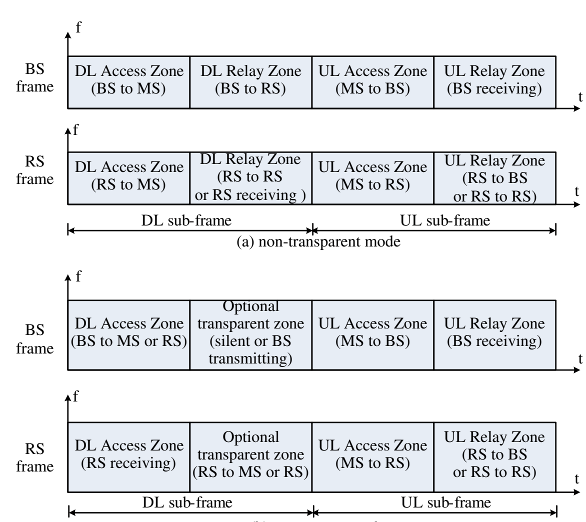

Fig. 2. IEEE 802.16j frame structure.

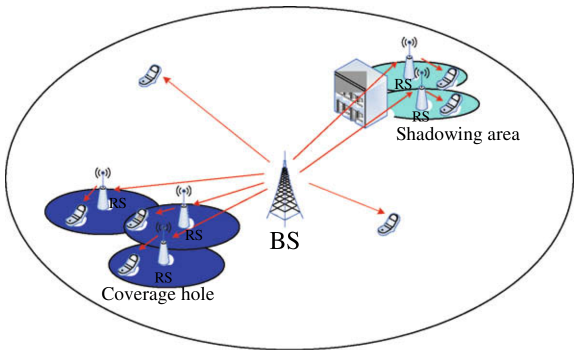

Fig. 3. The typical topology of relay network.

served by BS, especially for the users located close to their coverage area. In order to mitigate such interference from the RSs and improve the performance of the access zone, in this paper, an isolation band based frequency reuse scheme (IBFRS) between BS and RSs is introduced. Then, the frequency reuse scheme among RSs and the selective frequency reuse scheme between the isolation band and the RS cluster are proposed to further improve the system throughput.

3. Throughput analysis

In this section, throughput analysis of the relay network is carried out for the access zone, as shown in Fig. 2(a). There are two kinds of links, the access link including BS to MS and RS to MS, and the relay link including BS to RS. Let their throughputs be T_{BM}, T_{RM} and T_{BR}, respectively. Then

$$T_{RM} = \sum_{i=1}^{N} T_{RM}^{(i)}, \quad (1)$$

where $T_{RM}^{(i)}$ denotes the throughput achieved between RS i and its corresponding MSs, and N is the number of RSs in the network. In order to utilize the frequency efficiently, the following condition should be satisfied

$$T_{RM}t_A = T_{BR}t_R, \quad (2)$$

where t_A and t_R are the durations of the access zone and relay zone, respectively. Otherwise, the buffer in RS could be overflowed if $T_{RM}t_A < T_{BR}t_R$, or some resource between RS and MS could be wasted if $T_{RM}t_A > T_{BR}t_R$.

Thus, by (2), the effective system throughput could be denoted as

$$T_{sys} = \frac{T_{BM}t_A + T_{BR}t_R}{t_A + t_R} = \frac{T_{BM}t_A + T_{RM}t_A}{t_A + t_R} = T_{BR}\frac{T_{BM} + T_{RM}}{T_{BR} + T_{RM}}. \quad (3)$$

Let $T_A = T_{BM} + T_{RM}$, which means the throughput of the access link, (3) can be rewritten as

$$T_{sys} = \frac{T_{BR}}{1 + \frac{T_{BR} - T_{BM}}{T_A}}. \quad (4)$$

After the deployment of RSs, the relay link is determined; thus, T_{BR} in (4) could be regarded as a constant. Therefore, decreasing $\frac{T_{BR}-T_{BM}}{T_A}$ is the best way to improve the effective system throughput. Assume $\zeta = \frac{T_{BR}-T_{BM}}{T_A}$, the following situations should be noticed.

1. T_{BM} is not decreased (fixed or increased). Apparently, if T_A could be increased by some schemes, ζ is definitely decreased.
2. T_{BM} is decreased. Assume T_{BM} is decreased by $\Delta T_{BM}^{-}(>0)$ and T_A is increased by $\Delta T_A^{+}(>0)$. Then, the following condition should be satisfied for decreasing ζ

$$\frac{T_{BR} - (T_{BM} - \Delta T_{BM}^{-})}{T_A + \Delta T_A^{+}} - \frac{T_{BR} - T_{BM}}{T_A} < 0$$
$$\Rightarrow \frac{T_A\Delta T_{BM}^{-} - \Delta T_A^{+}(T_{BR} - T_{BM})}{T_A(T_A + \Delta T_A^{+})} < 0. \quad (5)$$

Therefore,

$$\frac{\Delta T_{BM}^{-}}{\Delta T_A^{+}} < \frac{T_{BR} - T_{BM}}{T_A}. \quad (6)$$

The above inequality indicates the conditions of decreasing ζ. The right-hand side of (6), as the original ζ, could be regarded as a fixed value; therefore, the left-side of (6) should be as small as possible. In other words, some schemes should be designed to make sure that less decrease on T_{BM} and more increase on T_A would be achieved.

From these two situations, we could confidently conclude that increasing T_A has positive effects on improving the effective system throughput. Therefore, the following discussion will focus on improving the throughput of the access link, T_A.

4. Isolation band based frequency reuse scheme

4.1. Introduction of IBFRS

For simplicity, hexagonal cells are used to denote the areas covered by BS and RS. Define the RS cluster which denotes a separate RS or several adjacent RSs. Because our focus is on the frequency reuse between BS and RSs, we assume all RSs in a RS cluster serve same MS simultaneously to provide macro-diversity. The IBFRS is illustrated by considering the DL. However, the similar idea can be applied for UL. As shown in Fig. 4, the IBFRS follows three rules:

- each RS cluster is surrounded by an isolation band;
- the users in the isolation band are served by BS;
- the RSs in the RS cluster can reuse the resource, which is not used by the users in the isolation band.

In Fig. 4, the whole coverage of the BS is separated into three subareas, which are the area covered by the RS cluster (RS-area), an isolation band, and the rest area called reuse-area. The RS-area is surrounded by the isolation band. Users locating in both isolation band and the reuse-area can access the whole system

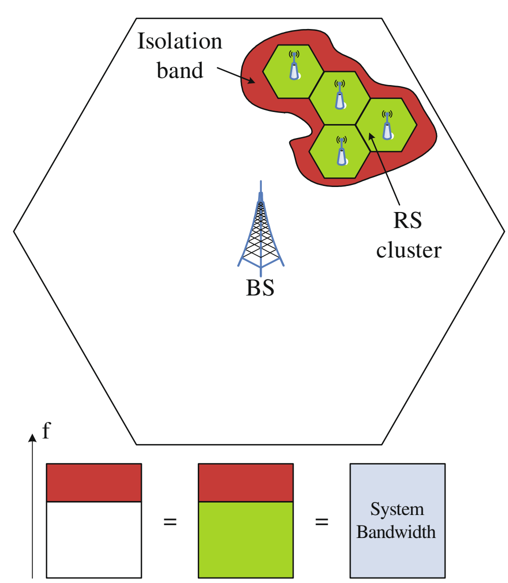

Fig. 4. Illustration of IBFRS.

bandwidth for transmission, while only the frequency band used in the reuse-area can be exploited in the RS-area. As a result, the users served by the BS and close to the edge of the RS cluster would not be interfered by the RSs therein, and the interference is mitigated for the users out of the isolation band even RSs reuse their frequency due to the large distance from the RSs.

4.2. Determination of isolation band

Determining the isolation band of the RS cluster is the key for the performance of the proposed IBFRS. In this subsection, an analytical method is introduced for isolation band determination based on the system model defined in Fig. 4.

(1) Definition of variables

- S: the total acreage of the cell;
- A_{BS}: the area served by the BS with the acreage of S_{BS};
- A_{RSc}: the area served by the RS cluster with the acreage of S_{RSc};
- A_{BS}^{nr}: the isolation band with the acreage of S_{BS}^{nr};
- A_{BS}^{r}: the area served by the BS but out of the isolation band, which has an acreage of S_{BS}^{r};
- B: system bandwidth;
- C_{BS} (bit/s/Hz): the spectrum efficiency of A_{BS} when no frequency reuse between the BS and the RS cluster;
- C_{RSc} (bit/s/Hz): the spectrum efficiency of the RS cluster.

From the definitions, we have

$$S_{BS} + S_{RSc} = S, \tag{7}$$

$$S_{BS}^{r} + S_{BS}^{nr} = S_{BS}. \tag{8}$$

(2) Optimal isolation band

Assume the users are uniformly distributed in A_{BS}. Let $\theta \in [0,1]$ be the decrease of the spectrum efficiency of A_{BS}^{r} after the RSs reuse the frequency from the reuse-area. The throughput of A_{BS}, denoted as T_{BS}, is

$$T_{BS} \geqslant \frac{S_{BS}^{nr}(\theta)}{S_{BS}} \cdot B \cdot C_{BS} + \frac{S_{BS}^{r}(\theta)}{S_{BS}} \cdot B \cdot C_{BS} \cdot (1-\theta), \tag{9}$$

where $\frac{S_{BS}^{nr}(\theta)}{S_{BS}}B$ is the frequency used in the isolation band and $\frac{S_{BS}^{r}(\theta)}{S_{BS}}B$ is the potential frequency band, which could be reused by the RS cluster. For the worse-case scenario, where all potential reusable frequency bands are applied by the RS cluster, the throughput of the RS cluster after the frequency reuse is given as

$$T_{RSc} = \frac{S_{BS}^{r}(\theta)}{S_{BS}} \cdot B \cdot C_{RSc}. \tag{10}$$

Therefore, the system throughput of the DL access zone is

$$\begin{aligned} T &\geqslant T_{RSc} + T_{BS} \\ &= \frac{S_{BS}^{r}(\theta)}{S_{BS}} B \cdot C_{RSc} + \frac{S_{BS}^{nr}(\theta)}{S_{BS}} B \cdot C_{BS} + \frac{S_{BS}^{r}(\theta)}{S_{BS}} \cdot B \cdot C_{BS} \cdot (1-\theta) \\ &= C_{BS}B + \frac{S_{BS}^{r}(\theta)}{S_{BS}} B(C_{RSc} - C_{BS}\theta). \end{aligned} \tag{11}$$

Obviously, maximizing the right-hand side of (11) could improve the throughput of the access link. Therefore, the optimal value of θ should satisfy

$$\theta_{opt} = \underset{\theta \in [0,1]}{\operatorname{argmax}} \left\{ C_{BS}B + \frac{S_{BS}^{r}(\theta)}{S_{BS}} B(C_{RSc} - C_{BS}\theta) \right\}. \tag{12}$$

To derive C_{BS}, C_{RSc} and $S_{BS}^{r}(\theta)$ in (12), we consider a cellular system with 19 cells and let the central one is the home cell. First, we calculate C_{BS} in (12). Assume a location, $x_{BS}^{(0)}$, in A_{BS} of the home cell. The signal to interference plus noise ratio (SINR) at $x_{BS}^{(0)}$ is given as

$$\gamma_{x_{BS}^{(0)}} = \frac{P_{BS}^{(0)} L_{BS}^{(0)} \chi_{BS}^{(0)}}{\sum_{m \in I_{BS}} P_{BS}^{(m)} L_{BS}^{(m)} \chi_{BS}^{(m)} + \eta_{BS}^{(0)}} \quad (x_{BS}^{(0)} \in A_{BS}), \tag{13}$$

where I_{BS} is the set of the interference sources to $x_{BS}^{(0)}$ in two-tier cells. In both numerator and denominator of (13), $P_{BS}^{(d)}$ is the transmitting power of BS in cell d, $L_{BS}^{(d)}$ and $\chi_{BS}^{(d)}$ are the path loss and shadowing from BS in cell d to $x_{BS}^{(0)}$, respectively. In general, the latter one in dB is modeled as a lognormal variable. $\eta_{BS}^{(0)}$ means the noise which is ignored in the following analysis due to its smaller value compared to the interference. According to [15], $\gamma_{x_{BS}^{(0)}}$ in (13) can be approximated by a lognormal variable with mean $\mu(x_{BS}^{(0)})$ and standard variance $\sigma(x_{BS}^{(0)})$ in dB. Therefore, the cumulative density function (CDF) of $\gamma_{x_{BS}^{(0)}}$ is given as

$$F_{x_{BS}^{(0)}}(\gamma) = P(\gamma_{x_{BS}^{(0)}} < \gamma) = 1 - Q\left(\frac{10\log_{10}(\gamma) - \mu(x_{BS}^{(0)})}{\sigma(x_{BS}^{(0)})}\right), \tag{14}$$

where $Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{Z^2}{2}\right) dZ$. Given CDF, the probability density function (PDF) of SINR, $f_{x_{BS}^{(0)}}(\gamma)$, can be obtained by differentiating $F_{x_{BS}^{(0)}}(\gamma)$. Let the relationship between the SINR and the throughput in unit bandwidth be $v = g(\gamma), (v \in V)$, where V is the set of possible values of v. Then, the PDF of the throughput in unit bandwidth at $x_{BS}^{(0)}$ is

$$T_{x_{BS}^{(0)}}(v) = \int_{\gamma \in \Phi} f_{x_{BS}^{(0)}}(\gamma) d\gamma \quad (v \in V, \Phi = \{\gamma | v = g(\gamma)\}). \tag{15}$$

From (15), the average throughput in unit bandwidth at $x_{BS}^{(0)}$ is

$$\overline{T_{x_{BS}^{(0)}}} = \sum_{v \in V} v T_{x_{BS}^{(0)}}(v). \tag{16}$$

Finally, C_{BS} is derived as

$$C_{BS} = \oint_{A_{BS}} \overline{T_{x_{BS}^{(0)}}} P(x_{BS}^{(0)}) dx_{BS}^{(0)}, \tag{17}$$

where $P(x_{BS}^{(0)})$ is the probability that the user is located at $x_{BS}^{(0)}$.

For C_{RSc} in (12), let a location of $x_{RSc}^{(0)}$ in A_{RSc} of the home cell. Then, its SINR could be written as

$$\gamma_{x_{RSc}^{(0)}} = \frac{\sum_{n \in \Omega} P_{RSc}^{(n)} L_{RSc}^{(n)} \chi_{RSc}^{(n)}}{\sum_{m \in I_{RSc}} P_{RSc}^{(m)} L_{RSc}^{(m)} \chi_{RSc}^{(m)} + \eta_{RSc}^{(0)}} \quad \left(x_{RSc}^{(0)} \in A_{RSc}\right), \tag{18}$$

where Ω is the set of RSs in the RS cluster, and I_{RSc} is the set of the interference sources to $x_{RSc}^{(0)}$. Due to the frequency reuse between the BS and the RS cluster, I_{RSc} should include the BS which covers the RS cluster and BSs in two-tier cells. Here, the interference from the RS cluster in other cells is ignored due to the relatively small transmitting power of the RS. By the similar method used for C_{BS}, we could derive C_{RSc} as

$$C_{RSc} = \oint_{A_{RSc}} \overline{T_{x_{RSc}^{(0)}}} P(x_{RSc}^{(0)}) dx_{RSc}^{(0)}, \tag{19}$$

where $\overline{T_{x_{RSc}^{(0)}}}$ is the average throughput in unit bandwidth at $x_{RSc}^{(0)}$ and $P(x_{RSc}^{(0)})$ is the probability that the user is located at $x_{RSc}^{(0)}$.

Similarly, for $S_{BS}^{r}(\theta)$ in (12), consider a location of $x_{BS}^{(0),r}$ in A_{BS}^{r} of the home cell. Since the resource used by users located at $x_{BS}^{(0),r}$ is reused by the RS cluster, its SINR is

$$\gamma_{x_{BS}^{(0),r}} = \frac{P_{BS}^{(0),r} L_{BS}^{(0),r} \chi_{BS}^{(n),r}}{\sum_{m \in I_{BS}^{r}} P_{BS}^{(m),r} L_{BS}^{(m),r} \chi_{BS}^{(m),r} + \eta_{BS}^{(0),r}} \quad \left(x_{BS}^{(0),r} \in A_{BS}^{r}\right), \tag{20}$$

where I_{BS}^{r} is the set of interference sources to $x_{BS}^{(0),r}$, which includes BSs in two tiers and the RSs in the RS cluster which is within the same BS coverage. The interference from the RSs in the other cells is ignored. Likewise, the average throughput in unit bandwidth at $x_{BS}^{(0),r}$ is given as

$$\overline{T_{x_{BS}^{(0),r}}} = \sum_{v \in V} v T_{x_{BS}^{(0),r}}(v), \tag{21}$$

where $T_{x_{BS}^{(0),r}}$ is the PDF of the throughput in unit bandwidth at $x_{BS}^{(0),r}$ after the resource is reused by RS cluster. Therefore, A_{BS}^{r} is given by

$$A_{BS}^{r} = \left\{ x_{BS}^{(0),r} | x_{BS}^{(0),r} \in A_{BS}, x_{BS}^{(0),r} = x_{BS}^{(0)}, \frac{\overline{T_{x_{BS}^{(0)}}} - \overline{T_{x_{BS}^{(0),r}}}}{\overline{T_{x_{BS}^{(0)}}}} < \theta \right\}. \tag{22}$$

Eq. (22) indicates that at any location in A_{BS}^{r}, the average throughput in unit bandwidth is decreased by no more than θ after the frequency reuse between the BS and the RS cluster. Combining (12), (17), (19) and (22), the optimal θ and the corresponding isolation band can be obtained.

5. Further discussion

In Section 4.1, we introduce macro-diversity among RSs in one RS cluster. To further improve the throughput of the access link, other two frequency reuse methods are discussed as follows:

- in each RS cluster, frequency could be reused among RSs;
- there is the possibility of reusing the frequency in the isolation band.

Thus, in this section, the above two aspects would be further discussed.

5.1. Dynamic frequency partition scheme among RSs

Due to the similarity between the BSs in the traditional cellular network and the RSs in one RS cluster, the frequency reuse scheme used for the BSs may be applied to the RSs. As a new frequency reuse scheme, soft frequency reuse (SFR) [16,17] has attracted lots of interest, which divides the frequency of each cell into two power levels, and the high-power frequency of the adjacent BSs should be orthogonal. The main advantage of SFR is that FRF = 1 could be applied among BSs and the co-channel interference of the edge area of each cell could be mitigated. Further discussion could be found in [18]. However, due to the possible uneven service distribution, the coordination among BSs is needed to change the ratio of the high-power frequency to the low-power one, which brings high signal overhead. Thus, the application of the dynamic SFR in practical scenarios is still under study. On the contrary, in the relay network, since the service requirement of each RS serving area is known to the BS, the SFR could be implemented among RSs dynamically. Based on this fact, we propose a dynamic frequency power partition scheme (DFPP) for the frequency reuse among RSs in the RS cluster, which is elaborated as follows:

- the frequency of each RS serving area is divided into two parts: primary frequency and secondary frequency;
- the primary frequency, which is orthogonal among adjacent RSs, is transmitted by the high power level; while the secondary frequency is transmitted by the low power level;
- the ratio of the primary frequency to the secondary frequency could be adjusted dynamically according to the service requirement of each RS serving area.

5.1.1. Determination of the primary frequency

Let $G = (V, E)$ denote an interference graph, where the node set V denotes RSs, and the edge set E represents geographical proximity of RS serving area and therefore the possibility of co-channel interference. Here, due to the small transmission power of RSs, only interference among adjacent RSs is considered. Therefore, the RSs in one RS cluster form a weighted graph (G, ω), where G is an interference graph and ω is a weight vector indexed by the nodes of G, and $\omega(\upsilon)$ represents the bandwidth requirement of node υ. Assume C subchannels are included in the system. Since the orthogonality of the primary frequency of the adjacent RSs is required, a proper multicoloring of G is needed to allocate the primary frequency. In this paper, the method in [19] could be used. Since a hexagonal cell is used to denote the RS serving area, the G is a 3-colorable graph. Therefore, RS serving areas in one RS cluster could be represented by three colors: red, blue and green. Define the nominal subchannel of each colored area as one third of the system bandwidth, then three steps should be followed to allocate the primary frequency of each RS serving area:

1. allocate the nominal subchannel to the corresponding RS serving area;
2. if there are RS serving areas whose bandwidth requirements are not satisfied, the red (blue/green) RS serving areas borrow the nominal subchannels which are not used by all the adjacent blue (green/red) RS serving areas;
3. if there are still RS serving areas whose bandwidth requirements are not satisfied, the red (blue/green) RS serving areas borrow the nominal subchannels which are not used by all the adjacent blue and green (green and red/ red and blue) RS serving areas.

5.1.2. Determination of the secondary frequency

If the bandwidth requirement of the RS serving area is not satisfied, the secondary frequency should be allocated. Obviously, the secondary frequency of the RS serving area could interfere with the primary frequency of the adjacent RS serving areas; therefore, it should be the frequency causing fewer interference. Taking a RS serving area as the reference, denoted by RS_k, the requirements of its primary and secondary frequencies are supposed to be $|PF_k|$ and m_k subchannels, respectively; thus

$$|PF_k| + m_k \leqslant C, \tag{23}$$

where C is the number of the system subchannels. Then, the following two situations should be discussed:

1. If $m_k = C - |PF_k|$, there is no possibility to reduce the interference to the adjacent RS serving areas since all of the rest subchannels should be used as the secondary frequency in RS_k.
2. If $m_k < C - |PF_k|$, there is the extra frequency after the frequency requirement of RS_k is satisfied, which means there are several choices when allocating the secondary frequency. Therefore, in order to reduce the interference to the adjacent RS serving areas as much as possible, the secondary frequency of RS_k should be chosen from the subchannels, which are used as the primary frequency by the adjacent RS serving areas, but with the descending order of the number of the adjacent RS serving areas which use them.

5.1.3. Allocation of the frequency reused by IBFRS

After determining the primary frequency and the secondary frequency of each RS serving area, the RSs in the RS cluster could be divided into several reuse groups, each of which includes the RSs reusing the same subchannel. Then, the subchannels reused by IBFRS could be allocated to the reuse groups one by one according to the descending order of the number of the RSs in each reuse group.

5.2. Selective reuse scheme between the isolation band and the RS cluster

Obviously, after the allocation of the frequency reused by IBFRS, there are still some RS serving areas under bandwidth requirement. An interesting problem is whether there is any space to reuse more frequency? The answer is positive. As mentioned in Section 5.1.3, some reuse group may include few RSs; therefore, it could cause small interference to the users in the isolation band. For instance, as in Fig. 5, due to the long distance, the subchannel used by user A may be reused by the RS in the reuse group 2. Therefore, based on the interference measurement, the reuse groups could be sorted by the ascending order of the interference to each user in the isolation band. Then, in order to guarantee the fairness of the users served by BS, the frequency used by the user in the isolation band could be reused by the reuse group which causes the throughput decreasing less than θ_{opt}.

6. Implementation of the proposed frequency reuse schemes

In each BS cell, when a RS cluster is established, the corresponding isolation band can be determined through the method defined in Section 4.2 and could be maintained for a long period unless the RS cluster is changed. After that, the frequency schemes mentioned above could be implemented frame by frame. Through the frame structure in Fig. 2, since BS and RS work at the same time in the DL access zone, in each frame, the BS should schedule the frequency of the next BS frame and inform the RS in the relay zone of the current frame what the reusable resource is in the next RS frame. In summary, the implementation at each frame follows three steps:

1. BS schedules the resource of the next BS frame and pre-allocates the frequency of each RS according to DFPP;
2. BS finds out the users in the isolation band of the RS cluster by the location technology, such as GPS (Global Position System), and then allocates the reusable resource of the RS cluster in the next BS frame, which includes the frequency used in and out of the isolation band;
3. BS informs the RSs in the RS cluster the reusable resource of the next RS frame through the message in the relay zone.

Compared to the existed schemes, the additional implementations of our scheme are fixing the isolation band by a long period and pre-scheduling the resource of the next frame. Thus, the complexity of the proposed scheme is acceptable.

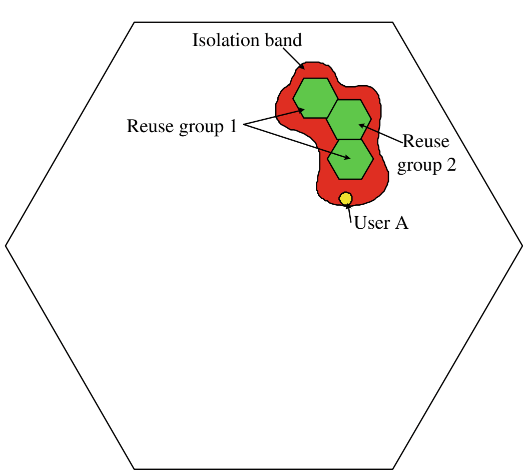

Fig. 5. Example of reusing the frequency in the isolation band.

7. Simulation and discussions

An OFDM cellular network with 19 BS cells is considered in both numerical analysis and simulation. Soft frequency reuse scheme is used among BS cells. The main simulation parameters are listed in Table 1.

According to (22), we first study the isolation band of the RS cluster. RSs are placed in the BS cell randomly and at most 10 RSs are included in a RS cluster. Fig. 6 shows an example of the isolation band (A_{BS}^{nr}) of a RS cluster and its corresponding θ. The area enclosed by the contour except the coverage area of the RS cluster is the isolation band and the number on the contour denotes the corresponding θ. Obviously, with the decrease of the area of the isolation band, θ is increased since the RS cluster will interfere with the users out of the isolation band more severely. Fig. 7 shows the average ratio of S_{BS}^{r} to S_{BS} with respect to the number of RSs in the RS cluster. It can be seen that the ratio is decreased with the increase of the number of RSs. That is because the interference to the users served by the BS increases as the number of RSs increases. Nevertheless, the ratio is still above 80% which means most frequency could be reused by the RS cluster.

We compare the proposed scheme with a traditional scheme where the BS and the RSs in the RS cluster use different frequency bands to serve the respective users [8] by extensive simulations with Matlab. For simplicity, each user is allocated one subchannel, so that both the BS and the RS cluster could serve 30 users at most. During the simulation, 20 kinds of topology are emulated. For each topology, the RS clusters are deployed randomly. The number of RS clusters in each BS cell and the number of RSs in each RS cluster are uniformly distributed in [1, 3] and [1, 5], respectively. One hundred samples are simulated for each topology, and the steps for user generation in each sample are as follows:

1. Generating 30 users distributed randomly in the BS cell (including RS serving areas) for the traditional scheme.
2. Based on the users in step 1, for IBFRS, increase the number of users in the BS serving area (except RS serving areas) to 30, while the number of users in each RS cluster is uniformly distributed in [1, 30].
3. Based on the users in step 2, for all the schemes in this paper, the number of users in each RS serving area is increased to be uniformly distributed in [1, 30].

In step 1, due to no frequency reuse in the traditional scheme, 30 users means the system is fully loaded. However, actually, the reason of the deployment of the RS is that more users can be sup-

Table 1
Simulation parameters.

Carrier frequency	2.5 GHz
System bandwidth	10 MHz
Number of subchannels	30
Number of sub-carriers in a subchannel	24
BS cell radius	1 km
BS TX power	38dBm (high); 33dBm (low)
BS path loss	$138.6 + 34.79\log_{10}(d)$, d is the distance in km
RS cell radius	0.1 km
RS TX power	5dBm (high); 1dBm (low)
RS path loss	$143.69 + 37.2\log_{10}(d)$, d is the distance in km
Shadowing	Lognormal variable with mean 0 dB and standard variance 8 dB
Modulation and coding scheme	See IEEE 802.16e [20]

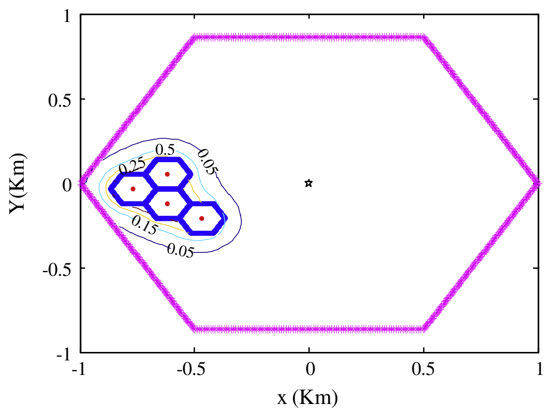

Fig. 6. An example of the isolation band.

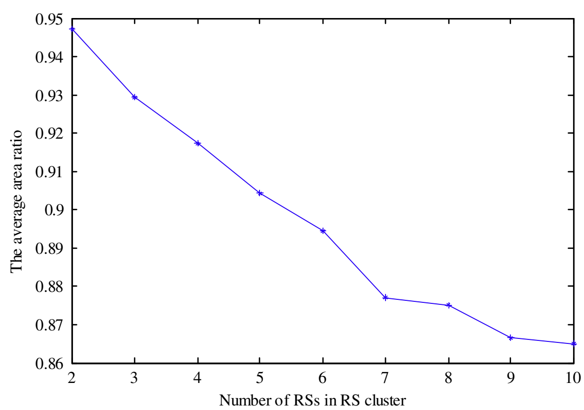

Fig. 7. The average area ratio of S_{BS}^{r} to S_{BS}.

ported in the RS serving areas; thus, in step 2, by considering the frequency reuse in IBFRS, 30 users could be served by BS; while 30 users could be served by each RS cluster at most due to the assumption of the macro-diversity. Finally, in step 3, due to the further frequency reuse among RSs, more users could be generated in each RS-area.

Fig. 8(a)–(d) gives the average throughput of the system, BS serving area, RS serving area and the isolation band, respectively, in the access zone. In the figures, IBFRS+DFPP+SR means the schemes including IBFRS, DFPP and selective reuse scheme between the isolation band and RS cluster. For the traditional scheme, since only 30 users could be supported in the whole BS cell, there is only one point in Fig. 8(a), and in Fig. 8(b) and (c), the number of users in the BS and RS serving areas would not exceed 30, respectively. From Fig. 8(a) and (c), due to frequency reuse between BS and RS clusters in IBFRS, more users could be served by RSs. Further, in IBFRS+DFPP+SR, frequency reuse among RSs and the selective reuse between the isolation band and the RS cluster are permitted; thus, the throughput is improved significantly with the increase of users. In Fig. 8(b), only one point corresponding to 30 users is illustrated for IBFRS and IBFRS+DFPP+SR because the number of users served by the BS has reached the maximum of the system. Obviously, the throughput of BS serving area in IBFRS and IBFRS+DFPP+SR decreases a little because of the frequency reuse by the users in the RS cluster, and since the selective reuse scheme causes the interference to the users in the isolation band, the value in IBFRS+DFPP+SR is smaller than that in IBFRS. In Fig. 8(d), the throughputs of the isolation band in IBFRS and IBFRS+DFPP+SR are also decreased a little. As mentioned before, in the simulation, each BS cell may include several RS clusters. Since the frequency used by one isolation band may be reused by other RS clusters, the throughput of the isolation band is lower than that in the traditional scheme; moreover, due to the selective reuse scheme, the throughput of the isolation band in IBFRS+DFPP+SR is the smallest. In summary, through IBFRS and IBFRS+DFPP+SR, the throughput of the access link is improved largely with little negative influence to the users served by the link of BS to MS, and IBFRS+DFPP+SR brings the largest improvement.

8. Conclusions

In this paper, three frequency reuse schemes for the two-hop relay network based on IEEE 802.16j has been proposed. By introducing an isolation band for each RS cluster, the proposed isolation band

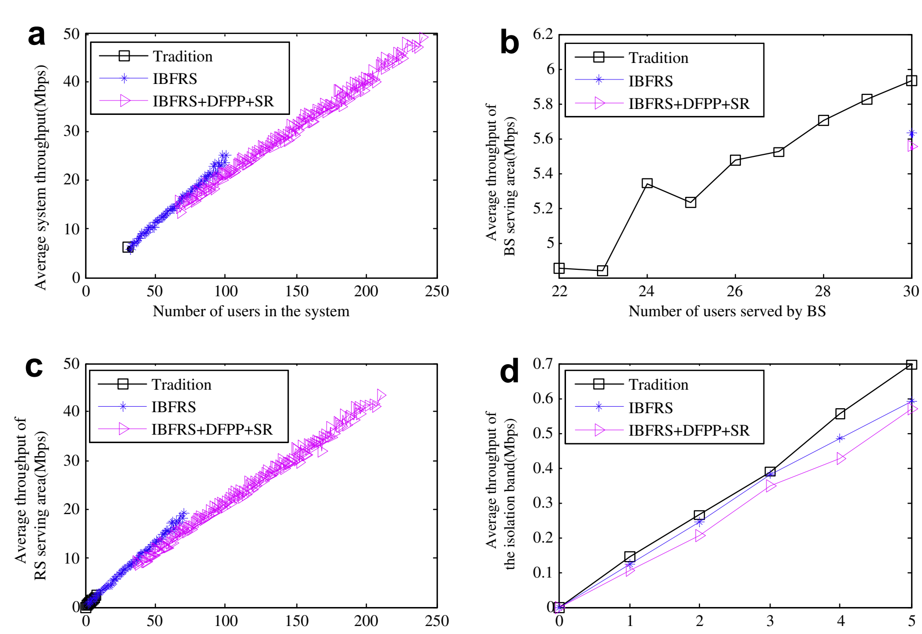

Fig. 8. Throughput comparison.

based frequency reuse (IBFRS) scheme allows each RS cluster reuses all frequency resources out of the isolation band. The DFPP scheme defines how to use the reused frequency effectively among RSs, and the selective reuse scheme utilizes the possibility of reusing the frequency in the isolation band. The simulation results indicate that the proposed IBFRS+DFPP+SR scheme can significantly improve the throughput of the access links with little negative influence to other users served by the BS. Our future work will focus on more complex scenarios, such as networks with directional antennas.

References

[1] R. Pabst et al., Relay-based deployment concepts for wireless and mobile broadband radio, IEEE Commun. Mag. 42 (9) (2004) 80–89.
[2] J. Cai, X. Shen, J.W. Mark, A.S. Alfa, Semi-distributed user relaying algorithm for amplify-and-forward wireless relay networks, IEEE Trans. Wireless Commun. 7 (4) (2008) 1348–1357.
[3] J. Cai, A.S. Alfa, P. Ren, X. Shen, J.W. Mark, Packet level performance analysis in wireless user-relaying networks, IEEE Trans. Wireless Commun., in press.
[4] IEEE 802.16j-06/026r4, Baseline document for draft standard for local and metropolitan area networks, 2006.
[5] <http://www.ieee802.org/16/relay/index.html>.
[6] IEEE 802.16m-07/002r4, IEEE 802.16m system requirements, 2007.
[7] <http://www.ist-winner.org>.
[8] P. Li, M. Rong, Y. Xue, E. Schulz, Reuse one frequency planning for two-hop cellular system with fixed relay nodes, in: Proc. IEEE WCNC'07, Hong Kong, China, March 2007.
[9] P.W. Hyoung, B. Saewoong, Resource management policies for fixed relays in cellular networks, in: Proc. IEEE GLOBECOM'06, San Francisco, USA, November 2006.
[10] P. Li, M. Rong, T. Liu, Y. Xue, D. Yu, E. Schulz, Reuse partitioning based frequency planning for relay enhanced cellular system with nlos bs-relay links, in: Proc. VTC-2006 Fall, Montreal, QC, Canada, September 2006.
[11] O. Mubarek, H. Yanikomeroglu, Dynamic frequency hopping in cellular fixed relay networks, in: Proc. IEEE VTC 2005-Spring, Stockholm, Sweden, May 2005.
[12] K. Doppler, X. He. C. Wijting, A. Sorri, Adaptive soft reuse for relay enhanced cells, in: Proc. IEEE VTC'07-Spring, Dublin, Ireland, April 2007.
[13] IEEE 802.16j-06/015, Harmonized contribution on 802.16j (mobile multihop relay) usage models, 2006.
[14] W. Wang, Z. Guo, J. Cai, X. Shen, C. Chen, Isolation band based frequency reuse scheme for IEEE 802.16j wireless relay networks, in: Proc. Qshine'08, Hongkong, China, July 28–31, 2008.
[15] W. Choi, J.G. Andrews, Downlink performance and capacity of distributed antenna systems in a multicell environment, IEEE Trans. Wireless Commun. 6 (1) (2007) 69–73.
[16] 3GPP R1-050507, Soft frequency reuse scheme for UTRAN LTE, Huawei, May 2005.
[17] 3GPP, R1-050841, Further analysis of soft frequency reuse scheme, Huawei, August 2005.
[18] W. Wang, Z. Guo, X. Shen, C. Chen, J. Cai, Flow-satisfaction-degree based scheduling algorithm in static reuse partitioning system, in: Proc. IEEE Globecom'07, Washington, DC, USA, November 26–30, 2007.
[19] Lata Narayanan, Channel Assignment and Graph Multicoloring, Handbook of Wireless Networks and Mobile Computing, John Wiley and Sons, 2001.
[20] IEEE Standard 802.16-2005, IEEE standard for local and metropolitan area networks – Part 16: Air interface for fixed and mobile broadband wireless access systems, 2005.