Enhanced Throughput and QoS Fairness for Two-Hop IEEE 802.16j Relay Networks

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Abstract: **Frequency reuse among relay stations (RSs) in a downlink access zone is widely adopted for throughput enhancement in IEEE 802.16j relay networks. Since the areas covered by the RSs or the base station (BS) may overlap, some mobile stations (MSs) at the border between two neighboring transmitting stations (RS or BS) using an identical frequency band may suffer severe interference or outage. This co-channel interference within the cell degrades the quality of service (QoS) fairness among the MSs as well as the system throughput. Exclusive use of a frequency band division (orthogonal resource allocation) among RSs can solve this problem but would cause degradation of the system throughput. We observe a trade-off between system throughput and QoS fairness in the previously reported schemes based on frequency reuse. In this paper, we propose a new frequency reuse scheme that achieves high system throughput with a high fairness level in QoS, positioning our scheme far above the trade-off curve formed by previous schemes. We claim that our scheme is beneficial for applications in which a high QoS level is required even for the MSs at the border. Exploiting the features of a directional antenna in the BS, we create a new zone in the frame structure. In the new zone, the RSs can serve the subordinate MSs at the border and prone to interference. In a 3-RS topology, where the RSs are located at points 120° apart from one another, the throughput and Jain fairness index are 10.64 Mbps and 0.62, respectively. On the other hand, the throughput for the previously reported overlapped and orthogonal allocation schemes is 8.22 Mbps (fairness: 0.48) and 3.99 Mbps (fairness: 0.80), respectively. For a 6-RS topology, our scheme achieves a throughput of 18.38 Mbps with a fairness of 0.68; however, previous schemes with frequency reuse factors of 1, 2, 3, and 6 achieve a throughput of 15.24 Mbps (fairness: 0.53), 12.42 Mbps (fairness: 0.71), 8.84 Mbps (fairness: 0.88), and 4.57 Mbps (fairness: 0.88), respectively.**

Index Terms: **Co-channel interference, frame structure, frequency reuse, relay, WiMAX, wireless networks.**

I. INTRODUCTION

Mobile stations (MSs) at the cell edge may experience service degradation or outage owing to pathloss. The IEEE 802.16j task group has been actively studying the feasibility of deploying fixed relay stations (RSs) between the base station (BS) and the MSs, in order to solve the aforementioned problem [1]–[5]. Since RSs cover smaller cells that are spatially separated, the same frequency band is reused among the RSs in order to enhance the system throughput.

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Park and Kang [4] considered two extreme cases with 3-RS topology (illustrated in Fig. 2); full reuse (overlapped allocation) and no reuse (orthogonal allocation). Overlapped allocation allows for all the three RSs to use the same frequency band, and this may result in co-channel interference. MSs at the border between two neighboring sub-cells (a sub-cell is a small area covered by an RS) covered by RSs using the same frequency band may experience severe service degradation or outage. The quality of service (QoS) levels for MSs located at the border between two sub-cells are usually very low and in some cases, are lower than the outage. Orthogonal allocation helps eliminate outage for MSs at the border, but the system throughput is very low in this scheme.

Table 1 summarizes the relationship between known frequency reuse schemes and the outage rate. Overlapped allocation for a 3-RS topology allows for full frequency reuse, but the outage is as high as 16.24%, while orthogonal allocation does allow not reuse, and hence, no outage is observed [4]. Park and Bahk [2] varied the level of reuse in a relay network with six RSs surrounding a BS (a 6-RS topology). The frequency reuse factors (FRF), 1, 2, 3, and 6 represent scenarios where 6, 3, 2, and 1 RS(s) share the same frequency band, respectively. FRF $= 1$ represents the highest level (full reuse), while FRF $= 6$ represents the lowest level (no reuse). As the level of reuse increases, the outage rate also increases, indicating a trade-off between reuse level and outage rate.

We also observe a trade-off between system throughput and fairness level for the abovementioned schemes [2], [4], as illustrated in Fig. 1. The X-axis denotes fairness level, while the Y-axis denotes system throughput. The suqares represent the schemes in [4] for a 3-RS topology. The square on the upper left represents overlapped allocation, in which high throughput is achieved at a low fairness level. The square on the lower right represents orthogonal allocation, in which low throughput is achieved at a high fairness level. The broken line connecting the two squares is an imaginary trade-off curve. Our scheme for the 3-RS topology aims for a location well above this trade-off curve with improved throughput against orthogonal allocation and improved fairness against overlapped allocation. The four red circles represent four scenarios for a 6-RS topology studied in [2]: FRF $= 1$, FRF $= 2$, FRF $= 3$, and FRF $= 6$, respectively. The trade-off between system throughput and fairness is clear from the imaginary curve connecting the circles. Our scheme for the 6-RS topology aims for a location well above the curve with improved throughput against FRF $= 6$ and 3 and improved fairness against FRF $= 1$.

Our contribution involves the development of a new scheduling algorithm that combines *spatial division*, *time division*, and

Table 1. Service outage rate for known frequency reuse schemes.

Frequency reuse schemes	Service outage rates
Overlapped allocation [4]	24.59
Orthogonal allocation [4]	0%
FRF = 1 [2]	16.34%
FRF = 2 [2]	6.59%
FRF = 3 [2]	2.44%
FRF = 6 [2]	0%

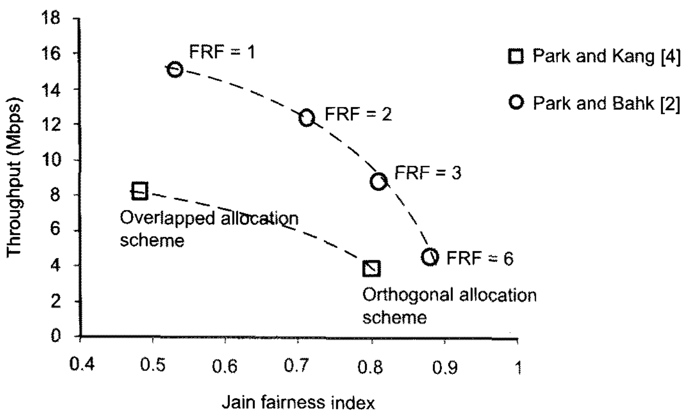

Fig. 1. Trade-off between system throughput and fairness.

frequency division in a new manner. *Spatial division* refers to the separation of RSs, which allows for frequency reuse. If k RSs are set apart from one another, the same frequency band is used k times. Thus, we regard the frequency reuse as an efficient way of exploiting spatial division. However, this gives rise to interference for the MSs located at the border where the spatial regions overlap.

In order to reduce the interference for MSs at the border, we design a new scheme. By exploiting the features of a directional antenna for the BS, we create a new zone within the frame structure, in which RSs can serve their subordinate MSs at the border. We call the new zone *relay_access zone* since it serves as a relay zone for the BS and an access zone for all RSs except that involved in relay communication. During relay communication between the BS and RSs, the RSs share the relay zone (interval) in a *time division* manner. The BS performs relay transmission to each RS in turn. We employ a directional antenna for relay transmission from the BS to an RS, and hence, the other RSs are free of interference from the on-going BS-RS relay transmission (combination of time division and spatial division from the directional antenna). The free RSs serve their subordinate MSs in this time interval. In other words, the relay zone for BS-RS communication for one RS overlaps with the access zone for RS-MS communication for other RSs, and this increases the access throughput for RS-MS communication. This implies that more MSs can be served by the RSs, thus allowing the BS to reduce the number of MSs directly served by it and increase the QoS levels for the remaining MSs. As a result, both system throughput and fairness level are increased. Finally, the interference among RSs can be reduced by applying *frequency division* since we have a greater number of frequency bands available in the newly created *relay_access zone*. We develop a new frame structure on the basis of the IEEE 802.16j standard in order to implement our scheme.

The new frame structure allows BS-RS relay transmission (performed with a directional antenna in the BS) to be overlapped with RS-MS access for RSs that do not interfere with the on-going relay transmission. The simulation results show that the system throughput in the proposed frame structure is considerably higher than that in previous schemes [2], [4], in which the conventional frame structure based on the IEEE 802.16j standard [6] is used. Additionally, in our scheme, the service outage, which is observed in the full or partial frequency reuse scenarios in previous schemes.

Section II discusses the co-channel interference problem along with a brief review of the related work. Section III presents our solution and the corresponding new frame structure used to implement our scheme. Section IV discusses mathematical modeling, and Section V includes performance evaluation. Section VI concludes the paper.

II. IEEE 802.16J STANDARD FRAME STRUCTURE AND CO-CHANNEL INTERFERENCE PROBLEM

Multihop relay networks have been proposed for user throughput improvement and coverage extension to traditional mobile cellular networks. In a traditional cell architecture, where the BS is the only serving station in a cell, the cell coverage has to be maintained at a low level so as to provide high-data-rate services to users near the cell boundary, because of the limited energy available for each transmission bit; this causes an increase in the number of the BSs and the system cost [7] for coverage extension. A multihop relay cell architecture is a feasible solution to the abovementioned problem [1], [8]. In such an architecture, RSs are set up in a cell for relay information from a BS to MSs. The use of RSs helps improve cell coverage, user throughput and system capacity [1], [8]. The multihop relay network is being standardized by the IEEE 802.16j track group [6].

A typical IEEE 802.16j network model with three RSs (a 3-RS topology) is shown in Fig. 2. This model consists of one BS and three RSs that are attached to the BS via one or more wireless hops. The number of hops is usually small. Even through more than two hops can be exploited via multiple RSs, we consider a simple relay with two hops via a single RS, as shown in Fig. 2. Two different modes of relay operation are defined in the IEEE 802.16j standard: Transparent mode and non-transparent mode. A main difference between these two modes of operation lies in the transmission of framing information. Devices operating in the transparent mode rely on the BS to transmit such information; however, in the non-transparent mode, this information is transmitted by the RSs [6]. Our scheme works in the transparent relay mode. Only the BS knows about the proposed relay_access zone (Section III). Therefore, every MS should receive MAP information from the BS. For this purpose, our scheme must work in the transparent relay mode. The frame structure in the IEEE 802.16j standard is composed of a downlink part and an uplink part, each of which is further divided into *access zone* for BS (or RS) to MS transmission and *relay zone* for BS to RS transmission, as shown in Fig. 3. For

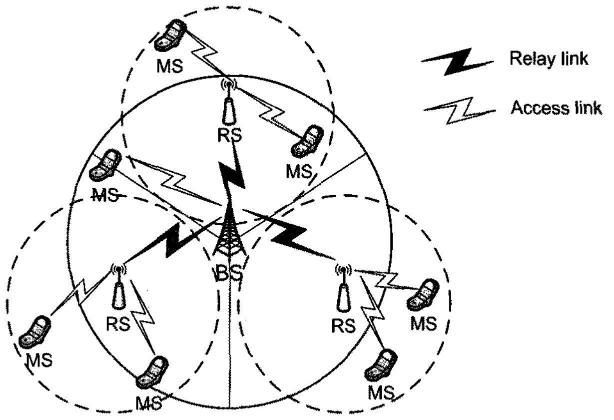

Fig. 2. An IEEE 802.16j relay network with three RSs.

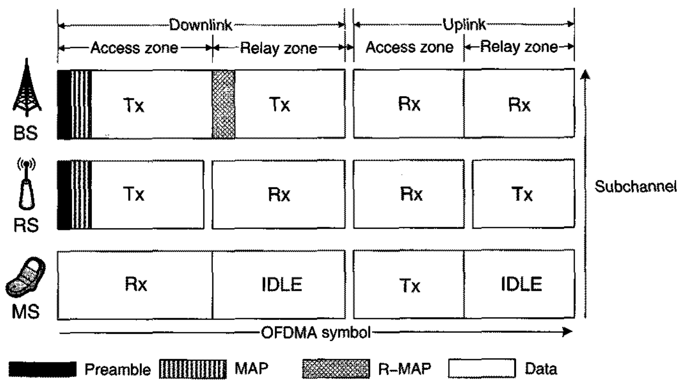

Fig. 3. Frame structure of IEEE 802.16j draft standard.

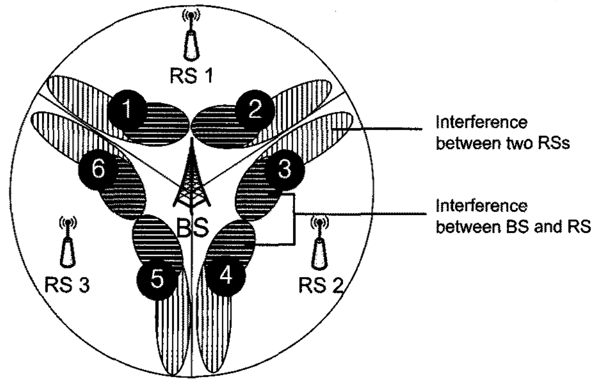

Fig. 4. Interference areas for a 3-RS topology.

example, in the access zone in the downlink part, the BS and RSs are in the transmitting (Tx) mode, and the MSs are in the receiving (Rx) mode. The horizontal and vertical axes denote time and frequency, respectively. Fig. 3 shows overlapped resource allocation, where the BS and RSs share same frequency band in the same time interval, and this may cause interference among them. On the basis of frequency reusability over the access zone, Park and Kang [4] defined two extreme cases with three RSs: Full reuse (overlapped allocation) and no reuse (orthogonal allocation). In orthogonal allocation, the same subchannels are not reused over the access zone, i.e., no subchannels can be shared by the serving stations (a BS and a group of RSs). In this scheme, co-channel interference within the cell is prevented, but resource efficiency is limited, and hence, system throughput becomes low [4]. On the other hand, in overlapped allocation, all subchannels are fully reused by all serving stations. This helps maximize the bandwidth efficiency but results in co-channel interference, which decreases the overall system throughput and induces service outage for a few MSs located at the boundary between neighboring stations (BS or RSs). There exists an obvious trade-off between frequency reuse gain and co-channel interference, as summarized in Table 1.

Park and Bahk [2] varied the level of reuse in a relay network with six RSs surrounding a BS (a 6-RS topology). The FRF 1, 2, 3, and 6, represent the scenarios where 6, 3, 2, and 1 RS(s) share the same frequency band, respectively. FRF $= 1$ and FRF $= 6$ are similar to those in the case of overlapped allocation and orthogonal allocation, respectively. In these cases, there is a trade-off between throughput and fairness level when the FRF is varied, as shown in Fig. 1.

The co-channel interference problem in a relay network with three RSs is illustrated in Fig. 4, where the following assumptions are made.

1) The BS is equipped with three directional antennas so that the range of each antenna is 120°.
2) The RS is equipped with an omnidirectional antenna.

In overlapped allocation, we identify six *interference areas* during the access zone, as illustrated in Fig. 4. For example, the MSs in interference area 1 are covered by RS 1 and interfered by RS 3 and BS. Similarly, the MSs in interference area 4 are covered by RS 2 and interfered by RS 3 and BS. the RS 1 may interfere with the MSs in interference area 4, but the interference intensity is expected to be weaker than that with RSs 2 or 3.

We call some of the areas interference areas if we expect the nodes in these areas to suffer strong interference because of the relative distance between the nodes BS or RSs. In our scheme, we target these interference areas order to improve QoS fairness as well as system throughput. It is not our assumption that only the nodes residing in interference area suffer interference. It is not on-off situation. We simply estimate the carrier to interference-plus-noise ratio (CINR) for every node when we choose the MCS level. Clearly, the MSs located in the interference areas are expected to suffer severe interference and service outage. This may result in poor QoS levels for the MSs and low QoS fairness for the network.

Fig. 5(a) illustrates a frame structure allowed by the current IEEE 802.16j standard. The relay zone can be divided in the time domain, frequency domain, or both. RSs 1 and 3 share the same subchannel in a time division manner, and RS 2 is assigned a subchannel thath does not overlap with the subchannel shared by RSs 1 and 3. In the relay zone, the RSs are in the Rx mode or in the idle mode.

III. THE PROPOSED SCHEME

The number of RSs in a cell is generally assumed to be three or six [2], [4]. Hence, in our proposed scheme, we consider two cases, one with three RSs and the other with six RSs. For simplicity of presentation, we assume that the amount of assigned

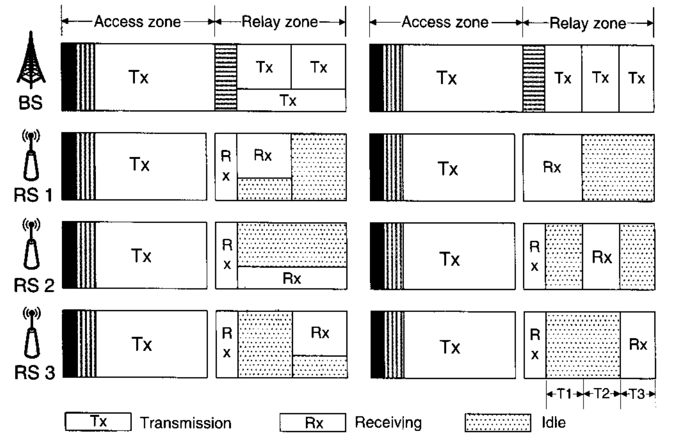

Fig. 5. Examples of resource allocation in accordance with IEEE 802.16j draft standard: (a) Relay zone is divided in time and frequency division and (b) relay zone is divided in time division only.

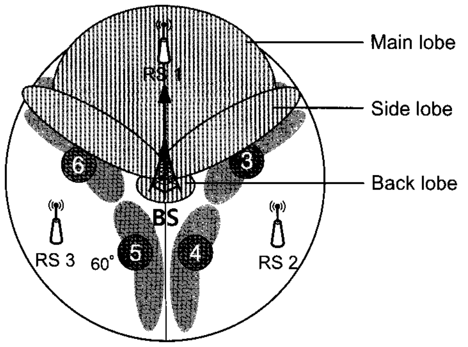

Fig. 6. BS and RSs coverage in time T1.

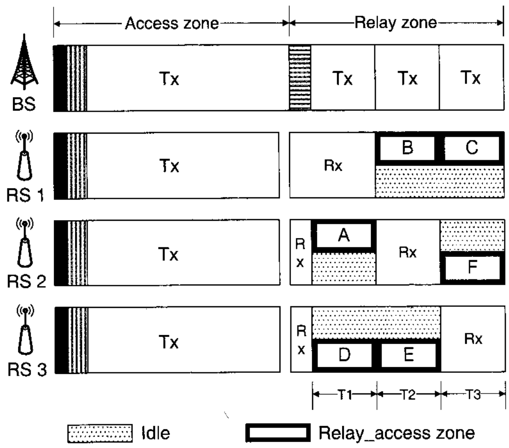

Fig. 7. Proposed frame structure for a 3-RS topology.

Table 2. Mapping slots to interference areas (refer to Figs. 4 and 7) for a 3-RS topology.

Slots	Transmitting RSs	Interference areas
A	RS 2	4
B	RS 1	1
C	RS 1	2
D	RS 3	5
E	RS 3	6
F	RS 2	3

relay traffic and the wireless environment for all the RSs are identical.

A. Proposed Frame Structure for a 3-RS Topology

Fig. 5(b) shows a basic frame structure to be used in our scheme, where the relay zone is divided among the RSs in a time division manner, accordance with the standard. In addition to this structure, we use directional antennas to improve system throughput while maintaining the interference at a low level. As shown in Fig. 5(b), for a relay network with three RSs, the relay zone is divided into three time periods T1, T2, and T3. During T*i*, RS *i* receives data from the BS via a directional antenna facing RS *i*. Assuming that the amount of relay traffic to each RS is equal, we set the sizes of T1, T2, and T3 to be the same.

In time T1, RS 1 receives from the BS with a directional antenna facing RS 1. The coverage of the BS in time T1 is shown in Fig. 6 using a directional antenna model [9]. The main lobe is in the direction of maximum radiation or reception. In addition to the main lobe, there are side lobes and back lobes. These side lobes and back lobes do not overlap with interference areas 4 and 5 during T1 because the directional antenna gain is near zero outside the beam width [9]. In [10] and [11], too the gain of the directional antenna outside the beam width is assumed to be zero. Thus, in our scheme, we allow RSs 2 and 3 to provide access service to the MSs located in interference areas 4 and 5 in a frequency division manner during T1. RSs 2 and 3 transmit to the MSs located in interference areas 4 and 5 respectively, in the same time interval when the BS transmits to RS 1 via the directional antenna. RSs 2 and 3 do not interfere with each other's transmission since they divide the frequency band (orthogonal allocation). The MSs in area 4 (area 5) are not interfered by RS 3 (RS 2). Since the BS uses a directional antenna for transmission to RS 1, as shown in Fig. 6, it does not interfere with the MSs in areas 4 and 5. Thus, the MSs in areas 4 and 5 are expected to achieve a higher CINR level than do the MSs in overlapped allocation.

The interference our new scheme may introduce can be classified into two types. The first is the interference at the receiving RS, which is in the Rx mode during relay transmission from the BS. We claim that this interference is negligible since the receiving RS receives strong directed signals from the BS, while the interfering signals from the neighboring RSs are weak. For example, RS 1 may be interfered by RSs 2 and 3 since the frequency bands used by these RSs partially overlap with the band used by the BS, as shown in Figs. 6 and 7. However, the interference is expected to be small because the BS is closer to RS 1, the transmitting power of BS is large, and it is directed toward RS 1. In our simulation setup in Section V, the result shows CINR high enough to warrant the highest MCS level, 64QAM 3/4.

The second type of interference is the mutual interference between two neighboring RSs involved in relay_access zone transmission. We claim that this interference is also negligible since the RSs do not share subchannels. For example, consider RS 1 to be in the Rx mode and RSs 2 and 3 to be in the relay_access zones A and D, respectively, as illustrated in

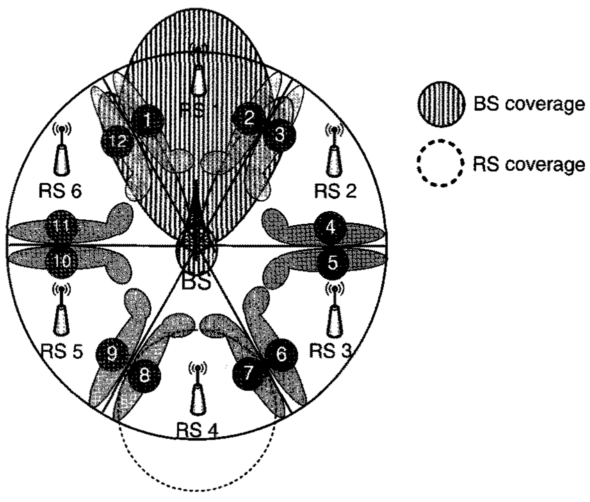

Fig. 8. Interference areas for a 6-RS topology.

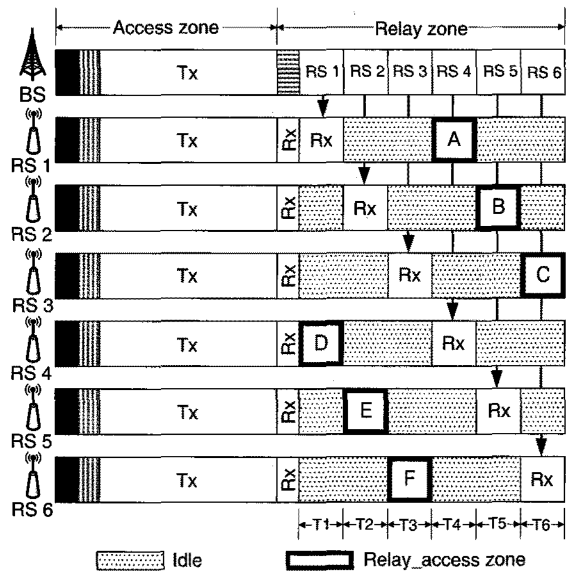

Fig. 9. Proposed frame structures in a 6-RS topology.

Figs. 6 and 7. Clearly, A and D do not use different subchannels, and hence, RSs 2 and 3 do not suffer from mutual interference.

A and D in Fig. 7 represent the slots in which RSs 2 and 3 provide access to the MSs located in interference areas 4 and 5, respectively, as mentioned in Table 2. A and D share the same frequency band during the BS-RS1 relay transmission in T1, but because of the use of a directional antenna facing only RS 1, prevented interference to RSs 2 or 3 (*spatial division*) is. RSs 2 and 3 divide the frequency band, and there is no interference between them (*frequency division*). The (B, E) pair and (C, F) take turns in repeating scheduling similar to that by the (A, D) pair (*time division*). We claim that in our approach, the throughput and fairness are better than, those in previous approaches [4], while outage is relatively low; this is because spatial division, frequency division, and time division are combined in a novel manner in our approach.

Table 2 summarizes the slots assigned to provide access service to the corresponding interference areas. In this manner, the MSs located in the interference areas can be provided access services with reduced interference. Since those MSs would have been provided access service with poor QoS levels in overlapped allocation [4], our scheme allows us to obtain improved fairness. Since in our scheme, the access zone of each RS is virtually increased, the system throughput is also greatly improved.

The relay_access zones in Fig. 7 appear to be static. However, our scheme does not require relay_access zones to be static. Our scheme can be implemented even under varying traffic conditions. As the duration for relaying to individual RSs changes, the duration of the corresponding relay_access zones also changes. For example, if the duration of relay transmission to RS 2 increases because of heavy traffic to RS 2, the sizes of relay_access zones B and E also increase. We focus on the creation of a new zone rather than on optimizing our scheme under varying traffic. The related work in [2] and [4] also does not focus on optimizing schedules for varying traffic conditions.

B. Proposed Frame Structure for a 6-RS Topology

For a 6-RS topology, the angle covered at a time by the directional antenna from BS is reduced to 60°. We identify 12 interference areas when six RSs are used, as shown in Fig. 8. For example, the MSs in interference area 1 are covered by RS 1 and interfered by RS 6 and the BS. Similarly, the MSs in interference area 4 are covered by RS 2 and interfered by RS 3 and the BS. Clearly, the MSs located in interference areas suffer severe interference and service outage. Fig. 9 shows a frame structure where the relay zone is divided into six time periods T1 through T6 for six RSs in a time division manner, in accordance with the current IEEE standard [6]. In addition to this structure, we use directional antennas to improve system throughput while maintaining the interference at a low level. During Ti, RS i receives data from the BS via the directional antenna facing RS i. Assuming that the amount of relay traffic to each RS is equal, we set the sizes of T1, T2,$\cdots$, T6 to be equal.

Table 3. Mapping slots to interference areas (refer to Figs. 8 and 9) for a 6-RS topology.

Slots	Interference areas	Slots	Interference areas
A, B	1, 2	G, H	7, 8
C, D	3, 4	I, J	9, 10
E, F	5, 6	K, L	11, 12

Table 3 summarizes the mapping of slots to interference areas. In time T1, all the RSs except RS 1 can serve their subordinate MSs, while the BS transmits to RS 1. However, RS 1 is expected to suffer severe interference if the remaining RSs simultaneously transmit. Therefore, we allow only the RS that is farthest from RS 1 to transmit. For example, RS 4 is chosen when the BS transmits to RS 1, as illustrated in Fig. 8.

We identify three different choices for each MS, to obtain access service. Refer to Fig. 7 for a 3-RS topology. The MS can be served directly by the BS, by an RS in the access zone, or by an RS in the relay zone when the BS is involved in relay transmission to other RSs via a directional antenna. For example, an MS located between the BS and RS 1 can be served by the BS or RS 1 in the access zone in Fig. 7, or by RS 1 in slots B or C of the relay zone, where the BS is involved in relay transmission to

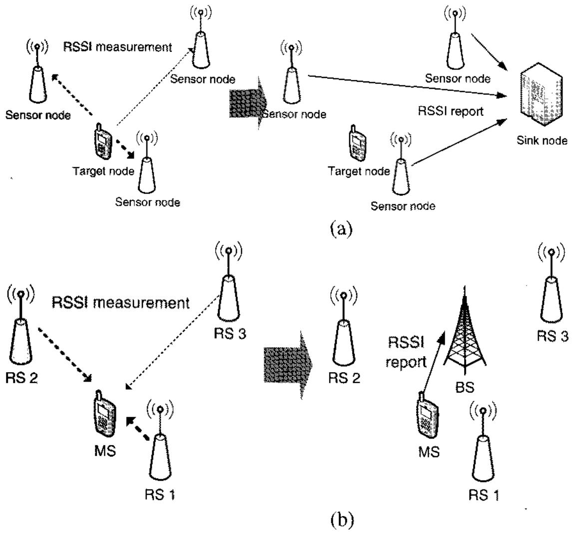

Fig. 10. Localization using RSSI measurement: (a) Localization method in sensor networks and (b) proposed localization scheme to be used in the IEEE 802.16j network.

RS 2 or RS 3. Similarly, the MSs in a 6-RS topology have three choices for being served. Refer to Fig. 9 for a 6-RS topology.

C. *Proposed Scheme to Determine Which Station (BS or Which RS) Provides Access Service to Which MS*

Our scheme differs from previous schemes [2], [4], [6], in which only two choices are available, i.e., to be served directly by the BS or by an RS in the access zone for the BS. In other words, there is no difference between the access zone for the BS and that for an RS. However, the RSs in our scheme have two different access zones, one overlapping with the access zone for the BS, and the other partially overlapping with the relay zone for the BS. Refer to Fig. 9 for an example. Here, RS 1 has two access zones and one relay zone. The first access zone overlaps with the BS, and the second access zone (slots A, B, and C combined together) overlaps with a part of the relay zone for the BS when RS 2–RS 6 take turns in receiving relay transmission from the BS. T1 is the relay zone for RS 1; in this zone, RS 1 receives relay transmission from the BS. Let us denote the newly added access zone that partially overlaps with the relay zone as *relay_access zone* for our description.

The basic idea of our scheme is to use the *relay_access zone* to provide access service to the MSs located exactly in between two neighboring RSs and suffer considerable interference. Such MSs may mostly belong to one of the interference areas. The exact number of MSs to be served during *relay_access zone* and the exact size of each interference area may depend on many factors, including the wireless environment, distribution of the RSs and MSs, and tolerable interference threshold. We believe that it is better to develop a basic algorithm that can be adapted to suit the given details for specific applications in a specific wireless environment.

Once an MS is chosen to be served in *relay_access zone* (this may be done by comparing the CINR level of an MS against a threshold), the next step is to guess which interference area the MS may belong to. Then, we use Tables 2 or 3 to determine the slot during which the MS will be served. We use the relative strength of the signals from the surrounding RSs to guess which interference area an MS belongs to. Fig. 10 shows a comparison of our scheme with a localization method on the basis of the received signal strength indicator (RSSI) measurement, which is widely used in sensor networks [12]–[14]. As illustrated in Fig. 10(a), a target node transmits multiple packets to sensor nodes, which measure the RSSI for each received packet. A computer gathers information about the measured RSSIs through a sink node and finally estimates the location of the target node by the location estimation method.

Table 4. Localization table.

MS	Descending order of RSSI			Location
	1st	2nd	3rd	
MS#1	RS 2	RS 1	RS 3	3
MS#2	RS 1	RS 3	RS 2	1
MS#3	RS 1	RS 2	RS 3	2
⋮	⋮	⋮	⋮	⋮
MS#n	RS 3	RS 2	RS 1	5

Our scheme in Fig. 10(b) does the reverse of the abovementioned process to localize an MS. RSs transmit packets to a target MS, which measures the RSSI for each RS. The reason for adopting the reverse process, as mentioned above, is to carry out the scanning procedure established in the current IEEE standard [6] and avoid additional overhead for localization. The scanning procedure is originally set for hand-off between RSs. The scanning procedure in IEEE 802.16j is as follows [3], [6].

1) A BS shall generate MOB_NBR-ADV messages, which include a neighbor BS and RSs for an MS.
2) A MOB_SCN-REQ message may be transmitted by an MS to request a scanning interval for the purpose of seeking available serving stations and determining whether they can be used as targets for handover.
3) A BS may transmit MOB_SCN-RSP to start MS scan reporting.
4) The MS scans neighbor serving stations.
5) The MS shall transmit a MOB_SCN-REP message to report the scanning results to its servicing BS.

Once the the BS obtains the RSSIs of the RSs surrounding an MS, it can run an algorithm to guess which interference area the MS belongs to and determine the slot and the corresponding RS. A simple algorithm would sort the RSSIs in the descending order, as shown in Table 4, and use the relative strength to guess a candidate interference area. For example, MS#1 receives the strongest RSSI from RS 2, then from RS 1, and finally from RS 3. Since there is a high probability of the MS in interference area 3 receiving RSSIs in the same order, we guess that MS#1 is located in interference area 3 if it experiences a certain level of interference. One can devise a more complex algorithm to obtain better estimates with more possible overhead. However, our simple algorithm is effective, through our simulations.

We summarize our scheme as follows:

1) Select a target MS that has the lowest CINR value.
2) Localize the target MS to obtain an interference area using RSSI reports and Table 4.
3) Use Tables 2 or 3 to identify candidate slots for the MS (to use *relay_access zone*).

Table 5. Transmission scenarios for a 3-RS topology.

Scenario	Schemes	Description	Interference, throughput
#1	Orthogonal	RSs divide the channel in the access zone	Little interference the three RSs, low throughput because of no frequency reuse
#2	Overlapped	RSs reuse the channel in the access zone	Considerable interference among RSs, high throughput owing to full frequency reuse
#3	Proposed (3-RS topology)	Directional antenna and creation of a new access zone for zone for RS-MS (*relay_access zone*)	Access zone: Same scheme as that in #2, same interference and throughput Relay zone: Extra throughput gain by overlapping a BS-RS relay with the transmission of the other RSs to their respective subordinate MSs. Little interference among RSs in the relay zone since RSs divide the channel

4) If the candidate slots are fully occupied, and then allocate an access zone for the MS.
5) Select the next MS having the lowest CINR.
6) Repeat steps 2 to 5, until all MSs are allocated a resource.

IV. MODELING

Mathematical modeling for our scheme as well as that for previous schemes, in terms of capacity and intracell interference is provided for analytic understanding.

A. Throughput

Equations (1) through (10) are derived for analytic modeling of the capacity for our approach and other known schemes [2], [4]. The capacity of each scheme can be modeled on the basis of the product of the size of the aggregated slots and the average spectral efficiency estimated for the slots. Slots can be defined in two dimensions—time and frequency—and hence can be represented in [s·Hz]. $\mathrm{NS}(x, y, \#s, z)$ [s·Hz] denotes the aggregated size of the slots assigned to transmission from x to y in zone z in scenario $\#s$. $\mathrm{SE}(x, y, \#s, z)$ [bps/Hz] denotes the average spectral efficiency for transmission from x to y in zone z in scenario $\#s$, and $C(\#s)$ [bits] denotes the capacity.

For example, (1) models the network capacity for scenario #1, which corresponds to orthogonal allocation [4], as summarized in Table 5. Each scenario in Table 5 corresponds to a scheme. The number of available slots for the overlapped allocation [4] is greater than that in the case of orthogonal allocation [4] because of frequency reuse, as represented in (4).

Spectral efficiency depends on many factors related to the surrounding wireless environment. When other factors are assumed to remain unchanged, a high interference level would imply low spectral efficiency. Thus, we expect schemes with overlapped allocation to yield a lower average spectral efficiency than do schemes with orthogonal allocation, as indicated in (7).

The capacity of our scheme for a 3-RS topology is represented by (3) as scenario #3. The number of slots assigned to BS-MS transmission in the access zone is the same as that in scenario #2 (overlapped allocation), as (5) indicates. Moreover, the average spectral efficiency for BS-MS transmission in scenario #3 in the access zone is equal to that in scenario #2, as shown in (8).

The throughput enhancement in our scheme as compared to that in scenario #2 is represented by the third term in (3). $\mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#3, \mathrm{relay\_access})$ is the number of slots added to our scheme; this addition allows all RSs except that involved in relay from the BS to provide access service to their subordinate MSs. Since the access service from other RSs overlaps with the relay zone for an RS, we call the created zone relay_access. The boxes labeled A, B, C,$\cdots$, F in Fig. 7 are examples of relay_access zones.

The relay_access zone is created by taking advantage of directional antennas (allowed in the IEEE standard [6]) and our proposed scheme of scheduling using the new interference area concept. Our scheduling algorithm chooses appropriate RSs to cover the interference areas, as illustrated in Tables 2 and 3 for a 3-RS topology and a 6-RS topology, respectively.

$$C(\#1) = \mathrm{NS}(\mathrm{BS,MS}, \#1, \mathrm{access}) \cdot \mathrm{SE}(\mathrm{BS,MS}, \#1, \mathrm{access}) + \sum_{i=1}^{3} \mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#1, \mathrm{access}) \cdot \mathrm{SE}(\mathrm{RS}\ i, \mathrm{MS}, \#1, \mathrm{access}), \tag{1}$$

$$C(\#2) = \mathrm{NS}(\mathrm{BS,MS}, \#2, \mathrm{access}) \cdot \mathrm{SE}(\mathrm{BS,MS}, \#2, \mathrm{access}) + \sum_{i=1}^{3} \mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#2, \mathrm{access}) \cdot \mathrm{SE}(\mathrm{RS}\ i, \mathrm{MS}, \#2, \mathrm{access}), \tag{2}$$

$$C(\#3) = \mathrm{NS}(\mathrm{BS,MS}, \#3, \mathrm{access}) \cdot \mathrm{SE}(\mathrm{BS,MS}, \#3, \mathrm{access}) + \sum_{i=1}^{3} \mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#3, \mathrm{access}) \cdot \mathrm{SE}(\mathrm{RS}\ i, \mathrm{MS}, \#3, \mathrm{access}) + \sum_{i=1}^{3} \mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#3, \mathrm{relay\_access}) \cdot \mathrm{SE}(\mathrm{RS}\ i, \mathrm{MS}, \#3, \mathrm{relay\_access}), \tag{3}$$

$$\mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#2, \mathrm{access}) > \mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#1, \mathrm{access}), \tag{4}$$

$$\mathrm{NS}(\mathrm{BS,MS}, \#3, \mathrm{access}) = \mathrm{NS}(\mathrm{BS,MS}, \#2, \mathrm{access}), \tag{5}$$

$$\mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#3, \mathrm{access}) = \mathrm{NS}(\mathrm{RS}\ i, \mathrm{MS}, \#2, \mathrm{access}), \tag{6}$$

$$\mathrm{SE}(\mathrm{RS}\ i, \mathrm{MS}, \#1, \mathrm{access}) > \mathrm{SE}(\mathrm{RS}\ i, \mathrm{MS}, \#2, \mathrm{access}), \tag{7}$$

$$\mathrm{SE}(\mathrm{BS,MS}, \#3, \mathrm{access}) = \mathrm{SE}(\mathrm{BS,MS}, \#2, \mathrm{access}), \tag{8}$$

$$\mathrm{SE}(\mathrm{RS}\ i, \mathrm{MS}, \#3, \mathrm{access}) = \mathrm{SE}(\mathrm{RS}\ i, \mathrm{MS}, \#2, \mathrm{access}). \tag{9}$$

From (2), (3), (5), (6), (8) and (9), we have

$$C(\#3) > C(\#2). \tag{10}$$

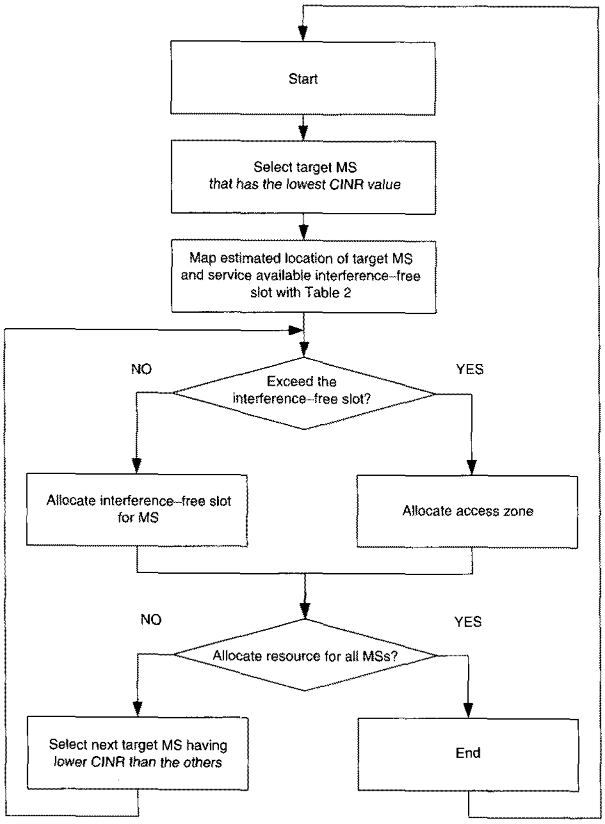

Fig. 11. Interference-aware packet scheduling algorithm.

B. Intracell Interference

The CINR of each MS is determined by calculating the average of all the slots assigned to the MS. Let C_k denote the received signal power of slot *k* among the slots assigned to an MS and I_k denote the corresponding interference. Then, the average CINR for each MS can be represented by computing the average of all the slots used by the MS, as follows

$$\frac{C}{I} = \frac{1}{N_{\text{used}}} \sum_{k=1}^{N_{\text{used}}} \frac{C_k}{I_k + N_0 NF}. \tag{11}$$

where N_0 and NF denote the thermal noise power and noise figure, respectively, and N_{used} denotes the number of slots used by the MS. For overlapped allocation, intracell interference is observed during the access zone. The interference can be represented as

$$I_{k,\text{overlapped}} = (P_{\text{received}}^{\text{BS}_k} + \sum_{j=1}^{N_r} P_{\text{received}}^{\text{RS}_{j,k}}) - C_k. \tag{12}$$

where $P_{\text{received}}^{\text{BS}_k}$ and $P_{\text{received}}^{\text{RS}_{j,k}}$ denote the received signal power for slot *k* served by the BS and the received signal power for slot *k* served by the RSs with the BS, respectively. N_r is the number of RSs associated with the BS. For orthogonal allocation, very small intracell interference is expected as

$$I_{k,\text{orthogonal}} = 0. \tag{13}$$

In our scheme, the MSs are served not only in the access zone but also in the relay_access zone. In the access zone, the interference experienced by the MSs is expected to be similar to that in the case of overlapped allocation. In the relay_access zone, a small intracell interference is expected, as in the case of orthogonal allocation. Thus, we have

$$I_{k,\text{proposed}} = \begin{cases} (P_{\text{received}}^{\text{BS}_k} + \sum_{j=1}^{N_r} P_{\text{received}}^{\text{RS}_{j,k}}) - C, & \\ \quad \text{if slot belongs to } \textit{access zone} & \\ 0, \quad \text{if slot } k \text{ belongs to } \textit{relay\_access zone}. & \end{cases} \tag{14}$$

Table 6. Setup for simulation environment.

	BS	RS	MS
Transmit power	20 W	10 W	30 mW
Antenna gain	13 dB	12 dB	0 dB
Antenna height	32 m	15 m	1.5 m
Transmit frequency	2.3 GHz	2.3 GHz	2.3 GHz
System bandwidth	10 MHz	10 MHz	10 MHz

Table 7. MCS table for adaptive modulation and coding.

MCS level		Required CINR (dB)	Bits/slot
BPSK	1/2	3.0	24
QPSK	1/2	6.0	48
QPSK	3/4	8.5	72
16QAM	1/2	11.5	96
16QAM	3/4	15.0	144
64QAM	2/3	19.0	144
64QAM	3/4	21.0	216

V. PERFORMANCE EVALUATION

Using C++, we perform a simulation of our scheme as well as that of known schemes [2], [4] in order to evaluate the efficiency of our approach. The simulation environment is set up according to a procedure accepted in the literature. Owing to space constraints, we describe in detail the 3-RS topology and give a brief description of the 6-RS topology. Three RSs in the cell are located 120° apart, thus creating three sub-cells, each of which is covered by an RS. The cell radius is 1 km. Each RS is assumed to be located at 3/4 position in a line from BS to the cell boundary. This RS position is chosen by considering throughput enhancement, coverage expansion, and interference in the wireless environment specified in Table 6. The BS has three directional antennas and the transmit power of each antenna is limited to 20 W. Each RS has an omnidirectional antenna, and its transmit power is limited to 10 W. The antenna gain, antenna height, transmit frequency, and system bandwidth assumed in the simulation are summarized in Table 6. We consider a full-buffer traffic model, i.e., a model in which each MS always has packets in the buffer ready to be transmitted, and apply the PUSC subchannelization scheme [6]. Table 7 shows the MCS level of the IEEE 802.16e system used in our simulation; this table lists the CINR levels required for the given modulation and coding set (MCS) subject to the given channel model [15]. For the IEEE 802.16j system, we consider the performance of our scheme and two different allocation schemes: overlapped and orthogonal allocations. We investigate the MCS level distribution, system throughput, fairness, and service outage for downlink.

The simulation is performed for two scenarios. In the first scenario, we assume that the static MSs are evenly distributed with one MS in each grid of size 100 m $\times$ 100 m. In this scenario, we may obtain an estimate close to the average performance (throughput, outage, and fairness). The actual performance for a specific distribution of MSs may be different from this estimate. If we average the estimates obtained from a sufficiently large number of random distributions, the average will converge to a certain value. The above scenario serves as a simple alternative to an intensive simulation involving many random distributions. In the second scenario, we allow the MSs to move according to a random-walk model [16].

We obtain MCS levels for all individual MSs by using (11) and Table 7. In (11), C_k (where k denotes one of the slots assigned to an MS) denotes the received signal power in slot k from the serving station. Similarly, I_k denotes the corresponding interference signal power received from the interfering stations. Then, the average CINR for each MS is obtained from the average CINR of all the slots used by the MS, as mentioned in [4]. The MCS level and bit/slot equivalent for the obtained CINR is determined from Table 7 (as illustrated in Fig. 12)

A. Scenario with Even and Static Distribution of MSs

In this scenario, the MSs are uniformly distributed throughout a cell at intervals of 100 m, and no MS moves. Fig. 12 shows the MCS level distribution in one-half of a cell for orthogonal allocation, overlapped allocation, and our scheme with a 3-RS topology. Three RSs in the cell are located 120° apart, thus forming three sub-cells, each of which is covered by an RS. Only one-half of a cell is illustrated in Fig. 12 since the MCS level distribution is bilaterally symmetrical. The circle represents an MS attached to the BS, while the box represents an MS attached to an RS. The gray levels of the shade circles or boxes represent the MCS level, with the dark representing a higher MCS level and a light shade representing a lower MCS level, as denoted at the bottom of Fig. 12. Circles with broken lines represent MSs suffering outage. Figs. 12(a), 12(b), and 12(c) show the MCS level distributions for orthogonal allocation, overlapped allocation, and our scheme with a 3-RS topology, respectively.

The MSs in orthogonal allocation exhibit a higher MCS level distribution than do those in overlapped allocation or our scheme. No frequency reuse is employed in orthogonal allocation, and hence, there is very less interference. This allows the MSs to have higher MCS levels, as illustrated by the dark circles and boxes in Fig. 12. 148 MSs are attached to the BS (denoted by circles), and the remaining 316 MSs (denoted by boxes) are evenly divided among the three RSs. Fig. 12(b) shows the MCS level distribution in overlapped allocation. The MSs in overlapped allocation exhibit a lower MCS level distribution owing to intracell interference, as frequency is fully reused. 20.41% of MSs at the border between neighboring RSs or that between a BS and an RS suffer service outage, as denoted by circles with broken lines. Service outage occurs when the CINR does not reach the level required to support the minimum MCS level. 97 MSs are attached to the BS, and the remaining 211 MSs are served by the RSs.

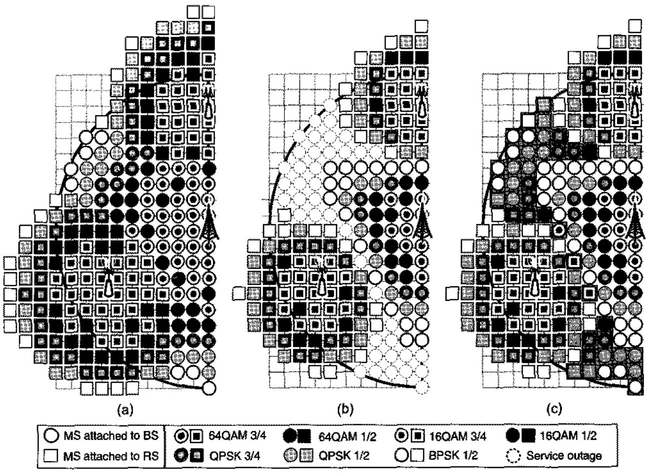

Fig. 12. MCS levels for individual MSs with even and static distribution of MSs over a cell (1/2 of the cell is shown): (a) Orthogonal allocation scheme, (b) overlapped allocation scheme, and (c) proposed scheme.

The MCS level distribution in our scheme is shown in Fig. 12(c). Note that the MSs that would have had suffered outage in overlapped allocation are served with a relatively higher MCS level in our scheme (denoted by the shaded region in Fig. 12(c)). Access service to these MSs is provided by the RSs in the *relay_access zone*, which exists only in our scheme and overlaps with the relay zone; for this reason, no extra time or frequency band other than that used by in overlapped allocation is required in our scheme.

B. Scenario with Random-Walk Model

In this scenario, we use the random walk mobility model [16]. We allow each MS to move from its current location to a new location by randomly choosing the direction and speed over the range [0, 2π] and [0.5 m/s, 1.5 m/s], respectively. Each movement occurs in a constant time interval t, 100 s. The simulation is performed for 10,000 s to estimate the influence of the random walk of MSs on the throughput and service outage ratio.

Fig. 13 shows the simulation result (throughput and service outage). In the orthogonal allocation scheme, the MCS levels for individual MS are the highest, but the total cell throughput is the lowest (3.99 Mbps, as shown in Table 8) since there is no frequency reuse. The system throughput in overlapped allocation (8.22 Mbps, as shown in Table 8) is much higher than that in orthogonal allocation, while the fairness is expected to be lower in overlapped allocation since some of the MSs suffer low MCS level or outage.

Fairness is an important metric since many future multimedia services, including VOIP and videophones, require uniform a QoS level to the MSs, regardless of the proximity of the MS to the BS or an RS. We use Jain's fairness index, which is commonly used [17], [18] for fairness measurements. The fairness is obtained as

$$\text{Fairness} = \frac{\left(\sum_{i=1}^{N} R_i\right)^2}{N \sum_{i=1}^{N} R_i^2} \tag{15}$$

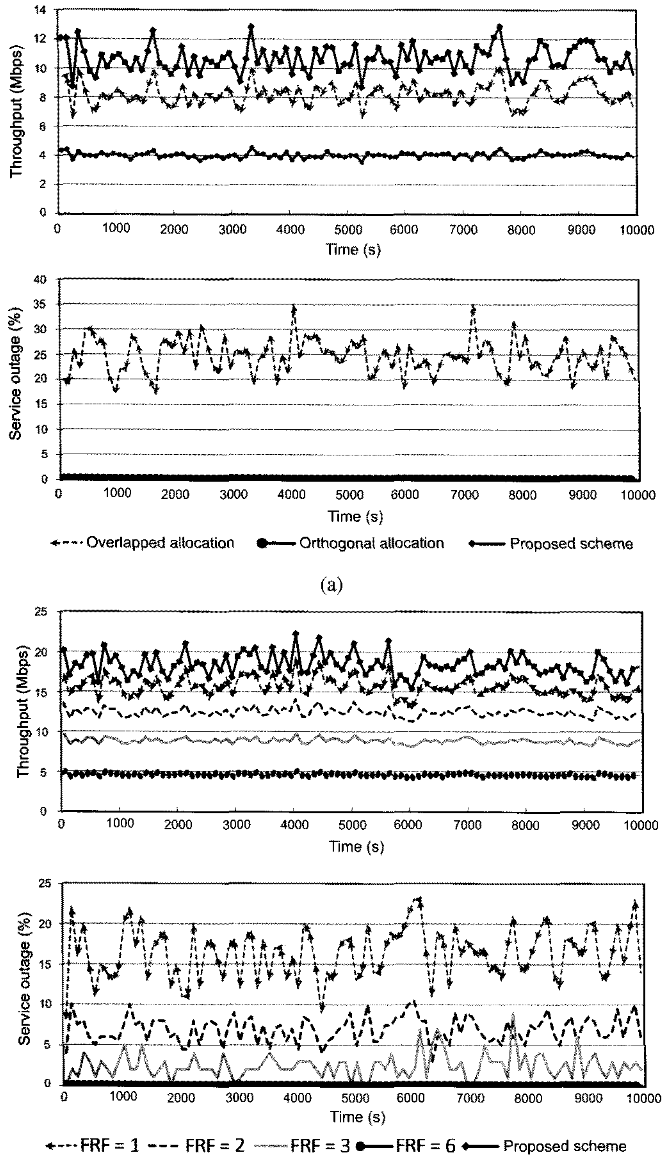

Fig. 13. Performance evaluation with random distribution and fixed speed motion: (a) 3-RS topology and (b) 6-RS topology.

where R_i is the achievable service rate for MS i, and N is the number of MSs. The system throughput of our scheme is the highest (10.64 Mbps, as shown in Table 8), and the fairness is expected to improve as a result of reduction of service outage for the nodes in the interference area.

C. *Performance Comparison*

Table 8 lists the fairness along with system throughput, outage ratio, and Jain fairness index for known schemes [2], [4] and our scheme with a 3-RS topology and a 6-RS topology. In the case of the 3-RS topology, the fairness in our scheme is better than in overlapped allocation but poorer than that in orthogonal allocation. However, the system throughput of our scheme is 2.66 times that of orthogonal allocation and 1.29 times that of overlapped allocation. As in the case of orthogonal allocation, there is no outage in our scheme; however, the outage in overlapped allocation is 24.59%. For the 6-RS topology, our scheme shows very high fairness; similar to FRF = 2. The fairness is highest (0.88) for FRF = 6, but in this case, system throughput is very low (4.57 Mbps); however, in our scheme, throughput is the highest (18.38 Mbps). The system throughput of our scheme is 1.21 times that of the FRF = 1 scheme, the fairness (0.53) and service outage ratio (16.34%) of which are lower and higher than those in our scheme, respectively.

Table 8. Performance comparison.

Topology	Scheme	System throughput (Mbps)	Service outage (%)	Fairness
3-RS	Overlapped	8.22	24.59	0.48
	Orthogonal	3.99	0	0.80
	Proposed	10.64	0	0.62
6-RS	FRF = 1	15.24	16.34	0.53
	FRF = 2	12.42	6.95	0.71
	FRF = 3	8.84	2.44	0.81
	FRF = 6	4.57	0	0.88
	Proposed	18.38	0	0.69

VI. CONCLUSION

In the IEEE 802.16j standard of overlapped allocation, interference between the serving stations can cause significant system performance degradation. Orthogonal allocation can solve this problem. However, in this scheme, both cell capacity and system throughput are reduced. We plot trade-off curves for system throughput vs. fairness (or outage) in the previously proposed schemes. We propose a new scheme which positions itself well above the trade-off curves, achieving high system throughput with high fairness or low outage rate. This is obtained by combining spatial division, time division, and frequency division, which we state is a novel approach. The evaluation results show that the performance of our scheme is superior to that of the two most recent schemes. In our future research, we plan to consider an optimizing schedule under varying traffic conditions.

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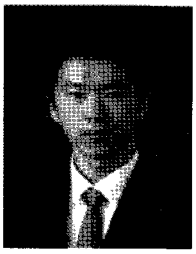

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