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Generalized Hybrid Scheduling Scheme for Multihop Relaying WiMAX Networks

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***Abstract*—In this paper, we propose a heuristic scheduling scheme, named hybrid resource allocation scheme that can reduce the time complexity of scheduling scheme and improve the efficiency of resource utilization while minimizing interference. We first focus on the two-hop relaying scenario, since this scenario has the largest throughput gain, and then explore an extension of the proposed hybrid scheme to a general multihop relaying scenario. We evaluate the performance of our proposed hybrid scheme by comparing it with the optimal scheduling scheme as well as the well-known two schemes, namely, *orthogonal* and *overlapped* in terms of cell throughput, outage rate, and computation time. The numerical results show that the proposed hybrid scheme achieves a higher throughput than the orthogonal scheme while maintaining as low an outage rate as orthogonal scheme. In addition, the computational time is significantly less than the optimal scheme at the expense of minimal throughput degradation.**

I. INTRODUCTION

The addition of relay stations (RSs) to a traditional WiMAX network is seen as an attractive technology for providing throughput enhancement and coverage extension. IEEE 802.16j for WiMAX with RSs was published in 2009 [1]. Furthermore, multihop relaying is considered an essential feature in the IEEE 802.16m standard [2] and 3GPP Long Term-Evolution (LTE) Advanced standard [3]. According to the IEEE 802.16j standard, two kinds of relay operation modes are defined: *transparent* relay mode and *non-transparent* relay mode. The transparent RSs allow only throughput enhancement, whereas non-transparent RSs can extend the coverage and also increase the throughput. In this paper, we focus on deploying non-transparent RSs transmitting on the same carrier frequency as the base station (BS) for the purpose of coverage extension, and a single tier of RSs since additional hops can cause a higher delay and lower bandwidth efficiency. A non-transparent mode frame structure consists of a downlink (DL) and an uplink (UP) subframe, and each subframe includes two zones, namely the *access* and *relay* zones [1]. During the DL access zone period, the BS and RSs can transmit to the associated SSs simultaneously, and the SSs can transmit to the BS and RSs in a similar way during the UL access zone period.

Due to the frequency reuse in non-transparent RS mode, it is more complex and challenging to explore a scheduling scheme that maximizes cell throughput while serving the SSs in a fair manner. Many researchers have recently proposed scheduling schemes for OFDMA based WiMAX networks. The simplest scheduling scheme is fixed assignment scheduling [4], in which a BS allocates a fixed amount of bandwidth for every RSs. In this simple scheduling scheme the system throughput is significantly degraded due to inefficient resource utilization. To enhance network performance, Park et al. [5] present two scheduling schemes named *orthogonal* and *overlapped* and compare the performance of the two schemes. The orthogonal scheme assumes that only one RS or the BS transmit at any one time (thus eliminating interference from multiple service nodes, but disallowing frequency reuse), while the overlapped scheme assumes that all service nodes transmit at the same time (thus maximizing frequency reuse, but increasing the interference to each node). However the boundary between access and relay zones was not dynamically selected according to the traffic load but statically determined for each scenario.

In our previous paper [6], we propose an optimal scheduling scheme to maximize cell throughput under a max-min fairness constraint in two-hop relaying networks. The path selection and boundary between the access and relay zone intervals are determined optimally based on the traffic load in order to achieve high efficiency of resource utilization, however its time complexity is significantly high due to expensive operations, especially when the densities of active SSs and RSs are high in a cell. To reduce the time complexity of scheduling scheme, we propose a heuristic scheduling, named hybrid scheduling scheme [7] that combines the advantages of the orthogonal and overlapped schemes under the max-min fairness constraint such that frequencies are reused and outage is avoided by minimizing interference.

In this paper, we extend the proposed hybrid scheme to a general multihop relaying scenario to show that the hybrid scheme can be applicable to general multihop scenarios. Moreover, the impact of an increased number of relay hops on the hybrid scheme are addressed in this paper.

The rest of this paper is organized as follows. In the next section, we present the system model. In Section III, we present three scheduling schemes, orthogonal, overlapped, and hybrid schemes in two-hop relaying networks. The extended multihop relaying hybrid scheme is presented in Section IV. Numerical results and analysis are shown in Section V. Finally, Section VI concludes the paper.

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II. SYSTEM MODEL

We consider a WiMAX network enhanced with non-transparent RSs, with each cell consisting of a BS, RSs, and SSs. We assume that every node has a single omni-directional antenna, hence, no terminal can transmit and receive simultaneously. The cell radius, 1200m, is determined by the condition that the cell coverage probability under Rayleigh fading channel is greater than 90% [8], [9]. For the path loss model, we use the Erceg-Greenstein model, which is recommended by the IEEE 802.16 working group [8]. Depending on the link quality, a variety of modulation and coding schemes (MCS) are supported in WiMAX networks. Table I shows the achievable data rates denoted as $d_1, d_2, ..., d_7$ and the corresponding MCS; the last column represents the minimum required threshold values of signal to interference and noise ratio (SINR), $\overline{\gamma}_m$, computed by bit error rate expression for M-QAM [10] when bit error rate is 10^{-6}. With the assumption of a Rayleigh fading channel, the received SINR, γ, is an exponential random variable [11]. Therefore, the probability that a transmitter can achieve data rate d_m can be expressed as:

$$p(d_m) = \int_{\overline{\gamma}_m}^{\overline{\gamma}_{m+1}} \frac{1}{\gamma^*} \exp\left(-\frac{\gamma}{\gamma^*}\right) d\gamma, \tag{1}$$

where γ^* is the average SINR. Consequently, the average achievable data rate, d_s, can be computed by:

$$d_s = \sum_{m=1}^{7} d_m \cdot p(d_m). \tag{2}$$

The relay data rate (BS-RS-SS) is influenced by the link capacities of both hops involved. In order to utilize channel bandwidth efficiently, i.e., avoid wasting resource and overflowing data, the incoming and outgoing data at the relays should be equal:

$$d_{BS-RS} \cdot t_A = d_{RS-SS} \cdot t_B, \tag{3}$$

where d_{BS-RS} and d_{RS-SS} are the capacities of BS to RS and RS to SS links respectively when each link is given the entire bandwidth, and t_A and t_B are the durations of BS to RS and RS to SS link allocations respectively. The average data rate of an SS using a relay is equal to the amount of data received divided by the time required to receive it:

$$d_{BS-SS} = \frac{d_{BS-RS} \cdot t_A}{t_A + t_B}, \tag{4}$$

as the RS cannot receive from the BS while transmitting to the SS. Using (3), (4) can be rewritten as:

$$\frac{1}{d_{BS-SS}} = \frac{1}{d_{BS-RS}} + \frac{1}{d_{RS-SS}}. \tag{5}$$

Figure 1 shows a coverage extension scenario with three RSs: the BS is located at the center of the cell and three RSs are deployed at the edge of the BS's transmission range to extend the cell's coverage. Thus, the SSs can receive data either directly from the BS or through one of the RSs according to link capacity and scheduling scheme. All RSs and the BS are referred to as *service nodes* in the rest of this paper, the links between BS and RS are referred to as *relay links*, and links between a service node and its associated SSs as *access links*. Each contour line in Fig. 1 represents the achievable average data rate of an SS according to its location inside a cell. However, the actual data rate of an SS varies according to its current SINR value. We assume that all channels have a flat fading over one frame interval, such that the channel gains remain fixed over a frame interval but change independently from one frame interval to the next.

TABLE I
SINR THRESHOLD SET

MCS	Downlink Data Rate d_m[Mbps]	Spectral Efficiency [bps/Hz]	SINR Threshold $\overline{\gamma}_m$[dB]
QPSK 1/2	5.25	1.0	9.1
QPSK 3/4	7.87	1.5	11.73
16 QAM 1/2	10.49	2.0	13.87
16 QAM 3/4	15.74	3.0	17.55
64 QAM 2/3	20.99	4.0	20.86
64 QAM 3/4	23.61	4.5	22.45
64 QAM 5/6	26.23	5.0	24.02

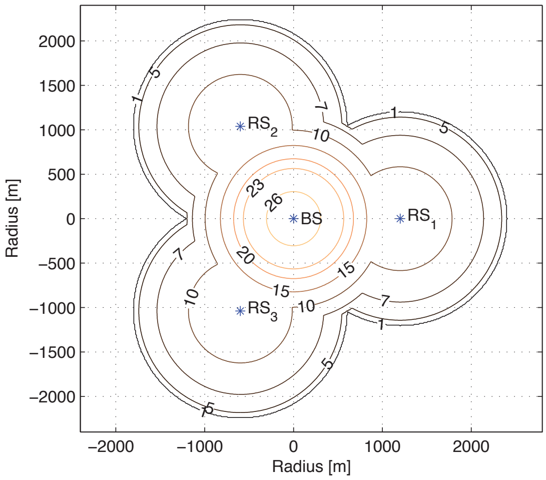
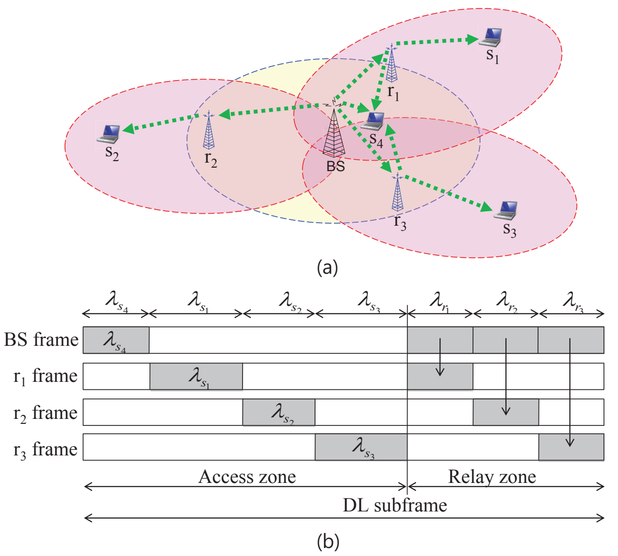


Fig. 1. A coverage extension scenario with three RSs and the achievable data rates in the cell.

III. SCHEDULING SCHEMES IN TWO-HOP SCENARIO

In this section we first present two well-known scheduling schemes: orthogonal and overlapped schemes in a two-hop relaying scenario. The orthogonal scheme minimizes interferences by not allowing frequency reuse, however it can lead to lower throughput performance, whereas the overlapped scheme can achieve higher throughput by using frequency reuse but the outage rate is also increased due to interference. We then introduce our proposed hybrid scheduling scheme that can harmonize the orthogonal and overlapped schemes. Due to the fact that the original tile (two-dimensional time×frequency) scheduling problem is NP-hard [12], we shall not deal with multiuser resource allocation over the frequency domain. In other words, we do not consider frequency selectivity, thus the entire spectrum is allocated to each node whenever they are allowed to transmit, i.e., scheduling is done by assigning time slots to every node.



(a)

(b)

Fig. 2. (a) A sample scenario with three RSs and four SSs. (b) a possible orthogonal resource allocation in the sample scenario (a).

A. Orthogonal Scheme

The orthogonal scheme is an extreme solution for schedule resources since it does not allow frequency reuse in order to minimize intra-cell interference during the access zone period. In this scheme, only one service node can be active at a time to transmit to the associated SSs. Hence, there is no outage problem due to interference, but the achievable network throughput will be degraded due to inefficient radio resource utilization. Although it is possible that one active SS can be served by multiple service nodes at different times, it is most likely that every active SS will be served only by the one service node that has the highest link capacity to that SS during one DL subframe period in order to maximize cell throughput under fairness constraint. For the general case, when R RSs $(r_1, ..., r_R)$ are deployed and N SSs $(s_1, ..., s_N)$ are active in a cell, each SS will be served by one of the service nodes. We denote with S_0, S_1, ..., S_R the set of SSs served by the BS, r_1, ..., r_R respectively. The number of active SSs in the set S_i is denoted by n_i. Although there is no interference between service nodes in the orthogonal scheme, some of the active SSs may encounter outage due to Rayleigh fading channels, hence, the summation of n_i is less than or equal to N:

$$n_0 + n_1 + ... + n_R \leq N. \tag{6}$$

We also denote with λ_{s_1}, ..., λ_{s_N} and λ_{r_1}, ..., λ_{r_R} the time fractions allocated to s_1, ..., s_N in the access zone and the time fractions allocated to r_1, ..., r_R in the relay zone respectively. Thus, the summation of access and relay zone time fractions should be equal to 1 (for full frame utilization):

$$\sum_{i=1}^{N} \lambda_{s_i} + \sum_{j=1}^{R} \lambda_{r_j} = 1. \tag{7}$$

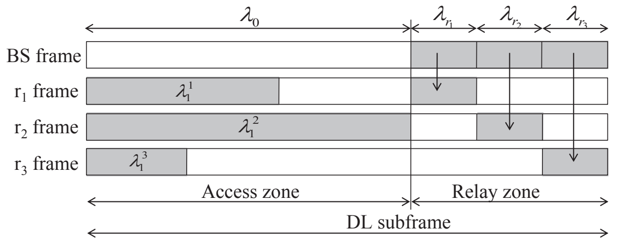


Fig. 3. Overlapped resource allocation example for the sample scenario in Fig. 2(a).

Let us also denote with d_{s_1}, ..., d_{s_N} and d_{r_1}, ..., d_{r_R} the achievable data rate of s_1, ..., s_N with its service node and the achievable data rate of r_1, ..., r_R from the superordinate service node (the BS is the superordinate node of every RS in two-hop scenario). The throughput of each node should be equal for fairness and the incoming data from the BS to an RS should be equal to the outgoing data from the RS to the associated SSs as follows:

$$d_{s_1}\lambda_{s_1} = ... = d_{s_N}\lambda_{s_N} = \frac{d_{r_1}\lambda_{r_1}}{n_1} = ... = \frac{d_{r_R}\lambda_{r_R}}{n_R}. \tag{8}$$

Using (7) and (8), the time fraction of one of the SSs can be expressed as:

$$\lambda_{s_1} = \frac{1}{1 + \frac{d_{s_1}}{d_{s_2}} + ... + \frac{d_{s_1}}{d_{s_N}} + \frac{n_1 d_{s_1}}{d_{r_1}} + ... + \frac{n_R d_{s_1}}{d_{r_R}}}. \tag{9}$$

Once the time fraction for an SS is computed by (9), the rest of the time fractions λ_i can be easily calculated by (8), hence, the cell throughput for the orthogonal scheme can be computed by:

$$Cell\ Throughput = \sum_{i=1}^{N} d_{s_i}\lambda_{s_i}. \tag{10}$$

B. Overlapped Scheme

The focus of the overlapped scheme is to reuse radio resources fully during the access zone period. Multiple service nodes can transmit data to the associated SSs simultaneously, thereby enhancing network throughput, but at the same time outage events increase due to significant intra-cell interference. The cell throughput and outage probability for the overlapped scheme vary according to the selection of the active service nodes, since not every service node has to be active during the access zone. We assume that the set of active service nodes is selected to maximize the number of served SSs. Three different objectives of determining the set of active service nodes are introduced in [6]. By using the same example scenario shown in Fig. 2(a) with an assumption that every SS has different achievable data rates from its service node $(d_{s_3} > d_{s_1} > d_{s_2})$, one possible resource allocation for the overlapped scheme is shown in Fig. 3. Every RS can be active simultaneously to serve associated SSs during the access zone period, however the SS_4 can not be served due to strong interference. Another unique aspect of the overlapped scheme is that there may be wasted resources due to fairness. If we denote with λ_0 the fraction time allocated to the entire access zone, (7) will be rewritten as:

$$\lambda_0 + \lambda_{r_1} + \cdots + \lambda_{r_R} = 1. \tag{11}$$

Let us also denote with d_j^i and λ_j^i the achievable data rate of the j^{th} active SS ($j = 1, ..., n_i$) with its service node and the time fraction allocated to the j^{th} active SS in the set S_i ($i = 0, ..., R$) respectively. The SSs in the same set S_i have to share the access zone:

$$\lambda_0 \geq \lambda_1^i + \lambda_2^i + ... + \lambda_{n_i}^i, \quad i \in \{0, 1, ..., R\}. \tag{12}$$

When the access zone is fully utilized, inequality (12) becomes an equality. In each set S_i, the throughput of each node should be equal for fairness:

$$d_1^i \lambda_1^i = d_2^i \lambda_2^i = \ ... \ = d_{n_i}^i \lambda_{n_i}^i, \quad i \in \{0, 1, ..., R\}. \tag{13}$$

However, the throughput per node of each set S_i could be different from the others since each set could have a different number of active SSs as well as link capacities. It is likely that the throughput of each node in the set with the highest number of active SSs will be the smallest. The throughput of the other nodes is also restricted to achieve equal throughput throughout the cell. We define the average data rate (H_i) of each set S_i as the sum of the throughput of active nodes in S_i divided by the total time duration of the access zone:

$$H_i = \frac{n_i d_1^i \lambda_1^i}{\lambda_1^i + \lambda_2^i + ... + \lambda_{n_i}^i}, \quad i \in \{0, 1, ..., R\}. \tag{14}$$

Using (13), we can eliminate times λ_j^i in (14):

$$H_i = \frac{n_i}{\frac{1}{d_1^i} + \frac{1}{d_2^i} + \cdots + \frac{1}{d_{n_i}^i}}, \quad i \in \{0, 1, ..., R\}. \tag{15}$$

To ensure that every active SS can achieve the same amount of throughput regardless of their associated link capacities, it is necessary to control the time fractions allocated to RSs. Let H_x and n_x be the average data rate and the number of active SSs of the set that has minimum throughput per node. Only this set can fully use resources during the access zone λ_0, while the rest of the sets excluding S_0 are constrained by the data transferred from the BS to RSs, $d_{r_i}\lambda_{r_i}$ ($i = 1, ..., R$):

$$\frac{H_x \lambda_0}{n_x} = \frac{d_{r_1}\lambda_{r_1}}{n_1} = \frac{d_{r_2}\lambda_{r_2}}{n_2} = \ ... \ = \frac{d_{r_R}\lambda_{r_R}}{n_R}. \tag{16}$$

Only S_0 is not constrained by the relay zone transmissions since every SS in S_0 is directly connected with the BS. Therefore, unless S_0 has a minimum throughput per node, the active SSs in S_0 can achieve higher throughputs since they can fully use resources during λ_0. If we use (16) to substitute for λ_{R_i} in (11), λ_0 can be expressed as:

$$\lambda_0 = \frac{1}{\frac{n_1}{n_x}\frac{H_x}{d_{r_1}} + \frac{n_2}{n_x}\frac{H_x}{d_{r_2}} + \cdots + \frac{n_R}{n_x}\frac{H_x}{d_{r_R}} + 1}. \tag{17}$$

After determining λ_0 from (17), the time fractions λ_{R_1}, ..., λ_{R_R} can be easily computed using (16). Consequently, the cell throughput can be computed by:

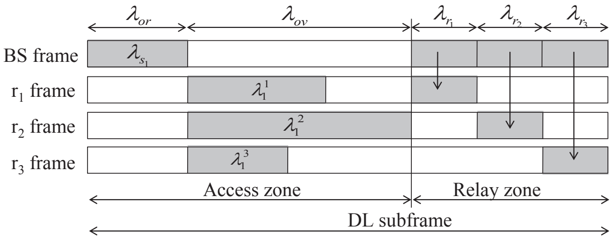


Fig. 4. Hybrid resource allocation example for the sample scenario in Fig. 2(a).

$$\mathit{Cell\ Throughput} = H_0\lambda_0 + \sum_{i=1}^{R} d_{r_i}\lambda_{r_i}. \tag{18}$$

C. Hybrid Scheme

The main goal of the proposed hybrid scheme is to combine the orthogonal and overlapped schemes in order to improve performance in terms of the cell throughput and outage rate, while preserving a low computational complexity. To achieve a higher throughput than the orthogonal scheme, the resources should be utilized by allowing the service nodes to be active simultaneously; at the same time, the outage events due to interference should be avoided. In other words, the hybrid scheme performs like an overlapped scheme when there are no active SSs affected by interference; however, when outage events occur, the resources are orthogonally allocated to those SSs. Therefore, the active SSs in each set S_i are divided into two groups denoted as S_i^{or} and S_i^{ov}: one is served as in the orthogonal scheme, and the other is served as in the overlapped scheme. Let n_i^{or} and n_i^{ov} be the number of active SSs in the set S_i^{or} and S_i^{ov} respectively, i.e., $n_i = n_i^{or} + n_i^{ov}$. If we denote with M the total number of SSs that are served orthogonally, (6) can be rewritten as:

$$M + n_0^{ov} + n_1^{ov} + ... + n_R^{ov} \leq N. \tag{19}$$

By using the same example scenario in Fig. 2(a) with an assumption that the subscriber s_4 can not be served due to strong interference and that the other subscribers have different achievable data rates from their service nodes ($d_{s_3} > d_{s_1} > d_{s_2}$), one possible resource allocation for the hybrid scheme is depicted in Fig. 4. The access zone time fraction is divided into two subsections: the orthogonal and overlapped subsections are denoted by λ^{or} and λ^{ov}. The summation of time fractions allocated to the active SSs that are served orthogonally is equal to λ^{or}:

$$\lambda^{or} = \lambda_{s_1} + \lambda_{s_2} + ... + \lambda_{s_M}. \tag{20}$$

Thus, the equation (7) can be rewritten as:

$$\sum_{i=1}^{M} \lambda_{s_i} + \lambda^{ov} + \sum_{j=1}^{R} \lambda_{r_j} = 1. \tag{21}$$

The SSs in the same set S_i^{ov} have to share the access zone overlapped subsection:

$$\lambda^{ov} \geq \lambda_1^i + \lambda_2^i + ... + \lambda_{n_i^{ov}}^i, \quad i \in \{0, 1, ..., R\}, \tag{22}$$

where λ_j^i is the time fraction allocated to the j^{th} active SS in the set S_i^{ov}. The throughput of each node in S_i^{ov} should be equal for fairness:

$$d_1^i \lambda_1^i = d_2^i \lambda_2^i = \ ... \ = d_{n_i^{ov}}^i \lambda_{n_i^{ov}}^i, \quad i \in \{0, 1, ..., R\}. \tag{23}$$

We define the average data rate (H_i^{ov}) of each set S_i^{ov} as the sum of the throughput of active nodes in S_i^{ov} divided by the total time duration of the access zone overlapped subsection when it is fully utilized (i.e., $\lambda^{ov} = \lambda_1^i + \lambda_2^i + ... + \lambda_{n_i^{ov}}^i$):

$$H_i^{ov} = \frac{n_i^{ov} d_1^i \lambda_1^i}{\lambda_1^i + \lambda_2^i + ... + \lambda_{n_i^{ov}}^i}, \quad i \in \{0, 1, ..., R\}. \tag{24}$$

Using (23), we can eliminate times λ_j^i in (24):

$$H_i^{ov} = \frac{n_i^{ov}}{\frac{1}{d_1^i} + \frac{1}{d_2^i} + \cdots + \frac{1}{d_{n_i^{ov}}^i}}, \quad i \in \{0, 1, ..., R\}. \tag{25}$$

Let H_x^{ov} and n_x^{ov} be the average data rate and the number of active SSs of the set S_x^{ov} that has minimum throughput per node. Only this set can fully use resources during the access zone overlapped subsection λ^{ov}. To ensure fairness, the orthogonally served SSs should also achieve equal throughput as minimum per node throughput and the service nodes have to relay more data to support them, thus the following equation is satisfied:

$$\begin{aligned} \frac{H_x^{ov} \lambda^{ov}}{n_x^{ov}} &= \frac{d_{r_1} \lambda_{r_1}}{n_1^{or} + n_1^{ov}} = \frac{d_{r_2} \lambda_{r_2}}{n_2^{or} + n_2^{ov}} = \ ... \ = \frac{d_{r_R} \lambda_{r_R}}{n_R^{or} + n_R^{ov}} \\ &= d_{s_1} \lambda_{s_1} = d_{s_2} \lambda_{s_2} = \ ... \ = d_{s_M} \lambda_{s_M}. \end{aligned} \tag{26}$$

Only S_0^{ov} is not constrained by the relay zone transmissions since every SS in S_0^{ov} is directly connected with the BS. Therefore, unless S_0^{ov} has a minimum throughput per node, the active SSs in S_0^{ov} can achieve higher throughputs since they can fully use resources during λ^{ov}. If we use (26) to substitute for λ_{s_i} and λ_{r_i} in (21), the time fraction allocated to the overlapped section can be expressed as:

$$\lambda^{ov} = \frac{1}{1 + \frac{n_1^{or} + n_1^{ov}}{n_x^{ov}} \frac{H_x^{ov}}{d_{r_1}} + ... + \frac{n_R^{or} + n_R^{ov}}{n_x^{ov}} \frac{H_x^{ov}}{d_{r_R}} + \frac{H_x^{ov}}{n_x^{ov} d_{s_1}} + ... + \frac{H_x^{ov}}{n_x^{ov} d_{s_M}}}. \tag{27}$$

Consequently, the cell throughput from the hybrid scheme can be computed by:

$$\text{Cell Throughput} = H_0^{ov} \lambda^{ov} + \frac{H_x^{ov} \lambda^{ov}}{n_x^{ov}} \left(\sum_{i=1}^{R} n_i - n_0^{ov} \right). \tag{28}$$

IV. GENERALIZATION FOR MULTIHOP SCENARIOS

In this section, we explore the impact of an increased number of relay hops on the hybrid scheduling scheme as well as orthogonal and overlapped schemes. Although the two-hop scenario is technically a multihop scenario, we will use the term "multihop" to refer to scenarios with more than one relay tier. The interference between relay links (BS to RS or RS to RS) is much higher than the interference between access links (BS to SS or RS to SS), hence, simultaneous transmissions seldom exist among relay links especially when the number of hops is small. Therefore, in this section we assume that the resources are always orthogonally shared by RSs during the relay zone period of the DL subframe in a multihop scenario. To explore an extension of the hybrid scheme to a general multihop relaying scenario, we also assume that every RS has only one route to/from the BS for data transmission. In other words, the superordinate service node of an RS does not change after the location of an RS is carefully determined in a cell. For example, if an RS r_1 is a superordinate service node of an RS r_2, whenever r_2 has to transmit/receive to/from the BS, the r_1 is responsible for relaying data between the BS and r_2 all the time. To evaluate the performance of the multihop hybrid scheduling scheme, we present an extended version of the orthogonal and overlapped schemes for the multihop scenario.

A. Orthogonal Scheme for Multihop Scenarios

When an SS is receiving data from the BS through multiple RSs, the optimal path selected by the scheduling scheme is corresponding to the path that has the highest achievable relay data rate of the SS, i.e., a higher capacity link is always preferable for RSs to relay data during relay zone period. When there are N active SSs in a cell, each SS will be served by one of the service nodes as in the two-hop scenario. The main difference between two-hop and multihop scenarios is that the RSs that are responsible for relaying data between service nodes have not only to serve the SSs directly connected to that RS but also the SSs associated with the subordinate RSs of that RS. Therefore, it is likely that more resources are allocated to the RSs that are close to the BS than the RSs that are far away from the BS. We denote with n_i^{re} ($i = 1, ..., R$) the number of SSs that are not directly connected to the RS r_i but need to be relayed by r_i. As in the two-hop scenario, the throughput of each node should be equal for fairness and the incoming data to an RS should be equal to the outgoing data from that RS, thus the equation (8) is modified for multihop scenario:

$$d_{s_1} \lambda_{s_1} = ... = d_{s_N} \lambda_{s_N} = \frac{d_{r_1} \lambda_{r_1}}{n_1 + n_1^{re}} = ... = \frac{d_{r_R} \lambda_{r_R}}{n_R + n_R^{re}}. \tag{29}$$

Using (7) and (29), the time fraction of one of the SSs can be expressed as:

$$\lambda_{s_1} = \frac{1}{1+\frac{d_{s_1}}{d_{s_2}}+...+\frac{d_{s_1}}{d_{s_N}}+\frac{(n_1+n_1^{re})d_{s_1}}{d_{r_1}}+...+\frac{(n_R+n_R^{re})d_{s_1}}{d_{r_R}}}. \quad (30)$$

Once the time fraction for an SS is computed by (30), the remaining time fractions λ_i can be easily calculated by (29), hence, the cell throughput for the multihop orthogonal scheme can be computed by:

$$\mathit{Cell\ Throughput} = \sum_{i=1}^{N} d_{s_i}\lambda_{s_i}. \quad (31)$$

B. Overlapped Scheme for Multihop Scenarios

As with the multihop orthogonal scheduling scheme, we extend the two-hop overlapped scheme to a general multihop relaying scenario. As we increase the number of hops to extend cell coverage, the number of service nodes that can be active simultaneously also increases, hence, the efficiency of frequency reuse is significant, but at the same time intra-cell interference degrades network performance. The main difference between two-hop and multihop overlapped scheme is that the RS to RS communication is necessary for the multihop scenario. Therefore, an RS r_i must consume more resources in the relay zone to support the n_i^{re} SSs unless the RS is located at the last tier. To ensure fairness, only the set S_x that has the minimum throughput per node can fully use the resources during the access zone λ_0, while the rest of sets $S_1, ..., S_R$ are constrained by the relay link throughput. To take into account the n_i^{re} SSs for each RS, the following equation should be satisfied:

$$\frac{H_x\lambda_0}{n_x} = \frac{d_{r_1}\lambda_{r_1}}{n_1+n_1^{re}} = \frac{d_{r_2}\lambda_{r_2}}{n_2+n_2^{re}} = \ ... \ = \frac{d_{r_R}\lambda_{r_R}}{n_R+n_R^{re}}, \quad (32)$$

where H_x and n_x are the average data rate and the number of active SSs in S_x that has minimum throughput per node, the second term represents the throughput for nodes in S_1, the third term represents the throughput for nodes in S_2, etc. Using (32) and assuming that the summation of the time fraction allocated to the access zone and the time fractions allocated to the RSs is equal to one (i.e., $\lambda_0 + \lambda_{r_1} + \cdots + \lambda_{r_R} = 1$), the access zone time fraction λ_0 can be expressed as:

$$\lambda_0 = \frac{1}{1+\frac{n_1+n_1^{re}}{n_x}\frac{H_x}{d_{r_1}}+\frac{n_2+n_2^{re}}{n_x}\frac{H_x}{d_{r_2}}+\cdots+\frac{n_R+n_R^{re}}{n_x}\frac{H_x}{d_{r_R}}}. \quad (33)$$

By using λ_0 determined from (33), the cell throughput for the multihop overlapped scheme is computed by (18).

C. Hybrid Scheme for Multihop Scenarios

When we increase the number of hops in relaying data by deploying more RSs in a cell, it is obvious that the percentage of the relay zone in a frame increases because more resources need to be allocated for the relay links. This leads to throughput degradation regardless of scheduling scheme used. For the multihop hybrid scheme, the percentage of the orthogonal subsection of the access zone in a frame is also likely to be increased because the outage probability of the active SSs when multiple RSs are active at the same time is higher than with the two-hop scenario. The more outage events occur, the more resources are orthogonally assigned to those SSs. To consider the additional data transfer between service nodes due to multihop relaying, we modify the equation (26) such that an RS r_i has to support additional n_i^{re} SSs, hence, the actual throughput per node is likely to be smaller than two-hop scenario for fairness:

$$\begin{aligned}\frac{H_x^{ov}\lambda^{ov}}{n_x^{ov}} &= \frac{d_{r_1}\lambda_{r_1}}{n_1^{or}+n_1^{ov}+n_1^{re}} = \ ... \ = \frac{d_{r_R}\lambda_{r_R}}{n_R^{or}+n_R^{ov}+n_R^{re}} \\ &= d_{s_1}\lambda_{s_1} = \ ... \ = d_{s_M}\lambda_{s_M}. \end{aligned} \quad (34)$$

Using (34) to substitute for λ_{s_i} and λ_{r_i} in (21), the time fraction allocated to the overlapped section can be expressed as:

$$\lambda^{ov} = \frac{1}{1+\frac{n_1^{or}+n_1^{ov}+n_1^{re}}{n_x^{ov}}\frac{H_x^{ov}}{d_{r_1}}+...+\frac{n_R^{or}+n_R^{ov}+n_R^{re}}{n_x^{ov}}\frac{H_x^{ov}}{d_{r_R}}+\frac{H_x^{ov}}{n_x^{ov}d_{s_1}}+...+\frac{H_x^{ov}}{n_x^{ov}d_{s_M}}}. \quad (35)$$

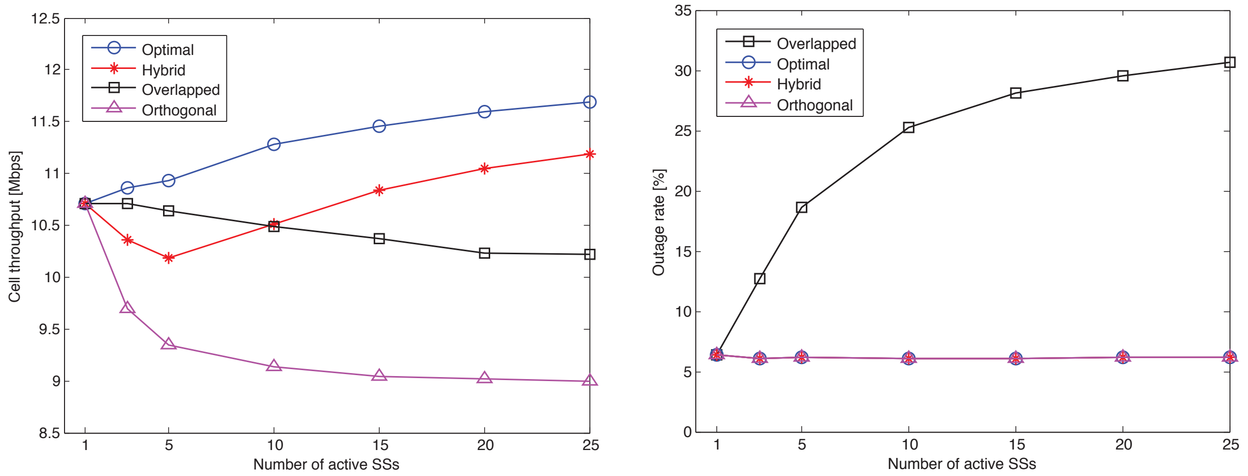
Consequently, the cell throughput from the hybrid scheme can be computed by (28).

V. NUMERICAL RESULTS AND ANALYSIS

In this section we evaluate the performance of the proposed hybrid scheduling scheme for the two-hop scenario by comparing it with the orthogonal, overlapped, and optimal schemes in terms of the cell throughput, outage rate, and computation time. We then consider the multihop case with six and nine relays and compare its performance with the two-hop case with three relays.

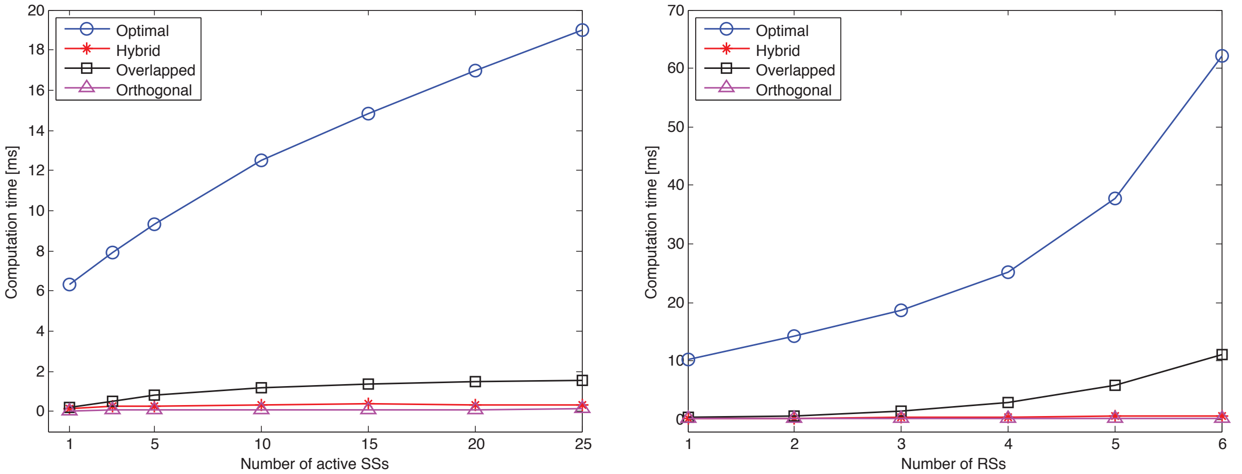
A. Two-hop Scenario

We analyze the cell throughput and outage rate as a function of the number of active SSs in a cell. The cell throughput for each scheduling scheme is computed by equations presented in Section III. Figure 5 shows the cell throughput, outage rate, and computation time results when three RSs are deployed at the edge of the transmission range of the BS. To obtain the average cell throughput value, the simulation is repeated 10,000 times for each scenario with N active SSs randomly placed within a cell. When there is only one active SS in a cell, hence no frequency reuse and co-channel interference, the average throughput of the SS under different scheduling schemes is equal to 10.67Mbps. As the number of active SSs increases, the cell throughput achieved by orthogonal scheme decreases because it is more likely to have SSs with low link capacities consuming large fractions of the time in order to preserve fairness. In contrast, the cell



(a) Throughput vs Number of SS

(b) Outage rate vs Number of SS



(c) Computation time vs Number of SS

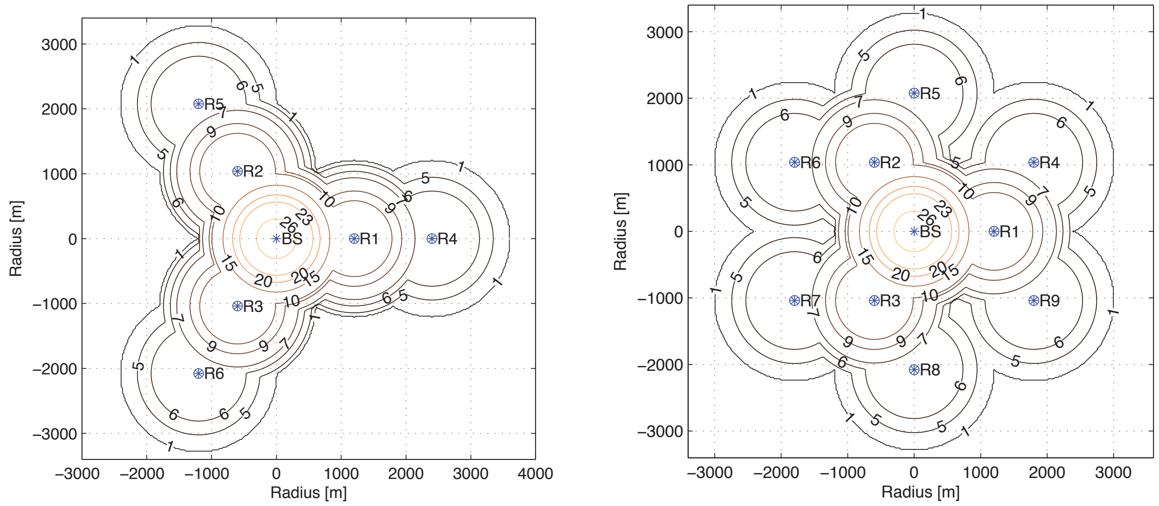
(d) Computation time vs Number of RS

Fig. 5. Cell throughput, outage rate, and computation time results as a function of the number of active SSs and RSs repectively for different scheduling schemes.

throughput for the optimal scheme grows as the number of active SSs increases, since the optimal scheme maximizes frequency reuse while minimizing co-channel interference in order to avoid outage. The cell throughput of our proposed hybrid scheme is only 4% to 7% lower than that of the optimal case (the higher the number of SSs, the lower the difference.) For the overlapped scheme, the set of active service nodes is selected to maximize the number of served SSs. Figure 5(b) shows that the outage rate from proposed hybrid scheme is identical to the results from the optimal and orthogonal schemes, whereas the outage rate for the overlapped case continues to rise significantly as more SSs join the cell because the number of active service nodes also increases leading to an insufficient SINR for many SSs. Figures 5(c) shows computation time results as a function of the number of active SSs in a cell. The computation time of the optimal scheme is substantially higher than the rest of the schemes. The computation time of the orthogonal and hybrid schemes is always less than 1ms regardless of the increase in the number of SSs in a cell; however the computation time of the overlapped scheme increases with the number of SSs because it must go through the process of determining the set of the service node before allocating resources. Since we assume that the set of active service nodes is selected to maximize the number of served SSs for the overlapped scheme, every possible combination of the service nodes must be examined to select the best set of service nodes for that objective. Figure 5(d) shows other computation time results when the number of RSs vary from one to six when there are 25 active SSs in a cell. As the number of active RSs increases, the computational time of an optimal scheme increases exponentially, while the three suboptimal schemes have relatively low computation times. The increase in the number of RSs does not affect the computation times of the orthogonal and hybrid schemes. The reported times are based on Matlab computations (not a particularly fast language).

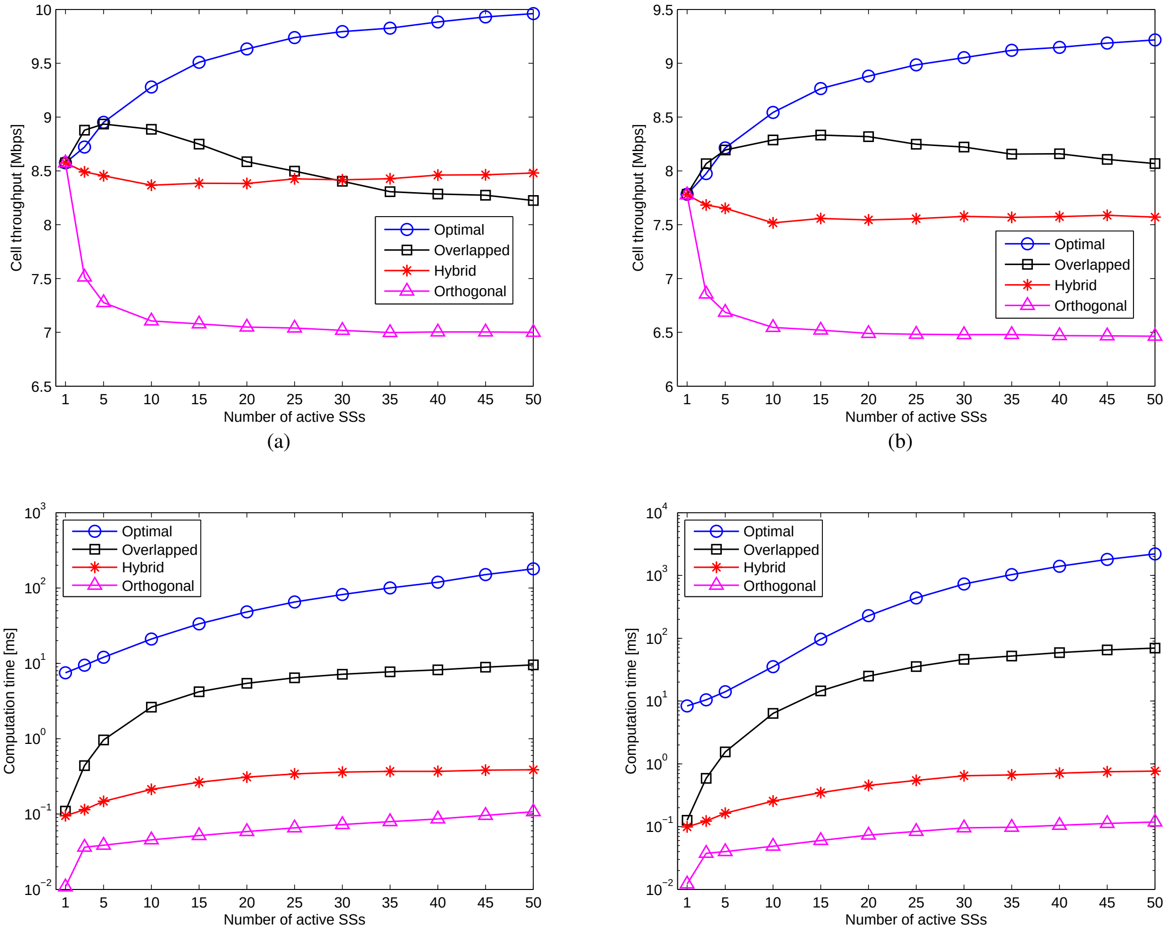
B. Multihop Scenario

To evaluate the performance of the multihop hybrid scheduling scheme, we show two three-hop relaying sce-



(a) (b)

Fig. 6. (a) Six RSs and (b) nine RSs contour graphs in multihop scenario.



(a) (b)

(c) (d)

Fig. 7. Cell throughput and computation time results as a function of the number of active SSs for three-hop relaying scenario

narios with six and nine RSs respectively. Figure 6 shows the locations of RSs and the achievable average data rate of an SS in the considered multihop scenarios with six RSs and nine RSs. When an SS is located near the RSs and receiving data from the BS via two RSs, the average achievable data rate of an SS is only 6.69Mbps.

Figure 7 shows cell throughput and computation time results as a function of the number of active SSs for three-hop relaying scenario with six and nine RSs respectively. Overall, it is obvious that the highest throughput is achieved by the optimal scheme and the lowest throughput is attained by the orthogonal scheme. However, when the number of active SSs is three, the throughput of the overlapped scheme was even higher than that of the optimal scheme. This is because the outage event due to interference can only occur in the overlapped scheme, thus leading to a higher throughput for the rest of active SSs. But, as the number of active SSs increases, the throughput from the overlapped scheme tends to decrease since we assumed the max served nodes subset selection objective for the overlapped scheme. When the number of active SSs is greater than 30, the throughput from the overlapped scheme is even lower than that of the hybrid scheme. As shown in Figure 7(b), there is a throughput degradation between six RSs and nine RSs for each scheduling scheme as the cell coverage area is extended by 40%. The interference between service nodes when they are active at the same time for the nine RSs scenario is more significant than the six RSs scenario not only because of the number of RSs but also because of the locations of the RSs. The overlapped scheme with max served nodes objective may use few service nodes, hence, the impact of interference can be relatively smaller than for the other schemes. The cell throughput of our proposed multihop hybrid scheme is less than 14% and 17% lower than that of the optimal case for the six RSs and nine RSs scenarios respectively. The outage rate performances for each multihop scheduling scheme are similar to the results of the two-hop scenario. The hybrid scheme outage rate is identical to the results from the optimal and orthogonal schemes, while the overlapped scheme outage rate grows as the number of active SSs increases in a cell.

Since the computation time of an optimal scheme is much higher than the other schemes, we change the y axis to a logarithmic scale in Figure 7(c) and 7(d). When 50 SSs are active in a cell, the computation time of the optimal scheme is about 180ms for the six RSs scenario and even longer than 2s for the nine RSs case. Those results demonstrate that the optimal scheme is not applicable to real systems. The computation time result of the overlapped scheme is relatively high compared to the orthogonal and hybrid schemes because it must go through the process of determining the set of the service node before allocating resources. However, the computation times of the orthogonal and hybrid schemes are always less than 1ms regardless of the increase in the number of SSs in a cell. When there are 50 active SSs in a cell, the computation time of the hybrid scheme is only 0.38ms and 0.76ms for the six RSs and nine RSs scenarios respectively.

VI. CONCLUSION

In this paper we propose a hybrid resource allocation scheme that combines advantages from both the orthogonal and overlapped schemes in order to improve the efficiency of resource utilization, while minimizing interference. We first focus on a two-hop relaying scenario and evaluate the performance of the hybrid scheme by comparing it with the orthogonal and overlapped schemes as well as the optimal scheme. We then explore an extension of the proposed hybrid scheme to a general multihop relaying scenario by taking into account RS to RS communications. Our results show that the outage rate of the proposed hybrid scheme is always as good as the orthogonal scheme, but a higher cell throughput can be achieved with a hybrid scheme than in the orthogonal case. Moreover, the computational time of the hybrid scheme is significantly lower than the optimal scheme at the expense of the small amount of throughput degradation.

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