Spatial Resource Reuse in the Multi-hop Cellular Networks: Difficulties and Benefits

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***Abstract*— The introduction of relays into legacy cellular networks is gaining more of an interest in the 4th generation (4G) wireless systems. In the presence of relays, simultaneous transmission of both base stations (BS) and relay stations (RS) on the same resources is possible, and consequently much higher throughput can be achieved. However, determining the set of links which will be turned on at the same time is usually considered a NP-complete combinatorial problem. Moreover, it requires cooperation between BSs and RSs of independent cells. In such context, we briefly address the difficulties of spatial resource reuse from the graph-theoretical perspective. Next, our focus shifts to developing a simple but efficient radio resource management algorithm which enables the spatial resource reuse, the pricing-based radio resource management (PRRM) strategy. The PRRM performs spatial reuse for interference-free users operating in the high signal-to-interference-and-noise ratio (SINR) region, while guaranteeing the signal quality of interference-susceptible users usually located near the coverage boundary. By applying the PRRM, we evaluate the potential benefits of the spatial resource reuse.**

I. Introduction

In recent years, there has been an upsurge of interest in the development of relays into legacy cellular networks. By introducing relays, both throughput enhancement and coverage extension can be obtained [1]. The rationale for deploying relays is that the path loss can be significantly reduced by splitting a long single-hop link into several multi-hop links when the signal quality of the single-hop link is relatively low [2]. Along with the fundamental analysis of the relaying system [3], several practical applications have been made. Cooperative relaying [4], by allowing multiple signal sources to synchronously transmit correlated data, can improve the decoding performance of mobile station (MS). Space-time coding techniques also can be applied to exploit the cooperative transmit diversity. Currently, for example, the IEEE P802.16j is working on standardizing multi-hop relays for the Broadband Wireless Access (BWA) system [5].

By taking advantage of the geographical separation of the nodes, the simultaneous transmission of both BSs and RSs on the same frequency-time resources is possible. As a consequence of the spatial resource reuse, the total system throughput will be raised as the opportunity of simultaneous transmission increases. That said, it must be noted however that the amount of interference suffered by the users located near the coverage boundary will also increase proportionally. As a result, transmission is prone to fail. However, due to the combinatorial nature of determining the set of links turned on at the same time, finding the optimal active link set requires an exhaustive search which makes it impractical. Moreover, such a centralized approach entails cooperation between BSs and RSs of several independent cells. Thus, well-designed spatial resource reuse algorithms having distributed properties are required, but not much work has been done on this topic.

For example, Park et al. [6] proposed a pattern-based frequency reuse scheme between 6 fixed RSs in the hexagonal cell layout, in which each set of RSs would transmit on the same frequency according to the frequency reuse factor (FRF). In reality, however, BS and RSs cannot be deployed regularly even in a single cell. Also, due to the shadowing and multipath fading effects, it is quite difficult to predetermine the pattern in a static manner. Pourahmadi et al. [5] developed an effective node assignment algorithm enabling the spatial resource reuse in a centralized manner to maximize the sum rate of uplink networks. However, the algorithm needs to know not only all the channel gains of the associated links but also of the interfering links. Furthermore, when we consider *non-transparent* type relays having the ability of *own resource scheduling* [5], the algorithm cannot be applied because of its centralized property.

This paper will deal with the problem of downlink spatial resource reuse. In the next section, we describe the system model and explain some assumptions. In Section III, we briefly address the difficulties of spatial resource reuse from the graph-theoretical perspective. In Section IV, we propose a low-complexity but efficient algorithm, the Pricing-based Radio Resource Management (PRRM), which can be implemented in a distributed manner. In the PRRM, users are classified and served differently whether they are dominantly affected by inter-cell or intra-cell interference, and the decision will be made by individual users rather than via cooperation of independent cells. By applying the PRRM, we evaluate the potential benefits of the spatial resource reuse through simulation in Section V. The results verify that the proposed PRRM can increase overall system throughput while keeping the outage occurrence to almost zero.

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II. System Model

A multi-cell multi-hop cellular network (MCN) based on the orthogonal frequency division multiplexing (OFDM) technology is considered, where each BS has extended functionality to support multi-hop relaying. We designate a radio link between a BS and a RS as the relay link, and a radio link which is terminated at a MS as the access link, which are terminologies used in the IEEE P802.16j [5]. In the majority of the frame structures proposed in the IEEE P802.16j, downlink resources are divided into the relay zone and the access zone. Spatial resource reuse is usually considered in the access zone for access links.

To make an association between a BS/RS and a MS, we adopted the association policy proposed in [2], where authors developed the multi-hop criterion to determine the optimal number of hops. In two-hop scenarios, which is mainly dealt with by current MCN research [5], an association to the BS via a RS has better aggregate spectral efficiency than to the BS directly if

$$\frac{1}{\eta_{bs\_rs}} + \frac{1}{\eta_{rs\_ms}} < \frac{1}{\eta_{bs\_ms}}, \quad (1)$$

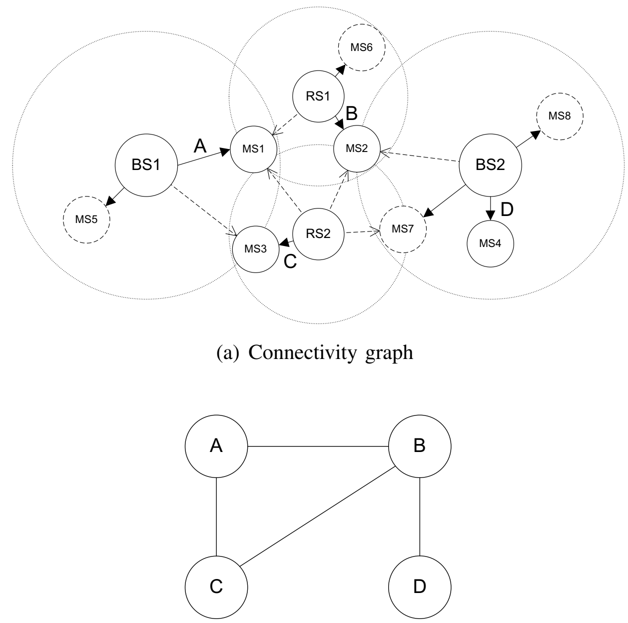
where η is spectral efficiency (in bits/sec/Hz) of the link. In this paper, two-hop scenarios will be mainly discussed and we adopted (1) in making an association between a BS/RS and a MS. However, it should be noted that our proposed algorithm is not restricted to the two-hop scenarios.

III. Spatial Resource Reuse: A Graph-Theoretical Perspective

In this section, we address the difficulties of spatial resource reuse from the graph-theoretical perspective and its limitations. The connectivity graph, G in Fig .1(a) describes spatial relationships between network nodes. The solid arrows are the associated links, and the dotted arrows are the interfering links between neighboring BSs or RSs. Each BS and RS selects a MS which will be scheduled at a next time slot on a certain resource allocation unit[1]. Those candidate MSs were represented by solid circles, whereas the non-candidate MSs were represented by dotted circles. Among the candidate MSs, the connectivity graph, G can be converted into the contention graph, $G_c = (V, E)$ as shown in the Fig. 1(b). In the contention graph, the vertex set V corresponds to the links of G and the edge set E represents the contention relationships between the links such that the connected links cannot be activated simultaneously.

In the context of the graph theory, we can find either independent sets or cliques from the contention graph, G_c. An independent set is defined by a set of links which can be activated at the same time and similarly a clique is defined by a complete subgraph in which only one link in the clique can be activated at a time. In the example topology of Fig. 1, the set of maximal independent sets which are not a subset of any other independent sets is $\mathcal{I} = \{\{A, D\}, \{C, D\}, \{B\}\}$,

[1]e.g., a bin which is a basic allocation unit in the IEEE 802.16e system.



(a) Connectivity graph

(b) Contention graph

Fig. 1. An example connectivity of nodes and the contention relationship.

and the set of maximal cliques which are not a subgraph of any larger complete subgraphs is $\mathcal{C} = \{\{A, B, C\}, \{B, D\}\}$. In most of the network utility maximization (NUM) literature, either the maximal independent sets or the maximal cliques are corresponds to the constraints of the optimization problem. For more details on this topic, see [9] and [10].

It should be noted however that the above mentioned approaches are somewhat theoretical. If we consider interfering relationships between multiple cells, such an independent set itself is quite hard to be determined by each cell in a distributed manner. Even in a centralized manner, such a problem is known to be NP-complete. Moreover, because interfering relationships depend on each MS's location, the topology of the connectivity graph and also the contention graph would be changed as the set of candidate MSs is changing. Thus, if there are totally N resource units, then maximally N different NP-complete problems should be solved in each time slot which makes its realization more difficult in practice.

IV. Pricing-based Radio Resource Management (PRRM) Strategy

Due to the combinatorial complexity of the graph-theoretical approaches, determining the optimal set of links which will be turned on at the same time requires an exhaustive search. Also, such approaches entail cooperation between independent cells. Therefore, we propose a low-complexity radio resource management strategy for spatial resource reuse having distributed properties, named PRRM. By applying the PRRM into multi-cell MCN, we will evaluate the potential benefits of the spatial resource reuse.

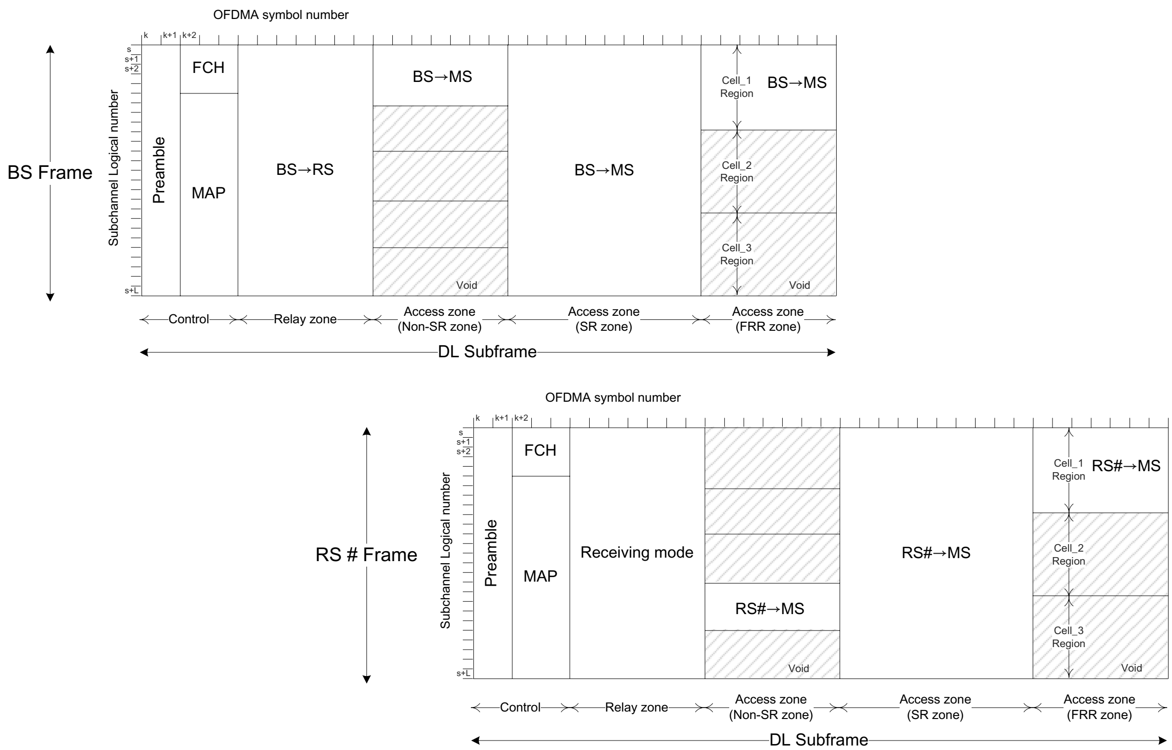


Fig. 2. Proposed frame structure for MCN

A. Proposed Frame Structure

By letting only one BS or RS in a cell transmits at a time or all of the BS and RSs in a cell transmit at the same time, we transform the combinatorial problem into a tractable form. The remaining problem now is to determine which MSs will be served alone and which MSs will be served together. To realize such an approach into practical systems such as the IEEE P802.16j, we divide the access zone resources into three subzones as shown in Fig. 2: the Non-Spatial Reuse (Non-SR) zone, the Spatial Reuse (SR) zone, and the Fractional Resource Reuse (FRR) zone. By allocating the Non-SR zone resources to each BS or RS exclusively, a transmission would be kept orthogonal within a cell but inter-cell interference still exists. We let the SR zone resources to be shared by every BS and RSs in a cell, and thus both intra and inter-cell interference exists. Finally, FRR zone with reuse factor 3 was taken into our frame structure to mitigate inter-cell interference[2]. However, since we will let the BS and RSs in a cell share the same resources, intra-cell interference still exists. In brief, our access zone resources are classified into:

– Non-SR zone: no intra-cell interference, but inter-cell interference exists.
– SR zone: both intra and inter-cell interference exists.
– FRR zone: no inter-cell interference, but intra-cell interference exists.

[2]Fractional Frequency Reuse (FFR) was proposed by Qualcomm and is one of the most practical inter-cell interference coordination/avoidance schemes.

Throughout the paper, we assume that the measurement of SINR at each subzone is possible which is a reasonable assumption. In the legacy IEEE 802.16e system, BS can direct MSs to measure the channel either on a preamble or on a specific permutation zone via the REP-REQ (channel measurement report request) medium access control (MAC) message [7], [11].

B. Zone Selection Algorithm

Under our proposed frame structure, users will be served in different subzones whether they are dominantly affected by intra-cell interference due to the spatial resource reuse or inter-cell interference from adjacent cells. Conceptually in Fig. 1(a), if RS1 and RS2 belongs to BS1 and BS2, respectively, then $\{MS1, MS7\}$ will be served in the Non-SR zone, $\{MS4, MS5, MS6, MS8\}$ will be served in the SR zone and $\{MS2, MS3\}$ will be served in the FRR zone.

However, in reality, determining the service zone for each MS is not an easy task because of the shadowing and multipath fading effects. We thus propose a zone selection algorithm which is based on the normalized zone switching gain. For example, let's assume that the price of Non-SR zone resources is twice expensive than SR zone resources. For an arbitrary user, if the estimated throughput per unit resource at the Non-SR zone is more than twice of the throughput at the SR zone, then it is profitable to service the user in the Non-SR zone than SR zone at the same expense. We define the normalized zone switching gain from the SR zone to Non-SR and FRR

Algorithm 1 PRRM: zone selection algorithm

1: Initialization: set $\mathcal{I} = \{0, 1, 2\}$, and compute normalized zone switching gains using (2).

2: Zone selection:
   - if $\mathcal{I} = \emptyset$, then the user is in the outage and go to STEP 4.
   - else, determine a zone which gives the highest switching gain:

$$i^* = \arg\max_i \{gain_i\}, i \in \mathcal{I}. \tag{3}$$

3: Outage check:
   - if SINR at i^*-th zone is above the outage level, then confirm the zone switching.
   - else, update $\mathcal{I} = \mathcal{I}/\{i^*\}$ and go to STEP 2.

4: Inform the zone selection result to the anchor BS/RS.

zones as follows:

$$gain_i = \frac{rate_i}{rate_0} \times \frac{price_0}{price_i}, \quad i \in \mathcal{I} \tag{2}$$

where $\mathcal{I} = \{0, 1, 2\}$ indicates SR zone, Non-SR zone and FRR zone, respectively. $rate_i$ denotes the estimated throughput per unit resource at the i-th zone, and $price_i$ is the price per unit resource at the i-th zone. Always $gain_0 = 1$ and if $gain_i$, $\forall i \in \{1, 2\}$ is smaller than 1, then it means the switching gain is not enough to counterbalance the price differences. Thus, in such a case, staying at the SR zone will be the most profitable choice.

Estimated throughput at each zone can be obtained by using Shannon's formula or by mapping SINR to the modulation and coding scheme (MCS) table which is a more realistic way. We priced each zone based on the transmission opportunity. If there are totally N_{tx} number of BS and RSs in a cell, then N_{tx} simultaneous transmission is possible in the SR zone, whereas only single transmission is allowed in the Non-SR zone. Thus, the Non-SR zone resources are regarded as N_{tx} times expensive than SR zone resources. Likewise, we priced the FRR zone resources as *reuse factor* times expensive than the SR zone resources. The proposed zone selection algorithm is summarized in Algorithm 1. After calculating the normalized zone switching gains, each MS selects a zone which gives the highest switching gain[3]. We can further change the service zone to recover a user from outage when the SINR at the selected zone is lower than the required SINR for the minimum MCS level. This is possible because we introduced different subzones and they would provide different interfering environment.

Fig. 3 shows zone selection example using Algorithm 1. From the empirical example, we can see that users located near BS or RSs mainly select the SR zone. This is because these users are operating at the high SINR region, and thus

[3]If more than one zone give the same highest gain, then a suitable random tie-breaking rule is used.

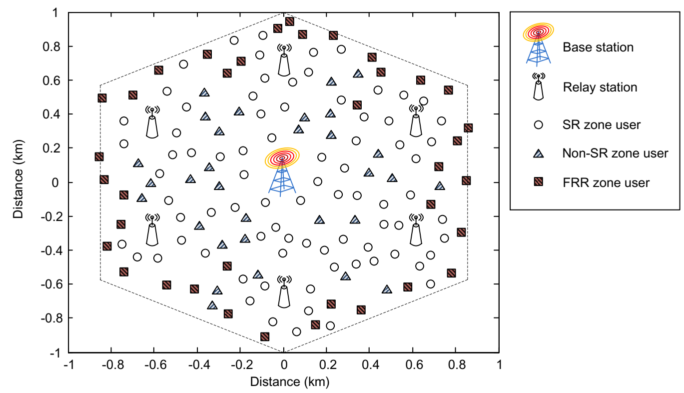


Fig. 3. Zone selection example using Algorithm 1

the rate degradation due to the simultaneous transmission is insignificant. On the other hand, users located at an intermediate distance from BS and RSs in a cell select the Non-SR zone, because they are vulnerable to intra-cell interference caused by the simultaneous transmission of BS and RSs in a cell. Likewise, the FRR zone is preferred by the users located near the boundary of a cell to avoid inter-cell interference. Users are classified and served differently whether they are dominantly affected by intra or inter-cell interference, and the decision is made by individual users.

C. Resource Allocation

Determining a portion of each subzone is also one important remaining problem. The decision can be made by the radio network controller (RNC) at a medium time scale($\sim 1sec$) based on the portion requested from each cell. An arbitrary cell j can decide a portion based on the number of users at each subzone which is normalized by the price as follows:

$$p_0^j = \left\{ \frac{\sum_{k=1}^{N_{tx}^j} N_{user(0)}^{j,k}}{N_{tx}^j} \right\} / \alpha \cdot price_0, \tag{4}$$

$$p_1^j = \left\{ \sum_{k=1}^{N_{tx}^j} N_{user(1)}^{j,k} \right\} / \beta \cdot price_1, \tag{5}$$

$$p_2^j = \left\{ \frac{\sum_{k=1}^{N_{tx}^j} N_{user(2)}^{j,k}}{N_{tx}^j} \right\} / \zeta \cdot price_2 \tag{6}$$

where p_i^j is a portion of each subzone, N_{tx}^j is the number of BS and RSs in the j-th cell, $N_{user(i)}^{j,k}$ is the number of i-th zone users associated with the k-th transmitter of the j-th cell where $i \in \mathcal{I}$ and α, β and ζ are control variables.

Because all the BS and RSs in a cell transmit simultaneously on the same SR and FRR zone resources, we average the number of users at those zones. Whereas because we allocated the resources to each BS and RS exclusively, we sum the number of users at that zone. On the other hand, we normalized the portion of each subzone by the price, which means we will serve each user at the same expense. For example, if the Non-SR zone resources are N_{tx} times expensive than the SR zone

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resources, then it is fair to allocate N_{tx} times smaller resources to the Non-SR zone to balance the expenses required to serve each user. Finally, we set $\alpha = \beta = \zeta = 1$ for our simulation in Section V, but if required, by setting β and ζ smaller than α, one can put more resources for the interference-susceptible users to raise the overall fairness.

Based on the requested portion from each cell, the RNC would make a final decision on the portion of each subzone. Among one FRR group[4], the RNC can easily determine the portion by solving the linear equation. However, for more than one FRR group, there might arise a gap between the portion that is determined by the RNC and required from each cell. This happens because of the heterogeneous user distribution at each cell. To deal with such a load unbalance problem, expected throughput based intra and inter-cell handover scheme was proposed in our previous work [12]. However, such an issue is out of scope of this paper, and thus we will not further discuss it.

V. Simulation Results

By applying the proposed PRRM into the IEEE P802.16j system with 6 fixed RSs, we examine the benefits of the spatial resource reuse [5], [7]. We consider a two-tier network composed of 19 hexagonal cells using the wrap-around technique. The radius of a cell is set to 1km, and MSs are uniformly generated within a cell. Because the location of RSs can be determined to be strategic, good channel conditions are assumed between a BS and a RS link. Hence, we adopt the WINNER LOS path loss model for relay links, and the NLOS model for access links as usual [8]. Log-normal shadowing with standard deviation $\sigma_s = 8$dB is taken into consideration, and shadowing correlation among paths from different BSs and RSs is assumed to be 0.5. For multipath fading, we apply ITU pedestrian B parameters to standard delay-spread models [13], [14]. The system bandwidth and length of time slot is set to 10MHz and 5ms, respectively. At each time slot, proportional fair (PF) scheduling is performed. The modulation, coding rates and the corresponding minimum SINR for 0.01 target packet error rate (PER) are listed in Table. I. We define a user is in the outage if the channel quality is worse that the required SINR of the minimum MCS level.

The performance of the MCN under 3 different resource allocation schemes are compared: the *Orthogonal allocation*, the *full spatial reuse*, and the proposed PRRM schemes. The orthogonal allocation scheme allocates access zone resources to each BS or RS exclusively without considering any spatial reuse. Whereas under the full spatial reuse scheme, entire access zone resources are shared by every BS and RSs in a cell. We demonstrate SINR CDF in Fig. 4(a). In the case of our proposed scheme, we can see that the overall SINR distribution is lower bounded by the minimum required SINR of the minimum MCS level. This is because interference-susceptible users are served in the interference mitigating zone, such as the Non-SR or FRR zone. On the other hand, the PRRM let the relatively interference-free users to be served in the SR zone, the overall SINR distribution is worse than the orthogonal allocation scheme. However, the rate degradation at the high SINR region is less sensitive, and thus the increased opportunity of simultaneous transmission will compensate the SINR degradation. In Fig. 4(b)-(c), we compare the cell throughput and the outage occurrence. The cell throughput was obtained by summing each user's average end-to-end throughput. Fig. 4(b) shows that there is a remarkable cell throughput enhancement under both the full spatial reuse and our proposed schemes. For instance, under the PRRM, the cell throughput was increased approximately by a factor of 2 compared to the single-hop networks or the MCN under the orthogonal allocation scheme. However, in the case of full spatial reuse scheme, even though the cell throughput enhancement is remarkable, there is a quite large number of outage users as shown in Fig. 4(c).

Note that in Fig. 4(b), the throughput performance of the MCN under orthogonal allocation scheme is worse than that of single-hop network, even though the outage performance is quite better than that. This is because additional resources should be expended to feed data from BS to RSs through relay links, even though channel conditions are obviously improved by introducing relays as shown in Fig. 4(a). In the same context, the full spatial reuse and our proposed schemes require more relay link resources than the orthogonal scheme to feed enormous data for the simultaneous transmission. This explains why the throughput gain achieved by spatial resource reuse is around 2, not by a factor of the possible number of simultaneous transmission.

[4]A FRR group is comprised of number of *reuse factor* cells. In our case, the FRR zone reuse factor is 3 as shown in Fig. 2.

TABLE I
Modulation and Coding Scheme

MCS Level	Modulation	Coding Rate	Min. Required SINR
1	QPSK	1/12	-4.3 dB
2	QPSK	1/8	-3.0 dB
3	QPSK	1/4	-0.1 dB
4	QPSK	1/2	3.8 dB
5	16QAM	1/2	9.0 dB
6	16QAM	3/4	12.9 dB
7	64QAM	2/3	16.0 dB
8	64QAM	5/6	19.0 dB

VI. Concluding Remarks

This paper dealt with the problem of downlink spatial resource reuse. First, we discussed the spatial resource reuse from the graph-theoretical perspective. However, determining the set of links which will be turned on at the same time is a NP-complete combinatorial problem, and it requires cooperation between BSs and RSs of independent cells. Therefore, we developed a heuristic low-complexity algorithm which enables spatial resource reuse, the PRRM. The principle behind the PRRM is that only one BS or RS in a cell transmits at a time or all the BS and RSs in a cell transmit at the same time. The proposed frame structure for the PRRM is comprised of SR zone, Non-SR zone and the well-known FRR zone. The zone selection algorithm is based on whether users are

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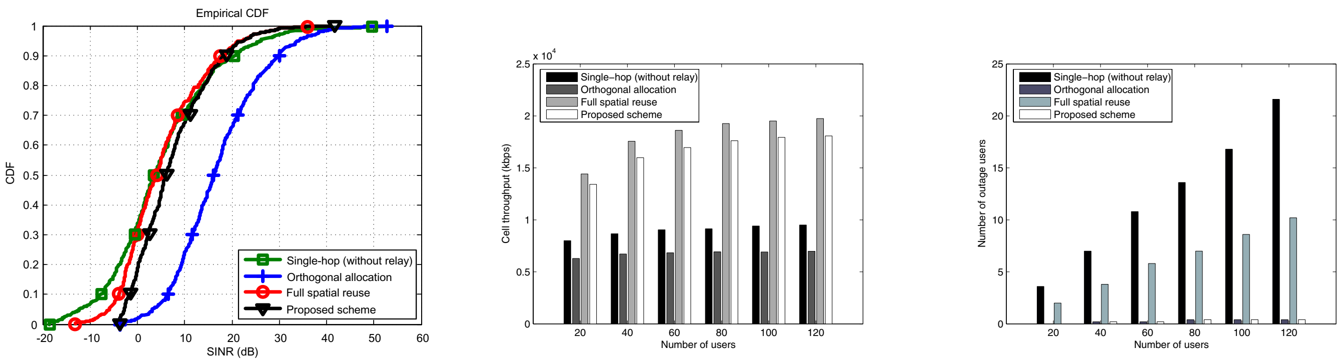

(a) CDF of SINR (b) Cell throughput (c) Outage occurrence

Fig. 4. Comparison of proposed and other resource allocation schemes

dominantly affected by inter-cell or intra-cell interference, and each user selects their own service zone rather than via cooperation of independent cells. Finally, by applying the PRRM, we evaluated the potential benefits of the spatial resource reuse. Simulation results showed us that the PRRM can not only increase overall system throughput but also keep the outage occurrence to almost zero. Thus, we conclude that any kind of well-designed spatial resource reuse algorithms are indispensable to fully exploit the potential of multi-hop cellular networks.

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