

Reuse Partitioning in Fixed Two-hop Cellular Relaying Network

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Abstract—This paper proposes a new cellular network architecture that simultaneously employs reuse partitioning and fixed relay nodes. Several key issues of the proposed architecture, e.g., the placing positions of relay nodes and the assignments of available carriers, are addressed with theoretic analysis and computer simulations. Our studies show that in comparison with the conventional cellular network our proposed scheme not only improves the system capacity, but also provides better quality of service (QoS) for users located at cell edges.

Keywords—reuse partitioning; fixed relay; two-hop cellular system; capacity

I. INTRODUCTION

Future mobile wireless communication systems demand for high data rates and spectral efficiency in addition to ubiquitous coverage. To simultaneously satisfy these requirements, a frequency band with higher central frequency (well above 2GHz) has to be considered. Communications over such a band, however, suffer from severe fading, which consequently reduces the effective communication distance. Since neither brute-force cell splitting nor advanced antenna technologies appear to be able to solve this dilemma economically, the concept of infrastructure-based relaying network has been proposed [1] [2].

Relay technology is a well-accepted economical approach to enlarge the cell coverage. However, when system capacity or spectral efficiency is of concern, we are embarrassed by that fact that a multi-hop link may consume multiple times of frequency resource comparing to a direct link, which could result in a penalty of the scarce radio resource. Thus, some smart radio resource management on the relay links is necessary, such as using the unlicensed spectrum [3] or reusing adjacent cell frequencies [4], to fully exploit the potential of relay based cellular network. Unfortunately, using unlicensed spectral complicates the design of user terminals, while pre-configured frequency allocation scheme can cause some relay nodes to become bottleneck under non-balanced traffic distribution. In Addition, fixed resource allocation increases the probability of handover between relay nodes, which augments signaling overhead.

Reuse partitioning is an effective concept to obtain high spectrum efficiency in cellular systems [5]. The key idea

therein is to divide the cell into several concentric zones and assign these zones different frequency reuse factors. The rationale behind reuse partitioning is that users located closer to the base station (BS) can tolerate a lower reuse distance than that at cell edges.

In this paper, we propose a new cellular network architecture that simultaneously employs reuse partitioning and the concept of relay. In particular, we divide each cell in the considered system into two concentric regions and place fixed relay nodes (FRNs) on the boundary between the inner zone and the outer zone. Moreover, we consider a routing strategy, with which a mobile station (MS) will be connected to the BS directly or be relayed by a FRN, i.e., linked to the BS through a two-hop link. The available spectral resources are partitioned into three subsets, and different reuse factors are chosen for the links between MSs and BSs, those between MSs and FRNs, and those between FRNs and BSs. Several key issues are addressed with both theoretical analysis and computer simulations. It is demonstrated that our proposed architecture, owing to its simultaneous employment of reuse partitioning and relaying, not only improves the system capacity and spectral efficiency, but also provides better link quality for users located at cell edges. Furthermore, all FRNs in one cell share the same frequency subset, which can effectively alleviate the FRN bottleneck and link drop during handover due to the frequency shortage in the target FRNs [4].

The remainder of this paper is organized as follows. The next section gives a brief introduction of the system model. Section III analyzes the uplink interference and the achieved system capacity in both the traditional reuse partitioning (TRP) based cellular system and our proposed one. Simulation results and discussions are presented in Section IV, which is followed by our conclusions in Section V.

II. SYSTEM MODEL AND ROUTING STRATEGY

A. System Configuration

We consider an (O)FDMA/TDMA based cellular system that consists of 19 hexagonal cells. Each cell is divided into two concentric zones, with the BS located at the centre. With the TRP scheme, the reuse factor in the inner zone (of radius R_i) is N_i while the reuse factor in the outer zone is N_o . As shown in Fig. 1, in our relaying system six FRNs are placed in

each cell as new network elements. Each FRN is located on the line that connects the BS to one of the six cell vertices. As aforementioned, we partition the available spectral resources in this relaying system with reuse partitioning (RRP) and assign them respective reuse factors. In particular, the reuse factor in the inner zone is N_i , the reuse factor in the outer zone is N_o , and the reuse factor used for links between FRNs and BS is N_f . Throughout this paper, the reuse factor N is equal to the number of cells per cluster, which sometimes is also referred to as cluster size. It is well-known that N should satisfy equation [6]:

$$N = i^2 + ij + j^2 \quad i, j = 0, 1, 2, 3 \dots \quad (1)$$

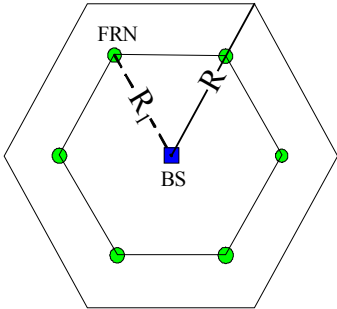


Figure 1. A cell in the two-hop relay based cellular system with reuse partitioning

When numerical analysis or computer simulation is invoked, we make the following assumptions. In particular, we set $R = 500$ meters. The number of sub-channels M is 128, and the bandwidth B of each sub-channel is 200 kHz. In our system, each sub-channel can only be assigned to one MS. Thus, there is no intra-cell interference and the system performance will be mainly determined by the co-channel inter-cell interference. The MSs are independently distributed following a uniform distribution, and each MS can communicate with both the FRN and the BS but not simultaneously. The radiation power of each MS and that of each FRN, P_M and P_R , is 100mW. Finally, all antennas in our system are omni-directional.

B. Propagation Model

We assume the propagation links between the BS and the FRNs are line-of-sight (LOS), while others are non-LOS (nLOS). In practice the LOS assumption can be satisfied by placing FRNs at carefully selected locations, such as on the roof of a building. A modified free-space path loss formula is considered. In particular, we assume that the path loss, denoted by PL, between transmitter and receiver with distance d is of the form

$$PL = P_T / P_R = \left(\frac{4\pi f}{c} \right)^2 d^\gamma \quad (2)$$

where $f = 5.0 \text{ GHz}$, $c = 3 \cdot 10^8 \text{ m/s}$, P_T and P_R denote transmission power and reception power respectively, and the

path loss exponent γ is equal to 2 for LOS links and equal to 4 for nLOS links, respectively. For simplicity, in the following

we will use λ to denote $\left(\frac{4\pi f}{c} \right)^2$.

In our system-level simulation we use independent lognormal random variables with a standard deviation of 8 dB to model the shadowing, and set the noise power to -120 dBW.

C. Routing Strategy

Routing is an indispensable issue in multi-hop communications. For the sake of simplicity, we consider a simple routing algorithm. In particular, with the considered routing algorithm, a MS will connect to the BS directly if its distance to the BS is less than the distance between the FRN and the BS, i.e. R_f ; otherwise the considered MS will connect to the nearest FRN. This routing strategy is based on the intuition that the direct link should be given higher priority in relaying network. For alternative routing algorithms, please refer to [7].

III. COMPARISON OF CAPACITY

To offer comparison between the TRP based cellular system and the RRP based one, we analyze the interference power, the signal-to-interference power ratio (SIR) of users in outer zones, and the cell capacity in the uplink. For the tractability of theoretical analysis, we make assumptions as follows:

- The system is fully loaded, i.e., all interferers take effect with the possibility of 1;
- Noise is trivial in comparison with the co-channel inter-cell interference.
- The effect of the small-scale fading is omitted.

For the MSs' location, using excircle instead of hexagonal for simplicity, we have the following probability density function (PDF) of the distance between a MS and its BS

$$P_r(r) = \begin{cases} \frac{2r}{R^2 - R_0^2}, & R_0 \leq r \leq R \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

where $R_0 = 20\text{m}$ is the closest distance between the MS and the respective BS or FRN.

A. TRP Scheme

The uplink SIR from the MS located in inner zones and outer zone can be obtained according to the path loss formula:

$$\Gamma_i^{bs}(r, N_i) = \frac{\frac{P_M}{\lambda r^\gamma}}{\sum_{k=1}^n \frac{P_M}{\lambda d_{k,i}^\gamma(N_i)}} = \frac{1}{r^\gamma} \frac{1}{\sum_{k=1}^n \frac{1}{d_{k,i}^\gamma(N_i)}} \quad (4)$$

where $l=i, o$ denotes the inner zone or the outer zone respectively, r is the distance between the MS and the BS, $d_{k,l}(N_l)$ denotes the distance between the considered BS and the interfering MS k , and n is the number of interfering sources.

For simplicity, let us consider two extreme cases with respect to the uplink interference. That is, the case when all interfering MSs are located at the nearest (-) positions and that when all MSs are located at the furthest (+) positions. An example is illustrated in Fig. 2, where $N_i = 1, N_o = 4$, and red stars denote the interfering MSs in the worst interference case while black stars denote the interfering MSs in the best interference case.

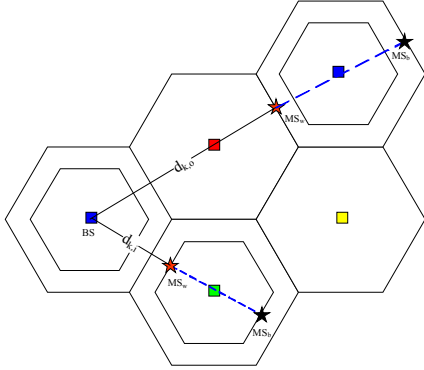


Figure 2. Example of interference case in TRP scheme ($N_i=1, N_o=4$)

For a given reuse factor N , the reuse distance between the BSs using the same channel is $\sqrt{3NR}$ [6]. Using $d_{k,i}^{\pm}(N_i)$, $d_{k,o}^{\pm}(N_o)$ to denote the distance between BS and the interfering MS in the best case or that in the worst case respectively, we have:

$$d_{k,i}^{\pm}(N_i) = \sqrt{3N_i}R \pm \frac{\sqrt{3}R_1}{2} \quad (5)$$

$$d_{k,o}^{\pm}(N_o) = \sqrt{3N_o}R \pm \frac{\sqrt{3}R}{2} \quad (6)$$

Then, the SIR in the worst case (-) and that in the best case (+) can be obtained

$$\Gamma_i^{bs\pm}(r, N_i) = \frac{1}{r^\gamma} \frac{1}{\sum_n \frac{1}{d_{k,i}^{\pm \gamma}(N_i)}} \quad (7)$$

Due to the uniform distribution of MSs in each cell, the number of users in any region is proportional to its area. Here we assume that every link would be allocated one sub-channel, and then we obtain:

$$m_i = \left\lfloor \frac{M \times R_1^2}{R_1^2 \times N_i + (R^2 - R_1^2) \times N_o} \right\rfloor \quad (8)$$

$$m_o = \left\lfloor \frac{M \times (R^2 - R_1^2)}{R_1^2 \times N_i + (R^2 - R_1^2) \times N_o} \right\rfloor \quad (9)$$

where M is the number of total sub-channels, m_i and m_o is the number of sub-channels allocated to the inner zone and that of the outer zone in each cell respectively, and $\lfloor x \rfloor$ denotes the integer part of x . Here we have neglected the area determined by R_o .

We obtain the cell capacity by calculating the number of users and the average channel capacity of each user [8]. Obviously, according to (7), for a given N_i , $\Gamma_i^{bs\pm}(r, N_i)$ is a function of r . Integrating (7), (8) and (9) over the PDF of positions (3) yields the cell capacities in the two extreme interference cases as:

$$C^{\pm}(N_i, N_o) = m_i B \int_{R_0}^{R_1} \log_2(1 + \Gamma_i^{bs\pm}(r, N_i)) P_r(r) dr \quad (10)$$

$$+ m_o B \int_{R_1}^R \log_2(1 + \Gamma_o^{bs\pm}(r, N_o)) P_r(r) dr$$

where B is the bandwidth of each sub-channel, which is defined in section II.

B. RRP Scheme

In the RRP scheme, the spectrum resources are divided into three subsets f_i, f_f and f_o , whose corresponding reuse factors are N_i, N_f and N_o respectively. The subset f_i is employed by the BS to communicate with MSs located in the inner zone, while f_f and f_o are used on the links between BS and FRNs and those between FRNs and MSs located in the outer zone. Please note that the sub-channels in the subset f_f and those in f_o are shared by all six FRNs, and can be assigned dynamically according to the traffic density.

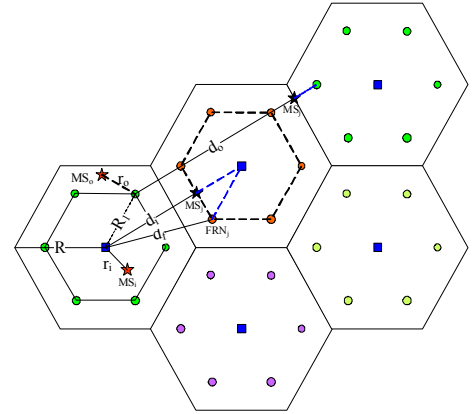


Figure 3. The worst interference case under RRP scheme ($N_i=1, N_f=1, N_o=4$)

We study the performance of the RRP based system by focusing on the worst interference case and the best interference case. An example of the worst interference case is

illustrated in Fig. 3, where N_i , N_f and N_o are set to one, one and four respectively. With the aid of Fig. 3, we obtain the SIR of the BS received from a MS in inner zone and FRN as follows:

$$\Gamma_{ms_i}^{bs \pm}(r, N_i) = \frac{\frac{P_M}{\lambda r^\gamma}}{\sum_{k=1}^n \frac{P_M}{\lambda d_i^{\pm\gamma}(N_i)}} = \frac{\frac{1}{r^\gamma}}{\sum_{k=1}^n \frac{1}{d_i^{\pm\gamma}(N_i)}} \quad (11)$$

$$\Gamma_{frn}^{bs \pm}(N_f) = \frac{\frac{P_R}{\lambda R_1^{\gamma_f}}}{\sum_{k=1}^n \frac{P_M}{\lambda d_f^{\pm\gamma}(N_f)}} = \frac{\frac{1}{R_1^{\gamma_f}}}{\sum_{k=1}^n \frac{1}{d_f^{\pm\gamma}(N_f)}} \quad (12)$$

where $d_i^\pm(N_i)$, $d_f^\pm(N_f)$ are the distance between the desired BS and its interfering MS and FRN in either the worst (-) or the best interference case (+), n corresponds to the number of interfering sources, and $\gamma_f = 2$ is the path loss coefficient of in link between BS and FRN. Note that $d_i^\pm(N_i)$ and $d_f^\pm(N_f)$ can be calculated in the same way as in (5) and (6).

When the interference of the FRN is of concern, we know that the interference is contributed by MSs located in other cells that are using the same channel to communication with their corresponding FRNs. Hence, considering the worst and the best case, the SIR value of a FRN is expressed as:

$$\Gamma_{ms_o}^{frn \pm}(r_o, N_o) = \frac{\frac{P_M}{\lambda r_o^\gamma}}{\sum_{k=1}^n \frac{P_M}{\lambda d_o^{\pm\gamma}(N_o)}} = \frac{\frac{1}{r_o^\gamma}}{\sum_{k=1}^n \frac{1}{d_o^{\pm\gamma}(N_o)}} \quad (13)$$

Where $d_o^\pm(N_o)$ is either the furthest or the nearest distance between the FRN and its interfering MS_j , r_o is the distance between the desired FRN and its counterpart MS_o . We simplify the analysis by:

$$r_o \approx r - R_1 \quad (14)$$

Note that the end-to-end throughput over a multi-hop link is determined by the minimum of those of all hops. Hence, we take the minimum SIR value between the MS-FRN hop and the FRN-BS hop to calculate the end-to-end throughput:

$$\Gamma_{ms_o}^{bs \pm}(r, N_f, N_o) = \min(\Gamma_{frn}^{bs \pm}(N_f), \Gamma_{ms_o}^{frn \pm}(r, N_o)) \quad (15)$$

The two-hop link consumes twice as radio resources as in direct link, that is, the MSs which connect to BS via FRN not only consume the resources in outer zone, but also need sub-channels to be allocated in inner zone. Consequently, the frequency resources assigned to inner and outer zones can be expressed as follows respectively:

$$m_i = \left\lfloor \frac{M \times R_1^2}{R_1^2 \times N_i + (R^2 - R_1^2) \times N_f + (R^2 - R_1^2) \times N_o} \right\rfloor \quad (16)$$

$$m_o = \left\lfloor \frac{M \times (R^2 - R_1^2)}{R_1^2 \times N_i + (R^2 - R_1^2) \times N_f + (R^2 - R_1^2) \times N_o} \right\rfloor \quad (17).$$

Note that $\Gamma_{ms_i}^{bs \pm}(r, N_i)$ and $\Gamma_{ms_o}^{bs \pm}(r, N_f, N_o)$ are the functions of r for given reuse factors N_i , N_f and N_o . Then similar approach can be used to compute the cell capacity under the worst and the best case as in the TRP scheme:

$$C^\pm(N_i, N_f, N_o) = m_i B \int_{R_0}^{R_1} \log_2(1 + \Gamma_{ms_i}^{bs \pm}(r, N_i)) P_r(r) dr + m_o B \int_{R_1}^R \log_2(1 + \Gamma_{ms_o}^{bs \pm}(r, N_f, N_o)) P_r(r) dr \quad (18)$$

From the above analysis, it can be observed that resource assignment to relay nodes is important. On one hand, from (16) and (17) it can be found that the reuse factor of FRNs, i.e. N_f , should be as small as possible when the efficiency is of concern. On the other hand, if the reuse factor is too small, the co-channel interference will be too strong. This can result in a too low SIR value received by BSs from FRNs, which will influence the whole end-to-end throughput. Therefore, the investigation on the compromise will be an interesting and important topic.

IV. SIMULATION RESULTS AND DISCUSSIONS

Computer simulation is conducted to investigate the performance of our proposed cellular architecture. Several key issues, including the radius of inner zone (which means the location of FRN in RRP scheme), the reuse pattern in the RRP scheme, the cell capacity and the QoS of user in outer zone, are studied as what follows.

A. Radius of inner zone and reuse patterns

We first examine above analysis with computer simulations. The simulation is carried out under the scenario specified in Section II. Fig. 4 reports the obtained results of the case with $N_i = 1$ and $N_o = 4$.

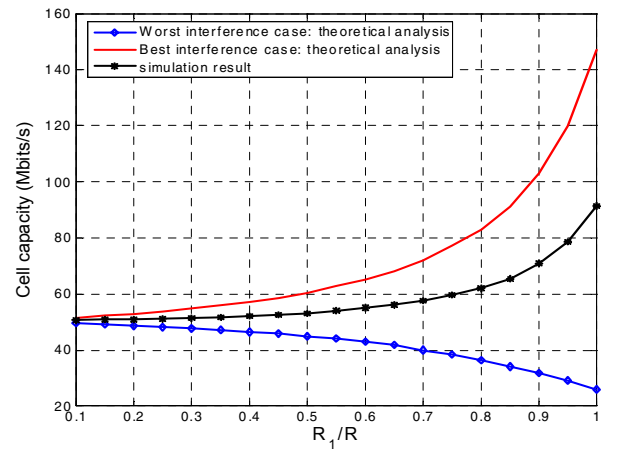


Figure 4. Cell capacity in TRP scheme (theoretical analysis vs. simulation)

In particular, Fig. 4 depicts the effect of the radius of inner zone on cell capacity. The simulation confirms our theoretical analysis, since the simulated values lie between the predicted theoretical bounds corresponding to the two extreme interference cases. When the radius of inner zone is very small, our simulation results match the theoretical values well. This is reasonable since under this circumstance, the reuse factor is almost equal to four and thus the impact of locations of interfering sources is trivial comparing to reuse distance. In addition, in Fig. 4 the maximum cell capacity is achieved when the radius of the inner zone is equal to the cell radius. This means that the whole system uses reuse factor 1. Although interference is considerably high in this case, the loss in SIR is compensated by the increase number of available sub-channels, since each BS can reuse the whole available spectrum. However, in practice this is not meaningful since users located at cell edges can not be served due to the very poor SIR. Therefore, in the next simulation, we set up a constraint that the SIR should be no lower than 9 dB. According to (4), the radius of inner zone should be less than about $0.6R$ when reuse factor is set to one.

Then the combinations of reuse factors $\{N_i, N_f, N_o\}$, named as reuse patterns, in the RRP scheme and their effects on the system performance are examined. In TRP scheme, reuse factors must be in strictly ascending order from inner zone to outer zone due to the fact that users in inner zone can receive stronger signal and, thereby can tolerate a shorter reuse distance. However, this criterion does not work for the relay enhanced cellular network. In RRP scheme, the link quality of MSs in outer zone is not necessarily worse than the link quality of MSs in inner zone. Therefore the selection of N_i , N_f and N_o could be somehow arbitrary. According to (1), the reuse factor could be set as 1, 3, 4, 7... For simplicity, only 1, 3 and 4 are considered in our simulation. Moreover, considering the severe interference if reuse factor of outer zone is set to one, we exclude one from the set of N_o . Then the possible reuse patterns are: $\{1, 1, 3\}$, $\{1, 1, 4\}$, $\{1, 3, 3\}$, $\{1, 3, 4\}$, $\{1, 4, 3\}$, $\{1, 4, 4\}$, $\{3, 1, 3\}$, $\{3, 1, 4\}$, $\{3, 3, 4\}$, $\{3, 4, 3\}$, $\{3, 4, 4\}$, $\{4, 1, 3\}$, $\{4, 1, 4\}$, $\{4, 3, 3\}$, $\{4, 3, 4\}$, $\{4, 4, 3\}$. However, to satisfy the aforementioned SIR threshold of 9 dB, there is a constraint condition for the radius of inner zone, which is tabulated in Tab. 1.

TABLE I. CONSTRAINTS OF RADIUS OF INNER HEXAGON

Reuse patterns $\{N_i, N_f, N_o\}$	Constraints of radius of inner hexagon
$\{1,1,3\}, \{1,3,3\}, \{1,4,3\}, \{3,1,3\}, \{4,1,3\}, \{1,1,4\}, \{1,3,4\}, \{1,4,4\}, \{3,1,4\}, \{4,1,4\}$	$R_0 < R_1 < 0.6R$
$\{3,4,3\}, \{4,3,3\}, \{3,3,4\}, \{3,4,4\}, \{4,3,4\}, \{4,4,3\}$	$R_0 < R_1 < R$

B. Comparison of cell capacity

In this subsection, we perform computer simulation to examine the cell capacities under all kinds of reuse patterns satisfying the constraint condition. The simulation results are shown in Fig. 5. This figure shows that the maximum capacity

is obtained by the reuse pattern $\{1, 1, 3\}$, which is followed by the reuse pattern $\{3, 1, 3\}$ and $\{1, 1, 4\}$ when $R_f = 0.6R$. The capacity of the traditional cellular network is also shown in Fig. 5. In particular, when the radius of inner zone is equal to R , the black point in fact shows us the capacity of the conventional system with cluster size being equal to three. Therefore, from Fig. 5 we can draw the conclusion that RRP with $\{1, 1, 3\}$ can offers as high as 50% increase in cell capacity in comparison with the corresponding traditional cellular network.

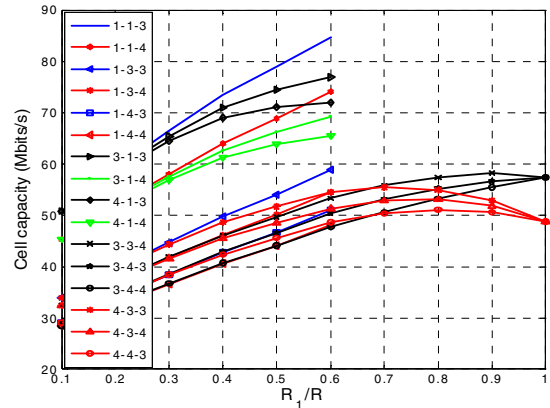


Figure 5. Cell capacity under different reuse patterns

In the following we will further compare the performance of three kinds of network architecture: TRP, RRP and the conventional cellular network. The considered conventional cellular network has a reuse factor of 3. For the TRP scheme, its inner zone has a reuse factor of 1 and its outer zone has a reuse factor of 3. As for the RRP network, we consider two configurations, i.e., the reuse pattern $\{1,1,3\}$ and $\{1,3,3\}$. The simulation results are presented in Fig. 6. From this figure we can observe that RRP with $\{1,1,3\}$ can offer 50% more capacity than the conventional system and 35% more capacity over the TRP architecture. However, if N_f is set to three, the capacity of RRP is generally smaller than the conventional system except in the case when we set the radius of the inner zone to its maximal allowed value. This result verified our analysis in section III. That is, due to the penalty of radio consumption in two-hop link, the selection of reuse factor N_f has a significant impact on the system performance.

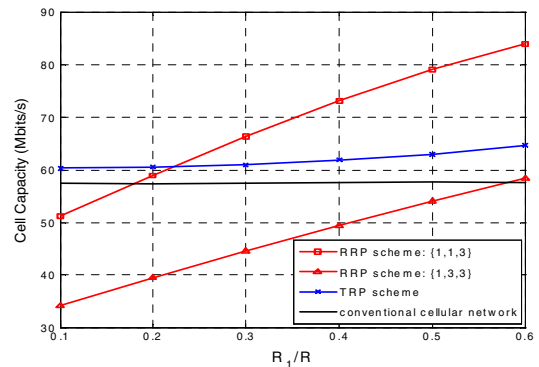


Figure 6. Comparison of capacity under different schemes

C. Comparison of SIR in outer zone

In this subsection, we study the QoS represented by SIR of MSs. Same reuse pattern is adopted as in Fig. 6 (only {1, 1, 3} is considered in RRP scheme), and the FRNs in RRP are put at the location of $0.4R$ and $0.6R$ away from BS respectively. The SIR when MS's position varies from the center to the edge of the cell is shown in Fig. 7, while the CDF curves of SIR in outer region in TRP and RRP cases is depicted in Fig. 8.

It can be seen from Fig. 7 that, if the same reuse factor is adopted in outer zone as conventional cellular system, the TRP architecture can not improve the QoS of the users scattered in the cell perimeter. On the contrary, the RRP architecture can improve the SIR significantly. However, when FRNs are located at the position $0.6R$ away from BS (coined as "RRP- $0.6R$ "), the SIR in the edge of inner zone is annoyingly low. When FRNs are put at the position of $0.4R$ away from the BS, all values of SIR are above 18dB. The cost is that the capacity under this case is 15% lower than that in "RRP- $0.6R$ " shown in Fig. 6. Nevertheless, the capacity is still 20% larger than that in the TRP architecture.

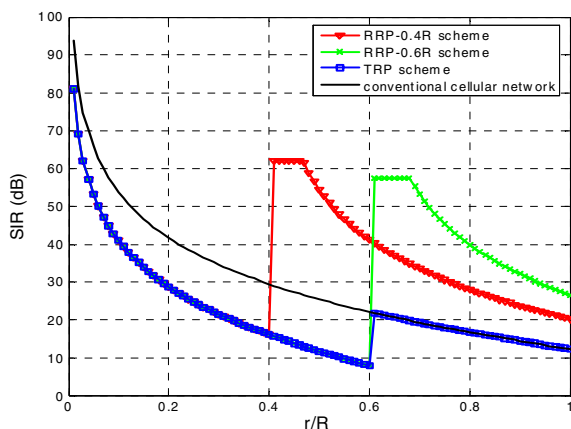


Figure 7. SIR in dependence on distance under different schemes

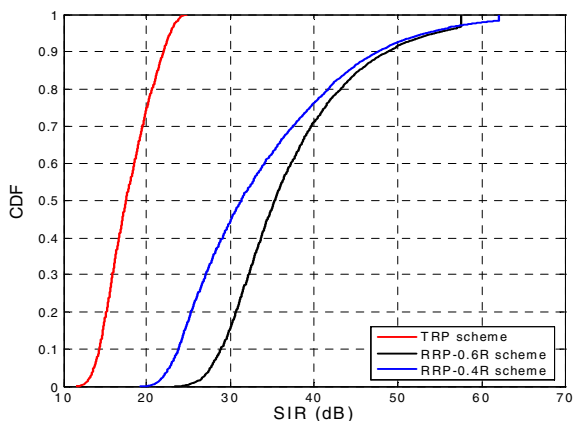


Figure 8. Comparison of SIR in outer zones

In Fig. 7 two horizontal lines can be seen in the RRP architecture. The reason is that, when a MS is located at the corresponding positions, the FRN's reception SIR from the MS

is higher than the BS's reception SIR from FRN. Therefore the FRN-BS link becomes the bottleneck.

If different routing strategies are introduced, such as "nearest-based" routing, which means the MS will connect to the nearest access point, the curve will ascend from the point of $0.3R$ in the "RRP- $0.6R$ " architecture. Under such circumstance, the minimum SIR will be more than 20 dB, and MSs can obtain better QoS. However, the capacity penalty is similar to the "RRP- $0.4R$ scheme" as more MSs are using two-link connections. Therefore, the selection of reuse pattern, FRN location and the routing depend on the optimizing criteria. In addition, it is worth mentioning that the presented scheme may not be optimal. However, it can serve as a benchmark for further research on how to fully exploit the potential of introducing reuse partitioning into relay enhanced cellular network. Especially, if the characteristics of OFDMA were taken into consideration, more optimistic results can be expected.

V. CONCLUSIONS

This paper proposed a new cellular network architecture utilizing reuse partitioning and fixed relay nodes. The combination of reuse partitioning and relay enables us to take advantage of both mechanisms. The investigation of the system performance of the proposed scheme with various values of reuse factors and FRN locations are studied. It was showed by our theoretical analysis and simulation results that the proposed scheme not only improves the system capacity, but also provides better QoS for users located in perimeter of cells.

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