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On Interference Coordination for Directional Decode-and-Forward Relay in TD-LTE Systems

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***Abstract*—Interference coordination is the key to reduce inter-cell interference in a TD-LTE system. Because of implementation complexity, partial and soft frequency reuse schemes are hardly suitable to TD-LTE systems. The decode-and-forward relay scheme, which may generate some additional interference, is presented to extend coverage and improve performance of TD-LTE systems. To mitigate the relay related interference, a directional relay topology is proposed in this paper. The radio resource is reused between the isolated RSs to improve the spectrum efficiency. The joint interference coordination and directional relay can suppress most inter-cell and inter-relay interferences and improve the capacity. The signal to interference plus noise ratio (SINR) distributions and throughput for the traditional non-relay scenario and the proposed directional relay scenario are derived. The analysis and simulation results show the effectiveness of the proposal scheme.**

I. INTRODUCTION

The LTE (Long Term Evolution) system launched by the 3GPP (3rd Generation Partnership Project) is based on OFDMA (Orthogonal Frequency Division Multiplexing), multiple antennas and other innovative techniques to achieve a high transmission rate and enhance the coverage [1]. The LTE systems may work at both FDD (Frequency Division Duplex) and TDD (Time Division Duplex) modes. It is noted that TDD mode has already been implemented in TD-SCDMA. There are two LTE systems based on TDD technique, and their differences in physical layer lie on two types of frame structures: one is called FDD LTE system and is named as Type 1, while the other called TD-LTE system which uses a special frame structure to be aligned with TD-SCDMA and is named as Type 2.

Interference mitigation techniques in LTE systems can be classified into three major categories such as interference cancelation through receiver processing, interference randomization by frequency hopping, and interference coordination achieved by restrictions imposed in resource usage in terms of resource partitioning and power allocation. For the interference coordination, the partial frequency reuse (PFR) [2] and soft frequency reuse (SFR) [3] are two variations. Due to the complex signal transmission patterns between base stations (eNB) over X2 interface and difficulty to determine locations of user equipments (UEs), the PFR and SFR schemes remain to have a huge gap to achieve a maximum interference avoidance gain in practice.

To improve cell-edge users' service quality, increase the system throughput and enlarge the cell coverage, the decode-and-forward (DF) relay station (RS) technique has been used in wireless cellular networks. In [4], a cellular network with a fixed RS was designed to provide a good spectral efficiency for UEs located at cell boundary, where the issues on some radio resource management policies, such as path selection, frequency reuse and frame transmission pattern matching among cells, were discussed. It was demonstrated in [5] that the RS will generate additional interference, which in turn may degrade the channel quality for edge UEs in neighboring cells. To overcome the severe performance degradation occurring in the outer region of multi-cells due to significant interference from neighboring cells or RSs, impacting on overall performance, a fixed RS cooperated beam-forming (FCBF) was presented in [6], which combined MIMO, multi-hop relay and multi-cell coordination techniques together.

The DF based RS has been standardized in 3GPP, where Type I [7] and Type II [8] relay schemes were proposed. Type I relay has its own physical cell indication (ID), and should appear to a UE as a separate cell different from the donor cell, and it transmits its own synchronization channels, reference symbols and control signals. Type II relay was proposed to achieve a cooperative diversity gain, which should not have a separate cell ID and thus would not create any new cell. Due to the difficulty to synchronize direct and relay transmissions, this paper focuses on Type I relay to extend the coverage. When the DF based RS is utilized in LTE systems, the TDD mode is more suitable than FDD because downlink and uplink resources can be assigned adaptively in a TD-LTE system. Consequently, this paper addresses the issues on the interference coordination for a DF relay based TD-LTE system.

II. SYSTEM MODEL

In order to support the relay transmission in Type 2 frame structure of a TD-LTE system, some time slots should be reserved for signal transmissions between the eNB and RSs. Meanwhile, the directional RS should be used to extend the coverage and suppress the interference from adjacent cells or RSs.

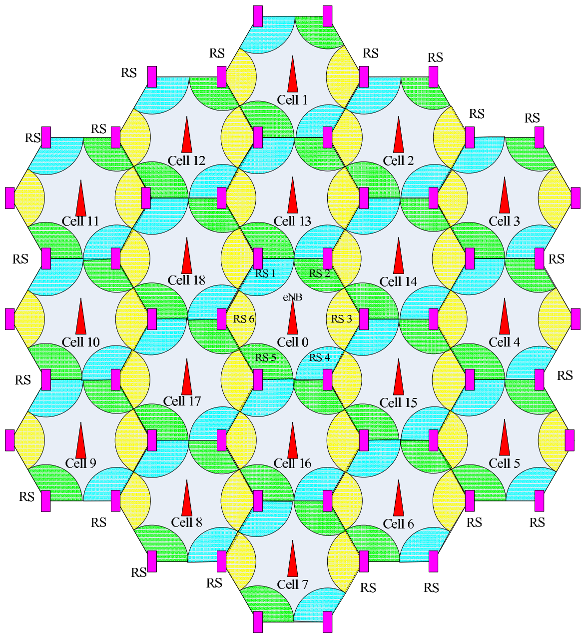

Fig. 1. Directional relay topology.

A. Directional Relay Topology

A directional relay topology is shown in Fig. 1, where eNB is marked as a red triangle and RS is denoted as a pink rectangle. It is assumed that eNBs are fixed at cell centers and RSs are at each vertex of hexagonal cells. In the proposed DF-relay based system model, each eNB is equipped with one omni-directional antenna while each RS is equipped with three 120-degree directional antennas. Thus, three cells are served by one RS, and six RSs are configured in one cell. To avoid inter-cell interference between adjacent eNBs, the coverage of eNB is limited and the UEs at cell edges are only served by RSs. i.e., only UEs located in the inner loop of the cell (named as inner UE) are served by eNB, while RSs will serve UEs in the outer loop of the cell (named as outer UE). Considering huge interference between adjacent RSs, the directional antennas are deployed in RSs. Furthermore, to improve spectrum efficiency, the non-adjacent RSs will reuse the same radio resources. Both outer and inner UEs are administrated by the serving eNB.

B. Frame Structure Design for Relay Transmission

To be fully compatible with TD-LTE systems, the frame structure for the proposed directional relay topology is shown in Fig. 2, which is inherited from the configuration 2 frame pattern for the TD-LTE systems [2]. For the configuration 2 frame pattern, each radio frame consists of two half-frames with a length $T_{\mathrm{f}} = 153600 \cdot T_{\mathrm{s}} = 5\mathrm{ms}$. Each half-frame consists of eight slots and three special fields, or DwPTS, GP, and UpPTS. To be compatible with the Type 1 frame structure (defined for FDD-LTE systems), two time slots are combined as one subframe, i.e., the subframe i consists of slots $2i$ and $2i + 1$. Subframes 0, 5 and DwPTS are always reserved for downlink transmissions.

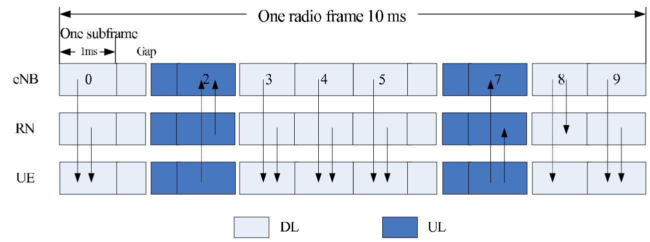

Fig. 2. TD-LTE frame pattern for DF based relay protocol.

In this paper, we investigate the downlink performance, and thus most subframes are reserved for downlink channels, where six subframes (marked in gray blocks) are reserved for downlink and two subframes (marked in dark blue blocks) are reserved for uplink in each frame. It is noted that there are two subframes for DwPTS, GP, and UpPTS. Every subframe has one long arrow and one short arrow, where the long one indicates the direct link between eNBs and inner UEs, while the short one represents the relay link between eNBs and RNs, or the access link between RNs and outer UEs. Since eNB and RS can communicate with their own UEs simultaneously, the RSs are non-transparent and categorized as Type I. For demonstration simplicity, the inner UEs and outer UEs are denoted as the same UEs in Fig. 2.

To reduce the interference, especially the interference from the adjacent RSs, the static interference coordination mechanism is adopted. Fig. 3 shows the time-frequency resource allocation design for the direct and relay transmissions in downlink. For the right subfigure in Fig. 3, the gray block resource is used for the direct link (denoted as B4), and the pink block is for the relay link (denoted as B3). Since all radio resources are orthogonally allocated, there is no intra-cell interference in each subframe, i.e., there is no interferences between different UEs, UE and RS, and different RSs located in the same cell.

For the left subfigure in Fig. 3, the B1 resource block is used for the access link for the communications between RSs and UEs. If all RSs in the same cell are allocated with the same time-frequency resources, a huge interference may occur between RSs. Due to the geometrical isolations, only RSs at the opposite positions will occupy the same time-frequency resource, which will degrade most RSs' interference and improve the transmission spectrum efficiency between eNB and RS. Therefore, if there are six RSs for each cells and the RS is numbered in sequential, the RS pairs, such as 3 and 6, 2 and 5, 1 and 4, can use the same radio resources. Consequently, the radio resources for the access links between the RS and UE are divided into three parts, each of which is presented by a different color in the left subfigure of Fig. 3. Although the radio resource reuse between the opposite RSs will help increase the interference, the interference can be suppressed to a satisfactorily low level due to the geometrical isolation.

Accurately, according to the radio channel conditions, the radio resource blocks (B1, B2, B3, and B4) should be opti-

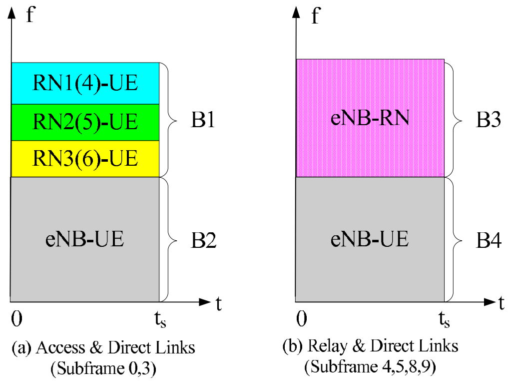

Fig. 3. Radio Resource Reuse for access links.

mized in both the time and frequency domains. In Fig. 3, the subframes 0 and 3 are allocated to the access and direct links, while the subframes 4, 5, 8, and 9 are allocated to the relay and direct links. More subframes are recommended to allocate to the relay link because the radio resource can be reused at the access links.

III. Theoretical Analysis

To evaluate the performance of the proposed directional relay protocol, the signal to interference plus noise ratio (SINR) distribution is derived first. According to the SINR probability distribution, the throughput can then be calculated.

For analysis simplicity, the shadow and fast fading models are not considered here when evaluating the statistical performance. The path loss model is utilized as the basis for our theoretical analysis, which can be written as

$$PL(d,\gamma) = \left(\frac{4\pi f_c}{c_0}\right)^2 d^{\gamma}, \tag{1}$$

where d is the distance between the transmitter and receiver, c_0 is the light propagation velocity, f_c is the carrier frequency, and γ is the path loss factor.

To compare the performances between the proposed directional relay protocol and the traditional non-relay protocol, the SINR distributions for these two protocols are derived as follows.

A. SINR Analysis in Non-relay Scenario

It is assumed that UEs are distributed randomly in a ringlike area. UEs are not nearer to the transmitter than 0.1 times cell radius, and not farther than the serving radius. In this scenario, all UEs are connected with eNB directly, and the probability density function (PDF) for a UE being at a distance of d_B to the eNB is [9]

$$f(d_B) = \frac{2\pi d_B}{\pi R^2 - \pi(0.1R)^2} = \frac{2d_B}{R^2-(0.1R)^2}, \tag{2}$$

where R is the cell radius. It is noted that all interferences in downlink come from the eNBs in neighboring cells. Considering a good geometrical isolation, we need only take into account the closest two tiers of interfering eNBs, and the SINR expression can be derived as

$$\Gamma_{w/o} = \frac{\frac{P_B}{M}/PL(d_B)}{\sum\limits_{i=1}^{18}\left(\frac{P_B}{M}/PL(d_i)\right) + PD_N\frac{B}{M}} = \frac{d_B^{-\gamma}}{T_{w/o}}, \tag{3}$$

where

$$T_{w/o} = 6(\sqrt{3}R)^{-\gamma} + 12(2\sqrt{3}R)^{-\gamma} + \frac{PD_N}{P_B}\times B \times \left(\frac{4\pi f_c}{c_0}\right)^2. \tag{4}$$

It is noted that $\Gamma_{w/o}$ stands for the received SINR of UEs in the non-relay scenario, M is the average number of serving UEs in each cell, PL denotes the pass loss function, d_B is the distance from the UE to the serving eNBs, d_i is the distance from the UE to the ith interfering eNB, PD_N is the noise power density, and B is the entire frequency bandwidth.

According to (3), we can derive the cumulative probability function (CDF) of SINR as

$$F(\Gamma_{w/o}) = \begin{cases} 1 - \frac{(\Gamma_{w/o}\times T_{w/o})^{-\frac{2}{\gamma}}}{R^2-(0.1R)^2}, \\ \frac{1}{R^{\gamma}T_{w/o}} \le \Gamma_{w/o} \le \frac{1}{(0.1R)^{\gamma}T_{w/o}} \\ 0, \quad 0 < \Gamma_{w/o} < \frac{1}{R^{\gamma}T_{w/o}} \end{cases} \tag{5}$$

based on which the probability density function (PDF) of SINR can be obtained as

$$f(\Gamma_{w/o}) = \frac{2}{\gamma\left(R^2-(0.1R)^2\right)} T^{-\frac{2}{\gamma}}\Gamma_{w/o}^{-\frac{2}{\gamma}-1}. \tag{6}$$

Consequently, the expectation value of $\Gamma_{w/o}$ can be derived as

$$\begin{aligned} E\left(\Gamma_{w/o}\right) &= \int_{\frac{1}{R^{\gamma}T_{w/o}}}^{\frac{1}{(0.1R)^{\gamma}T_{w/o}}} \Gamma_{w/o} f\left(\Gamma_{w/o}\right) d\Gamma_{w/o} \\ &= \frac{2}{T_{w/o}(\gamma-2)}\frac{(0.1R)^{2-\gamma}-R^{2-\gamma}}{R^2-(0.1R)^2}. \end{aligned} \tag{7}$$

B. SINR Analysis in Directional Relay Scenario

To study the directional relay protocol, the SINR distributions for direct, relay and access links should be derived, respectively. It is noted that the direct link means that the UE is located in the inner loop of the cell and it only communicates with BS directly. For the relay link, the eNB will allocate the radio resource to RS, and RS will be interfered by the adjacent eNBs. For the access link, the UE is located in the outer loop of the cell and it will only communicate with RS. Obviously, the SINR calculations for these three links may vary.

To access the eNB or RS, the path selection strategy used in this paper is based on the received signal power strength. If the received signal power from the eNB is stronger than that from the RS, the UE will communicate with the eNB directly, and vice versa. Due to the property of Type I relay, a UE can not be connected to eNB and RS simultaneously. We set eNB's transmitting power as P_B and RS's as P_R. Therefore, at the boundary of one eNB serving area and one RS serving area, we can get

$$\frac{P_B}{R_0^{\gamma}} = \frac{P_R}{r_0^{\gamma}}, \tag{8}$$

where R_0 is the radius of the inner loop of the cell, and r_0 is the radius of the RS' serving coverage, i.e., the radius of the outer loop of the cell. Furthermore, we have $R_0 = R - 2r_0$.

If the transmitting power ratio of eNBs and RSs is assumed as η, the following relationship can be obtained

$$\eta = \frac{P_B}{P_R} = \left(\frac{R_0}{r_0}\right)^{\gamma} = \left(\frac{2R_0}{R - R_0}\right)^{\gamma}. \quad (9)$$

When UEs are distributed uniformly in one cell, the numbers of UEs in the inner and outer loops are assumed to be M_{outer} and M_{inner}, respectively. It is assumed that there are on the average M UEs per cell, or

$$M_{outer} = \left(\frac{1}{1+\eta^{\frac{2}{\gamma}}}\right)M;\ M_{inner} = \left(\frac{\eta^{\frac{2}{\gamma}}}{1+\eta^{\frac{2}{\gamma}}}\right)M. \quad (10)$$

For the direct link in the directional relay scenario, UEs are effected by the neighboring eNBs. The SINR calculation is given as follows:

$$\Gamma_{inner} = \Gamma_{BU} = \frac{P_B/PL(d_B)}{\sum_{i=1}^{18}(P_B/PL(d_i))} = \frac{d_B^{-\gamma}}{T_{BU}}, \quad (11)$$

where

$$T_{BU} = 6(\sqrt{3}R)^{-\gamma} + 12(2\sqrt{3}R)^{-\gamma} + \frac{PD_N}{P_B/M_{inner}} \times \frac{B}{2M_{inner}} \times \left(\frac{4\pi f_c}{c_0}\right)^2 \quad (12)$$

According to (11), the CDF of SINR for the direct link can be calculated as

$$F(\Gamma_{inner}) = \begin{cases} 1 - \frac{(\Gamma_{BU}T_{BU})^{-\frac{2}{\gamma}}}{R_0^2-(0.1R)^2}, \\ \frac{1}{R_0^{\gamma}T_{BU}} \le \Gamma_{BU} \le \frac{1}{(0.1R)^{\gamma}T_{BU}} \\ 0, \quad 0 < \Gamma_{BU} < \frac{1}{R_0^{\gamma}T_{BU}} \end{cases} \quad (13)$$

Consequently, the SINR expectation value for the direct link in the directional relay scenario is

$$\begin{aligned} E(\Gamma_{inner}) &= \int_{\frac{1}{R_0^{\gamma}T_{BU}}}^{\frac{1}{(0.1R)^{\gamma}T_{BU}}} \Gamma_{inner} f(\Gamma_{inner})\, d\Gamma_{inner} \\ &= \frac{2}{T_{BU}(\gamma-2)} \frac{(0.1R)^{2-\gamma} - R_0^{2-\gamma}}{R_0^2-(0.1R)^2}. \end{aligned} \quad (14)$$

For the relay link, the RS will be interfered by all eNBs around. Consequently, the exact SINR value for the relay link can be expressed as

$$\Gamma_{BR} = \frac{P_B/PL(d_B)}{\sum_{i=1}^{7}(P_B/PL(d_i))} = \frac{R^{-\gamma_1}}{T_{BR}} = \xi_0, \quad (15)$$

where

$$\begin{aligned} T_{BR} &= 2(\sqrt{7}R)^{-\gamma} + 2(\sqrt{13}R)^{-\gamma} + 2(\sqrt{19}R)^{-\gamma} + (4R)^{-\gamma} \\ &+ \frac{PD_N}{P_B/M_{outer}} \times \frac{B}{M_{outer}} \times \left(\frac{4\pi f_c}{c_0}\right)^2. \end{aligned} \quad (16)$$

Due to the fact that location of each RS is fixed, the SINR for each RS is kept the same and can be calculated according to (15) directly.

For the access link, UE will be communicated with RSs, and it will be interfered by the surrounding RSs, i.e., the SINR calculation for the access link is determined by the surrounding RSs' interfering signals. Considering the impacts from the directional antenna, we infer that most interferences from the adjacent cells will be suppressed. The SINR calculation is

$$\Gamma_{RU} = \frac{P_R/PL(d_R)}{\sum_{i=1}^{17}(P_R/PL(d_i))} = \frac{d_R^{-\gamma}}{T_{RU}}, \quad (17)$$

where

$$\begin{aligned} T_{RU} &= 3(3R)^{-\gamma} + 2(2\sqrt{3}R)^{-\gamma} + 2(\sqrt{3}R)^{-\gamma} + 2(\sqrt{7}R - r_0)^{-\gamma} \\ &+ (2R - r_0)^{-\gamma} + 2(\sqrt{19}R - r_0)^{-\gamma} + 2(\sqrt{13}R - r_0)^{-\gamma} + \\ &(5R - r_0)^{-\gamma} + 2(2\sqrt{7}R - r_0)^{-\gamma} + \frac{PD_N B}{P_R}\left(\frac{4\pi f_c}{c_0}\right)^2. \end{aligned} \quad (18)$$

Therefore, the CDF of SINR for UEs at the access link can be expressed as

$$F(\Gamma_{RU}) = \begin{cases} 1 - \frac{(\Gamma_{RU}\times T_{RU})^{-\frac{2}{\gamma}}}{r_0^2-(0.1R)^2}, \\ \frac{1}{r_0^{\gamma}T_{RU}} \le \Gamma_{RU} \le \frac{1}{(0.1R)^{\gamma}T_{RU}} \\ 0, \quad 0 < \Gamma_{RU} < \frac{1}{r_0^{\gamma}T_{RU}} \end{cases} \quad (19)$$

For UEs in the serving scope of RSs, their SINRs will be decided by the smaller SINR of the relay and access links. In this paper, the relay link's SINR value is assumed to be far larger than that for the access link. Thus, these UEs' SINRs are solely decided by the quality of the access link. Hence, the joint CDF can be expressed as

$$\begin{aligned} &F(\Gamma_{outer}) = \Pr\{\min(\Gamma_{BR}, \Gamma_{RU}) \le \Gamma\} \\ &= 1 - \Pr\{\Gamma_{BR} \ge \Gamma, \Gamma_{RU} \ge \Gamma\} \\ &= 1 - (1 - \Pr\{\Gamma_{BR} \le \Gamma\})(1 - \Pr\{\Gamma_{BR} \le \Gamma\}) \\ &= \begin{cases} 0,\ 0 < \Gamma_{outer} < \frac{1}{r_0^{\gamma}T_{RU}} \\ 1 - \frac{(\Gamma_{outer}T_{RU})^{-\frac{2}{\gamma}}}{r_0^2-(0.1R)^2},\ \frac{1}{r_0^{\gamma}T_{RU}} < \Gamma_{outer} < \frac{1}{(0.1R)^{\gamma}T_{RU}} \\ 1,\ \Gamma_{outer} \ge \frac{1}{(0.1R)^{\gamma}T_{RU}} \end{cases} \end{aligned} \quad (20)$$

The SINR expectation for the relaying UEs is calculated as

$$\begin{aligned} E(\Gamma_{outer}) &= \int_{\frac{1}{r_0^{\gamma}T_{RU}}}^{\frac{1}{(0.1R)^{\gamma}T_{RU}}} \Gamma_{outer} f(\Gamma_{outer})\, d\Gamma_{outer} \\ &= \frac{2}{T_{RU}(\gamma-2)} \frac{(0.1R)^{2-\gamma} - r_0^{2-\gamma}}{r_0^2-(0.1R)^2}. \end{aligned} \quad (21)$$

C. Throughput Analysis in Non-relay Scenario

In the traditional non-relay scenario, if there are on the average M active UEs in each cell and each UE possesses a frequency band of B/M, thus the overall throughput can be expressed as

$$C_{w/o} = M\left[B/M \log_2(1 + \Gamma_{w/o})\right] = BQ_{w/o}. \quad (22)$$

According to the probability characteristics of SINR given in Eq. (5), the CDF of $Q_{w/o}$ in (22) can be expressed as

$$F(Q_{w/o}) = \begin{cases} 1 - \frac{\left[\left(2^{Q_{w/o}}-1\right)\times T_{w/o}\right]^{-\frac{2}{\gamma}}}{R^2-35^2},\ \log_2\left(\frac{1}{\mathrm{R}^{\gamma}T_{w/o}}+1\right) \le \\ Q_{w/o} \le \log_2\left(\frac{1}{(0.1R)^{\gamma}T_{w/o}}+1\right) \\ 0,\ 0 < Q_{w/o} < \log_2\left(\frac{1}{\mathrm{R}^{\gamma}T_{w/o}}+1\right) \end{cases} \quad (23)$$

In the case of large $Q_{w/o}$, we have $2^{Q}_{w/o} - 1 \approx 2^{Q}_{w/o}$. Hence, the throughput expectation for the traditional non-relay scenario can be written as

$$E\left[Q_{w/o}\right] = \frac{T_{w/o}^{-\frac{2}{\gamma}} 2^{-\frac{2Q_{w/o}}{\gamma}}}{R^2 - (0.1R)^2} \left[1 - \frac{Q_{w/o}}{\ln 2}\right] \Bigg|_{\log_2\left(\frac{1}{R^\gamma T_{w/o}}+1\right)}^{\log_2\left(\frac{1}{(0.1R)^\gamma T_{w/o}}+1\right)} \tag{24}$$

D. Throughput Analysis in Directional Relay Scenario

In directional relay scenario, the overall system throughput is the sum of all the inner and outer UEs' throughput. To achieve the optimal throughout, the radio resource should be allocated optimally between the inner and outer UEs. The radio resource allocation factor α is defined as the ratio of resources allocated to the outer and inner UEs, where each outer UE gets $\frac{2\alpha B}{(1+\alpha)M_{outer}}$, and each inner UE gets $\frac{B}{(1+\alpha)M_{inner}}$. Since the outer UE occupies two of three subframes for the relay link communication time, and one for the access link communication time, the throughput should be divided by three. Hence, the overall throughput equals to

$$\begin{aligned} E\left[C\right] &= E\left[C_{outer}\right] + E\left[C_{inner}\right] \\ &= \tfrac{2\alpha B}{3*(1+\alpha)} E\left[Q_{outer}\right] + \tfrac{B}{1+\alpha} E\left[Q_{inner}\right] \end{aligned} \tag{25}$$

To optimize (25), we can define $Q_{inner} = \log_2(1 + \Gamma_{inner})$, and the CDF of Q_{inner} can be expressed as

$$F\left(Q_{inner}\right) = \begin{cases} 1 - \frac{\left[\left(2^{Q_{inner}}-1\right)\times T_{BU}\right]^{-\frac{2}{\gamma}}}{R_0^2-(0.1R)^2}, \\ \log_2\left(\frac{1+\mathrm{R}_0^\gamma T_{BU}}{\mathrm{R}_0^\gamma T_{BU}}\right) \le \mathrm{Q}_{inner} \le \log_2\left(\frac{1+(0.1R)^\gamma T_{BU}}{(0.1R)^\gamma T_{BU}}\right) \\ 0, 0 < \mathrm{Q}_{inner} < \log_2\left(\frac{1}{\mathrm{R}_0^\gamma T_{BU}} + 1\right) \end{cases} \tag{26}$$

Based on (26), the PDF of Q_{inner} can be derived as

$$\begin{aligned} & f\left(Q_{inner}\right) = \tfrac{2\ln 2}{\gamma} \tfrac{T_{BU}^{-\frac{2}{\gamma}}}{R_0^2-(0.1R)^2} \left(2^{-\frac{2}{\gamma}}\right)^{Q_{inner}} \\ & \text{s.t.}, \log_2\left(\tfrac{1+\mathrm{R}_0^\gamma T_{BU}}{\mathrm{R}_0^\gamma T_{BU}}\right) \le Q_{inner} \le \log_2\left(\tfrac{1+(0.1R)^\gamma T_{BU}}{(0.1R)^\gamma T_{BU}}\right) \end{aligned} \tag{27}$$

Substituting (26) and (27) into (25), we have the average throughput for the inner UEs as

$$\begin{aligned} & E\left[\log_2\left(1+\Gamma_{inner}\right)\right] = \tfrac{2\ln 2}{\gamma} \tfrac{T_{BU}^{-\frac{2}{\gamma}}}{R_0^2-(0.1R)^2} \\ & \times \left[\frac{Q\left(2^{-\frac{2}{\gamma}}\right)^Q}{\ln\left(2^{-\frac{2}{\gamma}}\right)} - \frac{\left(2^{-\frac{2}{\gamma}}\right)^Q}{\ln^2\left(2^{-\frac{2}{\gamma}}\right)}\right] \Bigg|_{\log_2\left(\frac{1}{\mathrm{R}_0^\gamma T_{BU}}+1\right)}^{\log_2\left(\frac{1}{(0.1R)^\gamma T_{BU}}+1\right)} \end{aligned} \tag{28}$$

Similarly, we can derive $E\left[Q_{outer}\right]$ as

$$\begin{aligned} & E\left[\log_2\left(1+\Gamma_{outer}\right)\right] = \tfrac{2\ln 2}{\gamma} \tfrac{T_{RU}^{-\frac{2}{\gamma}}}{r_0^2-(0.1R)^2} \\ & \left[\frac{Q\left(2^{-\frac{2}{\gamma}}\right)^{Q_{outer}}}{\ln\left(2^{-\frac{2}{\gamma}}\right)} - \frac{\left(2^{-\frac{2}{\gamma}}\right)^{Q_{outer}}}{\ln^2\left(2^{-\frac{2}{\gamma}}\right)}\right] \Bigg|_{\log_2\left(\frac{1}{r_0^\gamma T_{RU}}+1\right)}^{\log_2\left(\frac{1}{(0.1R)^\gamma T_{RU}}+1\right)} \end{aligned} \tag{29}$$

TABLE I
SINR EXPECTATION.

Mean SINR	Theo. (dB)	Sim. (dB)
$Non-relay: eNB->UE$	11.10	11.08
$Relay: eNB->UE$	19.73	19.70
$Relay: eNB->RS$	36.50	36.50
$Relay: RS->UE$	17.20	17.31

TABLE II
THROUGHPUT EXPECTATION.

Throughput	Theo. (Mbps)	Sim. (Mbps)
$Non-relay$	9.11	12.87
$Relay: innerUEs$	20.84	22.43
$Relay: outerUEs$	11.08	12.74

IV. SIMULATIONS AND DISCUSSIONS

In this section, we will compare the performances between the traditional non-relay and the proposed directional relay scenarios. In the simulations, the carrier frequency is set to 2 GHz, the frequency bandwidth is 10 MHz. The eNBs' transmission power is 46 dBm. The path loss factor is 2.5 for LOS (line of sight), and 4 for NLOS (non-line of sight). The noise power density is -174 dBm/Hz. The cell radius is 1000 meters. The simulations generated 50000 snapshots, each of which refers to a different and independent UE's location. We use the full buffer service mode, and set the resource allocation factor as α =1, and the transmission power ratio as η =1.

Table I presents the SINR comparisons for different transmission links between the analysis and simulation results. It is shown that the theoretical analysis results are matched very well to the simulation results. Meanwhile, the proposed scheme can achieve a higher SINR than the non-relay scenario.

Table II shows the average throughput comparisons between the directional relay and non-relay scenarios. When the proposed directional relay protocol is utilized, the UEs in the inner loop of cell have about two times better performance than that in the non-relay scenario. Meanwhile, the UEs in the outer loop of cell can achieve almost the same performance as the average throughput of the non-relay scenario.

In Tables I and II, it is seen that the SINR is not constrained and it can be infinite. However, in a real network, the SINR should be in a limited range due to the hardware restriction and the definition of the feedback information to RS or BS. Consequently, the maximum allowed SINR of UEs should be limited. The following simulations were performed under the assumption that the UE's SINR is not higher than 22 dB.

Table III shows the SINR comparison between the directional relay and the traditional non-relay scenarios. It is noted that the SINR received at RSs is not limited. There is a relatively big difference between the theoretical analysis and the simulation results because only the simulation considered the impact from the limited SINR. Comparing the simulation SINR results with that given in Table I, the average SINR becomes lower, especially for our proposed directional relay

TABLE III
SINR EXPECTATION (SINR IS RESTRICTED).

SINR	Theo. (dB)	Sim. (dB)
$Non-relay: eNB->UE$	11.10	8.67
$Relay: eNB->UE$	19.73	15.97
$Relay: eNB->RS$	36.50	36.50
$Relay: RS->UE$	17.20	14.73

TABLE IV
THROUGHPUT EXPECTATION VALUE (SINR IS RESTRICTED).

Throughput	Theo. (Mbps)	Sim. (Mbps)
$Non-relay$	9.11	12.73
$Relay: innerUEs$	20.84	21.48
$Relay: outerUEs$	11.08	12.37

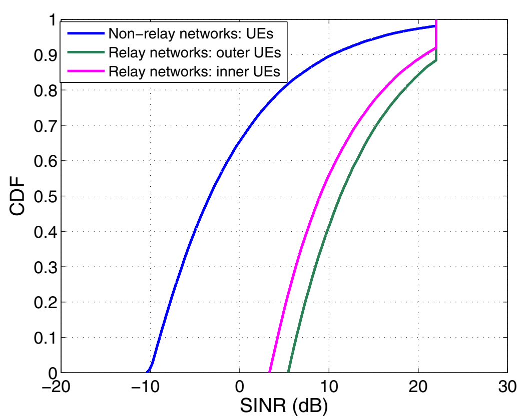

Fig. 4. CDF of SINR in UEs when SINR is not bigger than 21dB.

scheme. Consequently, due to the SINR restriction in UEs, the performance gain of our proposed scheme is not significantly high. One possible solution is to improve UE's SINR.

Table IV shows the average throughput comparison between the directional relay and traditional non-relay scenarios, showing the impacts from the maximal allowed SINR on the average throughput.

To take a fair comparison with the SINR distributions for different scenarios, the CDF curves of SINR obtained from the simulations are depicted in Fig. 4. In the traditional non-relay scenario, about 30 percent of UEs experience a SINR less than 0 dB, which means that they have to resort to other signal processing techniques to recover useful signals from overwhelming interference and noises. On the contrary, when utilizing the proposed directional relay scheme, both the outer and inner UEs will have a good transmission quality, where all SINRs are higher than 3 dB.

Fig. 5 gives an explicit view of the geometrical SINR profile, where we assumed that a UE is moving from the cell center to the cell edge. The blue curve represents SINRs for UEs in non-relay networks, and the SINR decreases almost linearly with the increasing distance. However, for UEs in the

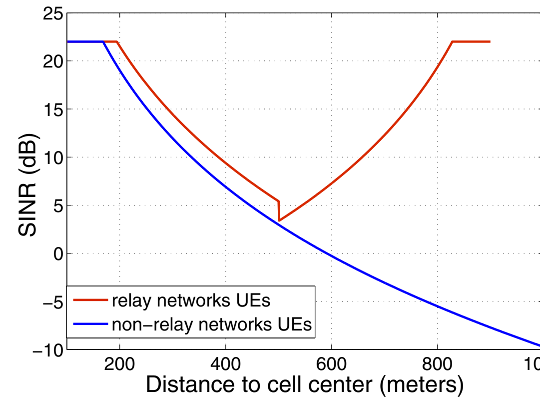

Fig. 5. SINR profiles (maximum allowable SINR is 21 dB.)

proposed directional relay scenario, UEs experience a rising curve of SINR after they have gone across the eNB's serving boundary and into the served coverage by the RS. We can see that cell-edge UEs's SINR can be improved remarkably with the assistance of directional relay nodes.

V. CONCLUSION

The simulation results show that the theoretical analysis results are matched to those from simulations very well. Compared with the traditional non-relay scenario, the proposed directional relay scheme offers a huge SINR and throughput gain. Meanwhile, the transmission power and radio resources between inner and outer UEs are optimized for achieving the best performance in the proposed directional relay protocol.

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