An Overlaid Hybrid-Duplex OFDMA System with Partial Frequency Reuse

Jung Min Park†, Young Jin Sang‡, Young Ju Hwang†, Kwang Soon Kim‡ and Seong-Lyun Kim†

School of Electrical and Electronic Engineering
Yonsei University, 134 Sinchon-Dong, Seodaemun-Gu
Seoul 120-749, Korea
Email: {jmpark, yjhwang, slkim}@ramo.yonsei.ac.kr† and {yjmich, ks.kim}@yonsei.ac.kr‡

***Abstract*— For the overlaid HDD cellular system, where TDD and FDD coexist in the inner region [1], we suggest a new frame structure adopting partial frequency reuse (PFR). We found that the overlaid HDD system with PFR outperforms other conventional systems by the optimal downlink power allocation. We also found that cooperative transmission with network coding improves the capacity of the cell border in the overlaid HDD. The simulation results are promising in that the performance gain in the overlaid HDD, mostly comes from multi-hop transmission in the uplink direction and from network-coded cooperative communication in the downlink.**

***Index Terms*— Hybrid division duplex, partial frequency reuse, cooperative transmission, network coding, interference mitigation, power allocation.**

I. Introduction

HDD (Hybrid Division Duplex) [1]-[3] aims to combine the advantages of TDD (Time Division Duplex) and FDD (Frequency Division Duplex) by providing high data rates and asymmetric service for nomadic users with TDD, and reliable service to high-speed mobile users with FDD. In [3], downlink (DL) communication is available in TDD DL, whereas uplink (UL) traffic is through either TDD UL or FDD UL band. The cell area is divided into two regions: mobiles in the inner region send UL signals via TDD UL, while those in the outer region send via FDD UL. The base station can direct the mobiles to send UL data in either TDD UL or FDD UL, according to the locations of mobiles. This means that mobiles approaching their base station have to carry out the handover of channels from FDD UL to TDD UL.

In our previous work [1], we proposed the overlaid HDD, where TDD and FDD coexist in the inner region. As each cell is partitioned into the two regions, we applied reuse partitioning (RP) [4]-[6] to the overlaid HDD system, and considered two frequency reuse factors corresponding to the inner and outer regions, respectively. Moving further from RP, in this paper, we introduces *Partial Frequency Reuse* (PFR), in which the inner region reuses the channels assigned to the outer regions of neighboring cells. PFR yields more available channels in the inner region at the cost of increased inter-cell interference. This paper investigates how to combine PFR and the overlaid HDD optimally to maximize the spectral efficiency.

Meanwhile, introducing a relay generally increases the capacity of wireless networks, particularly when it is combined with *cooperative transmission* [7], [8]. Using a relay also enables *network coding* [9], which can improve the capacity of the wireless network as well. Another important issue in this paper is how cooperative transmission performs with network coding in our overlaid HDD system.

The results of this paper are summarized as follows:

- We adopt HDD on the overlaid cellular structure where the cell is divided into the inner and outer regions. Since it is overlaid, a mobile station approaching the inner region from outside does not need the handover of channels. For this purpose, we designed a two-band system that supports PFR.
- Joint optimization of the downlink power level and the inner region radius significantly enhances the downlink capacity of the overlaid HDD.
- The up- and downlink spectral efficiency of the overlaid HDD is superior to that of a conventional OFDMA system. In particular, this is accelerated by multi-hop transmission and network-coded cooperative communication.

The rest of this paper is organized as follows: in the next section, we overview our overlaid HDD system. In Section III, we suggest joint optimization of DL power levels and cell partitioning. Section IV introduces how we select relays for cooperative transmission combined with network coding. Section V presents the numerical results, and Section VI concludes the paper.

II. Overlaid HDD System

A. Overlaid HDD with PFR

A high-level view of our proposed overlaid HDD is described in Figs. 1 and 2. TDD is used by the base station (BS) and mobiles in the inner region. FDD is mainly for mobiles in the outer region, although it can also be used for mobiles in the inner region. This means that handover may not be needed by the mobiles approaching the inner region from

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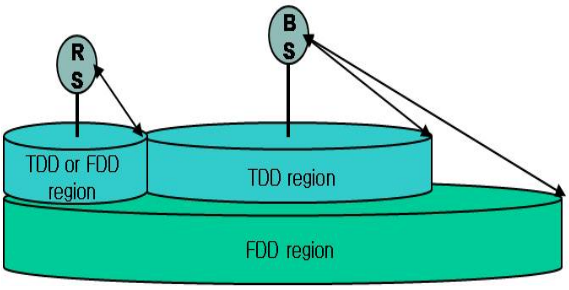


Fig. 1. Overlaid HDD system.

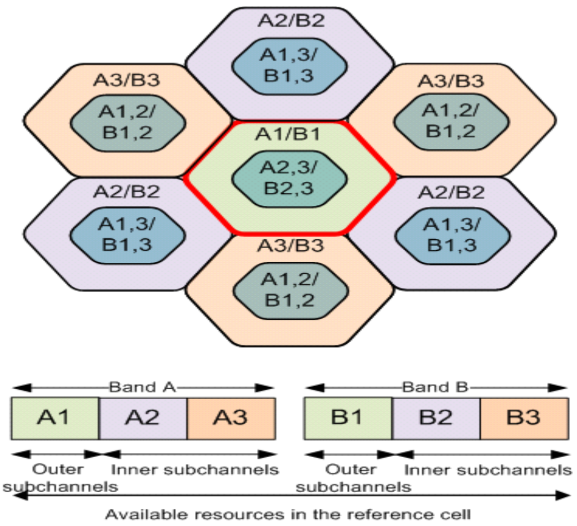


Fig. 2. Partial frequency reuse for two paired frequency bands. In this example, frequency reuse factors of the inner and outer regions are 1 and 3, respectively.

outside. To compensate the performance degradation at the cell border due to the path-loss, the overlaid HDD adopts multi-hop transmission for the mobiles of the outer region. For this, the mobiles in the inner region can act as a relay to support UL transmission and DL reception of the outer region mobiles, similar to *Opportunity Driven Multiple Access* (ODMA) [10]. The transmission between relays (RS) and mobiles works in either TDD or FDD.

B. Subchannelization

Our overlaid HDD uses two paired frequency bands, bands A and B, to support both TDD and FDD. Each frequency band is composed of the inner subchannels and outer subchannels as shown in Fig. 2. In a cell, outer subchannels are allocated according to the reuse factor of the outer region, while all the remaining subchannels are inner subchannels. In principle, all subchannels can be allocated in a cell, yielding the cost of inter-cell interference. To mitigate such interference, we introduce joint optimization of DL power levels and the inner region radius in the next section.

Each band of PFR is made up of both *band-type* and *comb-type* subchannels, as shown in Fig. 3. The subchannels used by the TDD in the inner region are band-type (composed of adjacent subcarriers for adaptive power allocation), while the outer subchannels in FDD mode are comb-type (composed of

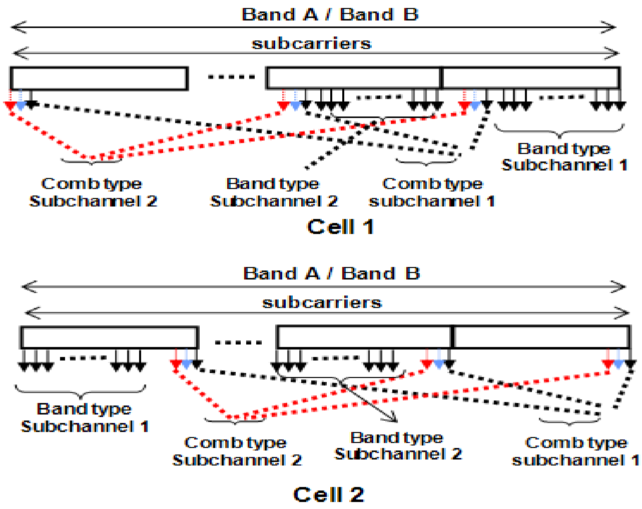


Fig. 3. PFR subchannelization.

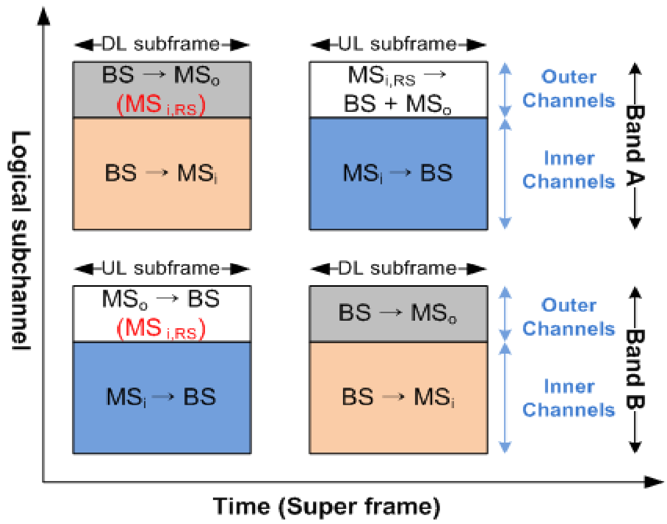


Fig. 4. PFR frame structure. BS, MS_i, MS_o, $\mathrm{MS}_{i,RS}$ and BS→MS_i denote the base station, a mobile station in the inner region, a mobile station in the outer region, a mobile station serving as a relay in the inner region, and DL transmission for a mobile in the inner region, respectively. $\mathrm{MS}_{i,RS}$ in parentheses means that a mobile serving as a relay overhears the transmission from BS or MS_o. The other notations are straightforward.

distributed subcarriers for frequency diversity) [11]. Note that the group of subcarriers for comb-type subchannels in a cell does not overlap with those in neighboring cells, so that the outer subchannels in neighboring cells do not interfere with each other. However, the outer subchannels of a cell are reused as the inner subchannels at neighboring cells, generating the inter-region interference between neighboring cells.

C. Cooperative Transmission and Network Coding

When the transmission occurs between a pair of communicating nodes, neighboring nodes can overhear it. We can improve the network throughput by allowing the neighboring nodes to jointly transmit these signals in their communication, which is known as cooperative transmission (see [8] and literature therein).

In the proposed HDD system, we utilize this cooperative transmission to enhance the throughput of outer region mobiles, and some of inner region mobiles are used as relays for outer region mobiles. These relays help both UL and DL transmission for outer region mobiles, communicating their own traffic with the BS as well. When introducing relays, however, medium access in the network necessarily increases. In order to reduce the excessive medium access, we have incorporated network coding into cooperative transmission at the relay nodes. Network coding is especially attractive in cellular systems, where bidirectional traffic between the BS and mobiles frequently occurs [12].

Fig. 4 shows the frame structure of our overlaid HDD system which is designed to accommodate cooperative transmission and network coding. When a mobile in the outer region communicates with the BS using FDD during the first subframe, the mobile selected as a relay in the inner region overhears UL and DL traffic. Then, the relay mixes them together and multicasts them to both the BS and the mobile in the outer region during the second subframe of band A. The BS and the mobile in the outer region carry out MRC (Maximal Ratio Combining) for UL and DL transmission.

In the case of cooperative transmission with a relay, two subframes must be needed for UL and DL traffic, respectively, so in total four subframes. By network-coded transmission of UL and DL traffic at the relay ($MS_{i,RS} \rightarrow BS+MS_o$ in Fig. 4), however, one subframe can be saved. This saved subframe can then be used for DL transmission of mobiles in the outer region. In Fig. 4, $BS \rightarrow MS_o$ in the second subframe of band B is saved by the network coding.Therefore, an additional TDD pair of mobiles is obtained in the outer region. This will lead to a *network coding gain* [13], which we will investigate numerically in Section V.

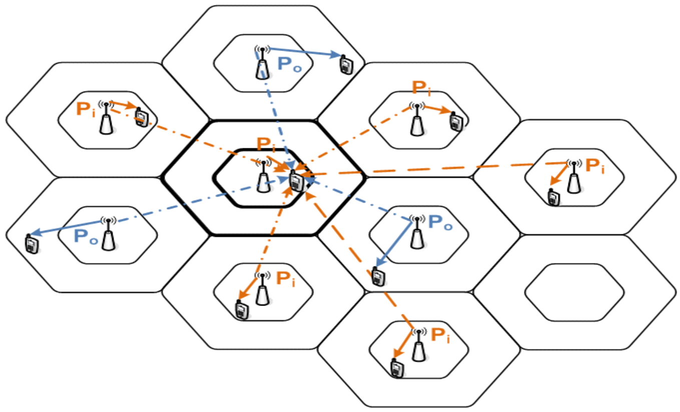
III. Joint Optimization of DL Power Levels and Inner region Radius

Due to the increased interference caused by adopting PFR, some mobiles at the cell border may suffer from performance degradation, especially in the downlink. To cope with this problem, the DL power levels for both regions and the radius of the inner region can be jointly optimized, which determine the mutual interference between the inner and outer region in the overlaid HDD system (in Fig. 5).

For this purpose, we make the following assumptions:

- Each cell is a regular hexagon.
- The target system is interference-limited, and we ignore the noise power.
- The transmitted signal is uniformly propagated, and we consider only the path-loss.
- The mobiles located at the border (inner or outer region) have to be supported with some minimum target SIR, γ_o.

Let us denote the BS transmission powers for the inner and the outer region by P_i and P_o, respectively. Furthermore, the minimal co-channel reuse distances for each region are denoted by D_i and D_o, which are determined by the frequency reuse factor of each region. The cell radius is R, and we assume that the radius of the inner region is r_i $(< R)$. Then,



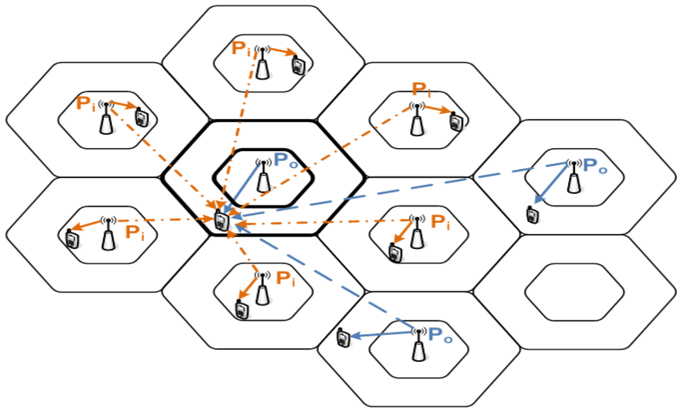


Fig. 5. Co-channel interference model at the border of the inner region (a) and outer region (b) in PFR. The reuse factor of the outer region is 3 in this example. In the case of (a), dashed lines denote the co-channel interferences from the inner subchannel according to the reuse factor, and chain lines denote the co-channel interferences from the inner (orange) or outer (blue) subchannel of neighboring cells. In the case of (b), dashed lines denote the co-channel interferences from the outer subchannel according to the reuse factor, and chain lines denote the co-channel interferences from the inner subchannel of neighboring cells. Solid lines denote the transmitted signal in both cases. Here, P_i and P_o denote BS transmission powers for the inner and outer regions, respectively.

the mobile located at the border of the inner region will have the received SIR given by (1). Also, the received SIR of the mobile at the cell border is given by (2), where D_i/R and D_o/R are equivalent to $\sqrt{3K_i}$ and $\sqrt{3K_o}$ [6]. Here, K_i and K_o denote reuse factors of the inner and outer regions, respectively.

In this section, we jointly optimize DL power levels and inner region radius to support the mobiles at the border of both regions with a given minimum target SIR γ_o. For example in (2), assuming $K_i = 1$ and $K_o = 3$ yields the following relationship between the minimum target SIR γ_o and optimal power levels:

$$\frac{P_i}{P_o} = \frac{1.3567}{\gamma_o} - 0.1249. \tag{3}$$

Substituting (3) into (1), we have the radius of the inner region as a function of γ_o:

$$SIR_i = \frac{P_i/r_i^4}{3(P_i/D_i^4 + 2\cdot P_i/(\sqrt{3}D_i)^4 + P_i/(\sqrt{4}D_i)^4 + \cdots) + 3(P_o/D_i^4 + P_o/(\sqrt{4}D_i)^4 + P_o/(\sqrt{7}D_i)^4 + \cdots)}$$
$$\approx \frac{1}{(r_i/D_i)^4 \cdot \{4.1463 + 3.3170\cdot(P_o/P_i)\}} = \gamma_o \quad (1)$$

$$SIR_o = \frac{P_o/R^4}{6(P_o/D_o^4 + P_o/(\sqrt{3}D_o)^4 + P_o/(\sqrt{4}D_o)^4 + \cdots) + 6(P_i/D_i^4 + P_i/(\sqrt{4}D_i)^4 + P_i/(\sqrt{7}D_i)^4 + \cdots)}$$
$$\approx \frac{1}{7.4633\cdot(R/D_o)^4 + 6.6340\cdot(R/D_i)^4\cdot(P_i/P_o)} = \gamma_o \quad (2)$$

$$r_i = \sqrt[4]{\frac{9 - 0.8286\gamma_o}{\gamma_o(4.1463 + 2.0632\gamma_o)}}\cdot R, \quad (4)$$

where $K_i = 1$ and $K_o = 3$.

Thus, with (3) and (4), we can determine P_i, P_o and r_i for given K_i, K_o and R, to support the mobiles at the border of both regions with the minimum target SIR γ_o.

IV. Relay Selection for Cooperative Transmission

Consider the following two conditions (5) and (6), given by:

□ UL-perspective condition for multi-hop transmission

$$\frac{1}{2}\cdot\frac{1}{2}\log_2\left(1 + \min(\gamma_{MS\to RS}, \gamma_{RS\to BS})\right) > \frac{1}{2}\log_2(1 + \gamma_{MS\to BS}), \quad (5)$$

□ DL-perspective condition for multi-hop transmission

$$\frac{1}{2}\cdot\frac{1}{2}\log_2\left(1 + \min(\gamma_{BS\to RS}, \gamma_{RS\to MS}\right) > \frac{1}{2}\log_2(1 + \gamma_{BS\to MS}), \quad (6)$$

where $\gamma_{MS\to RS}$ denotes the received SIR at a relay station from a mobile station.

In (5), the left-hand side represents the amount of transmitted data (i.e., spectral efficiency) in UL by the multi-hop transmission. The right-hand side describes direct UL transmission between the mobile and the BS. The first constant of the left-hand side $\frac{1}{2}$ refers to the relative time fraction by using the relay transmission. Similar relationship is shown in (6) for DL traffic. If (5) or (6) is satisfied, then the multi-hop transmission is more beneficial than the direct transmission. If there exists no relay where either (5) or (6) is satisfied, mobiles in the outer region directly transmit to the BS.

In order to cooperatively transmit using a relay, a mobile has to satisfy a certain throughput-related condition [8]:

□ UL-perspective condition for cooperative transmission

$$\frac{1}{2}\cdot\frac{1}{2}\log_2(1 + \min(\gamma_{MS\to RS}, \gamma_{RS\to BS} + \gamma_{MS\to BS}) > \frac{1}{2}\log_2(1 + \gamma_{MS\to BS}), \quad (7)$$

□ DL-perspective condition for cooperative transmission

$$\frac{1}{2}\cdot\frac{1}{2}\log_2(1 + \min(\gamma_{BS\to RS}, \gamma_{RS\to MS} + \gamma_{BS\to MS}) > \frac{1}{2}\log_2(1 + \gamma_{BS\to MS}). \quad (8)$$

In (7) and (8), the left-hand side represents the amount of transmitted data in UL and DL, respectively, by cooperative transmission when adopting the decode-and-forward strategy [8]. The first term in the minimum operator of (7) and (8) means the maximum rate at which the relay can reliably decode the source signal. On the other hand, the second term represents the maximum rate at which the destination adopting MRC can reliably decode the source signal. Both the relay and the destination are required to decode the source signal without errors, resulting in the minimum operator in (7) and (8). The others, except for the left-hand side, are the same as in the multi-hop transmission case.

So far, the relays for UL and DL transmit their relaying signals without mixing UL and DL data using their own subchannels. However, the cooperative transmission can be combined with the network coding that mixes (usually eXclusive OR, XOR operation) UL and DL traffic. In this combined scheme, whether or not a mobile transmits using the network coding can be decided by one of two conditions (7) and (8). In this paper, we use (7) to determine relay nodes because the network-coded transmission has to be performed within UL subframe as shown in Fig. 4. If the network-coded transmission is in the second subframe at band B (DL subframe), BS has to perform both transmission and reception in one band, simultaneously. This is against the characteristic of half-duplexing. The relay node broadcasts the network-coded information, which is combined with the direct transmission later at the destination. Thus, the position of the relay node may not be optimal for DL cooperative transmission, since the selection of the relay node is based on the UL-perspective condition (7).

V. Simulation Results

In order to get insights into our overlaid HDD, simulations were conducted using 1024-point FFT for each of the bands A and B. Each band has 36 subchannels, and a subchannel is comprised of 24 subcarriers. We consider a regular hexagonal cellular system with 19 cells and a cell radius of 5km, and

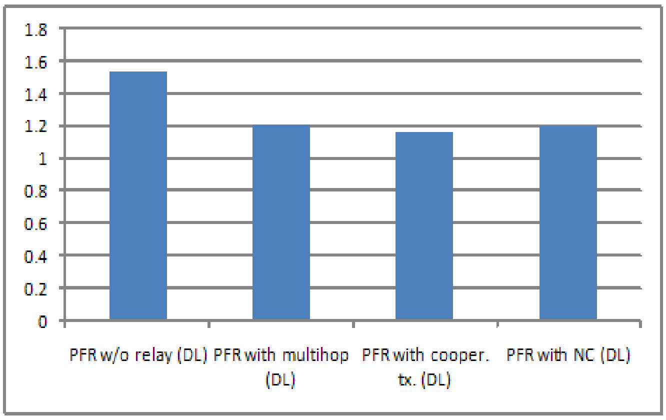


Fig. 6. Ratio between the spectral efficiency of the outer region with- and without DL optimization.

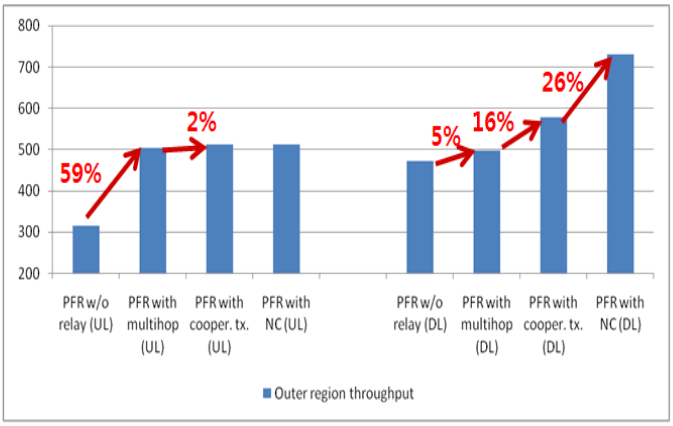


Fig. 7. Spectral efficiency of the overlaid HDD system.

100 mobiles are distributed uniformly in each cell. The path-loss exponent is set to 4, and the ITU-R vehicular A channel model is used. We assume that if a mobile transmits with full power from the cell edge, then the average received SNR at the BS is 3 dB. All mobiles send their data with full power as if they were at the cell edge. The frequency reuse factors of the inner and outer regions are set to 1 and 3, respectively. The BS determines whether or not a mobile should get the assistance from relays based on (5)-(8).

We assume the capacity of a subchannel is the sum of Shannon capacity of subcarriers in the subchannel, $\sum_{l=1}^{L}\log_2(1+SINR_l)$, where L is the number of subcarriers in the subchannel and $SINR_l$ is the SINR at the l^{th} subcarrier. We cannot predict the actual throughput but the assumption is sufficient to compare the relative throughput among different schemes.

In the simulations, the performances of the overlaid HDD without relays, with multi-hop transmission only, with cooperative transmission, and with cooperative transmission combined with network coding are examined. The system with multi-hop transmission does not utilize the directly transmitted signal between a mobile and the BS, and only the retransmitted signal from a relay is used in both the BS and mobiles. In the system with cooperative transmission, a mobile in the outer region selects its relay for UL and DL transmission, separately. Two time or frequency slots are needed for UL and DL transmission.

Fig. 6 shows the ratio of the spectral efficiency between with- and without joint optimization of DL power level and inner region radius of the overlaid HDD. [1] The performance gain of the optimization is 53%, when direct transmission is used, and it is about 20% when relays are allowed. The performance gain from the optimization is reduced when it is applied to the overlaid HDD with relays. This is because only some portion of outer mobiles rely on direct transmission that may get benefit from the joint optimization.

Fig. 7 shows the performance of the outer region of the overlaid HDD system with DL optimization. Introducing PFR, the relay simultaneously transmits its own signal and the relayed signal using inner subchannels and outer subchannels, respectively. Therefore, there exists no performance degradation of the inner region in any transmission schemes. The performance improvement of each transmission scheme occurs only in the outer region. In UL transmission, the performance improvement from relay transmission is dominant. The improvement due to the cooperative transmission over the multi-hop transmission is low because the power of direct transmission from a mobile to the BS is not strong enough to bring meaningful performance improvement. Using the UL perspective condition (7) in Section IV, the performance of network coding is roughly the same as that of cooperative transmission in UL transmission.

In DL transmission, the transmission power for the direct transmission is much higher than that for the transmission to the inner region, so the performance improvement due to the relay transmission is relatively small compared to that in UL transmission. The performance improvement of the cooperative transmission over multi-hop transmission is considerable since the signals received at a mobile in the outer region from the BS are high enough to result in performance improvement. In network coding, the subchannels for UL transmission are used, so there are vacant subchannels for DL transmission. The performance improvement of the network coding over the cooperative transmission in DL arises from such saved subchannels, which is mentioned as a reason for the network coding gain in Section II. C.

VI. Conclusions

The HDD scheme utilizes the merits of TDD and FDD by dividing a cell into an inner and an outer region. In this paper, the overlaid HDD system based on PFR has been proposed under two band channelization, and the frame structure for the system has been suggested. The proposed overlaid HDD system can significantly improve spectral efficiency due to two key factors: the PFR scheme with optimal power levels and cell partitioning, and cooperative transmission with network coding to increase the throughput of the outer region. Simulation results showed how these factors enhance the network throughput.

[1] In the simulations, the inner region radius is set to a half of the cell radius when the optimization is not applied.

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