An Overlaid Hybrid-Division Duplex OFDMA System with Multihop Transmission

Young Jin Sang, Jung Min Park, Seong-Lyun Kim, and Kwang Soon Kim

In this letter, we propose an overlaid hybrid division duplex (HDD) concept for cellular systems which divides a cell into inner and outer regions and utilizes the merits of both time division duplex (TDD) and frequency division duplex (FDD). The proposed system can take advantage of both TDD and FDD without handover between two duplex schemes. Moreover, it is shown that the proposed HDD system outperforms the conventional TDD or FDD system with mobile relay stations when the synchronization issue is considered in orthogonal frequency division multiple access systems. Thus, the proposed overlaid HDD can be considered as a new framework for future cellular systems.

Keywords: Hybrid division duplex, interference mitigation, relay, reuse partitioning.

I. Introduction

Frequency division duplex (FDD) and time division duplex (TDD) are the two most prevalent duplexing schemes in cellular radio systems. One of the main reasons to introduce TDD is to achieve a trunking gain by merging uplink (UL) and downlink (DL) channels into one. On the other hand, it has been pointed out that TDD is not suitable for mobile stations (MSs) near the cell boundary because of the adjacent cell interference generated by the MSs. In addition, TDD suffers from problems such as 3-dB-loss in signal-to-noise ratio (SNR) due to the doubled bandwidth with a given power amplifier at transmitters. In order to utilize the advantages of both FDD and TDD, a hybrid of the two has been proposed, which is known as hybrid division duplex (HDD) [1].

On the other hand, the implementation of multihop transmission for a cellular system has been widely studied to extend the cell coverage and improve user throughput of the cell edge [2]. However, as mentioned in [3], the orthogonal frequency division multiple access (OFDMA)-based multihop cellular system has a synchronization issue due to the different timing arrival of signal from the base station (BS) and relay stations (RSs).

The system proposed here is also based on HDD. However, it differs from the one in [1] in the sense that our system is TDD-FDD overlaid. In other words, TDD and FDD coexist in the inner region, where an MS can choose between the two. Thus, we can take advantage of TDD; for example, channel reciprocity and flexible UL/DL allocation. FDD can also be used for high-speed users and users at cell edge. Moreover, the overlaid HDD system can easily adopt mobile RSs (mRSs) due to the band separation between the BS and RSs. As the cell of the overlaid HDD system is partitioned into the two regions, we consider the reuse partitioning (RP) as a cell planning scheme [4]. The results of this letter are summarized as follows:

- We adopt HDD on the overlaid cellular structure that divides the cell into inner and outer regions. Since it is overlaid, an MS approaching the inner region does not need the handover of channels. For this purpose, a frame structure for HDD using two bands is proposed which supports RP as a cell planning scheme.
- The overlaid HDD system utilizes the advantages of both TDD and FDD systems, and additional improvement is

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achieved compared to a conventional TDD/FDD-OFDMA system when mRSs are adopted.

II. Proposed Overlaid HDD System

Various HDD schemes have been attempted, from both the device perspective and spectrum allocation perspective [5], in which time or frequency separation is mixed. In particular, the scheme in [1] aims to combine the advantages of TDD and FDD by providing high data rates and asymmetric service for nomadic users in TDD and reliable service to high-speed mobile users in FDD. The TDD is not suitable for large cells due to the long guard time between the DL and UL.

In the HDD system in [1], DL communication is available in TDD DL, whereas UL traffic is through either the TDD UL or the FDD UL band. The cell area is divided into two regions. MSs in the inner region send UL signals via TDD UL, while those in the outer region send via FDD UL. This means that MSs approaching their BS have to carry out the handover from FDD UL to TDD UL.

A high-level view of our proposed system, the overlaid HDD system, is described in Fig. 1. TDD is used between the BS and MSs in the inner region. Although, FDD is mainly for the MSs in the outer region , it can also be used for the MSs in the inner region, which implies that handover from FDD to TDD is not necessary for the MSs approaching the inner region from outside. Such structure enables the system to leverage the advantage of TDD which allows the asymmetry between DL and UL. At the same time, the overlaid HDD system does not require long guard time for a large cell as FDD is used in the outer region. In a nutshell, the overlaid HDD system takes advantage of both TDD and FDD without intracell handover.

Moreover, the overlaid HDD system has also adopted mRSs to increase the data rate of the outer region. The transmission between the BS and an mRS uses TDD through band A, and that between an mRS and the MS in the outer region uses TDD through band B. By separating the transmission from the BS and that from an mRS into two different bands, intercarrier interference (ICI) within a cell can be mitigated (see details in subsection III.2).

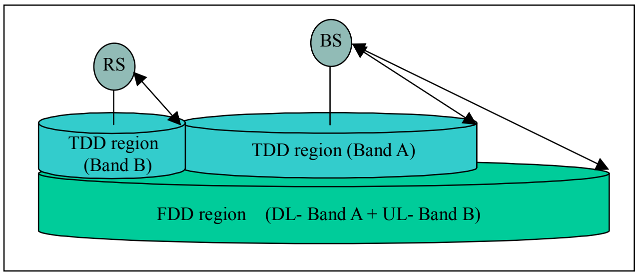

Fig. 1. Overlaid HDD system.

III. Proposed Frame Structure Citations

1. Frame Structure and Subchannelization

Our overlaid HDD uses two frequency bands, band A and band B, and the OFDMA is employed in each band. As shown in Fig. 2, the frame structure of the overlaid HDD for RP consists of two subframes to support the overlaid HDD. The inner-region MSs, denoted as MS_i, operate in TDD mode using two subframes of band A or in FDD mode using band A and band B. Also, some inner-region MSs can act as mRSs, denoted as $MS_{i,RS}$. Thus, the transmission between $MS_{i,RS}$ and the BS also uses the TDD mode using band A. The outer-region MSs, denoted as MS_o, who transmit directly to the BS, operate in FDD mode using the first subframe of band A for DL and that of band B for UL. The transmissions between MS_o and $MS_{i,RS}$ use TDD via the two subframes of band B. The frame structure for the overlaid HDD system without RSs is given as in the brackets of Fig. 2. The DL transmission in band B should be changed to the transmission between the BS and MS_i. Therefore, the MSs in the inner region use TDD and FDD, and the MSs in the outer region use FDD. Thus, switching between TDD mode and FDD mode for users moving toward inner region is easily done by subchannel allocation without handover of two duplex modes.

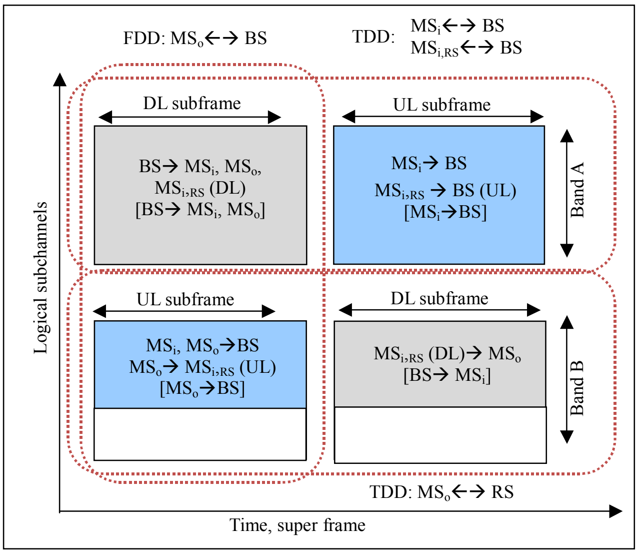

Fig. 2. Frame structure of overlaid HDD system.

2. RP Immunity against ICI

The proposed overlaid HDD system allows the inner-region MSs to relay the traffic of the outer region to enhance the throughput of the MSs on the cell border. However, TDD/FDD-OFDMA system has some disadvantages when transmitting simultaneously in the same band to multiple

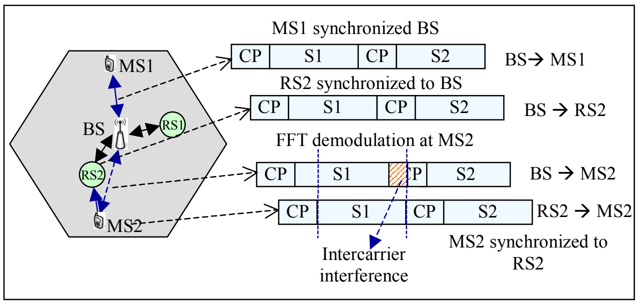

Fig. 3. OFDMA ICI with multiple sources and destination.

destinations, although it uses orthogonal subchannels. As shown in Fig. 3, the BS transmits to MS1 in the inner region and the RS2. MS1 and RS2 are synchronized to the signal received from the BS. When RS2 tries to relay the signal to MS2, the transmission timing is delayed compared to that of the BS and ICI may occur at MS2 due to the delayed transmission timing and the propagation delay difference. In the proposed overlaid HDD system with RP scheme, the MSs in the outer region do not suffer from such ICI because MSs in the inner and outer regions use different bands. From this perspective, the overlaid HDD system combined with RP is robust to the ICI problem compared to TDD/FDD-OFDMA systems using RSs.

IV. Simulation Results

In order to gain insights into the proposed overlaid HDD, simulations were conducted using 1,024-point FFT with 10 MHz for each of the bands A and B. The single-band TDD system uses 2,048-point FFT for 20 MHz, and the single-band FDD uses 1,024-point FFT for each 10 MHz in DL and UL. We consider a regular 5 km hexagonal cellular system with 19 cells, in which 100 MSs are distributed uniformly in each cell. The pathloss exponent is set to 4, and the ITU-R vehicular A channel model is used. The radius of the inner region is set as the half of cell radius, and we assume that if an MS transmits with full power from the cell edge, the average received SNR at the BS is 3 dB for the overlaid HDD and FDD. The transmit power of the BS is set in the same method as an MS. Note that the transmit power of the three systems are the same, so that the received SNR in TDD system is 3 dB less than FDD or the overlaid HDD system as mentioned earlier. The cyclic prefix (CP) of an OFDMA symbol is 1/8 of the symbol length. Also, the CP length of 1/12 is considered for the comparison. The frequency reuse factors of the inner and the outer regions are set to 1 and 3, respectively. For the multihop transmission, an MS in the outer region selects an MS in the inner region as an RS which gives twice higher rate than the direct transmission for UL and DL, independently.

The capacity of system k ($k \in \{HDD, FDD, TDD\}$) is

$$C_k = \sum_{l=1}^{L} \log_2(1 + SINR_{l,k}), \tag{1}$$

where L is the number of subcarriers used by each system, and $SINR_{l,k}$ is the signal-to-interference-plus-noise ratio (SINR) at the l-th subcarrier of system k which is given as

$$SINR_{l,k} = \frac{|h_{l,k}|^2 P_{tx,k} / d_k^{\alpha}}{\sum_{i=1}^{I} |h_{i,l,k}|^2 P_{tx,i,k} / d_{i,k}^{\alpha} + \sigma^2}, \tag{2}$$

where $P_{tx,k}$ is the transmitted signal power of system k; $h_{l,k}$ is the fading channel gain at the l-th subcarrier of system k; d_k is the distance between the transmitter and the receiver of system k; α is the pathloss exponent; I is the the total number of interferers; $P_{tx,i,k}$ is the transmitted signal power of i-th interferer of system k; $h_{i,l,k}$ is the fading channel gain at the l-th subcarrier of i-th interferer of system k; $d_{i,k}$ is the distance between the i-th interferer and the receiver of system k; and σ^2 is the noise variance at the receiver. On the other hand, the capacity of each system using RSs is given as

$$C_k^R = \sum_{l=1}^{L} \frac{1}{2} \log_2(1 + \min(SINR_{l,k,1}, SINR_{l,k,2}), \tag{3}$$

where $SINR_{l,k,1}$ is the SINR at the l-th subcarrier of an RS of system k and $SINR_{l,k,2}$ is the SINR at the l-th subcarrier of the destination of system k, respectively given as

$$SINR_{l,k,1} = \frac{|h_{l,k,1}|^2 P_{tx,k,1} / d_{k,1}^{\alpha}}{\sum_{i=1}^{I} |h_{i,l,k,1}|^2 P_{tx,i,k,1} / d_{i,k,1}^{\alpha} + \sigma^2}, \tag{4}$$

$$SINR_{l,k,2} = \frac{|h_{l,k,2}|^2 P_{tx,k,2} / d_{k,2}^{\alpha}}{\sum_{i=1}^{I} |h_{i,l,k,2}|^2 P_{tx,i,k,2} / d_{i,k,2}^{\alpha} + \sigma^2}, \tag{5}$$

where $P_{tx,k,1}$ and $P_{tx,k,2}$ are the transmitted signal power of the the system k's transmitter and its RS, respectively; $h_{l,k,1}$ and $h_{l,k,2}$ are the fading channel gains at the l-th subcarrier of the system k's RS and its destination, respectively; $d_{k,1}$ is the distance between the system k's transmitter and its RS; $d_{k,2}$ is the distance between the system k's RS and its destination; $P_{tx,i,k,1}$ and $P_{tx,i,k,2}$ are the transmitted signal power of the system k's i-th interferer for the RS and the destination, repectively; $h_{i,l,k,1}$ and $h_{i,l,k,2}$ are the fading channel gains at the l-th subcarrier of the i-th interferer of the RS and the destination, respectively; $d_{i,k,1}$ is the distance between the system k's i-th interferer and the RS; and $d_{i,k,2}$ is the distance between the system k's i-th interferer and the destination. Note that the capacity evaluation using (1) and (3) is not appropriate to predict the exact throughput using practical modulation and coding. However, it is sufficient to compare different systems, which is the main focus of this

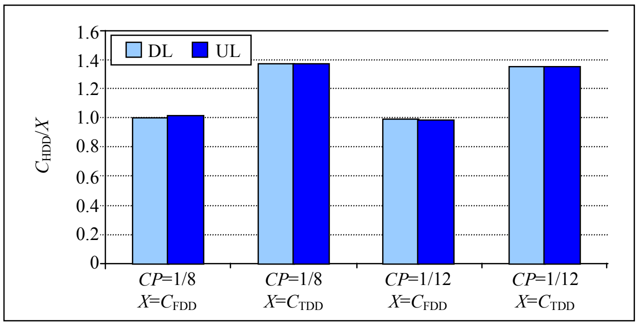

Fig. 4. Ratio between C_{HDD} and C_{FDD} (or C_{TDD}).

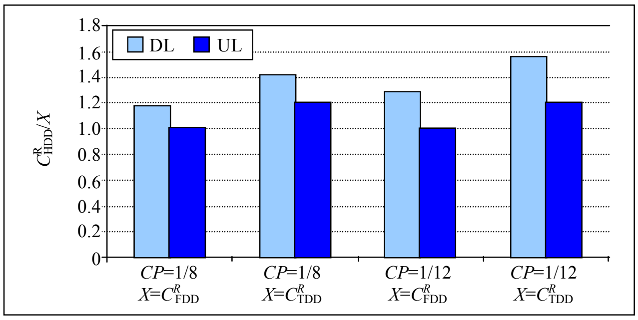

Fig. 5. Ratio between C^R_{HDD} and C^R_{FDD} (or C^R_{TDD}).

letter. To show the advantages of the proposed system, we compare the overlaid HDD system with the TDD/FDD-OFDMA system in two different situations: when RSs are adopted and when they are not.

The y-axis of Fig. 4 shows the ratio between the sum capacity (bits per second) of users in the outer region of the overlaid HDD system (C_{HDD}) and that of TDD/FDD-OFDMA system (C_{TDD} or C_{FDD}) when RSs are not adopted with different CP length. C_{HDD}, C_{TDD}, and C_{FDD} are the sum of Shannon capacity of each system. As shown in Fig. 4, the proposed system has 37% performance gain against a TDD system which originates from the 3 dB power-gain advantage of FDD, while exploiting the DL/UL asymmetry advantage of TDD.

The y-axis of Fig. 5 shows the ratio between the data rate of the outer region of the overlaid HDD system with RSs and those of FDD and TDD. As shown in Fig. 5, the data rate of the overlaid HDD with RSs respectively has 55% and 19% gain for DL and UL transmissions in the outer region compared to that of TDD-OFDMA system with RSs when the CP length is 1/12 of an OFDMA symbol. The improvement from the overlaid HDD compared to the conventional TDD or FDD system with multihop is less significant in UL because all MSs are synchronized to their destinations, and the ICI caused by the propagation delay difference exceeding the CP length is well attenuated. However, during DL, the transmission timings of the BS and RSs are different, which causes the received signal timing difference to be greater than the CP length in some MSs without sufficient attenuation.

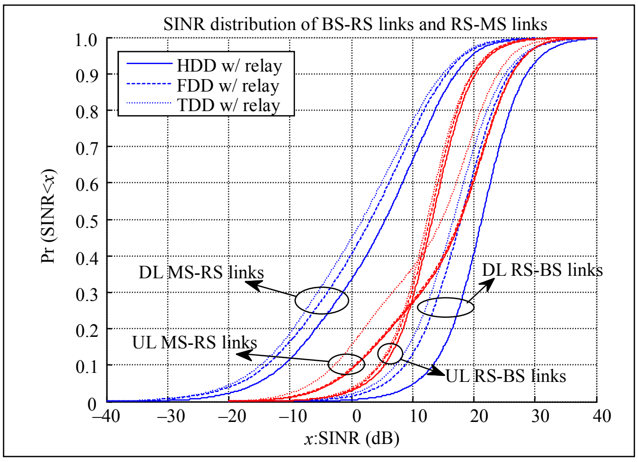

Fig. 6. SINR distribution of proposed, FDD, and TDD systems.

Figure 6 shows the SINR distribution at the BS and an RS of the proposed, TDD, and FDD systems when the CP length is 1/12 of an OFDMA symbol. As shown in Fig. 6, the SINR at the BS and an RS of the overlaid HDD system with RSs gives higher SINR distribution compared to those of FDD and TDD systems especially in the case of DL due to reason mentioned in the result of Fig. 5.

V. Conclusion

In this letter, an overlaid HDD cellular system was proposed to utilize the benefits of both TDD and FDD. A frame structure for the overlaid HDD system using RP was also proposed. It was shown that the overlaid HDD system can exploit the power gain of FDD with the DL/UL asymmetry of TDD. Moreover, the proposed system can also solve the synchronization issue in multihop for OFDMA systems. Therefore, the overlaid HDD can be considered as a promising duplexing scheme for future cellular communication systems.

References

[1] S.-B. Yun, S.-Y. Park, and Y.-W. Lee, "Hybrid Division Duplex System for Next-Generation Cellular Services," *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, 2007, pp. 3040-3059.

[2] IEEE 802.16j-06/026r4, *Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems - Multihop Relay Specification*, June 2007.

[3] B. Can et al., "Implementation Issues for OFDM-Based Multihop Cellular Networks," *IEEE Commun. Mag.*, vol. 45, no. 9, 2007, pp. 74-81.

[4] J. Zander and S.-L. Kim, *Radio Resource Management in Wireless Networks*, Artech House, Mar. 2001.

[5] E. Costa et al., "Duplex Arrangements for Future Broadband Radio Interfaces," *IST-2003-507581 WINNER D2.5 v1.0*, Oct. 2004.