

Dynamic Hybrid Duplex for Rate Maximization in OFDMA

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Abstract

Orthogonal frequency division multiple access (OFDMA) is considered as one of the technologies for 4th generation (4G) due to its robustness against multi-path environment. OFDMA also has the advantage of flexibility in resource allocation, which cannot be supported by existing duplex schemes. In this paper, we propose dynamic hybrid duplex (DHD) which will enhance the efficiency and flexibility of the OFDMA system. To establish the framework of resource allocation for the DHD, we formulate DHD resource allocation problem (DRAP) which maximizes the total users' data rate under power, rate, and subcarrier allocation constraints. A heuristic algorithm is developed to solve the problem. The algorithm finds the best mode and the best amount of resources allocated to downlink and uplink. Simulation is performed with five scenarios to evaluate the DHD. Its results show that the proposed DHD outperforms other duplex schemes in various environments.

Keywords

OFDMA, hybrid duplex, dynamic resource allocation, flexible resource allocation

1. Introduction

After the successful development of 2nd generation wireless cellular communication systems, researchers have studied 3rd generation communication for many years. Recently, the focus of the technology is moving forward to beyond 3rd generation or 4G.

4G has many requirements and challenges: high data rate, handoff, quality of service, low cost, traffic asymmetry and so on [1]. Among these, one noticeable requirement is very high data rate over a wireless channel environment. To satisfy this requirement, 4G is expected to use broadband [1], which may be vulnerable in a wireless environment. Multi-path fading generates frequency selective fading and inter-symbol interference (ISI). Frequency selective fading makes specific frequency undergo deep fading, which decreases efficiency of the system. ISI limits symbol rate and reduces throughput.

Among various multiple access technologies, orthogonal frequency division multiple access (OFDMA) is regarded as a good candidate technology because OFDMA is robust against multi-path environment [2]. Its narrow-band subcarrier overcomes frequency selective fading and the insertion of guard interval reduces the effect of ISI.

In addition to robustness against multi-path effect, OFDMA systems have the advantage of flexibility in resource allocation. In OFDMA, controllable resources are subcarriers, symbols and power, and they can be allocated very freely to users compared to other systems. However, despite its flexibility, OFDMA cannot be properly supported by existing duplex schemes.

In this paper, we propose dynamic hybrid duplex (DHD) to enhance the flexibility and efficiency of OFDMA for data transmission. It is a cross layer approach that considers the user's traffic and channel status to allocate resources and select a proper duplex mode. Two solid duplex schemes, frequency division duplex (FDD) and time division duplex (TDD) [2, 3], are widely implemented in many communication systems. However, FDD has the problem of inefficiency in supporting asymmetric downlink (DL) and uplink (UP) traffic due to its fixed bandwidth allocation. TDD is spotlighted because of its free slot allocation by which TDD system can be adapted to traffic asymmetry. However, TDD uses all subcarriers during a given time period. Thus, even bad channels are allocated to increase throughput. DHD is expected to overcome the inefficiency of the two duplex schemes by flexibly allocating resources and properly selecting the right mode.

Many research results are available for resource allocation in OFDMA systems [4 – 15]. In OFDMA, the channel status of each user on one subcarrier can be different. Thus, the system efficiency can be increased by allocating a subcarrier to the user with good channel status. It is the concept of multiuser diversity which is an important issue of resource allocation in OFDMA systems. Many existing studies are based on multiuser diversity [4 - 15]. They can be categorized according to its objectives: power minimization or rate maximization. In power minimization, total transmission power is minimized under rate constraints [4, 6 - 8]. In rate maximization, minimum of the user's data rate or the total users' rate is maximized under power constraint [5, 7, 9, 11 - 15]. Especially, when the total users' rate is maximized in DL, optimal allocation can be obtained by a two-step algorithm: the first step is subcarrier assignment employing 'best user selection' and the second step is power allocation employing 'water-filling method,' where 'best user selection' means that for a subcarrier only a single user who has the best channel gain is selected [9, 11]. For the UL case, a two-step heuristic is suggested by employing 'marginal user selection' with which a subcarrier is allocated to

the user who has maximal marginal rate [11], and Nash bargaining solution is considered [13].

Previous research on OFDMA can also be classified according to the DL and/or UL. Most of them consider only DL [5, 7 - 9, 12, 15]. Pietrzyk and Janssen [6] and Kim et al. [11] consider both DL and UL. However, they do not consider how to distribute total resources to DL and UL. In this paper, we primarily scope how to distribute resources to DL and UL in OFDMA systems.

With the suggestion of the DHD, we formulate resource allocation problem in OFDMA/DHD mathematically. The problem is to maximize the total users' data rate under power and rate constraints and the restriction of allocating a subcarrier to one DL (or UL) user. We propose a heuristic to solve the problem efficiently. The heuristic is an iterative search algorithm which finds the best mode and the best amount of resources to DL and UL.

The remainder of this paper is organized as follows. In Section 2, we propose DHD and discuss its system requirements and advantages. In Section 3, we model and formulate resource allocation in OFDMA/DHD. In Section 4, we suggest an iterative search algorithm to solve the DHD resource allocation problem (DRAP). Simulation results are shown in Section 5 with conclusion in Section 6.

2. Dynamic Hybrid Duplex in OFDMA

In OFDMA, subcarriers, symbols, and power are controllable resources. To allocate the resources flexibly to DL and UL users, we propose dynamic hybrid duplex (DHD). Features, system requirements, and advantages of DHD are discussed in this section.

2.1 Features of Dynamic Hybrid Duplex

DHD has the following three features as discussed below: (1) changeable duplex mode, (2) flexible resource allocation, and (3) use of user information.

(1) Changeable duplex mode

DHD has three modes for duplex: FDD, reversed FDD (rFDD), and TDD mode. Reversed FDD mode is the case where the frequency bands for DL and UL are alternated compared to FDD mode. In a cellular system, DL normally employs higher frequency band than UL. Therefore, we regard this normal situation as FDD mode. Figure 1 shows three modes of DHD. DHD can change the mode every frame.

(2) Flexible resource allocation

Traditionally, TDD employs flexible slot allocation while FDD employs fixed frequency band allocation. However, in DHD, flexibility is also given to FDD and

rFDD mode. Bandwidth can be flexibly partitioned to DL and UL depending on the system parameters or the channel status. We can show that bandwidth allocation for DL and UL of the FDD (or rFDD) mode are changing per frame in Figure 1.

(3) Use of user information

DHD takes into account users' data traffic and channel status information. Based on the information, DHD selects the mode to employ at each frame. It also decides the required DL and UL bandwidths for FDD (or rFDD) mode and the time periods for TDD mode to maximize system performance by reflecting the user information.

2.2 System Requirement

First, to apply DHD, the transmitters and receivers of base stations (BSs) and mobile stations (MSs) have to be equipped with the capability to change corresponding frequency bands in real time. In OFDMA, it can be implemented by the change of the number of allocated subcarriers. However, this implementation cannot be provided easily in normal OFDMA, since the inverse fast Fourier transform (IFFT) and the fast Fourier transform (FFT), which are the core parts of the OFDMA system, require that the number of allocated subcarriers should be the integer power of two. To deal with this problem, we modify the OFDMA system such that the number of inputs to the IFFT (or the FFT) is the integer power of two even though the number of allocated subcarriers is not. To do that, we use total frequency band for the IFFT (or the FFT) and allocate zero power to the unavailable subcarriers. For example, as for FDD mode in a BS, data for DL and zeros for UL are inputs of IFFT and zeros for DL and data for UL are outputs of FFT. Refer to [16] for more details about IFFT and FFT.

Second, DHD requires the capability to change the mode in real time. Note that FDD and rFDD modes are easily implemented by total frequency band usage and aforementioned zero adding technique, since allocated frequency bands of rFDD mode are simply alternated as compared to FDD mode. However, in the case of TDD mode, time periods for DL and UL are separated and timing control is needed to implement the mode. To support the three modes efficiently, we add a system controller to the system as shown in Figure 2. The system controller realizes the change of mode in the system by controlling both subcarrier allocation and its allocation timing. Note that there is no delay in switching the mode in our approach. The only overhead is control signals for allocation and timing.

The third problem is how to obtain users' channel information. In OFDMA, channel estimation is necessary to obtain the channel gain for various purposes. For example, the gain is used for resource allocation in medium access control (MAC) layer and for

transmission power control in physical layer. When TDD is employed as a duplex scheme in a normal OFDM system, channel information can be easily obtained by reciprocity [16]. To obtain channel information, a MS receives a signal from a BS and estimates the channel status. This estimation can be applied to the system directly since the same frequency band is employed for DL and UL. On the other hand, when FDD is employed, channel information should be feedbacked by means of other link, since the frequency bands for DL and UL are different. Channel information can also be obtained by estimating channel transfer function via pilot tone [16]. However, the above-mentioned channel estimation schemes cannot be directly applied to DHD due to the changeable mode. One way to deal with this is to change channel estimation according to the selected mode. Further research for this third problem will help better implementation of DHD, but is not in the scope of this paper.

The last problem is related to the high complexity of DHD. Obviously DHD increases the system complexity, since it considers three modes and each with different resource allocation. To analyze the complexity theoretically, suppose that a frame has S subcarriers and T symbols with a suitable resource allocation algorithm for FDD. For simplicity, we assume a complexity measure as the number of times the algorithm is applied to find optimal resource allocation. Then, the complexity of TDD becomes $O(T)$, when an exhaustive search is considered using the FDD algorithm as a sub-function. This is because the number of combinations to allocate symbols to DL and UL is $T+1$. Similarly, the complexity of DHD becomes $O(T+2S)$. Since the complexity of DHD is dependent on the number of subcarriers in a frame, real-time implementation of DHD may be limited. However, note that the complexity increase is linear to the number of subcarriers. Thus, we expect that the development of an efficient resource allocation algorithm for DHD together with a fast calculation device will overcome the high complexity problem of DHD.

2.3 Advantages

Advantages of DHD include flexibility, adaptability and efficiency. As explained in previous sections, DHD can freely change the mode and the amount of resources for DL and UL. Thus, traffic asymmetry can be solved easily by the flexibility of DHD.

DHD also provides optimized duplexing which is adapted to the given physical layer. Given the numbers of subcarriers and symbols in a frame and other parameters such as the size of the guard band, DHD can adaptively support proper duplexing in the OFDMA system.

The most important advantage of DHD is channel efficiency. DHD can efficiently

allocate subcarriers with high channel gain to proper DL and UL users. Figure 3 shows the efficiency of DHD over FDD and TDD. In the figure, dotted and solid lines respectively represent the cases of subcarrier allocation to users with low and high channel gains. Clearly, the channel gain of each user is increased by using DHD. DHD applies rFDD mode in Figure 3(a) and FDD mode in Figure 3(b). When the channel gains of the four users are the same as in Figure 3(c), DHD/TDD mode presents higher channel performance than DHD/FDD. Obviously, the channel status of a real wireless environment may be more complex. However, even in the case, DHD can have more opportunities to increase system performance by flexibly allocating subcarriers with high channel gain to proper DL and UL users.

3. Resource Allocation in OFDMA/DHD

In this section, we model the OFDMA system. Then, resource allocation problem in DHD is considered.

3.1 OFDMA System Modeling

We consider a multi-user OFDMA system in a cell. Figure 2 shows the main functions of a BS in the system. In the figure, the system controller receives user's channel and traffic information as inputs, then allocates resources to DL and UL users. We are interested in resource allocation to maximize system performance in OFDMA.

The OFDMA system we consider has a frame structure which consists of S subcarriers and T symbols as shown in Figure 4. k_{down} DL users and k_{up} UL users are assumed in the system and $K = \{1, 2, \dots, k_d, k_d + 1, \dots, k_d + k_u\}$ is the set of DL and UL user indices. For simplicity, we assume that a user can request either a DL service or a UL service in a frame. Each user has a rate requirement as in the set of rate requirements $\Theta = \{\theta_1, \theta_2, \dots, \theta_{k_d}, \theta_{k_d+1}, \dots, \theta_{k_d+k_u}\}$.

In each mode, DHD allocates resources differently. Subcarriers are allocated to DL and UL in FDD (or rFDD) mode and symbols are allocated in TDD mode. To prevent interference between DL and UL, the guard band is considered with s_g subcarriers for FDD (or rFDD) mode and the guard interval with t_g symbols for TDD mode.

Note that though the resources are differently allocated according to the mode, the resource allocation to DL and UL can be represented irrespective of the mode. To formalize this, we define resource allocation vector as $A = \{s_{d1}, s_{d2}, t_d, s_{u1}, s_{u2}, t_u\}$,

where s_{d1} and s_{d2} are the first and the last indices of subcarriers allocated to DL, s_{u1} and s_{u2} are those to UL, and t_d and t_u are the numbers of allocated symbols to DL and UL. The equations in Figure 4 are constraints the variables should satisfy in each mode.

By assuming perfect channel estimation, the average channel gain for subcarrier i allocated to user j , g_{ij} , can be known. With the gain, the signal to noise ratio (SNR) of user j with subcarrier i is obtained as $g_{ij}p_{ij}$, where p_{ij} is the allocated power to user j with subcarrier i for one symbol period. From the SNR, the achievable data rate c_{ij} of user j with subcarrier i during one symbol period can be obtained by the Shannon capacity formula as follows:

$$c_{ij} = \log_2(1 + g_{ij}p_{ij}) .$$

Note that the total available transmission power is limited in a BS (or a MS). To represent this, we define $\Pi = \{\pi_0, \pi_1, \pi_2, \dots, \pi_{k_u}\}$, where π_0 and π_j are the total maximal transmission power of a BS and UL user $j + k_d$, respectively. The above explained terms are summarized in Table 1.

3.2 Formulation of Resource Allocation Problem

In each frame of DHD, we need to decide the mode and the amount of resources to DL and UL. To deal with this, we formulate the resource allocation problem for DHD. The problem we consider is to maximize the total users' data rate with power and rate constraints and the restriction of allocating a subcarrier to one DL (or UL) user, considering users' channel condition, traffic information, and system parameters.

Although our scope is restricted to the mode and the amount of resources to DL and UL, resource distribution to each user should be considered to calculate the total users' rate. Thus, we consider 'resource allocation' for the mode and the amount of resources to DL and UL and 'user-level distribution' for distribution to each user.

First, for user-level distribution, we introduce the subcarrier assignment indicator, x_{ij} , which is defined as

$$x_{ij} = \begin{cases} 1, & \text{if subcarrier } i \text{ is allocated to user } j \\ 0, & \text{otherwise} \end{cases} ,$$

and assume the allocation vector $A = \{s_{d1}, s_{d2}, t_d, s_{u1}, s_{u2}, t_u\}$ is given.

Then, power constraints are expressed as in Equation (1) and (2). DL transmission is limited by total transmission power π_0 of a BS and UL transmission is limited by π_j of MS $j + k_d$.

$$\sum_{i=s_{d1}}^{s_{d2}} \sum_{j=1}^{k_d} t_d p_{ij} \leq \pi_0 \quad (1)$$

$$\sum_{i=s_{u1}}^{s_{u2}} t_u p_{ij} \leq \pi_{j-k_d} \text{ for } j = k_d + 1, k_d + 2, \dots, k_d + k_u \quad (2)$$

Another constraint in resource allocation is rate constraint. By using the achievable data rate, c_{ij} , which is defined in the previous section, the rate constraints for DL and UL are expressed as follows.

$$\sum_{i=s_{d1}}^{s_{d2}} t_d x_{ij} \log(1 + g_{ij} p_{ij}) \geq \theta_j \text{ for } j = 1, 2, \dots, k_d \quad (3)$$

$$\sum_{i=s_{u1}}^{s_{u2}} t_u x_{ij} \log(1 + g_{ij} p_{ij}) \geq \theta_j \text{ for } j = k_d + 1, k_d + 2, \dots, k_d + k_u \quad (4)$$

Now, each DL (or UL) subcarrier has to be assigned to exactly one DL (or UL) user. This subcarrier assignment constraint can be expressed as

$$\sum_{j=1}^{k_d} x_{ij} \leq 1 \text{ for } i = s_{d1}, \dots, s_{d2} \quad (5)$$

$$\sum_{j=k_d+1}^{k_d+k_u} x_{ij} \leq 1 \text{ for } i = s_{u1}, \dots, s_{u2} \quad (6)$$

$$x_{ij} = 0 \text{ for } i < s_{d1}, i > s_{d2} \text{ and } j = 1, 2, \dots, k_d \quad (7)$$

$$x_{ij} = 0 \text{ for } i < s_{u1}, i > s_{u2} \text{ and } j = k_d + 1, k_d + 2, \dots, k_d + k_u \quad (8)$$

Recall that we have assumed the resource allocation vector A is given to derive user-level distribution that satisfies the above constraints. Thus, we introduce a function,

$\Omega_{\Pi, \Theta}(A)$, which returns the set of all possible user-level distribution with A under power constraint Π and rate requirement Θ . It can be expressed as follows.

$$\Omega_{\Pi, \Theta}(A) = \{(X, P) \mid (1) \sim (8)\} \quad (9)$$

Here, X and P are the matrices for x_{ij} and p_{ij} , respectively.

Finally, the total data rate is defined with the following objective function

$$f(A, X, P) = \sum_{i=s_{d1}}^{s_{d2}} \sum_{j=1}^{k_d} t_d x_{ij} \log(1 + g_{ij} p_{ij}) + \sum_{i=s_{u1}}^{s_{u2}} \sum_{j=k_d+1}^{k_d+k_d} t_u x_{ij} \log(1 + g_{ij} p_{ij}) \quad (10)$$

and the formulation of DHD resource allocation problem (DRAP) results as follows.

$$\begin{aligned} & \max_{A, X, P} f(A, X, P) \\ & \text{s.t. } (X, P) \in \Omega_{\Pi, \Theta}(A) \end{aligned} \quad (11)$$

4. Heuristic Algorithm for DRAP

DRAP, which is a nonlinear problem, is hard to solve even if the mode and the amount of resources allocated to DL and UL are fixed. Thus, we propose a heuristic algorithm which can solve DRAP effectively. We first suggest a simple greedy heuristic to deal with user-level distribution, then provide an overall algorithm which use the user-level distribution heuristic as a sub-function.

4.1 User-Level Distribution

In our algorithm, user-level distribution for DL and UL is necessary to calculate the total data rate, when the mode and the amount of resources allocated to DL and UL are given. Recall that user-level distribution deals with how to allocate subcarriers and power to users under power, rate and subcarrier assignment constraints. We assume users are accepted by an appropriate call admission control such that resources are sufficient to serve all accepted users.

Our basic idea for the heuristic is to allocate a subcarrier to a user iteratively such that the rate requirement of each user is satisfied as much as possible. First, the candidate subcarrier is decided for each user. For that purpose, we suggest a modified water-filling procedure based on [9]. In the procedure, a temporary set is employed for each non-allocated subcarrier and water-filling is applied to the set to calculate the corresponding user rate. In the case of an UL user, the temporary set is made by adding a non-allocated

subcarrier to the subcarriers already allocated to the user. Water-filling is applied with the maximal transmission power of the user. For a DL user, however, since all DL users share the available power of a BS, the temporary set is made by adding a non-allocated subcarrier to all subcarriers allocated to DL users. The power for water-filling is the maximal transmission power of a BS. By selecting a subcarrier with the maximal rate among all non-allocated subcarriers, the candidate subcarrier of a user is obtained. After the selection of the candidate subcarrier, we select a user to assign the subcarrier. If there exist users whose rate requirements are not satisfied, the user with the maximal gap between the requirement and the currently allocated rate is selected. Otherwise, the user whose rate increase is maximized with the additional subcarrier is selected. The procedure is terminated when all subcarriers are assigned to users. Figure 5 shows the flow chart of the procedure.

4.2 Overall Algorithm

Our algorithm is an iterative search procedure which selects the best mode and the best resource allocation vector to maximize the total data rate of all users. For that purpose, the algorithm changes the amount of resources allocated to DL and UL in each mode and calculates the objective value with the heuristic in Section 4.1. By comparing the result of each mode, the best mode and the best resource allocation vector are obtained.

In each mode of the search, initial resource allocation vector A_{init} is obtained by allocating subcarriers in FDD (or rFDD) mode and symbols in TDD mode. To maximize the total data rate that satisfies power constraints (1) and (2) in Section 3.2, we need to balance the power efficiencies of DL and UL. Thus, in the initial solution, total subcarriers (or symbols) are allocated to DL and UL in proportion to the sum of SNR values of corresponding users. Note that the allocated power p_{ij} should be calculated to obtain the SNR, which is defined in Section 3.1. To solve this problem, the average channel gain over all subcarriers and the equally distributed power are calculated, then the SNR value of each user is estimated by multiplying the two calculated values.

The initial vector A_{init} is sequentially updated to increase the total data rate. On each update, a subcarrier (or symbol) is removed from UL and added to DL or vice versa. Two different vectors which reflect the two cases are generated, then compared by the user-level distribution heuristic. The vector with a higher total rate is determined. This hill-climbing update procedure is continued until a better resource allocation vector cannot be found. Figure 6 shows the pseudo-code of FDD mode. In the pseudo-code,

A_{init} is obtained by estimating the value of s_{u2} with s_{FDD}^* given below.

$$s_{FDD}^* = \frac{\sum_{j=k_d+1}^{k_d+k_u} \pi_j \bar{g}_j}{\frac{\pi_0}{k_d} \sum_{j=1}^{k_d} \bar{g}_j + \sum_{j=k_d+1}^{k_d+k_u} \pi_j \bar{g}_j}$$

\bar{g}_j in the equation is the average channel gain of user j over all subcarriers. In

Figure 6, $u_{\Pi, \Theta}(A)$ is a function of resource allocation vector A and returns the total rate obtained by the user-level distribution heuristic. $A|_{a \leftarrow b}$ represents the resource allocation vector which reflects that a variable a is b . Similarly to the pseudo-code of FDD mode, those of rFDD and TDD modes are obtained. In rFDD (or TDD), s_{u2} is changed to s_{d2} (or t_d) with s_{rFDD}^* (or t_{TDD}^*) given below.

$$s_{rFDD}^* = t_{TDD}^* = \frac{\frac{\pi_0}{k_d} \sum_{j=1}^{k_d} \bar{g}_j}{\frac{\pi_0}{k_d} \sum_{j=1}^{k_d} \bar{g}_j + \sum_{j=k_d+1}^{k_d+k_u} \pi_j \bar{g}_j}$$

5. Simulation

In this section, we perform simulations for various environments to compare DHD with other duplex schemes. We consider the OFDMA system in which a frame has 256 subcarriers and 20 symbols over 2GHz. The guard band (or guard interval) is fixed to 10% of the total number of subcarriers (or symbols). In order to consider frequency selective fading environment, we employ a 6-ray Rayleigh fading model. The default power of a BS and a MS are 1W and 200mW, respectively.

The performance of DHD is evaluated by considering five different scenarios as shown in Table 2. Scenarios 1 and 2 consider different power settings of a BS and MSs. Scenarios 3 and 4 deal with various rate requirements of DL and UL users. Scenario 5 is considered to examine the effect of guard band ratio, which is the ratio of the number of subcarriers for the guard band to the total number of subcarriers.

In the simulation, we compare DHD with TDD and FDD. The performance measure is the total data rate by UL and DL users. 20 simulations are performed in each scenario

and the average is plotted in the figures.

Figures 7 and 8 show results of scenarios 1 and 2, respectively. In each figure, DHD gives a better performance than TDD and FDD in all cases. This is because DHD efficiently selects the optimized mode and allocates the optimized resources according to the available power. In FDD, resource allocation cannot be adapted to the change of available power due to its fixed bandwidth. TDD supports more efficient resource allocation than FDD. However, its inefficiency is due to the constraint in which all subcarriers should be allocated to DL (or UL).

The results of scenarios 3 and 4 are shown in Figures 9 and 10, respectively. Again, DHD outperforms other duplex schemes. It can be interpreted that DHD supports efficient resource allocation irrespective of various rate requirements by changing its mode and allocating resources dynamically. Note that the total data rate of each duplex scheme is slightly increasing with the lower rate requirement in Figure 9, which is in contrast with the result of Figure 10. The decrease of rate requirement means the increase of opportunities to enhance system performance. Thus, the result illustrates that the user-level distribution is much more affected by DL rate requirement than by UL rate requirement irrespective of the duplex method. This is because DL users share the BS power and have more opportunities to increase the total rate than UL users.

Figure 11, which is the result of scenario 5, shows that DHD can be adapted to various physical parameter settings. In the figure, the total rate of TDD is not changing, since TDD is affected not by the guard band but by the guard interval. On the other hand, the total rate of FDD decreases with the increase of the guard band ratio. DHD is also affected by the increase of the guard band. However, even in the case, DHD demonstrates efficient resource allocation compared to other duplex schemes.

Finally, the complexity and the total rate of the proposed DHD are compared with other duplex schemes. The resource allocation for each duplex scheme is calculated by the user-level distribution algorithm suggested in Section 4.1. The number of run times of the user-level distribution algorithm is considered as the complexity measure. Exhaustive search which considers all possible resource allocation combinations is also compared. Figure 12 shows the results of FDD, TDD, DHD and exhaustive search. As shown in the figure, the complexity of DHD is not serious considering the throughput increase. The throughput gain of DHD over FDD and TDD well mitigates its complexity. However, the cost of the exhaustive search is too expensive to apply. From the results, we conclude that DHD with the proposed algorithm enhances the system performance with a reasonable complexity.

6. Conclusion

In this paper, a new duplex scheme, DHD, is proposed, which changes the mode and the amount of allocated resources dynamically according to the traffic situation and user's channel status. System requirements to implement DHD are discussed with the advantages of flexibility, adaptability and efficiency. Especially, efficiency is a noticeable advantage which can enhance system performance according to the given channel environment. To allocate resources in DHD, the OFDMA system is modeled and DHD resource allocation problem (DRAP) is formulated which maximizes total data rate with power, rate and subcarrier assignment constraints. An effective iterative search algorithm is suggested to solve the DRAP. The algorithm initially allocates resource to DL and UL in proportion to the sum of SNR values, then searches for the best resource allocation vector by changing the amount of resources allocated to DL and UL.

The proposed duplex scheme, DHD, is simulated in various environments and compared with other duplex schemes. In the five different scenarios, DHD always outperforms FDD and TDD. DHD efficiently increases its system performance in various settings by adapting its mode and allocating its resource dynamically.

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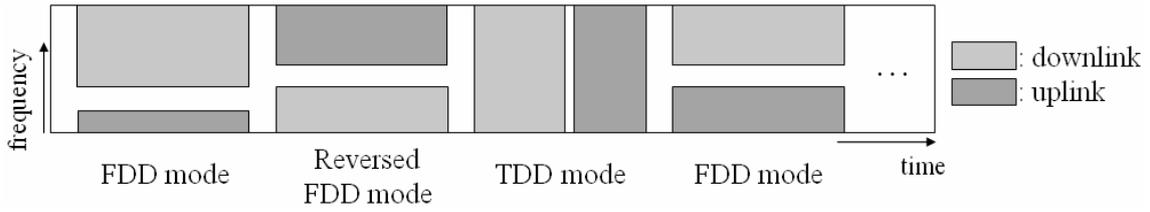


Figure 1. Three modes of DHD: FDD, reversed FDD, and TDD

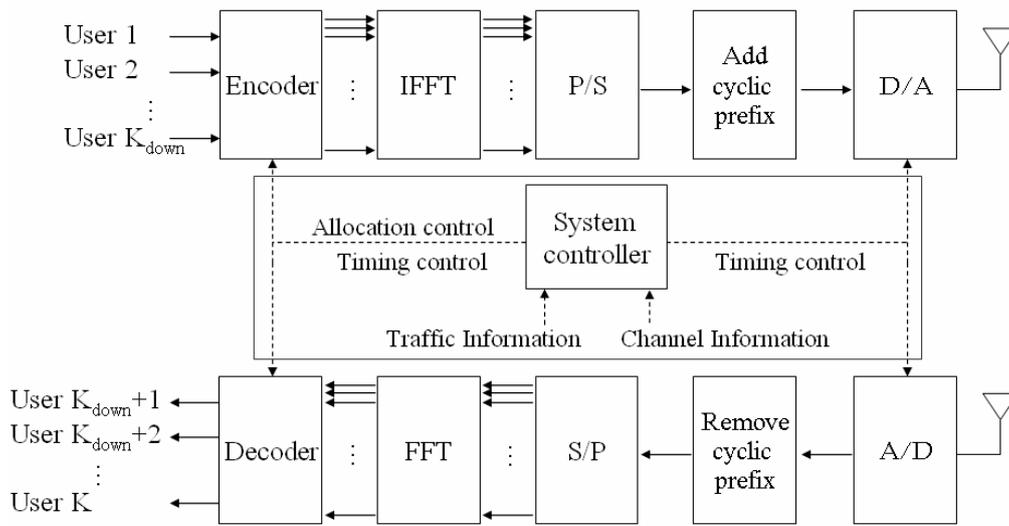


Figure 2. The base station block diagram

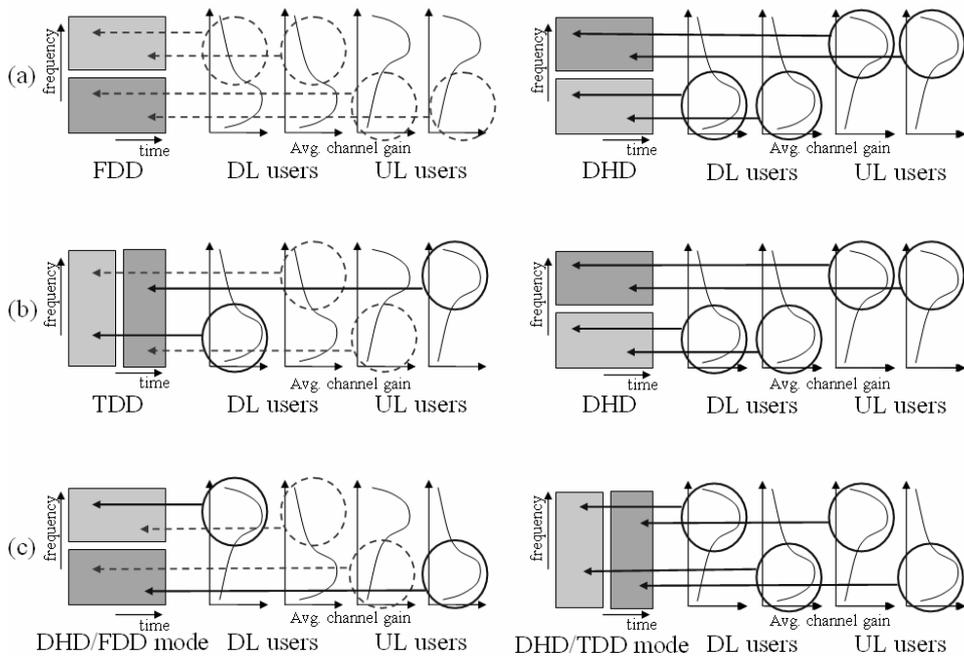


Figure 3. Efficiency of DHD with higher channel gain

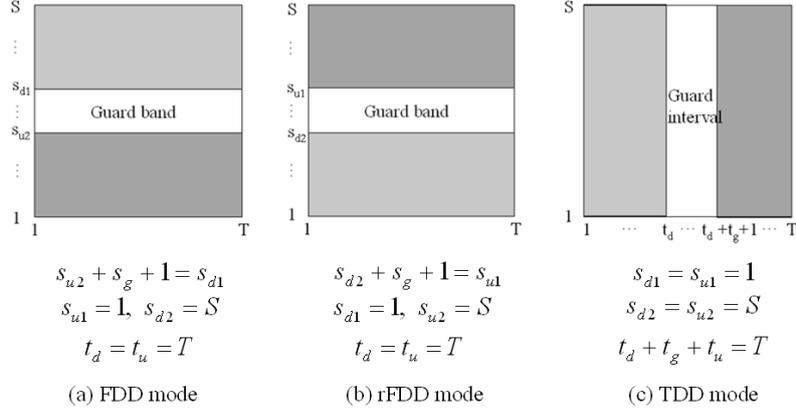


Figure 4. Frame structure description for (a) FDD, (b) rFDD and (c) TDD mode

S	the number of subcarriers
T	the number of symbols during one frame
s_g	the number of subcarriers of which the guard band consists
t_g	the number of symbols of which the guard interval consists
K	the set of DL and UL user indices ($= \{1, 2, \dots, k_d, k_d + 1, \dots, k_d + k_u\}$)
Θ	the set of required rates for DL and UL users ($= \{\theta_1, \theta_2, \dots, \theta_{k_d}, \theta_{k_d+1}, \dots, \theta_{k_d+k_u}\}$)
A	the resource allocation vector ($= \{s_{d1}, s_{d2}, t_d, s_{u1}, s_{u2}, t_u\}$), where s_{d1} and s_{d2} (s_{u1} and s_{u2}) are the first and the last indices of subcarriers allocated to DL (UL), and t_d and t_u are the numbers of allocated symbols to DL and UL.
g_{ij}	the average channel gain of user j with subcarrier i
p_{ij}	the allocated power to user j with subcarrier i for one symbol period. Its matrix is P .
c_{ij}	the achievable data rate of user j with subcarrier i
Π	the set of total transmission power ($= \{\pi_0, \pi_1, \pi_2, \dots, \pi_{k_u}\}$), where π_0 and π_j are the total maximal transmission power of a BS and UL user $j + k_d$
x_{ij}	the indicator variable of allocating subcarrier i to user j . Its matrix is X .

Table 1. Summary of the used terms

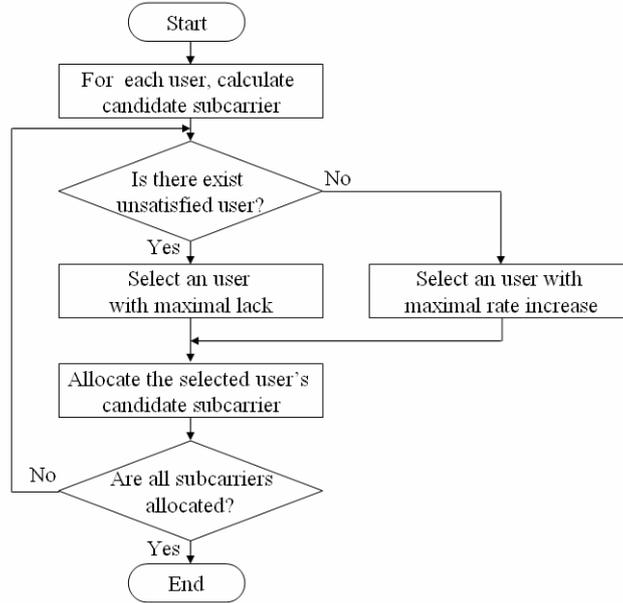


Figure 5. The flow chart of user-level distribution heuristic

Step 1: *initialize*
 estimate s_{FDD}^*
 calculate $temp \leftarrow u_{\Pi, \Theta}(A|_{s_{u_2} \leftarrow s_{FDD}^*})$

Step 2: *select direction*
 if $u_{\Pi, \Theta}(A|_{s_{u_2} \leftarrow s_{FDD}^* + 1}) > u_{\Pi, \Theta}(A|_{s_{u_2} \leftarrow s_{FDD}^* - 1})$
 then $w \leftarrow 1$,
 else $w \leftarrow -1$

Step 3: *allocation vector update*
 if $temp < u_{\Pi, \Theta}(A|_{s_{u_2} \leftarrow s_{u_2} + w})$
 then $temp \leftarrow u_{\Pi, \Theta}(A|_{s_{u_2} \leftarrow s_{u_2} + w})$ and go to Step 3
 else go to Step 4

Step 4: *termination*
 $best \leftarrow temp$
 terminate

Figure 6. The pseudo code of search algorithm for FDD mode

<i>Index</i>	<i>BS power</i>	<i>MS power</i>	<i>DL rate requirement</i>	<i>UL rate requirement</i>	<i>Guard band ratio</i>
Scenario 1	0.8~1.2W	200mW	10	10	10%
Scenario 2	1W	100~300mW	10	10	10%
Scenario 3	1W	200mW	10~90	10	10%
Scenario 4	1W	200mW	10	10~90	10%
Scenario 5	1W	200mW	10	10	6~14%

Table 2. Five different scenarios for the performance evaluation.

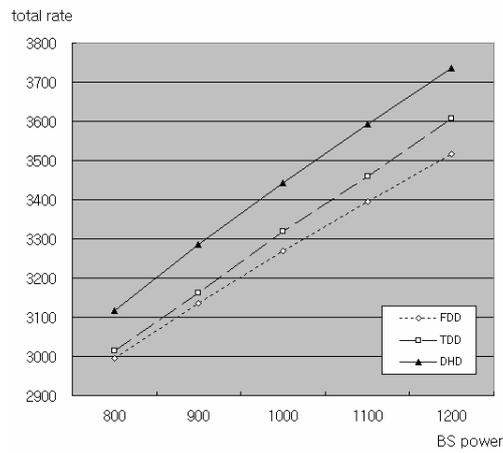


Figure 7. The total rate for different BS power

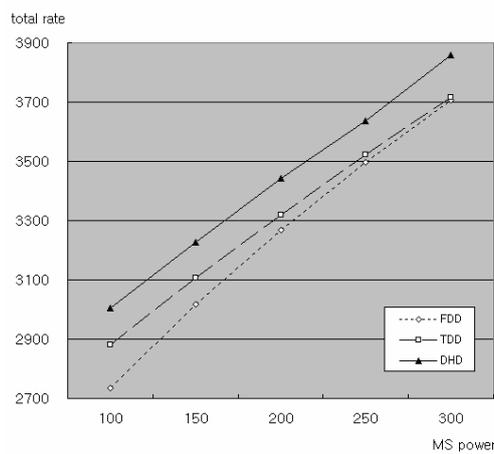


Figure 8. The total rate for different MS power

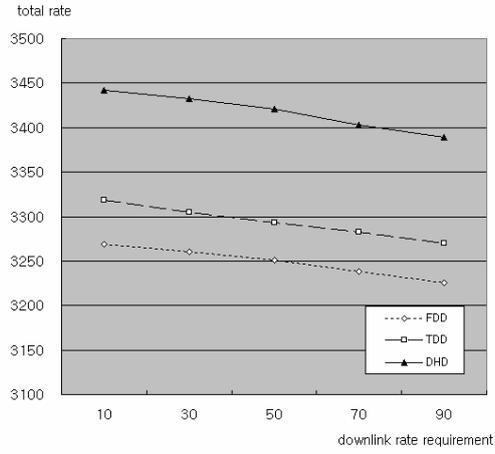


Figure 9. The total rate for different DL rate requirement

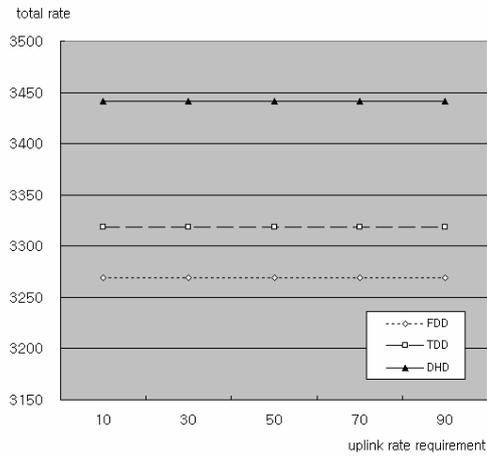


Figure 10. The total rate for different UL rate requirement

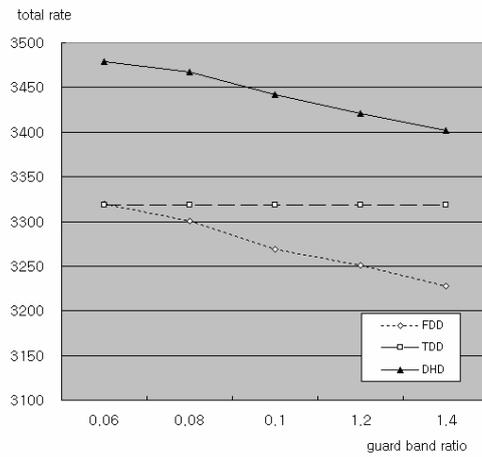


Figure 11. The total data rate for different guard band ratio

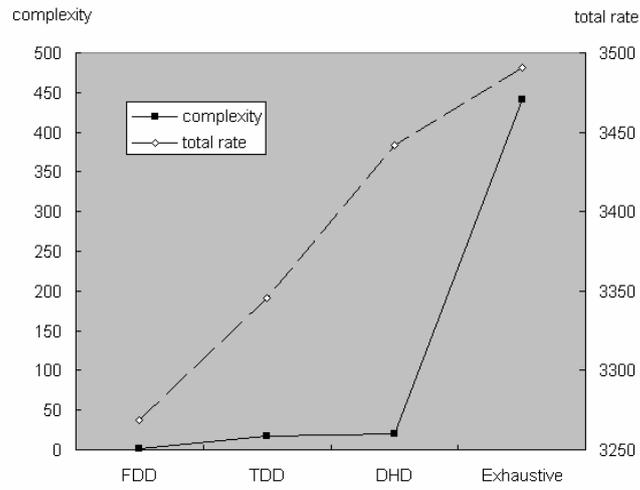


Figure 12. The complexity and the total rate for FDD, TDD, DHD and exhaustive search