A Novel Broadband Wireless OFDMA Scheme for Downlink in Cellular Communications

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***Abstract*-A new air interface scheme based on adaptive resource allocations method is proposed for downlink in cellular OFDMA systems. The proposed method is featured as a novel technique for high spectral efficiency (i.e. frequency reuse factor approaching one) and high power efficiency. In order to reduce the co-channel interference (CCI) and improve the capacity in a cell, a cell is partitioned into three 120^0 sectors and three adjacent sectors from different cells are composed as a "virtual cell" which is centrally controlled. Assuming knowledge of the instantaneous channel information for all sub-channels, bit rates and Quality of Service (QoS) requirements of all active users in Base-Stations (BSs), an adaptive resource allocations based wireless multi-user OFDM access is employed independently in each "virtual cell" by using the techniques such as multi-user diversity, interference measurement and bad channel avoidance over the whole system bandwidth. It is demonstrated that the system performance is greatly improved compared to the traditional systems with fixed channel allocation in cellular communications.**

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is an effective multiplexing technique that can significantly mitigate inter-symbol-interference (ISI) induced by wireless multi-path fading channels while supporting high data rate transmission over wireless radio channels [1]. As this technology advances, OFDM is promising to be the key modulation technique in the next generation mobile communication systems. It is well known that a cellular system uses frequency reuse concept to enhance the efficiency of spectral utilization, which introduces co-channel interference mainly from adjacent co-channel cells that is one of the major sources of performance degradation. In contrast to the traditional OFDMA scheme based on adaptive allocations of sub-carriers, bits and power in the single cell case [5,6,7,11], these access schemes based on the water-filling algorithm no longer maintain their optimality in the multi-cell environment because the water-filling algorithm assigns greater power to sub-carriers with high channel gain and lower interference level so that the assigned greater power will cause larger CCI to users in other co-channel cells. Due to the effect of CCI in the cellular OFDMA systems, it is not easy to find the optimal solution of sub-carriers, bits and power allocations. On other hand, in order to track the dynamic nature of the radio channel, a fast and low complexity resource allocation algorithm should be required for the new air interface in the practical systems

In recent years, the interference averaging based broadband wireless access schemes have been proposed as in [2,3]. In [3], interference averaging is achieved due to interference diversity effect by random frequency hopping between cells as in BDMA (Band Division Multiple Access). Similar interference averaging method using multi-carrier CDMA is proposed for downlink access in [2], where it was demonstrated that one and a half times bit throughputs could be obtained over the traditional OFDM-TDMA scheme. According to [8,9], it was shown that interference averaging techniques could perform better than fixed channel assignment techniques (i.e. OFDM-TDMA and fixed OFDM-FDMA), whereas interference avoidance techniques outperform interference averaging techniques by a factor of 2-3 in spectrum efficiency. Thus, the combination of OFDM, sectored antennas, adaptive modulation, interference avoidance based on dynamic sub-channel allocations with low complexity is promising to significantly mitigate the effect of deep fading and CCI while improving the system capacity [10].

In this paper, we consider a new air interface for wireless OFDMA systems with time-division duplex (TDD) mode in cellular communications systems to improve the spectrum and power efficiency, where we assume that the transmitting BS knows the instantaneous channel characteristic of the mobile users (e.g., such estimation can be obtained for the downlink channels using received uplink transmissions in the TDD scheme). Since the CCI is one of the major sources of performance degradation, our object is to mitigate the effect of CCI while achieving high spectrum efficiency and power efficiency as well as satisfying the required QoS along with multi-rates of all active users. In the proposed new air interface, a new concept of "virtual cell" which is defined as a cell composed of three centrally controlled adjacent sectors from different cells is given and the cellular structure based on the "virtual cell" is effective to improve the spectrum efficiency and the resistance to the CCI compared to the conventional structure. As mentioned in [11], it is unlikely that a sub-carrier will be in a deep fade or with high CCI levels over all the links between BSs and MSs in "virtual cell". This is because of the multi-user diversity where the statistics of fading and interference over all these links are mutually independent. Thus, with the information of channel estimation and rapid interference measurements, adaptive resource (i.e. sub-carriers, bits and power) allocations can be realized in the "virtual cell". By doing

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This work is supported by I-networking Lab of Samsung Advanced Institute of Technology, Korea so, high spectrum efficiency by means of hign frequency reuse approaching 1 and high power efficiency can be achieved by interference avoidance based on dynamic sub-carrier allocations, adaptive modulations and power control.

This paper is organized as follows. In Section II, the proposed new air interface scheme is described for the downlink OFDMA systems including a new cellular structure and adaptive OFDMA. Numerical results are then presented in Section III. Finally, our conclusions are drawn in Section IV.

II. PROPOSED NEW AIR INTERFACE SCHEME

In this section, we develop a new air interface for broadband wireless OFDMA systems. Multi-cell structure along with adaptive OFDMA based on dynamic resource allocation scheme is investigated. Firstly, we describe the channel model in a cellular environment.

2.1 Channel Model

In a macro cellular environment, the following path loss (*PL*) notation was used with assumption for the carrier frequency around 5GHz. We assume that the average received power decreases with distance d as d^{-n}, $n = 4$, and the large-scale shadow fading is log-normal distribution with a standard deviation of $\sigma = 10$ dB, which is given by

$$PL(d)(dB) = \overline{PL}(d) + X_{\sigma} = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_{\sigma} \quad . \tag{1}$$

Multi-path Rayleigh fading is assumed in a small-scale radio environment. With a further assumption that the mobile speed is not too high so that the Doppler frequency shift and ICI (Inter-Channel Interference) can be ignored, the received SINR (Signal-to-Interference-and-Noise Ratio) for a particular *n*-th sub-channel at the *k*-th mobile in "virtual cell" can be expressed as

$$SINR_{k,n} = \frac{H_{k,n}P_{k,n}}{N_o + I_{k,n}} \quad , \tag{2}$$

where $H_{k,n}$ is the channel gain resulting from large path loss (shadow-fading) and small scale Rayleigh fading. P_{kn} is the transmitted power to the *k*-th mobile station at the *n*-th sub-channel, N_0 denotes the AWGN and $I_{k.n}$ is interference on the *n*-th sub-channel at the *k*-th mobile station which is the summation value of the total CCI from all adjacent "virtual cell". We assume the sum in the denominator of (2) can be treated as a Gaussian process.

2.2 Multi-cell structure

Since the bandwidth is limited and expensive, the concept of frequency reuse is adopted in cellular communication systems to improve the spectrum efficiency. In order to further improve the spectrum efficiency and increase the resistance to the CCI coming from the downlink of the co-channel cells. In Fig. 1, a new multi-cell structure is proposed, where three adjacent sectors from three adjacent cells BS 1,2 and 3 are composed as a "virtual cell". Within a "virtual cell", the total bandwidth F is adaptively assigned among the active users by the centrally controlled BSs in the "virtual cell", which is based on the information of interference measurement and channel estimation fed back to BSs. To realize the measurement of the CCI of the active users in the "virtual cell", the downlink signals transmitted by all the neighboring "virtual cell" are measured by the active users while the desired "virtual cell" (i.e. desired three sectors) turns off its downlink transmitted signals. The downlink CCI measurement is obtained by monitoring the interference within an assigned time slot. In an adjacent "virtual cell", the total frequency bandwidth can be reused and the sub-carriers are dynamically allocated within the active users. Such processing seems independent among "virtual cells". In practical situation, the traffic is random in each sector and the CCI mainly comes from BS4 through BS12 randomly, the strong co-channel interference can then be avoided by using interference avoidance scheme. In the macro-cell environment, both sectoring and adaptive beamforming techniques can be used in each "virtual cell" as in Fig.2 (a) and (b), it is evident that much high frequency reuse can be achieved by using adaptive beamforming because of refined spatial separation. For simplicity, we assume that the antenna gain is equal to 1, and sectoring technique is adopted in the following sections.

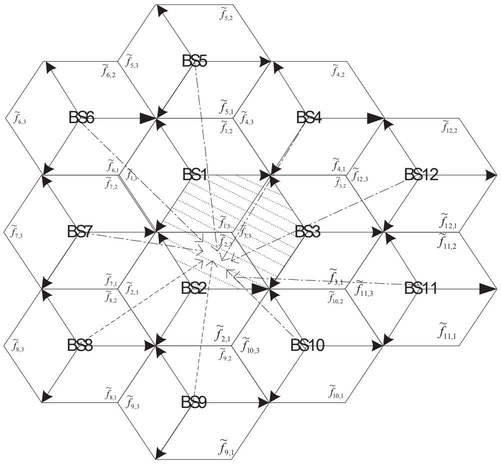
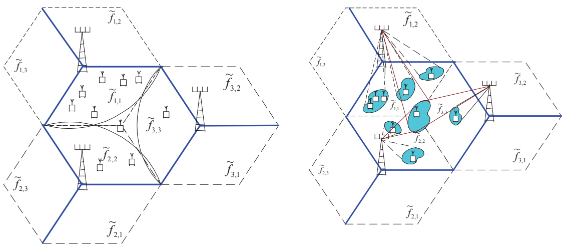


Figure 1: Multi-cell scheme with dynamically frequency band allocation in "virtual cells"

2.3 Adaptive OFDMA within "Virtual Cell"

According to multi-user diversity, a sub-carrier with deep fading or strong CCI cannot be used by a user, however, it may not be in a deep fading or strongly interfered over all links between BSs and MSs in "virtual cell", where the statistics of fading and interference over all these links are mutually independent. Thus, within the "virtual cell", the frequency channels, bits and power can be adaptively allocated according to the noise and interference measurement, channel gains for all sub-carriers, the bit rates and the required QoS of all the active users. Since it is difficult to complete the optimization problem over the whole cellular network, we propose a multi-stage sub-optimal method with low complexity to realize the sub-carrier allocation, bit allocation and power control, separately, in one "virtual cell" independently.



(a) (b)

Figure 2: (a): Sectoring based "virtual cell"; (b) Adaptive bemforming based "virtual cell"

A downlink OFDM system with K users and N sub-carriers is shown in Fig. 3. The users can transmit multimedia data such as speech and video with each satisfying data rate requirements of R_k. The bandwidth of each sub-carrier is much smaller than the channel coherent bandwidth so that the fading on each sub-carrier is flat. The BS is able to know the instantaneous channel characteristics of all BSs -to- MSs links as long as the channel varies relatively slowly. The basic information of channel and interference are exchanged among BSs and centrally controlled by BS control (BSC). According to channel information, total N sub-channels are adaptively allocated by the K active users in the "virtual cell". Each sub-carrier can only be occupied by one user and the information on resource allocations is sent to mobiles via a dedicated channel so that the mobiles are able to extract its own data from the received OFDM symbols. Within the "virtual cell", Macro transmit diversity (MTD) can be easily achieved by transmitting the same data through the same sub-channels by three sectored antennas of three sectors to improve the performance of "weak" user who is located at the center of "virtual cell".

Our objective is to minimize the total transmitted power in a "virtual cell" while satisfying the service requirement of each user in each sector. Especially, the problem can be formulated as

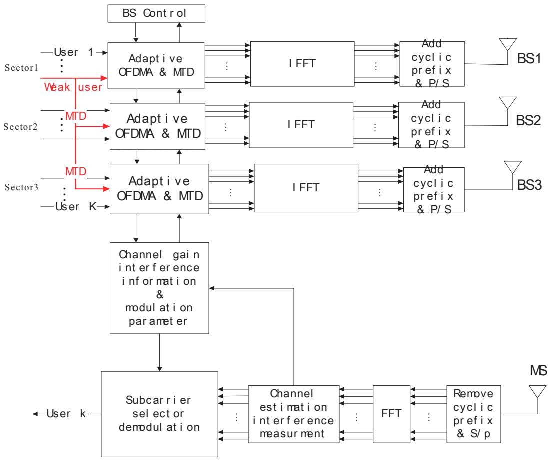


Figure 3: Adaptive resource allocation OFDMA with Marco Transmit Diversity in a "virtual cell"

$$\min \quad \sum_{k=1}^{K}\sum_{n=1}^{N} p_{k,n} \cdot \qquad (3)$$

$$\text{Subject to:} \quad R_k = \sum_{n=1}^{N} c_{k,n} \quad \forall k \in \{1,2,...,K\}$$

$$\text{and} \quad P_{e,n} \le SER_k$$

where each sub-carrier can only be used by one user at one time slot. $p_{k,n}$ is the transmitted power at the n-th sub-carrier of the k-th user, $c_{k.n}$ is the number of the bits of the MQAM, and the symbol error rate $P_{e,n}$ over the n-th sub-carrier occupied by the k-th user which satisfies the QoS requirements. We consider the uncoded transmission and assume that an adaptive MQAM constellation is used on the sub-channels over the whole frequency bandwidth. In particular, based on the Gaussion approximation of the sum of the AWGN and the interference, in high signal-to-noise ratio with large signal constellation size, the symbol error probability (or bit error probability, assuming the use of gray encoding) of an M-ary QAM transmission can be approximated by

$$P_{e,n} \approx 4Q\left(\sqrt{\frac{3\cdot SINR_{k,n}}{M_{k,n}-1}}\right), \qquad (4)$$

where the symbol error probability (P_e) on the sub-channel is related to the SINR and modulation level. $M_{k.n}$ is the modulation level at the n-th sub-channel occupied by the k-th user and $Q(\cdot)$ denotes the normal probability integral. We define a service requirement parameter, $\Gamma_{k,n}$, satisfying

$$\Gamma_{k,n} = \sqrt{\frac{3\cdot SINR_{k,n}}{M_{k,n}-1}} = Q^{-1}\left(\frac{P_{e,n}}{4}\right). \qquad (5)$$

Since the average power of the QAM symbol mainly depends on $d_{\min}$, defined as the minimium distance between two points on the signal constellation [12]. Approximately, we have

$$P_{k,n}\left(c_{k,n}\right) \approx \frac{2^{c_{k,n}}-1}{6} d_{k,n}^2 \quad \text{where} \quad c_{k,n} \in \{2,3,4,5,6\} \qquad (6)$$

Here, we set the modulation level as between 4QAM to 64QAM as long as the energy is poured into sub-channel with good channel characteristics (i.e., channel gains and interference) [6]. We get the minimum distance of the constellation at the n-th sub-channel of the k-th mobile as

$$d_{k,n} = \sqrt{\frac{2\Gamma_{k,n}^2\left(N_o + I_{k,n}\right)}{H_{k,n}}} \qquad (7)$$

In order to realize the real time allocations of sub-carriers, bits and power with low complexity in practical systems, we divide the joint optimal allocations into three steps with the decision of the number of sub-channels of each users, the sub-channel selection of each user, and the bits and power allocation of each user based on water filling.

Step1: Bandwidth allocations (# of sub-carriers) & initial bits allocation

In a wireless environment, due to the effect of "near-far" problem, the users with distance far from the BS is expected to achieve a lower overall SINR than other users, these users tend to require much higher power to transmit the same bits over a sub-channel. If each user is given enough sub-channels to satisfy their minimum rate requirements, giving the extra sub-channels to users with lower average SINR will help to reduce the total transmission power [7].

Let α_k be the shadow-fading gain of the k-th user, the bit rate requirement of the k-th user R_k, and the k-th user be allocated m_k sub-carrier. According to [6], since each user selects the best sub-channels for bits allocation, it is argued that flat transmit PSD (power spectral density) could hardly reduce the data throughput of a multiuser OFDM system, so the initial bit allocations after the decision of the number of sub-carrier of the k-th user is given as

$$c_{k,n} = \begin{cases} \left\lfloor \frac{R_k}{m_k} \right\rfloor + 1 & \text{the } R_k - \left\lfloor \frac{R_k}{m_k} \right\rfloor \times m_k \text{ best subcarriers} \\ \left\lfloor \frac{R_k}{m_k} \right\rfloor & \text{Other subchannel} \end{cases} \tag{8}$$

Thus, the average total transmit power of the *k*-th user can be presented as

$$P_{k,total} = \frac{\left(R_k - \left\lfloor \frac{R_k}{m_k} \right\rfloor \cdot m_k\right)}{\alpha_k} \times P\left(\left\lfloor \frac{R_k}{m_k} \right\rfloor + 1\right) + \frac{\left(m_k - R_k + \left\lceil \frac{R_k}{m_k} \right\rceil \cdot m_k\right)}{\alpha_k} \times P\left(\left\lfloor \frac{R_k}{m_k} \right\rfloor\right) \tag{9}$$

Our objective is to find a set of m_k, $k = 1, \cdots, K$, such that

$$\min \sum_{k=1}^{K} P_{k,total} \tag{10}$$

subject to

$$\sum_{k=1}^{K} m_k = N, \qquad m_k \in \left\{ \left\lceil \frac{R_k}{R_{\max}} \right\rceil, \ldots, N \right\},$$

where $R_{\max}$ is the maximum number of modulated bits over sub-carriers (e.g. $R_{\max} = 6$) . The optimal distribution of sub-carriers among users can be found as follows,

```
Initialization: $m_k = \left\lceil \frac{R_k}{R_{\max}} \right\rceil$ , $k = 1, \cdots, K$,
While $\sum_{k=1}^{K} m_k < N$ do
        $\widehat{P}_k = P_{k,total}(m_k + 1) - P_{k,total}(m_k)$ ,
    $k = 1, \cdots, K$,
        $l = \arg\min_{1 \le k \prec K} \widehat{P}_k$
        $m_l = m_l + 1$
End while
```

Step2: Sub-carriers allocation

We define the channel characteristic parameter $G_{k.n}$ at the n-th sub-carrier of k-th user as

$$G_{k,n} = \frac{N_0 + I_{k,n}}{H_{k,n}} \tag{11}$$

After reordering the parameter $G_{k.n}$ in the ascending order. We assign the index of sub-carriers of $\hat{G}_{k,n}$, l, to each user, where the *l*-th sub-carrier can be used by only one user at a time slot, especially, the sub-carrier allocation process is as follows:

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Initialization: $\Phi_k = \text{null}$  $k = 1, \cdots, K$, and $\Phi = null$,
where $\Phi = \bigcup_{k=1}^{K} \Phi_k$
While $\sum_{k=1}^{K} m(\Phi) < N$, do
    For k=1,...,K
            if $l \notin \Phi$ and $m(\Phi_k) < m_k$
        $l \in \Phi_k$ and $l \in \Phi$
            End if
        End for
End while
```

where $m(\cdot)$ denotes the number of elements in coset.

Step3: Refined bit allocation

After the sub-carrier allocation, we initialize the bit allocations as in the Eqn. (8). we then refine the bit allocations by water-filling algorithm. Mathematically, we have the optimization problem for the *k*-th user as

$$\min \sum_{l \in \Phi_k} P_{k,l} \tag{12}$$

subject to

$$R_k = \sum_{l \in \Phi_k} c_{k,l} \quad \text{and} \quad P_{e,l} \le SER_k.$$

Since the initialized bit allocation approaches the optimal bit allocation, we can use the greedy method proposed in [5] to refine bit allocation. By finding two sub-carriers, indexed by l and l', such that

$$P_{k,l}(c_{k,l}) - P_{k,l}(c_{k,l} - 1) > P_{k,l'}(c_{k,l'} + 1) - P_{k,l'}(c_{k,l'}) \tag{13}$$

if such as (l, l') pair exits, moving one bit from sub-channel l to sub-carrier l' will lower the overall transmit power of the *k*-th user. The optimal bit allocations for the *k*-th user can be obtained by satisfying

$$\underline{\Delta P_k^+} \ge \overline{\Delta P_k^-}, \tag{14}$$

where

$$\underline{\Delta P_k^+} = \min_{\forall l \in \Phi_k} \left\{ P_{k,l}(c_{k,l} + 1) - P_{k,l}(c_{k,l}) \right\}$$

and

$$\overline{\Delta P_k^-} = \max_{\forall l \in \Phi_k} \left\{ P_{k,l}(c_{k,l}) - P_{k,l}(c_{k,l} - 1) \right\}$$

Since the minimum distance in the signal constellation of the transmitted symbol is given in Eqn. (7), both BS and MSs can calculate the value of $d_{k,n}$ directly in order to reduce the side information transmitted to MSs by BSs.

III. NUMERICAL RESULTS

In this section, we provide some simulation results, which demonstrate the potential of our proposed adaptive resource allocation based OFDMA systems in the downlink for cellular communications. In the following simulations, channel model "Vehicular A" in Table.1 is adopted with a maximum Doppler frequency of 550 Hz, which is corresponding to the coherent time $0.4/f_d = 720$ µs. The available bandwidth F is assumed to be 18 MHz at 5GHz radio frequency and the total number of sub-carriers N =1024. This corresponds to a sub-channel separation of 16 kHz and an effective OFDM frame duration of 56.8889 µs, which means that the channel is static for 12 OFDM frame duration. In each OFDM frame, a cyclic prefix of 5.68889 µs duration is added which is larger than the maximum time delay of multi-path Rayleigh fading channel

Type	Delay Profile (nsec)	Power (dB)
Vehicular A	(0,250,500,750,1000,1700,1900,2400,2600,2700)	(0,-3,-6,-9,-12,-13,-15,-25,-21,-25)

Table1: Channel model for simulations

Without loss of generality, we consider a "virtual cell" with (6, 3, 2) users in each sector and the bit rates of all users are (4Mbps, 4Mbps, 4Mbps, 4Mbps, 8Mbps, 8Mbps; 4Mbps, 4Mbps, 8Mbps; 4Mbps, 8Mbps), respectively. We consider the reference distance $d_0 = 0.5R$, and average propagation distance of CCI from the adjacent co channel "virtual cell", $d = 2.5R$. The standard deviation of large-scale shadow-fading distribution is $\sigma = 10$ dB over all sub-carriers. We adopt a set of shadowing gain of the active users in "virtual cell" with values (0.70, 1.13, 1.04, 1.33, 0.84, 0.72; 0.91, 0.89, 0.54; 0.77, 1.22). The value of gamma, $\Gamma_{k,n}$, of all users over all sub-carriers is set to be the same for convenience. We consider Fig. 4, where we present the performance comparison between our proposed adaptive resource allocations based OFDMA scheme and a traditional fixed OFDM-FDMA scheme. It is demonstrated that the proposed scheme can greatly improve the system performance compared to the traditional fixed OFDM-FDMA scheme with the same total transmit power and the same bit throughout.

IV. CONCLUSIONS

A new air interface scheme based on adaptive resource allocations method was proposed for downlink in the multi-cell OFDMA systems. Based on the statistic multiplexing and bad quality channel avoidance, our proposed method can achieve high spectral efficiency (i.e., frequency reuse factor approaching 1) and high power efficiency. Assuming perfect knowledge of the instantaneous channel information at all sub-channels, bit rates and QoS requirements of all active users in the "virtual cell", adaptive resource allocations based wireless multi-user OFDM access is employed independently in each "virtual cell" benefiting from multi-user diversity. From the numerical results, it is demonstrated that the system performance is greatly improved compared to the traditional systems with fixed channel allocation.

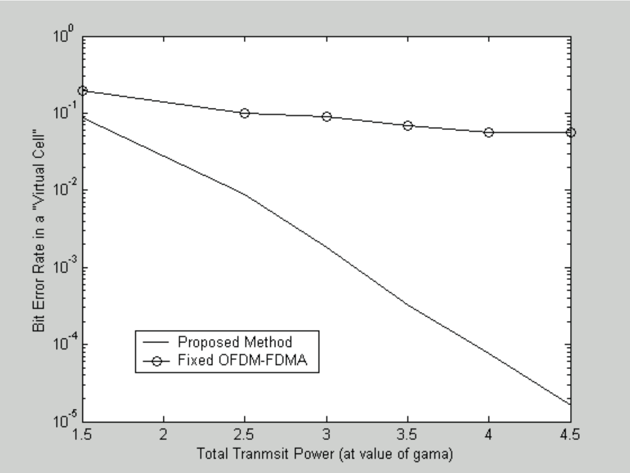

Figure 4: Performance comparison between proposed method and fixed OFDM-FDMA scheme

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