A Distributed Opportunistic Access Scheme for OFDMA Systems

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[1] ***Abstract*— In this paper, we propose a distributed opportunistic access scheme for uplink OFDMA systems. The sub-carriers are grouped into several sub-channels. Users access these sub-channels through a distributed access scheme without requiring extensive information exchange with the access point. Our scheme allows several parallel contention sub-channels to exploit the multiuser diversity. Using knowledge of all the sub-channels obtained through a periodically transmitted beacon signal from the access point, all users contend on their strongest sub-channel(s). The proposed scheme applies a novel backoff mechanism utilizing this sub-channel knowledge to yield further throughput improvement in addition to the throughput gain obtained by the collision reduction design. To a user, the better the sub-channel gain is, the smaller the backoff time on that sub-channel, and hence, the higher the access priority of the user on that sub-channel. Compared with the traditional centralized OFDMA systems, our proposed scheme reduces overhead significantly and achieves a better spectral efficiency as corroborated by the simulation results.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) has become a well-established transmission technology for broadband wireless communication systems and has been adopted in several wireless standards [1], [2]. There are mainly three multiple access schemes in OFDM systems: OFDM/TDMA (time division multiple access), OFDM/FDMA (frequency division multiple access), and OFDMA (orthogonal frequency division multiple access). In TDMA or FDMA schemes, only a single user can transmit on all sub-carriers of OFDM symbols within a certain time slot or frequency band. However, in a typical wireless transmission environment, the channel responses of different users are different. Some sub-channels might be in deep fade for one user while they might be good for others, hence naturally providing a diversity component for capacity enhancement. This multiuser diversity cannot be exploited in TDMA and FDMA systems but is beneficial to OFDMA systems which allow multiple users to transmit simultaneously on different sub-carriers. Since the probability that all users experience a deep fade on a particular sub-carrier is very low, it would be beneficial if sub-carriers are assigned to the users who experience good channel gains on them.

There are several works on the sub-carrier allocation of OFDMA systems in the literature [3]-[5]. However, in the centralized approach, the base station or access point has to collect channel information from all users to allocate the sub-carriers among different users. Centralized algorithms need significant information exchange between the base station and the users. Furthermore, this information should be received correctly and with no delay. This requires prohibitive overhead for the practical implementation of OFDMA systems with centralized access and (sub)optimal resource allocation. Therefore, a distributed access (and resource allocation) scheme which does not require a lot of information exchange but can utilize the multiuser diversity will be very promising. The increased interests in wireless ad hoc and sensor networks also highlight the need for efficient distributed access schemes.

In distributed systems, all users only get to know the information of their own channels, which is also called decentralized channel state information (CSI). There are some access schemes recently proposed to utilize this decentralized CSI for single carrier systems. A binary distributed scheduling scheme is derived in [6] which asymptotically achieves a fraction $(\frac{1}{e})$ of the centralized throughput obtained with multiuser diversity. To resolve the problem of collision, an opportunistic splitting algorithm is proposed in [6],[7]. Although the opportunistic splitting algorithm can guarantee the access of the user with the best channel gain when the contention length is unlimited, its overhead is not minimized since its design is mainly based on two user contending to access. Thus, when the contention length is limited (which is the case in most practical systems), there may be some frames on which no user successfully accesses. Another problem of the opportunistic splitting algorithm is that it needs frequent handshakes between the access point and users. When the channel is not good, it is highly possible that these handshaking signals can be detected incorrectly which results in a further increased collision probability.

In this paper, to fully utilize multiuser diversity gain in OFDMA systems, we propose a distributed opportunistic OFDMA scheme which encodes the channel information into the access (and resource allocation) scheme. In our proposed scheme, all sub-carriers are grouped into several sub-channels.

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According to channel characteristics of each sub-channel, a novel backoff mechanism is designed such that the user with the highest channel gain on that sub-channel has access to it. This scheme does not need to feedback any CSI to the access point, and hence prohibitive overhead is avoided.

The rest of the paper is organized as follows. In Section II, OFDMA system model is given. The proposed distributed access scheme is presented in Section III, and the design of the novel backoff scheme is provided in Section IV. In Section V, both theoretical and simulation results are given. Conclusions are drawn in Section VI.

II. System model

We consider an uplink OFDMA system model with N users. First, all the sub-carriers are grouped into several sub-channels. Each sub-channel is composed of adjacent sub-carriers as shown in Fig. 1. To simplify our analysis, we assume that all sub-channels have the same number of sub-carriers. Due to the correlation of the channel frequency response (or equivalently, due to the limited channel delay spread much less than the OFDM symbol duration), the sub-carriers within each sub-channel have highly correlated channel gains. To simplify the design, we use the statistics of a particular channel which captures the essence of practical wireless channels while facilitating a tractable design. In the simulation section, we evaluate our proposed scheme for different channel environments. Let N_s denote the total number of sub-carriers in the system. For design purpose, we consider a multipath Rayleigh fading channel consisting of N_c independent and identically distributed (i.i.d.) taps with a uniform power delay profile. Let $h_{i,j}$ denote the channel gain of user i $(i = 1, 2, \ldots, N)$ on the j-th $(j = 1, 2, \ldots, N_s)$ sub-carrier. Then, $\{h_{i,j}\}$ are circularly-symmetric complex Gaussian random variables with zero mean and unit variance. Suppose $\frac{N_s}{N_c}$ is an integer and all N_s sub-carriers are divided into N_c sub-channels. Then, each sub-channel has N_s/N_c sub-carriers and the average channel power gain of the n-th sub-channel for user i is given by

$$G_{i,n} = \frac{\sum_{j=\frac{N_s}{N_c}*(n-1)+1}^{\frac{N_s}{N_c}n} |h_{i,j}|^2}{N_s/N_c} \cong |h_{i,\frac{N_s}{N_c}*(n-1)+1}|^2, \quad (1)$$

which can be estimated from the beacon signal periodically transmitted from the access point. From (1), we obtain that $\{G_{i,n}, n = 1, 2, ..., N_c\}$ are i.i.d. exponentially distributed random variables with mean 1. The cumulative distribution function (CDF) of $G_{i,n}$ is given by

$$F_G(g) = (1 - e^{-g})u(g), \quad (2)$$

where $u(g)$ is the unit step function.

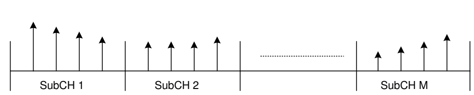

Fig. 1. Sub-carriers and sub-channels

III. Proposed opportunistic OFDMA scheme

Users estimate their CSI on all sub-carriers through a periodically transmitted beacon signal from the access point. Then, each user contends on its β strongest sub-channels. When β equals the number of sub-channels, each user contends on all all sub-channels. We call this scheme **CAC** (contending on all sub-channels). otherwise, it is denoted as **CSC** (contending on selected sub-channels). The parameter β can be adjusted adaptively according to the traffic load in the system which will be shown in the adaptive scheme in the simulation part. The frame structure of this access scheme in the uplink is given in Fig. 2. Each frame is divided into three sub-frames. The

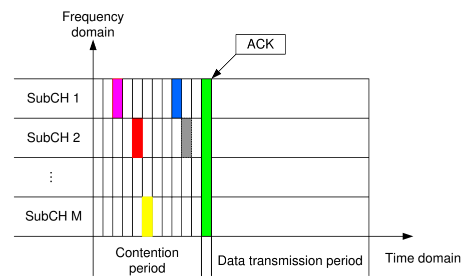

Fig. 2. Distributed OFDMA frame structure

first sub-frame is the contention period in which users contend to access the network on their strongest sub-channels. In the second sub-frame, the access point sends an acknowledgment packet (ACK) containing the addresses of the users which successfully accessed (the successful users) in the first sub-frame. The third sub-frame is the data transmission period in which all successful users will transmit their data.

The detailed protocol works as follows. Users obtain knowledge of their sub-channels through a periodically transmitted beacon signal from the access point and determine their β strongest sub-channels to contend on. Then, according to the frame structure of the system, the protocol proceeds as follows:

- Contention period: This period consists of several mini-slots. The length of this period is set much smaller than the length of data transmission period to reduce the contention overhead. All users contend to access the system only at their scheduled mini-slot. A user with packets to transmit will generate a backoff time (in mini-slots) according to our novel backoff scheme (which will be described later in this section) on its strongest sub-channels. This user waits until its backoff period has elapsed and then sends a preamble. The preamble contains the address information of this user. The access point decodes the received preambles and keeps the address information of all successful users. Note that for each sub-channel there may be several successfully decoded preambles on different mini-slots. However, only one user can transmit on each sub-channel and hence there is only one or no successful user on each sub-channel. The successful user on each sub-channel is the earliest one whose preamble is correctly decoded on that sub-channel.

- ACK period: This period only consists of one minislot which is used to transmit the ACK message. From the contention period, the access point has the information of the successful user of each sub-channel. The access point broadcasts the addresses of all successful users of all sub-channels through the ACK message. All unsuccessful users will try to access the network in the next frame.
- Data transmission period: In this period, all successful users transmit their packets.

We use the ordered statistics to analyze this scheme. Define

$$Z_{i,m} = G_{i,(m)}, \tag{3}$$

where $\{G_{i,(m)} : m = 1, 2, ..., N_c\}$ is the ordered sequence of $\{G_{i,n} : n = 1, 2, ..., N_c\}$ such that $G_{i,(1)} \leq G_{i,(2)} \leq ... \leq G_{i,(N_c)}$. Each user chooses its β best sub-channels based on $\{G_{i,n}\}$. Then, the CDF of the mth order statistics $Z_{i,m}$ is

$$F_{Z_{i,m}} = \sum_{l=m}^{N_c} \left(\begin{array}{c} N_c \\ l \end{array} \right) F_G^l(z)[1 - F_G(z)]^{N_c - l}, \tag{4}$$

where F_G is given in (2). In this paper, we only consider the homogenous OFDMA systems, then we can simply ignore the index i of $F_{Z_{i,m}}$. In this approach, for a specific sub-channel, some users may choose it as its best channel, while some other users may view it as the βth strongest channel. Thus, the users contending on one sub-channel have different statistical distributions. Let $N_{m,j}, m = 1, 2, ..., N_c, j = 1, 2, ..., \beta$ denote the exact number of nodes choosing mth sub-channel as its jth strongest contention channel. Then, on the mth sub-channel, the channel power gain of these $N_{m,j}$ users has the CDF of $F_{Z_{i,N_c-j+1}}$. By combining the distributions of the channel power gain of all the users contending on the mth sub-channel, the CDF of the channel power gain on the mth sub-channel F_{H_m} is obtained as

$$F_{H_m} = \sum_{j=1}^{\beta} \frac{N_{m,j}}{\sum_{i=1}^{\beta} N_{m,i}} F_{Z_{N_c-j+1}}. \tag{5}$$

Then the number of users contending on the m-th sub-channel is $N_u = \sum_{i=1}^{\beta} N_{m,i}$. Please note that when $\beta = N_c$, F_{H_m} is the same as F_G in (2) and $N_u = N$.

IV. Novel Backoff Scheme Design

In this section, a novel backoff scheme is proposed to utilize CSI and reduce collision for homogenous systems. In the network, system throughput instead of access probability is a design criterion as it considers the effects of both physical channels and access schemes. Thus, in this paper, we adopt this cross-layer view to design our backoff scheme. The key idea of this backoff scheme is to encode knowledge of the channel power gain into the backoff time. A user with better channel gain is designed to have higher probability to access the system so that the overall throughput of the system is improved. Let K denote the number of mini-slots in the contention period. All users compare their channel power gains with a set of thresholds associated with backoff minislots.

Look us look into the m-th sub-channel. Suppose there are N_u users contending on m-th sub-channel and let $\eta = \{\eta_0, \eta_1, ..., \eta_K\}$ denote the set of the thresholds associated with the backoff mini-slots. For the jth user, if the m-th sub-channel is one of its β strongest sub-channels and $\eta_i < G_{j,m} < \eta_{i-1}, i = 1, 2, .., K$, then it will send its preamble on the ith mini-slot. For each mini-slot, only if there is exactly one user sending its preamble, that preamble can be decoded correctly. Therefore, the probability that one preamble can be decoded correctly (success access probability) at the ith mini-slot is

$$p_i = N_u \left(\int_{\eta_i}^{\eta_{i-1}} f(x)dx \right) \left(1 - \int_{\eta_i}^{\eta_{i-1}} f(x)dx \right)^{N_u - 1}. \tag{6}$$

Then, the throughput of the system corresponding to the ith mini-slot is defined as

$$\begin{aligned} s_i = & \left[\prod_{j=1}^{i-1} (1 - p_j) \right] N_u \left(\int_{\eta_i}^{\eta_{i-1}} R(x) f(x)dx \right) * \\ & \left(1 - \int_{\eta_i}^{\eta_{i-1}} f(x)dx \right)^{N_u - 1}, i = 1, 2, ..., K \end{aligned} \tag{7}$$

where $\eta_0 = \infty$ and $\prod_{j=1}^{i-1}(1 - p_j) = 1$ for $i = 1$. Thus, the throughput of the system over all K mini-slots is

$$S = \sum_{i=1}^{K} s_i. \tag{8}$$

Now, our design problem is reduced to solve the following optimization problem

$$\begin{aligned} & \max_{\eta_1, \eta_2, ... \eta_K} \{S = \textstyle\sum_{i=1}^{K} s_i\} \\ s.t. \quad & 0 \leq \eta_K \leq \eta_{K-1} \leq ... < \eta_1 \leq \eta_0 (= \infty). \end{aligned} \tag{9}$$

This optimization problem can be solved by setting the gradients of S with respect to all $\eta_i, i = 1, 2, ...K$ to zeros, i.e.

$$\frac{\nabla S}{\nabla \eta_i} = 0, i = 1, 2, ..., K. \tag{10}$$

It is analytically quite intractable to get the closed form solution of (10). However, a lot of simulation toolkits provide numerical solutions for it, such as $fminsearch$ function in MATLAB. By optimizing the throughput on each sub-channel, we maximize the throughput of the OFDMA system.

V. Numerical and Simulation Results

In the simulation, the channels of different users are modeled as independent 3-tap Rayleigh fading channels with an exponential power delay profile. Since the access point periodically sends out beacon signals, we assume that the average sub-channel gains are known by the users. We consider OFDM/OFDMA systems with $N = 256$ sub-carriers. The simulation results are obtained from $N_f = 100,000$ independent frames. In this simulation, we assume BER=10^{-5} and SNR=15dB.

In our proposed schemes, one sub-channel has 64 sub-carriers and hence, there are $N_c = 4$ sub-channels for $N = 256$. Note that this channel model used in the simulation is not the same as the one used in our design described in Section II. Correspondingly, the average channel power gains in the simulation will not have an exponential distribution. For analytical tractability in our design, we will still use (26) as an approximation to design the thresholds for the simulation. With the fixed frame length, there are 48 OFDM symbols in one frame. For the contention period, each mini-slot is composed of the transmission time of one preamble and the maximum propagation delay of the system. A preamble consists of the address information of the transmitting user. Only 32 sub-carriers are used to transmit this preamble and one mini-slot is $1/2$ of one OFDM symbol duration. According to the frame structure given in Fig. 2, we consider $K = 7$ mini-slots in the contention sub-frame. Then, the length of the data subframe is $M = 2*48-7-1 = 88$ mini-slots. The following four schemes are given as benchmarks:

- Upper bound: All the sub-channels are always allocated to the user with the best average sub-channel gain. This is an upper bound of OFDM/TDMA since not all the users can access the network and the channels are always given to the best users.
- OFDM/TDMA: Users access the system according to a TDMA scheme. All the sub-carriers are allocated to one user.
- Centralized OFDMA: In this scheme, the access point uses uplink feedback channel to obtain users' channel state information and applies the following centralized resource allocation scheme to allocate the sub-carriers to users. The first randomly selected user chooses its best 64 sub-carriers and, then the second randomly selected user chooses its best 64 sub-carriers till all the carriers are assigned to users or all the users are assigned with sub-carriers.
- Opportunistic splitting scheme: The opportunistic splitting scheme in [6] is directly applied on each sub-channel.

In the following, we investigate two cases:

1) Number of users known: According to an acceptable BER performance, successful users can use adaptive modulation to send higher data rates at better channel conditions to improve the overall throughput. The rate function $R_{i,n}$ achieved by a successful user i on the n-th $(n = 1, 2, ...N_c)$ sub-channel with continuous rate adaption is

$$R_{i,n} = \frac{\sum_{j=\frac{N}{N_c}*(n-1)+1}^{\frac{N}{N_c}n} \log_2(1 + \frac{\gamma*|h_{i,j}|^2}{\sigma_i^2})}{N/N_c} \tag{11}$$

where σ_i^2 is the noise power at the i-th sub-channel and γ is the SNR gap given by

$$\gamma = -\frac{1.5}{\ln(5 \text{ BER})}. \tag{12}$$

Let $M_n, n = 1, 2, ..., N_c$ denote the number of busy frames on the n-th sub-channel and $c_{n,j}$ denote the corresponding rate on the jth busy frame of the nth sub-channel which is calculated as in (11) for the successful user on the n-th sub-channel. Then, the throughput of the system is given by

$$S = \frac{\sum_{n=1}^{N_c} \sum_{j=1}^{M_n} c_{n,j} * M}{N_f * (K + M + 1) * N_c}. \tag{13}$$

The results in Fig. 3 show that our proposed scheme is even better than the centralized OFDMA. Note that we have not taken into account the overhead associated with the centralized schemes. If we include the prohibitive overhead of the centrally controlled access schemes, our proposed scheme will be much better than the centralized OFDMA, and even comparable with the upper bound. Note that the mismatch between the simulation and theoretical results is due to the channel model mismatch between the design and the simulation.

Fig. 4 shows the performance of CSC under different β. For $\beta = 4$, CSC is equivalent to CAC. The simulation results show that at the low traffic load, CAC outperforms CSC while at medium and high traffic loads, the throughput of CAC and CSC with larger β values are almost the same. Intuitively, CSC could outperform CAC at high traffic load since the number of users contending on each sub-channel is smaller for CSC, hence, yields larger success access probability. However, with the contention length of $K = 7$ for our proposed schemes and equivalently $K = 4$ for the opportunistic splitting algorithm, the success access probability is already very high (0.94) even for a very large number of users as shown in Fig. 5. Hence, for $K = 7$, CSC's marginal improvement in the success access probability does not outweight its loss in the multiuser diversity gain over CAC, yielding almost the same throughput for CAC and CSC with larger β values at high traffic load.

2) Number of users unknown: When the exact number of users in the system is unknown, the backoff thresholds are designed according to the average number of users in the system. In this simulation, The number of users in the system is assumed to have a Gaussian distribution with mean '30' and standard deviation changing from '0' to '200'. Fig. 6 shows the simulation results with different β of CSC. It can be seen that when the standard deviation is large (e.g, larger than 100), the collision probability with CAC scheme will be very high. It is better to switch to CSC with smaller β to reduce the collision. Here, we propose an adaptive scheme. First, all the users try to access the system according to CAC scheme. If there is no successful access, the access point will notify through the ACK message whether there are no users sending preambles or all the transmitted preambles collided. If the latter happens, which means the traffic load is high, the protocol will reduce the current β to 1. There is a timer to record the number of frames with successful access or with no user attempting to transmit. In both cases, the timer will be increased by '1'. When the timer reaches '10', it will be reset and β will be increased by '1'. The performance of this adaptive scheme can be seen from Fig. 6. It can be seen that adaptive scheme performs well under diverse user's statistics.

VI. CONCLUSIONS

In this paper, novel distributed opportunistic access schemes for OFDMA systems are proposed to achieve the multiuser diversity. All users estimate their channel gains through a periodically sent out beacon signal and then use a carefully designed backoff scheme to reduce the collision. The basic idea is to assign smaller backoff mini-slots to users with better channel gains. Each user compares its channel gain with the predefined thresholds to decide its backoff mini-slot. The design criterion is to maximize the sum of the throughput of all the users. Compared with the other distributed schemes in the literature and the centralized approach, our proposed scheme reduces overhead significantly and achieves a better spectral efficiency as corroborated by the simulation results and theoretical analysis.

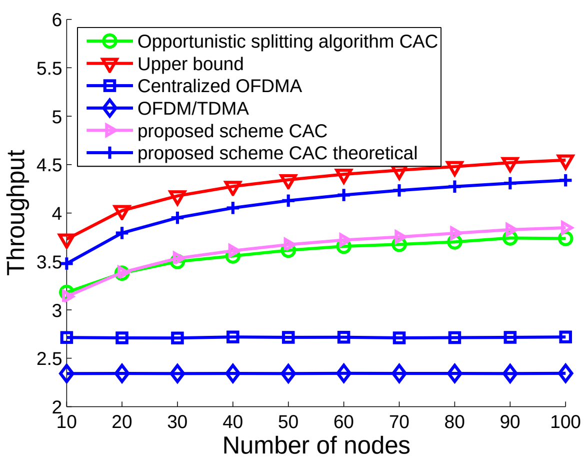

Fig. 3. Throughput comparison of OFDMA systems

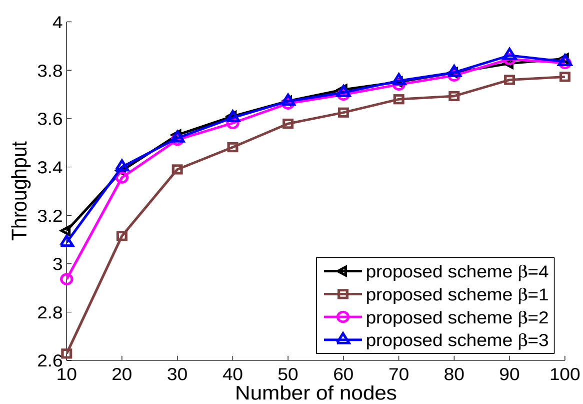

Fig. 4. Throughput comparison of OFDMA systems

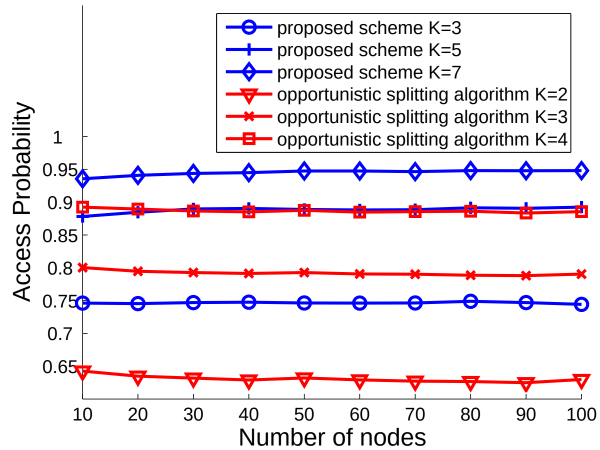

Fig. 5. Comparison of successful access probability on one sub-channel ($\beta = 4$)

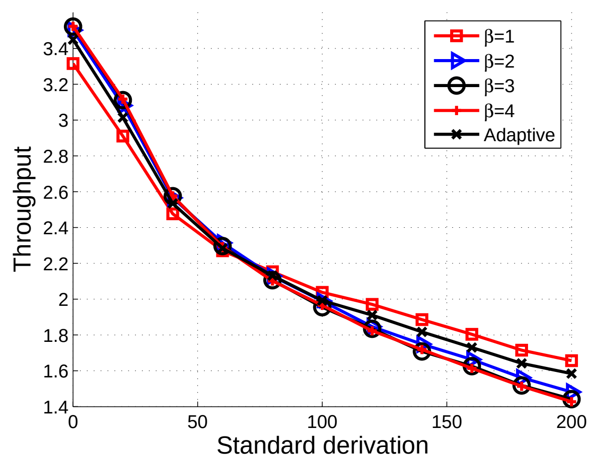

Fig. 6. Throughput comparison of OFDMA systems

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