Ad Hoc Networks 24 (2015) 200–213

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Full duplex random access for multi-user OFDMA communication systems

Xudong Wang *, Aimin Tang, Pengfei Huang

UM-SJTU Joint Institute, Shanghai Jiao Tong University, Shanghai, China

ARTICLE INFO

Article history:
Received 19 March 2014
Received in revised form 23 July 2014
Accepted 1 September 2014
Available online 6 September 2014

Keywords:
Full duplex communications
Medium access control
Orthogonal frequency division multiple access (OFDMA)

ABSTRACT

Random medium access control (MAC) plays a critical role in OFDMA wireless networks to support services with bursty traffic. However, the existing OFDMA random access protocols suffer from low efficiency due to the constraints in half-duplex communications. In this paper, the capability of full-duplex communications is leveraged to propose novel mechanisms such as full duplex carrier sensing, collision detection, and collision jamming. With these mechanisms, a full-duplex carrier sense multiple access with collision detection (FD-CSMA/CD) protocol is developed for OFDMA wireless networks. It is based on a hierarchical design: (1) with full-duplex communications, operation of subchannels is decoupled, and a CSMA/CD-like protocol is implemented in each subchannel as a random access scheme; (2) on top of random access per-subchannel, a simple but effective subchannel selection scheme is executed locally on each client to harvest multi-user diversity. Both theoretical analysis and simulations are carried out to validate the effectiveness and efficiency of our protocol.

1. Introduction

Orthogonal frequency division multiple access (OFDMA) has been widely adopted by several next-generation wireless networks including WiMAX, 802.22 WRAN and LTE-A [1–3]. In an OFDMA system, multiple nodes share different set of subchannels (i.e., a block of subcarriers) simultaneously based on a certain medium access control (MAC) protocol, which is either scheduled access or random access. The scheduled access mechanism is well suited for providing connection-oriented services with guaranteed quality of service (QoS). Based on optimization theories, many scheduling schemes are proposed to maximize different system utilities [4–6]. In data networks, traffic is bursty, so it is unreasonable to reserve wireless resources (e.g., subchannels). As a result, random access is a preferred option.

So far there exist a few random access protocols for OFDMA wireless networks. In [7], a multi-channel ALOHA protocol is developed, but its throughput turns out to be low as a result of high collision probability. Based on carrier sense multiple access with collision avoidance (CSMA/CA), other subchannel random access protocols are proposed in [8,9]. These protocols can achieve much better performance than the multi-channel ALOHA protocol in [7]. However, there still remain several major problems. *Problem 1*: When a node transmits a packet on one of subchannels, it cannot sense the status of other subchannels. Thus, even other subchannels are idle, transmissions on these subchannels cannot be conducted immediately. Due to this drawback, the system throughput is highly related to the number of subchannels. When the number of subchannels is smaller than the number of contending nodes, the throughput drops quickly as the number of nodes increases, as a result of high collisions [8]. When the number of subchannels is larger than the number of nodes, the throughput also decreases due to

---

* Corresponding author.
E-mail address: wxudong@ieee.org (X. Wang).

http://dx.doi.org/10.1016/j.adhoc.2014.09.002
1570-8705/© 2014 Elsevier B.V. All rights reserved.

low utilization of all subchannels [8]. In [9], the number of subchannels must be adjusted dynamically to be equal to the number of nodes, which is difficult in system implementation. *Problem 2*: Acknowledgement (ACK) cannot be returned without using an extra independent channel [8] or the ACK of an uplink (i.e., clients to access point (AP)) packet is delayed to the downlink (i.e., AP to clients) transmission period [9]. The delayed ACK is not suitable for random access protocols. *Problem 3*: Once a transmission collision happens, it lasts for the entire packet. Thus, the collision time is long. *Problem 4*: The downlink subframe and the uplink subframe (where random access is adopted) are operated in a time-division duplexing (TDD) fashion, which is not flexible to support fast time-varying unbalanced bursty traffic between downlink and uplink.

An approach to address the above issues is to make sure a radio of each node can transmit and receive signals at the same time in the same frequency. To facilitate this operation, the radio needs to have the capability of full-duplex communications. Recently, full-duplex wireless communications have become practical through a combination of antenna cancelation (AC), RF interference cancelation (RIC), and digital interference cancelation (DIC) [10–12]. Full-duplex radios bring two major benefits: (1) for a point-to-point link, its capacity can be significantly improved by up to twice [10]; (2) functions of a communication node are greatly enhanced, e.g., a node can transmit signals and sense the transmission status of other nodes simultaneously, which is a useful function for cognitive radios [13].

In this paper, by leveraging the capability of full-duplex communications in the physical (PHY) layer, a novel random access protocol, called full-duplex carrier sense multiple access with collision detection (FD-CSMA/CD) protocol, is designed for OFDMA wireless networks. It is distinguished by the following key features:

(1) A radio operates in a full-duplex way: it can transmit signals on some occupied subchannels, and at the same time receive signals on all subchannels [12], i.e., transmissions on all subchannels are decoupled from each other. Thus, an idle subchannel can be detected and utilized in time whether another subchannel is in transmission mode or not. Thus, *Problem 1* is solved. Moreover, when a packet on one subchannel is received, an ACK can be returned immediately regardless of the status of other subchannels, which addresses *Problem 2*. To improve throughput, a novel virtual MAC header (VMAC-hdr) is designed and added in the PHY preamble of a packet. It serves two purposes. *Firstly*, it is an identifier used for a corresponding node to capture a *full-duplex opportunity* to improve the link throughput. *Secondly*, it is used for *collision detection* by all nodes. When a transmitting node detects a collision, it gives up the current transmission immediately. For hidden nodes, collision is detected by a third node like AP, and then the AP sends a *jamming signal* to terminate all transmissions to reduce the collision time and thus improve the throughput. Therefore, *Problem 3* is solved.

(2) With the full-duplex feature in the PHY layer, a CSMA/CD-like random access protocol is operated on each subchannel by contending nodes (including AP and clients), i.e., transmissions on different subchannels are decoupled. In addition, transmissions in uplink and downlink are multiplexed in parallel. Thus, *Problem 4* is solved.

(3) In an OFDMA system, each node experiences frequency-selective fading independently, so a certain set of subchannels that are in deep fading for some nodes may have high channel quality for other nodes. Thus, packets from the network layer of each node are scheduled locally and mapped to properly selected subchannels to harvest the multi-user diversity. As a result, the entire system throughput is greatly enhanced.

The remainder of this paper is organized as follows. The features of a full-duplex OFDMA wireless network are presented in Section 2. The FD-CSMA/CD protocol is developed in Section 3. The system performance is analyzed in Section 4. Simulation results are presented in Section 5, and the paper is concluded in Section 6.

2. Features of full-duplex OFDMA wireless networks

We consider a point-to-multipoint (PMP) full-duplex OFDMA wireless network, which is a widely deployed network infrastructure, as shown in Fig. 1a. The network consists of $N+1$ nodes, i.e., an AP and N clients. Each node is equipped with a full-duplex radio. The communication bandwidth is divided into M subchannels (i.e., a block of N_C subcarriers). Each subchannel is frequency-flat and reciprocal. To ensure subcarriers from different nodes are time-aligned in each OFDMA symbol, AP and clients are synchronized with each other, which is a default requirement of an OFDMA system.

In an OFDMA system, multiple orthogonal subchannels are formed by an inverse fast Fourier transform (IFFT) processing, so a node can obtain each subchannel information only after performing a fast Fourier transform (FFT) operation on the received OFDMA symbol. Thus, the subchannel status detection is conducted symbol by symbol. We assume σ is the required time to determine whether a subchannel is idle or busy. Such a time is called clear subchannel assessment (CSA) time and is defined as ρT_{sym}, where ρ is the number of OFDMA symbols and T_{sym} is a symbol time.

Our full-duplex OFDMA random access protocol design consists of three parts, as shown in Fig. 1b. In the PHY layer, each node has a full-duplex radio, so when it transmits signals on some subchannels, it can receive signals on all subchannels simultaneously [12]. Thus, from the perspective of the MAC layer, access to each subchannel can be decoupled from each other, i.e., one subchannel is an independent and basic unit for random access. For the MAC layer, to fully take advantage of the full-duplex operation, a new frame structure is designed as shown in Fig. 2a. It contains three fields: the PHY header (PHY-hdr), the VMAC-hdr, and the MAC-data. The mapping from the frame structure to one

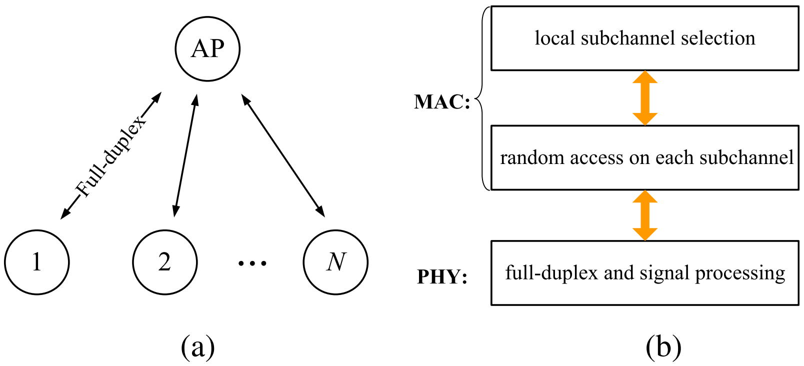


Fig. 1. (a) The network model and (b) a hierarchical perspective of our protocol design.

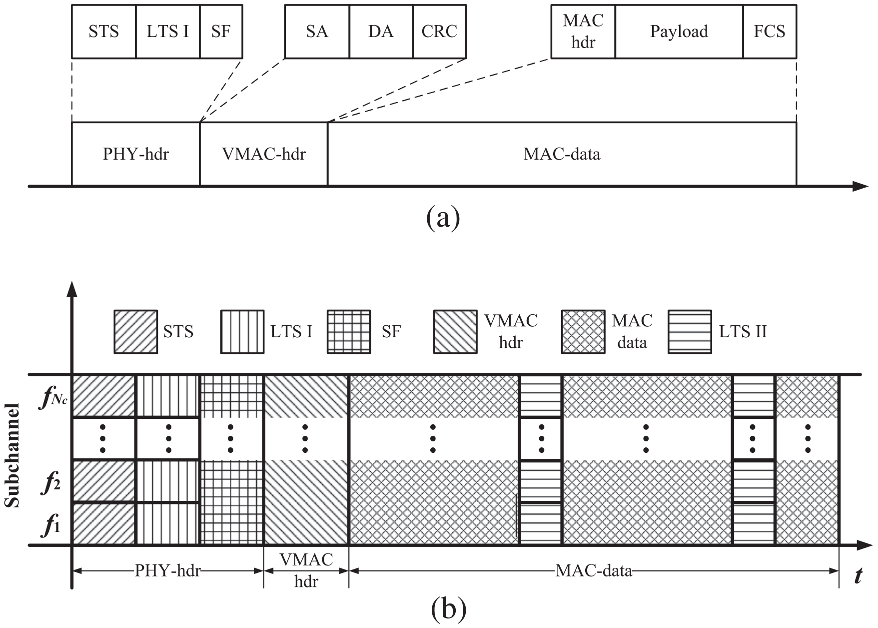


Fig. 2. (a) The frame structure and (b) the mapping from the frame structure to one of subchannels in an OFDMA system.

subchannel in an OFDMA system is shown in Fig. 2b. Compared to that in IEEE 802.11 standard, the PHY preamble is modified: the PHY-hdr is changed and the VMAC-hdr is added. The MAC-data, which includes MAC header (MAC-hdr), payload, and frame check sequence (FCS), is unchanged and compatible with existing standards.

The PHY-hdr in the PHY preamble consists of three fields: the short training sequence (STS) is used to detect the arrival of a packet, the long training sequence (LTS) I is designed for channel estimation, and the signal field (SF) indicates the modulation and coding type of the MAC-data. The STS and the LTS I are transmitted on each subcarrier of a subchannel with binary phase shift keying (BPSK) modulation without coding. The SF adopts BPSK modulation and 1/2 coding rate. In addition, due to the channel variation with time, the known LTS II is periodically (the period is less than the channel coherence time) inserted in between the MAC-data symbols to correct channel estimation errors, similar to LTE-A [3]. The receiver removes LTS II symbols to recover the MAC-data.

Since the MAC frame is scrambled and interleaved, its MAC addresses (both source and destination) cannot be detected at the PHY layer. Thus, a VMAC-hdr is added. It includes three parts: the source address (SA) is a 48-bit MAC address of the transmitter, the destination address (DA) is a 48-bit MAC address of the receiver, and the cyclic redundancy check (CRC) is utilized to determine whether the VMAC-hdr is corrupted or not. All SA, DA, and CRC sequences adopt BPSK modulation and 1/2 coding rate. The VMAC-hdr supports two critical functions. *First*, it helps catch a *full-duplex opportunity*. Taking Fig. 3a as an example, clients *A* and *B* can hear each other and communicate with AP. In Fig. 3b, *A* initiates a transmission to AP. After AP receives the VMAC-hdr, it knows *A* is sending a packet to itself. Thus, if AP also has a packet for *A*, it catches this *full-duplex opportunity* and transmits the packet to *A*.

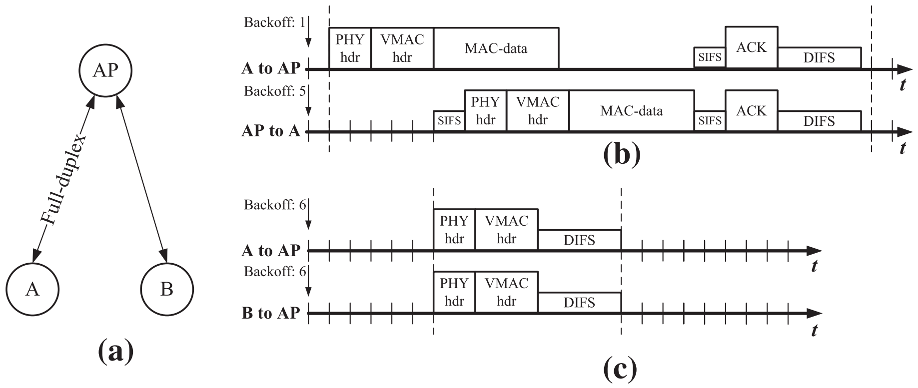


Fig. 3. Functions of VMAC-hdr. (a) The communication topology, (b) AP captures a full-duplex opportunity, and (c) two clients suspend transmissions.

Second, VMAC-hdr helps enable *collision detection*. As shown in Fig. 3c, clients *A* and *B* are sending packets to AP at the same time. Since *A* and *B* can hear each other due to full-duplex communications, each client knows there is another client transmitting to AP after decoding the VMAC-hdr. Thus, each client infers that a collision occurs at AP, and suspends its transmission immediately.

To support full-duplex random access, another important function at AP is to send *jamming signals*, i.e., the same jamming sequence is sent in parallel on all N_C subcarriers in a subchannel, as shown in Fig. 4a. The *jamming signal* plays two roles. The *first* is to terminate the collision at AP caused by concurrent transmissions of hidden nodes. For instance, in Fig. 4b, clients *A* and *B* communicate with AP and they cannot hear each other. Thus, it is possible that their transmissions collide at AP, as shown in Fig. 4c. After receiving the signal for a period of $T_{(PHY_{hdr}+VMAC_{hdr})}$, AP finds the VMAC-hdr is collided. It continues listening to the subchannel for a short interframe space (SIFS) time. If AP finds the subchannel is still busy, it transmits a *jamming signal* to stop the transmissions of *A* and *B*. *Second*, AP broadcasts two consecutive *jamming signals* on all subchannels periodically to help clients harvest multi-user diversity distributedly. The first *jamming signal* is to keep all clients silent, so that the second one can be used by each client to accurately measure its subchannel signal-to-noise-ratio (SNR), that is needed for subchannel selection, as discussed in Section 3.2.

To facilitate above two functions, a *jamming signal* needs to resist multi-user interference and noise. Thus, a pseudorandom sequence (e.g., *m*-sequence [14]) can be used as a *jamming signal*. For an L length *m*-sequence $c = [c[1], c[2], \ldots, c[L]]$ known to all clients, each client searches for it in an incoming signal by performing cross-correlation between c and the arrival signal. When c exists in the received signal, the correlation would yield a high correlation value. For example, on subchannel k, there exist N clients transmitting to AP simultaneously. AP sends the same jamming sequence c on all N_C subcarriers. For client 1, the correlation value $\theta_1(r)$ can be used to indicate the existence of a *jamming signal*:

$$\begin{aligned}\theta_1(r) &= \sum_{n=1}^{N_C}\left|\sum_{i=1}^{L} c^*[i]\,y_n[i+r]\right| \Bigg/ \sum_{n=1}^{N_C}\sum_{i=1}^{L}|c[i]|^2 \\ &= \sum_{n=1}^{N_C}\left|\sum_{i=1}^{L} c^*[i]\left(H_n^{(01)}c[i+r] + \sum_{j=2}^{N} y_n^{(j1)}[i+r] + w_n[i+r]\right)\right| \Bigg/ \sum_{n=1}^{N_C}\sum_{i=1}^{L}|c[i]|^2, \qquad (1)\end{aligned}$$

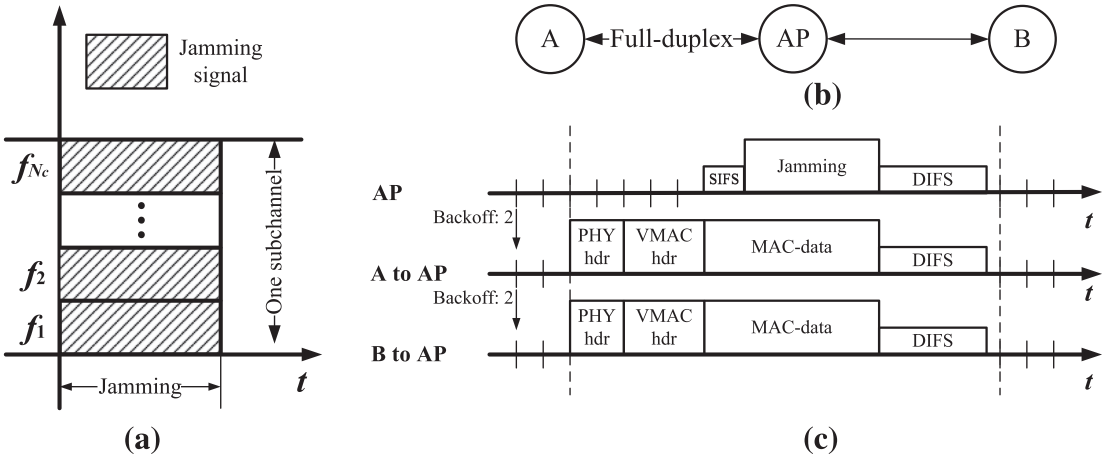


Fig. 4. Jamming signal: (a) jamming signal is transmitted on each subcarrier in a subchannel, (b) the communication topology, and (c) AP sends a jamming signal to stop clients *A* and *B* to reduce collision time.

where $H_n^{(01)}$ is the channel gain of subcarrier n between AP and client 1, and $H_n^{(01)}c$ is the received *jamming signal* from AP at client 1. The $y_n^{(j1)}$ represents the signal from client j to client 1 and w_n is the additive white Gaussian noise, on subcarrier n. Since the pattern c is independent of the signal from client j and the noise, the correlation with these terms approaches 0. Thus, $\theta_1(r)$ can be approximated by

$$\theta_1(r) \approx \sum_{n=1}^{N_C} \left| \sum_{i=1}^{L} c^*[i] H_n^{(01)} c[i+r] \right| \Big/ \sum_{n=1}^{N_C} \sum_{i=1}^{L} |c[i]|^2. \tag{2}$$

3. Design of our FD-CSMA/CD protocol

In this section, we present a hierarchical design of the FD-CSMA/CD protocol: a novel full-duplex random access is developed on each subchannel; on top of the random access per-subchannel, two simple but effective subchannel selection schemes are proposed, and either of them can be locally operated by each client to harvest multi-user diversity.

3.1. Random access design on each subchannel

Since each subchannel can be considered independently, we focus our random access design on one subchannel. Other subchannels adopt the same random access mechanism in parallel.

It should be noted that some MAC mechanisms for full duplex communication networks have been studied in [15]. However, our paper are featured by several differences. First, this paper is focused on a typical point-to-multipoint network where a complete design is developed to address various scenarios of full duplex communications. Second, a novel mechanism is designed for detecting collisions in a fast way. Third, a more concrete mechanism is provided for sending jamming signals and handling ACKs in full duplex communications. Such differences will be illustrated in the detailed mechanisms of our protocol.

In our protocol, all the nodes (AP and clients) contend for transmissions distributedly. Each node with a packet to transmit monitors the activity of the subchannel. If the subchannel is idle for a period of DCF interframe space (DIFS), each node starts the backoff process, and initiates a transmission when the backoff timer decreases to 0. If the subchannel is busy, each node freezes its backoff timer and takes different actions corresponding to the VMAC-hdr information, e.g., capturing a *full-duplex opportunity*.

The backoff time is uniformly chosen in the range of $[0, cw-1]$, where cw is determined by the binary exponential backoff algorithm: cw is set to the minimum window size value CW_{min} at the first attempt or after a successful initiation of a transmission, and is doubled after each unsuccessful initiation of a transmission, up to a maximum value $CW_{max} = 2^{N_B} CW_{min}$, where N_B is the number of maximum backoff stage. AP and clients can have different CW_{min} and N_B. It should be noted that a successful initiation of a transmission of a node means that the node launches a transmission as well as the packet is successfully transmitted. In other words, a successful packet transmission by catching a *full-duplex opportunity* is not considered as a successful initiation of a transmission, which is different from the standard CSMA protocol. The backoff slot is equal to the clear subchannel assessment (CSA) time σ, and a node is allowed to start a backoff process and initiate a transmission at the beginning of each time slot σ.

Due to the full-duplex feature in the PHY layer, each node conducts a *full-duplex sensing*: sensing the subchannel status no matter it is transmitting or not. The basic rules for random access at the clients and AP are twofold. The *first* rule is about capturing a *full-duplex opportunity*. For the case of non-transmitting clients and AP, by decoding the VMAC-hdr after receiving the arrival signal for $T_{(PHY_{hdr}+VMAC_{hdr})}$, if the client (AP) finds the packet is from AP (the client) to itself and it also has a packet for AP (the client), it can capture a *full-duplex opportunity*, as shown in Fig. 5a and b. If AP transmits to a client, but it finds another client is transmitting to itself based on the VMAC-hdr, it terminates its current transmission and then captures a *full-duplex opportunity* with the new client, as shown in Fig. 5c.

The *second* rule is on *collision detection* and transmission suspension. With a correctly decoded VMAC-hdr, for a transmitting AP, if it finds another client is sending a packet to itself, it suspends its current transmission immediately, as shown in Fig. 5c; for a transmitting client, if it finds another client is sending a packet to AP, it suspends its transmission immediately, as shown in Fig. 6a. If the VMAC-hdr is found collided (i.e., CRC is wrong), the transmitting client (AP) suspends its transmission immediately, as shown in Fig. 6b.

Besides the above two rules, AP also takes the responsibility of preventing collisions caused by hidden nodes via two mechanisms: (1) when AP is receiving a packet from a client but is not transmitting, it protects this transmission by sending a *busytone signal* that is known to all clients, as shown in Figs. 5a and 7; (2) when AP identifies a collision caused by hidden nodes, it transmits a *jamming signal* to stop all transmissions to reduce the collision time, as shown in Fig. 8a and b. It should be noted that all clients and AP constantly detect the *jamming signal*. When a *jamming signal* is detected, they suspend transmissions immediately.

The detailed operations of clients and AP are described below.

Operations of clients: For clients, two scenarios (initiating a transmission or not) are considered.

(I) During the backoff process, the subchannel becomes busy. The client freezes its backoff timer. After receiving the arrival signal for a period of $T_{(PHY_{hdr}+VMAC_{hdr})}$, it takes actions based on the VMAC-hdr. If the client finds the packet is from AP to itself and it also has a packet for AP, it continues listening to the subchannel for a period of SIFS: if the subchannel is still busy, the client transmits its packet to AP, capturing the *full-duplex opportunity*, as shown by the action of client A in Fig. 5a; if the subchannel becomes idle, the client keeps silent. However, if the client finds the packet is not for itself

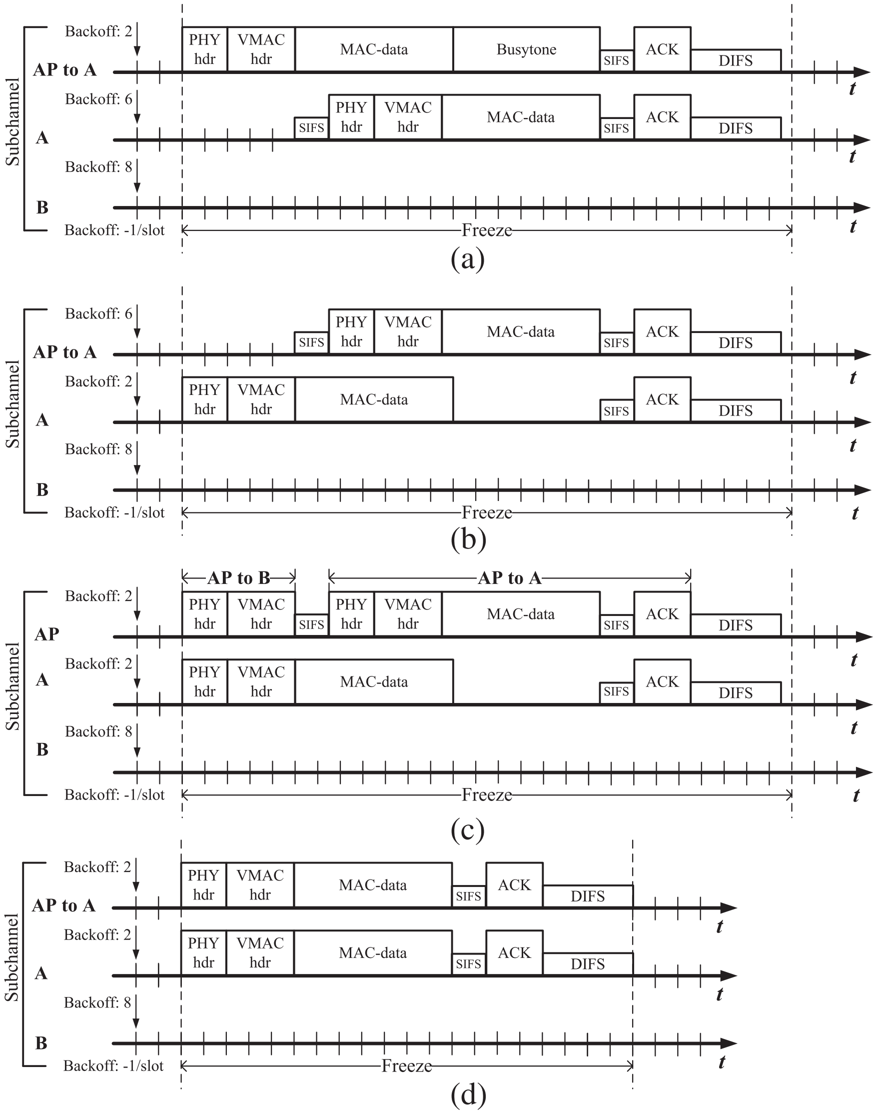


Fig. 5. Successful full-duplex transmissions (clients *A* and *B* can hear each other and communicate with AP): (a) *A* captures a full-duplex opportunity with AP, (b) AP captures a full-duplex opportunity with *A*, (c) a transmitting AP suspends its transmission to *B* and captures a full-duplex opportunity with *A*, and (d) *A* and AP initiate transmissions to each other simultaneously.

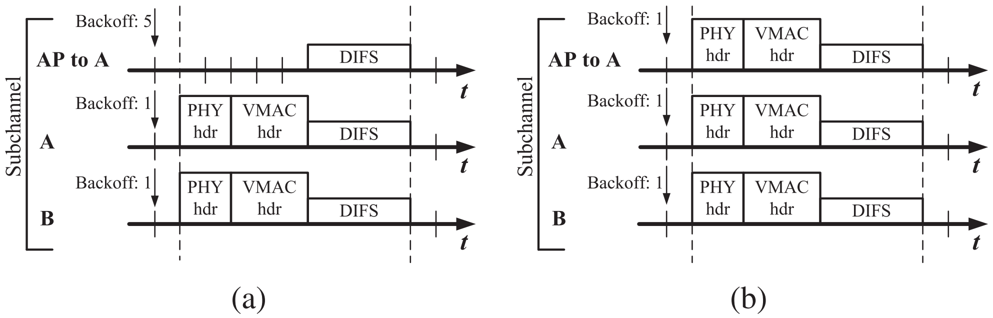


Fig. 6. Collisions are detected and all nodes suspend transmissions to stop collisions (clients *A* and *B* can hear each other and contend for transmissions to AP): (a) AP is listening and (b) AP is transmitting.

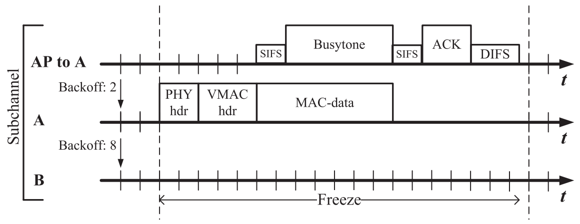


Fig. 7. Client *A* sends a packet to AP, but AP has no packet for *A*. Thus, AP transmits a busytone signal to prevent transmissions of hidden nodes.

or the VMAC-hdr is collided, it keeps silent until the transmission is over, as shown by the action of client *B* in Fig. 5a.

(II) During the backoff process, the subchannel is idle until the client initiates a transmission. The client keeps sensing the subchannel status while transmitting. If the client observes the following four cases, then it continues transmitting until the transmission is over. *First*, the non-transmitting AP captures a *full-duplex opportunity*. The client realizes the packet is from AP to itself by decoding the VMAC-hdr, as shown in Fig. 5b. *Second*, AP initiates a transmission to another client simultaneously. By decoding the VMAC-hdr, the client knows the transmission is from AP to another client, so it keeps transmitting. However, AP suspends its current transmission (one operation rule of AP). Then, AP can capture a *full-duplex opportunity* if it has a packet for the client, as shown in Fig. 5c. *Third*, AP initiates a transmission to the client simultaneously. The client knows the packet is from AP to itself based on the VMAC-hdr, as shown in Fig. 5d. *Fourth*, the subchannel is busy with a *busytone signal* sent by AP (one function of AP), as shown in Fig. 7.

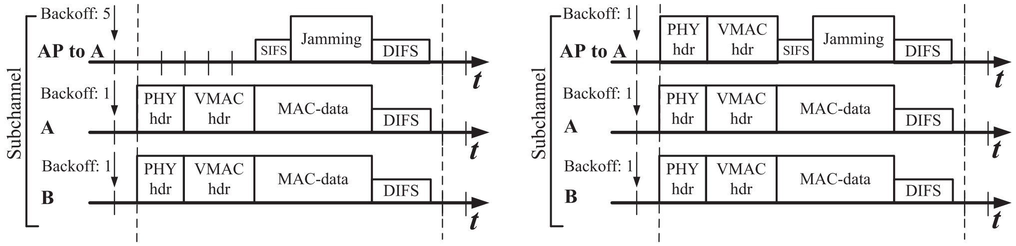
Apart from above successful cases, if the client detects the following two cases, then it suspends its transmission immediately. *First*, by decoding the VMAC-hdr, the client knows another client is transmitting a packet to AP, as shown in Fig. 6a. *Second*, based on the collided VMAC-hdr, the client knows its packet is in collision, as shown in Fig. 6b.

Operations of AP: We also consider two scenarios depending on whether AP is initiating a transmission or not. Since AP is more powerful than clients and is able to communicate with hidden clients, two more functions are supported by AP: sending *busytones* and *jamming signals*.

(I) During the backoff process, the subchannel becomes busy. AP freezes its backoff timer. After receiving the incoming signal for a period of $T_{(PHY_{hdr}+VMAC_{hdr})}$, it takes actions according to the VMAC-hdr. *First*, the VMAC-hdr is correctly decoded, indicating only one client is transmitting to AP. If AP also has a packet for this client, it catches the *full-duplex opportunity* to send its packet to the client after SIFS (SIFS is a preparation time between receiving and transmitting signals), as shown in Fig. 5b. If AP has no packet for the client, it needs to send a *busytone* during the client's transmission to prevent transmissions of hidden clients, as shown in Fig. 7. *Second*, if AP finds the VMAC-hdr is collided, it continues listening to the subchannel for a time of SIFS: if the subchannel becomes idle, AP keeps silent and then starts the backoff process after a total DIFS idle time, as shown in Fig. 6a; if the subchannel is still busy, AP sends a *jamming signal* to terminate all transmissions, as shown in Fig. 8a.

(II) The subchannel is idle until the backoff timer of AP becomes 0. As a result, AP initiates a transmission. If AP has packets to more than one clients, it randomly chooses one of them as the intended client. When AP is transmitting, it keeps on sensing the subchannel. If AP observes the following three cases, then it keeps on sending the packet until the transmission is over. *First*, the subchannel is idle, because the intended client has no packet for AP. *Second*, the intended client captures a *full-duplex opportunity*, as shown in Fig. 5a. *Third*, the intended client initiates a transmission simultaneously with AP, as shown in Fig. 5d.

Besides the above successful cases, if AP detects the following two cases, it needs to suspend its transmission immediately. *First*, another client initiates a transmission simultaneously with AP. Based on the correctly decoded VMAC-hdr, AP knows the packet is from another client instead of the intended client. Thus, AP suspends its current transmission immediately. Then, if AP has a packet for this new client, it captures the *full-duplex opportunity*, as shown in Fig. 5c. *Second*, with a collided VMAC-hdr, AP knows a collision occurs. Thus, it suspends its transmission immediately and keeps on listening to the subchannel for SIFS: if the subchannel becomes idle, AP keeps silent, as shown in Fig. 6b; if the subchannel is still busy, the collision is caused by hidden clients, so AP transmits a *jamming signal*, as shown in Fig. 8b.



(a) (b)

Fig. 8. Jamming signal is transmitted by AP to stop the collision caused by hidden nodes (clients *A* and *B* cannot hear each other and communicate with AP): (a) AP is listening and (b) AP is transmitting.

Full duplex opportunity for a *asymmetrical dual-link* [15] are not considered in our MAC protocol. In other words, parallel communications from AP to one (e.g., client A) and from another client (e.g., client B which is hidden from client A) to AP are not allowed in our MAC protocol. The reason is twofold. In the first scenario, AP transmits a packet to client A first, but client A has no packets for AP. In this case, there is no way to expect an uplink transmission must be from a hidden node (e.g., client B). To avoid possible collisions (to client A) caused by the uplink transmission from another client to AP, AP has to disable all uplink transmissions except for that from client A. In the second scenario, client A transmits a packet to AP first, but AP has no packets for client A. In this case, AP can potentially send a packet to a hidden node (e.g., client B). To do so, AP needs to determine which node is hidden from client A. Moreover, an ACK mechanism needs to be redesigned such that ACKs from AP and client B can form a proper full duplex communication. To avoid such complications, the second scenario is not taken into account in our protocol. It should be noted that ignoring the second scenario does not impact the saturated network throughput, because AP can always form full duplex communications with any of its client under saturated mode.

3.2. Subchannel selection scheme

On top of the full-duplex random access on each subchannel, each client needs to select a set of subchannels to access. The most straightforward scheme is to access all subchannels, denoted as the *Access-All* scheme.

In an OFDMA system, each client experiences independent frequency-selective fading and adopts adaptive modulation and coding (AMC) for different subchannels. As shown in Table 1, given a target bit error rate (BER) 10^{-5}, the range of the received SNR value γ is divided into 7 regions, each of which corresponds to a specific modulation and coding mode. Therefore, instead of the *Access-All* scheme, an effective subchannel selection scheme is needed to harvest multi-user diversity. Taking Fig. 9 for example, subchannel 3 is in deep fade for client B, but is great for client A. Thus, it is preferred to let A use this subchannel. If A and B employ the *Access-All* scheme, B will contend to share subchannel 3, which degrades the throughput. Intuitively, the best performance can be achieved by assigning a subchannel to the client with the best subchannel quality. To implement such a scheme, subchannel information of the entire network needs to be collected by the central node (AP), and then the subchannel selection problem can be solved via centralized optimization algorithms to achieve various objectives as in [4–6].

However, we focus on a simple but effective decentralized approach, as it can be locally executed by each client and thus is more practical. One simple subchannel selection is to let each client choose the best X subchannels to access, denoted as the *Access-Best-X* scheme. This scheme is effective thanks to two facts: (1) the good subchannels of one client are often different from those of another client, so multi-user diversity can be harvested; (2) since all the clients select the same number of subchannels, fairness among all clients is considered. Another simple scheme is to let each client select subchannels in high AMC modes Y (i.e., in high SNR), denoted as *Access-Mode-Y* scheme. For example, with $Y = \{6, 7\}$, each client only selects subchannels in AMC mode 6 or 7. In this scheme, only subchannels with enough high SNR are selected, so the system throughput is enhanced.

To realize *Access-Best-X* and *Access-Mode-Y* schemes, each client needs to track its subchannel status. Since AP periodically broadcasts known *jamming signals*, each client can easily measure its subchannel SNR, which can be considered as the subchannel status between the client and AP (assuming the channel is reciprocal).

Table 1
Adaptive modulation and coding (target BER 10^{-5}).

Mode	Modulation	Coding rate	R_i (bits/symbol)	γ_i (dB)
1	BPSK	1/2	0.5	8.3–11.6
2	QPSK	1/2	1.0	11.7–13.2
3	QPSK	3/4	1.5	13.3–18.9
4	16-QAM	1/2	2.0	19.0–20.9
5	16-QAM	3/4	3.0	21.0–28.0
6	64-QAM	2/3	4.0	28.1–29.1
7	64-QAM	3/4	4.5	$\geqslant 29.2$

4. Performance analysis

To conduct throughput analysis of our FD-CSMA/CD protocol, we consider the saturation throughput (i.e., AP and clients always have packets for transmission). All nodes in the network are assumed to hear each other, and they can perfectly catch *full-duplex opportunities* and *detect collisions* with the VMAC-hdr. Since the random access on each subchannel is operated independently in our protocol, our analysis is focused on a certain subchannel k (other subchannels have the same result). On subchannel k, one AP and N clients contend to transmit packets. There are 7 AMC modes as shown in Table 1, and N_i clients are in mode i. Thus, $N = \sum_i^7 N_i$.

To analyze the FD-CSMA/CD protocol, the discrete-time Markov chain model proposed in [16] is extended. In our protocol, AP and clients have different Markov chains. For AP, CW_{min} and N_B are set to W_0 and m_0; P_{t0} and p_0 represent the transmission probability and the conditional collision probability in a randomly chosen time slot. For all N clients, CW_{min} and N_B are set to W and m; P_t and p are

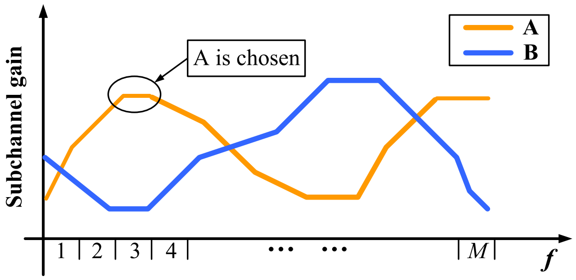


Fig. 9. Harvesting the multi-user diversity.

the transmission probability and the conditional collision probability in a random time slot. The following relationships among above different parameters exist:

$$P_{t0} = \frac{2}{1 + W_0 + p_0 W_0 \sum_{i=0}^{m_0-1} (2p_0)^i}, \tag{3}$$

$$p_0 = 1 - \left[(1 - P_t)^N + \frac{C_N^1}{N} P_t (1 - P_t)^{N-1} \right], \tag{4}$$

$$P_t = \frac{2}{1 + W + pW \sum_{i=0}^{m-1} (2p)^i}, \tag{5}$$

$$p = 1 - (1 - P_t)^{N-1}, \tag{6}$$

where (3) and (5) are obtained based on the Markov chains of AP and clients by applying the result in [16]. According to our protocol, a successful initiation of a transmission of AP occurs when all the clients are silent or the intended client initiates a transmission simultaneously, which leads to (4). For a client, a successful initiation of a transmission happens when all other clients are silent. Thus, (6) is obtained. With above four equations, P_{t0}, p_0, P_t and p can be calculated. Let P_{tr} be the probability that there exists at least one transmission on the subchannel in a considered time slot:

$$P_{tr} = 1 - (1 - P_{t0})(1 - P_t)^N. \tag{7}$$

Thus, $1 - P_{tr}$ is the probability that the time slot is idle.

To obtain the saturation throughput, the probabilities of successful and failed full-duplex transmissions need to be calculated, respectively.

For a successful full-duplex transmission on subchannel k, there exist four cases as follows.

(1) AP initiates a transmission to a client and all clients are listening. The corresponding client catches the *full-duplex opportunity* for transmission, as shown in Fig. 5a. This probability, denoted as P_{s1}, is given as:

$$P_{s1} = P_{t0}(1 - P_t)^N, \tag{8}$$

and the transmission time lasts $T_{s1}[i]$ for AMC mode $i : T_{s1}[i] = 2T_{Hdr} + T_{MAC_{data}}[i] + 2T_{SIFS} + T_{ACK}[i] + T_{DIFS}$, where $T_{Hdr} = T_{PHY_{hdr}} + T_{VMAC_{hdr}}$ and $T_{MAC_{data}}[i] = T_{MAC_{hdr}}[i] + T_{Payload}[i] + T_{FCS}[i]$.

(2) One client initiates a transmission to AP, while AP and other clients are listening. AP catches the *full-duplex opportunity*, as shown in Fig. 5b. This probability, denoted as P_{s2}, is calculated as:

$$P_{s2} = C_N^1 (1 - P_{t0}) P_t (1 - P_t)^{N-1}, \tag{9}$$

and the transmission time lasts $T_{s2}[i]$ for AMC mode $i : T_{s2}[i] = 2T_{Hdr} + T_{MAC_{data}}[i] + 2T_{SIFS} + T_{ACK}[i] + T_{DIFS}$.

(3) A client initiates a transmission to AP, but AP initiates a transmission to another client at the same time. AP first suspends its transmission after checking the VMAC-hdr, and then captures a *full-duplex opportunity*, as shown in Fig. 5c. This probability, denoted as P_{s3}, is calculated as:

$$P_{s3} = C_N^1 \frac{N-1}{N} P_{t0} P_t (1 - P_t)^{N-1}, \tag{10}$$

and the transmission time lasts $T_{s3}[i]$ for AMC mode $i : T_{s3}[i] = 2T_{Hdr} + T_{MAC_{data}}[i] + 2T_{SIFS} + T_{ACK}[i] + T_{DIFS}$.

(4) AP initiates a transmission to a client, and the intended client initiates a transmission to AP simultaneously, as shown in Fig. 5d. This probability, denoted as P_{s4}, is computed as:

$$P_{s4} = \frac{C_N^1}{N} P_{t0} P_t (1 - P_t)^{N-1}, \tag{11}$$

and the transmission time lasts $T_{s4}[i]$ for AMC mode $i : T_{s4}[i] = T_{Hdr} + T_{MAC_{data}}[i] + T_{SIFS} + T_{ACK}[i] + T_{DIFS}$.

As for the failed transmission on subchannel k, it happens when more than one of N clients are transmitting packets to AP simultaneously, as shown in Fig. 6. This probability, denoted as P_c, is given as:

$$P_c = 1 - (1 - P_t)^N - C_N^1 P_t (1 - P_t)^{N-1}, \tag{12}$$

and the collision time lasts T_c for all AMC modes: $T_c = T_{Hdr} + T_{DIFS}$.

The performance of our FD-CSMA/CD protocol can be measured by the following four metrics:

(a) Normalized throughput $T_r[k]$: the fraction of the total time used to send payload symbols successfully on subchannel k,

$$T_r[k] = \frac{2(P_{s1} + P_{s2} + P_{s3} + P_{s4}) \Sigma_{i=1}^{7} \frac{N_i T_{Payload}[i]}{N}}{(1 - P_{tr})\sigma + T_s + P_c \widetilde{T_c}}, \tag{13}$$

where $T_s = \Sigma_{i=1}^{7} \frac{N_i(\widetilde{T_{s1}}[i]P_{s1} + \widetilde{T_{s2}}[i]P_{s2} + \widetilde{T_{s3}}[i]P_{s3} + \widetilde{T_{s4}}[i]P_{s4})}{N}$. Here $\widetilde{Z}$ is the minimum number that is larger than Z and divisible by backoff slot σ.

(b) Absolute throughput $T_a[k]$: payload bits transmitted successfully per second on subchannel k,

$$T_a[k] = \frac{2(P_{s1} + P_{s2} + P_{s3} + P_{s4}) \Sigma_{i=1}^{7} \frac{N_i T_{Payload}[i] R_i}{N}}{(1 - P_{tr})\sigma + T_s + P_c \widetilde{T_c}}, \tag{14}$$

where R_i is the rate in AMC mode i, as shown in Table 1. For the entire OFDMA system, there are M subchannels, so the system absolute throughput T_a^s can be calculated by: $T_a^s = \sum_{k=1}^{M} T_a[k]$.

(c) Average idle time per successful full-duplex transmission on subchannel k (normalized by σ) $T_{idle}[k]$:

$$T_{idle}[k] = \frac{1 - P_{tr}}{P_{s1} + P_{s2} + P_{s3} + P_{s4}}. \tag{15}$$

(d) Average collision time per successful full-duplex transmission on subchannel k (normalized by σ) $T_{col}[k]$:

$$T_{col}[k] = \frac{P_c \widetilde{T_c}}{(P_{s1} + P_{s2} + P_{s3} + P_{s4})\sigma}. \tag{16}$$

5. Simulation results

In this section, the performance of the FD-CSMA/CD protocol is evaluated by extensive simulations and our analytical model is validated. The bandwidth of the OFDMA system is 20 MHz and the symbol duration is 4 us. There are total 16 subchannels, each of which is formed by a block of 4 subcarriers. The channel is frequency-selective Rayleigh fading, and the delay spread is assumed to be 300 ns. All the nodes can hear each other in the network. The basic simulation parameters are shown in Table 2. Two kinds of applications are considered: (1) data application: the payload of a packet is set to 1500 Bytes; (2) voice application: the corresponding payload is set to 240 Bytes. For these two applications, $T_{MAC_{data}}$, $T_{Payload}$ and T_{ACK} under different AMC modes are shown in Table 3. Without loss of generality, the minimum window sizes W_0 and W are set equal to CW_{min}, and the maximum backoff stages m_0 and m are set to N_B in simulations.

In Figs. 10 and 11, the saturation throughputs of the FD-CSMA/CD protocol are shown with respective to (w.r.t) the number of clients for data and voice applications, respectively, on one subchannel. Thanks to full-duplex communications, the throughput is significantly improved. For instance, for the case of Mode = 1 and $CW_{min} = 16$ in Fig. 10a, the normalized throughput T_r is about 1.85, nearly twice the throughput of perfect half-duplex communications (T_r=1). Moreover, unlike half-duplex random access (e.g., 802.11 DCF), the throughput of our protocol is not sensitive to the number of clients due to the CSMA/CD-like operation. Thus, our protocol is scalable to the network size. The throughput variation trend is related to the minimum window size CW_{min}. For $CW_{min} = 16$, the throughput decreases slowly as the number of clients increases. In contrast, for $CW_{min} = 256$, the trend is opposite. For the data application in Fig. 10, the throughput gap between our random access scheme and the scheduled one (i.e., no wasted idle and collision time) is small in AMC mode 1, e.g., for $CW_{min} = 16$, this gap is about 3%. However, with AMC mode 7, the gap is enlarged to about 17%, because the payload of a packet is shorter using a higher AMC mode but the overhead is unchanged. On average of all AMC modes, the throughput of our random access scheme is about 90% of the scheduled one, which shows the high efficiency of our FD-CSMA/CD protocol. For the voice application in Fig. 11, the throughput versus the number of clients has the same variation trend as the data application. Since the payload of a packet in the voice application is 240 Bytes, much smaller than 1500 Bytes in the data application, the throughput gap between the random access and the scheduled scheme becomes larger. In addition, we also check the validity of our analytical model. It is shown that our analytical model is extremely accurate (differences below 0.5%): the analytical results (lines) coincide with the simulation results (marks) in all cases.

Fig. 12a and b shows the idle and collision time per successful full-duplex transmission w.r.t different number of clients on one subchannel by simulations. We observe that the idle time decreases but the collision time increases, as the number of clients increases. Moreover, the rate of change varies with different CW_{min}. For a certain CW_{min}, if the idle time drops faster than the collision time rises, the throughput is improved, as shown by the case of $CW_{min} = 256$ in Fig. 10. In contrast, if the idle time decreases more slowly than the collision time increases, the throughput drops, as in the case of $CW_{min} = 16$ in Fig. 10.

Table 2
Basic simulation parameters for OFDMA systems.

$T_{PHY_{hdr}}(STS)$	24 us	$T_{VMAC_{hdr}}(SA)$	96 us
$T_{PHY_{hdr}}(LTSI)$	64 us	$T_{VMAC_{hdr}}(DA)$	96 us
$T_{PHY_{hdr}}(SF)$	48 us	$T_{VMAC_{hdr}}(CRC)$	16 us
$T_{Jamming}$	252 us	σ	24 us
T_{SIFS}	32 us	T_{DIFS}	56 us

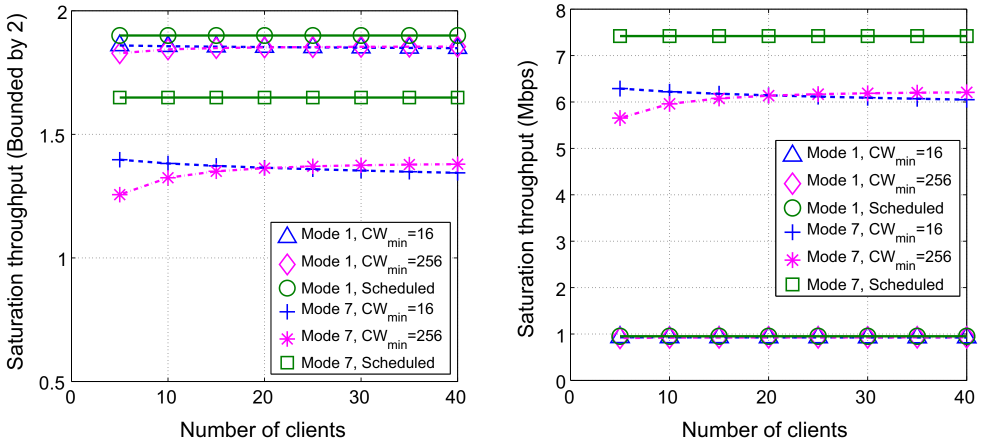
Table 3
$T_{MAC_{data}}$, $T_{Payload}$ and T_{ACK} in different AMC modes.

Mode	$T_{MAC_{data}}$ (us)		$T_{Payload}$ (us)		T_{ACK} (us)
	Data	Voice	Data	Voice	
1	24,560	4384	24,000	3840	360
2	12,280	2192	12,000	1920	248
3	8188	1464	8000	1280	212
4	6140	1096	6000	960	192
5	4092	732	4000	640	176
6	3068	548	3000	480	164
7	2728	488	2668	428	164

In Fig. 13, the saturation throughputs w.r.t the minimum window size CW_{min} and the maximum backoff stage N_B on one subchannel are shown respectively by simulations. In Fig. 13a, for different number of clients, we can choose appropriate CW_{min} to achieve the maximum throughput, e.g., for 5 clients, the maximum throughput is achieved at a CW_{min} of 16. Fig. 13b shows that the throughput is enhanced as the maximum backoff stage N_B increases, for each case of different number of clients. When N_B is larger than 5, the increment rate is small and the throughput becomes stable.

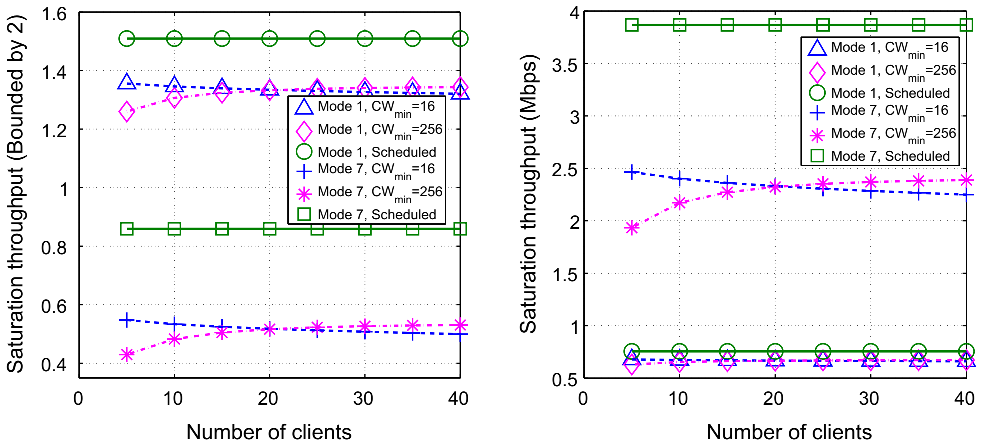
The simulation results of the average packet delay of each client for different cases are shown in Table 4, where CW_{min} and N_B are fixed to 16 and 6, respectively, and S_{ch} is the number of subchannels occupied by each client for transmission. The results show that the average delay of the data application is larger than that of the voice application in each case, due to the longer payload of a packet in data applications. Moreover, the packet delay drops in a higher AMC mode due to a higher transmission rate, increases with more contending clients because of reduced transmission opportunity per client, and decreases with the number of occupied subchannels as a result of parallel packet transmissions on several subchannels. For the voice application, the delay is sensitive (requirement: $\leqslant$100 ms). Consider the scenario of 20 clients on each subchannel. For our *Access-Best-X* (X = 2) scheme, if AMC mode 1 is adopted by all clients (i.e., the worst case), the packet delay is only 58 ms (i.e., the case of Mode = 1 and $S_{ch} = 2$). If a moderate AMC mode 4 is used, the delay is reduced to 23 ms. For our *Access-Mode-Y* ($Y = \{6, 7\}$) scheme, only subchannels in mode 6 or 7 are selected by each client, so the delay is smaller than 45 ms (i.e., the case of Mode = 4 and Sch = 1). Thus, our two subchannel selection schemes are applicable to delay sensitive applications.

The system throughput w.r.t the number of clients for different subchannel selection schemes is shown in Fig. 14. The average SNR of each client is uniformly



(a) (b)

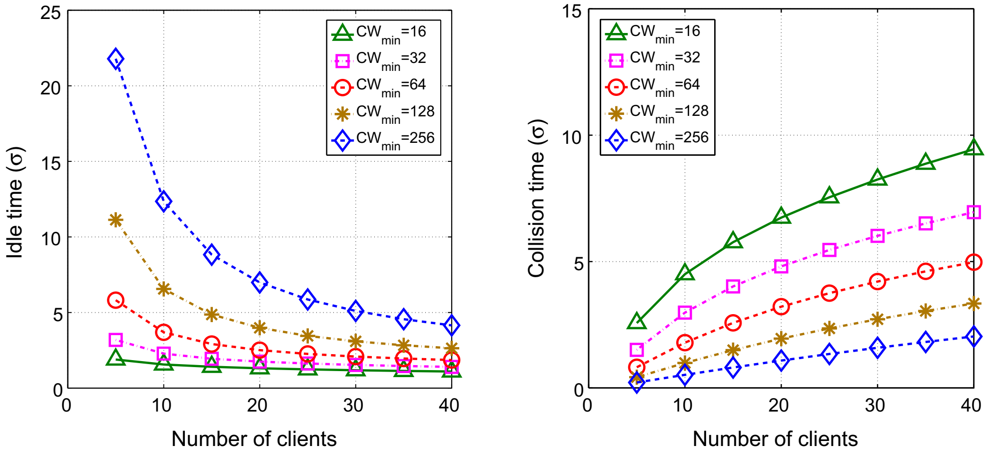
Fig. 10. Saturation throughput of the data application, w.r.t the number of clients for different CW_{min} and AMC modes: (a) normalized throughput T_r and (b) absolute throughput T_a; N_B is set to 6. (Analytical results: lines; simulation results: marks.)



(a) (b)

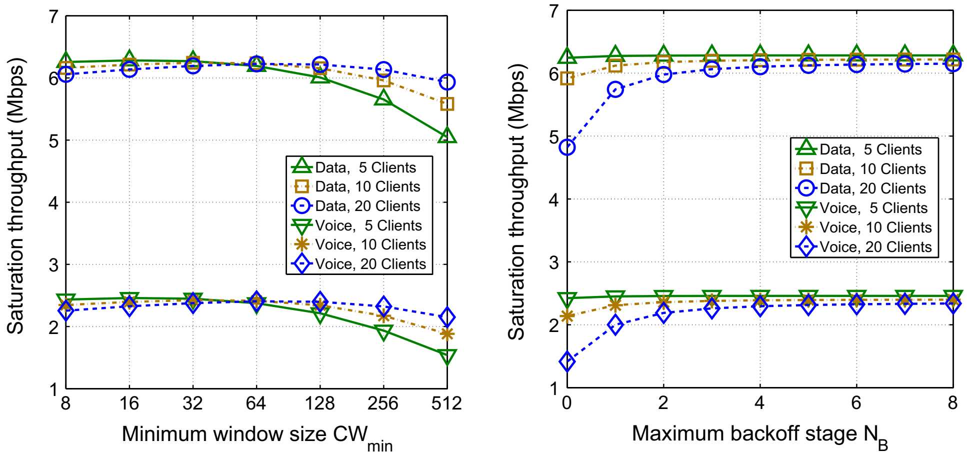
Fig. 11. Saturation throughput of the voice application w.r.t the number of clients for different CW_{min} and AMC modes: (a) normalized throughput T_r and (b) absolute throughput T_a; N_B is set to 6 (analytical results: lines; simulation results: marks).

distributed in [15,25] dB. The *Scheduled* scheme is conducted as follows: allocate each subchannel to clients that use the highest AMC mode on this subchannel, and our random access mechanism is adopted by the selected clients on each subchannel. It shows that the *Access-All* scheme has the worst performance and its throughput slowly decreases as the number of clients increases due to collisions. In contrast, the throughputs of our *Access-Best-X* and *Access-Mode-Y* schemes are much higher and increase with more clients because of the multi-user diversity. On average, they can achieve about 80% and 94% of the throughput of the *Scheduled* one for data applications, which indicates the high efficiency of our schemes. Moreover, the *Access-Mode-Y* scheme is better than the *Access-Best-X* scheme, which is more evident in a dense network (e.g., 20 clients) where it is highly possible that at least one client uses high AMC modes Y in each subchannel. However, with the *Access-Mode-Y* scheme, some clients may not have a chance to access subchannels, when none of their subchannels is within modes Y. Thus, fairness is compromised. In the *Access-Best-X*, each client accesses X subchannels, which maintains fairness. As a result, when comparing subchannel selection schemes, it is necessary to consider tradeoff between fairness and throughput. To achieve the best performance in *Access-Best-X* and *Access-Mode-Y* schemes, parameters X and Y vary with different network sizes, e.g., $X = 8$ and $Y = \{5, 6, 7\}$ for 5 clients, but $X = 6$ and $Y = \{6, 7\}$ for 10 clients. Thus, each client needs to adjust X or Y properly according to the updated network size, which can be estimated with accumulated VMAC-hdr information or can be determined by AP.



(a) (b)

Fig. 12. (a) Idle and (b) collision time per successful full-duplex transmission (normalized by σ) w.r.t the number of clients for different CW_{min}; N_B is set to 6.



(a) (b)

Fig. 13. Saturation throughput for data and voice applications in AMC mode 7 w.r.t: (a) minimum window size CW_{min} (N_B is fixed to 6), and (b) maximum backoff stage N_B (CW_{min} is fixed to 16).

Table 4
Average packet delay of each client for different cases.

Mode	S_{ch}	5 Clients (ms)		10 Clients (ms)		20 Clients (ms)	
		Data	Voice	Data	Voice	Data	Voice
1	1	128	28	259	57	517	115
	2	64	15	130	29	258	58
	4	32	7	65	14	129	29
4	1	36	11	73	23	146	45
	2	18	6	36	12	73	23
	4	9	3	18	6	37	11
7	1	20	8	39	16	78	33
	2	10	4	19	8	39	16
	4	6	2	10	5	19	8

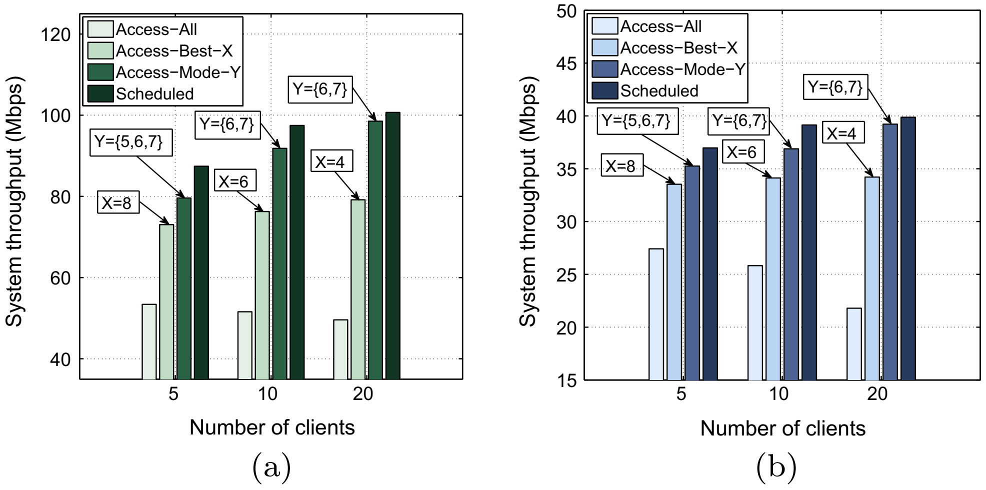


Fig. 14. System throughput T_a^s w.r.t the number of clients for different subchannel selection schemes: (a) data application and (b) voice application; CW_{min} and N_B are set to 16 and 6, respectively.

Among the existing random MAC protocols [7–9] for OFDMA wireless networks, the scheme in [9] achieves the highest throughput, but its performance is much lower than FD-CSMA/CD (even if the subchannel selection scheme is *Access-All*). The reason is twofold: (1) each radio considered in FD-CSMA/CA is capable of full duplex communications, which results in higher spectrum efficiency; (2) by leveraging full duplex communications, the problems in existing random MAC protocols have been solved and thus greatly improve throughput.

6. Conclusion

In this paper, a novel full-duplex OFDMA random access protocol was proposed by exploiting the full-duplex feature in the PHY layer. Compared to random access mechanisms in conventional half-duplex OFDMA systems, the throughput is significantly improved by utilizing idle subchannels, capturing full-duplex opportunities, reducing collision time, and harvesting multi-user diversity. In the future research, detailed analysis on fairness and throughput tradeoff of our schemes will be conducted. In addition, how to implement our protocol in a real system is also an interesting topic.

Acknowledgment

This research work is supported by ZTE Cooperation, the Oriental Scholar Program of Shanghai Municipal Education Commission, and National Natural Science Foundation of China (NSFC) No. 61172066. The authors would like to thank these sponsors for their generous support.

References

[1] K. Etemad, Overview of mobile wimax technology and evolution, IEEE Commun. Mag. 46 (10) (2008) 31–40.

[2] C. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer, W. Caldwell, IEEE 802.22: the first cognitive radio wireless regional area network standard, IEEE Commun. Mag. 47 (1) (2009) 130–138.

[3] A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, T. Thomas, Lte-advanced: next-generation wireless broadband technology, IEEE Wireless Commun. 17 (3) (2010) 10–22.

[4] M. Ergen, S. Coleri, P. Varaiya, Qos aware adaptive resource allocation techniques for fair scheduling in OFDMA based broadband wireless access systems, IEEE Trans. Broadcast. 49 (4) (2003) 362–370.

[5] L. Wan, W. Ma, Z. Guo, A cross-layer packet scheduling and subchannel allocation scheme in 802.16e OFDMA system, in: IEEE Wireless Communications and Networking Conference, IEEE, 2007, pp. 1865–1870.

[6] V. Singh, V. Sharma, Efficient and fair scheduling of uplink and downlink in IEEE 802.16 OFDMA networks, IEEE Wireless Communications and Networking Conference, vol. 2, IEEE, 2006, pp. 984–990.

[7] Y.-J. Choi, S. Park, S. Bahk, Multichannel random access in OFDMA wireless networks, IEEE J. Select. Areas Commun. 24 (3) (2006) 603–613.

[8] H. Kwon, H. Seo, S. Kim, B.G. Lee, Generalized CDMA/CA for OFDMA systems: protocol design, throughput analysis, and implementation issues, IEEE Trans. Wireless Commun. 8 (8) (2009) 4176–4187.

[9] X. Wang, H. Wang, A novel random access mechanism for OFDMA wireless networks, in: Proceedings of the IEEE GLOBECOM, IEEE, 2010, pp. 1–5.

[10] J.I. Choi, M. Jain, K. Srinivasan, P. Levis, S. Katti, Achieving single channel, full duplex wireless communication, in: Proceedings of the ACM MobiCom, ACM, 2010, pp. 1–12.

[11] M. Jain, J.I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, P. Sinha, Practical, real-time, full duplex wireless, in: Proceedings of the ACM MobiCom, ACM, 2011, pp. 301–312.

[12] Y. Hua, P. Liang, Y. Ma, A.C. Cirik, Q. Gao, A method for broadband full-duplex mimo radio, IEEE Signal Process. Lett. 19 (12) (2012) 793–796.

[13] W. Cheng, X. Zhang, H. Zhang, Imperfect full duplex spectrum sensing in cognitive radio networks, in: Proceedings of the 3rd ACM Workshop on Cognitive Radio Networks, ACM, 2011, pp. 1–6.

[14] D. Tse, P. Viswanath, Fundamentals of Wireless Communication, Cambridge University Press, 2005.

[15] N. Singh, D. Gunawardena, A. Proutiere, B. Radunovic, H.V. Balan, P. Key, Efficient and fair mac for wireless networks with self-interference cancellation, in: 2011 International Symposium of Modeling and Optimization of Mobile, Ad Hoc, and Wireless Networks, IEEE, 2011, pp. 94–101.

[16] G. Bianchi, Performance analysis of the IEEE 802.11 distributed coordination function, IEEE J. Select. Areas Commun. 18 (3) (2000) 535–547.

Xudong Wang is currently with the UM-SJTU Joint Institute, Shanghai Jiao Tong University. He is a distinguished professor (Shanghai Oriental Scholar) and is the director of the Wireless and NetworkinG (WANG) Lab. He is also an affiliate faculty member with the Electrical Engineering Department at the University of Washington. Since he received the Ph.D. degree in Electrical and Computer Engineering from Georgia Institute of Technology in August 2003, he has been working as a senior research engineer, senior network architect, and R&D manager in several companies. He has been actively involved in R&D, technology transfer, and commercialization of various wireless networking technologies. His research interests include wireless communication networks, smart grid, and cyber physical systems. He holds several patents on wireless networking technologies and most of his inventions have been successfully transferred to products. Dr. Wang is an editor for IEEE Transactions on Mobile Computing, IEEE Transactions on Vehicular Technology, Elsevier Ad Hoc Networks, and ACM/Kluwer Wireless Networks. He was also a guest editor for several journals. He was the demo co-chair of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (ACM MOBIHOC 2006), a technical program co-chair of Wireless Internet Conference (WICON) 2007, and a general co-chair of WICON 2008. He has been a technical committee member of many international conferences and a technical reviewer for numerous international journals and conferences. Dr. Wang is a senior member of IEEE and was a voting member of IEEE 802.11 and 802.15 Standard Committees.

Aimin Tang received the B.S. degree in Electrical and Computer Engineering from Shanghai Jiao Tong University (SJTU), Shanghai, China, in 2013. He is currently a Ph.D. student with the Wireless and Networking Lab at the University of Michigan-Shanghai Jiao Tong University Joint Institute. His current research interests include full duplex communications, rateless coding, and software defined wireless networks.

Pengfei Huang received the B.E. degree in electrical engineering from Zhejiang University, Hangzhou, in 2010, and the M.S. degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, in 2013. He is currently working toward the Ph.D. degree in the Department of Electrical and Computer Engineering at the University of California, San Diego.