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Research Article

OFDMA-Based Medium Access Control for Next-Generation WLANs

H. M. Alnuweiri,[1] Y. Pourmohammadi Fallah,[2] P. Nasiopoulos (EURASIP Member),[3] and S. Khan[3]

[1] *Department of Electrical and Computer Engineering, Texas A&M University at Qatar, P.O. Box 23874, Doha, Qatar*
[2] *Institute of Transportation Systems (EECS, CEE), University of California Berkeley, 604 Davis Hall, Berkeley, CA 94720-1710, USA*
[3] *Department of Electrical and Computer Engineering, The University of British Columbia, 5500-2332 Main Mall, Vancouver, BC, Canada V6T 1Z4*

Correspondence should be addressed to H. M. Alnuweiri, hussein.alnuweiri@qatar.tamu.edu

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Existing medium access control (MAC) schemes for wireless local area networks (WLANs) have been shown to lack scalability in crowded networks and can suffer from widely varying delays rendering them unsuited to delay sensitive applications, such as voice and video communications. These deficiencies are mainly due to the use of random multiple access techniques in the MAC layer. The design of these techniques is highly linked to the choice of the underlying physical (PHY) layer technology. The advent of new PHY schemes that are based on orthogonal frequency division multiple access (OFDMA) provides new opportunities for devising more efficient MAC protocols. We propose a new adaptive MAC design based on OFDMA technology. The design uses OFDMA to reduce collision during transmission request phases and makes channel access more predictable. To improve throughput, we combine the OFDMA access with a carrier sense multiple access (CSMA) scheme. Data transmission opportunities are assigned through an access point that can schedule traffic streams in both time and frequency (subchannels) domains. We demonstrate the effectiveness of the proposed MAC and compare it to existing mechanisms through simulation and by deriving an analytical model for the operation of the MAC in saturation mode.

1. Introduction

The throughput and scalability of a wireless local area network (WLAN) are greatly dependent on its medium access control (MAC) protocol and its associated multiple access (MA) scheme. The most important aspect of a MAC protocol is the ability to efficiently coordinate access among multiple contending stations (STA) for a shared resource. MAC protocols for WLANs must also address several other key issues, such as coping with a varying and potentially large number of users, maintaining acceptable delays for multimedia traffic, transmitting over a randomly varying wireless channel, and introducing minimal overhead to the transmitted data stream.

The original designs of MAC protocols for WLANs included the CSMA/CA (CSMA with collision avoidance) mechanism in IEEE 802.11 WLANs and time division multiple access (TDMA) in HIPERLAN [1–3]. The latter was never really accepted by the industry, while IEEE 802.11 (dubbed WiFi) quickly became the technology of choice for WLANs worldwide. TDMA required complex scheduling in a central node and used fixed time slot-based transmissions, as opposed to variable length packet transmissions. Such a scheme had limited flexibility in low cost WLANs that are dominated by bursty data traffic. Instead, simpler random access CSMA-based protocols were preferred. However, as the experience with deploying 802.11 based networks matured, it became obvious that the simple CSMA/CA MAC mechanism can become quite inefficient, mostly due to its collision prone random access and recovery processes. Although mechanisms to control and minimize the impact of collisions (such as collision detection in the CSMA/CD mechanism of Ethernet) exist, a wireless medium does not allow for collision detection through power measurement. Furthermore, the collision avoidance mechanism (CA), used in CSMA/CA protocols, has a very limited capacity in improving the performance of the MAC. In fact, the performance of the CSMA/CA protocol used in IEEE 802.11 standard deteriorates rapidly as the number of stations increases and/or the amount of traffic grows [4].

One of the main objectives of our proposed MAC is to address this issue of low throughput (or efficiency) of the CSMA/CA MAC layer under heavy loading conditions in crowded WLANs. Another major issue is to improve support for persistent real-time traffic, produced by multimedia applications, while maintaining the random access and variable length packet transmission features of the original MAC. To achieve these goals, we utilize the orthogonal frequency division multiple access (OFDMA) scheme [5, 6]. OFDMA is currently used in the IEEE 802.16e standard for wireless metropolitan area networks [7]. Multimedia traffic has traditionally suited more centrally controlled MAC protocols such as TDMA, over a random access network [8]. In our proposed MAC, we utilize controlled CSMA access to provide better scheduling opportunity for multimedia traffic. At the same time, we preserve and increase the efficiency of the random access feature through combining OFDMA with CSMA.

In the next section, we briefly review some relevant works and techniques and elaborate on the advantages of an OFDMA-based MAC. We present our OFDMA-based MAC design in Section 3. The proposed design is then analyzed and evaluated in Section 4. Open issues and future research directions are discussed in Section 5.

2. Multiple Access Scheme for WLANs

Providing contention minimized random access is one of the main aspects of our proposed design. For this purpose, we can combine CSMA with any multiple access scheme such as frequency division multiple access (FDMA), code division multiple access (CDMA) (similar to the method in [9]), TDMA, or OFDMA.

It is well known that OFDMA has a clear capacity advantage over FDMA, therefore we do not discuss FDMA here. Also FDMA-based schemes such as multichannel slotted Aloha have been well examined in the past [10]. As described below OFDMA has several advantages over CDMA and TDMA schemes as well and is our primary choice.

In CDMA technique, the transmitted signal is multiplexed with a high bit rate pseudocode sequence, to distinguish it from other simultaneous transmissions in time and frequency. However, this high bit rate transmission is susceptible to channel frequency selectively and requires complex channel equalization at the receiver to recover from the resulting intersymbol interference. It is widely known that indoor radio channels experience high frequency selectively due to their rich scattering environments. Furthermore, CDMA schemes suffer from the near-far phenomenon; a nearby STA's high power transmission may completely block out faraway STA's lower power transmissions. OFDM-based techniques such as OFDMA have been proven to perform well and are more easily implemented for WLANs.

TDMA-based MAC designs are known to be mostly suitable for constant bit rate voice communications but not for bursty data or video traffic [8]. Moreover, in TDMA, where STAs share the available bandwidth in time, uplink connection request transmissions have to happen in exact time slots. Such a mechanism has strict synchronization that needs and requires all STAs to be aware of these time slots and to be perfectly aligned with the central controller. If CSMA rules are used with TDMA to avoid collision and relax synchronization requirements, the interframe spacing required between slots will reduce the throughput of the system.

OFDMA, on the other hand, is based on OFDM, which is inherently more suited for wireless channels. OFDM can convert the frequency selective channel into a parallel but orthogonal set of smaller frequency-flat channels which the receiver can deal with without needing expensive channel equalization. With the use of guard intervals, ISI can be completely avoided in OFDM systems. OFDMA allows assigning these subchannels to different STAs. Given this ability of OFDMA and its superior performance in wireless environment typical to WLANs, a system using OFDMA is of more interest to future multiple access wireless networks.

Some recent works on MAC design based on OFDMA or OFDM are reported in [11, 12]. The design in [12] is based on a combination of OFDM and TDMA and attempts to provide better performance through intelligent assignment of subcarriers in time domain. This scheme is not designed for efficient random access which is one of our objectives. The work in [11] presents a MAC that relies on OFDMA for all of its operation and resolves collisions through changing subchannel assignments. While such methods and the standard 802.16 MAC protocol [7] provide novel schemes using OFDMA, they require complex scheduling, are more suitable for consistent voice-like traffic, and do not provide efficient random access capabilities. We present a new design that is different in many aspects and is more suitable for heterogeneous traffic, which is typical for WLANs. Our design is also more flexible and easily extendable for operation in different environments.

2.1. OFDMA System Specifications. An important aspect of an OFDMA system that is of interest to the design of a MAC scheme is the number of subchannels. OFDMA allows subcarriers to be grouped and assigned to different users. These groups of subcarriers are known as subchannels (also called subbands in some literature). In our scheme, the number of subchannels is primarily determined by the MAC to achieve optimal performance. This issue is discussed in Section 4.

The number of subcarriers in an OFDMA scheme is a design factor that can be adjusted for different environments. For IEEE 802.16 standard, a fixed separation of subcarriers is considered [7, 13]. Depending on channel bandwidth, which may range from 1.25 to 40 MHz, the number of subcarriers ranges from 128 to 2048. The 802.11 a/g standard uses OFDM with 64 subcarriers in a 20 MHz BW [1]. We do not make an assumption on the number of subcarriers in this article.

Our scheme does not require any specific choice of guard interval for OFDM symbols, or the guard bands for the channel. Any existing PHY specification for OFDMA or OFDM systems (e.g, from 802.16 or 802.11 standards) is acceptable. Subchannels formed from grouping subcarriers together may be adjacent or may be distributed. In general, distributed permutations outperform adjacent subchannels in high mobility applications while adjacent subcarriers can be used to provide higher throughput in fixed, portable, and low mobility environments [13].

3. Hybrid OFDMA/CSMA MAC Design

Our proposed MAC uses a two-stage frame delivery process, consisting of a transmission opportunity request (TR) phase, followed by a scheduled data transmission (ST) phase. A station willing to send data has to inform the central controller, the access point (AP), of its required transmission opportunity (TO). The TO request is sent in a contention phase with reduced collision (using OFDMA). Once the AP receives this message, it will assign contention free TOs to the station. A station can also transmit a more elaborate TO request, such as, a periodic TO assignment for its voice or video traffic. The AP can then regularly assign TOs to the station, without needing subsequent TO requests from the station (similar to unsolicited access grant in 802.16 [7]). Apart from the obvious decrease in control messages that need to be sent, such a mechanism reduces contention-based TO requests, thereby providing additional QoS guarantees for multimedia traffic. Following the grant of a contention free TO, the station can send longer data frames.

The two phases (ST and TR) are separated by time spaces (called interframe spaces or IFSs) that coordinate transition between phases using carrier sensing. A simplified view of the MAC operation timeline is depicted in Figure 1. We define the IFS values in our mechanism as: minimum IFS (MIFS), controlled access IFS (CIFS), and random access IFS (RIFS); where MIFS < CIFS < RIFS. These values are PHY specific and are, as in the 802.11 standard [1], determined by the specifications of the clear channel assessment (CCA) mechanism, MAC and PHY processing delays, and transceiver turn around times. For example, MIFS is the nominal time that the MAC and PHY will require to receive the last symbol of a frame at the air interface, process the frame, and prepare to respond with the first symbol on the air interface. CIFS is MIFS plus the CCA time, and RIFS is CIFS plus CCA time.

The TR phase starts after an MIFS interval, following an explicit TR start message from the AP or automatically after sensing the entire channel (not just the subchannel) idle for RIFS seconds. Transition between TR and ST phases happens after sensing the entire channel idle for CIFS after the backoff slots in the TR phase. If there has been no message in the TR phase, and AP has no data or message to send, the TR phase is repeated with stations starting to count backoff slots after a RIFS again. In our scheme, the TR phase always uses OFDMA, whereby a set of subcarriers (i.e., a subchannel) is assigned to each station for sending the TR messages. When the number of subchannels is equal to or more than the number of stations, the TR phase will be contention free. To increase the utilization and the multiplexing gain for the TR phase, we can assign more than one station to each subchannel; this means that a probability of collision between stations exists within each subchannel. However, this probability can be capped through dynamically adjusting the number of subchannels and the number of stations assigned to each subchannel. A CSMA/CA scheme is used to resolve the probable collisions, and a limited number of time slots are allocated for the backoff process. This constitutes a hybrid and dynamic OFDMA/CSMA scheme for the TR phase. We evaluate the operation of different TR phase settings later in this article.

When the TR phase completes, the AP processes the received TRs and schedules the subsequent ST phase. Transmission in the ST phase is contention free and can be from one station to the AP or to another station. The contention free transmission may be done in several ways. A simple method is to assign all subcarriers to one station and schedule stations in the time domain (i.e., OFDM with time domain multiplexing). In this mode, either a transmission schedule (TS) for stations is broadcasted, or individual TO assignment messages are sent to stations at appropriate times. The other option for the ST phase is to utilize OFDMA to allow concurrent data transmission by multiple stations. In this mode, a subchannel assignment (SA) map is broadcasted to inform the stations of their assigned subchannels. The SA map may include downlink transmissions by the AP, and therefore it is not equivalent to the uplink map (UL Map) in other standards. Utilizing OFDMA in the ST phase incurs great complexity in scheduling stations and may lead to inefficiency if a schedule that fills all subchannels at all times is not feasible. In this article, we only consider the former case where OFDMA is used in the TR phase and the ST phase uses controlled CSMA.

3.1. TO Request (TR) Phase.

During the TR phase, each station can transmit its TO requests in its assigned subchannel according to the CSMA/CA rules. Each subchannel runs its own separate CSMA/CA procedure. An important part of the design for our system is the subchannel assignment for random access messages, that is, TO requests. Assuming that N subcarriers (e.g., $N = 256$) are available, and there are n stations, we divide the channel to M subchannels, or in other words, assign $k = N/M$ subcarriers to each station. If $M = 1$ or $k = N$, we have an all OFDM system with CSMA/CA operation, similar to 802.11. If $M = n$, we have the other extreme ($k = N/n$), which is an OFDMA system without contention (no need for CSMA). A balance can be found between the wasted bandwidth due to collision and that due to subchannels sometimes remaining unused. This is discussed in more detail in the next section.

To handle the possible contention in each subchannel, we employ a CSMA/CA mechanism. Each subchannel uses its

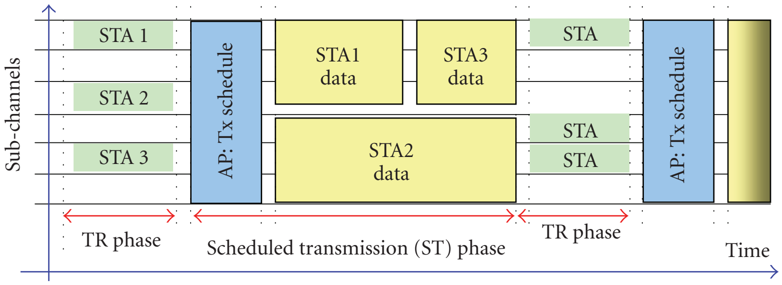


FIGURE 1: Two-phase MAC operation: TO request (TR) phase, scheduled transmission (ST) phase.

own separate CSMA/CA procedure. Collisions are resolved using a random exponential backoff process. There are other collision resolution mechanisms such as changing subchannel assignment as described in [11]. However, such methods increase system complexity without providing significant gain in performance. Thus we use independent CSMA/CA mechanisms in each subchannel. The CSMA/CA scheme operates similarly to the process used in 802.11, except for the carrier sensing in each subchannel that uses OFDM symbol detection instead of simple channel power sensing.

The TR phase timeline includes a limited number (denoted as q) of minimum length time slots followed by a transmission opportunity for the TR message. The minimum time slots are used by the backoff process of the CSMA/CA scheme to avoid collision. The duration of such time slots is derived from the minimum time that is needed for the detection of an OFDMA symbol in the subchannel. When a station wants to transmit a TR message, it chooses a random backoff number from the interval $(0, CW_{\min})$. The stations decrement their backoff counter with each empty slot in the TR phase passing; when the counter reaches zero, they transmit the TR message immediately if they sense no other station already transmitting in the subchannel. After a station transmits a TR message, it will wait for a response from the AP, in the form of a poll or position in the schedule. If no response is received, the station will interpret this as a collision (or lost packet), double its contention window size, and then select a new random backoff number from the new contention window. The lower and upper limits of the contention window size can be traffic class dependent to provide prioritized quality of service. These values can also be adaptively assigned to stations by the AP, to achieve better performance.

To achieve even higher performance, the AP can dynamically change the number of subchannels and assign stations to different subchannels. This can be done using the network allocation vector (NAV) field in the standard CTS frame sent by the AP. The access point keeps track of the number of associated stations (Q) and the number of active stations (n). Active stations are ones that have set up a traffic stream with the AP, have indicated a nonzero queue size, or have transmitted in the past L beacon intervals (L being a configuration parameter). When assigning stations to subchannels, the access point first assigns the active stations and then distributes the rest of the stations.

3.2. Scheduled Transmission (ST) Phase.

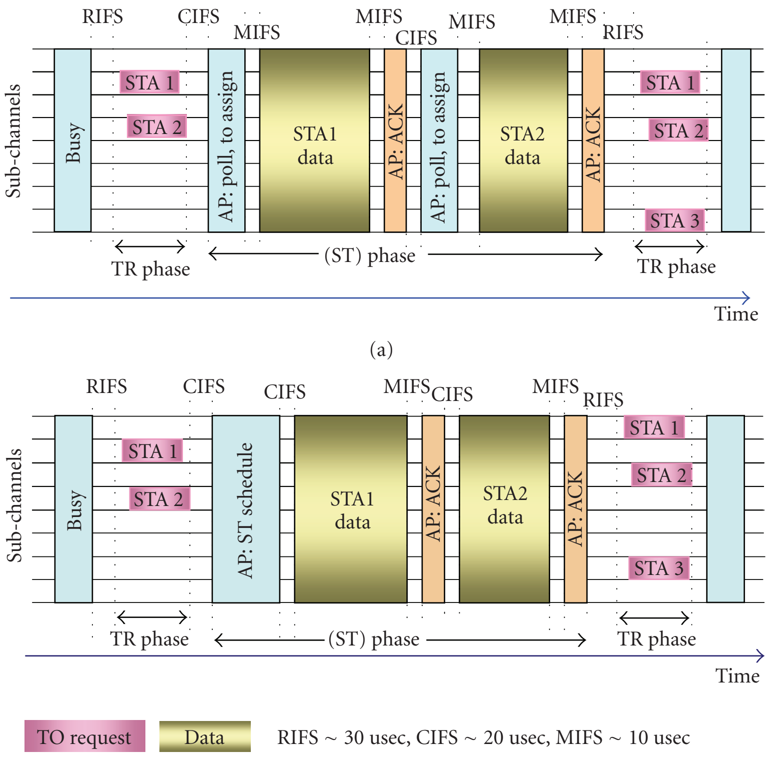
The ST phase starts after sensing the channel idle for a CIFS following a TR phase (Figure 2). Transmission of TR messages in the TR phase starts during the first q backoff slots and lasts for a fixed duration of the TR message. This means that if there is at least one TR message, the ST phase has to wait until the end of the TR messages. If there are no TR messages, the ST phase may start after the backoff slots plus CIFS.

All subchannels in the ST phase are assigned to only one station at a given time (i.e., OFDM operation), and stations are scheduled in time. The schedule and order of access to the medium are determined by the access point and enforced through broadcast messages indicating the schedule, or through explicit poll (TO assignment) messages. Transmission by stations is only allowed in response to such messages. This policy along with a carrier sense mechanism is used to coordinate contention free access to the medium during the ST phase. This mechanism utilizes the interframe spaces described earlier.

The first message in ST is sent by the AP. If this message is a schedule announcement, the stations will send their responses in the specified order with CIFS spacing. Acknowledgements are sent after MIFS following the data frame. This process continues until the end of the scheduled TOs with CIFS spacing separating the TOs. Since MIFS < CIFS, the AP can reclaim the channel by transmitting after an MIFS, and change the schedule or end the ST phase.

If explicit poll messages are used instead of transmission schedules, the AP will send the first poll (TO assignment) message after CIFS > MIFS. All message exchanges during a transmission opportunity use MIFS spacing. The use of time-based TO allows for multirate operation of the PHY while maintaining the temporal fairness (as discussed in other works [14]). The next TO is always initiated by the AP after a CIFS. This process continues until the end of the ST phase when the AP either indicates the end through an *ST end* frame or leaves the channel idle for at least RIFS > CIFS (triggering a TR phase). Figure 2 demonstrates the timeline of the ST phase in two modes: using the explicit polling and using schedule announcement messages.

There are several options for enhancing the efficiency of the ST phase. One option is to piggyback the poll messages on the acknowledgement packets if the recipient of the station's packet is the access point (which is the case in most scenarios). Further enhancements can be achieved using block acknowledgment.



(b)

Figure 2: Hybrid MAC operation, different operation methods for ST phase: (a) explicit polls, (b) schedule broadcast.

3.3. Quality of Service and Multimedia Support. To enable QoS and multimedia provisioning for the proposed MAC, we propose two classes of service: prioritized random access and scheduled guaranteed access. To provide priority services, we specify different limits for contention window sizes. The smaller the limits are, the higher the priority of access to the channel will be. In this case, it is also required that the access point schedules TOs for higher priority stations ahead of the others (using a simple priority scheduler).

The scheduled guaranteed access mechanism is usually used for traffic of persistent session (e.g., voice or video) type. This mode requires more complex scheduling schemes in the access point. The AP must also be aware of the traffic behavior of the requesting stations and their QoS requirements. When a traffic stream is set up between the AP and a station, the scheduler inside the AP is configured to send unsolicited TO assignments (e.g., polls) to the station. For this purpose any scheduling mechanism can be used. An example of such mechanisms is the controlled access phase scheduling mechanism [9], which was originally developed for 802.11e MAC but is applicable with modifications to the MAC protocol proposed here.

4. Analysis and Performance Evaluation

To analyze the performance of the proposed MAC, we first analytically model the MAC operation and derive the throughput in saturation mode (in which all stations always have data to send). We extend the analysis by simulation experiments for different traffic load conditions.

4.1. Analytical Modeling of the MAC in Saturation Mode. Knowing that each subchannel employs a CSMA/CA scheme with exponential random backoff, similar to the distributed coordination function (DCF) of 802.11, we can reuse the model developed for its backoff process [4]. This model has been shown to accurately model the exponential backoff process in saturation mode [14–16].

A further extension of the model described here can include nonsaturation scenarios, but this will not be considered here any further. The work in [4] models the MAC events of successful transmission, collision, and idle waiting. The duration between transitions to each state is called a “slot” and the probability of a slot containing each event is found. For the model in [4] to be correct, two fundamental assumptions are made. First, after each idle slot, each station may attempt to transmit with an independent and constant probability τ. Second, regardless of the number of past collisions, a transmission attempt may result in a collision with an independent and constant probability p. The backoff process is then modeled by a two-dimensional Markov chain and the following two equations are found for τ and p [4]:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW\left(1-(2p)^{m}\right)}, \qquad (1)$$
$$p = 1-(1-\tau)^{n-1},$$

where n is the number of contending stations, W is $CW_{\min}$, and m is defined so that $CW_{\max} = W \cdot 2^m$. Solving these equations using numerical methods, one can find τ and p based on the known values of W, m, and n. Using the values of τ and p, we can find the probability that at least one transmission happens in a given slot (P_{tr}) and the probability of a transmission in a slot being successful (P_s). P_{tr} is the complement of the probability of no station transmitting ($P_{\text{idle}} = (1-\tau)^n$) and is simply derived as follows:

$$P_{\text{tr}} = 1 - (1-\tau)^n. \tag{2}$$

P_s can be described as the probability of exactly one transmission given that there has been a transmission on the channel, thus

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{3}$$

The above probabilities are valid for our system and 802.11 DCF; however, their meanings are different in each MAC. For DCF, these probabilities describe the transition probabilities between successful collision and idle states. Whereas, in our system they only describe the probabilities that each of the q backoff slots in a TR phase subchannel contains a transition to successful collision or idle states. For our MAC scheme, the value of n in the above equations changes to the number of stations assigned to each subchannel.

For our system, we need to find the probability that a TR phase subchannel is successful in delivering a request. This probability, denoted as $P_{\text{suc}}^{\text{TR}}$, can be found considering that a successful transmission can happen at any slot during a TR phase (P_sP_{tr}), assuming that its previous slots were idle ($(P_{\text{idle}})^{i-1}$ for ith slot). This can be written by summing the probabilities of the ith slot being successful and all i-1 previous slots empty. Knowing that the number of backoff slots in a TR phase is q, we have

$$\begin{aligned} P_{\text{suc}}^{\text{TR}} &= P_sP_{\text{tr}} + P_{\text{idle}}P_sP_{\text{tr}} + (P_{\text{idle}})^2P_sP_{\text{tr}} + \cdots + (P_{\text{idle}})^{q-1}P_sP_{\text{tr}} \\ &= P_sP_{\text{tr}}\sum_{i=1}^{q}(P_{\text{idle}})^{i-1}. \end{aligned} \tag{4}$$

Similarly, we can find the probability of a TR phase subchannel being idle as the probability that all q slots are idle:

$$P_{\text{idle}}^{\text{TR}} = (P_{\text{idle}})^q. \tag{5}$$

Using the above probabilities, we can find the expected throughput of the system by dividing the expected amount of traffic delivered in each ST phase, by the expected duration of the ST phase ($E[\text{ST}]$) plus the expected duration of the TR phase ($E[\text{TR}]$). The expected amount of traffic served in each ST depends on the size of the TOs assigned by the AP. For simplicity, we assume that the TOs of all stations contain a single packet transmission. The expected length of a packet ($E[P]$) times the expected number of successful TR subchannels ($\overline{M}_{\text{suc}}$) gives the expected amount of data served in an ST. If the number of stations assigned to all subchannels is equal, we have $\overline{M}_{\text{suc}} = M \cdot P_{\text{suc}}^{\text{TR}}$, otherwise $\overline{M}_{\text{suc}} = \sum_{i=1}^{M} P_{\text{suc}}^{i}$, where P_{suc}^{i} is the $P_{\text{suc}}^{\text{TR}}$ of the ith subchannel. With these values, we have the throughput as follows:

$$S = \frac{\overline{M}_{\text{suc}} \cdot E[P]}{E[\text{ST}] + E[\text{TR}]}. \tag{6}$$

The length of the ST phase can be found by multiplying the expected number of successful TR subchannels and the expected duration of a TO ($E[\text{TO}]$), plus the duration of transmitting the SA map of length L_{SA} (T_{SA}) if one is used

$$\begin{aligned} E[\text{ST}] &= T_{\text{SA}} + \overline{M}_{\text{suc}} \cdot E[\text{TO}], \\ E[\text{TO}] &= 2 * H_{\text{phy}}/R_b + (H_{\text{mac}} + E[P] + L_{\text{ack}})/R \\ &\quad + T_{\text{MIFS}} + 2\delta + T_{\text{CIFS}}, \\ T_{\text{SA}} &= H_{\text{phy}}/R_b + L_{\text{SA}}/R + \delta + T_{\text{CIFS}}, \end{aligned} \tag{7}$$

where δ is the propagation delay, R and R_b are the PHY operational and basic rates, for example, $R = 54$ Mbps and $R_b = 6$ for IEEE the 802.11 a/g standard. Also, L_{ack} is the length of the Ack message and H_{phy} is the length of the PHY header.

We approximate the expected length of a TR phase as the duration of one TR message plus half of the backoff slots (since the random backoff number is uniformly chosen from the contention window). For the case of M subchannels, the length of the TR message sent using OFDMA is stretched due the use of a lower number of subcarriers. Thus,

$$E[\text{TR}] = T_{\text{RIFS}} + M * (H_{\text{phy}}/R_b + (L_{\text{TR}})/R + T_{\text{slot}} * q/2) + \delta, \tag{8}$$

where L_{TR} is the length of a TR message in bits and T_{slot} denotes the duration of backoff slots in each TR phase.

To evaluate the analytical model and examine the performance of the proposed MAC scheme, we assumed a specific OFDMA-based PHY similar to the one specified in the IEEE 802.16 standard and computed the normalized throughput (throughput provided to layers above the MAC divided by the PHY operational rate). We then compared the results with those obtained from simulation experiments, using a discrete event simulator written in C language. The results are depicted in Figure 3, which shows that the model matches the simulation very closely and is therefore quite accurate. The accuracy and simplicity of using the model for calculating the throughput make it easy to devise adaptive schemes for the access point that can maximize the system throughput as the number of active stations changes over time.

To compare the achievable throughput of the proposed MAC to that of the basic CSMA/CA, we repeat the derivations for the saturation throughput of the 802.11 DCF here [4, 15]:

$$S_{802.11} = \frac{P_sP_{\text{tr}}E[P]}{(1-P_{\text{tr}})T_{\text{slot}} + P_{\text{tr}}P_sT_s + P_{\text{tr}}(1-P_s)T_c}, \tag{9}$$

where T_c and T_s denote the durations of time spent in collision or successful transmission and are given as follows

Table 1: Parameters used for simulation and numerical analysis.

Symbol	Quantity	Symbol	Quantity
T_{slot}	16 μs	BW	20 Mhz
T_{MIFS}	10 μs	Number of subcarriers	256
T_{CIFS}	20 μs	R_b	6 Mbps
T_{RIFS}	30 μs	R	54 Mbps
ACW_{Min}	16	Lack	12 B
ACW_{Max}	256	Lcts,Lrts	18 B
q	8	H_{phy}	120 bits
δ	1 μs	H_{mac}	30 B

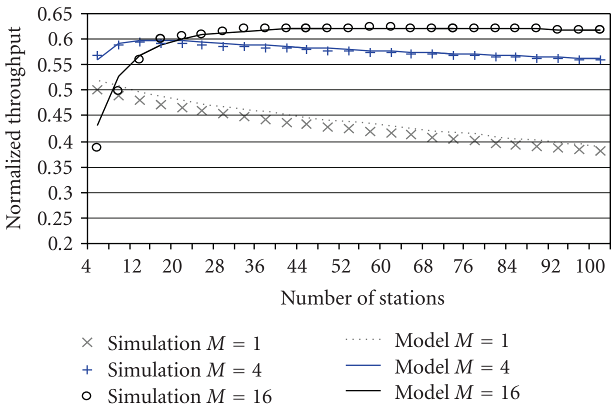


Figure 3: Model validation, comparing simulation and analytical results.

for normal CSMA/CA and CSMA/CA in RTS/CTS mode (where each transmission is preceded by an RTS/CTS cycle):

$$
\begin{aligned}
T_s &= 2H_{\text{phy}}/R_b + (H_{\text{mac}} + E[P] + L_{\text{ack}})/R \\
&\quad + T_{\text{MIFS}} + 2\delta + T_{\text{RIFS}}, \\
T_c &= H_{\text{phy}}/R_b + (H_{\text{mac}} + E[P^*])/R + T_{\text{RIFS}} + \delta,
\end{aligned}
\tag{10}
$$

and for (RTS/CTS) case:

$$
\begin{aligned}
T_s &= 4H_{\text{phy}}/R_b + (H_{\text{mac}} + E[P] + L_{\text{rts}} + L_{\text{cts}})/R \\
&\quad + 3T_{\text{MIFS}} + 4\delta + T_{\text{RIFS}}, \\
T_c &= H_{\text{phy}}/R_b + (H_{\text{mac}} + L_{\text{rts}})/R + T_{\text{RIFS}} + \delta,
\end{aligned}
\tag{11}
$$

where H_{mac} is the length of the MAC header. For a fair comparison, we replaced the IFS values of 802.11 DCF in (10)and (11) with the IFS values defined in our MAC.

Figure 4 shows that, compared to a pure CSMA/CA system, the proposed hybrid MAC scheme achieves up to 30% performance gain. It also shows that for the parameters used in the simulation, the maximum throughput is achieved when each subchannel is assigned to around 4 stations. This is due to the use of the specific contention window sizes given in Table 1. Using the model developed in this section, one can devise an optimization scheme that maximizes the throughput by adjusting the values of the contention window sizes, as well as the number of subchannels. Further analysis of Figure 4 shows that by dynamically adjusting the number of subchannels, we can always maintain a higher throughput than CSMA/CA-based schemes for WLANs with more than 4 stations. With less than 4 stations, pure CSMA schemes perform well, due to lower overhead.

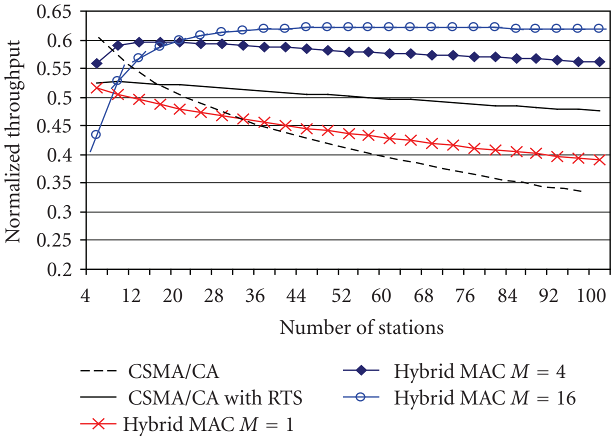


Figure 4: CSMA/CA versus hybird OFDMA/CSMA (M: no. of subchannels).

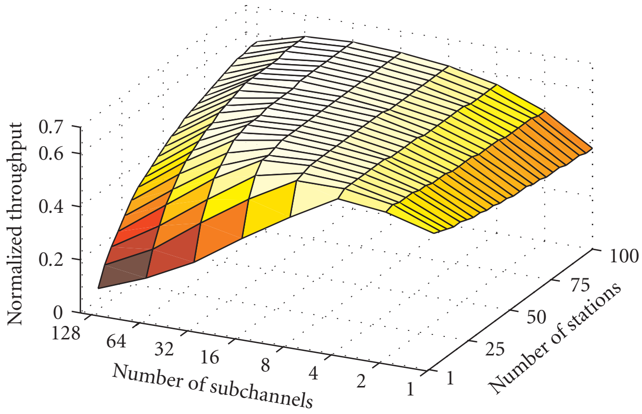


Figure 5: Normalized saturation throughput versus number of stations and number of subchannels.

To better understand the effect of the number of subchannels on the throughput of the proposed MAC, we have set up two experiments that allowed us to observe the normalized throughput (based on the presumed 54 Mbps PHY transmission rate) versus the number of subchannels

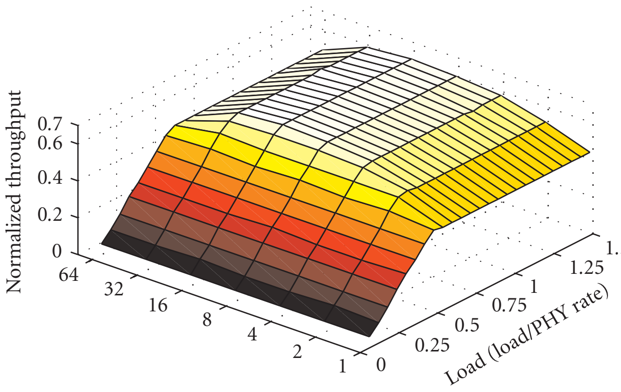


Figure 6: Normalized throughput versus load and number of subchannels: 32 stations throughput versus offered load.

and the number of stations in a 3D graph. In the first experiment, we measured the total MAC throughput in saturation mode. The results depicted in Figure 5 show that the maximum throughput is achieved when the number of stations is almost 4 times the number of subchannels, for the set of parameters defined in Table 1. The figure also shows that throughput performance is not very sensitive to the number of subchannels, when a high number of stations are accessing the channel. This can simplify the task of finding an optimum number of subchannels.

To see the effect of increasing the load in the network, we set up another experiment with 32 stations and observed the normalized throughput for different number of subchannels, as the network load increased. The traffic sources in this experiment were Poisson sources generating 2000-byte packets (Poisson model is only important for nonsaturation cases). The experiment results shown in Figure 6 indicate that at low loads the performance of the MAC is more or less the same for any number of subchannels. However, when the load nears 35% of the PHY bit rate, the cases with larger number of stations assigned to each subchannel experience more performance degradation. The case with 64 subchannels also performs poorly since there are only 32 stations and half the subchannels are wasted. As in the previous experiment, the best performance is achieved when 8–32 subchannels are used.

5. Conclusion

The MAC protocol proposed in this article combines OFDMA with CSMA/CA mechanisms and significantly increases the performance and utilization efficiency of a WLAN in the MAC layer. Our results indicate that our protocol works best when the ratio of stations to channels is about 4 or 8. Below and above these ratios, performance tends to degrade. That may become a bottleneck if the AP can only offer a few channels; say 4. From practical perspective, one does not expect more than 20 to 30 stations to be associated with the same AP, making our scheme suitable for most practical WLANs.

We have selected OFDMA as the basis of our system due to its several advantages over other systems. Compared to CDMA systems, OFDMA can combat fading with less complexity. OFDMA can also achieve higher spectral efficiency. In comparison to TDMA-based systems, our system has a simpler random access scheme, that does not require synchronization, and it is suitable for a combination of data and multimedia traffic.

We presented the fundamental regulations and requirements of the proposed OFDMA-based MAC and developed a model for saturation throughput analysis. This model can be used for dynamically adjusting the number of subchannels and subchannel assignment to achieve optimal performance. Devising more complex analytical models and optimization algorithms for the OFDMA-based MAC is an interesting area of research. Another research subject that can be based on the proposed MAC is the design of scheduling algorithms for the contention free phase of the MAC operation. Such schedulers are required for QoS provisioning in the MAC layer.

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