Asynchronous Medium Access Protocol for Multi-user MIMO based Uplink WLANs

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Abstract

Multi-user multiple-input multiple-output (MIMO) technology makes it possible for wireless nodes to successfully receive multiple packets from simultaneous transmitters in wireless networks. As it can provide more transmission opportunities without causing collisions, the network throughput performance can be dramatically improved. In this paper, we propose an asynchronous medium access control (MAC) protocol, which enables senders to independently start their transmissions if the access point (AP) can receive more simultaneous packets up to its multi-packet reception capability. This asynchronous protocol makes the multi-user MIMO channel more efficiently used, especially in wireless networks where transmission durations are dynamically varying due to different packet sizes and transmission rates. Through our performance analysis and extensive simulations, we show that the proposed asynchronous MAC protocol achieves significantly higher uplink throughput performance in multi-user MIMO wireless networks.

Index Terms

Asynchronous MAC protocol, multi-user MIMO WLANs, throughput analysis, multi-packet reception capability.

I. Introduction

In conventional wireless local area networks (WLANs), nodes can receive only one packet at a time, while two or more concurrent transmissions cause all packet reception to fail. This is called packet collision. However, as the technology level of MIMO and multi-user detection (MUD) increases, it has become possible for wireless nodes to successfully receive multiple packets from

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simultaneous transmitters [1]–[4]. The mixed signal from simultaneous transmissions, which was previously treated as a packet collision event on conventional wireless networks, can be properly separated and decoded, and is preferred because it enhances the achievable throughput performance. The maximum number of packet transmissions that can be successfully decoded is defined as multi-packet reception (MPR) capability (denoted by M) and is determined by the capture threshold ratio [10], [15] or the number of antennas [12], [13].

However, most traditional MACs have been designed without any consideration for MPR capability and do not function well in multi-user MIMO based WLANs. For example, an AP with MPR capacity can receive multiple packets simultaneously, but if the CSMA/CA based IEEE 802.11 distributed coordination function (DCF) protocol is applied, the AP attempts to make only one successful transmission for each transmission opportunity. As a result, the multi-packet reception capability of the multi-user MIMO WLANs is not fully utilized and the throughput performance of multi-user MIMO WLANs would not be improved at all. Therefore, new types of MACs, which take MPR capabilities into consideration are highly desired for multi-user MIMO WLANs. Recently, several MACs have been proposed in [5]–[12]. Most of them are basically synchronous channel access protocols, in which each node with packets to transmit is not allowed to start a new packet transmission until all of the on-going transmissions complete. However, these kinds of synchronous protocols for transmission coordination may significantly hamper the channel efficiency of the multi-user MIMO WLANs when transmission durations are dynamically varying due to different transmission rates and packet sizes.

In this paper, we propose an asynchronous MAC protocol that allows senders to asynchronously start their transmissions without waiting for the completion of all the on-going transmissions in multi-user MIMO WLANs. Under this asynchronous channel access protocol, whenever a node notices there exists a vacant space that accommodates more simultaneous packet receptions, it can start a new transmission although on-going transmissions still exist. In this manner, the channel efficiency of multi-user MIMO WLANs can be dramatically improved. We provide a Markov chain model for throughput performance of our proposed asynchronous MAC protocol. Simulation results demonstrate how the proposed channel access mechanism can improve aggregate uplink throughput performance in WLANs with multi-user MIMO technology.

The remainder of this paper is organized as follows. In Section II, we provide a summary of related work in literature. Section III includes our system model and motivation. We then propose the asynchronous medium access protocol for maximizing uplink throughput performance of multi-user MIMO based wireless networks. In Section IV, we introduce the description of our analytical throughput model for the proposed channel access protocol based on a Markov chain analysis. This is then followed by a performance evaluation in Section V. Finally, we conclude this paper in Section VI.

II. Related Work

Several MAC protocols for the network system with MPR capability have been proposed in [5]–[12]. Zheng *et al.* [5] introduced the concept of MPR-capable wireless networks, and derived a throughput performance of network under the assumption that the all packets are synchronously transmitted. In [6], Chen *et al.* proposed the MRMA scheme for wireless multimedia networks based on the use of MPR channels. The MRMA scheme is a reservation based channel access protocol in which reservation and information slots are allocated in different ways depending on the traffic type of wireless multimedia networks. Liu and Lin [7] proposed the distributed splitting-tree-based channel access protocol that can exploit the MPR capability of the channel. They also provided a closed-form of the throughput expression for MPR capable networks. In [8], Jin *et al.* numerically showed that the multi-user MIMO system reduces the collision probability, providing a shorter delay and high throughput performance. In addition, they also showed the performance comparison of between single-user MIMO system and multi-user MIMO system.

Jin *et al.* [9] presented the throughput imbalance problem between uplink and downlink traffic in multi-user MIMO based WLANs, and derived the analytical model for throughput performance. They proposed the contention window adjustment scheme, which attempts to solve the unfairness throughput problem. Celik *et al.* [10] also considered the throughput unfairness problem due to the different transmission rates, eventually causing a decrease in throughput in networks with MPR capability. To overcome this unfairness problem, Celik *et al.* proposed alternative back-off mechanisms, which provide more transmission attempts for distant nodes in MPR systems. Recently, in order to prevent the under-utilized wireless channel of MPR systems, Zhang [11] proposed the multi-round contention random access mechanism, in which the stations have more chances to contend for the channel until there exists sufficient winning stations.

To the best of our knowledge, Babich and Comisso [12] first proposed an asynchronous channel access approach for IEEE 802.11 networks with multi-packet reception capability where all nodes can simultaneously receive multiple packets. In [12], each node is allowed to decrease its backoff counter not only when the channel is sensed idle but also when the number of active transmitters is less than a predefined threshold value under the assumption that all the nodes can obtain the number of active transmitters over the channel. Therefore, two or more contending nodes can access the wireless channel at the same time whenever the back-off counter reaches zero in an asynchronous manner. Unlike the approach in [12], we consider an uplink communication case where AP can simultaneously receive multiple packets by exploiting multi-packet reception capability and stations contend for transmission opportunities with each other in a random access manner without multi-packet reception capability. Our proposed channel access protocol allows each node to independently start a new transmission in the asynchronous manner whenever the AP informs that there exists a vacant space for multi-packet reception.

III. Proposed Asynchronous MAC Protocol

A. System model and assumptions

We consider an uplink case for one-hop networks, where one AP is located at the center of the network and the other transmitters are located around the AP. For simplicity, it is assumed that each node has backlogged packets under saturation condition, and the packet size is geometrically distributed. We also consider that the AP has M multiple antennas while each transmitter has one antenna for the data transmissions. In this system, the mixed signal (denoted by $\mathbf{y}$) from N multiple transmitters can be expressed as

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{w}, \tag{1}$$

where $\mathbf{s} = [s_1,\ s_2,\ \cdots,\ s_N]^{\mathrm{T}}$ and $\mathbf{y} = [y_1,\ y_2,\ \cdots,\ y_M]^{\mathrm{T}}$ denote the transmitted and received signal vector, respectively. Also, $\mathbf{H}$ is the channel matrix and $\mathbf{w}$ is the channel noise. Here, the channel matrix $\mathbf{H}$ can be written as

$$\mathbf{H} = \begin{pmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M,1} & h_{M,2} & \cdots & h_{M,N} \end{pmatrix}, \tag{2}$$

where $h_{m,n}$ denotes the channel coefficient between the pair of n-th user and m-th receiving antenna.

In this paper, we consider a multiuser orthogonal frequency-division multiplexing (OFDM)-based WLAN system as a practical MPR-capable system. Here, we assume that each frame includes an orthogonal training sequence in the preamble in order to make it possible for APs to estimate the channel coefficients as like IEEE 802.11n standard. Once an AP obtains the channel coefficients from the training sequences, it can properly decode the mixed signal from simultaneous transmitters and then simultaneously serve multiple users at a time. We also make the following assumptions in this paper:

(A1) ***AP with MPR-M capability***: The AP can successfully receive multiple packets up to the packet reception capability (denoted by M) at the same time. Because M is determined by the number of antennas, antenna correlation, and wireless channel fading status, M needs to be dynamically decided for each signal reception. For simplicity, we make an assumption that the channel state does not change within one transmission interval such that the AP can compute the number of vacant channel spaces by estimating M with a sufficient margin whenever one of ongoing transmissions completes. Note that the estimation accuracy of M is an important factor because it determines the number of concurrently transmitting nodes that affects the throughput perfomrnace. For example, if M is overestimated, the nodes would aggressively transmit packets to fully utilize the MPR-M channel but may experience a number transmission failure because it happens that the number of simultaneous transmissions is instantaneously larger than M. In contrast, if M is under-estimated, the channel would not be fully utilized.

(A2) ***Separate feedback channel***: A separate feedback channel is available to enable the AP to immediately send ACK packets to the intended transmitter. Therefore, when one of the ongoing multiple data transmissions ends, the AP can immediately transmit ACK packets [10], [14], [16]. Note that the feedback channel is set to a small portion of the radio frequency because control packets are transmitted with a small size and a low rate [22].

Under the above assumptions, we propose the asynchronous channel access protocol that can fully exploit the multi-packet reception capability of multi-user MIMO based uplink WLANs.

B. Overview

Consider a network that operates using a synchronous MAC protocol for coordinating transmissions. Under this synchronous channel access, once a set of nodes starts its transmissions, all the other nodes are prohibited from sending data frames until all the on-going transmissions finish. However, as the durations of on-going transmissions are different due to different packet sizes and transmission rates, the next transmission is significantly delayed by the longest duration of on-going transmissions. Suppose that one of on-going transmissions has a long duration, while the other on-going transmissions have much shorter durations. In this case, the other nodes with packets pending for transmission must wait for the completion of the transmission with the longest transmission duration for the next stage of data transmission, and the channel utilization performance significantly degrades.

Figure 1(a) shows the operation of the synchronous channel access protocol in the wireless network where there are three transmitters and one AP in the network. The packet reception capability (M) is set to two for multiple packet reception. Suppose that Tx1 and Tx3 choose the same back-off number and are transmitting Request to Send (RTS) packets at the same time. As depicted in Figure 1(a), the transmission duration of Tx1 is much shorter than that of Tx3. Consequently, Tx1 and Tx2 should wait for the transmission completion of Tx3 even though there exists available space for more packet reception because M is two. As long as the transmission of Tx3 finishes, every node performs its back-off mechanism for the next data transmissions under the synchronous channel access protocol. This example clearly demonstrates the potential inefficiency of the synchronous channel access protocol in the multi-user MIMO network with different transmission durations.

To overcome this problem of inefficient MPR capability in multi-user MIMO wireless networks, we propose an asynchronous protocol that allows nodes to independently start their transmissions without waiting for the completion of on-going transmissions when there exists a vacant space for multi-packet reception.

Whenever the channel becomes idle, every node performs a back-off mechanism and transmits RTS packet to the AP. After AP receives an RTS packet from one or multiple nodes, the AP identifies the number of vacant spaces for multiple packet reception. Note that if the number of simultaneous RTS packets is less than M, the multiple RTS packet reception is successful.

Otherwise, RTS packets collide at the AP. Once the RTS transmission succeeds, the AP broadcasts a Clear to Send (CTS) packet with the vacant space information. On receiving the CTS packet, the node that has sent the RTS packet starts the data transmission. At the same time, the other nodes that have not sent the RTS packet may decide to transmit with a transmission probability (denoted by τ). (How to determine the transmission probability τ will be discussed in more detail in the Section IV-B.) By enabling the nodes that have not sent the RTS packets to transmit data packets, multiple transmissions are simultaneously and immediately performed.

After the on-going transmission with the shortest duration finishes, the AP immediately transmits an acknowledgement (ACK) packet with the vacant space information. Under the assumption of (A2), the AP can immediately send an ACK packet while receiving packets. Using this vacant space information, the nodes decide whether or not to transmit while on-going transmissions still exist. In other words, the nodes should receive or overhear the CTS or ACK packet to initiate the transmission in the proposed protocol. Suppose that only one transmission is in progress over the wireless channel. We emphasize here that after the end of single transmission, the channel becomes idle so that all nodes again perform the back-off mechanism.

Figure 1(b) shows the operation of the proposed asynchronous channel access protocol. On receiving RTS at the AP, the AP gives the senders the vacant space information by broadcasting the corresponding CTS packet. Because M is two, another transmission is possible without causing collisions. The number of vacant channel spaces specified in the CTS packet is one in this example. As soon as the nodes obtain this vacant space information from the feedback frames they can transmit data packets immediately with a probability of τ. In Figure 1(b), Tx1 is the first transmitter that has sent the RTS packet, and after receiving the CTS packet, Tx3 decides to transmit packets so that Tx1 and Tx3 are transmitting data packets simultaneously. Once Tx1 completes its transmission first (because of the shorter transmission duration), the AP immediately sends the ACK frame with the vacant space information. Tx1 and Tx2 can overhear this ACK frame and decide again whether or not to transmit data frames while Tx3 is still transmitting its first frame.

As shown in the above example, after the AP informs that there exists the vacant channel space by using the CTS and ACK frames, a candidate node can opportunistically initiate a data transmission if it has a pending packet in its transmission queue. In contrast, if a packet arrives at the candidate node after the vacant channel space information was received, the node defers the transmission of the nearly received packet and waits for the next transmission opportunity.

C. Detailed procedure

The detailed procedure of the proposed asynchronous MAC protocol is as follows:

- (P1) When nodes sense that the channel is idle, each node independently performs a back-off mechanism as per the IEEE 802.11 DCF protocol. The node with the smallest back-off number transmits an RTS frame to the AP first.
- (P2) After the AP successfully receives the RTS frame, the AP identifies the number of vacant channel spaces, and then broadcasts a CTS frame including the vacant channel space information.
- (P3) On receiving the CTS frame, the node that has sent the RTS frame begins to send a data frame. At the same time, the other nodes that are not supposed to be transmitters become *candidate transmitters*. These candidate transmitters compute τ based on the channel space information and the number of competing nodes. After computing τ, the candidate transmitters decide whether to transmit packets with the probability of τ.
- (P4) As soon as the AP finishes receiving one of the on-going multiple transmissions, it immediately sends the ACK frame including newly updated vacant channel space information.
- (P5) The nodes that receive or overhear the ACK packet decide whether to transmit data frames based on a newly computed τ without waiting for the completion of the current on-going transmissions.

As soon as the candidate nodes obtain the vacant channel space information from the AP, the nodes may immediately transmit packets even though there are still on-going transmissions. Therefore, the proposed asynchronous channel access protocol dramatically enhances the uplink network capacity of multi-user MIMO based WLANs. The proposed protocol outperforms synchronous channel access protocols, especially when the transmission durations of on-going transmissions are significantly different. Suppose a network where the packet sizes are the same because they are bounded by the maximum transmission unit (MTU). Even in this case, the transmission durations could be different, because they depend on the transmission rates as well as the packet sizes. In this case, our proposed asynchronous protocol improves the overall uplink network throughput by reducing the waiting time for the next transmissions.

Under the proposed protocol, the RTS, CTS, and DATA frames are transmitted over the data channel while the ACK frames are transmitted over the feedback channel. When a node senses that the data channel is idle, it independently performs the back-off mechanism and attempts to transmit data frames. The node that has finished its transmission on the data channel should return to the feedback channel to receive the corresponding ACK frame. If it fails to receive the ACK frame, it needs to retransmit the frame on the data channel. In contrast, if the data channel is busy, the candidate nodes do not perform the back-off mechanism, and thus switch to the feedback channel to obtain the vacant channel space information. If the vacant channel space information is received, they go back to the data channel and opportunistically initiate their transmissions in the asynchronous manner. If the information is not received within an average transmission duration interval, the candidate nodes switch to the data channel and perform the back-off mechanism.

IV. Analytical Throughput Model

In this section, in order to validate the proposed asynchronous MAC protocol, we derive an analytical model for the system throughput and numerically validate the analytical results by comparing them with the simulation results. In this analytical model, the candidate nodes are assumed to have pending packets so that they can immediately start their transmissions as soon as they receive the CTS and ACK frames. We also assume that the transmission durations of all on-going transmissions are different such that each node finishes its transmission at different times. This assumption is based on the fact that every node independently generates its data packet, and the packet size is geometrically distributed.

A. Markov chain analysis

Our analysis is based on the Markov chain model for multi-user MIMO based WLANs. Figure 2 illustrates the Markov chain model for the channel status of the network where M is the maximum number of multiple packets that can be simultaneously received. Note that when more than M packets are simultaneously transmitted packet collision occurs; consequently, no packet can be decoded. Therefore, the multi-user MIMO wireless channel only sustains multiple packets up to M as shown in Figure 2.

In this model, S_i represents the state where i multiple on-going data packets are being transmitted at the same time. Specifically, the state remains in S_i until the other candidate nodes decide whether or not to transmit. Note that the candidate nodes make a decision whether or not to transmit whenever the candidate nodes receive the ACK frame including the vacant channel space. Consequently, one of the following three events occurs at the instant that one node finishes its transmission: no transmission, success, and collisions. We emphasize here that after collisions occur among multiple transmissions, all the packets including on-going transmissions and attempted transmissions are lost. Therefore, the state becomes S_0 in the case of collisions.

In Figure 1(b), after exchanging RTS-CTS frames, two nodes (Tx1 and Tx3) successfully initiate to transmit their packets such that the state moves to S_2 in the Markov chain model. Among two simultaneous transmissions, the transmission of Tx1 completes earlier than Tx3 as shown in Figure 1(b). After completing to receive the packet from Tx1, the ACK packet for Tx1 is being transmitted. Until this time, the state continuously remains in S_2. At the instant that the other nodes receive this ACK packet, one of the three following events occurs: no transmission, a successful initiation, and a failed initiation. In Figure 1(b), Tx2 successfully initiates its transmission so that the state moves to S_2 again. At this time, if there is no incoming packet, S_2 moves to S_1. In the case of a failed initiation, S_2 becomes S_0.

Transitions from S_0: First, we consider the case that j multiple transmissions are successfully initiated from S_0, expressed as $P(S_j|S_0)$. To achieve the successful data transmissions, two consecutive successes for RTS and DATA transmissions are required in the proposed channel access protocol. Note that in the proposed protocol even though RTS transmission is successful, the success for the following DATA transmission is not guaranteed. This is due to the fact that after receiving a CTS packet other nodes also have a chance to transmit and cause packet collisions. Therefore the probability that j multiple DATA transmissions succeed from S_0 is represented by

$$\begin{aligned} P(S_j|S_0) &= P\{\text{RTS success},\ \text{DATA success} \mid S_0\} \\ &= \sum_{k=1}^{j} \binom{N}{k} \tau_0^k (1-\tau_0)^{N-k} \binom{N-k}{j-k} \tau_k^{j-k} (1-\tau_k)^{N-j}, \end{aligned} \tag{3}$$

where N is the number of nodes in the network, k is the number of RTS transmissions, and τ_k

is the channel access probability at S_k.

Under the proposed asynchronous channel access protocol, we differentiate the channel access probability (τ_i) for senders according to S_i in order to reduce packet collisions. Note that it has been shown in previous studies [17], [18], the channel access probability of τ_0 is given as a function of the contention window size (CW) of IEEE 802.11 DCF protocol, i.e., $2/(\text{CW}+1)$ when CW $=$ CW$_{\text{min}}$ in an average sense. In contrast, τ_k for $k > 1$ is the determined by the number of on-going transmissions, the number of vacant channel spaces, and the number of competing nodes at the instant. We emphasize here that this analytical throughput model is based on these channel access probabilities.

In the case that no node transmits or collisions happen at S_0, then the state becomes S_0 again, expressed as $P(S_0|S_0)$. In the asynchronous scheme, although RTS-CTS transmissions are successful, data transmissions may not be successful because a large number of candidate nodes can transmit packets after receiving CTS. Therefore, we classify the collision from S_0 into two cases:

- RTS collision ($P(\text{Coll}^{\text{RTS}}|S_0)$) - During RTS transmission phase, collisions occur.
- DATA collision ($P(\text{Coll}^{\text{DATA}}|S_0)$) - After successful RTS and CTS exchanges, multiple data frames are corrupted.

Considering the above cases, $P(S_0|S_0)$ can be expressed as

$$\begin{aligned} P(S_0|S_0) &= P(\text{Idle}|S_0) + P(\text{Coll}^{\text{RTS}}|S_0) + P(\text{Coll}^{\text{DATA}}|S_0) \\ &= 1 - \textstyle\sum_{j=1}^{M} P(S_j|S_0), \end{aligned} \tag{4}$$

where Coll$^{\text{RTS}}$ and Coll$^{\text{DATA}}$ denote the collisions during RTS and DATA transmissions, respectively.

Transitions from S_1: Recall that S_1 indicates the state where only one transmission is being transmitted. S_1 lasts until this transmission completes. After completion of this single transmission, the channel becomes idle so that every node again performs the back-off mechanism detailed in the IEEE 802.11 DCF mode. In other words, after the end of the single transmission over the channel, the back-off mechanism always starts again. Therefore, the transition from S_1 always goes to S_0 as depicted in Figure 2 and expressed as

$$P(S_0|S_1) = 1. \tag{5}$$

Transitions from S_i with $i > 1$: We also obtain the transition probability from S_i for $i > 1$. At the instant that S_i finishes its state, if there is no incoming node to transmit, the state goes to S_{i-1}. Note that because the on-going transmissions have different transmission durations and thus they end at different instants, the state S_i goes to S_{i-1} in the case of no incoming transmissions. At the same instant, the transmission success or collision occurs in the asynchronous manner. For example, if the appropriate number of candidate nodes start their transmissions, then the next transmissions are successful. To the contrary, a large number of candidate nodes leads to packet reception failure, regarded as collisions.

Each probability of the above cases (no transmission, success, and collision) in the asynchronous channel access is expressed as

$$\begin{cases} P(S_{i-1}|S_i) = (1-\tau_i)^{N-i+1} \\ P(S_j|S_i) = \binom{N-i+1}{j-i+1}\tau_i^{j-i+1}(1-\tau_i)^{N-j} \quad j \in [i, M] \\ P(S_0|S_i) = 1 - \sum_{j=1}^{M} P(S_j|S_i). \end{cases} \tag{6}$$

Suppose that the AP can receive multiple packets up to M simultaneously, the transition probability between each state can be represented by M-by-M matrix $\mathbf{P}$, that is,

$$\mathbf{P} = \begin{pmatrix} P(S_0|S_0) & P(S_1|S_0) & \cdots & P(S_M|S_0) \\ P(S_0|S_1) & P(S_1|S_1) & \cdots & P(S_M|S_1) \\ \vdots & \vdots & \ddots & \vdots \\ P(S_0|S_M) & P(S_1|S_M) & \cdots & P(S_M|S_M) \end{pmatrix}. \tag{7}$$

Since we assume that the transition probability is stationary at the equilibrium state, and thus,

$$\mathbf{S} = \mathbf{PS}, \tag{8}$$

where $\mathbf{S}$ is the probability vector for each channel state, which is equivalent to [$P(S_0)$, $P(S_1)$, $\cdots$, $P(S_M)$]$^{\mathrm{T}}$.

Moreover, from the property of the Markov chain model, the total probability of each channel status is equal to 1, given by $\sum_{i=0}^{M} P(S_i)$ = 1. From (8) and the law of total probability, $\mathbf{S}$ is numerically obtained.

B. Determining per-state channel access probability (τ_k)

In order to fully exploit the packet reception capability of the multi-user MIMO based wireless channel, it is necessary to differentiate the channel access probability (τ) for *candidate nodes* according to the current channel status (S_k), which is referred to the *per-state channel access probability* (denoted by τ_k).

For example, when there are k number of on-going transmissions among N nodes at an instant, in this time we need to enable (M-k) nodes to transmit packets in order to fully utilize the packet reception capability M. If more than (M-k) candidate nodes are trying to access the channel simultaneously, then all packets collide. It is obvious that the optimal level of the per-state channel access probability (τ_k) at S_k totally depends on the packet reception capability M, the number of nodes N, and the number of on-going transmissions k.

In order to determine τ_k, we first consider the probability that there exist i multiple simultaneous transmissions among (N-k) candidate nodes at state S_k. This probability follows a binomial distribution and is given by

$$P[X=i]=\binom{N-k}{i}\tau_k^i(1-\tau_k)^{N-k-i}, \quad i=0,1,\cdots,N-k. \tag{9}$$

where X is a binomial random variable indicating the number of transmitting nodes among (N-k) candidate nodes when the nodes decide whether or not to transmit data frames with τ_k.

Since X is a binomial random variable, the expected value of the number of transmitting nodes X is as follows:

$$E[X]=(N-k)\tau_k. \tag{10}$$

With a higher value of τ_k, the average number of candidate transmitters deciding to transmit is very large in the asynchronous channel access protocol. This may experience a number of transmission failures because it happens that the number of simultaneous transmissions is instantaneously larger than ($M-k$). To the contrary, the channel of the multi-user MIMO based wireless networks would not be utilized with a low value of τ_k.

In this paper, we can appropriately choose τ_k to fully utilize the channel efficiency of multi-user MIMO based WLANs such that the expected value of X should be equal to the number of the channel vacant space for multiple packet reception, which is equivalent to M-k i.e., $E[X]=M-k$. Then, the channel access probability is expressed as follows:

$$\tau_k=\begin{cases}(M-k)/(N-k), & k<M;\\ 0, & \text{otherwise.}\end{cases} \tag{11}$$

Note that once the AP receives multiple packets, the AP is immediately aware of the number of vacant channel spaces (M-k), where k is the number of on-going transmissions at that instant. Therefore, the value of the vacant channel space is easily obtained at the AP. Also, the total number of competing nodes (N) in the network can be obtained by the estimation methods, for example, the estimation method using the Kalman filter in [19] or the Bayesian estimation method in [20]. In the proposed protocol, we can estimate N by a similar estimation method as done in [21], which counts the number of the consecutive idle slots and determines the estimated number of competing nodes by $\widetilde{N} = log(\frac{E[idle]}{E[idle]+1})/log(1-\tau)$, where $E[idle]$ is the average number of successive idle slots. Consequently, the optimal level of per-state channel access probability is readily available. With the appropriate setting of the transmission opportunity probability (τ_k), we can fully utilize the efficiency of the multi-user MIMO wireless channel where M simultaneous transmissions are possible without causing packet collisions.

Note that the estimation accuracy of N is an important factor that affects the throughput performance, because N determines the number of concurrently transmitting nodes. For example, if N is overestimated, τ_k is set to a lower value, and the channel would not be fully utilized. To the contrary, if N is under-estimated, the candidate nodes would aggressively transmit packets with a higher value of τ_k, but may experience a number of transmission failures. Therefore, N should be carefully estimated.

C. Throughput derivation

To evaluate throughput performance, we first derive the average number of packets successfully decoded. In the proposed protocol, even though multiple packets are successfully being transmitted at the same time, it does not guarantee that all the on-going packets are successfully decoded at the AP. This is due to the fact that before the completion of all the on-going packet reception, candidate nodes can start transmissions, resulting in packet collisions.

Taking these possible collisions into consideration, we derive the average number of successfully decoded packets ($E[\text{Packets}]$) as given in (12).

Let v denote the average length of a slot time. Based on all the transitions in the system

$$
\begin{aligned}
E[\text{Packets}] &= P(S_0)\{\overbrace{P(S_1|S_0)}^{\text{packet at } S_1} \qquad\qquad /* \text{ Successful transmission for the packet from } S_0 \text{ to } S_1 \quad */ \\
&\quad + \overbrace{P(S_2|S_0)}^{\text{1st packet at } S_2} + \overbrace{P(S_2|S_0)(1-P(S_0|S_2))}^{\text{2nd packet at } S_2} \\
&\quad + \overbrace{P(S_3|S_0)}^{\text{1st packet at } S_3} + \overbrace{P(S_3|S_0)(1-P(S_0|S_3))}^{\text{2nd packet at } S_3} + \overbrace{P(S_3|S_0)(1-P(S_0|S_3))(1-P(S_0|S_2))}^{\text{3rd packet at } S_3} + \cdots\} \\
&+ P(S_2)\{P(S_2|S_2) + P(S_3|S_2) + P(S_3|S_2)(1-P(S_0|S_3)) + \cdots\} \\
&+ \cdots \\
&+ P(S_M)P(S_M|S_M) \\
&= P(S_0)\{P(S_1|S_0) + \textstyle\sum_{i=2}^{M}[P(S_i|S_0) + \sum_{j=1}^{i-1}\{P(S_i|S_0)\prod_{k=0}^{j-1}(1-P(S_0|S_{i-k}))\}]\} \\
&+ \textstyle\sum_{l=2}^{M-1} P(S_l)\{P(S_l|S_l) + \sum_{i=l+1}^{M}[P(S_i|S_l) + \sum_{j=1}^{i-l}\{P(S_i|S_l)\prod_{k=0}^{j-1}(1-P(S_0|S_{i-k}))\}]\} \\
&+ P(S_M)P(S_M|S_M).
\end{aligned} \tag{12}
$$

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model, we compute v, which is given by

$$
\begin{aligned}
v &= P(S_0)\{P(\text{Idle}|S_0)T_{idle} + P(\text{Coll}^{\text{RTS}}|S_0)T_c^{\text{RTS}} \\
&\qquad + P(\text{Coll}^{\text{DATA}}|S_0)T_c^{\text{DATA}} + \textstyle\sum_{i=1}^{M} P(S_i|S_0)T_s\} \\
&\quad + \textstyle\sum_{i=2}^{M}[P(S_i)\{P(S_0|S_i)T_{c'} + \sum_{j=i}^{M} P(S_j|S_i)T_{s'}\}],
\end{aligned} \tag{13}
$$

where T_{idle} is the duration of one idle time, T_s is the required time for the successful data transmission from the idle state, and T_c^{RTS} and T_c^{DATA} denote the wasted time for the collisions during RTS and DATA transmissions, respectively. $T_{s'}$ is the required time for asynchronous transmission success, and $T_{c'}$ is the wasted time for the packet collision in the asynchronous manner.

Each transmission duration mentioned above is defined as

$$
\begin{cases}
T_{idle} &= \sigma, \\
T_c^{\text{RTS}} &= T_{\text{RTS}} + T_{\text{DIFS}}, \\
T_c^{\text{DATA}} &= T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{DATA}} + 3\cdot T_{\text{SIFS}} + T_{\text{DIFS}}, \\
T_s &= T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{DATA}} + 3\cdot T_{\text{SIFS}} + T_{\text{ACK}}, \\
T_{c'} &= T_{\text{DATA}} + T_{\text{DIFS}}, \\
T_{s'} &= T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}},
\end{cases} \tag{14}
$$

where σ is the duration of one slot time, and T_{DATA} is the transmission time for the average payload size l. The other values such as T_{RTS}, T_{CTS}, T_{SIFS}, and T_{DIFS} are the corresponding time durations specified in the IEEE 802.11 standard.

Finally, the system throughput S is derived as the ratio of the average amount of payload successfully decoded during a slot time to the average time duration of a slot time. Here the average number of the packets successfully decoded is readily obtained in (12) such that the average payload successfully decoded is given by $E[\text{Packets}] \cdot l$, where l is the average payload size. Hence, S becomes $S = E[\text{Packets}] \cdot l \ / \ v$.

V. Numerical Results

To evaluate the performance of our proposed asynchronous channel access protocol and compare it with that of the IEEE 802.11 DCF protocol and one existing MAC protocol (Zheng's method [5]), we carry out various simulations using MATLAB. In the simulations, we assume that every node independently generates its data packet, and the packet size is geometrically distributed in order to represent a network where each node finishes its transmission at different times. The parameter values used in the simulations are given in Table I.

We first evaluate how the number of competing nodes N and the packet reception capability M affect throughput performance of multi-user MIMO based WLANs in a single rate scenario. We then show the throughput performance with the per state channel access probability in comparison with that of fixed channel access probability. Next, we provide throughput performance with respect to the average packet size l. Finally, we evaluate our propose protocol in a multi-rate scenario.

A. Throughput performance w.r.t. the number of users N in a single rate scenario

Figure 3 shows the analytical and simulation results of throughput performance for the proposed asynchronous MAC protocol with respect to the number of users (N). We vary N from 0 to 80 users, while M is fixed to 3 and 4, respectively. The transmission rate for the data transmission is set to 54 Mb/s. Under both synchronous and asynchronous methods, throughput performance increases as M is increased from 3 to 4. The reason is that collisions rarely happen for a larger value of M. This implies that M is a key parameter that determines throughput performance of multi-user MIMO based WLANs.

We observe that our proposed asynchronous MAC protocol significantly outperforms the synchronous protocol. The aggregate uplink throughput is improved by 22–129% as shown in Figure 3. This is due to the fact that every pending node has to wait for other nodes' data completion under the synchronous MAC protocol. Conversely, in the proposed protocol after one of the on-going transmitting nodes finishes its transmission, the other candidate nodes may attempt to transmit data frames without waiting for the completion of all the on-going transmissions resulting in a throughput improvement. In addition, the analytical results of the proposed scheme are very close to the simulation results for all cases of M=3 and 4.

B. Throughput performance w.r.t. the packet reception capability M

In this set of simulation experiments, we show how the packet reception capability affects the aggregate throughput performance in WLANs with multi-user MIMO technology, where N is fixed to 10.

In Figure 4, under the IEEE 802.11 DCF mode the aggregate uplink throughput is not improved even though M increases from 3 to 7. The reason is that the channel is under utilized in the synchronous channel access mode because every node must wait for the completion of the on-going transmissions. However, under the proposed asynchronous protocol the throughput gradually increases as we increase the packet reception capability from 3 to 7. This implies that this asynchronous MAC protocol makes the multi-user MIMO channel more efficient by enabling more candidate nodes to attempt transmissions if the AP can receive more simultaneous packets. In all the cases depicted in Figure 4, the throughput obtained by our proposed scheme is much higher than that of the synchronous MAC protocols.

C. Throughput effect of the per-state channel access probability

We also carry out the simulations in order to verify the effect of using the per-state channel access probability (τ_k). In this simulation, M and N are set to 4 and 10, respectively.

When the fixed channel access probability is used without considering the per-channel state at every instant that one of the on-going transmitters finishes its transmission, the throughput obtained is lower than that of using the per-state channel access probability. For example, as depicted in Figure 5 a lower value of the fixed channel access probability causes the multi-user MIMO based wireless channel to be under utilized, and as a result the throughput obtained is also low. To the contrary, when the fixed channel access probability is set to a higher value such as 0.5, the throughput also decreases due to a large number of collisions.

However, the proposed protocol with use of per-state channel access probability achieves a higher throughput as shown in Figure 5. The reason is that the number of candidate nodes to transmit data can be appropriately adjusted by considering the vacant channel space in the asynchronous manner.

D. Throughput performance w.r.t. the average packet size l

To investigate how the average packet size affects the network throughput, we carry out simulations by varying the average packet size from 0 to 12000 bits in the network. Figure 6 depicts the throughput result with respect to the average packet size when N and M are set to 10 and 4, respectively. From Figure 6, we see that throughput performance gradually improves as the average packet size increases in both synchronous and asynchronous protocol. This result implies that the packet size is one of the most important parameters significantly affecting network throughput.

In the proposed protocol, every candidate node has a chance to transmit a packet even though the channel is being used; however, there is still available channel space for multiple packet reception, so that the sender does not need to wait for the completion of other transmissions. Therefore, the channel efficiency of multi-user MIMO based WLANs is noticeably improved by allowing nodes to transmit packets although on-going transmissions exist. In all cases as depicted in Figure 6, the uplink throughput obtained by the proposed channel access scheme is higher than that of two synchronous schemes.

E. Throughput performance in a multi-rate scenario

We now evaluate the performance of our proposed protocol in a multi-rate scenario where four different transmission rates are used for data transmissions: 6, 18, 36, and 54 Mb/s. Figure 7 shows the simulation results of throughput performance for the proposed asynchronous MAC protocol with respect to N. We vary N from 0 to 64 users, while M is fixed to 3. As shown in Figure 7, our proposed MAC protocol outperforms the other synchronous MAC protocols. The reason is that when the transmission durations are quite different due to the different packet sizes and transmission rates, the synchronous MAC protocols may have long waiting periods before initiating the data transmissions if there exist on-going transmissions with long transmission durations. To the contrary, our proposed asynchronous protocol allows the nodes to start their transmissions without waiting for the completion of the on-going transmissions, finally resulting in the uplink throughput improvement.

In the previous simulations, we assumed that there exists an additional channel bandwidth of the feedback channel. However, the channel bandwidth for data transmission could be reduced if the channel bandwidth is split in the data and feedback channels. In this simulation, we consider the effect of the reduced data channel when the bandwidth overhead for the feedback channel is not negligible. As shown in Figure 7, the aggregate throughput for the case of the reduced data channel bandwidth is slightly lower than that obtained when the channel bandwidth is fully used for data transmissions. Even in this case, the throughput performance of our proposed protocol is still significantly higher than that of the synchronous protocols.

VI. Conclusion

We studied the issues of improving the uplink aggregate throughput of multi-user MIMO based WLAN systems where the transmission durations are dynamically varying. In particular, we focused on the inefficient channel use of the synchronous channel access protocol where every sender has to wait for other nodes to complete data transmissions. In a real network system, each transmission duration is different due to different packet sizes and different transmission rates; thus, the channel is not fully utilized under the synchronous medium access protocol.

To prevent this inefficient channel use problem, we propose the asynchronous channel access protocol in which every node decides whether or not to transmit packets if the AP with multi-packet reception capability can receive more simultaneous transmissions. Through performance analysis and various simulations, we show that our proposed channel access scheme outperforms the synchronous channel access scheme in terms of the aggregate uplink throughput. We also show that our analytical model for our proposed channel access scheme accurately predicts the throughput results.

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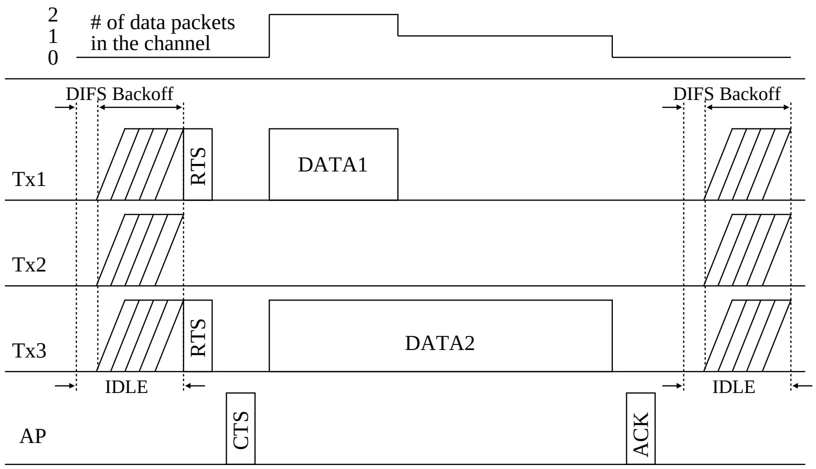
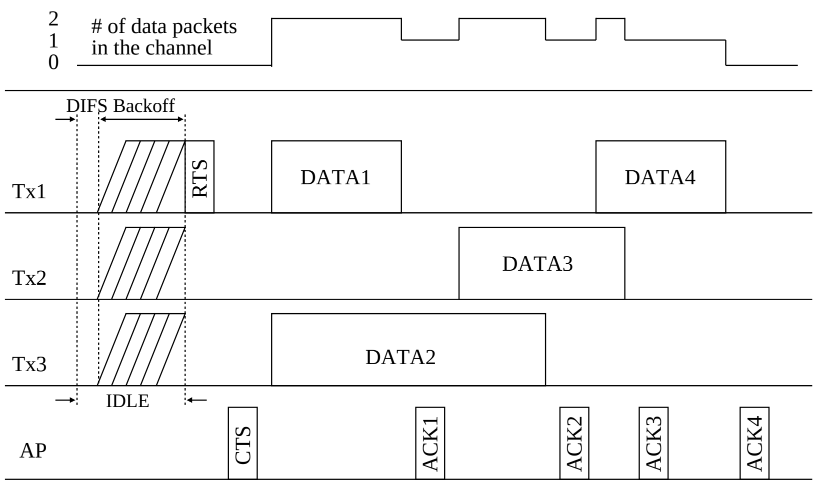


(a) Synchronous MAC protocol.



(b) Asynchronous MAC protocol.

Fig. 1. Operation example of traditional synchronous and proposed asynchronous MAC protocols.

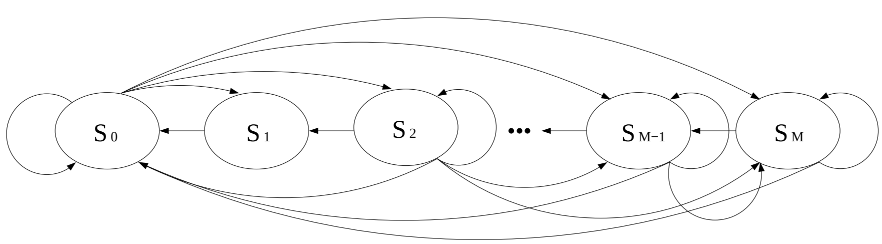
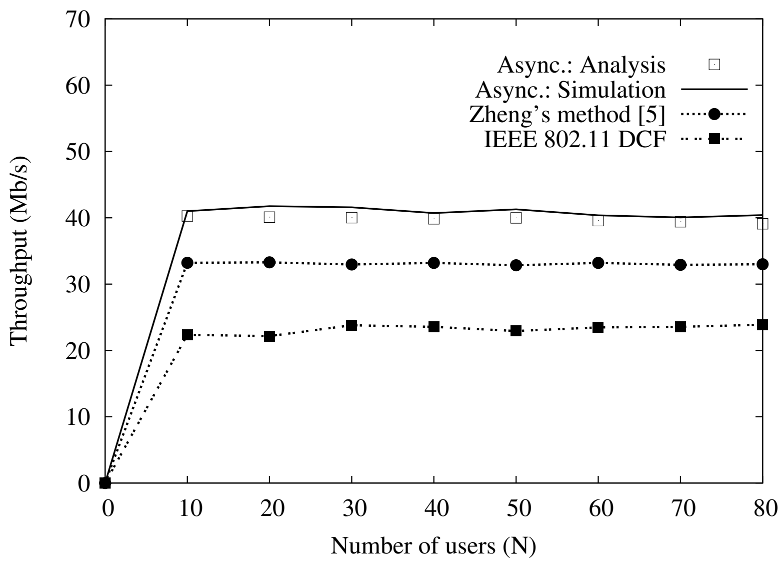
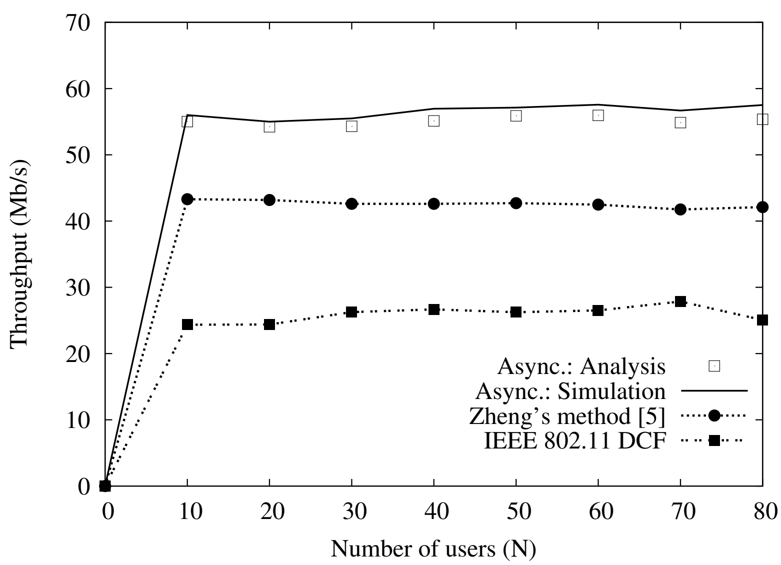


Fig. 2. A finite state of Markov chain model for the channel status of M multi-user MIMO systems.



(a) M=3.



(b) M=4.

Fig. 3. Throughput performance of asynchronous and synchronous MAC protocols w.r.t. the number of competing nodes N.

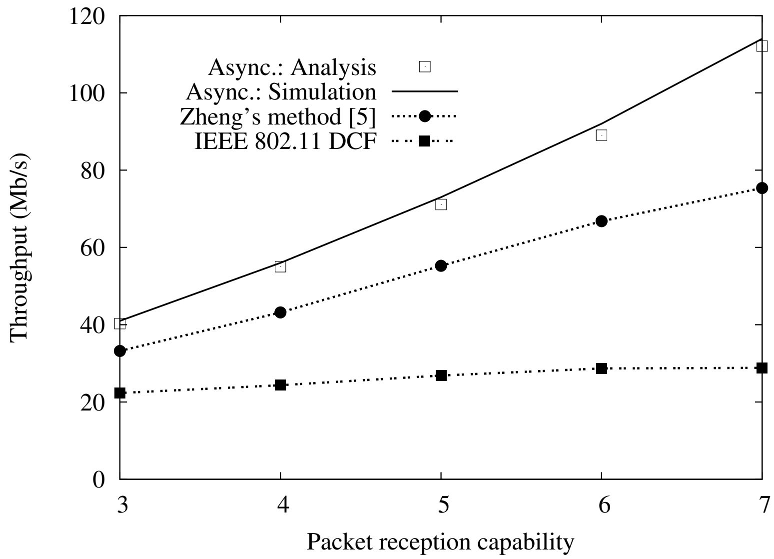


Fig. 4. Throughput performance of asynchronous and synchronous MAC protocols w.r.t. the packet reception capability M.

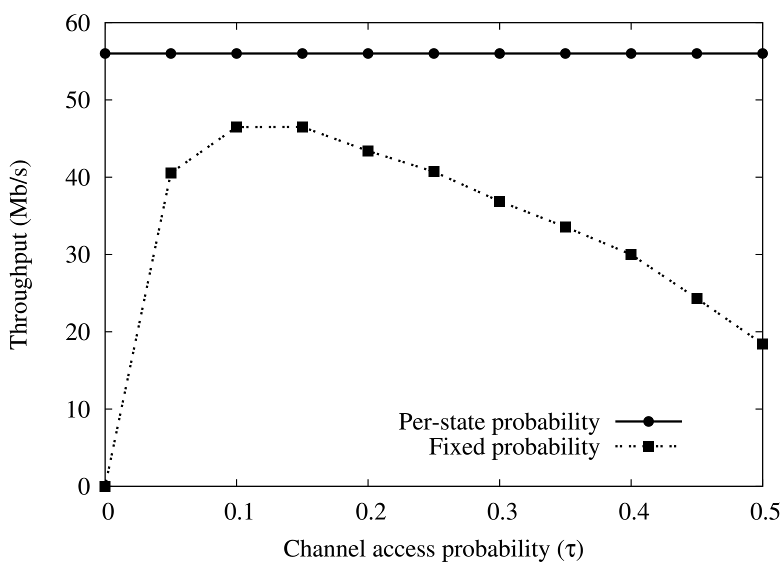


Fig. 5. Throughput performance comparison between using per-state channel access probability and fixed channel access probability.

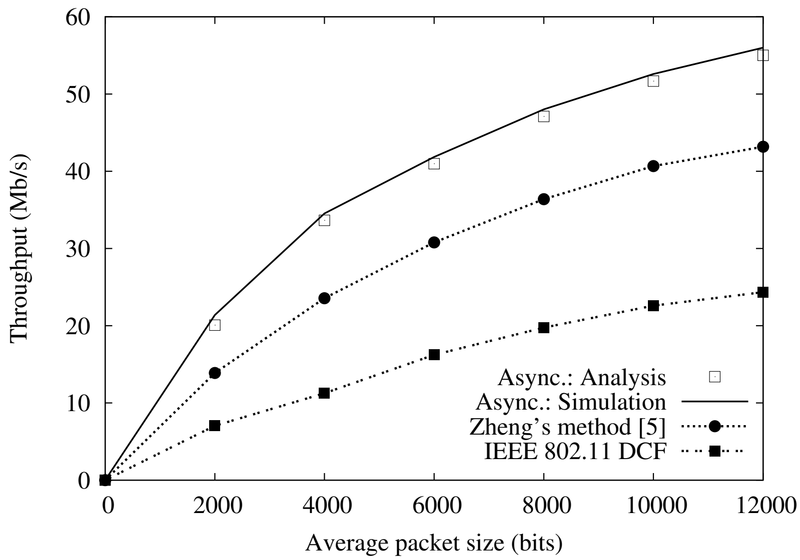


Fig. 6. Throughput performance of asynchronous and synchronous MAC protocols w.r.t. the packet size l.

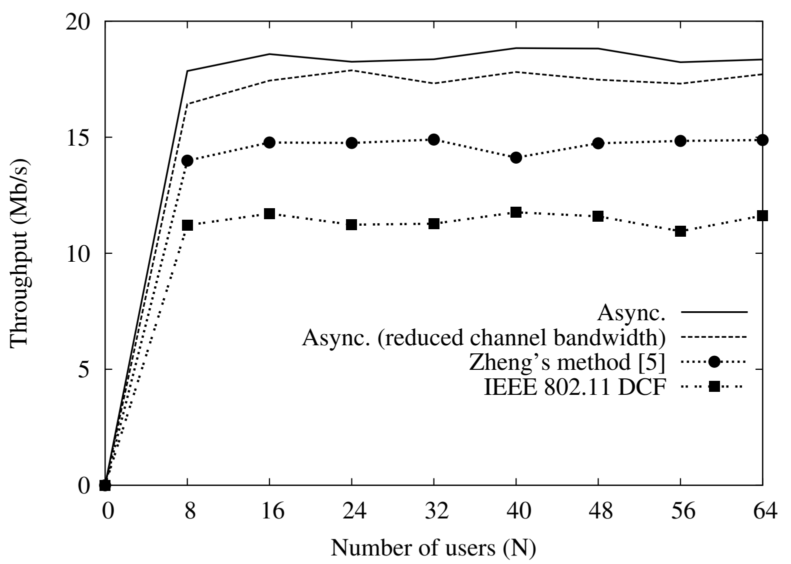


Fig. 7. Throughput performance of asynchronous and synchronous MAC protocols w.r.t. the number of competing nodes N in a multi-rate scenario.

TABLE I

SYSTEM PARAMETERS USED IN ANALYSIS AND SIMULATIONS.

Parameter	Value
T_{DIFS}	34 μsec
T_{SIFS}	16 μsec
T_{Slot}	9 μsec
PHY overhead	20 μsec
RTS frame	20 bytes + PHY overhead
CTS frame	14 bytes + PHY overhead
ACK frame	14 bytes + PHY overhead
Average payload (l)	10000 bits
Data transmission rate	54 Mb/s
Basic transmission rate	6 Mb/s
CW_{min}	15
CW_{max}	1023