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Performance evaluation of MIMO-aware media access control protocol

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ABSTRACT

Multiple-Input and Multiple-Output (MIMO) systems are recently being recognized for achieving simultaneous transmissions on wireless channels that overlap in time. As a result, new scheduling mechanisms are required that coordinate these multiple transmissions among wireless stations which share a single wireless channel. This paper proposes a new distributed MIMO-aware medium access control (MA-MAC) protocol which allows two simultaneous transmissions overlapped in time when stations are equipped with MIMO. The proposed MA-MAC protocol is compatible with the existing IEEE 802.11 standard for wireless local area networks (WLANs). It uses weighted nulling and intelligent packet fragmentation for its operation. Detailed performance analysis of MA-MAC protocol is carried out using the NS-2 network simulator. Firstly, this paper presents the concept of weighted nulling that is necessary for simultaneous transmissions on wireless channel, followed by a detailed description of the proposed MA-MAC scheme. Secondly, it presents the performance of MA-MAC scheme under various network scenarios that includes both saturated and unsaturated conditions. This paper presents the performance improvements shown by MA-MAC when compared with an existing medium access control scheme which is also proposed for scheduling simultaneous transmissions for MIMO.

1. Introduction

Wireless local area networks (WLANs) are now using Multiple-Input Multiple-Output (MIMO) antenna technology to improve overall network performance by achieving data rates beyond 100 Mega bits per second (Mbps). The initial goal of the upcoming IEEE 802.11n WLAN standard [1] is to at least provide the data rate of Fast Ethernet.

MIMO is also commonly seen in all IEEE 802.11a/b/g compatible wireless devices due to its various advantages. Multiple antenna systems have the ability to increase signal-to-interference-noise ratio (SINR) performance using antenna selection mechanisms which is not possible in Single-Input Single-Output (SISO) systems. MIMO systems also have the ability to capitalize on the scattering effects of the wireless channel. This allows a physical layer

designer to utilize the rich scattering phenomena in order to improve data link layer throughput through the use of spatial multiplexing. In addition, spectral efficiency can be improved by fully exploiting MIMO at the physical layer. For example, spectrum can be efficiently used through beamforming capability of MIMO. The new IEEE 802.11n standard exploits MIMO capabilities using spatial multiplexing in addition to providing optional beamforming capability [1].

Media access control (MAC) layer initially perceived MIMO as an improved physical layer link capable of providing higher data rates with increased reliability. The design of MAC protocols that exploits MIMO features is largely an unexplored problem. Since IEEE 802.11n standard endorses the usage of beamforming with MIMO, the MAC layer can utilize this to improve throughput performance of WLAN. Beamforming enables any particular wireless station to selectively tune in or tune out transmissions from other wireless stations. This will allow simultaneous transmissions on the wireless channel. Design of efficient MAC protocols that can schedule simultaneous

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transmissions are therefore essential to exploit the MIMO beamforming feature. Also these MAC protocols have to be backward compatible with IEEE 802.11 standard [2]. Therefore MAC layer designers have recently started to propose MAC protocols for MIMO systems that schedule simultaneous transmissions with in a single collision domain to improve throughput performance in WLANs.

In this work, a MIMO-aware MAC (MA-MAC) scheme is proposed that schedules two simultaneous transmissions.[1] These two simultaneous transmissions that overlap in time are scheduled within a single collision domain to improve channel utilization. This is achieved through a newly proposed MAC decision process along with intelligent packet fragmentation. The proposed MA-MAC scheme is compatible with the IEEE 802.11 standard. The scheme is proposed for a three element antenna array MIMO system. The selection of a small antenna size is mainly due to space limitations in mobile phones, personal digital assistants (PDAs) and laptops.

The remainder of the paper is as follows. Section 2 provides a review of the MAC protocols proposed in the literature for MIMO. Then the motivation for pursuing this work is given in Section 3. An overview of MIMO along with the concept of weighted nulling that is necessary for simultaneous transmission is given in Section 4. Detailed description of the MA-MAC protocol is given in Section 5. In Section 6 performance analysis of the proposed MA-MAC scheme is carried out using simulations in NS-2 network simulator. The performance of MA-MAC is compared with SPACE-MAC protocol which is proposed in literature for IEEE 802.11 standard. Finally conclusions are drawn on this work in Section 7.

2. Literature review

Recently several MAC protocols are proposed in literature for MIMO systems. All these protocols attempt to exploit MIMO capabilities to improve throughput performance in wireless networks. In this section some MAC protocols that schedule simultaneous transmissions using MIMO are briefly summarized along with their limitations.

2.1. MIMA-MAC

Mitigating interference using multiple antennas MAC (MIMA-MAC) allows multiple stations to communicate within a contention region by utilizing zero-forcing MIMO receivers in each wireless station [3]. This was further extended to support antenna selection [4]. The number of simultaneous transmissions available in MIMA-MAC and MIMA-MAC/AS is equal to the number of antennas per station. In these protocols, the authors have proposed a fixed size MIMA-MAC frame that is divided into a contention period and a contention-free period. During the contention period, wireless stations compete for channel access for the contention-free period. The contention period is divided into slots for multiple contentions. The order of channel acquisition during the contention period determines the order of transmission of training and

acknowledgment packets in the contention-free period by the wireless stations.

In the contention-free period, stations first send training sequences for channel estimation. As mentioned, the order in which stations acquired the channel during the contention slots defines the order of the training sequences. Following these sequences, all transmitting stations will send data packets simultaneously. Receivers decode data from their respective transmitters using the channel information resolved from the training sequences. Following data transmission, acknowledgment packets are also sent by the receivers to confirm successful transmission of the data packets. These are transmitted in the same order as the training sequences.

The main disadvantage with MIMA-MAC and MIMA-MAC/AS is the requirement of a fixed MIMA-MAC frame size which is not suitable for networks with varying packet sizes.

2.2. NULLHOC

Mundarath et al. [5] proposed the NULLHOC protocol which schedules simultaneous transmissions by applying gains to each antenna element at both transmitting and receiving stations. In this protocol, by designing antenna weights appropriately, any station may listen or ignore (i.e., tune in or tune out) any other station. This allows multiple packets to be sent over the channel simultaneously. In this protocol, the channel is divided into two sub-channels namely data and control sub-channels. The control sub-channel (CC) is used to monitor traffic levels on the network while the data sub-channel (DC) is used for data transmission. The NULLHOC protocol utilizes a five packet exchange sequence (RTS/CTS/DS/DATA/ACK). Request-To-Send and Clear-To-Send (RTS/CTS) packets are sent on the control channel. If these stations can successfully exchange these packets, then the transmitting station follows with a Data-Send (DS) packet on the data sub-channel to reserve the channel resource. This is followed by the data packet transmission by the transmitting station and positive acknowledgment packet by the receiving station on the data sub-channel. By exchanging antenna weights in the control channel, NULLHOC supports multiple transmissions.

The major limitation in NULLHOC is the need for channel partitioning. This protocol imposes hardware complexity restrictions. Although channel estimation is performed on the control sub-channel, the channel information required for tuning should be found for the data sub-channel which is impractical. The operation of NULLHOC is also not compatible with IEEE 802.11 standard.

2.3. SPACE-MAC

Park et al. later proposed SPACE-MAC [6] to schedule simultaneous transmissions on a single collision domain. However in SPACE-MAC, a wireless station uses the same adjusted weights for both transmission and reception. As in NULLHOC, antenna weights are exchanged via control packets (RTS and CTS). Stations should always transmit packets (including control packets) without interfering with existing active transmissions. In SPACE-MAC, the first station that gains access to the channel determines
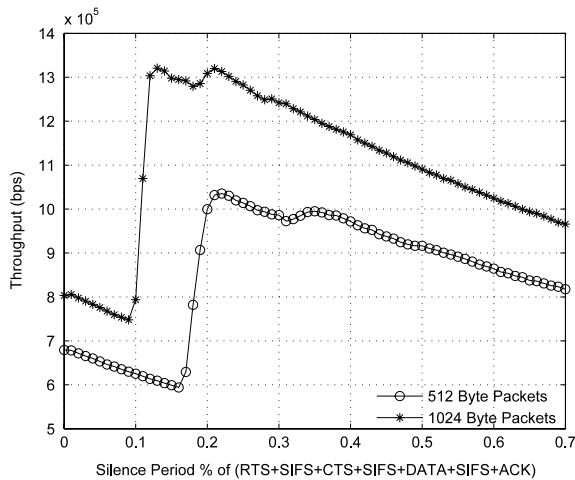
Fig. 1. Throughput versus silence period – 20 stations – 1 Mbps channel data rate.

the silence period. All other stations must remain idle following their transmission until the completion of the silence period. In SPACE-MAC, the silence period is required because any station currently involved in transmission is unaware of any other transmissions that began during its data packet or acknowledgment packet transmission phase. Additionally, any station that wishes to transmit must not interfere with this ongoing transmission as well as not transmit if it cannot complete its entire packet exchange sequence before the end of the silence period.

The performance of the SPACE-MAC protocol is heavily dependent on the length of the silence period. The optimal length of silence period varies with the network size and the traffic conditions. This is a major limitation with SPACE-MAC as suboptimal silence periods drastically reduce the maximum achievable throughput for a particular network scenario.

2.4. Antenna saturation

Examining these weighted MIMO MAC protocols (such as NULLHOC and SPACE-MAC), it is easy to see that these protocols reach saturation quickly in terms of the gain associated with an increasing number of antennas. In order to provide proper antenna spacing, the maximum number of antennas that can be supported in consumer devices such as laptops and PDAs is limited. As such, in this work we consider only a three antenna element MIMO system capable of achieving two simultaneous transmissions. Furthermore, in many practical networking scenarios, the number of stations within a given network are limited so that any additional transmission resources may not be fully exploited and therefore reduce the requirement of additional antennas.

3. Motivation

Though all the mentioned MAC protocols in the previous section schedule simultaneous transmissions over a single collision domain, only SPACE-MAC is compatible with the IEEE 802.11 standard. But the maximum achievable throughput in SPACE-MAC is dependent on the

optimal length of silence period. This optimal silence period varies with different network scenarios and traffic conditions. For example, consider a network with 20 wireless stations located closely to each other to share a single collision domain. All these stations are identical and use SPACE-MAC protocol for scheduling their transmissions. It is assumed that MIMO physical layer offers 1 Mbps bandwidth to the MAC layer. With this assumption, the throughput performance of SPACE-MAC for two different packet sizes (512 and 1024 bytes) is shown in Fig. 1. The length of the silence period is varied to observe the maximum achievable throughput in SPACE-MAC. The scheme achieves roughly up to a maximum of 1.3 Mbps overall throughput when the packet size is 1024 bytes. This maximum throughput is achieved only for a particular length of silence period which is optimal for this scenario. For any other silence periods, the throughput is reduced considerably. The same phenomenon can be observed when the packet size is changed to 512 bytes. When the size of packets is 512 bytes, SPACE-MAC barely achieves 1 Mbps throughput for optimal silence periods. Therefore, it is quite obvious that the throughput performance of SPACE-MAC is highly dependent on the length of silence period.

Furthermore, optimal silence period for SPACE-MAC also depends on the contention level and dynamics of the network traffic. This creates restrictions for designers in choosing an optimal silence period for nondeterministic network scenarios. As the dependency of SPACE-MAC on silence period is undesirable, more robust MAC protocols for MIMO are essential than SPACE-MAC. The primary motivation is to eliminate such dependence on silence period. The proposed MAC protocol should be compatible with IEEE 802.11 and capable of scheduling simultaneous transmissions similar to SPACE-MAC. With all these considerations, a new MIMO-aware MAC (MA-MAC) scheme is proposed to not only improve throughput but also delay performance in WLANs.

4. MIMO systems

4.1. MIMO overview

The possibility of having more than one transmission at a time on the wireless channel is due to the MIMO offered beamforming feature. Also MIMO systems generally offer better performance compared to Single-Input Single-Output (SISO) systems [7]. Assuming that each station on a WLAN has M antennas and by neglecting additive noise, the received signal at antenna element j of a wireless station is given by

$$r(t)_j = \sum_{i=0}^{M-1} s(t)_i h_{ij} \tag{1}$$

where $s(t)_i$ is the signal transmitted from ith antenna element on the transmitting wireless station and h_{ij} describes the amplitude and phase distortion between the ith transmitting antenna element on the transmitting station and the jth antenna element on the receiver station. More generally, the above equation can be written in a more condensed form as follows

$$\mathbf{r}(t) = \mathbf{s}(t)^T \mathbf{H} \tag{2}$$

where $\mathbf{r}(t)$ and $\mathbf{s}(t)$ represent the signal vectors across all receiver and transmitter antennas respectively, the superscript T denotes the matrix transpose operation and $\mathbf{H}$ is the $M \times M$ MIMO channel matrix with elements

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,M} \\ h_{2,1} & h_{2,2} & & h_{2,M} \\ \vdots & & \ddots & \vdots \\ h_{M,1} & \cdots & \cdots & h_{M,M} \end{bmatrix}. \tag{3}$$

A designer may exploit MIMO by using spatial multiplexing, spatial diversity and/or beamforming by pre- and/or post-processing of the transmitted/received signal. The proposed work in this paper exploits MIMO by applying gains to each antenna element on the transmitting station for pre-processing similar to the work carried out in NULLHOC and SPACE-MAC. Antenna weights are also applied post-reception at the receiver wireless station. Denoting this vector of antenna gains (or weights) as $\mathbf{w}_n$, where n denotes the index of a particular station, we can represent the output of the transmitting antenna array as

$$\mathbf{s}(t)^T = s(t)\mathbf{w}_n^\dagger \tag{4}$$

where $s(t)$ is data signal to be transmitted and the superscript $\dagger$ denotes the complex conjugate transpose. Using (2), the received signal vector at a receiving wireless station m can be expressed as

$$\mathbf{r}(t) = s(t)\mathbf{w}_n^\dagger \mathbf{H}_{nm} \tag{5}$$

where $\mathbf{H}_{nm}$ is the MIMO channel matrix between transmitting station n and receiving station m, and $\mathbf{r}(t)$ represents the signal at the input of the receiver station MIMO antenna array (as before).

In this work an assumption is made that the MIMO channel matrix can be estimated accurately using pilot symbols that are embedded in control packet headers. Also the channel between any two stations is assumed to remain static for the duration of one frame exchange sequence (RTS/CTS/DATA/ACK) as defined in IEEE 802.11 distributed coordination function (DCF). Also the channel is assumed to be reciprocal, i.e., $\mathbf{H}_{mn} = \mathbf{H}_{nm}^\dagger$. It is assumed that the receiver wireless station applies its antenna weights to the received signal $\mathbf{r}(t)$ in a manner that generates an overall received signal as

$$r(t) = \mathbf{r}(t)\mathbf{w}_m = s(t)\mathbf{w}_n^\dagger \mathbf{H}_{nm}\mathbf{w}_m \tag{6}$$

where $\mathbf{w}_m$ is the weights applied by the receiver station. The antenna weight vectors are assumed to not introduce additional power into the system and therefore $\mathbf{w}_n$ and $\mathbf{w}_m$ are always normalized to unity.

Using (6) along with the knowledge of $\mathbf{H}_{nm}$, transmitting and receiving stations can design $\mathbf{w}_n$ and $\mathbf{w}_m$ in such a manner to produce an overall complex gain across the channel. On the contrary, receiving stations can choose weights to tune out transmissions from particular transmitting wireless stations. This can be achieved as follows

$$\mathbf{w}_n^\dagger \mathbf{H}_{nm}\mathbf{w}_m = 0. \tag{7}$$

4.2. Weight adjustment

Stations can selectively tune in or tune out a particular transmission from a station by properly adjusting their antenna weights. The transmitting stations on the WLAN can either transmit when the wireless channel is
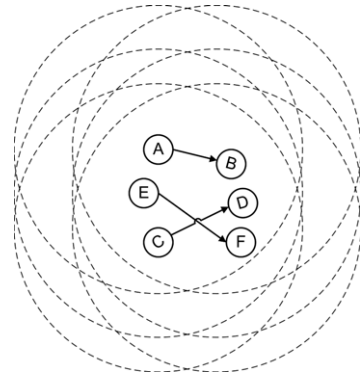

Fig. 2. Ad hoc network scenario.

absolutely idle or when some transmissions are already in progress. Therefore each transmitter–receiver pair would face interference from other transmitter–receiver pairs. In order to limit the interference (for proper data transmission on the network), only a limited number of simultaneous transmissions is allowed at any particular time instance in a WLAN. Therefore, with an M element MIMO system on each wireless station, the number of simultaneous transmissions on the channel is limited to $\frac{M+1}{2}$. This is necessary because each existing transmitter–receiver pair consumes two degrees of freedom. Since this work considers a three element antenna array MIMO system, it is possible to achieve two simultaneous transmissions within a single collision domain. For transmission on wireless channel, the stations adjust their weights during one of the following two situations: (1) when the channel is absolutely idle, and (2) when the channel has existing transmissions.

4.2.1. Idle channel weight adjustment

Wireless stations that initiate transmission when the channel is idle have the flexibility to adjust their antenna weights to obtain the best possible signal-to-interference-noise ratio (SINR). For this a transmitting wireless station uses default antenna weights to initiate its transmission. The intended receiver station then adjusts its antenna weights to maximize the SINR and responds to the transmitter to allow for transmission to proceed. The receiver station adjusts its antenna weights as follows

$$\max_{\text{norm}(\mathbf{w}_R)=1} \left(\mathbf{w}_T^\dagger \mathbf{H}_{TR}\mathbf{w}_R \right). \tag{8}$$

It is clear that with the knowledge of $\mathbf{H}_{TR}$ and $\mathbf{w}_T$, $\mathbf{w}_R$ should be

$$\mathbf{w}_R = \|(\mathbf{w}_T^\dagger \mathbf{H}_{TR})^\dagger\| \tag{9}$$

where $\|\mathbf{x}\|$ denotes the normalization operation (i.e., $\|\mathbf{x}\| = \frac{\mathbf{x}}{\text{norm}(\mathbf{x})}$).

The weight adjustment in this scenario can be understood from a simple ad hoc network scenario shown in Fig. 2. The ad hoc network has six stations, Stations A, B, C, D, E and F. Suppose that the channel is idle and Station A is the first station to transmit on the channel. Assuming that Station B is the intended receiver for Station A, Station B adjusts its antenna array element weights using (9). Other stations on the channel tune out the transmissions from both Station A and Station B using (7).
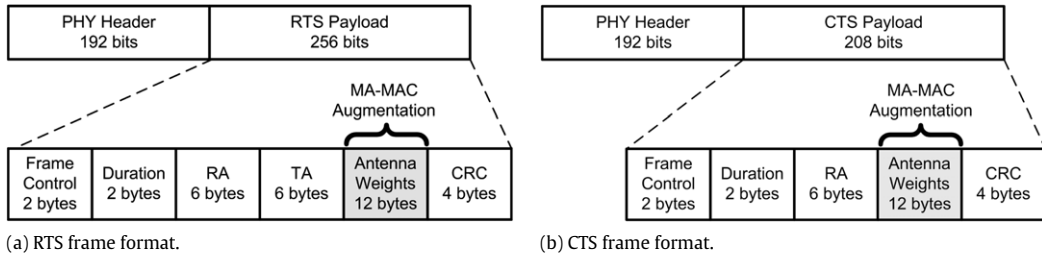
(a) RTS frame format.

(b) CTS frame format.

Fig. 3. Access control packets.

4.2.2. Busy channel weight adjustment

For other wireless stations on the channel to communicate during the ongoing transmission, they must null the existing transmission using (7) to not interfere with the first transmission. First defining $\mathbf{h}_{xy} = \mathbf{w}_x^\dagger \mathbf{H}_{xy}$, the above equation can be expressed as

$$\mathbf{h}_{AX}\mathbf{w}_X = 0 \quad \text{and} \quad \mathbf{h}_{BX}\mathbf{w}_X = 0 \qquad (10)$$

for any other Station in the network (e.g., Station X). Since at this point in time Station X is unaware of its intended receiver or transmitter, it would assume that the effective channel from an unknown Station Y is given by $\mathbf{h}_{YX} = [1\ 1\ 1]$. The weight vector design for Station X becomes

$$\mathbf{w}_X = \left\| \begin{bmatrix} \mathbf{h}_{AX} \\ \mathbf{h}_{BX} \\ \mathbf{h}_{YX} \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right\|. \qquad (11)$$

Referring again to the example scenario, suppose Station C wishes to transmit to Station D while the first transmission is ongoing. Firstly, both Stations C and D would have already designed weights using (11). Station C will utilize these weights to transmit. At this time Station D has the option to readjust its weights subject to the weights in use by Station C and the channel information from Station C (i.e., $\mathbf{h}_{CD}$). The resulting weight vector used by Station D will become

$$\mathbf{w}_D = \left\| \begin{bmatrix} \mathbf{h}_{AD} \\ \mathbf{h}_{BD} \\ \mathbf{h}_{CD} \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right\|. \qquad (12)$$

To demonstrate this example, suppose the two transmissions (i.e., from Station A to Station B and from Station C to Station D) are ongoing using weight vectors $\mathbf{w}_A$ through $\mathbf{w}_D$ respectively. Station B will receive the following signal

$$\begin{aligned} r_B(t) &= (s_A(t)\mathbf{w}_A^\dagger \mathbf{H}_{AB} + s_C(t)\mathbf{w}_C^\dagger \mathbf{H}_{CB})\mathbf{w}_B \\ &= s_A(t)\mathbf{w}_A^\dagger \mathbf{H}_{AB}\mathbf{w}_B + s_C(t)\underbrace{\mathbf{w}_C^\dagger \mathbf{H}_{CB}\mathbf{w}_B}_{0} \\ &= s_A(t)\mathbf{w}_A^\dagger \mathbf{H}_{AB}\mathbf{w}_B. \end{aligned} \qquad (13)$$

The above can also be shown for all pairs involving Stations A through D due to the design of their respective weights.

5. MA-MAC protocol

The proposed MIMO-aware MAC (MA-MAC) scheme in this section utilizes the beamforming feature in MIMO to schedule multiple transmissions on the wireless channel. Wireless stations adjust their antenna weights to selectively tune in or tune out a particular transmission as governed by MA-MAC. The proposed scheme uses a three element antenna array as MIMO physical layer to schedule up to two simultaneous transmissions in a single collision domain. This is achieved through a newly proposed MAC decision process along with intelligent packet fragmentation. MA-MAC utilizes the request-to-send/clear-to-send (RTS/CTS) access mechanism used in the IEEE 802.11 distributed coordination function (DCF). The antenna weights are conveyed through RTS and CTS packets. The following subsections present detailed description of MA-MAC.

5.1. RTS/CTS control packet format

For stations to selectively tune in or tune out a particular transmission, they have to be aware of the antenna weights that are in use by transmitting stations. This requires a mechanism for conveying the antenna weights to all neighboring stations. MA-MAC uses RTS and CTS control packets to convey antenna weights. The proposed format for RTS and CTS control packets is shown in Fig. 3. A separate 12 byte field is inserted in the payload of the RTS and CTS packets that stores three antenna element weights currently in use. RTS and CTS packets are also used to perform channel estimation using pilot symbols embedded in the physical (PHY) preamble.

5.2. Protocol operation

The MA-MAC protocol allows up to two simultaneous transmissions to proceed in a single collision domain. Wireless stations in MA-MAC adjust their antenna weights and take appropriate scheduling decisions depending on the channel status, i.e., depending on whether the channel is absolutely idle or a transmission is already taking place on the channel. The network scenario given in Fig. 2 will be used again for the description of the proposed MA-MAC scheme.

Initially, all stations observe the channel for a certain time which is the sum of partial weight sensing period and distributed inter-frame space (WSP$_{\text{partial}}$ + DIFS). The time WSP$_{\text{partial}}$ is a small period for which a station can be assured that there are no active transmissions on the channel and is equal to the sum of short inter-frame
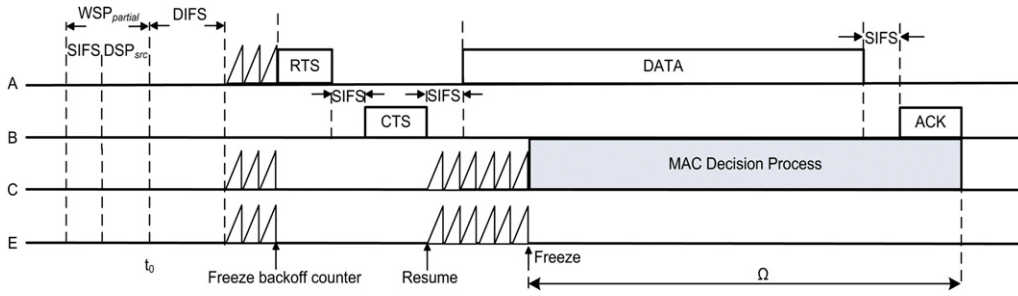
Fig. 4. MA-MAC scheme timing diagram.

spacing and the amount of time to send a special SP_{src} packet (SIFS + SP_{src}), while DIFS is a duration defined by the 802.11 DCF specifications. If the channel is found idle for this time, stations begin decrementing their backoff counter. When a station's backoff counter expires, it sends an RTS packet containing its currently used antenna weights. This is shown in Fig. 4, where Station A sends an RTS packet to Station B. Upon reception of RTS, all neighboring stations which are not the intended receivers (i.e., Stations C, D, E and F) store the duration of the transmission as well as the antenna weights used by Station A. The destination station (Station B), receives the RTS packet and adjusts its antenna weights to maximize the received signal SINR (as described in Section 4). In addition, this Station B responds with a CTS packet containing weight information. Stations A and B will now become the primary stations as they have successfully exchanged RTS and CTS packets between them. Station A will now proceed with DATA packet transmission to Station B which will in turn respond with positive acknowledgment (ACK) packet.

The primary stations transmit using the packet exchange sequence similar to the RTS/CTS scheme in DCF. When the packet exchange sequence between the primary stations (e.g., Stations A and B) is completed, they select a new weight vector and observe the channel for a certain time equal to $WSP_{partial}$. If the channel is found idle during this time, the stations continue to observe the channel to be idle for additional DIFS time before resuming the backoff process. Once a primary transmission has been established, other stations may compete for the remaining channel resource. After the primary transmission is established, other stations resume their backoff process as shown in Fig. 4. Assuming that Station C is the next station to complete its backoff process, it initiates a secondary transmission without interfering the ongoing primary transmission provided it is efficient to do so. The station must perform a proper MAC decision process to determine what actions must be taken based on the residual time remaining in the primary transmission (shown by Ω in Fig. 4). Assuming that Station C is successful in establishing transmission, the time taken to complete a full frame exchange is given by the expression

$$RTS + SIFS + \delta + CTS + SIFS + \delta + DATA$$
$$+ SIFS + \delta + ACK$$

where δ is the propagation delay experienced. In this case there are four unique cases that the secondary station

(Station C) can encounter based on the residual time Ω if it begins transmission, which are:

1. A secondary station will complete its full transmission before the primary finishes.
2. The secondary station will be transmitting an ACK packet when the primary transmission finishes.
3. The secondary station will be transmitting its DATA packet when the primary transmission finishes.
4. The secondary station will be still performing a control packet exchange (RTS/CTS) when the primary transmission finishes.

For each of the above cases, the secondary station makes a proper MAC decision to govern its transmission. For all cases the timing diagrams are shown in Fig. 5. The details of operation for each case is given below.

5.2.1. Scenario 1

When a secondary station determines that the residual time in the primary transmission is sufficient to complete the entire packet exchange, the station proceeds with its transmission. This is when

$$\Omega \geq RTS + SIFS + \delta + CTS + SIFS + \delta + DATA$$
$$+ SIFS + \delta + ACK + \delta \qquad (14)$$

where all quantities define the time taken to send the particular packet, SIFS is short inter-frame spacing defined by the 802.11 specifications and δ is the propagation delay. DATA denotes the data packet transmission time of a secondary station wishing to transmit.

In this case Station C proceeds with transmission using antenna weights designed not to interfere with the primary stations (Station A and Station B) as shown in Fig. 5(a). As mentioned before these weights are included in the RTS packets in order to disseminate this information to all other stations. Upon reception of this transmission, the intended receiver (i.e., Station D) readjusts its antenna weights to maximize reception from Station C while still tuning out the primary stations. Station D will subsequently respond with a CTS packet containing its antenna weights. This transmission is now active and referred to as the secondary transmission. At this time, all other stations in the network update and store the information (such as antenna weights and transmission duration). Since it is not possible to accommodate more than two simultaneous transmissions, the other stations set their network allocation vector (NAV) to the expiration of the earliest transmission.
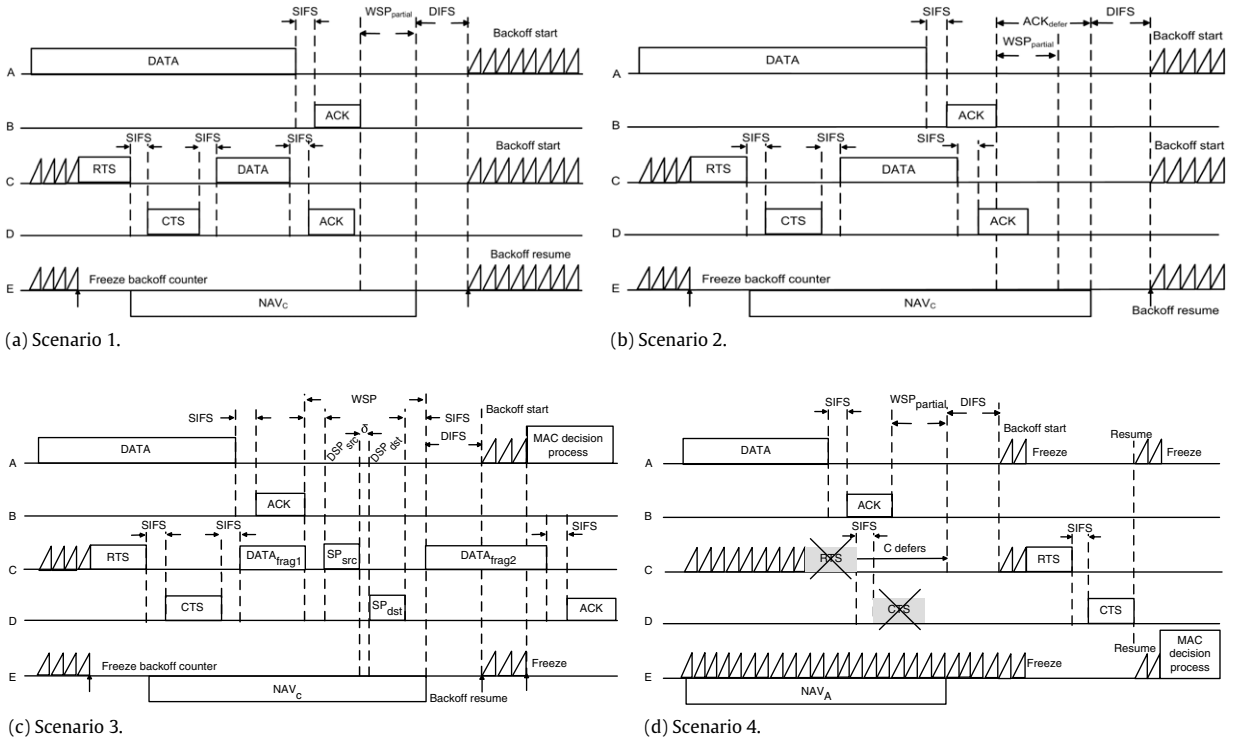
(a) Scenario 1.

(b) Scenario 2.

(c) Scenario 3.

(d) Scenario 4.

Fig. 5. Timing diagram of MAC decision process for secondary stations.

5.2.2. Scenario 2

Alternatively, if the secondary station determines that the primary transmission is completed during its ACK transmission, then that station proceeds with this transmission accordingly. This is when

$$\text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + \text{DATA} + \text{SIFS} + \delta$$
$$\leq \Omega < \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS}$$
$$+ \delta + \text{DATA} + \text{SIFS} + \delta + \text{ACK} + \delta. \quad (15)$$

Since the duration of ACK is small compared to the transmission duration of the entire DATA packet exchange sequence, it is efficient to start the secondary transmission. In this case the responsibility is given to primary stations to perform collision avoidance. The primary stations observe the channel for time equal to WSP$_{\text{partial}}$ to identify any ongoing transmission. When the channel is identified as busy and the primary stations cannot decode a specific packet, they defer for

$$\text{ACK} - \text{WSP}_{\text{partial}}. \quad (16)$$

This guarantees completion of the secondary transmission. For fairness, all other observing stations set their network allocation vectors (NAVs) to the duration of the primary transmission plus the duration of an ACK. The timing diagram for this is shown in Fig. 5(b).

5.2.3. Scenario 3

When a primary transmission finishes, the primary stations are unaware of the ongoing secondary transmission. To overcome this, secondary stations which are currently in the DATA packet transmission phase are required to relay information regarding their current transmission (including duration and antenna weights) using the weight sensing period (WSP). The secondary stations (i.e., Station C, Station D) convey the information regarding secondary transmission to the primary stations (i.e., Station A, Station B) using coordinated intelligent packet splitting. This situation occurs

$$\text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta$$
$$\leq \Omega < \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta$$
$$+ \text{DATA} + \text{SIFS} + \delta. \quad (17)$$

In this case, the secondary stations (i.e., Station C, Station D) perform the weight sensing procedure:

- At the instant the primary transmission completes, the secondary station transmitter (Station C) halts transmission of the DATA packet.
- After SIFS time, this station sends a SP$_{\text{src}}$ packet containing antenna weights, transmission duration and pilot symbols for channel estimation.
- Following SP$_{\text{src}}$ and a small time to account for propagation delay, the secondary receiving station (Station D) sends a SP$_{\text{dst}}$ packet containing antenna weights and pilot symbols for channel estimation.
- Again after SIFS time, the secondary transmitter attaches a short PHY header to the remaining portion of the DATA packet (now referred to as DATA$_{\text{frag},2}$).
- At this time, the secondary stations are now referred to as primary stations and are governed by MAC operation for primary stations.
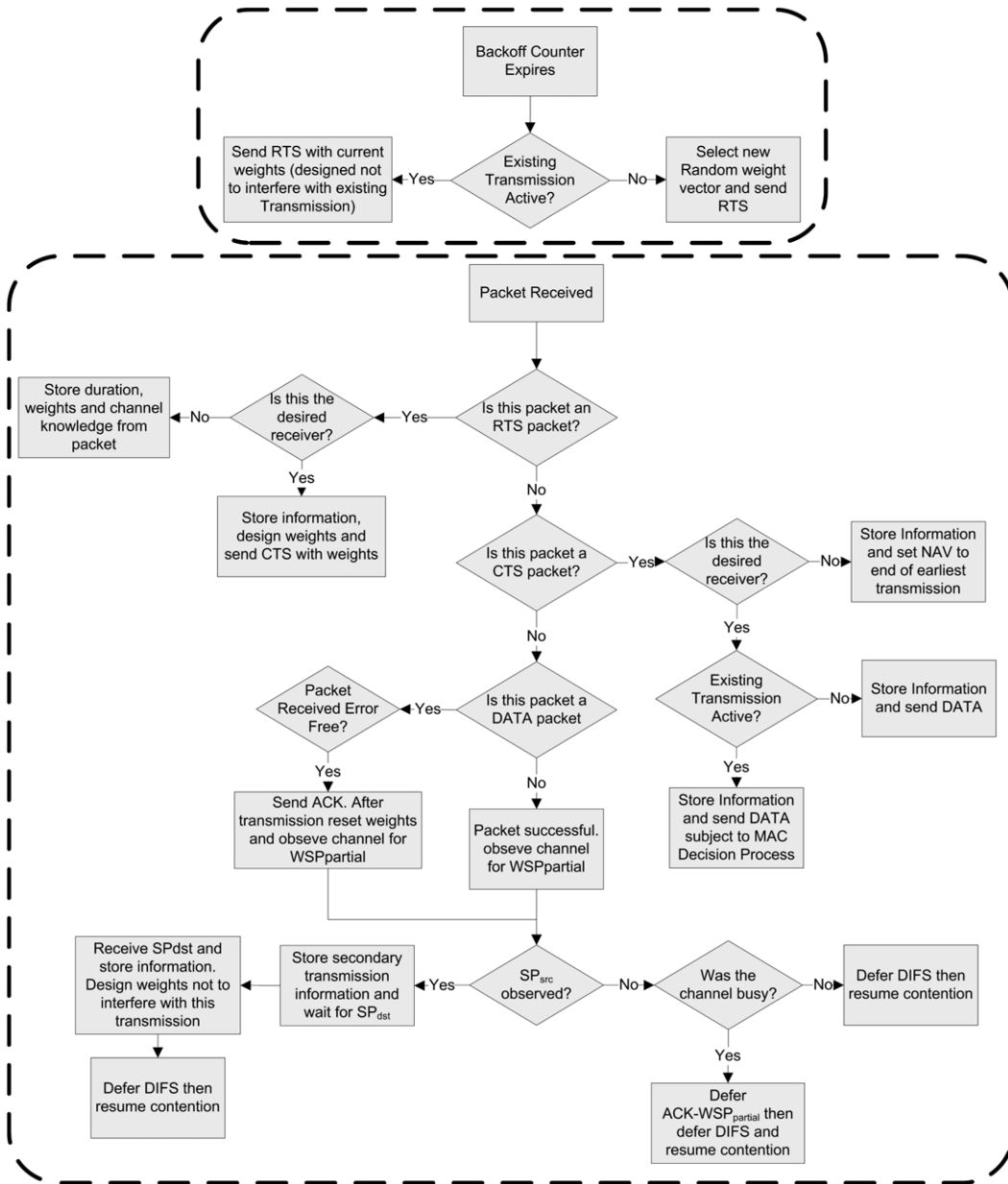
Fig. 6. Flowchart of MA-MAC operation.

The timing diagram for WSP is shown in Fig. 5(c). The packet formats for both SP_{src} and SP_{dst} are shown in Fig. 7(a) and (b) respectively. Both packets contain the weights currently used by the secondary stations as well as pilot symbols embedded in the PHY preamble for channel estimation. Furthermore, SP_{src} contains the duration of the remaining portion of transmission.

5.2.4. Scenario 4

Sometimes the residual time Ω is insufficient to complete a successful RTS/CTS exchange, meaning:

$$\Omega < RTS + SIFS + \delta + CTS + SIFS + \delta \qquad (18)$$

In this case the station does not send an RTS packet and alternatively defers to the end of the primary transmission

as well as increments its backoff counter. This action is taken as there is insufficient time to establish a successful transmission (perform RTS/CTS packet exchange). The flowchart describing operation of the MA-MAC protocol is shown in Fig. 6.

6. Simulation results

This section provides detailed simulation results of the MA-MAC protocol. The results are presented for both saturated and unsaturated conditions under different network scenarios and network parameters. Simulations of MA-MAC and SPACE-MAC are carried out using NS-2 network simulator [8]. Each time the performance of
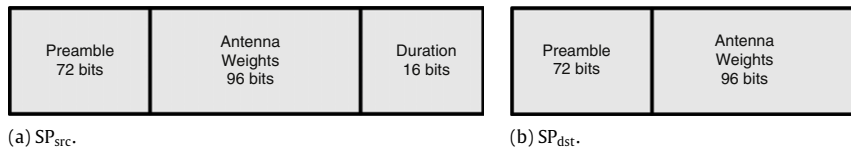
(a) SP$_{src}$.   (b) SP$_{dst}$.

Fig. 7. Weight exchange period packet formats.

(a) Saturation throughput versus number of stations in network.   (b) Average packet delay versus number of stations in network.
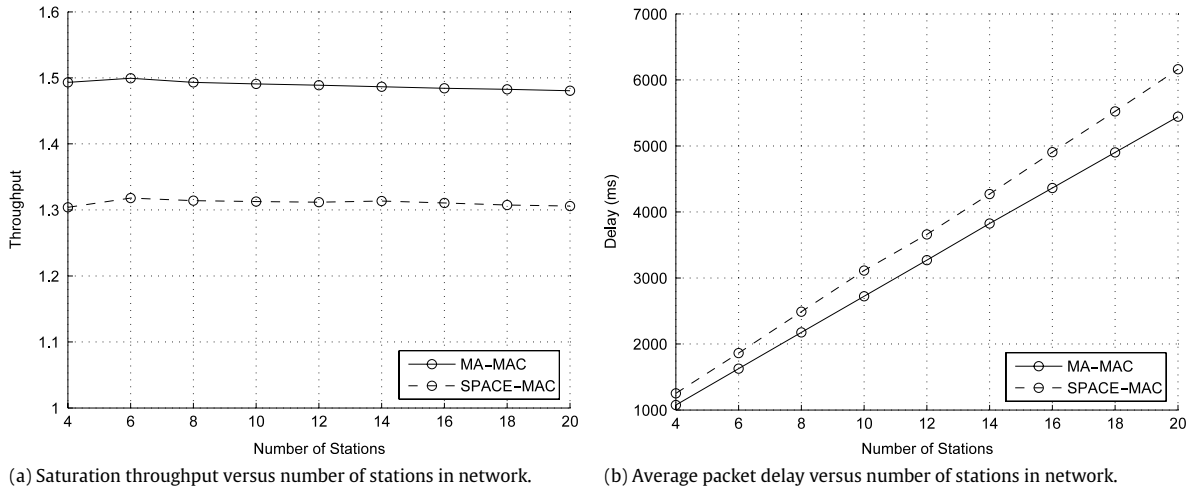
Fig. 8. Comparison of MA-MAC and SPACE-MAC schemes under saturated conditions.

MA-MAC is compared with SPACE-MAC. Since SPACE-MAC performance relies heavily on its silence period, in each simulation the SPACE-MAC silence period is optimized before comparing its performance with the proposed MA-MAC. The standard simulation parameters used throughout for both MA-MAC and SPACE-MAC are summarized in Table 1 unless otherwise specified.

6.1. Saturated performance

To analyze the performance of MA-MAC and SPACE-MAC schemes under saturated conditions, a network scenario is created with stations that send fixed size packets at a constant bit rate equal to the maximum data rate offered by the MIMO physical layer (i.e., 1 Mbps — as assumed). This forces the stations to always be in saturated condition as they always have packets to send in their buffer. In these simulations, all the stations are located within the transmission range of each other and therefore exist in a single collision domain.

6.1.1. Overall improvements

The performance of both MA-MAC and SPACE-MAC is shown for varying number of stations in order to provide an overall comparison of saturated throughput for these protocols. Fig. 8 shows the performance under saturated conditions for a varying number of stations. It can be seen that MA-MAC performs better than the best performance achievable with SPACE-MAC. Fig. 8(a) shows that the achievable overall throughput using SPACE-MAC is only around 1.3 Mbps, whereas MA-MAC achieves more than

Table 1
Simulation parameters.

Parameter	Value
SIFS	10 µs
DIFS	50 µs
Slot time	20 µs
SP$_{src}$	184 bits
SP$_{dst}$	168 bits
DATA$_{frag2}$ PHY header	72 bits
WSP$_{partial}$	194 µs
WSP	450 µs
Propagation delay (δ)	6 µs
Data rate	1 Mbps
CW$_{min}$	32
CW$_{max}$	1024
RTS (MA-MAC)	56 bytes
CTS (MA-MAC)	50 bytes
RTS (SPACE-MAC)	58 bytes
CTS (SPACE-MAC)	52 bytes

1.5 Mbps in overall throughput. Though delay values under saturated conditions have little significance, the average delay experienced by the transmitted data packets in MA-MAC scheme is smaller compared to SPACE-MAC for all network sizes (see Fig. 8(b)).

6.1.2. Effect on network parameters

The same saturated network scenario is utilized to understand the effect of the various network parameters on the performance of MA-MAC. In this case individual parameters are varied to study the effect on the overall network throughput.
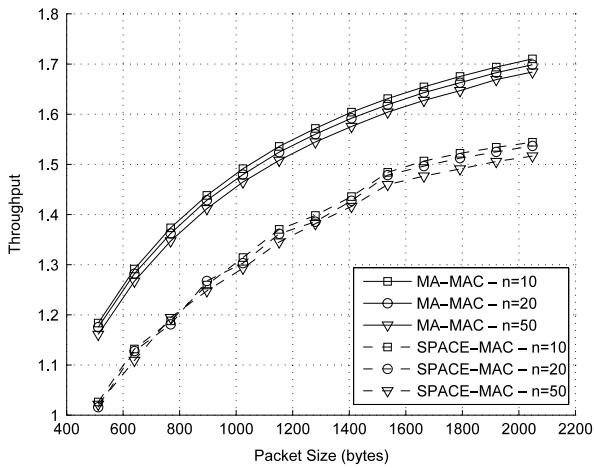
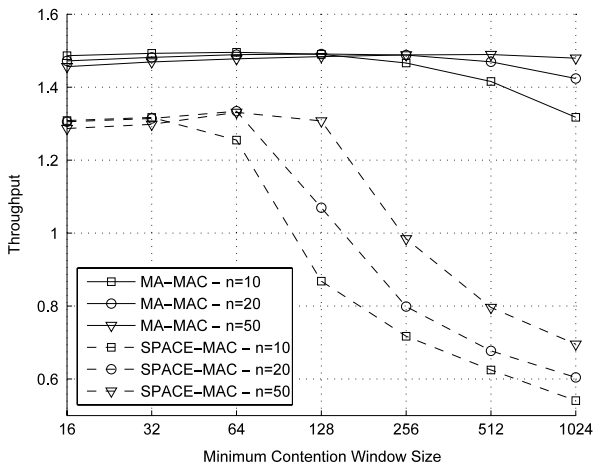**Fig. 9.** Throughput versus packet size.

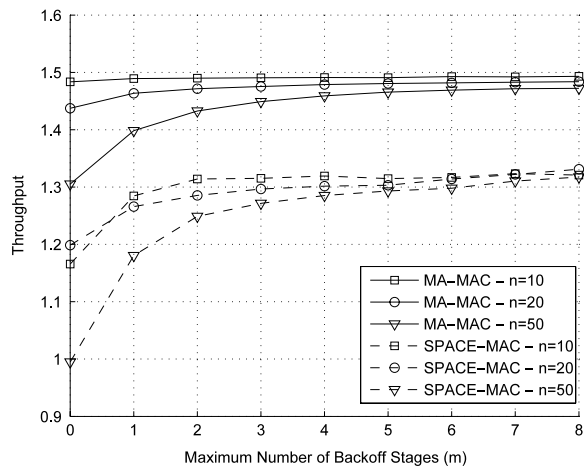**Fig. 10.** Throughput versus window size.

Fig. 11. Throughput versus backoff stages.

Fig. 9 shows the performance of both schemes for varying packet sizes and presented for various networks sizes. The throughput of both protocols increases with respect to packet size. However as the network size increases, the throughput is slightly reduced for both protocols. This is a result of the greater number of collisions experienced in the dense network. SPACE-MAC experiences the same trend as MA-MAC as a function of network size, however the overall throughput is less than that is achievable using MA-MAC. This is due to the presence of large silence periods in SPACE-MAC.

In Fig. 10 the packet size is fixed to 1024 bytes, and the size of the minimum contention window is varied for both protocols. The maximum number of backoff stages is also set to 6. It is observed that the contention window size that offers the maximum throughput depends largely on the number of stations in the network. For MA-MAC, the maximum throughput is achieved when the minimum contention window is set to 64 with a network size of 10 stations, however for a 50 station network, the window size must be 512 to achieve the best performance. Furthermore, increasing the window further beyond the maximum point causes rapid degradation in throughput. Varying the window size for SPACE-MAC reveals a major limitation in the protocol operation. As shown in Fig. 10, there is a rapid reduction in throughput once a threshold window size is reached based on the number of stations in the network. This occurs as the residual time in SPACE-MAC is small with such large contention windows, such that frequently stations cannot initiate a secondary transmission due to the restriction imposed by the SPACE-MAC silence period.

Next the effect of the maximum number of backoff stages on network throughput is studied. For this the minimum contention window size is fixed to 32 and the maximum number of backoff stages is varied. Fig. 11 shows the results of these simulations. For 10 stations using MA-MAC, the change in throughput as a function of backoff stage is negligible. This is due to the low number of stations involved in collision. For 20 and 50 station scenarios, it is observed that for low backoff stages, the throughput suffers degradation. At approximately a maximum backoff stage value of 6, the throughput gain associated with any additional increases is negligible. SPACE-MAC experiences similar trends as the number of backoff stages increases with respect to MA-MAC, however achieves lower aggregate throughput.

Finally the effect of a varying number of stations on network throughput is shown. In this case, three sets of values are used for the contention window size and number of backoff stages. The results are shown in Fig. 12. It can be observed that the throughput of both protocols reduces for an increasing number of stations. The window size of 128 offers the highest throughput for a large number of stations. It can be observed that when there are a small number of stations, there are many wasted idle slots causing a reduction in throughput. For a window size of 128 and a maximum backoff stage of 3, SPACE-MAC however experiences a slight gain in throughput unlike MA-MAC. This is due in part to the modification of the silence period parameter in SPACE-MAC to allow it to achieve maximum throughput.
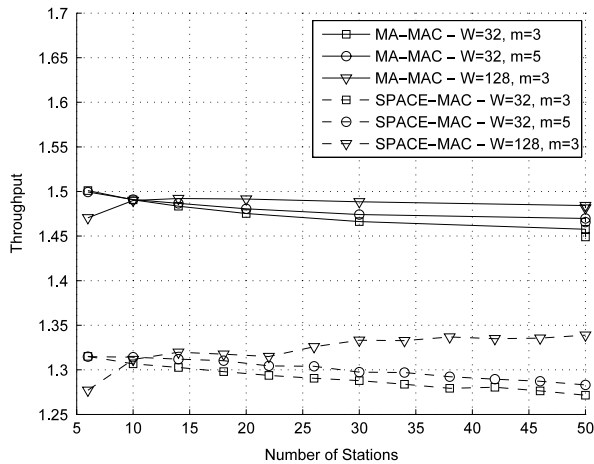
Fig. 12. Throughput versus stations.

Table 2
MA-MAC fairness comparison for 6 and 12 station networks.

Station ID	Throughput (kbps)	Delay (ms)	Throughput (kbps)	Delay (ms)
1	259.41	1571	128.12	3182
2	256.39	1589	128.75	3162
3	254.22	1603	123.04	3312
4	259.29	1571	122.49	3325
5	246.83	1651	131.79	3093
6	249.10	1635	128.45	3170
7	–	–	125.06	3261
8	–	–	127.65	3194
9	–	–	119.44	3413
10	–	–	129.16	3146
11	–	–	121.90	3342
12	–	–	126.22	3225
Std. deviation	8.05	33.38	3.65	95.38

6.1.3. Fairness

The fairness of the MA-MAC protocol is also studied thoroughly for numerous network sizes and under different scenarios. For clarity the results are presented for only 6 and 12 stations scenarios. The throughput and delay observed for each station in the scenario are tabulated to compare fairness. In this scenario, all the stations are under saturated conditions and send 1024 bytes packets. All other parameters are found in Table 1. These results are presented in tabular form in Table 2. From the table, it can be observed that the proposed MA-MAC protocol provides a reasonable degree of fairness to all the wireless stations on the channel.

6.2. Performance under unsaturated conditions

The performance of both protocols is also studied under unsaturated conditions. For this study, the networking scenario shown in Fig. 13 is created. All these stations are located in a single collision domain and have a queue length of 50 packets. Bi-directional transmission is enabled between the wireless stations as shown in the diagram. The transmissions are denoted as uplinks and downlinks for identifying the direction of data transmission between
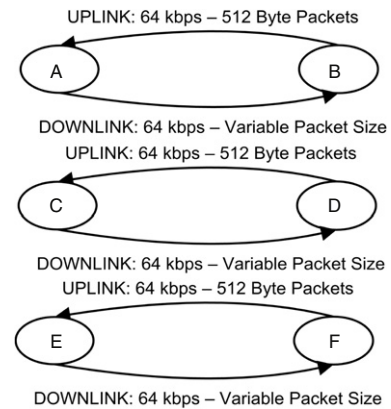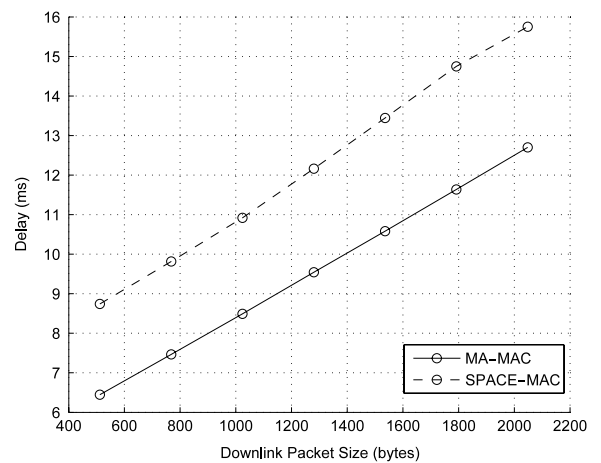

Fig. 13. Unsaturated network scenario.

Fig. 14. Total average delay versus downlink packet size.

stations. For example, Station A uses downlink to transmit to Station B while Station B uses uplink to transmit to Station A. All wireless stations are transmitting at 64 kbps for both types of links.

6.2.1. Effect of link packet size

Initially the effect of varying the data packet size is examined. For this, stations transmit at a constant bit rate. Uplinks transmit 512 byte packets while the size of downlink packets is varied to study the effect on network performance. The average throughput per station for both MA-MAC and SPACE-MAC is shown in Fig. 14. From this, it is observed that the overall average packet delay experienced in the network increases linearly as the data packet length of the downlink is varied. The average delay experienced per packet for MA-MAC is approximately 20%–25% less than that offered by SPACE-MAC.

6.2.2. Effect of increasing number of stations

Next, the effect of increasing the number of stations in the network is examined. To study this effect on throughput and delay performance for both schemes, more wireless stations are added to the network scenario given
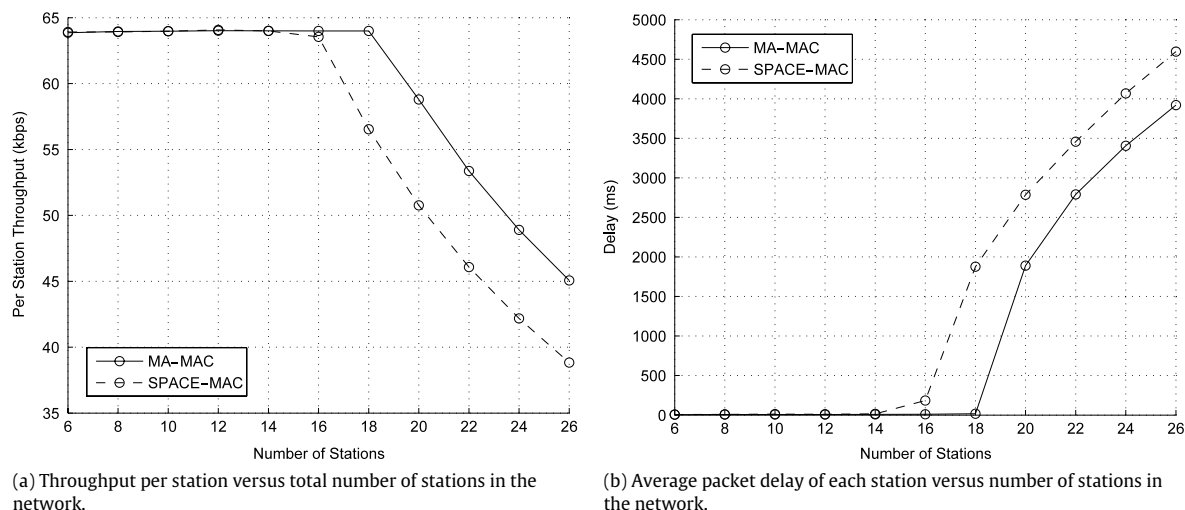
(a) Throughput per station versus total number of stations in the network.

(b) Average packet delay of each station versus number of stations in the network.

Fig. 15. Throughput and delay performance comparison of MA-MAC and SPACE-MAC.

in Fig. 13. In this case, instead of having only three pairs (i.e., 6 stations in total), the number of station pairs is increased on the network. Additionally, both types of links fix packet sizes to 512 bytes. The throughput and delay performance of each station under MA-MAC and SPACE-MAC for an increasing number of stations are shown in Fig. 15. MA-MAC performs better than SPACE-MAC as the network size increases. Also it can be seen that SPACE-MAC reaches saturation earlier than MA-MAC. When the number of stations in the network exceeds 14 for SPACE-MAC, the average throughput per station begins to drop whereas with MA-MAC, the network does not reach these saturated conditions until approximately 18 stations.

6.2.3. Packet delay distribution

Finally the distribution of packet delay is examined for the unsaturated network scenario. The previously used unsaturated network scenario is used with 10 stations. The number of stations for this scenario is chosen after studying the results presented in Fig. 15 as at this network size all stations achieve 64 kbps throughput using both MA-MAC and SPACE-MAC. The probability density function (PDF) of the delay performance for both MA-MAC and SPACE-MAC is shown in Fig. 16. From this it can be observed that the variation in delay experienced by packets in MA-MAC is less than that experienced in SPACE-MAC.

PDF analysis is also performed for other network sizes in unsaturated conditions to verify the performance of MA-MAC. In all cases the delay performance achieved by MA-MAC is better than that achievable with SPACE-MAC.

7. Conclusion

In this paper a new MA-MAC scheme is proposed for three element antenna array MIMO systems. The proposed scheme schedules two simultaneous transmissions at any instant of time in a distributed manner. MA-MAC is compatible with IEEE 802.11 standard similar to SPACE-MAC. The performance of both MA-MAC and SPACE-MAC is
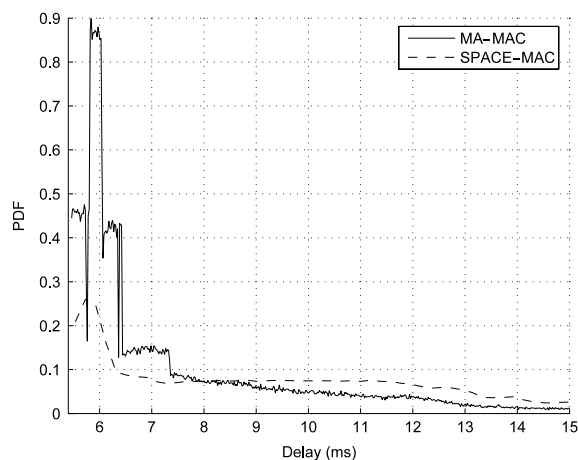

Fig. 16. PDF for packet delay. Network contains 10 stations.

studied under both saturated and unsaturated conditions. It is observed that MA-MAC achieves between 20 and 25% improvement compared to optimized SPACE-MAC.

For the future work, the effect of increasing the number of antennas in terms of antenna saturation will be studied. The MA-MAC scheme will be used as the basis scheme to support infrastructure networks.

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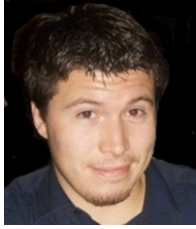
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