

Analysis and Enhancements for IEEE 802.11 Networks Using Directional Antenna With Opportunistic Mechanisms

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Abstract—Directional antennas are introduced to improve the performance of IEEE 802.11-based wireless networks by allowing stations equipped with directional antennas to beam the data in a specific direction. Since IEEE 802.11 has been developed with omni antennas in mind, deploying IEEE 802.11 in a directional antenna environment leads stations to be conservative in blocking their own transmissions in favor of the ongoing transmissions. This conservative behavior conflicts with the main directional antennas' objective of increasing the spatial reuse channel by supporting simultaneous transmissions. In this paper, we analytically show that an IEEE 802.11 station with directional antenna is conservative in terms of assessing channel availability, with as much as 60% of unnecessary blocking assessments. This percentage increases up to 90% in case we allow the station to alter the way it accesses its media access control (MAC) data queue. Motivated with this analysis, we design and evaluate two enhancement schemes for IEEE 802.11 networks when using directional antennas. The first enhancement is to augment the IEEE 802.11 protocol with additional information (location of the stations) that gives a station the flexibility to transmit data while there are ongoing transmissions in its vicinity. The second enhancement, using the augmented protocol, alters the way the IEEE 802.11 accesses its data queue. Simulation shows improvement in network throughput of up to 40% in the case of applying the first enhancement and up to 60% in the case of applying the second enhancement.

Index Terms—Capture effect, carrier sense, directional antenna, IEEE 802.11, network protocol, spatial reuse, wireless communication.

I. INTRODUCTION

DIRECTIONAL antennas have been introduced to improve the performance of IEEE 802.11-based wireless networks [1]–[5]. The main characteristic of directional antennas is the ability to beamform the data in the direction of the receiver with diminished interference in the remaining directions. Thus, the network capacity is increased as a consequence of interference reduction and spatial reuse of the channel [6], [7].

The IEEE 802.11 standard [8] was developed with omni antennas in mind. It assumes that all packets are transmitted as omni transmissions, and therefore, all nearby stations must remain silent to avoid any interference with the ongoing

transmissions. Many modifications to IEEE 802.11 (e.g., [5], [10], and [11]) were proposed to exploit the intrinsic feature of directional antennas (i.e., limited interference) to increase channel utilization and, consequently, the network performance. However, these proposed modifications still follow the original *conservative* approach of IEEE 802.11 standards in forcing stations to *block* their own transmissions in favor of the ongoing transmissions, even if their transmissions will not interfere with other transmissions.

In this paper, we start by analyzing the performance of IEEE 802.11 under the use of directional antennas. More specifically, we define two main blocking problems when using the directional antenna. We study analytically and through simulation the limitation and conservation of IEEE 802.11 under these two problems. We show that an IEEE 802.11 station with directional antenna is conservative in terms of assessing channel availability, with as much as 60% unnecessary blocking assessments. This percentage increases up to 90% if stations alter the way they access their IEEE 802.11 data queue. Then, motivated by these results, we propose the design of two *opportunistic* schemes to enhance IEEE 802.11 networks to increase the number of simultaneous data transmissions and thus improve the overall wireless network throughput when using directional antennas. The term *opportunistic* refers to mechanisms that exploit the directional antenna characteristics by taking immediate advantage of any circumstance of possible benefit. The first scheme augments the IEEE 802.11 protocol with additional information (location of the stations) that gives a station the flexibility to transmit data while there are ongoing transmissions in its vicinity. The second scheme, using the augmented protocol, alters the way the IEEE 802.11 accesses its data queue. Later, we evaluate the performance of the proposed schemes through extensive NS-2 simulation-based scenarios. Results show improvement in network performance over previous schemes up to 40% in the case of applying the first enhancement and up to 60% for the second scheme.

II. BACKGROUND

A. IEEE 802.11 DCF Mode

The IEEE 802.11 protocol is developed for wireless networks using omni antennas. The *basic* method of IEEE 802.11, i.e., the distributed coordination function (DCF), is a carrier-sense multiple access (CSMA) with collision-avoidance mechanism.

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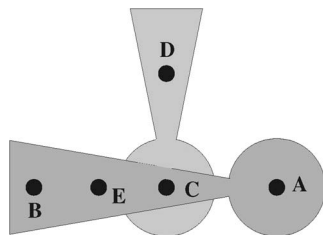


Fig. 1. Examples of CS_{Blocking} and HOL_{Blocking} blocking problems in IEEE 802.11.

The CSMA scheme of the DCF works as follows: Before a station transmits, it must sense the wireless channel to determine if any other station is transmitting. The channel is assessed as busy if a carrier signal is detected. If the channel is assessed as busy, then the station needs to wait until the carrier becomes idle plus another period known as the distributed interframe space (DIFS). Following the DIFS period, the station waits for a random backoff interval and then transmits if the channel is still free. An optional exchange of short request-to-send (RTS) and clear-to-send (CTS) control frames may precede the actual data frame transmission to reserve the channel.

Each station maintains a timer called the network allocation vector (NAV), which tracks the remaining time of any ongoing data transmission. After a station receives a RTS, CTS, DATA, or ACK frame not destined for itself, it sets its NAV according to the “Duration” field of the frame. Checking its NAV before a station attempting to transmit is also known as “virtual carrier sensing.” If the NAV is not zero, then the station needs to block its own transmissions to yield to the ongoing data delivery, even if there is no physical signal. In summary, *a station blocks its own transmissions if either physical carrier sensing or virtual carrier sensing indicates a busy channel.* For the rest of this paper, we use carrier sensing to refer to both physical carrier sensing and virtual carrier sensing.

B. Directional Antenna Model

Directional antennas can transmit data in both *omni* and *directional* modes. In omni transmissions, the station can transmit with equal power to all directions. In directional transmission, the station directs its energy toward the required direction, called the main lobe, with side and back lobes with lower energy [2], [9]. We adopt the antenna model in [2], which approximates all the side and back lobes into a single sphere with a station at its center. The 2-D shape of the adopted directional model is shown in Fig. 1.

The two common trends in directional antennas are *switched-beam* systems and *steering-beam* systems [2]. In a switched-beam system, the space of each station is divided into multiple sectors, each with a predefined fixed beam. Depending on the signal strength and direction, the station chooses one of the possible predetermined beams to transmit or receive data. A steering-beam system can point its beam at any direction depending on the transmitted or received signals. A switched-beam system is a special case of steering-beam system in which the steering is restricted to a set of predefined beams.

A station uses both omni and directional modes in receiving ongoing transmission. When the station is idle (not transmitting or receiving), it resides in the omni mode. Once it detects a signal from a certain direction, it starts receiving this signal in omni mode. While it is receiving this signal, it steers the antenna to the direction (or switches to one of the predefined beams) that maximizes the received power. If the station discovers that this transmission is not intended for itself,¹ then it switches back to omni mode. Otherwise, it stays in directional mode until it completely receives the packet and then switches back to omni mode.

The Directional Network Allocation Vector (DNAV), which was proposed in [5], [9], and [13], is used with a directional antenna instead of the original 802.11 NAV described earlier. Unlike NAV, each DNAV is associated with a direction and a width, and multiple DNAVs can be set for a station. A station maintains a unique timer for each DNAV and updates the direction, width, and expiration time of each DNAV every time the physical layer gives newer information about the corresponding ongoing transmission.

III. PROBLEM FORMULATION

In this section, we define two blocking problems of the IEEE 802.11 DCF when using directional antennas and the corresponding two enhancements to overcome these problems.

In the original 802.11 protocol, a station blocks its transmission when it senses a busy carrier. However, if the direction of this transmission does not interfere with the ongoing transmissions, then this blocking is unnecessary. Consider station A, which is engaged in a beamforming transmission to station B, as in Fig. 1. If station C wants to beam a data to station D, the running IEEE 802.11 carrier sense mechanism at station C will block this transmission because of the ongoing transmission between A and B. However, since the ongoing transmission is not destined to C, and since the C–D transmission direction would not interfere with the A–B transmission, as shown in the figure, station C should not be blocked. We refer to this problem as the *carrier sense blocking* (CS_{Blocking}) problem.

To overcome the CS_{Blocking} problem, we develop a scheme called $OPPCS$, in which we augment the 802.11 protocol with additional information (e.g., locations of the sender and the receiver). This scheme gives any station the flexibility, and hence the opportunity, to determine whether its own transmissions will interfere with any ongoing transmission. Several methods have been proposed in literature allowing a station to acquire its own location, examples include using Global Positioning System [14] and radio-frequency (RF)-based localization method [15], [16].

The second problem with IEEE 802.11 DCF happens when the transmission direction of the topmost data item in the station’s queue is blocked (due to some ongoing transmission). In this case, the station blocks its own transmission until this

¹Several techniques has been proposed in sensor and ad hoc networks to allow a station to discover whether the ongoing transmission is destined to itself. Among those techniques are the use of RTS/CTS and augmenting the physical layer convergence procedure (PLCP) header with additional parameters [12].

direction becomes free. However, there could exist a subsequent data item in the station's queue in which its transmission direction does not interfere with any ongoing transmission. Consider Fig. 1, where station A is engaged in a transmission by beamforming data to station B. Assume that the top two data items at station C should be beamed to stations E and D, respectively. Since, the C–E transmission is blocked because of the ongoing A–B transmission, the IEEE 802.11 running on station C blocks and waits until the C–E direction becomes free again. However, since the C–D transmission direction would not interfere with the A–B transmission, station C should not block and should transmit the second data item in its queue to D instead. We refer to this problem as the *head-of-line blocking* (HOL_{Blocking}) problem.

We develop the OPP_{HOL} scheme in which we change the access routines of the 802.11 data queue to allow a station to transmit another data item when the direction of its topmost data item is blocked. This scheme eliminates the HOL_{Blocking} problem by giving a station the opportunity not to block by trying other data items from its queue data instead of its current blocked data.

IV. RELATED WORKS

Previous works propose several modifications to IEEE 802.11 DCF to exploit the beamforming feature of the directional antennas for the purpose of increasing the number of concurrent transmissions in the network. A large number of these proposals target the modification of RTS/CTS handshake mechanisms with their corresponding analysis. In D-MAC [1], two schemes are proposed: 1) the DRTS scheme that utilizes a directional antenna by sending the RTS packets in a particular direction (DRTS), whereas CTS packets are transmitted in all directions (OCTS), and 2) the DRTS/ORTS scheme where a station may send omnidirectional RTS (ORTS) if none of its directional antennas are blocked or DRTS, provided that the desired directional antenna is not blocked. A variation of D-MAC is proposed in [13] and [17] to handle the broadcasting of RTS and CTS with only directional transmissions. The proposed scheme uses circular directional RTS/CTS transmissions to cover the area around the transmitter. However, the simulation results in [13] and [17] show that this scheme is more conservative than the D-MAC scheme. The effects of using different combinations of omni transmissions for one or both RTS/CTS frames on network performance are studied in terms of network throughput [2], [9], [10], [18] and power consumption [4], [19].

All of the foregoing mechanisms follow the CSMA mechanism in forcing a station to postpone its transmission once it senses a busy carrier in any direction, although the intended transmission may not affect the ongoing transmission. Several mechanisms are proposed to enhance the CSMA functionality by detecting the directions of the ongoing transmissions. Dual busy tone multiple access for directional antennas (DBTMA/DA) system [20] addresses this problem by using directional transmitting busy tones in a way similar to the directional RTS frame to reserve the network capacity in a finer grain. However, this mechanism requires the use of two separate

subchannels that does not follow the 802.11 standards. The authors in [11], [13], and [17] propose to augment RTS/CTS frames either with the exact location of the transmitter and receiver stations or with the direction of the transmission and receiver beams to allow a station to detect the relative direction of any ongoing transmission. These proposed schemes require the use of RTS/CTS frames or new additional frames. The angle-of-arrival (AOA) mechanism presented in [9] and [21] is used to detect the direction of the receiving data and, consequently, the relative direction of any ongoing transmission.

Several works on opportunistic scheduling for exploiting multiuser diversity gains were proposed [22]–[25]. Multiuser diversity refers to a type of diversity present across different users in a fading environment. This diversity can be exploited by scheduling transmissions so that users transmit when their channel conditions are favorable. For example, Bhagwat *et al.* proposed channel-state-dependent packet scheduling (CSDPS) in [22]. The basic idea of CSDPS is that when a wireless link experiences burst errors, it defers the transmission of packets on this link and transmits those on other links. Another example is the medium-access diversity scheme [24] that leverages the benefits of rate adaptation schemes by aggressively exploiting multiuser diversity. Along with that, the opportunistic auto rate [25] that transmits multiple packets when the channel condition permits higher data rates thus achieves high throughput. Liu and Knightly [23] provide a general formulation for wireless opportunistic fairness scheduling over multiple channels. Viewed in this light, our OPP_{HOL} scheme can be interpreted as performing opportunistic beamforming where transmission is scheduled to the user that is available.

Although some of the foregoing works share some similarities with our proposed mechanisms (OPP_{CS} and OPP_{HOL}), our mechanisms overcome several drawbacks of these previous mechanisms and significantly differ in the following ways: 1) Our mechanisms work in the 802.11 basic access mode and do not require the need for RTS/CTS, any additional frames, or additional channels as in [11], [13], [17], and [20]. 2) Our mechanisms allow a station, once it detects a busy carrier, to decide whether it needs to block, and hence, the station neither solely depends on DNAV for the decision nor force the station to block until the end of the frame reception as in the AOA mechanism [9], [13], [17], [21]. 3) We introduce new metrics in the OPP_{HOL} mechanism to guarantee network fairness. 4) We present the full design details and the required modifications in both physical (PHY) and media access control (MAC) layers of the IEEE 802.11 protocol. We are the first, to the best of our knowledge, to analyze, design, and evaluate these mechanisms in the context of IEEE 802.11 network with directional antennas.

V. ANALYSIS OF BLOCKING PROBABILITIES

In this section, we study 1) the CS_{Blocking} problem by deriving the probability that a station has an opportunity to directionally transmit despite the presence of transmissions in its vicinity and 2) the HOL_{Blocking} problem by deriving the probability that a station has an opportunity to directionally transmit given that the destined sector of the packet at the top

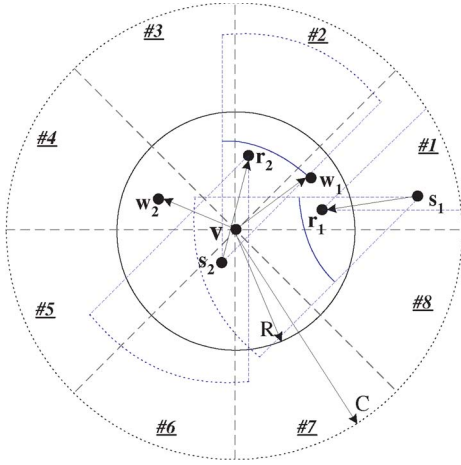


Fig. 2. Blocking analysis, where R is the transmission range, and C is the carrier sense range.

of the IEEE 802.11 MAC queue is blocked. Next, we validate the analytical results by simulation and show the potential improvements of the opportunistic schemes.

Although we adopt the steering-beam model in the designs in Section VI and in the simulations in Section VII, our analysis here assumes the switched-beam model for the sake of analytical simplicity. In addition, for the sake of simplicity, we assume an idealized directional sector (main lobe) with no side and back lobes in the analysis here. We will discuss the effect of this simplification assumption later.

In our analysis, we assume two sets of stations: one for transmitters and another for receivers. Each connection consists of a pair of stations: a transmitter and a receiver. We assume that the transmitters, and consequently the receivers, are uniformly distributed over an area with a density of δ . Each station has a transmission range R within which frames sent by the station can be received and decoded and a carrier sense range C along the directional transmission, which is the range within which transmissions of the station can be detected (channel busy).

All stations have the same traffic model, and all data packets are of the same length. Each packet requires transmission time τ and is randomly destined to a one-hop neighbor. As mentioned earlier, the space of each transmitter, and, consequently, each receiver, is divided into n sectors. Each transmitter has several ongoing connections in which the corresponding receivers are assumed to be uniformly distributed over m sectors of the n possible sectors, where $m \leq n$. Each transmitter generates data packets with a rate of $(1/T)$, where $T > \tau$. All transmitters use the same transmission power.

A. Analysis of Carrier Sense Blocking Probability

Sometimes, a station *unnecessarily* blocks its transmission because its carrier sense indicates a busy channel. We say “unnecessary” because, despite sensing a busy carrier, a station can still transmit without interfering with any of the ongoing transmissions.

Consider a scenario (see Fig. 2) where station v establishes a connection with station w_2 in sector #4. The 802.11 standard forces station v to block its transmission once it senses (either physically or virtually) the ongoing transmission between sta-

tion s_1 and station r_1 , or between station s_2 and station r_2 . However, the directional transmission from station v to station w_2 would not affect any of those ongoing directional transmission, and thus, station v should not block its transmission to w_2 .

For station v to avoid interfering with any of the ongoing transmissions of DATA and ACK packets, station v should block its transmission in a specific sector i only if 1) a sender station s in sector i is transmitting, and station v is in the transmission cone of s (to avoid interfering with ACK reception at s), or 2) a station r in sector i is receiving, and station v is in the reception cone of r (to avoid interfering with DATA reception at r). In case of omni reception, the condition for v being in the transmission or reception cone is not needed.

Assuming that a station v wants to directionally transmit to a sector i with an angular sector $\eta = 2\pi/n$, we define the following.

- 1) $P(CS_{Tr})$ is the probability that, for all the connections that have their transmitters inside sector i and their corresponding receivers outside sector i , every transmitter is either not transmitting $(1 - (\tau/T))$ or transmitting, and v is outside its transmission cone $((\tau/T)(2\pi - \eta/2\pi))$. The number of these connections is equal to $\delta(\eta/2)C^2 - (\delta/n)(\eta/2)C^2$. The negative term is equal to the number of connections that have both their transmitters and receivers in sector i .
- 2) $P(CS_{Rcv})$ is the probability that, for all the connections that have their transmitters outside sector i and their corresponding receivers inside sector i , every single receiver is either not receiving or receiving, and v is outside its reception cone. The number of these connections is equal to $\delta(\eta/2)C^2 - (\delta/n)(\eta/2)C^2$.
- 3) $P(CS_{TrRcv})$ is the probability that, for all the connections that have their transmitters and receivers inside sector i , every transmitter is either 1) not transmitting (and, thus, the receiver is not receiving) or 2) transmitting, and v is outside both transmission and reception cones of the transmitter and receiver, respectively. The number of these connections is equal to $(\delta/n)(\eta/2)C^2$.
- 4) $P(CS_{Idle})$ is the probability that sector i is not blocked, and thus, station v is able to carry out a directional transmission through sector i . $P(CS_{Idle})$ is equal to the multiplication of $P(CS_{Tr})$, $P(CS_{Rcv})$, and $P(CS_{TrRcv})$. Hence, $P(CS_{Idle})$ is calculated as follows:

$$\begin{aligned}
 P(CS_{Idle}) &= P(CS_{Tr}) \times P(CS_{Rcv}) \times P(CS_{TrRcv}) \\
 &= \left[\left(1 - \frac{\tau}{T}\right) + \frac{\tau}{T} \frac{2\pi - \eta}{2\pi} \right]^{(\delta - \frac{\delta}{n}) \frac{\eta}{2} C^2} \\
 &\quad \times \left[\left(1 - \frac{\tau}{T}\right) + \frac{\tau}{T} \frac{2\pi - \eta}{2\pi} \right]^{(\delta - \frac{\delta}{n}) \frac{\eta}{2} C^2} \\
 &\quad \times \left[\left(1 - \frac{\tau}{T}\right) + \frac{\tau}{T} \frac{2\pi - \eta}{2\pi} \frac{2\pi - \eta}{2\pi} \right]^{\frac{\delta}{n} \frac{\eta}{2} C^2} \\
 &= \left[\left(1 - \frac{\tau}{T} \frac{1}{n}\right) \right]^{\frac{\delta(n-1)}{n} \frac{\pi}{n} C^2} \\
 &\quad \times \left[\left(1 - \frac{\tau}{T}\right) + \frac{\tau}{T} \left(\frac{n-1}{n}\right) \right]^{\frac{\delta}{n} \frac{\pi}{n} C^2}. \quad (1)
 \end{aligned}$$

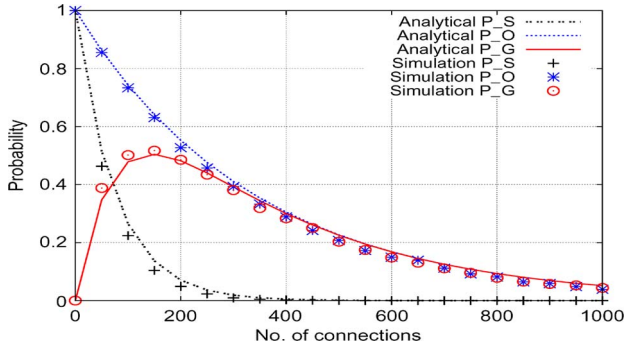


Fig. 3. Analytical and simulation values of the probabilities $P_S = P(Std_{Idle})$, $P_O = P(CS_{Idle})$, and $P_G = P(CS_{Blocking})$.

In IEEE 802.11 standards, a station v blocks its transmission to sector i if v is in the transmission cone of a transmitter in any sector, or v is in the reception cone of a receiver in sector i .

Similarly, we define $P(Std_{Idle})$ to be the probability that sector i is not blocked as follows:

$$P(Std_{Idle}) = \left[\left(1 - \frac{\tau}{T} \frac{1}{n} \right)^{\delta(n-1)\frac{\pi}{n}C^2} \right] \times \left[\left(1 - \frac{\tau}{T} \right) + \frac{\tau}{T} \left(\frac{n-1}{n} \right)^2 \right]^{\delta\frac{\pi}{n}C^2} \quad (2)$$

Therefore, $P(CS_{Blocking})$, which is the probability that station v blocks unnecessarily, is

$$P(CS_{Blocking}) = P(CS_{Idle}) - P(Std_{Idle}). \quad (3)$$

We verify this analytical model by generating random network topologies and traffic patterns and studying the blocking probabilities in each case. For constructing each random network, we place station v at the center of an area of $1000 \text{ m} \times 1000 \text{ m}$ and uniformly distribute transmitter stations in this area. Each transmitter is paired with a corresponding receiver, which is randomly located within a circular area of radius R that is centered at the transmitter. All packets require transmission time τ and are randomly generated at a constant rate: one packet every time interval T , where $T > \tau$. The transmission beamwidth is set at $2\pi/n$, where n is the number of neighbor sectors of a station. When station v has a frame to send, it randomly selects a sector to transmit to and checks whether it can transmit its frame. For the original 802.11 mechanism, the number of runs in which station v was able to transmit its frame is divided over the total number of transmission attempts to derive $P(Std_{Idle})$. Similarly, we can determine $P(CS_{Idle})$. We compare $P(CS_{Idle})$ and $P(Std_{Idle})$, in addition to $P(CS_{Blocking})$, to those calculated from the analytical result.

Fig. 3 plots the analytical and simulated curves of $P(CS_{Idle})$, $P(Std_{Idle})$, and $P(CS_{Blocking})$ versus $C = 550 \text{ m}$, $n = 8$, $\tau/T = 0.1$, and different numbers of stations (thus varying the station density δ). Fig. 3 shows that the simulation results closely match the analytical results, which validates our analysis.

Note that the calculated $P(CS_{Blocking})$ is still conservative because we assume, for simplicity, that all stations in the vicinity of v have the freedom of transmission. We do not take

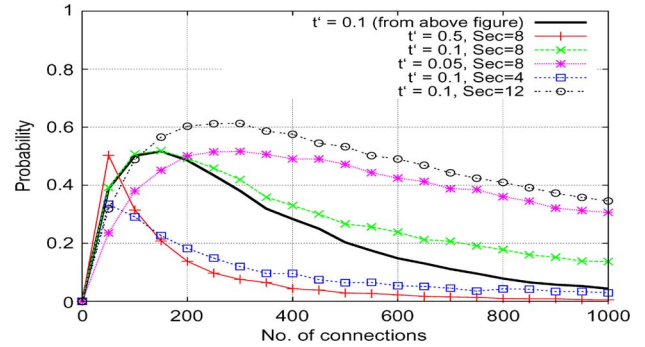


Fig. 4. Probability $P(CS_{Blocking})$ with different load values t' , where $t' = \tau/T$ and with different number of sectors n .

into account that some of these stations have to block because of other ongoing transmissions in their vicinities. Accounting for these blocked stations would increase $P(CS_{Blocking})$. To analyze how our simplified assumption affects our probability calculations, we relaxed this assumption in the simulation runs, as shown in Fig. 4. The figure also plots $P(CS_{Blocking})$ with different packet load values and different sector numbers to show how different parameters affect $P(CS_{Blocking})$. The $P(CS_{Blocking})$ plot with conservative assumption (copied from Fig. 3) is also included for easy comparison.

B. Analysis of Head-of-Line Blocking Probability

Following the $CS_{Blocking}$ problem, it happens that the corresponding sector of the packet at the top of the MAC queue of station v is blocked, whereas other sectors corresponding to other packets in the queue are not blocked. To improve the network performance, a station should transmit one of the packets corresponding to a nonblocked sector instead of obeying the standards 802.11 by postponing transmissions until the transmission of a packet at the queue's top.

Assuming that each transmitter has several connections and the corresponding receivers are distributed uniformly over m sectors of the n possible sectors, we define $P(HOL_{Idle})$ to be the probability that at least one sector of the m neighbor sectors is idle (not blocked). Calculating $P(HOL_{Idle})$ is tricky because the blocking probabilities of sectors are not independent, since a transmission may block either one or two sectors. For example, sectors #2 and #6 in Fig. 2 are blocked because of the transmission between stations s_2 and r_2 . On the other hand, the transmission between stations s_1 and r_1 only blocks sector #1.

To simplify the calculation of $P(HOL_{Idle})$, we assume that the blocking probabilities of the sectors are independent. In fact, this simplification will result in calculating the upper bound of $P(HOL_{Idle})$ instead. Later, we will show the effect of this simplification and the difference between the upper bound and the actual values using simulation. Given this simplification, the upper bound probability of $P(HOL_{Idle})$ is calculated as

$$P(HOL_{Idle}) = 1 - (1 - P(CS_{Idle}))^m \quad (4)$$

where m is the number of neighbor sectors, and $1 - P(CS_{Idle})$ is the probability that a sector is blocked. $P(CS_{Idle})$ is calculated in (1).

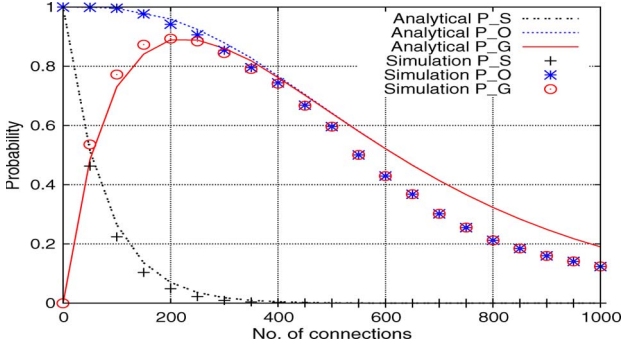


Fig. 5. Analytical and simulation values of the probabilities $P_S = P(Std_{Idle})$, $P_O = P(HOL_{Idle})$, and $P_G = P(HOL_{Blocking})$.

Consequently, the upper bound of $P(HOL_{Blocking})$, which is the probability of having at least one of the m neighbor sectors of station v idle, given that the sector corresponding to the topmost packet of the queue is blocked, is

$$P(HOL_{Blocking}) = P(HOL_{Idle}) - P(Std_{Idle}) \quad (5)$$

where $P(Std_{Idle})$ is given in (2).

Similar to the previous section, we verified our analytical results by simulations. In the simulations, whenever v has a frame to send, we randomly select an ordered list of m sectors from the n neighbor sectors, assuming station v has a queue of frames ready to be sent to their destinations in the corresponding m sectors. We study if station v can send any frame from its queue without affecting the ongoing transmissions. The number of runs in which station v is able to transmit is divided over the total number of transmission attempts to derive the probability of $P(HOL_{Idle})$. $P(Std_{Idle})$, $P(HOL_{Idle})$, and $P(HOL_{Blocking})$ are compared with the analytical result.

Fig. 5 plots both the analytical and the simulated values of $P(Std_{Idle})$, $P(HOL_{Idle})$, and $P(HOL_{Blocking})$ for $R = 250$ m, $C = 550$ m, $n = 8$, $m = 4$, $\tau/T = 0.1$, and different numbers of stations (thus varying the station density δ). Although the analytical $P(HOL_{Idle})$ and $P(HOL_{Blocking})$ are upper bounds, the simulation results closely match those values, particularly at the peak values, which is our main interest. Therefore, the simulation validates our analysis, and our simplifications are reasonable.

Similar to the analysis of $P(CS_{Blocking})$ in the previous section, Fig. 6 plots the simulation of $P(HOL_{Blocking})$ after relaxing the conservative assumption in calculating $P(HOL_{Blocking})$, as shown in Fig. 5. The figure plots $P(HOL_{Blocking})$ with different packet load values and different number of sectors.

All the previous figures show that the unnecessary blocking probability of a station using IEEE 802.11 DCF standards is large enough in case of using directional antenna (as high as 90% in case of $HOL_{Blocking}$). Note that we derived the gain probabilities using the switched-beam antenna model rather than the steering-beam model for the sake of simplicity. The potential gain of using the switched-beam model is less than that of using the steering-beam model due to the increased flexibility of the latter. Hence, the actual gains are expected to be higher than those presented here. On the other hand, we assumed in our calculations idealized directional sectors

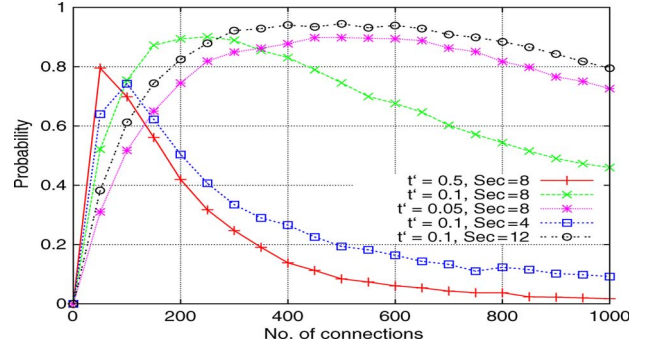


Fig. 6. Probability $P(HOL_{Blocking})$ with different load values t' , where $t' = \tau/T$, and with different number of sectors n while m is fixed to 4.

(no side and back lobes) rather than the model adopted in Section III. With an idealized sector, interference is ignored, and hence, the calculated gains are higher than the case with a more realistic antenna model. However, since the gain probabilities are significantly high, as previously shown, these simplifications are enough to motivate us to consider modifying the 802.11 to match and exploit the characteristics of directional antennas. In the following section, we will describe the newly proposed modification to the IEEE 802.11 DCF. In the design in Section VI and in the performance evaluation in Section VII, we adopt the steering-beam model and the directional antenna with side and back lobes.

VI. DESIGN OF THE OPPORTUNISTIC MECHANISMS

In this section, we describe the design of our opportunistic enhancements for IEEE 802.11 standards. First, we describe the design of the needed physical layer. Next, we present the proposed modifications to IEEE 802.11 MAC with the details of the proposed mechanisms.

In our $OPPC_S$ and $OPPHOL$ mechanisms, a station is only concerned if its own transmission affects any ongoing transmission. Our models do not consider if the station's own transmissions can correctly be received by the intended receivers, or even if they are able to reply back by CTS or ACK frame. This optimistic approach is largely for keeping the model simple at its current stage.

A. Physical Layer Design

The current IEEE 802.11 standard does not require a receiver PHY modem to be able to capture a new stronger frame after the receiver has been tuned to receive some other frame. Since our opportunistic mechanisms increase the simultaneous transmissions, the chances that the PHY of the intended receiver is already engaged in receiving another frame are high.

Fortunately, receiver designs that support the capture of a new frame after the receiver has already begun to receive another frame do exist. One example of such a receiver physical layer (PHY) design is Lucent's PHY design with "Message-In-A-Message" (MIM) support [26]. With a MIM-capable design, a receiver is able to correctly detect and capture a strong frame regardless of the current state of the receiver. This design fits well with the requirements of our proposed mechanisms, as stated earlier.

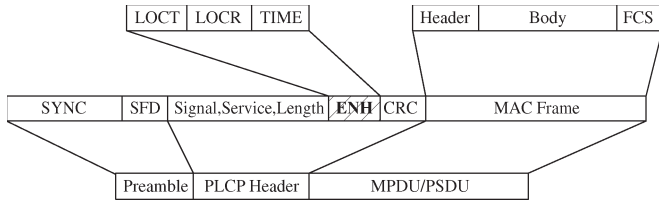


Fig. 7. Frame structure.

B. MAC Layer Design

Our enhanced design for IEEE 802.11 DCF MAC stands atop a MIM-capable PHY. Each of the new proposed mechanisms *OPPCs* and *OPPHOL* is a part of the MAC layer function. In this section, we will describe the needed modifications in the 802.11 MAC layer.

1) *OPPCs Mechanism*: Fig. 7 shows the frame format to support the enhanced functionalities of the new MAC. We insert a block of information called ENH (Enhanced). Similar to the work in [12] and [27], the ENH is inserted as part of the PLCP header since the PLCP header has its own cyclic redundancy checksum (CRC) field, and all stations within the service set can understand the ENH block since the PLCP header is transmitted at a base rate.

The ENH block consists of three fields. The LOCT and LOCR fields contain the location of the frame transmitter and receiver, respectively, and the TIME field specifies the total duration period for the delivery. When a source starts its unicast data delivery (RTS frame or DATA frame), it fills the LOCT, LOCR, and TIME fields with the corresponding parameter values, if known. If the LOCR parameter is unknown at this time, then it is set to NULL. Upon receiving such frame, the destination of the data delivery copies the LOCT field into the corresponding fields of its reply frame (CTS or ACK). It also fills or updates the TIME and LOCR fields with its own parameters. Note that the TIME field is updated to reflect the remaining duration period of the delivery in a fashion similar to updating the DNAV time field. For any subsequent frames of the delivery, full location descriptions of both the source and the destination are included, as well as the duration period of the remaining delivery. A station may maintain a parameter cache to store the location information of already-known stations.

Our mechanism determines blocked sectors based on the location information in the ENH block rather than the AOA estimation. This is because the AOA mechanism helps to determine the direction of the transmitter only and not the receiver unless the RTS/CTS scheme is forced to be used. Unlike the AOA mechanism, our mechanism does not require the use of RTS/CTS since information for both the sender and the receiver is contained in the ENH block.

In the IEEE 802.11 standards, normally, the PHY (PLCP in particular) signals three events to the MAC layer during frame reception: 1) clear channel assessment (PHY_CCA); 2) begin receiving PSDU (PHY_RXSTART); and 3) end receiving PSDU (PHY_RXEND). It does not deliver any data bits to the MAC layer until the PSDU reception has begun. Then, the receiver proceeds until the end of the frame (unless interrupted by carrier loss in the middle of the reception). The received bits

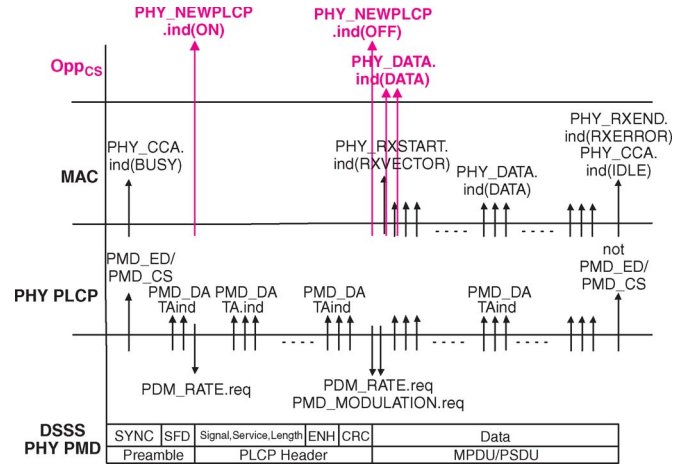


Fig. 8. PHY-MAC interactions.

are passed to the MAC layer as they are decoded and assembled into the MAC frame. At the end of the PSDU, there is a forward error detection CRC block called frame check sequence (FCS). If the MAC frame passes the CRC check, then it is accepted and passed up for further IEEE 802.11 MAC processing. If the CRC fails, then the frame is dropped.

Similar to the approach in the location enhanced DCF (LED) for IEEE 802.11 [12], [27], in addition to the preceding interactions, the *OPPCs* interact with the PLCP layer using an indicator called PHY_NEWPLCP, as illustrated in Fig. 8. Indicator PHY_NEWPLCP is turned on by the PLCP layer after it finishes receiving the start frame delimiter (SFD) field of a frame’s Preamble section and turned off after receiving the whole PLCP header.

Now, we will illustrate the *OPPCs* algorithm. In the original IEEE 802.11, once the PHY_CCA is triggered, the station blocks its transmission and freezes its counting down counter until the end of frame reception. In the *OPPCs* mechanism, the station similarly reacts until the PHY_NEWPLCP is turned off. That is when it starts the decision-making process by calculating $(|\gamma - \alpha_n^s| > (w/2))$ and $(|\gamma - \alpha_n^d| > (w/2))$. Variables α_n^s and α_n^d are the angles between station n itself and both the source and the destination of the ongoing data delivery, γ is the angle to the intended destination of its transmission, and w is the beamwidth. If the formula is false, then the station should block its transmission, else the station should not block its own transmission. In the case that any of the parameters corresponding to the ENH fields are unknown or the location of the destination, the assessing station assumes the worst and blocks its own transmission similar to the carrier sense in IEEE 802.11 standards.

If the station decides to block its own transmission, then it remains in the receiving state and continues the receiving procedure as specified by the standard. It disables any transmission requests from the upper layer and updates its DNAV value in the direction of the transmitter and receiver of this frame² according to the frame’s duration field, which is set to the time required for the full data-delivery frame-exchange sequence to

²The directions of the transmitter and receiver are calculated using the location information about them extracted from the PLCP header.

finish. Unlike the required conditions to block certain direction, as described in Section V, a station updates its DNAV regardless of whether it is within the transmission/reception cone of the transmitting/receiving stations of the ongoing transmission to cope with the DNAV described in the literature [5], [9]. Since the intended receiver of the frame has to block during the transmission of the frame, it has to compare the LOCR field to its own location. If its location is within a certain range threshold, then the station blocks during the reception of the frame. We choose this range to be 5 m in our simulations.

If the station decides not to block, then the receiver may still continue, but the upper layer transmission requests are not disabled. DNAV is updated similar to the case when the station decides to block. If there is indeed any outgoing frame ready, then the PHY modem can accept the request by switching to transmission state and starting the transmission. A PHY reset signal is needed in this case to force the PHY to leave the receiving state and to enable the PHY_TXSTART signal when the MAC has a frame to send.

The PHY_CCA indicator from the physical layer needs to temporarily be ignored when the OPP_{CS} decides not to block. The overriding of PHY_CCA in the OPP_{CS} layer is accomplished by proposing a new vector called CCA suppression vector (CSV), which is a suppression timer. CSV is set to the end of reception of the current frame, which is calculated based on the length field contained in the received PLCP header of the frame. A similar mechanism is adopted in LED [12], [27].

At the source or the destination station of the ongoing delivery, according to the IEEE 802.11 standards, the NAV is not set for the duration of the delivery. In OPP_{CS} , this specification is still followed but the CSV is not needed to be set to the estimated end of the delivery. This is because OPP_{CS} permits concurrent transmissions by other stations as long as they do not produce enough interference to disturb the ongoing delivery. If any other station indeed decides to transmit, then the energy of the transmission may cause the source and the destination of the ongoing data delivery to sense that PHY_CCA is busy and thus abort the data-delivery frame sequence. Hence, the PHY_CCA should be suppressed on the source and destination stations until the end of the data delivery.

In total, a OPP_{CS} station uses four indicators related to the transmission blocking estimation. The PHY_CCA indicator, which is the physical carrier indicator, is “TRUE” when the PHY layer detects carrier (or energy exceeding threshold, or both depending on equipment vendor implementation). The DNAV indicator, which is the virtual carrier indicator, is “TRUE” when there is a channel reservation, which corresponds to the desired transmission direction, that needs to be honored. The PHY_NEWPLCP indicator is “TRUE” while a PLCP header is being received. Finally, the CSV indicator tells the station whether it should ignore PHY_CCA. It is “TRUE” when the suppression timer is running. More precisely, the decision of whether this station should block its own transmission is made as follows:

if (PHY_NEWPLCP or
 ((CCA and (not CSV)) or DNAV)) then BLOCK.

As a final note about the case when a station detects a carrier but cannot decode the frame, in this case, a station is not able to estimate whether its transmission will affect this ongoing data delivery. We use an aggressive approach in which the station will not block its own transmission.

2) OPP_{HOL} Mechanism: The modifications for OPP_{HOL} are identical to the modifications used by OPP_{CS} in addition to modifying the procedure in which the MAC layer selects the next packet to transmit. In OPP_{CS} , the MAC layer assumes all the time that the next packet to transmit is the packet at top of the MAC queue. However, this is not the case in OPP_{HOL} , in which a station may select a packet other than that at the top to transmit.

In OPP_{HOL} , a station does not maintain a distinct queue for every direction. Instead, it maintains a single queue that can be accessed as a list, where the station can iterate through the items of the list and insert and delete an item in the list.

Here is how the OPP_{HOL} mechanism works. A station checks if the direction of transmission of the topmost item in the queue is blocked. If it is blocked and the remaining blocking time (obtained from DNAV table) is greater than a certain threshold called $blkThres$, then the station checks the transmission direction of the next item.

- 1) If it is not blocked, then the station sends this item, deletes it from the queue, and goes back to the top of the queue.
- 2) If it is blocked and the remaining time of block is less than $blkThres$, then the station waits for this time, transmits the data, and goes back to the top of the queue.
- 3) If it is blocked and the remaining blocking time is greater than $blkThres$, then the station checks the transmission direction of the next item in the queue.

We assume that the check and send times take a very small time with respect to $blkThres$. This guarantees that all packets will be delivered in order. If a station is sending items to some destination d , and the first item of these items is blocked, then the subsequent items to d will not be sent as their remaining time is still greater than $blkThres$. Another way to handle this case is as follows: Once the transmission of an item to station d is blocked, all the subsequent items are marked as blocked.

A station maintains the following for each item i in the queue. Service time $ServTime_i$ denotes the total time spent in servicing item i , that is, the summation of the total time spent in checking whether to transmit this item, time to delete the item from the queue, and time spent in transmitting this item. Starvation time $StarvTime_i$ denotes the total time that the transmission of item i is delayed due to servicing the items that come afterward in the queue. In short, whenever a station updates the $ServTime_i$ by δ , this δ is added to $StarvTime_{[0...i-1]}$. If the $StarvTime_i$ is greater than some threshold $Swap_Thresh$, then the OPP_{HOL} does not check any item beyond i . This ensures that altering the order of transmission of the queue does not jeopardize the fairness of the transmission and that no station will starve forever. $Count_{NH_i}$ denotes the number of items with index greater than i transmitted before item i . $ServTime$, $StarvTime$, and $Count_{NH}$ are the average of $ServTime_i$, $StarvTime_i$, and $Count_{NH_i}$ over all packets, respectively.

The final argument is how to handle the contention window (CW) of the backoff. For the sake of simplicity, we correlate the backoff with the station and not the packet. Thus, whenever a collision takes place, the station applies the original IEEE 802.11 backoff mechanism even if a new item is picked for retransmission.

VII. PERFORMANCE EVALUATION

In this section, we present an extensive simulation-based study on the performance of our opportunistic mechanisms OPP_{CS} and OPP_{HOL} . The performance comparisons are done using the *ns-2* simulator [28]. The underlying link layer is IEEE 802.11b with 11-Mb/s data rate. We have modified the capture model in *ns-2* to allow receivers to capture the stronger packet out of the weaker packet(s) if the stronger packet comes after the weaker to reflect the MIM PHY design, as discussed in the previous section. We adopt the capture ratio value of 10 in our simulations. This means that when a station is in the middle of receiving frame A and frame B arrives, one of the following will happen: If the received power of frame A P_A is ten times more than the power of frame B P_B , then the receiver continuously receives frame A. If P_B is ten times more than P_A , then the receiver drops frame A and begins receiving frame B. In all other situations, packets collide, and no frame is correctly received.

The IEEE 802.11 MAC and PHY layers in *ns-2* were enhanced to support the *sphere-cone* directional antenna model described in Section II and shown in Fig. 1. We model the radio propagation by separating the propagation model into two components [12]. The major component focuses on the relationship between transmitter-to-receiver distance and long-term average received power. We assume a basic two-slope propagation channel that combines the Friis free-space propagation model and the two-ray ground propagation model, as described in [29]. The minor component focuses on modeling the random variations caused by various types of short-term fading. We model the minor component as a random variable with normal distribution centered at the long-term average received power. In typical wireless systems, the standard deviation of the distribution is usually between 6 and 10 dB. In our experiments, we use a standard deviation of 6 dB. This type of variation is often referred to as shadowing. We also enhanced the IEEE 802.11 MAC layer by extending it with the designs of OPP_{CS} and OPP_{HOL} mechanisms.

Each of our simulated networks consists of a set of connections that are constructed as pairs of stationary sender and receiver stations. We fix the number of senders to 50 senders in our experiments. The senders and receivers are placed in a 1000 m \times 1000 m area. We assume that each sender has already cached the location of its corresponding receiver(s). We assume that the transmission ranges in omni and directional transmissions are identical. This could be accomplished by either increasing the transmission power at the sender in case of omni transmission or decreasing the transmission power in case of directional transmission. In the simulation, each of the LOCT, LOCR, and TIME fields in the ENH header is 32 bits.

In *ns-2*, we set the transmission radius R of a station to 250 m and the interference/carrier sense radius C to 550 m.

We calculate the spherical radius of the sphere-cone pattern as suggested in [2]. Each connection is a flow of user datagram protocol (UDP) packets of size 1000 B transmitted at 11 Mb/s. Each simulation runs for a fixed duration of 250 s. Each point on the presented curves is an average of ten simulation runs.

To study the performance of our suggested schemes, we compare both OPP_{CS} and OPP_{HOL} with D-MAC [1] under various scenarios. All the mechanisms use the extended *ns-2* capture model, as described earlier. During the simulation runs, we take the following measurements.

- 1) Network throughput counts the total number of data bits received by all the receiver stations per second.
- 2) Fairness index measures both a) the bandwidth sharing of all the network connections (Network fairness), and b) the bandwidth sharing of station's connections averaged over all stations in the network (Station fairness). We use Jain's fairness index [30], which is defined as follows:

$$F = \frac{\left(\sum_{i=1}^N \gamma_i\right)^2}{N \sum_{i=1}^N \gamma_i^2} \quad (6)$$

where N is the number of connections, and γ_i is the throughput of connection i .

- 3) Service time measures the average and maximum *ServTime*, which is defined in the previous section, averaged over all packets successfully transmitted during the simulation period. For the OPP_{HOL} mechanism, we also measure the average and maximum *StarvTime* and *CountNH*, which are also defined in the previous section, averaged over all successfully transmitted packets. We set the threshold *Swap_Thresh* to the short inter-frame space (SIFS) duration defined in IEEE 802.11 [8].

We have experimented both with and without RTS/CTS prior to data. Due to the space constraints of this paper, we limit our discussion here to the RTS/CTS case. One interesting finding regarding RTS/CTS is that forcing stations to be blocked during the whole RTS/CTS period of other deliveries will actually increase the network throughput. Blocking during the RTS/CTS frames increases the chances of transmitting other RTS/CTS frames using omni transmissions instead of directional transmissions. Hence, more stations know about the ongoing transmission that results in lower collision probabilities.

A. Impact of Network Degree

Network degree denotes the average number of connections that a station participates in as either a sender or a receiver. When the network degree is 1, each station participates in only one connection. As the network degree increases, the number of connections a station is involved in increases too. Fig. 9 shows the network throughput when the number of connections varies from 50 to 250 connections. This corresponds to a range of network degrees that varies from 1 to 5 since we use 50 stations for these scenarios. The data traffic between each pair of source and destination is a constant-bit-rate UDP flow at a rate of 100 packets/s to overload the network, and the beamwidth size is set to 30°. As in [2], the corresponding spherical radius is set to 65 m. Since the spherical radius is less than the

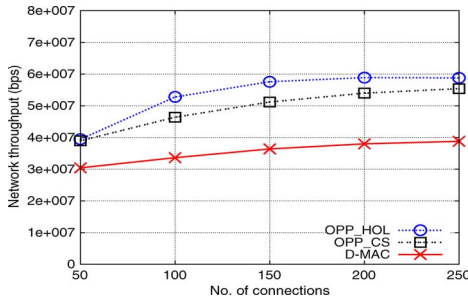


Fig. 9. Network throughput versus connections.

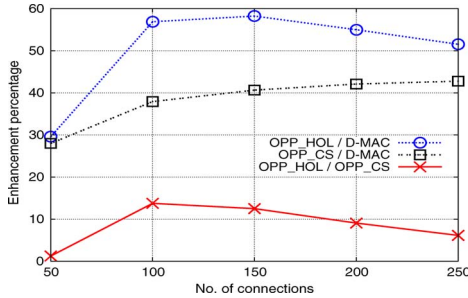


Fig. 10. Enhancement over D-MAC versus connections.

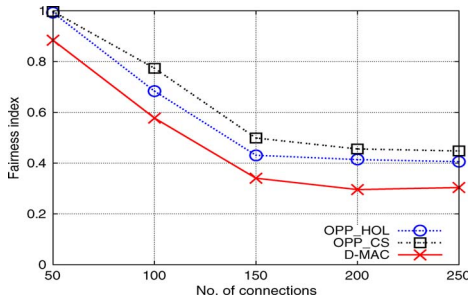
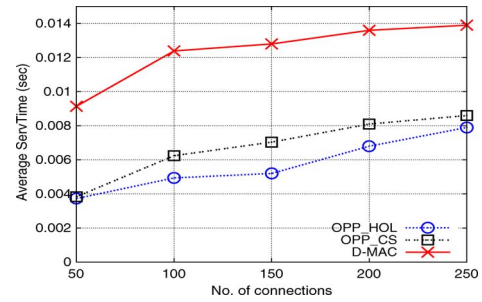


Fig. 11. Fairness index (network) versus connections

average distance between any two stations in such scenarios, the spherical interference has minimum effect on the network performance, particularly with small network degree scenarios. As shown, the OPP_{CS} and OPP_{HOL} mechanisms have higher data throughput than the D-MAC mechanism. The enhancements of those two mechanisms over the original in percentage are shown in Fig. 10. As shown, OPP_{CS} could achieve about 42% more throughput than D-MAC, whereas OPP_{HOL} could reach 58% throughput gain. This enhancement is due to the increase of the medium spatial reuse and the reduction of the well-known “exposed node/station” problem that affects the D-MAC mechanism. Note that the gain difference between the analytical model and simulation, for these results and the rest of the results in this section, is due to the simplified assumption we used in the analytical model. From the plot corresponding to the improvement of OPP_{HOL} over OPP_{CS} , OPP_{HOL} could achieve about 14% over OPP_{CS} since it makes more spatial use of the medium. However, as the network load increases by increasing the network degree, the space of improvements is reduced since the numbers of unblocked directions become smaller.

Fig. 11 shows the network fairness index of different mechanisms. OPP_{CS} and OPP_{HOL} have higher fairness than the D-MAC mechanism. An explanation for this is that these mech-

Fig. 12. Average *ServTime* versus connections

anisms reduce the “exposed station” problem in the D-MAC mechanism, which is one of the major sources for unfairness. However, OPP_{HOL} has a lower fairness than OPP_{CS} . Since different directions experience different blocking/unblocking shares, OPP_{HOL} favors directions with higher unblocking share, as described in the previous section. Thus, packets, and consequently their corresponding connections, in certain directions starve in the OPP_{HOL} mechanism, and this reduces the fairness index of the mechanism. Fairness among all connections belonging to a station averaged over all stations shows that OPP_{HOL} has the lowest station fairness due to this starvation issue.

We also measure the average *ServTime* for successfully transmitted packets under different mechanisms and plotted it in Fig. 12. As shown, OPP_{HOL} has the best average *ServTime* since the mechanism swaps the current packet it services with a ready-to-transmit packet as soon the direction of the original packet becomes blocked. Table I shows the average and maximum *CountNH* and *StarvTime* values.

B. Impact of Network Load

Next, we experiment with different network packet loads to see their effects on performance. We fix the number of connections in the network to 100, which makes each station on average involved in two connections. We vary the packet generation rate at each source station between 10 and 100 packets/s. Fig. 13 shows the network throughput for the different mechanisms. Similar to the previous results, OPP_{CS} and OPP_{HOL} outperform the D-MAC mechanism. In addition, the OPP_{HOL} mechanism outperforms the OPP_{CS} mechanism, particularly with moderate load, where the peak enhancement reaches 20% over the OPP_{CS} mechanism. With high packet loads, the chance that all the transmission directions are blocked increases. Thus, the enhancement of OPP_{CS} over OPP_{HOL} decreases. Fig. 14 shows the network fairness index for the different mechanisms. The OPP_{CS} and OPP_{HOL} mechanisms are higher than the D-MAC mechanism because of the “exposed station” problem, as explained earlier. An explanation for this is that these mechanisms reduce the well-known “exposed station” problem in the original mechanism, which is one of the major sources for unfairness. Since OPP_{HOL} try to maximize the spatial reuse by using the unblocked directions, stations favor some directions and their corresponding transmissions in which Opp_{Dir} cannot achieve as much fairness as the OPP_{CS} mechanism.

Fig. 15 shows the average packet service time in which a similar pattern to network degree is shown here.

TABLE I
AVERAGE AND MAXIMUM VALUES OF *CountNH* AND *StarvTime*

Connections	Average		Maximum	
	<i>CountNH</i>	<i>StarvTime</i>	<i>CountNH</i>	<i>StarvTime</i>
50	0	0.0	0	0.0
100	15.5	0.1123	570.8	4.76
150	16.2	0.1329	680.1	5.80
200	23.43	0.1979	740.4	6.92
150	39.94	0.2785	895.2	7.23

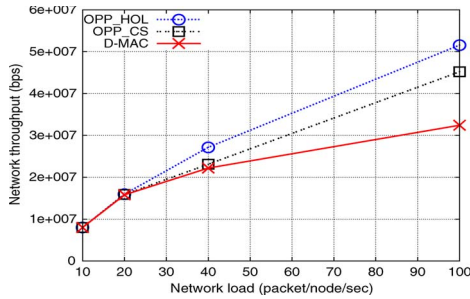


Fig. 13. Network throughput versus load.

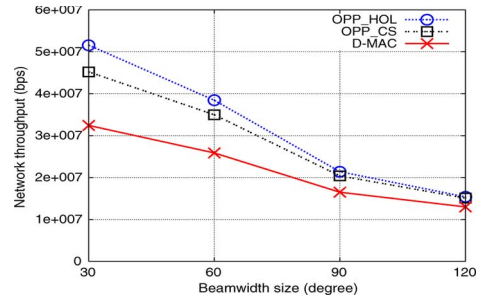


Fig. 16. Network throughput versus beamwidth.

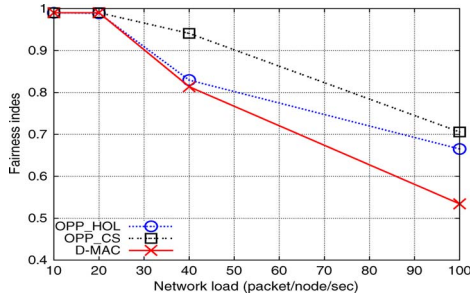


Fig. 14. Fairness (network) versus load.

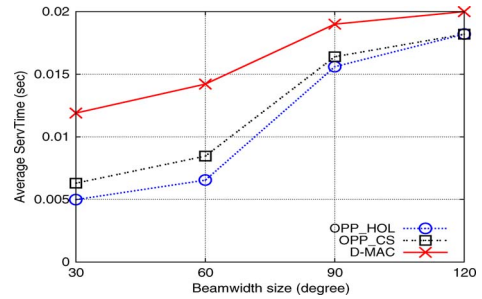


Fig. 17. Average *ServTime* versus beamwidth size.

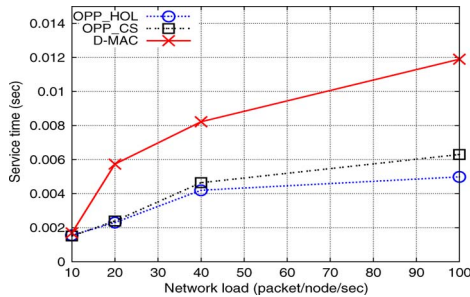


Fig. 15. Average *ServTime* versus load.

C. Impact of Beamwidth Size

Next, we experiment with different beamwidth values to see their effects on performance. We fix the number of connections in the network to 100 (i.e., network degree is 2) and the rate of packet generation to 100 packets/s. We varied the beamwidth size from 30° to 120°, where the corresponding spherical radius is adjusted for each beamwidth where the radius is increased with the increase of the beamwidth. Fig. 16 shows the network throughput for the different mechanisms. As shown, the performance of all mechanisms degrades with the increase in the beamwidth, particularly with large beamwidth. For the D-MAC case, this is due that stations will start to behave as omni stations particularly because of the large spherical interference. The way the opportunistic mechanisms are currently implemented, spherical interference has minor effect on the

TABLE II
AVERAGE VALUES OF *CountNH* AND *StarvTime*

Beamwidth size	<i>CountNH</i>	<i>StarvTime</i>
30°	16.86	0.1116
60°	3.74	0.0286
90°	0.92	0.0067
120°	0.18	0.0019

decision making of blocking or not the transmission. However, a large interference radius will increase the probability of collisions. For example, frames received at station E in Fig. 1 from station A will collide with frames transmitted by station C if E is within the spherical interference of station C. Increasing the collision probability results in degraded network performance.

Similar to previous scenarios, *OPPC_S* outperforms D-MAC in network and station fairness, whereas *OPPHOL* suffers from low fairness. Fig. 17 shows the average *ServTime* and Table II shows the average *CountNH* and *StarvTime* values for the different mechanisms. From these results, *OPPHOL* starts to render the *OPPC_S* performance as the beamwidth becomes large.

D. Impact of Transmission and Carrier-Sense Range

All the mechanisms under consideration are based on the transmission and the interference/carrier-sense ranges in the network. To examine the performance of those mechanisms

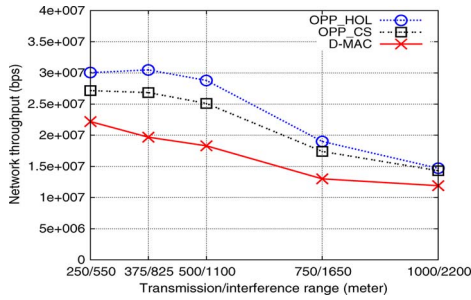


Fig. 18. Network throughput versus transmission/interference.

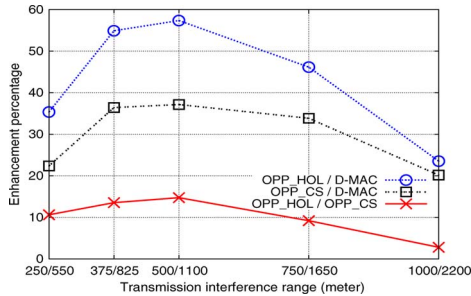
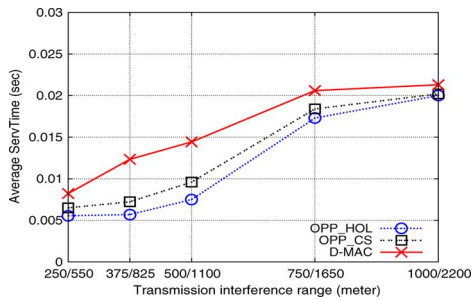


Fig. 19. Throughput enhancement over D-MAC versus transmission/interference.

Fig. 20. Average *ServTime* versus transmission/interference.

under different ranges, and respectively different densities, we fix the maximum distance for a connection to be within 250 m while changing the station transmission/carrier-sense range from 250 m/550 m to 1000 m/2200 m, respectively. The spherical radius is scaled with respect to the transmission range. We fix the number of connections in the network to 100 (i.e., network degree is 2), the rate of packet generation to 40 packets/s, and the beamwidth size to 30° . Figs. 18 and 19 show the network throughput for different mechanisms and the relative enhancement of each mechanism over D-MAC, respectively. Whereas the throughput of the D-MAC mechanism decreases as ranges increase, the throughputs of the OPP_{CS} and OPP_{HOL} mechanisms remain almost fixed for small range values. However, as ranges increase, all mechanisms suffer due to the same reasons earlier discussed in beamwidth performance. The average *ServTime* for different mechanisms is shown in Fig. 20, which emphasizes the previous observation.

VIII. CONCLUSION AND FUTURE WORKS

In this paper, we have studied the limitations of IEEE 802.11 standards on networks with directional antennas. Analytically

and through simulation, we have found that a station with directional antenna and using the 802.11 protocol is conservative in terms of assessing channel availability, with as much as 60% unnecessary blocking assessments. We have also shown that, by altering the way the 802.11 accesses its MAC queue, the unnecessary blocking assessments of a station could be increased up to 90%. Therefore, we have introduced two novel opportunistic enhancements to the IEEE 802.11 networks using directional antennas. These enhancements, known as OPP_{CS} and OPP_{HOL} , assist stations to better assess the channel condition and allow increased number of concurrent transmissions to take place in the presence of detecting a busy carrier. The simulation results have shown that our mechanisms improve throughput by as much as 40% over the original directional 802.11 in the case of applying the OPP_{CS} scheme and up to 60% in the case of using the OPP_{HOL} scheme with better fairness at the same time.

The presented opportunistic mechanisms adopt several simplifications to keep the model simple at its current stage. For example, a station is only concerned if its own transmission will affect an ongoing delivery, and consequently, it does not consider if its own transmission can correctly be received by its destination. As part of the future works, we plan to enhance the proposed opportunistic mechanisms to address these simplifications. In addition, we plan to investigate more the correlation between the *StarvTime* metric and the network fairness for the OPP_{HOL} scheme. We plan to study the effect of combining our schemes with other opportunistic mechanisms such as sending multiple back-to-back data packets [25] whenever a direction becomes available.

REFERENCES

- [1] Y.-B. Ko, V. Shankarkumar, and N. Vaidya, "Medium access control protocols using directional antennas in ad hoc networks," in *Proc. IEEE INFOCOM*, Tel-Aviv, Israel, Mar. 2000, pp. 13–21.
- [2] R. Ramanathan, "On the performance of ad hoc networks with beamforming antennas," in *Proc. ACM MobiHOC*, Long Beach, CA, Oct. 2001, pp. 95–105.
- [3] S. Yi, Y. Pei, and S. Kalyanaraman, "On the capacity improvement of ad hoc wireless networks using directional antennas," in *Proc. MobiHoc*, Annapolis, MD, Jun. 2003, pp. 108–116.
- [4] C. Srisathapornphat and C.-C. Shen, "Energy consumption behavior and performance of directional virtual carrier sensing schemes," in *Proc. IEEE WCNC*, New Orleans, LA, Mar. 2003, pp. 1895–1900.
- [5] R. Choudhury, X. Yang, R. Ramanathan, and N. Vaidya, "Using directional antennas for medium access control in ad hoc networks," in *Proc. ACM MOBICOM*, Atlanta, GA, Sep. 2002, pp. 57–90.
- [6] H. Yang, M. Herben, I. Akkermans, and P. Smulders, "Impact analysis of directional antennas and multiantenna beamformers on radio transmission," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1695–1707, May 2008.
- [7] E. Shihab, L. Cai, and J. Pan, "A distributed asynchronous directional-to-directional MAC protocol for wireless ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 9, pp. 5124–5134, Nov. 2009.
- [8] *IEEE 802.11, Part II: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std. 802.11-1999, 1999.
- [9] M. Takai, J. Martin, A. Ren, and R. Bagrodia, "Directional virtual carrier sensing for directional antennas in mobile ad hoc networks," in *Proc. ACM MobiHoc*, Lausanne, Switzerland, Jun. 2002, pp. 183–193.
- [10] N. Fahmy, T. Todd, and V. Kezys, "Ad hoc networks with smart antennas using IEEE 802.11-based protocols," in *Proc. IEEE ICC*, New York, Apr. 2002, pp. 3144–3148.
- [11] T. ElBatt, T. Anderson, and B. Ryu, "Performance evaluation of multiple access protocols for ad hoc networks using directional antennas," in *Proc. IEEE WCNC*, New Orleans, LA, Mar. 2003, pp. 982–987.

- [12] T. Nadeem and L. Ji, "Location aware IEEE 802.11 for spatial reuse enhancement," *IEEE Trans. Mobile Comput.*, vol. 6, no. 10, pp. 1171–1184, Oct. 2007.
- [13] T. Korakis, G. Jakllari, and L. Tassiulas, "A MAC protocol for full exploitation of directional antennas in ad-hoc wireless networks," in *Proc. ACM MobiHoc*, Annapolis, MD, Jun. 2003, pp. 98–107.
- [14] P. Enge and P. Misra, "Special issue on GPS: The global positioning system," *Proc. IEEE*, vol. 87, no. 1, pp. 3–15, Jan. 1999.
- [15] P. Bahl and V. Padmanabhan, "RADAR: An in-building RF-based user location and tracking system," in *Proc. IEEE INFOCOM*, Tel-Aviv, Israel, Mar. 2000, pp. 775–784.
- [16] P. Krishnan, A. Krishnakumar, W.-H. Ju, C. Mallows, and S. Ganu, "A system for LEASE: Location estimation assisted by stationary emitters for indoor RF wireless networks," in *Proc. IEEE INFOCOM*, Hong Kong, Mar. 2004, pp. 1001–1011.
- [17] G. Jakllari, I. Broustis, T. Korakis, S. Krishnamurthy, and L. Tassiulas, "Handling asymmetry in gain in directional antenna equipped ad hoc networks," in *Proc. IEEE 16th PIMRC*, Berlin, Germany, Sep. 2005, pp. 1284–1288.
- [18] K. Xu, M. Gerla, and S. Bae, "Effectiveness of RTS/CTS handshake in IEEE 802.11 based adhoc networks," *Ad Hoc Netw.*, vol. 1, no. 1, pp. 107–123, Jul. 2003.
- [19] A. Nasipuri, K. Li, and U. Sappidi, "Power consumption and throughput in mobile ad hoc networks using directional antennas," in *Proc. IEEE ICCCN*, Miami, FL, Oct. 2002, pp. 620–626.
- [20] Z. Huang, C.-C. Shen, C. Srisathapornphat, and C. Jaikao, "A busy-tone based directional MAC protocol for ad hoc networks," in *Proc. IEEE MILCOM*, Anaheim, CA, Oct. 2002, pp. 1233–1238.
- [21] V. Kolar, S. Tilak, and N. B. Abu-Ghazaleh, "Avoiding head of line blocking in directional antennas," in *Proc. IEEE LCN*, Tampa, FL, Nov. 2004, pp. 385–392.
- [22] P. Bhagwat, P. Bhattacharya, A. Krishna, and S. Tripathi, "Enhancing throughput over wireless LANs using channel state dependent packet scheduling," in *Proc. IEEE INFOCOM*, San Francisco, CA, Mar. 1996, pp. 1133–1140.
- [23] Y. Liu and E. Knightly, "Opportunistic fair scheduling over multiple wireless channels," in *Proc. IEEE INFOCOM*, San Francisco, CA, Apr. 2003, pp. 1106–1115.
- [24] Z. Ji, Y. Yang, J. Zhou, M. Takai, and R. Bagrodia, "Exploiting medium access diversity in rate adaptive wireless LANs," in *Proc. MobiCom*, Philadelphia, PA, Sep. 2004, pp. 345–359.
- [25] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "OAR: An opportunistic auto-rate media access protocol for ad hoc networks," *Wireless Netw.*, vol. 11, no. 1-2, pp. 39–53, Jan. 2005.
- [26] J. Boer, H. van Bokhorst, W. J. Diepstraten, A. Kamerman, R. Mud, H. van Driest, and R. J. Kopmeiners, "Wireless LAN with enhanced capture provision," U.S. Patent 5 987 033, Nov. 16, 1999.
- [27] T. Nadeem, L. Ji, A. Agrawala, and J. Agre, "Location enhancements to IEEE 802.11 DCF," in *Proc. IEEE INFOCOM*, Miami, FL, Mar. 2005, pp. 651–663.
- [28] *The Network Simulator ns-2*, [Online]. Available: <http://www.isi.edu/nsnam/ns/>
- [29] J. Proakis, *Digital Communications*, 4th ed. New York: McGraw-Hill, 2000, p. 270.
- [30] R. Jain, *The Art of Computer Systems Performance Analysis*. Hoboken, NJ: Wiley, 1991.



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