Directional MAC for 60 GHz using Polarization Diversity Extension (DMAC-PDX)

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Abstract— **This paper proposes a directional medium access control (DMAC) algorithm for wireless communication networks operating in the 60 GHz bands. Wireless communications using the 60 GHz spectrum must overcome many challenges that the conventional systems operating in the lower frequency bands do not encounter. These are mainly caused by the special characteristics of the 60 GHz signal such as its lack of penetration ability. Thus, information on whether the communications link has a line-of-sight (LOS) component or not is critical to optimize 60 GHz systems. We propose an efficient approach to determine the presence of a direct path between transmitter and receiver, which will be used to determine if the environment is LOS or non-LOS. We also propose a direction finding approach to be used with the proposed DMAC algorithm. We compare the performance of the proposed algorithm with that of the traditional MAC protocol when applied to 60 GHz systems, since there are no existing DMAC protocols that are specifically designed for 60 GHz communications.**

I. INTRODUCTION

The increasing demand for high-speed wireless networks in recent years and exhaustion of spectrum resources have motivated the use of the higher frequency region of the radio spectrum such as the 60 GHz band [1]–[3]. However, systems operating in the 60 GHz band must overcome some additional challenges that traditional radios do not encounter at lower frequency regions. These challenges originate from the unique characteristics of the 60 GHz radio frequency (RF) signal such as its poor ability to penetrate through obstacles [4], high free-space path loss [5], absorption of energy by gases like oxygen molecules and water vapor, and hydrometeors in the form of rain or snow [6].

For high-data-rate digital signaling, a large delay spread may cause excessive intersymbol interference (ISI) [7]–[9]. It is also well known that narrow-beamwidth antennas can effectively reduce the channel delay spread. The characteristics of 60 GHz band strongly favor directive communications in the physical layer, not only to align the signal energy in the appropriate direction, but also to reduce the channel delays (and thus ISI). Additionally, this allows spatial division for maximum network capacity.

However, using directional antennas presents many challenges in medium access control (MAC) for both multiple-access and point-to-point, single-user communication scenarios. Even with directional antennas, the penetration ability of 60 GHz waves is very weak when compared with its lower frequency counterparts. Therefore, as opposed to lower frequency bands, shadowing, as illustrated in Fig. 1, is a major challenge in the 60 GHz band. In lower frequency bands, electromagnetic waves could effectively penetrate through the obstacle in non-line-of-sight (NLOS) environments, but this is unlikely for 60 GHz wave. This challenge is not present in the traditional wireless communication structures. A possible approach to solve this problem is to rely on the reflective paths to the receiver as illustrated in Fig. 1. In the case of an omnidirectional antenna, the received power from a reflected path could be extremely low in an NLOS environment due to the increased reflection losses at higher frequencies. Moreover, the entire space is used by the transmitter and receiver radiating in all directions during the entire communication, which wastes channel resources. A directional antenna could be used to avoid these problems: if the direction of the antenna and the reflective path that gives the least time delay can be aligned, the network performance will increase significantly.

In order to use directional antennas efficiently at 60 GHz, special MAC protocols that take into consideration the unique characteristics of 60 GHz channels are needed. The concept of directional MAC (DMAC) has been studied for many years for wireless ad hoc networks to achieve simultaneous access in different directions [10]–[13]. Although DMAC and the advantages/disadvantages with directional antennas for lower frequency bands have been widely studied, they cannot be directly applied to 60 GHz communications due to the drastically different electromagnetic properties of waves.

Even for lower frequency bands, many physical-layer issues to implement DMAC remain unsolved. The most critical one is an efficient and feasible technique to find the path-arrival direction. At 60 GHz, this is especially important because communication in NLOS environments relies on this information. In most of the existing research on DMAC, it is usually assumed that the direction of path arrival is known *a priori*. Some research uses GPS on every node [14] or angle-of-arrival (AoA) measurements [15]; however, the former is usually not available in indoor environments and the latter could be either inefficient or too complex.

The goal of this paper is to efficiently exploit the different behaviors of linear and circular polarization schemes and use them in conjunction with a DMAC protocol at 60 GHz. The propagation characteristics at 60 GHz are very different from lower frequency bands; therefore, with an appropriate design, these unique features can be exploited for optimum performance and low-complexity of the network. We first develop a fast and effective method to characterize the communication environment employing polarization techniques. We then study a direction-finding algorithm that uses a pseudo-synchronization between the transmitter and the receiver. Based on these results, we will optimize a DMAC protocol with polarization diversity extension (DMAX-PDX) that fully exploits the unique characteristics of 60 GHz propagation to overcome its problems and to utilize its advantages. Although, there are no existing DMAC protocols specifically designed

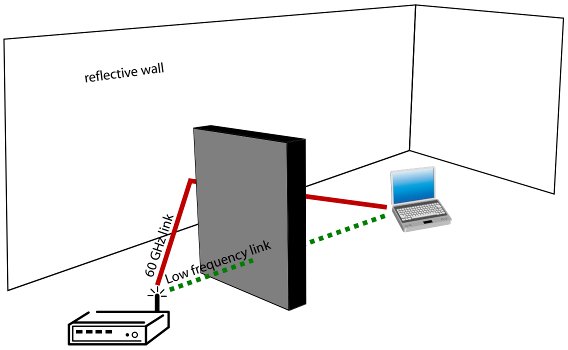

Fig. 1. Shadowing effects at 60 GHz: signals in lower frequency bands (e.g., the 2.4 GHz ISM band) could effectively penetrate through the obstacle, whereas 60 GHz signals must find a reflected path to reach the destination.

for wireless communications at 60 GHz, we can apply the traditional DCF MAC protocol to 60 GHz. This allows us to compare the performance of such scheme with that of the proposed scheme.

II. DMAC-PDX APPROACH

A. Detection of Presence/Absence of a Direct Path

The received signal power for linear and circularly polarized transmissions are same for the direct path from the transmitter, provided that the receiver has the same antenna polarization as the transmitter. For reflected paths, however, the received power at the receiver with different polarizations will be different because of different reflective characteristics of waves under different polarizations. This behavior is the key of our approach in detecting the presence or absence of a direct path between the transmitter and the receiver. In order to effectively take advantage of this characteristics, many key issues must be solved: (a) how to determine if the channel is LOS (i.e., direct path is present) or NLOS (i.e., direct path is absent) without invoking complex algorithms, and (b) how to switch the polarization in a dynamically changing environment?

The second issue can be solved by using a dual polarized smart antenna that can beamform in a sector or omnidirectionally at the transmitter side. Dual polarized antennas, especially with linear and circular polarization, are not as common as other antennas. However, they are realizable and many existing efforts have reported measurement results of such dual polarized antennas (e.g, [16], [17]). Beamforming and sectoring can be performed by smart antennas [18] and antenna arrays [19], [20], and there exists considerable research in these areas. Therefore, with such a dual polarized antenna, the polarization choices can be adaptively (but easily) selected for any communication scenarios.

The first key issue mentioned above can be effectively solved by exploiting the different reactions of linear and circular polarizations to multipath propagation. This is achieved as follows. Using the aforementioned antenna, a test frame (TEST) is sent in all directions with linear and circular polarization simultaneously. In order to avoid interference, these two signals could occupy different time slots or different frequency bands. The receiver is also equipped with a dual polarized antenna. Upon receiving both of the incoming test frames, the receiver compares the received power of the initial paths for both polarization schemes. LOS or NLOS conditions can be determined from this comparison: if the difference between the received powers of the first paths for both polarization schemes are within a certain threshold Δ_p, then it is an LOS scenario; otherwise, it is an NLOS scenario.

This scheme is very simple and feasible for actual implementation. Once the condition of the wireless channel (whether it is LOS or not) is determined, the appropriate polarization of the dual polarized antenna is activated to establish a reliable wireless connection. If LOS environment is detected, the receiver responds to the test frame with an acknowledgement (i.e., ACK/LOS) frame, which also contains the LOS information. The receiver also switches to operate with circular polarization, to match up with the transmitter after receiving the ACK/LOS frame. In the case of an NLOS scenario, the receiver replies with an NLOS information (ACK/NLOS) and both transmitter and receiver switch to linear polarization.

B. Detection of Transmission Direction

Once the condition of the wireless channel is determined, the system needs to determine the direction of transmission. This direction will be along the direct path for the LOS case, and the strongest reflected path for the NLOS case. The accuracy of the direction is critical for DMAC to work.

In order to determine the direction of transmission we propose a pseudo-synchronization scheme between the transmitter and the receiver to distinguish between the different paths that are received by the receiver. In this scheme, the transmitter applies a time stamp to every packet it sends according to its local clock. The only restriction with this local clock is that its period should be long enough so as not to interfere with several adjacent transmission cycles. If the environment is LOS, the first received path is the dominant path for communications. The receiver pseudo-synchronizes its internal clock with the time stamp on the received test frame. If the environment is NLOS, the receiver takes the strongest received path as the dominant path, which is not necessarily the first one received. The shortest reflected path might have a higher reflective loss than a slightly longer reflective path. The receiver also pseudo-synchronizes its internal clock with the time stamp on the received test frame for the dominant path. In either case, after pseudo-synchronization, there will be an offset between the internal clocks of the receiver and transmitter, and this offset represents the propagation delay of the selected dominant path. This information will be sufficient to find the direction of the receiver through the dominant path.

In the proposed algorithm, the communication environment is divided into a predefined number of sectors, each with a certain angular spread (i.e., sectored cell approach). The transmitter sends an RTS frame (with a time stamp) from each sector consecutively in a circular fashion. After each transmission in a sector, the transmitter stops and listens for a possible CTS from the intended receiver. In this fashion, all the sectors will be swept and all possible directions are covered. The receiver will most likely receive more than one RTS frames from different sectors. However, each time an RTS frame is received, the time stamp on the frame is compared with the local clock. When the time stamp and the local clock match, the receiver replies with a CTS frame indicating the correct direction of transmission. A matching RTS time stamp and receiver internal clock indicates that the transmitter has sent the RTS frame using the sector that contains the dominant path that was detected in the testing/sychnronization process.

III. DMAC ALGORITHM

Fig. 2 shows the algorithm for the transmitter in the testing stage. The algorithm is initiated by a packet transmission request from the upper layer. If the packet is addressed to the

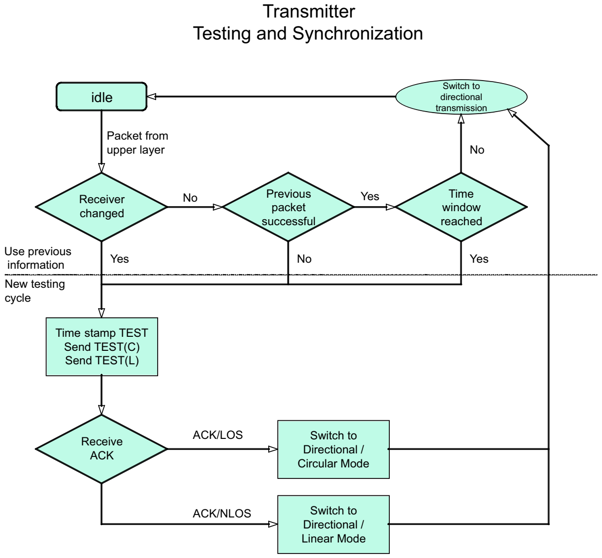

Fig. 2. Flowchart - transmitter in testing stage.

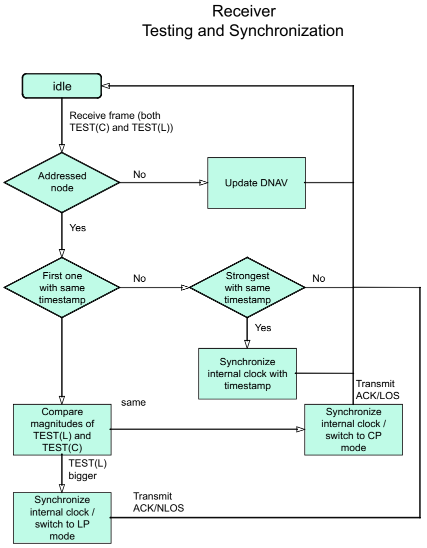

Fig. 3. Flowchart - receiver in testing stage.

receiver that was also the destination for the previous packet, the information from previous testing cycle could be used. If that is the case, the condition of successful delivery for the previous packet is checked. In either case, there will be an expiration time of the information that is obtained from the testing cycle: if the network topology is stationary, this time interval could be extended up to a maximum value of $t_{w,\max}$; when a failure of sending a packet occurs, or a when new destination is set, it will reset to a minimum value of $t_{w,\min}$. Based on these conditions, the algorithm either decides to use the previous information, or to start a new testing cycle.

The testing cycle is performed by sending a TEST frame in circular and linear polarization simultaneously (TEST(C) and TEST(L), respectively). This transmission is performed in an omni-directional manner to reach all directions. After this transmission, the transmitter sets back its mode to listening for potential ACK frames. If ACK/LOS is received from the receiver, transmitter switches to circular mode and initiates the direction-finding algorithm; if ACK/NLOS is received from the receiver, the transmitter switches to linear mode and initiates the direction-finding algorithm.

Fig. 3 shows the algorithm at the receiver in the testing cycle. The cycle is initiated when a TEST frame is received from lower level. The pseudo-synchronization process requires synchronization of the internal clock of the receiver with the timestamp on the most dominant path. Recall that the dominant path will be the first received path in the case of LOS, and the strongest one in the case of NLOS. Therefore, if NLOS is determined after comparison of TEST frames, the receiver keeps track of the magnitude of the received paths to determine the strongest one, and keeps updating the synchronization each time a stronger path is received.

Once the receiver determines the topology of the network and sends this information back to the transmitter, it initiates the direction finding and data transmission cycle shown in Fig. 4. Each frame sent out of the transmitter is time stamped. The transmitter starts to send out directional RTS frames from an initial sector and cycles all sectors in a cyclic manner. Failure to receive a CTS from the receiver for a specific period of time in each sector triggers the transmitter to advance to the next sector. If all sectors are probed with RTS and still no response from the transmitter is received, the packet is dropped.

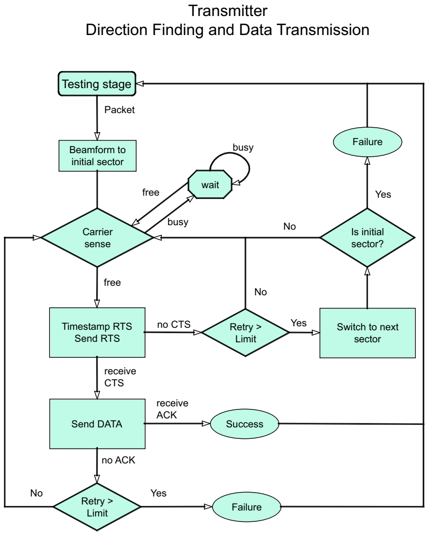

Fig. 4. Flowchart - transmitter in direction-finding stage.

In the data-transmission and direction-finding stage, the receiver executes an algorithm fairly similar to existing MAC algorithms; the only major difference is that, as shown in Fig. 5, the timestamp of each received frame is compared with the internal clock of the receiver. If they match, a reply will be sent to the transmitter to indicate that the sector it uses is the most efficient direction for communication; otherwise, the received frame is discarded.

IV. NUMERICAL RESULTS

We simulate various scenarios to compare the results with the traditional MAC that uses omnidirectional antennas (omni-MAC) and those with the prosed DMAC-PDX algorithm. The simulation environment is shown in Fig. 6 where reflections from ground and the ceiling are not considered.

In this scenario all of the receivers are equipped with an omnidirectional antenna, and the transmitter has a dual polarized smart antenna, which can be switched between omnidirectional and directional modes. For the directional mode, the antenna is assumed to have a 20 dB gain with a 20 degree of half-power beamwidth. With this antenna

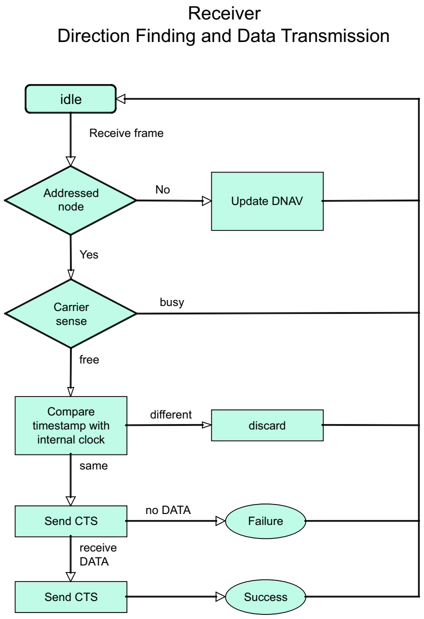

Fig. 5. Flowchart - receiver in direction-finding stage.

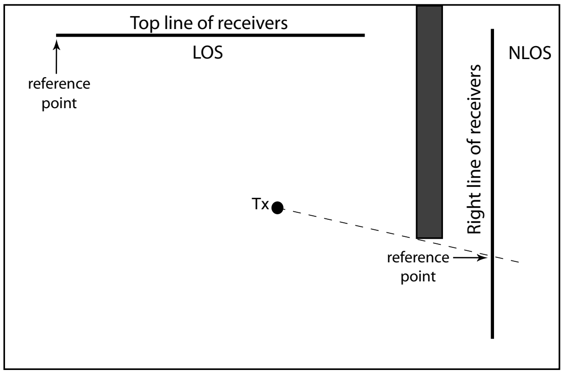

Fig. 6. Indoor environment used in simulation. There are two receiver lines, one lies entirely in LOS region, and the other mostly lies in the NLOS region. The reference points, as indicated in the figure, will be used later in simulation to determine the relative distance of receivers on the receiver line.

configuration, five sectors are needed to cover the entire LOS receiver line, and one sector to cover the NLOS receiver line. In the omni-MAC mode, the received power is written as

$$P_r = \sum_{n=1}^{N} P_n(\tau_n) \tag{1}$$

where P_n represents the received power at time τ_n and N represents the bound after which the received power falls below the noise level. The power of the dominant path can be expressed as

$$P_d = \max\{P_n\},\ n = 1, \cdots, N. \tag{2}$$

In an LOS scenario, $P_d = P_1$, since the shortest path is also the strongest received path. In NLOS scenario, however, the dominant path could be any of the received paths.

In the simulation of omni-MAC where the traditional MAC protocol with omnidirectional antennas is used, the linear vertical polarization is utilized. For the DMAC-PDX approach, the polarization is selected as either linear vertical or circular depending on the outcome of the algorithm's testing stage (i.e., depending on if the communication is LOS or NLOS).

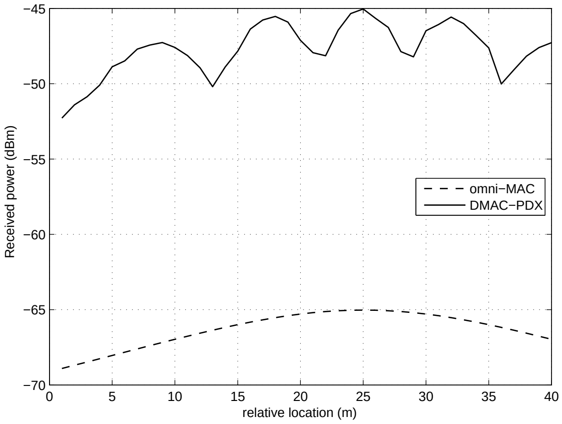

Fig. 7. Comparison of the traditional MAC (omni-MAC) and the proposed DMAC-PDX algorithms in terms of the received power from the most dominant path in LOS scenarios.

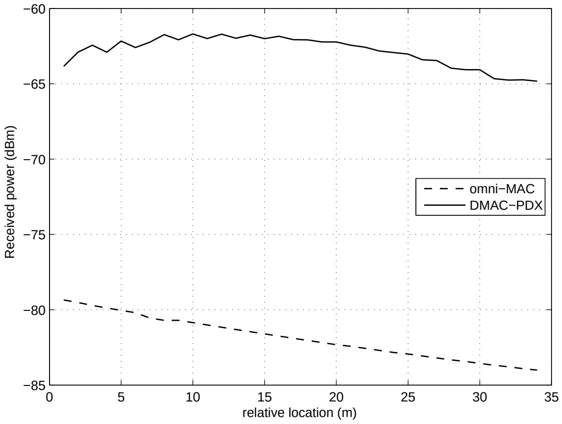

Fig. 8. Comparison of the traditional MAC (omni-MAC) and the proposed DMAC-PDX algorithms in terms of the received power from the most dominant path in NLOS scenarios.

The testing cycle also provides the receiver with the dominant path power P_d, which is then used in the direction-finding stage. Once the transmitter determines which sector to use, the communication cycle begins. In the direction-detection stage, the system tries to find the sector that covers that direction, instead of aligning the direction of P_d.

Figs. 7 and 8 compare omni-MAC and the proposed DMAC-PDX protocols in terms of the received power of the dominant path P_d. The relative distance represents the distance of a particular receiver to the reference point on the line. The ripples of received power of the proposed system that uses five sectors in the LOS scenario are due to the directivity of the antennas. Since there is only one sector serving the NLOS receivers, such ripples are not observed in Fig. 8. In both figures, the significantly performance improvement with the proposed DMAC-PDX algorithm is clearly observed.

In the LOS scenario, the transmitter is vertically aligned with the receiver that is located 25 meters apart. This receiver has the strongest reception due to the shortest distance to the transmitter among other receivers. Compared with the LOS case, NLOS receivers receive less power; however, the improvement due to the use of the DMAC-PDX algorithm is almost comparable to the LOS scenarios.

As discussed earlier, solely increasing the received signal power might not be sufficient for efficient wireless communications. For most high-speed communications sys-

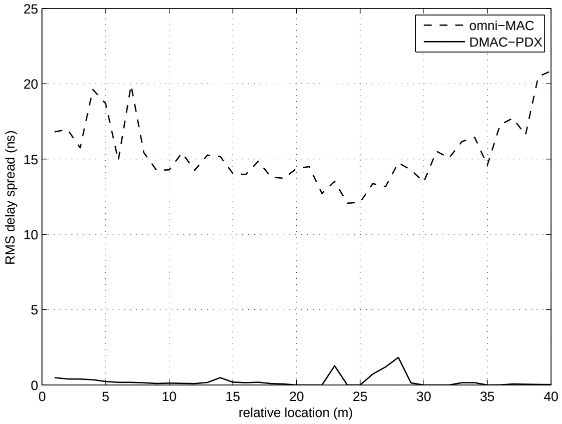

Fig. 9. Comparison of traditional MAC (omni-MAC) and the proposed DMAC-PDX algorithms in terms of rms delay spread in LOS scenarios.

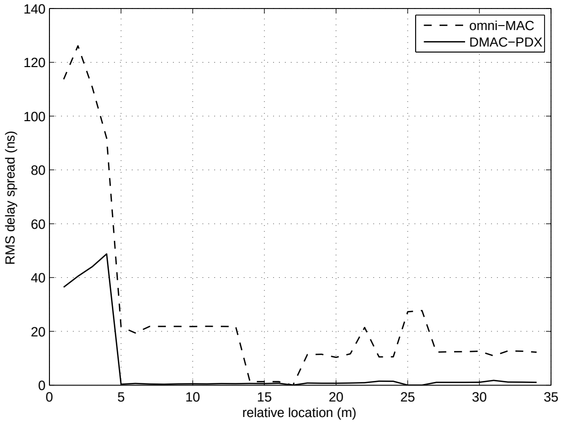

Fig. 10. Comparison of traditional MAC (omni-MAC) and the proposed DMAC-PDX algorithms in terms of rms delay spread in NLOS scenarios. The zero delay spread near the relative location of 15 meters is due to the fact that (coincidentally) only one path is available to the receiver at that location from the transmitter.

tems, the delay spread should also be as low as possible to decrease ISI and to reduce the effect of multipath fading. The rms delay spread for a receiver with the received power profile defined in (1) can be written as $\overline{\tau^2} = \left(\sum_{n=1}^{N} P_n(\tau_n)\tau_n^2\right) / \sum_{n=1}^{N} P_n(\tau_n)$.

Figs. 9 and 10 compare omni-MAC and the proposed DMAC-PDX protocols in terms of rms delay spread. There is a significant decrease in rms delay spread in LOS scenarios due to both polarization switching as implemented in the DMAC-PDX algorithm and the use of directive antennas. These improvements over the omni-MAC transmission eliminate some of the multipath components that are received by the receiver. On the other hand, the decrease in the rms delay spread for NLOS scenarios is solely due to the directive nature of the transmission enabled by the DMAC-PDX algorithm. The decrease in the delay spread will also decrease the ISI for high-data-rate digital signaling.

V. CONCLUSION

This paper focuses on efficient directional MAC algorithms for wireless communications networks using the 60 GHz spectrum. Currently there are not existing DMAC proposals specifically designed for 60 GHz. We modified the traditional MAC algorithm to adapt it for the specific propagation characteristics of 60 GHz signals (e.g., severe shadowing). We have proposed a novel approach for detection of presence or absence of a direct path between the transmitter and the receiver, which is used to determine if the communications link is LOS or NLOS. We also proposed a transmission-direction-finding algorithm, which is critical for the operation of DMAC algorithms. With these proposed techniques, we further study a DMAC algorithm, called DMAC-PDX that is specifically designed for the 60 GHz band. Simulation results show that DMAC-PDX significantly increases the received power for the dominant path and decreases the rms delay spread when compared with the traditional omnidirectional MAC protocol. The increased received power results in a higher signal-to-noise ratio and the low rms delay spread decreases the ISI for high-data-rate signaling. Although the main purpose of this paper is to solve problems associated with DMAC at higher frequency bands such as the 60 GHz band, the proposed approaches could be used at any frequency.

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