Directional CSMA/CA Protocol with Spatial Reuse for mmWave Wireless Networks

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***Abstract*—In this paper, we investigate the problem of medium access control in mmWave wireless networks, within which directional antennas are used to combat the high path loss incurred in the 60GHz frequency band. The conventional CSMA/CA protocol does not work well with directional antennas due to impaired carrier sensing at the transmitters. We propose a novel directional CSMA/CA protocol that not only works well with directional antennas but also achieves higher performance gain than the protocol previously proposed in [1]. The proposed protocol adopts virtual carrier sensing and allows non-interfering links to communicate simultaneously. Both performance analysis and simulation study show that the proposed mechanism incurs low overhead and has robust performance even when the network is heavily congested. Furthermore, the proposed protocol achieves higher throughput than other protocols.**

I. INTRODUCTION

In recent years, the millimeter wave (mmWave) technology has gained considerable interest from academia, industry, and standards bodies. One of the leading factors that make mmWave technology so attractive is due to the huge unlicensed bandwidth (i.e., up to 7GHz) available in the 60GHz band in most part of world. With this huge unlicensed bandwidth, many new applications that require gigabit data rate can be easily supported. Another important factor is that the 60GHz regulation allows much higher effective isotropic radiated power (EIRP) compared to other existing wireless local area networks (WLANs) and wireless personal area networks (WPANs). High EIRP is required to overcome the high path loss in the 60GHz band.

One of the biggest challenges for 60GHz is its high propagation loss. The propagation loss of 60GHz signals in free space is 22dB higher than that of 5GHz signals. 60GHz signals also suffer from high attenuation loss due to obstacles. For instance, a human body introduces at least 15dB loss to 60GHz signals compared to only 5dB loss to 5GHz signal. Therefore, directional antennas, such as phased antenna arrays, are required to overcome the high propagation loss. Directional transmissions should be explicitly considered in the design of MAC protocol for mmWave wireless networks.

Currently, several standards have been or are being defined to achieve multi-gigabit rate for 60GHz wireless networks. Examples include ECMA-387 [2] and IEEE 802.15.3c [3]. Both standards focus on using Time Division Multiple Access (TDMA) for data communications. Existing MAC protocols recently proposed for 60GHz networks are also based on TDMA [4], [6]. Because data traffic is bursty, the required medium time is often highly unpredictable. A TDMA-based MAC protocol may cause either high overhead for on-the-fly medium reservation, or under- or over-allocated medium time for individual users. Furthermore, as defined in IEEE 802.15.3 [7], a access point (AP) needs to schedule bandwidth requests from associated stations. Given that scheduling is computationally intensive and should be executed in real time, it is challenging to implement such a AP on a mobile station. Contention-based MAC protocols, such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), work well with bursty traffic and operate robustly in unlicensed bands [8]. However, the conventional CSMA/CA protocol does not work well with directional antennas due to impaired carrier sensing at the transmitter. Under CSMA/CA, stations (STAs) that see a busy medium compete for access to the medium by waiting a random number of slot times before the next attempt for transmission. Depending on the random numbers chosen by each STA, one STA (i.e., the one with the smallest random number) will typically gain access to the medium first. The other STAs will detect the transmission through a carrier sense mechanism and suspend their attempts to gain channel access until the medium becomes idle again.

In 60 GHz band systems, beamforming, both on the receive side and the transmit side, will be used to improve signal quality at the receiver. As a result of directional listening and transmitting, the signal strength could be very low at third party stations that are not involved in the current exchange, making it difficult to perform carrier sense. This is often referred to as the deafness problem. As illustrated in Fig. 1, while Node A is transmitting to and receiving from Node C, Node A's antenna beam points towards Node C. Because Node B cannot sense the directional transmission from Node A to Node C, Node B may keep on trying to transmit to Node A and keep on backing off with larger and larger contention window after each transmission failure. Due to the deafness problem, new mechanisms are needed to ensure that deferral by third party stations is effective in this environment.

Many contention-based MAC protocols that support directional antennas have been proposed for mobile ad hoc or mesh networks [9]–[12]. A short survey of directional MAC protocols can be found in [13]. Most of the schemes rely on

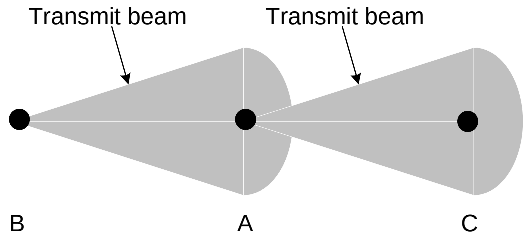

Fig. 1. Illustration of the deafness problem. Node B is deaf with regard to the directional transmission from Node A to Node C.

RTS and/or CTS to distribute the Network Allocation Vector (NAV), which contains duration information of the subsequent transmission(s). However, most existing directional MAC protocols either are based on assumptions that do not apply to the 60GHz band, or introduce too much overhead when adopted in the 60GHz band. Section II-A elaborates on why existing directional MAC protocols cannot be directly applied in the 60GHz band. In [1], we proposed a directional CSMA/CA-based medium access protocol that is tailored specifically for 60GHz wireless networks. This protocol utilizes the AP as a central collaborator for medium access and does not require scheduling. However, the protocol proposed in [1] does not take advantage of spatial reuse gain in a network. Due to the small interfering area of highly directional antennas, simultaneous communications in the same frequency channel and in the same physical space may be possible [5]. Therefore, a MAC protocol that takes advantage of the spatial reuse gain can increase the aggregated network capacity.

In this paper, we propose an enhanced directional CSMA/CA protocol that retains the advantages of the previously proposed protocol and enables spatial reuse in the network. Both theoretical analysis and OPNET simulation results show that the proposed CSMA/CA with spatial reuse protocol achieves much higher performance gain than the 802.11 MAC protocol and the directional CSMA/CA protocol proposed in [1].

The remainder of this paper is organized as follows. We introduce the system model and the proposed CSMA/CA MAC protocol is described in Section II. We then present our performance analysis of the proposed protocol in Section III and our simulation study in Section IV. Section V concludes this paper.

II. PROTOCOL DESCRIPTION

In this section, we describe a directional CSMA/CA protocol for 60GHz WLANs and explain how the proposed protocol exploits spatial reuse for throughput gains.

A. System Model

We consider a wireless LAN as illustrated in Fig. 2. In such a network, there is an access point (AP) that coordinates medium access for multiple mobile stations (STA). The AP also provides basic timing for the network and manages membership of the network. STAs can communicate with the AP or they can communicate directly with each other without having to bridge data through the AP.

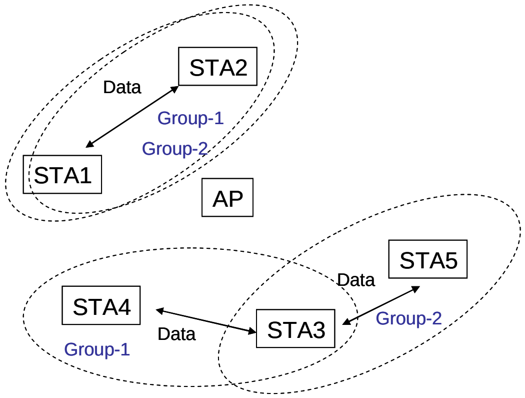

Fig. 2. A WLAN network consisting of one AP and five STAs.

A unique challenge in the design of 60GHz wireless networks arise from the requirement for high antenna gains at both the transmitter and receiver. However, before two stations can finish beam-forming training with each other, neither one can achieve proper beam-formed transmission or reception. Therefore, a low-rate modulation and coding scheme (MCS) needs to be defined to address the case when only one end of the link has high beam-forming gain. Here, we assume a range optimized MCS, i.e. MCS0, which has a receiver sensitivity about 12dB higher than that of a data-rate-optimized MCS that offers data rates higher than 1 Gbps.

Many existing directional contention-based MAC protocols assume that normal data rate can be used even when only one end of the link uses directional antennas. This assumption is not valid anymore in the 60GHz band. In 60GHz, MCS0 has to be used for beam-forming training, and, moreover, for transmissions when only one end of the link has high antenna gain. Furthermore, existing directional MAC protocols assume that beam-training or the so-called beam-locking can be performed on a single received packet. While this might be true for MIMO systems operating in lower frequency bands (e.g., 2.4GHz or 5GHz), beam-forming training at 60GHz with phased arrays is much more challenging and requires multiple iterations. In a 60GHz system, if an STA needs to transmit a frame (e.g., an RTS) in an omni-directional fashion, it needs to perform a sector sweep to transmit multiple copies of the RTS frame in different directions or sectors. During the RTS transmission, the STA may miss any transmission intended for it from other STAs. Thus, it would be nontrivial to solve the deafness problem in the 60GHz band with existing contention-based directional MAC protocols.

B. Directional CSMA/CA Protocol with Spatial Reuse

Consider the WLAN shown in Fig. 2. Before associating with the AP, STAs first perform beam-forming training for transmission and reception, such that both the transmitting and the receiving antennas can provide beam-forming gain. After an STA completes beam-forming training, it always beam-forms towards the AP in its idle mode (i.e., waiting to receive), meaning there is high receive antenna gain. While

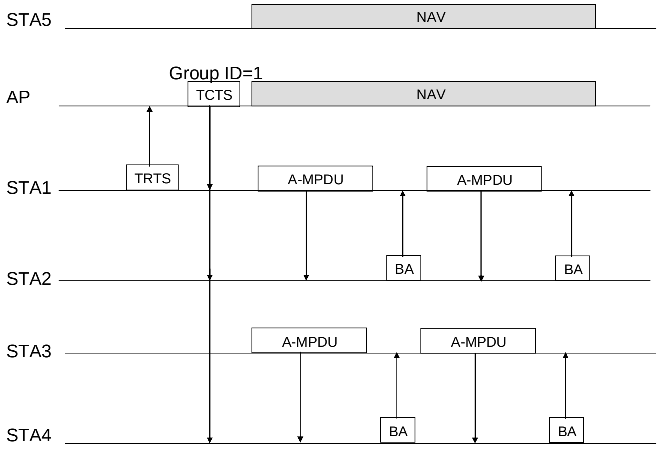

Fig. 3. Illustration of the high-performance directional CSMA/CA protocol.

idle, the AP receives in its omni mode, meaning that there is no significant receive antenna gain. In the proposed protocol, because an STA is always beam-formed towards the AP before any data transmission or reception and the AP coordinates the transmission within a WLAN, the deafness problem is thus easily solved.

To describe the proposed protocol, we consider a typical scenario shown in Fig. 2. In this scenario, STA1 and STA2, STA3 and STA4, STA3 and STA5 have set up peer-to-peer connections respectively. In the idle mode, all stations are beam-formed towards the AP. The AP schedules interference measurement for each peer link. For instance, the AP schedules STA1 and STA2 to transmit and receive over the peer link, while all other STAs stay in directional receive mode to measure the noise floor. Based on the interference measurement, the AP assigns non-interfering peer links into the same group. As shown in Fig. 2, peer link (STA1-STA2) and peer link (STA3-STA4) are assigned to Group 1, whereas peer link (STA1-STA2) and peer link (STA3-STA5) are assigned to Group 2. Because peer links in the same group do not interference with each other in directional transmission and receiving mode, they can communicate simultaneously.

As shown in Fig. 3, before STA1 can communicate with STA2 directly, it transmits a Target Request To Send (TRTS) to the AP. The TRTS contains three addresses: Receive Address (i.e. AP), Transmit Address (i.e. STA1), and Target Address (i.e. STA2). Upon receiving the TRTS, the AP will transmit a Target Clear To Send (TCTS) message in omni mode. This ensures that all associated STAs can receive it. The TCTS contains the following fields: Receive Address (i.e. the broadcast address), Transmit Address (i.e. AP), Target Address (i.e. STA2), a Group ID field, and a transmission priority field. In this case, the Group ID is set to 1, indicating that all peer links that belong to Group 1 may transmit in the following Transmission Opportunity (TXOP). If the transmission priority field is set to 1, the peer STA with higher MAC address transmits first. If the transmission priority field is set to 0, the peer STA with lower MAC address transmits first. If an STA with lower priority senses the medium idle PIFS after receiving the TCTS frame, it may start its transmission towards its peer STA in the same group. Both TRTS and TCTS indicate the duration of the TXOP and they are transmitted using MCS0 because only one end of the link has beam-forming gain. If the AP does not receive the TRTS either due to channel error or a collision on TRTS, STA1 will not receive a TCTS after transmitting a TRTS. Thus, STA1 assumes that a collision has occurred and starts an exponential backoff procedure as defined in [14].

After receiving the TCTS and recognizing that it belongs to Group 1, STA1 and STA2 steer its beam towards each other while STA3 and STA4 steer its beam towards each other. Upon receiving a TCTS with its own address as the Target Address, STA2 should wait for STA1 to transmit first. If PIFS (Point Inter-frame Space) after receiving the TCTS frame, an STA senses the medium free, it can starts its data transmission towards its peer STA. The TRTS/TCTS exchange also set up a transmission opportunity (TXOP) in the network. Within the TXOP, STA1 can transmit one or more Aggregated MAC Protocol Data Units (A-MPDUs) to STA2 at a high data rate. Up to 64 MPDUs may be aggregated in one A-MPDU, which has a maximum size limit of 64K. Upon receiving an A-MPDU, STA2 replies with a Block ACK (BA) that identifies which MPDUs in the A-MPDU have been received successfully. Other stations that do not belong to Group 1, such as STA5, learn from the TCTS that there will be an ongoing transmission and thus set their NAVs for the duration of the TXOP indicated in the TCTS. Note that STAs transmitting in the TXOP have to obey the TXOP duration and should not transmit beyond the TXOP boundary that was defined by the TRTS/TCTS exchange.

C. Remarks

Even though the proposed directional MAC protocol bears similarities with 802.11 DCF [14], there are a few important differences that are worth noting. First, DCF is a distributed MAC protocol, meaning any STA can transmit an RTS to any other STA. On the other hand, the proposed directional CSMA/CA protocol is a centralized protocol. Before any data transmission, an STA must transmit a TRTS to the AP to reserve medium time. TRTS and TCTS are control frames that carry three addresses, one of which identifies the destination STA. Due to antenna directionality, STAs adopting a distributed MAC protocol need to continuously track all neighboring STAs, which can incur prohibitively high communication overhead and high implementation complexity.

Second, to support directionality, some of the parameters in the proposed protocol are different from those defined in 802.11 DCF. For instance, aSlotTime is an important parameter in both DCF and our protocol and it is set to the time needed for any station to detect a transmission from any

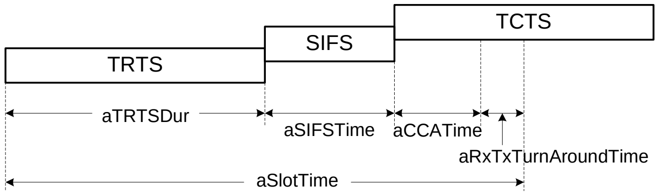

Fig. 4. Illustration of aSlotTime in the directional CSMA/CA.

other station. In 802.11 DCF, aSlotTime is set to:

$$\begin{aligned} & aSlotTime \\ = \; & aCCATime + aRxTxTurnaroundTime + \\ & aAirPropagationTime + aMACProcessingDelay, \end{aligned}$$

whereas in our protocol, aSlotTime is set to:

$$\begin{aligned} & aSlotTime \\ = \; & aTRTSDur + aSIFSTime + aCCATime + \\ & aRxTxTurnAroundTime. \end{aligned}$$

Here, aTRTSDur is the duration of a TRTS frame, which includes the PHY preamble, the PHY header and the TRTS frame body. aSIFSTime is a short inter-frame time between receiving a packet and sending out an acknowledgement. aCCATime is the time that a receiver needs to determine whether a valid packet is on the medium. aRxTxTurnaroundTime is the time that a half-duplex station needs to switch from Rx mode to Tx mode.

Because all STAs are beam-formed towards the AP and the width of the beam generated by an antenna array is narrow, most other STAs won't be able to receive the TRTS sent from the source STA. Therefore, for a third-party STA to detect an on-going transmission, virtual carrier sensing has to be used and thus aSlotTime needs to include aTRTSDur and aSIFSTime. The definition of aSlotTime in the proposed protocol is illustrated in Fig. 4.

Last but not the least, 802.11 DCF was designed mainly for omni-directional transmissions and it suffers from various problems, including the deafness problem, when being used with directional antennas. Our proposed protocol is designed specifically for directional transmissions in the 60GHz band and it addresses the deafness problem.

III. PERFORMANCE ANALYSIS

In this section, we present an analytical study of the proposed directional MAC protocol. We derive the saturation throughput of the proposed protocol, which is defined as the throughput level achieved at the top of the MAC layer when all nodes in the systems are continuously loaded.

It is assumed that stations use MAC frame aggregation schemes, such as A-MPDU, and make multiple transmissions in one TXOP. When TXOP is utilized, a station contends once to transmit TRTS. Upon successful reception of a TCTS that allows a station to transmit, the station can transmit as many A-MPDU as the TXOP duration permits, provided that the last BA can be received within the TXOP duration.

We follow the assumptions made in [8] and adopt the same 2-D Markov chain model for the proposed MAC protocol. In the Markov chain mode, each state is represented by $\{s(t), b(t)\}$, where $s(t)$ is defined to be the stochastic process representing the backoff stage $(0, \cdots, m)$ of the station at time t and $b(t)$ is the stochastic process representing the backoff time counter for a given station. The maximum backoff stage, i.e., m, takes the value such that $CW_{max} = 2^m CW_{min}$, where CW_{max} is the maximum contention window and CW_{min} is the minimum contention window.

Let S be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits. S can be expressed as the average number of payload bits transmitted in a TXOP divided by the average length of a TXOP. Based on the 2-D Markov chain model, we extend the analysis in [8] and derive the system saturation throughput as:

$$\begin{aligned} S \; = \; & P_{AP\_STA}\frac{P_s P_{tr}\sum_{j=1}^{N}\mathrm{E}[P_j]}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} + \\ & P_{STA\_STA}\frac{P_s P_{tr}\sum_{j=1}^{M}\sum_{i=1}^{N}\mathrm{E}[P_{ij}]}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c}, \end{aligned} \quad (1)$$

where

$$\begin{cases} T_s = \sigma + aTCTSDur + TXOP \\ T_c = \sigma \\ P_{tr} = 1 - (1-\tau)^2 \\ P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \end{cases} \quad (2)$$

In the above equations, P_{AP_STA} is the probability that an AP/STA communication pair wins the contention, P_{STA_STA} is the probability that an STA/STA communication pair wins the contention, M is the number of peer links in one group, T_s is the average time consumed by a successful TXOP, T_c is the average medium time a collision consumes, σ is the duration of a time slot, aTCTSDur is the transmission duration of the TCTS frame, τ is the probability that a station transmits in a randomly chosen time slot, P_s is the probability that a TXOP is successfully set up, and P_{tr} is the probability that there is at least one transmission in the considered slot time. M is the number of peer links that can operate simultaneously in one group. The sum $\sum_{j=1}^{M}\sum_{i=1}^{N_j}\mathrm{E}[P_{ij}]$ is the combined average payload size of A-MPDUs that are transmitted over M peer links in the TXOP.

Equation (1) can be rearranged as follows:

$$S = \frac{1}{n}\frac{\sum_{i=1} N\mathrm{E}[P_i] + (n-1)\sum_{j=1}^{M}\sum_{i=1}^{N}\mathrm{E}[P_{ij}]}{T_s - T_c + \frac{T_c-(1-\tau)^n(T_c-\sigma)}{n\tau(1-\tau)^{n-1}}}. \quad (3)$$

Under condition $\tau \ll 1$, τ can be estimated as [8]:

$$\tau \approx \frac{1}{n\sqrt{T_c/(2\sigma)}}.$$

Figure 5 illustrates the relationship between the optimal saturation throughput and the number of stations in the WLAN. When the transmission probability is small, i.e., $\tau \ll 1$, the throughput degradation is small with an increase in the number of stations.

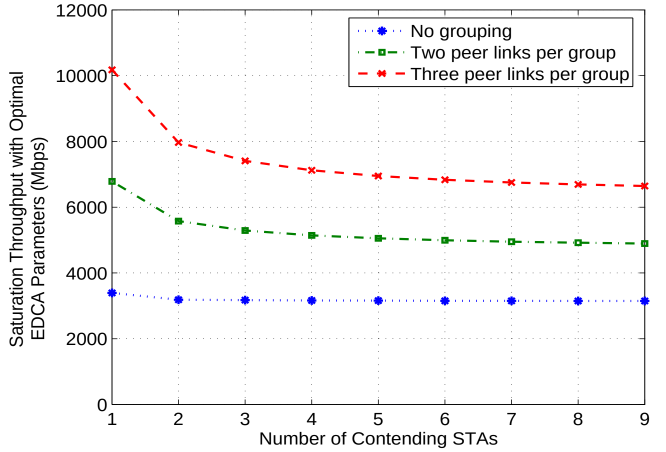

Fig. 5. Optimal saturation throughput vs. the number of STAs in the WLAN.

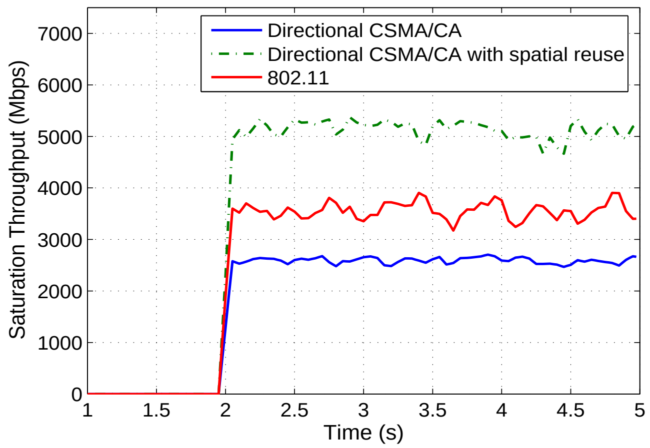

Fig. 6. Aggregated saturation throughput.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
MCS0 Rate (Mbps)	25	aSlotTime (us)	20
Data Rate (Mbps)	4063	aSIFSTime (us)	2
ACK Rate (Mbps)	1384	TXOP duration (us)	500
A-MPDU size (byte)	65536	MCS0 preamble (us)	3.75
TRTS (byte)	26	Data preamble (us)	1.75
TCTS (byte)	26	Default CWmin	15
BA size (byte)	32	Default CWmax	1023

IV. SIMULATION STUDY

We evaluate the performance of the proposed directional MAC protocol via extensive simulations using the OPNET Modeler. Our simulation uses a typical WLAN topology with one AP and a variable number of stations in the same network, as shown in Fig. 2. STA1 has fully loaded traffic destined for STA2 while STA4 and STA5 have fully loaded traffic destined for STA3. The simulation parameters and their values are given in Table I. The simulation results are presented in Figs. 6.

As shown in Fig. 6, the saturation throughput achieved by directional CSMA/CA protocol is about 3.5Gbps which is 37% less than that of the 802.11 protocol. On the other hand, the saturation throughput achieved by the directional CSMA/CA with spatial reuse protocol is about 5.2Gbps, which is about 47% more than that of the 802.11 protocol and almost twice more than that of the directional CSMA/CA protocol.

The directional CSMA/CA with spatial reuse protocol naturally inherits a main benefit of 802.11 protocol, which is spatial reuse from highly directional data transmission. By avoiding the deafness problem, the directional CSMA/CA with spatial reuse protocol significantly reduces the number of collisions within WLAN. There is also an additional gain provided by shortened channel access time in non interfering groups. While one peer link has finished contention and started a TXOP, another peer link in the same group may still be performing backoff. Reception of TCTS frame indicating transmission in the same non-interfering group enables data transmission for all peer links in this group.

V. CONCLUSION

We propose and evaluate a directional CSMA/CA with spatial reuse protocol for mmWave wireless networks. The proposed MAC protocol enables spatial reuse in a wireless network with directional antennas, does not suffer from the deafness problem, and incurs a small protocol overhead. Through OPNET simulations, we find that the proposed protocol achieves much higher throughput than the original 802.11 protocol and another directional CSMA/CA protocol. Moreover, both our analysis and simulation results demonstrate high MAC efficiencies achieved by the proposed directional MAC protocol for mmWave wireless networks.

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