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RESEARCH ARTICLE

CSMA/CA-based medium access control for indoor millimeter wave networks

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ABSTRACT

Millimeter wave (mmWave) communication is a promising technology to support high-rate (e.g., multi-Gbps) multimedia applications because of its large available bandwidth. Multipacket reception is one of the important capabilities of mmWave networks to capture a few packets simultaneously. This capability has the potential to improve medium access control layer performance. Because of the severe propagation loss in mmWave band, traditional backoff mechanisms in carrier sensing multiple access/collision avoidance (CSMA/CA) designed for narrowband systems can result not only in unfairness but also in significant throughput reduction. This paper proposes a novel backoff mechanism in CSMA/CA by giving a higher transmission probability to the node with a transmission failure than that with a transmission success, aiming to improve the system throughput. The transmission probability is adjusted by changing the contention window size according to the congestion status of each node and the whole network. The analysis demonstrates the effectiveness of the proposed backoff mechanism on reducing transmission collisions and increasing network throughput. Extensive simulations show that the proposed backoff mechanism can efficiently utilize network resources and significantly improve the network performance on system throughput and fairness. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS
millimeter wave; medium access control; CSMA/CA; backoff mechanism; contention window

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1. INTRODUCTION

Millimeter wave (mmWave) technology in the 60 GHz band is one of the most promising technologies to provide high data rate (e.g., multi-Gbps) for indoor applications of wireless personal area networks (WPANs) [1–4] and wireless local area networks (WLANs) [5]. Because of the abundant bandwidth (around 7 GHz) in the unlicensed 60 GHz band, mmWave communications enable multi-Gbps wireless connections for high-speed wireless multimedia services such as uncompressed high-definition TV and high speed downloading services. Because free space propagation loss is proportional to the square of carrier frequency, the propagation loss in 60 GHz band is much higher than that in lower frequency bands, for example, 28 dB higher than in 2.4 GHz [4]. High directional antennas are used to combat the severe propagation loss and achieve multi-Gbps throughput for bandwidth-intensive applications. The high propagation loss and the use of directional antennas can enable more efficient spatial reuse.

Although mmWave communications can achieve instantaneous transmission rate of multi-Gbps, the transmission throughput of each node cannot support multimedia applications requiring multi-Gbps throughput, when a large number of nodes contend for the wireless channel [5]. To provide multi-Gbps throughput for each node and support multimedia applications, it is important to improve the network capacity. Increasing the capacity of wireless networks requires increasing the concurrency with which shared channels are accessed or increasing the amount of information sent with each transmission [6]. Multipacket reception consists of the ability of allowing multiple nodes to transmit their packets simultaneously to the same receiver, and the receiver can decode all such packets successfully. Multipacket reception can be implemented by allowing a node to decode multiple concurrent packets using multiuser detection [6,7] or distributed multiple input multiple output techniques. It has been demonstrated that a gain of

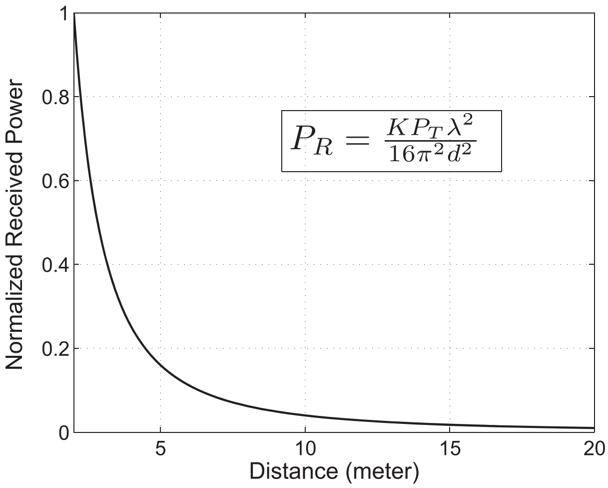

Figure 1. Normalized signal power over distance.

$\Theta(log(n))$ (n is the number of nodes in the network) can be achieved to increase mmWave network capacity by using multipacket reception instead of single packet reception [8,9]. The directional antennas for mmWave communications are helpful to enable multipacket reception in terms of reduced interferences because of the directivity.

Multipacket reception and the unique features of mmWave communications bring more challenges on mmWave medium access control (MAC) design. Current MAC protocols designed for narrowband systems cannot be directly applied to mmWave networks. Indoor mmWave networks are based on the hybrid multiple access of carrier sensing multiple access/collision avoidance (CSMA/CA) and time division multiple access (TDMA) [4,10,11]. Previous work has addressed the MAC design and analysis on the part of TDMA-based MAC in indoor mmWave networks [1,2,5,12]. In this paper, we focus on designing efficient CSMA/CA-based MAC protocol for mmWave networks with multipacket reception capability. A basic underlying assumption in the design and evaluation of legacy CSMA/CA-based MAC protocols was that any concurrent transmissions of two or more packets result in collision, which leads to a failure in reception of all the packets. The actual situation in many wireless communication systems is that the packet with the strongest power level can be received successfully (captured) in the presence of contending transmissions. As shown in Figure 1, the mmWave signal power significantly degrades over distance, thus the received signal power of nearby nodes are much stronger than that of distant nodes. Therefore, the channel is always captured by nearby nodes, resulting in serious unfairness. Moreover, for a receiver with multipacket reception capability, much stronger power of the nearest nodes also leads to significant degradation of system throughput. As shown in Figure 2, there are five nodes transmitting to the receiver (network controller) simultaneously. The stronger received signal power from the nearby node results in failure of the other four transmissions from the distant nodes. With multipacket reception capability at the receiver, the system can successfully receive four packets instead of one if the nearest node does not transmit. Therefore, we propose a backoff mechanism giving higher transmission priority to the distant nodes to achieve better system throughput and fairness, considering the high propagation loss of mmWave communications.

The main contributions of this paper are threefold. First, by changing the contention window size, we propose a novel backoff mechanism to adjust the transmission probability according to network congestion status and node transmission status. Second, we theoretically analyze the throughput of mmWave system with multipacket reception and demonstrate that the system throughput can be improved by giving a higher transmission probability to the node with a transmission failure than that with a transmission success. Finally, extensive simulations are conducted to demonstrate that the proposed mechanism is effective and efficient on improving system throughput and fairness.

The remainder of the paper is organized as follows. In Section 2, the system model is described. A novel backoff mechanism is proposed in Section 3. The system throughput is analyzed using a Markov model in Section 4. The performance of the proposed mechanism is evaluated by extensive simulations in Section 5. Related works are reviewed in Section 6 followed by concluding remarks in Section 7.

2. SYSTEM MODEL

We consider indoor mmWave networks for the scenarios such as large office, conference room, and airport, in which many active nodes contend for the mmWave channel and share the medium. Consequently, it is important to increase network capacity, in order to satisfy the transmission demands of these nodes in the network. Thus, multipacket reception is implemented to increase the network

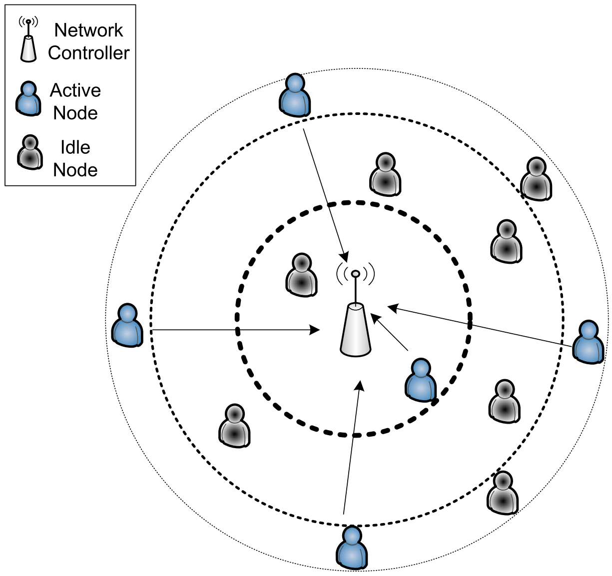

Figure 2. Indoor mmWave network architecture.

capacity in this paper. For the scenarios with a small number of active nodes in mmWave indoor networks, the transmission demands can be satisfied even without efficient resource utilization. Therefore, it is more interesting to consider the challenging cases where the network resources are limited compared with the traffic demands of nodes.

2.1. System architecture

Since mmWave indoor networks (e.g., WPANs/WLANs) are centralized in nature, we consider a network composed of multiple wireless nodes and a single network controller as shown in Figure 2. All wireless nodes are equipped with electronically steerable directional antennas. With beamforming technologies [13–15], the wireless nodes are able to select the best transmission beam and reception beam and direct the beams toward each other for transmission and reception. The communication mode for indoor mmWave networks is the hybrid of ad hoc mode and cellular mode. Specifically, there are two types of connections in the network: end-to-end transmission within the network (ad hoc mode) and the transmission between a node in the network and another node external to the network via network controller (cellular mode). CSMA/CA is mainly for non-delay sensitive applications, such as web browsing, which need to make connections external to the network via a network controller. Therefore, in this paper, the communication is based on the cellular mode. We consider n as spatially distributed nodes that communicate with a single network controller (e.g., a piconet controller or an access point) over a slotted channel.

2.2. MAC structure

As indicated in the standards [10,11] for mmWave WLAN and WPAN, the networks are based on hybrid multiple access of CSMA/CA and TDMA. Different applications have various transmission requirements, for example, applications such as video streaming and wireless display have stringent QoS requirements on delay and transmission rate, whereas applications such as web browsing are sensitive to response time and may not require bandwidth guarantees. Therefore, CSMA/CA is used for a burst type of application such as web browsing because of the lower average latency, whereas TDMA is more desirable for video transmission due to its better quality of service (QoS) and efficiency. As shown in Figure 3, we consider the IEEE 802.15.3 superframe structure as the MAC structure in this paper. A superframe is composed of three phases: the Beacon period for network synchronization and control messages among the network controller and wireless nodes, the contention access period (CAP) based on CSMA/CA for non-delay sensitive applications, and the channel time allocation period (CTAP) composed of M channel time slots for bandwidth-intensive and delay-sensitive applications, respectively.

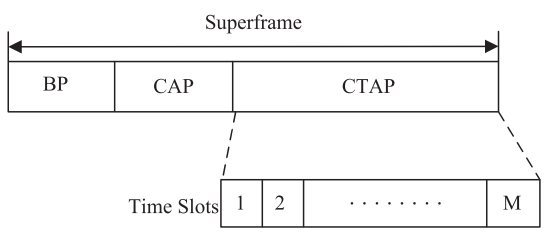

Figure 3. IEEE 802.15.3 MAC structure.

We have proposed concurrent transmission scheduling algorithms to exploit the spatial reuse for TDMA-based CTAP considering both interfering links [5] and non-interfering links [2,16] for delay-sensitive applications. This work focuses on enabling efficient multipacket reception in CAP for mmWave indoor networks.

2.3. Antenna model

The antenna model used in this paper is the one considered in the previous work [2,5,12]. The side lobes of directional antennas are generally small enough compared with the main lobe. For instance, the gain of the main lobe of typical directional antennas is more than 100 times the gain of the largest side lobe. Thus, the interference region of an antenna is principally determined by its main lobe. The simplified antenna model, considering the main lobe, will not result in a fundamental change on the results of this paper. We define the radiation pattern in a two-dimensional plane, and the gain of the antenna $G(\phi)$ is a function of the azimuth angle ϕ. Specifically, the antenna gain is constant within the beamwidth and zero outside the beamwidth,

$$G(\phi) = \begin{cases} C, & |\phi| \leq \frac{\Delta\phi}{2} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where $\Delta\phi = 2\pi/B$ is the antenna beamwidth, whereas B is the number of beams. The network controller is equipped with multiple antennas to receive multiple packets simultaneously.

2.4. Packet capture model

Because the throughput is one important aspect of the system performance and it is counted by the number of received packets, we describe the packet capture model to decide whether a packet is successfully received. Two packet capture models are adopted in this paper, namely, signal-to-interference-plus-noise ratio (SINR) capture model and vulnerability circle capture model. The SINR capture model describes the real situation of packet capture and is used to evaluate the performance of the proposed backoff mechanism while the vulnerability circle capture model is a simplified model based on the SINR capture model and is used for system throughput analysis.

2.4.1. SINR capture model.

The channel time is slotted and the transmission duration for packets is one slot long. The propagation model includes path loss and fading. The received power of a transmission from wireless node i, located at distance d_i from the receiver, is given by

$$P_R(d_i) = P_T K d_i^{-\gamma} F \tag{2}$$

where P_T is the transmission power, γ is the path loss exponent, which is usually determined using a measurement approach (typically in the range of 2 to 6 for indoor environments [17]), K is the attenuation constant, and F is the fading factor. The received SINR from node i at the receiver is

$$SINR(i) = \frac{P_R(d_i)}{N_0 W + \sum_{j=1, j\neq i}^{n} P_R(d_j)} \tag{3}$$

where N_0 is the one-sided power spectral density of noise and W is the system bandwidth. For SINR packet capture model, given a set of simultaneous transmission packets, the packet from node i is successfully received if

$$SINR(i) > h \tag{4}$$

where h is the packet capture threshold ratio. For single packet reception narrowband systems, $1 \leq h \leq 10$, whereas for wideband multipacket reception systems, such as UWB and mmWave, $h < 1$ [18]. Let M denote the multipacket reception capability, then the maximum number of packets will be captured if there are M equal received-power packets at the receiver with $M = \lceil 1/h \rceil$ [18,19], where $\lceil\rceil$ is the ceiling function.

2.4.2. Vulnerability circle capture model.

This model was proposed in [20] and studied in [21]. In this model, the node closest to the receiver can capture the channel due to its larger power at the receiver. Specifically, a node i with distance d_i from the receiver captures the channel if there are no simultaneous transmissions within a disk of radius $\alpha d_i (\alpha > 1)$. The parameter α is the vulnerability circle capture ratio. We extend the vulnerability circle capture model to the case of multipacket reception. Based on SINR capture model, a transmission from node i is successful if

$$SINR(i) > h, (h < 1) \tag{5}$$

To achieve this, the received power of the successful packets should be similar to each other. To make the analysis tractable, the successful packets are assumed to have similar distances to the receiver. Let β denote the number of successful transmission packets. For a receiver with multipacket reception capability, a transmission from a node with distance d_i is successful if there are $\beta (\beta \leq M)$ simultaneous transmissions around the circle with radius d_i and the other simultaneous transmissions (if they exist) are outside of the disk of radius ζd_i, where ζ is the vulnerability circle capture ratio for the case of multipacket reception ($\zeta > 1$). Because mmWave signal power degrades significantly over distance, the values of α and ζ could be relatively smaller than those at lower frequency bands.

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3. BACKOFF MECHANISM DESIGN

In CSMA/CA-based MAC, the backoff mechanism controls the transmission probability of each node. In a general backoff mechanism, each node i sets an integer backoff counter $B_{i,j}$ randomly generated from a contention window $W_{i,j}$, that is, $B_{i,j} \in \{0, 1, \ldots, W_{i,j} - 1\}$. The subscript j represents the backoff stage of node i. The contention window size is reset after a transmission attempt and node i retransmits packet after $B_{i,j}$ time slots.

In this section, we first present the design considerations for the proposed backoff mechanism. Then, a detailed backoff mechanism is proposed to adjust the contention window size considering the unique features of indoor mmWave systems, aiming to improve the system throughput and fairness.

3.1. Design considerations

A transmission failure may occur in two independent scenarios. (i) Both the nearby nodes and distant nodes send packets to the receiver. Because of shorter transmission distance, the nearby nodes usually have stronger received power to satisfy the SINR capture model $SINR(i) > h$, thus the transmissions from distant nodes fail. (ii) The transmissions arriving at the receiver are only from distant nodes and the received SINR of each node is not larger than the packet capture threshold ratio h in (4) if there are too many transmissions. Thus, no packet captures the channel. For the first scenario, we can mitigate the channel capture effect of nearby nodes by giving higher transmission probability to distant nodes, and the receiver can receive more packets because of its multipacket reception capability. The second scenario indicates that much higher transmission probability of the distant nodes can also result in system throughput reduction. It would make the case worse if the contention window size were further reduced after a transmission failure of distant nodes. Consequently, to achieve better system throughput, the transmission probability needs to be properly adjusted.

The transmission probability controlled by the backoff mechanism has a strong impact on both system throughput and fairness. Giving higher priority to the distant nodes can achieve higher system throughput due to the multi-packet reception capability at the receiver. Meanwhile, the nearby nodes would have less chance to access the channel and may even suffer starvation problem. During the CAP in each superframe, the transmission requests are also sent from the nodes that are active during the next CTAP. The number of received transmission requests has significant impact on the overall system throughput of mmWave indoor networks based on the hybrid multiple access of CSMA/CA and TDMA [22]. Thus, the proposed backoff mechanism needs to avoid starvation to nearby nodes if we give higher transmission priority to distant nodes.

We propose a novel backoff mechanism for CSMA/CA-based MAC with the following considerations. (i) Identify different scenarios for packet transmission failure and use different backoff strategies to deal with them in order to increase the number of successful packets. (ii) Try to avoid starvation problem in case there is large delay for the transmission requests of those flows operating in CTAP. In addition, the performance of response time would be improved by dealing with the starvation problem. (iii) The unique features of mmWave communication should be considered, for example, the mmWave signal strength is very sensitive to transmission distance due to its high propagation loss.

3.2. Proposed backoff mechanism

Initially, with neighbor discovery [23] and beamforming technologies [13], the wireless nodes register with the network controller and train their antenna array in the direction of the receiver to maximize the received signal power at the receiver. With the accurate localization service provided by the mmWave indoor system [24,25], the network controller has the valid network topology information. Considering that all the nodes are randomly distributed in a circular region, there are more nodes located in the distant area, thus, the transmission probability of distant nodes could have great impacts on the number of transmissions arriving at the receiver. To attain more transmission successes, the contention window size of distant nodes should be adjusted more moderately compared with nearby nodes. In addition, mmWave signal power degrades significantly over transmission distance and the received signal powers of all the transmissions determine whether a transmission is successful or not. Therefore, we use $d^{-\gamma}$ as the coefficient of the interval to adjust the contention window size. Specifically, the adjustment interval for node i after a transmission failure is $\lceil d_i^{-\gamma} W_w \rceil$, whereas the adjustment interval for node i after a transmission success is $\lceil d_i^{-\gamma} W_r \rceil$, where W_w and W_r denote the basic backoff intervals after a transmission failure and a transmission success, respectively. To give a higher transmission probability to the node with a transmission failure than that with a transmission success, we have $W_r > W_w$.

Both much higher transmission probability and lower transmission probability for distant nodes can result in system throughput reduction; therefore, we adjust the contention window after a transmission attempt according to the network congestion status. If the scenario in which transmission fails with no packet successfully received at the receiver occurs frequently, it is very likely that the transmission probability of distant nodes is much higher. Then we enlarge their contention window to reduce the transmission probability. Otherwise, the channel is captured by nearby nodes and we reduce the transmission probability of nearby nodes by increasing their contention window size while the transmission probability of distant nodes needs to be increased by reducing their contention window size.

During the k^{th} slot of the CAP period in the m^{th} superframe, the network controller receives a number of transmission packets and determines which transmission

Algorithm 1 Backoff Mechanism for CSAM/CA

```
BEGIN:
for slot k of CAP in m^th superframe do
    Several nodes send packets to network controller
    if Multiple packets arrive but no successful packets then
        Set f_a(k) = 1
        Update F_{k,m} = (sum_{l=k-T+1}^{k} f_a(l)) / T
        if F_{k,m} > F_thr then
            Update contention window W_i = W_i + ⌈d_i^{-γ} W_w⌉
        else
            Update contention window W_i = W_i - ⌈d_i^{-γ} W_w⌉
        end if
    else
        Set f_a(k) = 0
        if Transmission of node i is successful then
            Update contention window W_i = W_i + ⌈d_i^{-γ} W_r⌉
        else
            Update contention window W_i = W_i - ⌈d_i^{-γ} W_w⌉
        end if
    end if
    if W_i ≥ W_max then
        Update contention window W_i = W_max - ⌈d_i^{-γ} W_w⌉
    end if
    Update k = k + 1
    if No more slots in m^th CAP then
        FROZEN
        Until the CAP of next superframe
        Update m = m + 1
    end if
    Go to line 1
end for
END;
```

packets are captured, based on the SINR packet capture model in (4). Then it broadcasts a feedback packet to all the nodes in the network to indicate the transmission failures and transmission successes. We use packet capture failure frequency ($F_{k,m}$) to determine the contention window size. $F_{k,m}$ is defined as the number of time slots (during the previous T time slots from the current k^{th} time slot in the m^{th} superframe), in which there are transmissions arriving at the receiver but no packet is captured successfully, divided by T. $F_{k,m}$ is given as

$$F_{k,m} = \frac{\sum_{l=k-T+1}^{k} f_a(l)}{T} \tag{6}$$

where $f_a(l)$ is

$$f_a(l) = \begin{cases} 1, & M_T(l) > 1 \text{ and } M_R(l) = 0 \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

and $M_T(l)$ and $M_R(l)$ indicate the number of transmissions and successful receptions in the l^{th} time slot, respectively. If $F_{k,m}$ is larger than a specific threshold F_{thr}, the network becomes congested because of the higher transmission probability of distant nodes, thus the contention window of each transmission node i in the current time slot is increased by $\lceil d_i^{-\gamma} W_w \rceil$ to reduce transmission probability. Otherwise, the contention window of node i is increased by $\lceil d_i^{-\gamma} W_r \rceil$ following a transmission success and decreased by $\lceil d_i^{-\gamma} W_w \rceil$ after a transmission failure. The contention window size can be adjusted until it reaches the maximum value W_{max}. To deal with the starvation problem, when the contention window of node i is larger than or equal to W_{max}, it is set as $W_{max} - \lceil d_i^{-\gamma} W_w \rceil$ to increase its transmission probability. When all the transmissions are not successful at the receiver, although the contention window size is increased, it does not mean that the transmission probability after a transmission failure (p_w) is less than that after a transmission success (p_r). In this case, the transmission probability of distant nodes is much higher, thus, we reduce it moderately to achieve better system throughput. It is very likely that p_w is still larger than p_r after the contention window size is increased for the nodes with transmission failure.

As shown in Figure 3, the CAP is not continuous in different superframes. Therefore, the backoff status of each node is frozen at the end of each CAP and restarts at the beginning of the next CAP in the following superframe. The detailed procedure of the proposed backoff mechanism is described by the pseudocode in Algorithm 1.

4. SYSTEM THROUGHPUT ANALYSIS

In this section, we analyze the system throughput for indoor mmWave networks with multipacket reception capability. The packet capture model is based on the vulnerability circle capture model described earlier. The performance analysis of this section is to theoretically demonstrate that the transmission probability adjustment in the proposed backoff mechanism can significantly improve the system throughput, compared with traditional backoff mechanisms.

The transmission states of a wireless node can be described as the Markov state diagram shown in Figure 4. A node can be in two states: after success (AS) and after failure (AF). State transition may take place after a transmission attempt. A node moves into the AS (AF) state after a transmission success (failure). Because transitions take place after an attempt, a node does not change its state following an idle slot. A node in the AS state transmits with probability p_r at each slot, disregarding the status of the channel while the transmission probability is p_w for a node in the AF state. The values of p_r and p_w represent the size of contention window in the backoff mechanism. For example, a high value of p_r corresponds to maintaining a small contention window following a transmission success in the traditional backoff mechanisms as the one used

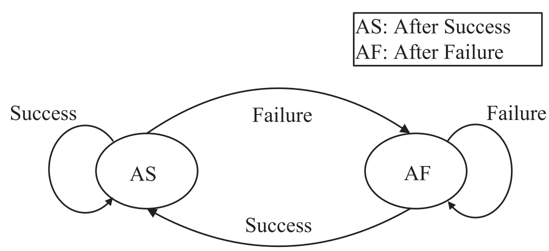

Figure 4. The state transition diagram.

in IEEE 802.11. Similarly, a low p_w value corresponds to maintaining a large contention window following a transmission failure. Therefore, traditional backoff mechanisms have a large value of p_r and a small value of p_w, which corresponds to the event the contention window is increased after a transmission failure and the contention window is reduced after a transmission success.

Generally, when a node transmits a packet, the loss probability due to collisions depends on other transmissions during that slot. However, in most work on the performance analysis, the loss probability of a packet transmitted by a node at distance d, defined as $PF(d)$, is assumed to be independent of the number of retransmissions suffered. The validity and accuracy of the assumption have been recently verified [26,27]. The state transition probability from state AS to state AF is $p_rPF(d)$. Similarly, the state transition probability from state AF to AS is $p_w(1 - PF(d))$. Hence, the transition probability matrix is given as

$$\mathbb{P} = \begin{bmatrix} 1 - p_rPF(d), & p_rPF(d) \\ p_w(1 - PF(d)), & 1 - p_w + p_wPF(d) \end{bmatrix} \quad (8)$$

With the transition probability matrix, steady-state probabilities of states AS (π_{AS}) and AF (π_{AF}) for a node at distance d can be obtained by solving the following equations:

$$\begin{cases} \pi_{AS} + \pi_{AF} = 1 \\ \overline{\pi}\mathbb{P} = \overline{\pi} \end{cases} \quad (9)$$

where $\overline{\pi} = \{\pi_{AS}, \pi_{AF}\}$. Then, we have

$$\begin{aligned} \pi_{AS} &= \frac{p_w(1 - PF(d))}{p_rPF_d + p_w(1 - PF(d))} \\ \pi_{AF} &= \frac{p_rPF(d)}{p_rPF_d + p_w(1 - PF(d))} \end{aligned} \quad (10)$$

The total transmission probability of a node at distance d is

$$\begin{aligned} p(d) &= \pi_{AS}p_r + \pi_{AF}p_w \\ &= \frac{p_rp_w}{p_w - p_wPF(d) + p_rPF(d)} \end{aligned} \quad (11)$$

According to the vulnerability circle capture model, for a receiver with single packet reception capability, a transmission from a node at distance d succeeds if there is no simultaneous transmission among the other $(n - 1)$ nodes within a disk with radius αd around the receiver, where n is the total number of transmission nodes in the network. For a receiver with multipacket reception capability M, a transmission of a node at distance d becomes successful if there is no simultaneous transmission among the $(n - \beta)(2 \le \beta \le M)$ nodes within a disk of radius ζd around the receiver; meanwhile, the β simultaneous transmissions are distributed around the circle with radius d. β is the number of simultaneous transmissions received successfully. The probability that all the $(n - \beta)$ nodes do not transmit packets within the disk of radius ζd is given as

$$\mathcal{P}' = \left[1 - \int_0^{\zeta d} p(y)f(y)dy\right]^{n-\beta} \quad (12)$$

where $f(d)$ is the probability density function of the distance from a node to the receiver, and $p(d)$ is the transmission probability of a node at distance d. To achieve successful reception of β packets simultaneously, the transmitting nodes of β packets need to be distributed around the circle of radius d. For example, the packet transmission of a node located within the disk of radius d/ζ can result in the transmission failure of a node at distance d according to the vulnerability circle capture model. To make the analysis tractable, it is assumed that the other $(\beta - 1)$ simultaneous transmitting nodes are distributed within the area between the circle of radius $d(1+\varepsilon)$ and the circle of radius $d(1 - \varepsilon)$. ε is a parameter determining the location area for the $(\beta - 1)$ transmitting nodes. Thus, the corresponding probability is

$$\mathcal{P}'' = \left[\int_{d(1-\varepsilon)}^{d(1+\varepsilon)} f(y)dy\right]^{\beta-1} \quad (13)$$

Therefore, the transmission failure probability for a node at distance d for multipacket reception case is

$$PF(d) = 1 - \binom{n-1}{\beta-1}\mathcal{P}'\mathcal{P}'' \quad (14)$$

Substituting (12) and (13) into (14), we have

$$\begin{aligned} PF(d) = 1 - \binom{n-1}{\beta-1} &\left[\int_{d(1-\varepsilon)}^{d(1+\varepsilon)} f(y)dy\right]^{\beta-1} \\ &\times \left[1 - \int_0^{\zeta d} p(y)f(y)dy\right]^{n-\beta} \end{aligned} \quad (15)$$

The throughput of a node at distance d from the receiver is

$$C(d) = p(d)(1 - PF(d)) \quad (16)$$

and the total system throughput is given as

$$\begin{aligned} C &= n\int_0^D C(y)f(y)dy \\ &= n\int_0^D f(y)p(y)(1 - PF(y))dy \end{aligned} \quad (17)$$

where D is the radius of the whole communication area. Given the probability density function $f(d)$, the transmission probability of a node at AS state p_r, and the transmission probability of a node at AF state p_w, we can obtain the system throughput C numerically. If all the nodes are uniformly distributed in the disk of radius D with the network

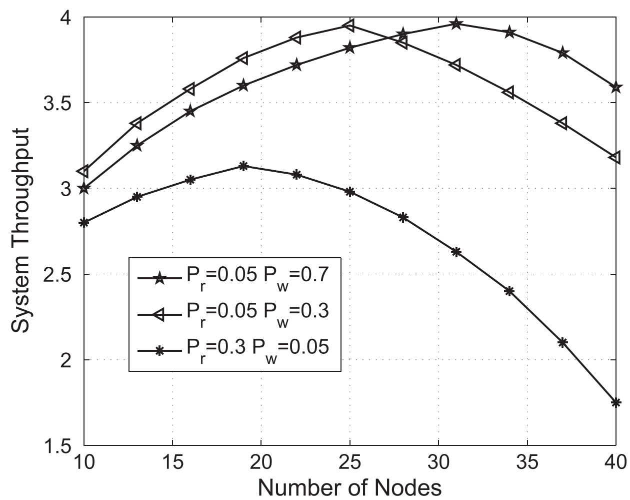

Figure 5. System throughput of different combinations of transmission probabilities.

controller in the center, we have

$$f(d) = \begin{cases} \frac{2d}{D^2}, & (0 < d \leq D) \\ 0, & \text{otherwise} \end{cases} \quad (18)$$

With multipacket reception capability for $M = \beta = 4$, Figure 5 shows the numerical results of system throughput for different combinations of p_r and p_w. In traditional CSMAC/CA, the transmission probability after transmission failure p_w is less than that after transmission success p_r, in order to reduce the transmission collision. In Figure 5, we show the system throughput for the cases of both $p_w < p_r$ and $p_w > p_r$. It can be seen that the network with multipacket reception capability can achieve much higher system throughput with the case of $p_w > p_r$, compared with the traditional case of $p_w < p_r$. Initially, the system throughput increases as more nodes transmit packets in the network and then it decreases because more collisions occur because of larger number of nodes involved in packet transmission. For the case of $p_w > p_r$, much larger p_w can result in fast degradation of system throughput.

In summary, the aforementioned analysis demonstrates that, in the case of multipacket reception, the system throughput can be improved by giving a higher transmission probability to the node after a transmission failure than that after a transmission success. Meanwhile, much higher transmission probability after transmission failure can also result in system throughput reduction. The aforementioned analysis theoretically verifies the performance of the proposed backoff mechanism.

5. PERFORMANCE EVALUATION

In this section, we describe the performance evaluation settings and present the simulation results for the proposed backoff mechanism compared with two other exponential backoff mechanisms.

We evaluate the performance of the proposed backoff mechanism in terms of system throughput, fairness, and power consumption in a typical mmWave indoor environment (i.e., large office space). The network controller is placed in the center of the room and all wireless nodes are randomly distributed in the circular region with a radius of 20 m. Each node is equipped with a directional antenna with a beamwidth of 60°, corresponding to six beams at each node. Each packet is one-slot long and the packet capture is based on SINR packet capture model with packet capture threshold ratio $h = 0.25$ (i.e., multipacket reception capability is 4). The signal propagation model is based on the free space Friis model with path loss exponent $\gamma = 2$. The reference distance is set to 1.5 m, which is also used to bound the adjustment interval because it is proportional to $1/d^{\gamma}$. The main parameters used in our simulations are listed in Table I.

We compare the proposed backoff mechanism with two other exponential backoff mechanisms, namely, traditional exponential backoff mechanism and alternative exponential backoff mechanism. In traditional exponential backoff mechanism, after every transmission failure, the contention window size is doubled while it is reduced half after a transmission success. The alternative exponential backoff mechanism doubles the contention window size after a transmission success and reduces the contention window by half following a transmission failure. We use the performance of traditional exponential backoff mechanism as the baseline for comparison. The alternative exponential backoff mechanism gives higher transmission probability after a transmission failure. However, its exponential backoff would give much higher transmission probability after transmission failure and results in congestions.

Figure 6 shows the normalized system throughput of the three backoff mechanisms as a function of the number of

Table I. Simulation parameters.

Parameters	Symbol	Value
System bandwidth	W	1200 MHz
Transmission power	P_T	0.1 mW
Background noise	N_0	−134 dBm/MHz
Reference distance	d_{ref}	1.5 m
Path loss at d_{ref}	PL_0	71.5 dB
Slot time	ΔT	10 μs
Beacon period	T_{BEA}	50 μs
Random access period	T_{RAP}	80 ms
Channel time allocation period	T_{CTAP}	500 ms
Maximum contention window	W_{max}	10 000
Basic success backoff interval	W_r	300
Basic failure backoff interval	W_w	200
Congestion threshold	F_{thr}	0.3
Congestion concern duration	T	20

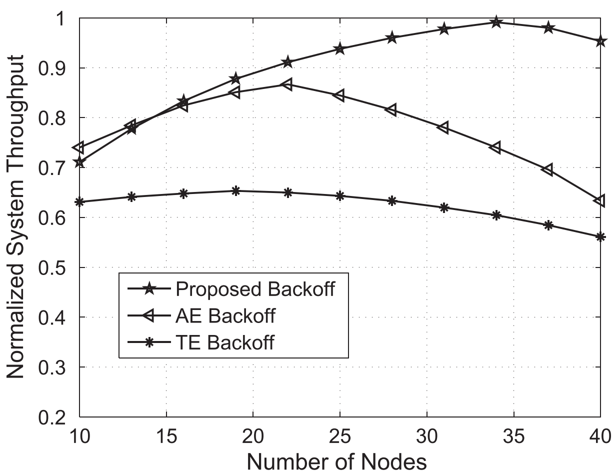

Figure 6. Normalized system throughput of three backoff mechanisms.

nodes in the network. The alternative exponential backoff mechanism and proposed backoff mechanism can achieve higher system throughput compared with traditional exponential backoff mechanism because it gives higher transmission probability after a transmission failure. As more nodes are involved in the network, the proposed backoff mechanism adjusts the contention window considering the network congestion status and thus achieves higher system throughput in comparison with the alternative exponential backoff mechanism.

Figure 7 shows the average throughput per node at different distances to indicate the fairness. We run the simulation 100 times with 30 nodes randomly distributed in the network. With the proposed backoff mechanism, the throughput of each node does not decrease much with the distance, whereas with traditional exponential backoff mechanism, the throughput of distant nodes is much less than that of nearby nodes. The proposed backoff mechanism considers both the network congestion status and the transmission status of each node to adjust the transmission probability and achieves better fairness. Although the achieved gain on the throughput of each node is not that much, the overall system throughput would be improved significantly because there are many nodes in the network.

Transmission failure probability is the probability that a transmission attempt experiences a failure. Note that a packet can suffer multiple transmission failures before it is successfully received. Figure 8 shows the transmission failure probabilities of the three backoff mechanisms. They have similar performance on transmission failure probability if there are not many nodes in the network. The alternative exponential backoff mechanism gives much higher transmission probability to distant nodes and more nodes are distributed in the distant area. Thus, there are many transmissions coming from distant area and the SINR of each cannot exceed the packet capture threshold ratio. As a result, the transmission failure probability of the alterna-

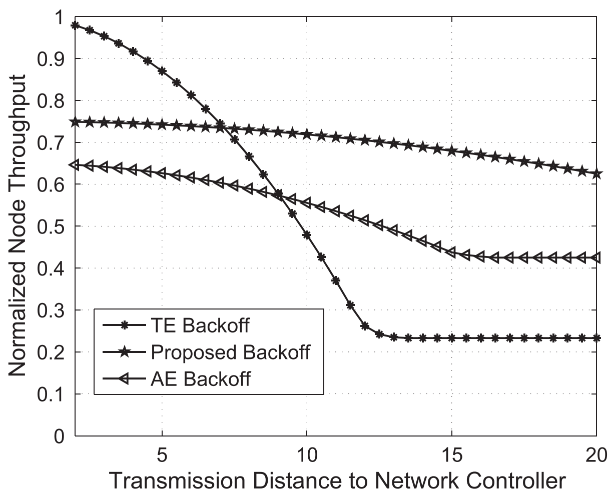

Figure 7. Average node throughput with different distance for fairness.

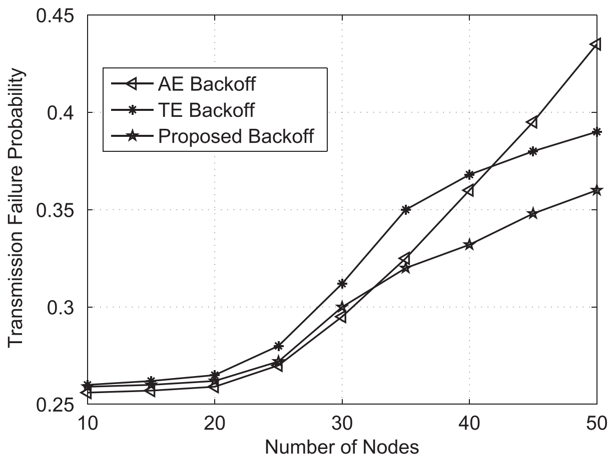

Figure 8. Transmission failure probability.

tive exponential backoff mechanism increases rapidly with the increased number of nodes. Although the transmission failure probability of the alternative exponential backoff mechanism exceeds that of the others for a dense network, the network throughput of it is still more than that of the traditional exponential backoff mechanism because there are more transmission attempts with the alternative exponential backoff mechanism due to its higher transmission probability for distant nodes.

The normalized average packet delays of the three mechanisms are shown in Figure 9. The packet delay is defined as the time duration from the time the packet is transmitted to the time the packet is received successfully. As the number of nodes increases, the network becomes more congested and the packet delay increases. The proposed backoff mechanism has shorter packet delay corresponding to less congestions in the network.

We then compare the energy consumption of the proposed backoff mechanism with that of the other two exponential backoff mechanisms. For fair comparison, we use the total transmission energy (consumed by both successful and unsuccessful packets) divided by the total number of successful packets to obtain the energy consumption per successful packet. From Figure 10, we can see that our proposed backoff mechanism is more energy efficient than the other two exponential backoff mechanisms. By adjusting the contention window, the proposed backoff mechanism can reduce the number of transmission failures (energy waste) and make the receiver accept more packets.

The proposed backoff mechanism can achieve better performance on system throughput, fairness, average packet delay, and energy consumption. Meanwhile, it introduces communication overheads and computational overheads

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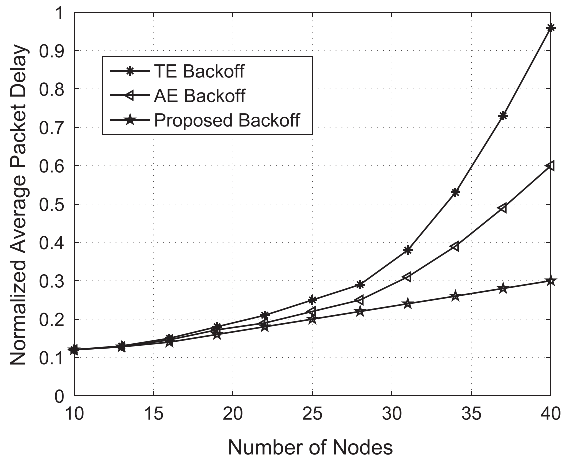

Figure 9. Average packet delay.

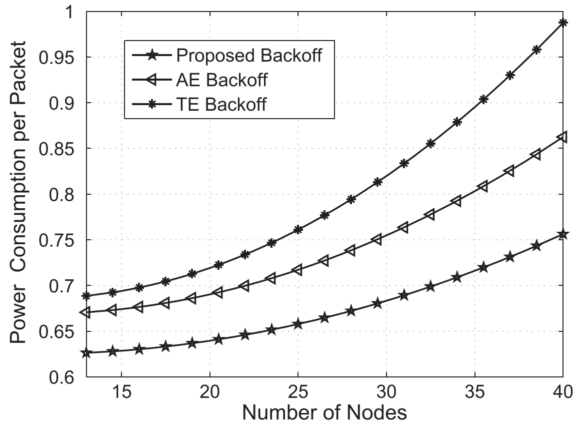

Figure 10. Normalized power consumption per packet.

as indicated in the proposed mechanism. The main communication overheads are the feedback packets from the network controller to other nodes in the network. However, in traditional backoff mechanisms in CSMA/CA, there are still ACK packets from the receiver to confirm the packet reception success. In the proposed backoff mechanism, the nodes need to compute packet capture failure frequency ($F_{k,m}$) and compare it with the threshold. It is a simple computation and does not consume much computational power. Therefore, the proposed backoff mechanism can significantly improve the network performance with limited extra cost.

6. RELATED WORKS

A wide range of MAC layer protocols and algorithms have been proposed for mmWave indoor networks [1,2,5,12,13,16,22,28–31]. One line of research focuses on transmission scheduling for TDMA-based MAC period to improve the system throughput [2,5,12,16,22,29,30]. The high propagation loss and the utilization of directional antenna result in relatively low multi-user interference, so that concurrent transmissions can be supported to exploit the spatial reuse [2,12,16,29,30]. In [2], a multi-hop concurrent transmission scheduling scheme is proposed to allow non-interfering transmission links to operate simultaneously over mmWave channels. To further improve the spatial reuse, spatial-time division multiple access-based concurrent transmission scheduling schemes are proposed to allow both non-interfering and interfering links to transmit concurrently either to achieve suboptimal system throughput [5] or to make the accumulated interference in each time slot below a specific threshold [30]. In [12,32], an exclusive region (ER)-based resource management scheme is proposed to exploit the spatial reuse of mmWave WPANs with directional antenna, and the optimal ER sizes are analytically derived.

Another line of research on mmWave MAC considers the mutual impact on system throughput of both

CSMA/CA-based MAC period and TDMA-based MAC period. A long period of CSMA/CA will cause a low data transmission time in TDMA period, whereas a short length of access time of CSMA/CA will cause a large number of data transmission collisions in CSMA/CA. In [22], system throughput is optimized by adjusting the access periods of CSMA/CA and TDMA without considering concurrent transmissions.

To the best of our knowledge, there are few works addressing the CSMA/CA-based MAC period for mmWave indoor networks. Most of existing works on mmWave MAC focus on TDMA-based MAC period which is mainly for bandwidth-intensive multimedia applications. Burst type of applications such as web browsing may not require bandwidth guarantees and uses CSMA/CA mechanism to access the channel. To apply applications within much shorter CSMA/CA access period compared with TDMA access period, it is important to improve the network capacity. Multipacket reception is implemented in wireless networks to significantly improve network capacity [19,33,34]. In [33], the proposed MAC protocol adaptively grants access to the MPR channel to several users to maximize the expected number of successfully received packets in each slot. The system throughput of networks with multipacket reception capability is analyzed in [19] considering spatially distributed nodes. [34] proposes a physical layer multipacket reception technique and the corresponding MAC layer which closely follows the IEEE 802.11 distributed coordination function scheme. In this paper, we propose a new backoff mechanism for CSMA/CA-based MAC for wideband mmWave indoor networks with multipacket reception capability, considering the high propagation loss resulting significant system throughput reduction.

7. CONCLUSION

In this paper, we have proposed a backoff mechanism for CSMA/CA-based MAC for mmWave indoor networks with multipacket reception capability. Generally, the proposed backoff mechanism gives higher transmission probability to distant nodes to take the advantage of multipacket reception capability at the receiver. The transmission probability can be adjusted by changing the contention window size according to the node's transmission status (failure or success) and network congestion status. With the proposed backoff mechanism, the mmWave indoor networks can achieve higher system throughput and better fairness.

To the best of our knowledge, this work is one of the first attempts to design CSMA/CA-based MAC for mmWave networks with multipacket reception capability, considering the severe signal power degradation over distance in mmWave band. Because different parameter settings can impact the system performance, we intend to develop mechanisms selecting appropriate parameter values to achieve optimal system performance, for example, system throughput. Moreover, mmWave links are highly susceptible to blockage because of the limited ability to diffract around obstacles such as moving people and furniture in indoor environment. Therefore, designing efficient CSMA/CA-based MAC for multi-hop scenario is an interesting and challenging problem in mmWave indoor networks.

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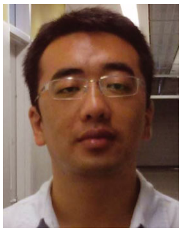
AUTHORS' BIOGRAPHIES



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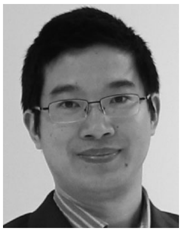

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