Performance Analysis of IEEE 802.11ad MAC Protocol

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Abstract—IEEE 802.11ad specifies a hybrid medium access control (MAC) protocol consisting of contention as well as non-contention-based channel access mechanisms. It also employs directional antennas to compensate for the high free-space path loss observed in 60 GHz frequency band. Therefore, it significantly differs from other IEEE 802.11(b/g/n/ac) MAC protocols and thus requires new methods to analyze its performance. We propose a new analytical model for performance analysis of IEEE 802.11ad employing a 3-D Markov chain considering all the features of IEEE 802.11ad medium access mechanisms including the presence of non-contention access and the different number of sectors due to the use of directional antennas. We show that the number of sectors has a high impact on the network throughput. We show that the MAC packet delay is significantly affected by the duration of the contention period. Our results indicate that a suitable choice of the number of sectors and contention period can improve the channel utilization and MAC delay performance.

Index Terms—5G, millimeter wave, IEEE 802.11ad, 60 GHz MAC.

I. INTRODUCTION

Due to the availability of large bandwidth, millimeter wave (mmWave) frequency bands (30 GHz to 300 GHz) have become key enablers for the multi-Gb/s connectivity envisaged under 5G visions. The high free-space path loss and limited ability to diffract around obstacles require high-gain and steerable directional antennas at mmWave frequencies, which significantly impacts the design of medium access control (MAC) mechanisms [1]. The IEEE 802.15.3c for Wireless Personal Area Networks (WPANs) [2] and IEEE 802.11ad for Wireless Local Area Networks (WLANs) [3] have proposed hybrid MAC protocols operating in 60 GHz bands. These hybrid MAC protocols employ carrier sense multiple access with collision avoidance (CSMA/CA) and time division multiple access (TDMA) for channel access.

Compared with the IEEE 802.11b/g/n/ac Distributed Coordination Function (DCF), the IEEE 802.11ad DCF has significantly distinct features due to the use of directional antennas and a hybrid access mechanism. Firstly, all the wireless stations (STAs) cannot simultaneously listen to- and hear from—the Access Point (AP) due to the directional communication. Hence the area around an AP is divided into several sectors, and STAs in a sector can compete for the channel only during the allocated time for that particular sector. Secondly, the CSMA/CA operation in a sector is suspended when either the TDMA based channel access is instantaneous or when the AP is busy facilitating CSMA/CA in other sectors. Lastly, when CSMA/CA operation is suspended, backoff counter of all the involved STAs is frozen and in the next round STAs resume the backoff process with the frozen values of backoff counters. Owing to these important differences, a thorough modeling framework of the IEEE 802.11ad MAC is needed that can take the above aspects into account.

The seminal work of Bianchi [4] on the modeling of the IEEE 802.11 DCF employing Markov chains has been widely used for modeling the CSMA/CA based MAC protocols. There are several modified versions of Bianchi’s model considering various factors such as finite retransmission limit [5] and differentiated quality-of-service [6]. However, these models are not directly applicable in case of the IEEE 802.11ad MAC due to its special features. In [7], Physical (PHY) layer performance analysis of IEEE 802.11ad considering different modulation and coding schemes (MCS) is studied without considering the impact of channel access schemes. [8], [9] have attempted to build a modeling framework for the IEEE 802.11ad MAC protocol. However, the presence of non-contention channel access is not taken into account in [8]. Although, Hemanth et al, [9] have considered the non-contention part of the IEEE 802.ad MAC protocol, the functioning of the IEEE 802.11ad DCF is misconstrued. It is assumed that after the end of every contention period, STAs refresh their backoff counters when the next contention period starts. On the contrary, this is not the case with the IEEE 802.11ad protocol, since STAs resume their backoff counters across the multiple CSMA/CA periods. In this letter, we propose a three-dimensional Markov chain to model the IEEE 802.11ad MAC protocol which allows us to accommodate the attributes associated with the hybrid access mechanism and the use of directional antennas. Our main contributions are: (i) deriving accurate analytical expression for the channel utilization in time shared CSMA/CA; (ii) deriving average MAC packet delay; (iii) understanding the effects of number of sectors on channel utilization; and (iv) finding the impact of contention period on the average MAC delay.

II. IEEE 802.11ad SYSTEM MODEL

A model of an IEEE 802.11ad Personal Basic Service Set (PBSS) formed by the 60 GHz STAs where one acts as PBSS Control Point/Access Point (PCP/AP) is shown in Fig. 1. Fig. 2 depicts channel access in an IEEE 802.11ad beacon interval (BI) consisting of: (i) beacon transmission interval (BTI); (ii) association beamforming training (A-BFT); (iii) announcement time interval (ATI) used to exchange the management information; and (iv) data transfer interval (DTI), consisting of contention-based access periods (CBAPs) and service periods (SPs) employing CSMA/CA and TDMA.

During the CBAP, STAs in each sector access the medium in a round-robin fashion. STAs use RTS-CTS mechanism and listen in the quasi-omni (QO) mode employing wide
beamwidths. The RTS and CTS frames are transmitted using QO beamwidths hence the hidden terminal problem can be neglected. Let $m$ be the maximum retry limit and $W_0$ be the minimum contention window size. Then considering the random binary exponential backoff process, the window size at the $i^{th}$ retransmission stage is $W_i = 2^i W_0 - 1$. After $m$ maximum transmission attempts the packet is dropped. The detailed description of the transmission procedure can be found in [3].

Let us assume that $n$ STAs are deployed in $Q$ sectors around the PCP/AP. We assume uniformly distributed STAs to keep our analysis simple. Let the $k^{th}$ sector having a beamwidth of $\Omega_k$ have $n_k$ STAs where $\sum_{k=1}^{Q} \Omega_k = 2\pi$ and $\sum_{k=1}^{Q} n_k = n$. Let $t_k$ and $p_k$ be the transmission and collision probabilities of a packet in the $k^{th}$ sector, respectively. $p_k$ is also known as the conditional collision probability under steady state which is independent of the number of retransmission attempts in a sector. For brevity, henceforth, we will represent $t_k$ and $p_k$ by $\tau$ and $p$, respectively. Note that each sector can have different $\tau$ and $p$ if they have a different number of STAs. Using the above definitions under saturation condition, we have,

$$p = 1 - (1 - \tau)^{n_k}.$$  \hspace{1cm} (1)

III. 3-D MARKOV CHAIN MODEL FOR PACKET TRANSMISSION

We define a three dimensional Markov chain as shown in Fig. 3 where each state is represented by the triplet $(s(t), b(t), h(t))$. Here, $s(t)$ represents the backoff stage $i$, $i \in [0, m]$ and $b(t)$ represents the residual backoff time counter $j$, $j \in [0, W_i - 1]$. To differentiate between contention and non-contention part of BI, we define $h(t)$,

$$h(t) = \begin{cases} 
0, & \text{if packet is part of an ongoing CBAP} \\
-1, & \text{otherwise} \end{cases} \hspace{1cm} (2)$$

A. Transition Probabilities

Let $N^{BI}$ and $N^{CBAP}$ be the lengths of BI and CBAP, respectively. Let the $k^{th}$ sector have a CBAP length of $N_k^{CBAP}$ ($\sum_{k=1}^{Q} N_k^{CBAP} = N^{CBAP}$). Let $N^*$ be the time required to successfully transmit a data frame. The time durations used here are measured in unit of slot time $\sigma$. According to the IEEE 802.11ad MAC protocol, when $j \in [2, W_i - 1]$, STAs jump to non-contention state if CBAP time counter reaches zero. However, when $j = 1$ STAs have to avert the packet transmission and jump to non-contention state even if the allocated CBAP duration is not yet finished but the CBAP counter has reached a value lower than the total required time to transmit a packet. Hence, the transition probabilities of going from contention to non-contention states are given by,

$$P[i, j, -1|i, j, 0] = \begin{cases} 
0, & j \in [2, W_i - 1], i \in [0, m] \\
p_H, & j = 1, i \in [0, m] \end{cases} \hspace{1cm} (3)$$

For the STAs in the $k^{th}$ sector we have $p_H = \frac{1}{N^{CBAP}}$ and $p_H' = \frac{N_k^{CBAP}}{N^{CBAP}}$. Let $p_r$ be the probability of transition from a non-contention state to a contention state and $p_f$ be the transition probability of staying in a non-contention state, then,

$$P[i, j, 0|i, j, -1] = p_r; \hspace{0.5cm} j \in [1, W_i - 1], i \in [0, m], (4a)$$

$$P[i, j, -1|i, j, -1] = p_f; \hspace{0.5cm} j \in [1, W_i - 1], i \in [0, m], (4b)$$

where, $p_r = \frac{N_k^{CBAP}}{N^{CBAP}}$ and $p_f = 1 - p_r$. Let $p_b$ be the state transition probability of channel being busy during the contention period, then,

$$P[i, j, 0|i, j, 0] = p_b; \hspace{0.5cm} j \in [1, W_i - 1], i \in [0, m]. \hspace{1cm} (5)$$

An STA observes a busy channel when at least one STA among the remaining $n_k - 1$ STAs occupies the channel. Hence $p_b$, i.e., probability of not decreasing the backoff counter during CBAP period, is calculated as, $p_b = 1 - (1 - \tau)^{n_k-1}$. The state transitions probabilities of a successful transmission and collision are,

$$P[0, j, 0|i, 0, 0] = (1 - p)/W_0; \hspace{1cm} j \in [0, W_i - 1], i \in [0, m]. \hspace{1cm} (6a)$$

$$P[i, j, 0|i, j, 0] = p/W_i; \hspace{0.5cm} j \in [0, W_i - 1], i \in [0, m]. \hspace{1cm} (6b)$$

The state transition probability due to decrementing the backoff counter is given by,

$$P[i, j, -1|i, j, 0] = \begin{cases} 
1 - p_b - p_H; & j \in [2, W_i - 1], i \in [0, m] \\
1 - p_b - p_H'; & j = 1, i \in [0, m] \end{cases} \hspace{1cm} (7)$$
\[ b_{0,0,0} = \frac{1}{\left(1 + \frac{W_0^{-1}}{W_0} \left(\eta' + \eta W_0^{-2} \right) \left(1 - p^{m+1} \right) + \frac{p^{1-p} m}{1-p} \left(1 + \eta' - \frac{3}{2} \eta \right) + \frac{p}{2 W_0^{1-2} \eta} \left(\eta - \eta'\right) + \eta p W_0^{-1} \left(1-p^{m}\right) \right)} \]  

(11)

**B. Steady State Probabilities**

For \(i \in [1, m]\), from Fig.3 we obtain,

\[ b_{i,j,0} = \frac{p(W_i - j)b_{i-1,0,0}}{(1 - p_b - p_H)W_i}; \quad i \in [1, m], \quad j \in [2, W_i - 1]. \]  

(7a)

\[ b_{i,1,0} = \frac{p(W_i - 1)}{(1 - p_b - p_H)W_i}b_{i-1,0,0}; \quad i \in [1, m], \quad j = 1. \]  

(7b)

\[ b_{i,0,0} = p^ib_{0,0,0}; \quad i \in [1, m]. \]  

(8)

Relationship amongst steady state probabilities for \(i = 0\),

\[ b_{0,j,0} = \frac{(1-p)(W_0 - j)}{(1 - p_b - p_H)W_0} \sum_{i=0}^{m} b_{i,0,0}; \quad j \in [2, W_0 - 1]. \]  

(9a)

\[ b_{0,1,0} = \frac{1-p}{1 - p_b - p_H}W_0 - 1 \sum_{i=0}^{m} b_{i,0,0}; \quad j = 1. \]  

(9b)

The sum of the steady state probabilities should be 1, hence,

\[ \sum_{j=0}^{m} \sum_{k=1}^{m} b_{i,j,k} = 1. \]  

(10)

Expanding (10) and using (7)–(9), we obtain (11), as shown at the top of this page, where,

\[ \eta' = \left(1 + \frac{p}{1-p}\right) \frac{1}{1-p_b-p_H} \]

\[ \eta = \left(1 + \frac{p}{1-p}\right) \frac{1}{1-p_b-p_H}. \]

From Fig. 3, transmission probability \(\tau\) is the sum of the steady state probabilities of being in the head-of-line states,

\[ \tau = \sum_{i=0}^{m} b_{i,0,0} = \frac{1-p^{m+1}}{1-p} b_{0,0,0}. \]  

(12)

where, \(b_{0,0,0}\) is given by (11). Given this relation, (1) and (12) can be solved for \(p\) and \(\tau\).

**C. Channel Utilization**

During the contention process, the probability of a slot being idle, having a successful transmission or a collision, can be expressed as \(P_{\text{idle}} = (1 - \tau)\nu_{\text{idle}}, P_{\text{success}} = n_k \tau (1 - \tau)\nu_{\text{idle}} - 1\), and \(P_{\text{col}} = 1 - P_{\text{idle}} - P_{\text{success}}\), respectively. Let \(T_{\text{idle}} = \sigma\), \(T_{\text{success}}\) and \(T_{\text{col}}\) be the duration of an idle time slot, a successful transmission and a failed transmission, respectively. Then the channel utilization or the normalized throughput \(U_k\) of the \(k\)th sector, which is defined as the fraction of the total allocated CBAP time \((N_{CBAP}^k)\) the channel is used in that sector for the successful packet transmissions. It is expressed as,

\[ U_k = \frac{P_{\text{success}}E[P]}{P_{\text{idle}}T_{\text{idle}} + P_{\text{success}}T_{\text{success}} + P_{\text{col}}T_{\text{col}}}, \]  

where \(E[P]\) is the average duration of a payload packet and \(T_{\text{idle}}\) is duration of one slot. Here, \(T_{\text{success}} = T_{\text{RTS}} + 2\text{SIFS} + T_{\text{CTS}} + \text{DIFS} + T_{\text{data}} + T_{\text{ACK}}\) and \(T_{\text{col}} = T_{\text{RTS}} + \text{SIFS} + \text{DIFS} + \text{RIFS}\), where \(T_{\text{RTS}}\) and \(T_{\text{CTS}}\) are the durations of the RTS and CTS frames, respectively. DIFS is the Distributed Backoff Inter-Frame Space and RIFS is the Retransmission Inter-Frame Space. We have neglected the sector switching time (it is around 3 to 18 ms), because it is negligible compared to the allocated CBAP time (which would be at least few ms duration) for a given sector. Since the sector-wise medium access during CBAP is carried in a round-robin fashion, the average channel utilization during whole CBAP period (considering all the sectors) is given by

\[ U = \frac{1}{NCBAP} \sum_{k=1}^{Q} U_k N_{CBAP}^k. \]

**D. MAC Delay Analysis**

MAC delay \(E[D]\) is the expected time between the arrival of a packet at the MAC layer until it is successfully transmitted. The probability that a packet is discarded after \(m\) backoff stages is given by \(p^{m+1}\). Thus the probability of a successful transmission in the \(i\)th backoff stage is expressed as \(P(TX = i(\text{success}) = \left(1-p\right)^{i-1}\). Note that the first transmission attempt corresponds to the 0th backoff stage. Let \(E[D_i]\) be the average delay encountered by a packet before successfully transmitted in \(i\)th backoff stage, then the average MAC delay, \(E[D]\), is,

\[ E[D] = \sum_{i=0}^{m} P(TX = i(\text{success})E[D_i]. \]

Here, \(E[D_i]\) consists of: (i) the delay accumulated during \(i\) collisions, (ii) the time taken by successful transmission in \(i\)th backoff stage, and (iii) the backoff process delay corresponding to the total \(i + 1\) backoffs (including the 0th backoff). The backoff process delay is composed of average delay incurred when the medium is busy because of other transmissions, backoff counter decrement during idle channel conditions, and delay caused due to the STA being in non-contention period. Thus, \(E[D_i]\) can be expressed as,

\[ E[D_i] = iT_{\text{col}} + T_{\text{success}} + \sum_{z=0}^{\nu_{\text{idle}} - 1} \frac{w_z - 1}{2} \sigma_{\text{avg}}, \]  

(15)

where \(\sigma_{\text{avg}}\) is one-step state transition period and can be calculated as \(\sigma_{\text{avg}} = (1 - p_H)(p_{\text{idle}}^\sigma + p_{\text{success}}^\sigma T_{\text{success}} + p_{\text{col}}^\sigma T_{\text{col}}) + p_H(N_{CBAP}^k - N_{CBAP}^k)\). Here \(p_{\text{idle}}^\sigma = (1 - \tau)\nu_{\text{idle}} - 1\), \(p_{\text{success}}^\sigma = (n_k - 1)\tau (1 - \tau)\nu_{\text{idle}} - 2\) and \(p_{\text{col}}^\sigma = 1 - p_{\text{idle}}^\sigma - p_{\text{success}}^\sigma\) represent the probability of channel being observed idle, busy with a successful transmission, and busy due to collision.

**IV. NUMERICAL RESULTS**

Fig. 4 shows the simulation (S) and analytical (A) results for the throughput and delay performance. We built a discrete event simulator in MATLAB using the IEEE 802.11ad specifications. We assumed an ideal flat-top directional antenna with main lobe gain \((G = \frac{1}{\pi r^2})\) without any side lobes. The IEEE 802.11ad Control PHY is used to transmit the RTS, CTS and ACK frames, while MCS4 with datarate of 2 Gb/s is used to
better throughput. Hence, intelligently determining the sector beamwidth will ensure better utilization of the channel.

To assess the impact of CBAP duration, we normalized CBAP with respect to BI duration \( \left( \frac{\text{NCBAP}}{N} \right) \). It can be seen that the throughput is unaffected with respect to CBAP. This is because it mainly depends on \( n, W_0 \) and \( m \). The amount of time when STAs are out of CBAP is not considered to calculate the throughput since during that time either STAs in other sectors would contend for the channel or the TDMA based access is provided. On the other hand, CBAP has a significant impact on the delay experienced by a packet as can be seen in Fig. 4(d). We can see that for CBAP value of 0.40, average packet delay is significantly higher compared with the CBAP value of 1. This is because in the former case if allocated CBAP period expires before a packet is transmitted the packet has to wait until the next round of CBAP to access the medium. Therefore selection of the duration of contention part of BI would play an important role in determining the channel access delay.

V. CONCLUSION

The analytical models developed for IEEE 802.11b/g/n/ac MAC protocol cannot be directly applied to the IEEE 802.11ad due to the use of directional antennas and hybrid access periods. Thus we presented here a thorough IEEE 802.11ad MAC protocol model using a three-dimensional Markov chain. We analyzed the dependencies on contention period and the number of sectors on the MAC delay and throughput. It is shown that the number of sectors has a significant impact on the channel utilization. For example, using four sectors resulted in up to 30-50% improvement in the channel utilization while the total number of STAs varies from 30 to 50. We have also shown that the average MAC delay is doubled when the CBAP is reduced to 40% from 100% of total BI duration with 50 contending STAs.

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