Enhance the Edge with Beamforming: Performance Analysis of Beamforming-Enabled WLAN

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***Abstract*—The ultra-dense edge networks with mmWave and beamforming are envisioned as a potential solution to satisfy the high rate and capacity requirements in 5G networks. In IEEE 802.11 ad, which is the first beamforming-enabled WLAN standard, all stations (STs) contend for beamforming (BF) training opportunities in associated beamforming training (A-BFT) slots. However, due to limited number of A-BFT slots, BF training suffers from a severe collision issue, especially in dense networks, which results in a low channel utilization in the A-BFT stage. To achieve the maximum channel utilization, it is of significance to allocate A-BFT slots efficiently. Therefore, in this paper, we propose an analytical model to analyze IEEE 802.11 ad medium access control (MAC) protocol in BF training stage. In particular, we analyze the successful transmission probability and channel utilization of IEEE 802.11 ad MAC protocol in the dense network. Based on theoretical analysis, we provide the optimal number of A-BFT slots. In addition, theoretical analysis indicates that the maximum channel utilization in the A-BFT stage is barely e^{-1} which is the same as that of slotted ALOHA protocol. Simulation results are provided to validate the accuracy of the analytical model and theoretical analysis.**

I. Introduction

The foreseeable future is expected to witness the exponentially increase in both wireless data traffic and computation requirements due to emerging data-hungry and computation-intensive applications, such as the high definition video transmission, cordless virtual reality (VR) gaming, self-driving, industrial Internet of things (IoT), etc [1]. To satisfy the requirements of high data rate, massive connectivity and intensive computation, in 5G networks, the mobile edge network has been proposed, which is featured by edge computing, caching, and network densification [2]. As one potential technology to enhance the data rate in ultra-dense networks, millimeter wave (mmWave) WLAN can offer a fiber-like wireless transmission for short range communications, by exploiting multi-GHz unlicensed bandwidth [3], [4]. The success of mmWave WLAN has fueled IEEE 802.11 ad, which is the first ratified standard operating in the unlicensed 60 GHz band and can provide a data rate up to 6.75 Gbit/s [5].

To compensate high free-space path loss in the mmWave band, beamforming (BF) is widely considered as a pivotal role in establishing reliable communication links [6], [7]. Beamforming, which is a narrow beam, focuses radio frequency (RF) power towards a narrow direction to provide a signal-to-noise (SNR) gain. To achieve this SNR gain, the transmitter and receiver must perform BF training to align their beams before data transmission [8]. Without well-aligned beams, data rate decreases significantly in mmWave systems.

As standardized in IEEE 802.11 ad, all stations (STs) have to perform BF training with an access point (AP) in the associated beamforming training (A-BFT) stage before data transmission. IEEE 802.11 ad defines a contention-based BF training protocol that all STs contend for BF training opportunities in A-BFT slots. One A-BFT slot only provides BF training opportunity for one ST. However, IEEE 802.11 ad can only support at most 8 A-BFT slots [5]. Hence, this contention-based BF training protocol can suffer from high collision probability, especially in the dense network, which renders low channel utilization in the A-BFT stage. Intuitively, increasing the number of A-BFT slots is one of the possible solutions to alleviate the collision probability and improve channel utilization. However, improper increasing A-BFT slots can result in low utilization of A-BFT slots and increases the overhead of BF training stage. Thus, it is crucially to study how to efficiently allocate A-BFT slots in the dense network is a key problem.

Performance analysis plays a vital role for improving the efficiency of IEEE 802.11 ad. Recently, several works analyze the medium access control (MAC) protocol in IEEE 802.11 ad in the data transmission stage. Hemanth *et al.* in [9] proposed an analytical model to analyze hybrid MAC in IEEE 802.11 ad. Considering the effect of number of sectors in directional transmission, the performance of IEEE 802.11 ad MAC is analyzed in [10]. A directional cooperative MAC protocol which is compatible with IEEE 802.11 ad is proposed and analyzed in [11]. However, few work analyzes the performance of IEEE 802.11 ad MAC protocol in the BF training stage, which has a great impact on the overall performance. Due to the directional propagation characteristics of mmWave systems, IEEE 802.11 ad defines a new MAC protocol in the BF training stage. This MAC protocol is totally different from traditional carrier-sense multiple access (CSMA) mechanism in current WLAN systems. Thus, analytical model of previous WLAN systems is not suitable for IEEE 802.11 ad and a new analytical model is needed.

In this paper, we make following contributions:

- We propose an analytical model to analyze the performance of IEEE 802.11 ad MAC protocol in the BF training stage. Based on the proposed model, theoretical analysis obtains the successful transmission probability in the dense network. To the best of our knowledge, this

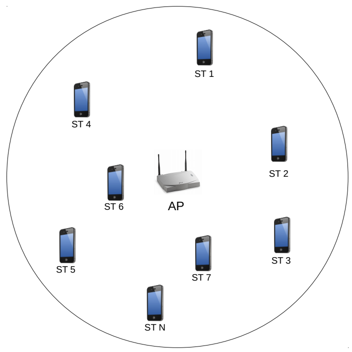

Fig. 1. Dense network model.

work is the first to analyze the performance of IEEE 802.11 ad MAC protocol in the A-BFT stage.

- To achieve the maximum channel utilization in the A-BFT stage, the optimal allocation of A-BFT slots is provided.
- Theoretical analysis shows that the maximum channel utilization in the A-BFT stage is only e^{-1} which is the same as that of slotted ALOHA protocol.

The remainder of this paper is organized as follows. We first present the system model in Section II. Analytical model and corresponding performance analysis are given in Section IV. In Section IV, simulation results are presented to validate the proposed analytical model. In Section V, concluding remarks are given.

II. System Model

In this section, the network model and IEEE 802.11 ad MAC protocol in the BF training stage are presented, respectively.

A. Network Model

Consider a dense network with an AP and N STs, as shown in Fig. 1. Directional multi-gigabit (DMG) mode is adopted in this paper, i.e., each ST has multiple antennas and can form several sectors for directional transmission and receiving. The downlink traffic from AP to STs is considered and all STs should establish communication links with AP before data transmission.

B. BF Training in IEEE 802.11 ad

To establish reliable mmWave communication links, all STs should perform BF training with AP. In the sequel, BF training procedure is presented.

As shown in Fig. 2, the beacon interval (BI) is the basic time frame of IEEE 802.11 ad. For the DMG mode, a BI consists of beacon transmission interval (BTI), A-BFT, announcement transmission intervals (ATI) and data transfer interval (DTI). The DTI includes multiple service periods (SPs) and contention-based access periods (CBAPs). Specifically, BF training should be performed in the A-BFT stage [5]. A-BFT stage is divided into multiple A-BFT slots to perform BF training for different STs.

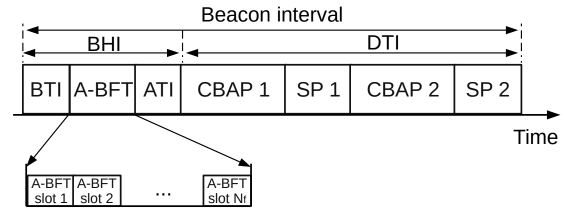

Fig. 2. Beacon interval structure in IEEE 802.11 ad.

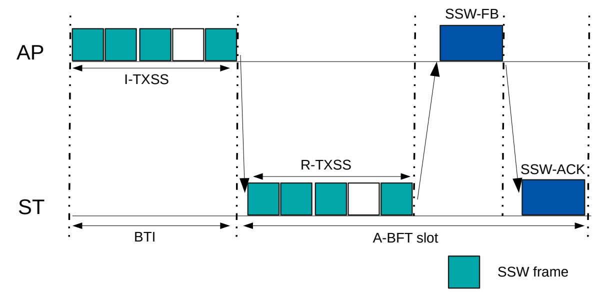

Fig. 3. An example of sector level sweep.

Beamforming training consists of three stages, namely sector level sweep (SLS), beam refinement protocol (BRP) and beam tracking (BT). In this paper, we focus on BF training in SLS stage. As shown in Fig. 3, SLS includes initiator transmitter sector sweep (I-TXSS), responder transmitter sector sweep (R-TXSS) and sector sweep feed (SSW-FB) and sector sweep acknowledgment (SSW-ACK). First, AP transmits multiple sector sweep (SSW) frames via different sectors in I-TXSS stage and ST identifies the best transmit sector via received signal strength. Similarly, ST transmits multiple SSW frames in the R-TXSS stage to obtain the best receive sector. Then, AP and ST exchange information via SSW-FB and SSW-ACK frames. Only one ST can perform BF training with AP in one A-BFT slot. But, at most 8 A-BFT slots can be allocated in the A-BFT stage according to IEEE 802.11 ad. Hence, all STs contend for limited A-BFT slots via the IEEE 802.11 ad MAC protocol.

C. MAC Protocol in BF Training Stage

IEEE 802.11 ad MAC protocol consists of two stages [5].

- Contention-based BF training stage: STs contend for BF training with AP in the A-BFT stage through sending R-TXSS frames. The number of A-BFT slots N_f is determined and broadcast by AP in the BI control frame. As the example shown in Fig. 4, at the beginning of the A-BFT stage, each ST selects a random A-BFT slot from a uniform distribution $[0, ..., N_f - 1]$ to transmit R-TXSS frames. A SSW-FB frame is fed back from AP if the transmission is successful. In this paper, we consider transmission is always successful unless there is a collision. Thus, when more than one STs select the same A-BFT slot, no SSW-FB frame would be fed back from AP, and the BF training is failed.
- Frozen stage: After N_c consecutive collisions, the ST enters the frozen stage and freezes from transmission in the A-BFT stage in the next W_f BIs. Here, frozen

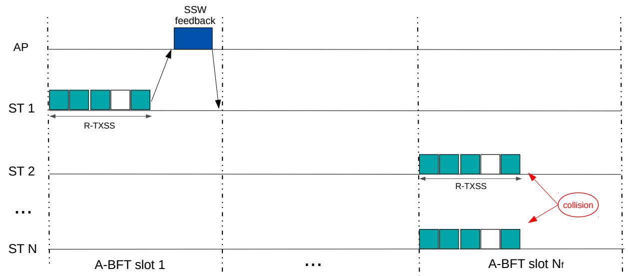

Fig. 4. An example of contention-based BF training.

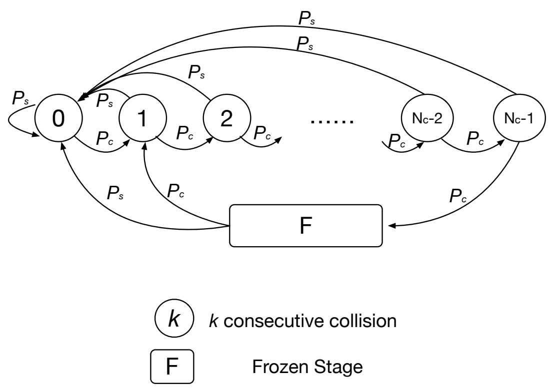

Fig. 5. State transition diagram.

time W_f is a random integer from a uniform distribution $[0, ..., N_c - 1]$. As a result, not all STs are contending for BF training opportunities in a BI. We refer to the STs that are contending as active STs, whereas the others are inactive STs.

III. Performance Analysis of IEEE 802.11 ad MAC Protocol

In this section, an analytical model is proposed to analyze the performance of IEEE 802.11 ad MAC protocol. Considering a dense network, successful transmission probability and channel utilization in the A-BFT stage are derived and analyzed, respectively.

A. Stationary Distribution of Active STs

Given the above procedure, we develop an analytical model to obtain the stationary distribution of active STs. Consider the number of consecutive collisions a ST experienced as the system state. The system state transition diagram is shown in Fig. 5. Circle (k) represents state (k) which has experienced k consecutive collisions, and the rectangle is used to represent frozen stage (F).

We assume that all STs are statistically identical. Let P_c and P_s denote the collision probability and successful transmission probability, respectively. For a ST which is not in frozen stage (F), a collision transits its state from state (k) to state $(k+1)$ for $k \in \{0, ..., N_c - 2\}$, whereas a successful transmission transits its state from state (k) to state (0) for $k \in \{0, ..., N_c - 1\}$. For a ST in state $(N_c - 1)$, a collision transits its state from state $(N_c - 1)$ to frozen stage (F). W_f BIs after entering frozen stage (F), a ST either enters state (0) given a successful transmission or state (1) given a collision.

The state transition diagram is governed by the following transition probabilities and duration.

- The consecutive collisions counter increments: A ST makes a transition from state (k) to state $(k+1)$ for $k \in \{0, ..., N_c - 2\}$, the transition probability is

$$\mathbb{P}(k+1|k) = P_c. \tag{1}$$

$$t(k+1|k) = T_{BI} \tag{2}$$

  where $t(x|y)$ denotes the duration of transition from state (y) to state (x).
- A successful transmission resets the counter: A ST makes a transition from state (k) to state (0) for $k \in \{0, ..., N_c - 1\}$.

$$\mathbb{P}(0|k) = P_s. \tag{3}$$

$$t(0|k) = T_{BI}. \tag{4}$$

- Consecutive collisions counter reaches the maximum value: A ST makes a transition from state $(N_c - 1)$ to frozen stage (F).

$$\mathbb{P}(F|N_c - 1) = P_c. \tag{5}$$

$$t(F|N_c - 1) = T_{BI}. \tag{6}$$

- Frozen stage ends: A ST makes a transition from frozen stage (F) to either state (0) or state (1). Note that a ST stays in frozen stage (F) for W_f BIs.

$$\mathbb{P}(0|F) = P_s. \tag{7}$$

$$\mathbb{P}(1|F) = P_c. \tag{8}$$

$$t(0|F) = W_f T_{BI}. \tag{9}$$

$$t(1|F) = W_f T_{BI}. \tag{10}$$

Based on the transition probabilities described above, we can calculate the stationary probability of state (k), denoted by $P_{cf}(k)$, and the stationary probability of frozen stage (F), denoted by P_F. Based on the property of stationary probability, we have

$$\begin{pmatrix} 0 & 0 & 0 & 0 & ...... & 0 & 0 & P_c \\ P_s & P_s & P_s & P_s & ...... & P_s & P_s & P_s \\ P_c & P_c & 0 & 0 & ...... & 0 & 0 & 0 \\ 0 & 0 & P_c & 0 & ...... & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & ...... & P_c & 0 & 0 \\ 0 & 0 & 0 & 0 & ...... & 0 & P_c & 0 \end{pmatrix} \times \mathbf{Q} = \mathbf{Q} \tag{11}$$

where $\mathbf{Q} = [P_F, P_{cf}(0), P_{cf}(1), P_{cf}(2), ..., P_{cf}(N_c - 2), P_{cf}(N_c - 1)]^T \in \mathrm{R}^{(N_c+1)\times 1}$ is the stationary probability vector.

Since the sum of stationary probabilities of all the states equals to 1, we have

$$P_F + \sum_{k=0}^{N_c-1} P_{cf}(k) = 1. \tag{12}$$

$$0 = P_c - 1 + \sum_{i=1}^{N} C_N^i \sum_{W_f=1}^{N_c-1} \frac{1}{N_c} \frac{[W_f P_c^{N_c}(1-P_c)]^{(N-i)}(1-2P_c^{N_c}+P_c^{N_c+1})^i}{[1-2P_c^{N_c}+P_c^{N_c+1}+W_f P_c^{N_c}(1-P_c)]^N} \frac{i}{N} (\frac{N_f-1}{N_f})^{(i-1)}. \quad (19)$$

Besides, it is obvious that the sum of successful transmission probability and collision probability equals to 1, i.e.,

$$P_s + P_c = 1. \quad (13)$$

Solving equations (11)-(13), we can have $P_{cf}(k)$ and P_F via P_c as

$$P_{cf}(k) = \begin{cases} 1-P_c, \ k=0 \\ P_c^k \dfrac{1-P_c}{1-P_c^{N_c}}, \ k \in \{1, ..., N_c-1\} \end{cases} \quad (14)$$

and

$$P_F = \frac{P_c^{N_c}(1-P_c)}{1-P_c^{N_c}}. \quad (15)$$

Since the duration of the frozen stage is different from that of other states, the average portion in time that a ST spends in the frozen stage, denoted by P_F^T, is

$$\begin{aligned} P_F^T =& \frac{P_f W_f}{\sum_{k=0}^{N_c-1} P_{cf}(k) + P_f W_f} \\ =& \frac{W_f P_c^{N_c}(1-P_c)}{1-2P_c^{N_c}+P_c^{N_c+1}+W_f P_c^{N_c}(1-P_c)}. \end{aligned} \quad (16)$$

With the average portion in time that a ST is in the frozen stage, we can calculate the stationary probability given i active STs in a BI, denoted by $P_a(i)$ for $i \in \{0, ..., N\}$, as

$$P_a(i) = C_N^i (P_F^T)^{(N-i)} (1-P_F^T)^i \quad (17)$$

where C_N^i denotes the i-permutations of N.

B. Successful Transmission Probability

Since successful transmission probability for a ST given i active STs in a BI is $\frac{C_{N-1}^{i-1}}{C_N^i} N_f \times \frac{1}{N_f} (\frac{N_f-1}{N_f})^{(i-1)}$ for $i \in \{1, ..., N\}$, the average successful transmission probability for a ST is

$$P_s = \sum_{i=1}^{N} P_a(i) \frac{i}{N} (\frac{N_f-1}{N_f})^{(i-1)}. \quad (18)$$

Substituting (16) and (17) into (18), we have (19).

Solving (19), we obtain the collision probability P_c. Yet, (19) is an implicit function of P_c, making it difficult to obtain the closed-form solution for P_c. Moreover, this complex equation can not clarify the relationship between successful transmission probability and MAC protocol parameters.

For the dense network, a simplified form of P_s can be derived.

Theorem 1. *When N approaches infinity, the successful transmission probability is given by*

$$\lim_{N\to\infty} P_s = e^{-(1-P_f^T)\frac{N}{N_f}} (1-P_f^T). \quad (20)$$

Proof. When N approaches infinity, (18) can be rewritten as

$$\lim_{N\to\infty} P_s = \lim_{N\to\infty} \sum_{i=1}^{N} P_a(i) \frac{i}{N} (\frac{N_f-1}{N_f})^{(i-1)}. \quad (21)$$

Firstly, according to (17), $P_a(i)$ is a binomial distribution random variable. When N is large, a normal distribution can be used to approximate a binomial distribution. Thus, we define a normal distributed random variable $x = \frac{i}{N} \in (0, 1]$ to replace $P_a(i)$. The above equation can be rewritten as

$$\int_0^1 f(x) x \lim_{N\to\infty} (\frac{N_f-1}{N_f})^{(Nx-1)} dx \quad (22)$$

where

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

is the probability density function of a normal distribution with mean $\mu = 1 - P_F^T$ and variance $\sigma^2 = \frac{P_F^T(1-P_F^T)}{N}$.

Secondly, when N tends to infinity,

$$\begin{aligned} \lim_{N\to\infty} (\frac{N_f-1}{N_f})^{(Nx-1)} =& \lim_{N\to\infty} (\frac{N_f-1}{N_f})^{(Nx)} \\ =& \lim_{N\to\infty} (\frac{N_f-1}{N_f})^{(\frac{N}{N_f} N_f x)} \\ =& (\lim_{N_f\to\infty} (\frac{N_f-1}{N_f})^{N_f})^{\frac{N}{N_f} x} \\ =& e^{-\frac{N}{N_f} x}. \end{aligned} \quad (23)$$

The third equality holds from that N_f tends to infinity in the dense network because more A-BFT slots should be allocated to serve more STs. The last equality above follows from $\lim_{N_f\to\infty} (\frac{N_f-1}{N_f})^{N_f} = e^{-1}$.

With (23), (22) is simplified as

$$\begin{aligned} \int_0^1 f(x) x e^{-cx} dx =& \int_0^1 \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} x e^{-\frac{N}{N_f} x} dx \\ =& e^{\frac{(\frac{N}{N_f}\sigma)^2}{2} - \mu c} \int_0^1 \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-(\mu-\frac{N}{N_f}\sigma^2))^2}{2\sigma^2}} x dx \\ =& e^{\frac{(\frac{N}{N_f}\sigma)^2}{2}} e^{-\mu\frac{N}{N_f}} (\mu - \frac{N}{N_f}\sigma^2) \\ =& e^{-\mu\frac{N}{N_f}} \mu \\ =& e^{-(1-P_F^T)\frac{N}{N_f}} (1-P_F^T). \end{aligned} \quad (24)$$

The first equality follows from the definition of $f(x)$ and the fourth equality follows from $\lim_{N\to\infty} \sigma^2 = 0$. Then, *Theorem 1* is proved. □

Theorem 1 illustrates that P_s depends on $\frac{N}{N_f}$. Therefore, intuitively increasing number of A-BFT slots adaptive to the number of STs is an effective solution to improve successful transmission probability in the dense network.

C. Channel Utilization in the A-BFT Stage

1) MAC Protocol in IEEE 802.11 ad: During contention-based BF training in the A-BFT stage defined by IEEE 802.11 ad, only if successful transmission occurs, the A-BFT slot can be utilized. Otherwise, A-BFT slot is wasted due to either collision or idle. Thus, channel utilization in the A-BFT stage can be represented by the fraction of average number of STs experienced successful transmissions and total number of A-BFT slots, which is given by

$$R = \frac{NP_s}{N_f}. \tag{25}$$

With result in (24), channel utilization in (25) can be rewritten as

$$R = e^{-(1-P_F^T)\frac{N}{N_f}}(1-P_F^T)\frac{N}{N_f}. \tag{26}$$

The objective is to maximize the channel utilization in the A-BFT stage via optimizing the number of A-BFT slots. The optimization problem can be formulated as

$$\begin{aligned} \underset{N_f}{\text{maximize}} \quad & e^{-(1-P_F^T)\frac{N}{N_f}}(1-P_F^T)\frac{N}{N_f} \\ \text{subject to} \quad & N_f \in \mathbb{Z} \end{aligned} \tag{27}$$

where $\mathbb{Z}$ is the positive integer set. This optimization problem is an integer programming problem. First, the integer constraint can be relaxed to a non-integer constraint, i.e., N_f is a positive non-integer variable. Then, this optimization problem can be easily solved by simple derivation. The optimal number of A-BFT slots is given by

$$N_f = N(1-P_F^T). \tag{28}$$

As N_f is an integer, the optimal value of N_f should be the integer less than or larger than $N(1-P_F^T)$ which achieves a higher channel utilization. (28) suggests that the optimal number of A-BFT slots depends on the average portion of frozen stage. Besides, by solving this optimization problem, the maximum channel utilization in the A-BFT stage is e^{-1}.

2) Slotted ALOHA: A comparison between IEEE 802.11 ad MAC protocol and slotted ALOHA in terms of channel utilization in the A-BFT stage is presented in this subsection. Without the frozen stage, IEEE 802.11 ad MAC protocol can be considered as a slotted ALOHA. i.e., each ST randomly chooses a A-BFT slot to transmit R-TXSS frames to perform BF training. In slotted ALOHA protocol, the number of active STs in a BI is fixed. The successful transmission probability of is given by

$$\begin{aligned} P_s^{ALOHA} =& C_{N_f}^1 \frac{1}{N_f}(\frac{N_f-1}{N_f})^{N-1} \\ =& (\frac{N_f-1}{N_f})^{N-1}. \end{aligned} \tag{29}$$

According to the definition of channel utilization in (25), corresponding channel utilization in the A-BFT stage is

$$R^{ALOHA} = \frac{N}{N_f}(\frac{N_f-1}{N_f})^{N-1}. \tag{30}$$

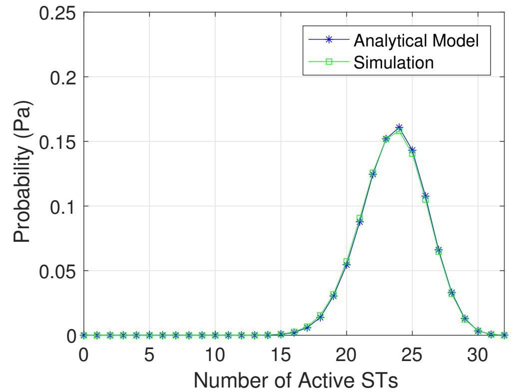

Fig. 6. Stationary distribution of active STs when $N = 32$.

Considering a dense network that N approaches infinity, channel utilization can be simplified as

$$\begin{aligned} \lim_{N\to\infty} P_s^{ALOHA} =& \frac{N}{N_f} \lim_{N\to\infty} (\frac{N_f-1}{N_f})^{N-1} \\ =& \frac{N}{N_f} e^{-\frac{N_f}{N}}. \end{aligned} \tag{31}$$

To achieve the maximum channel utilization given in (31), the number of A-BFT slots should be optimized. By solving this optimization problem, the optimal number of A-BFT slots in slotted ALOHA protocol is

$$N_f^{ALOHA} = N. \tag{32}$$

Moreover, theoretical analysis shows the maximum channel utilization in the A-BFT stage is also e^{-1}.

D. Discussion

Compared the theoretical analysis of IEEE 802.11 ad MAC protocol with slotted ALOHA protocol, two conclusions can be drawn.

- Compared the optimal number of A-BFT slots in (28) with (32), it is obvious that $N_f < N_f^{ALOHA}$. It is obvious that IEEE 802.11 ad MAC protocol achieves the maximum channel utilization with a smaller number of A-BFT slots.
- IEEE 802.11 ad MAC protocol achieves the same maximum channel utilization as slotted ALOHA protocol, which is e^{-1}. This channel utilization is low and many A-BFT slots are wasted. New MAC protocols should be developed to improve the channel utilization.

IV. Simulation Results

In this section, we present simulations to validate our proposed analytical model and theoretical analysis of IEEE 802.11 ad MAC protocol.

Fig. 6 compares the analytical model and simulation results when $N = 32$. Specifically, we simulate 1,000,000 BIs and study the statistics of interests. Initially, STs are set to be active and none of them has experienced collision. In order to accurately reflect stationary distribution, we ignore the

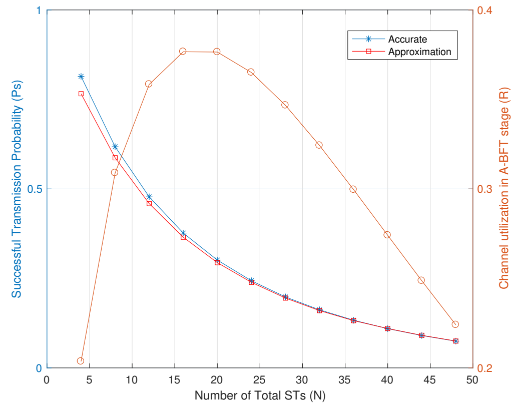

Fig. 7. Impact of the number of total STs (N) when $N_f = 16$.

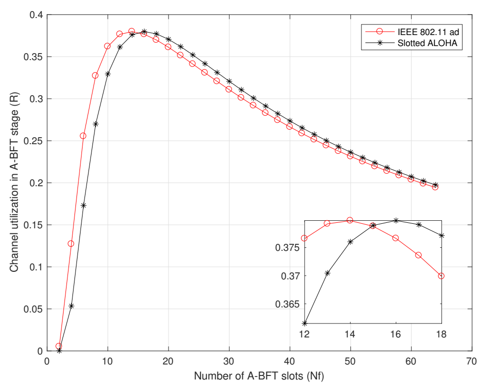

Fig. 8. Performance comparison between IEEE 802.11 ad MAC protocol and slotted ALOHA when $N = 16$.

first 500 BIs. It can be seen that the stationary distribution obtained by analytical model is highly consistent with that by simulations.

Fig. 7 shows the successful transmission probability P_s for a ST with respect to different numbers of STs in the network when $N_f = 16$. The blue line represents P_s with arbitrary number of STs, given in (19). The red line represents the approximation of P_s in the dense network, given in (20). It can be seen that the approximation of P_s in the dense work is highly consistent with the accurate value of P_s. Meanwhile, with the increase of the number of total STs, the successful transmission probability decreases from 81.4% to 7.49%. This is because that more STs contend for limited A-BFT slots which leads to a higher collision probability. It also suggests the challenge to support a large number of STs in a dense network. Besides, with the increase of number of STs, the utilization of A-BFT slots increases and then decreases, which implies that there exists an optimal number of STs such that the utilization of A-BFT slots can be maximized. In fact, the theoretical result obtained in (28) provides the optimal number of A-BFT slots to achieve the maximum utilization.

In Fig. 8, we compare the channel utilization in the A-BFT stage between IEEE 802.11 ad MAC protocol and slotted ALOHA protocol in terms of the number of A-BFT slots when $N = 16$. It can be seen that IEEE 802.11 ad MAC protocol has nearly the same maximum channel utilization as slotted ALOHA protocol, which validates our theoretical analysis. However, IEEE 802.11 ad MAC protocol achieves the maximum channel utilization with a low cost of A-BFT slots. More concretely, IEEE 802.11 ad MAC protocol achieves the maximum channel utilization with only 14 A-BFT slots, which is smaller than 16 A-BFT slots used in slotted ALOHA protocol.

V. Conclusion

In this paper, we have proposed an analytical model and analyzed the performance of IEEE 802.11 ad MAC protocol in the A-BFT stage. The analytical results have been validated via simulations. The results can provide guidelines for optimal parameter setting in IEEE 802.11 ad MAC protocol in the dense network. Furthermore, theoretical analysis indicates the inefficiency IEEE 802.11 ad MAC protocol in the A-BFT stage.

In future work, we will propose MAC protocols to achieve a higher channel utilization.

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References

[1] N. Cheng, N. Lu, N. Zhang, X. Shen, and J.W. Mark, "Vehicular WiFi Offoading: Challenges and Solutions," Vehicular Communications (Elsevier), vol. 1, No. 1, pp. 13-21, 2014.

[2] S. Wang, X. Zhang, Y. Zhang, L. Wang, J. Yang, and W. Wang, "A Survey on Mobile Edge Networks: Convergence of Computing, Caching and Communications," *IEEE Access*, vol. 5, pp. 6757-6779.

[3] T.S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G.N. Wong, J.K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," *IEEE Access*, vol. 1, no. 1, pp. 335-349, 2013.

[4] C. Park and T. S. Rappaport, "Short-Range Wireless Communications for Next-Generation Networks: UWB, 60 GHz Millimeter-Wave WPAN, And ZigBee," *IEEE Wireless Communications*, vol. 14, no. 4, pp. 70-78, Aug. 2007.

[5] IEEE Std 802.11ad-2012, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band," Dec. 2012.

[6] W. Roh, J.Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, and K. Cheun, "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 106-113, Feb. 2014.

[7] W. Wu, Q. Shen, M. Wang, X. Shen, "Performance Analysis of IEEE 802.11.ad Downlink Hybrid Beamforming," in *Proc. IEEE International Conference on Communications (ICC)*, 2017, pp.1-6.

[8] J. Qiao, X. Shen, J.W. Mark, and Y. He, "MAC-layer Concurrent Beamforming Protocol for Indoor Millimeter Wave Networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 1, pp. 327-338, Jan. 2015.

[9] C. Hemanth and TG. Venkatesh, "Performance analysis of contention-based access periods and service periods of 802.11 ad hybrid medium access control," *IET Networks*, vol. 3, no. 3, pp. 193-203, 2014.

[10] K. Chandra, R.V. Prasad and I. Niemegeersh, "Performance Analysis of IEEE 802.11 ad MAC Protocol," *IEEE Communications Letters*, vol. 21, no. 7, pp. 1513-1516, Jul. 2017.

[11] C. Qian, J. Tang, D.T.C. Wong and X. Peng and Y. Zhang, "Directional cooperative MAC protocol design and performance analysis for IEEE 802.11 ad WLANs," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 6, pp. 2667-2677, Jul. 2013.