Impact of Retransmission on VoWiFi Cell Capacity Estimation using IEEE 802.11ax WiFi Standard

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***Abstract*—Wireless Fidelity (WiFi) is becoming more popular for its ability to provide cost-effective solutions to overcome call drops occurring in cellular networks due to poor signal strength. We focused on Voice over Internet Protocol (VoIP) over WiFi as Voice over WiFi (VoWiFi) in our study. We have developed analytical models incorporating Arbitration Inter-frame Spacing (AIFS) to boost the VoWiFi cell capacity of IEEE 802.11ax (i.e. sixth generation Wireless Local Area Network (WLAN) standard). Using DCF Inter-frame Spacing (DIFS) and AIFS, we have estimated VoWiFi cell capacity with/without Request To Send (RTS) and Clear To Send (CTS) frames for constant bit rate (CBR) traffic. Further, we have extended our models to support retransmission mechanism to prevent packet loss and compared results using DIFS and AIFS to determine their efficiency.**

***Index Terms*—Retransmission, VoWiFi, CBR traffic, IEEE 802.11ax, capacity analysis.**

I. Introduction

Every day, the demand for WiFi is growing tremendously. The earlier IEEE 802.11 standards are becoming insufficient for handling increased user numbers and bandwidth requirements. The IEEE 802.11 working group is trying to improve WLAN standards to meet user expectations. Certain locations, such as basements, warehouses and subterranean metro stations, where cellular services are inaccessible to users due to a lack of coverage. To overcome this problem, the researchers developed VoWiFi, which provides similar services via WiFi Access Point (AP)s and aids in the expansion of the wireless communication network. We have presented the VoWiFi scenario in Fig. 1. As shown in Fig. 1, certain users who reside in a building rely on the cellular network. Users are being disconnected from the nearest cellular tower due to a lack of cellular signal strength. Cell towers have a limited range for transmitting and receiving data. After connecting to the WLAN AP, users can begin transmitting and receiving voice data packets using the VoWiFi service. The voice packets are transmitted via WLAN APs and then via IP Sec tunneling to cell towers and subsequently to cellular customers via the Packet Data Network (PDN) and other necessary equipments. VoWiFi enables the expansion of cellular communication to WiFi communication. Thus, users will obtain the proper signal strength for transmitting and receiving voice data without relying on a cellular tower. The scenario for multi-user VoWiFi communication through WiFi network is shown in Fig. 2. The VoWiFi service is based on packet-switched network. As shown using Fig. 2, we can observe that the VoWiFi users have connected using the WLAN AP. Then voice data packets can be transmitted up and down according to the bandwidth of WLAN AP. As a result, we can not prevent users from using the VoWiFi service over WLAN. To ensure the quality-of-service (QoS) of ongoing calls, it is necessary to determine the number of users that an AP can support. Therefore, in this paper we have developed analytical models to find the number of VoWiFi service calls a WLAN AP can support. Our analytical models will assist in determining whether accommodating a new VoWiFi voice call has any effect on the QoS of existing VoWiFi calls within a WiFi AP. Additionally, we employed AIFS to increase the number of users availing VoWiFi service using IEEE 802.11ax WLAN standard. Further, we utilized the retransmission mechanism to avoid VoWiFi packet loss. This paper's key contributions are listed below.

- We developed analytical models for IEEE 802.11ax WLAN standard to determine the number of VoWiFi calls that can be supported using G.729 voice codec.
- We compared the results found using IEEE 802.11ax to those obtained with older WLAN standards such as IEEE 802.11b/g/n/ac utilizing AIFS.
- Again, we have used packet retransmission technique to avoid VoWiFi packet loss.

We have structured the remaining part of our paper as follows. The related work of our study discussed in Section II. In Section III, we have developed analytical models to evaluate the cell capacity of WLAN AP providing VoWiFi service. In section IV, we have discussed the numerical results. Finally, in Section V we have concluded this paper.

II. Related Work

We investigated current analytical methods for predicting real-time VoIP call capacity using IEEE 802.11a/b/g/n standards. In [1], the maximum capacity of IEEE 802.11b is determined when both G.729 and G.711 voice codecs are considered. Additionally, the research presented in [2] used the Medium Access Control (MAC) protocols of IEEE 802.11a/b/g to estimate the VoIP call capacity using CBR and variable bit rate (VBR) voice traffic sources. To enhance the IEEE 802.11b standard AP's capacity, the work reported

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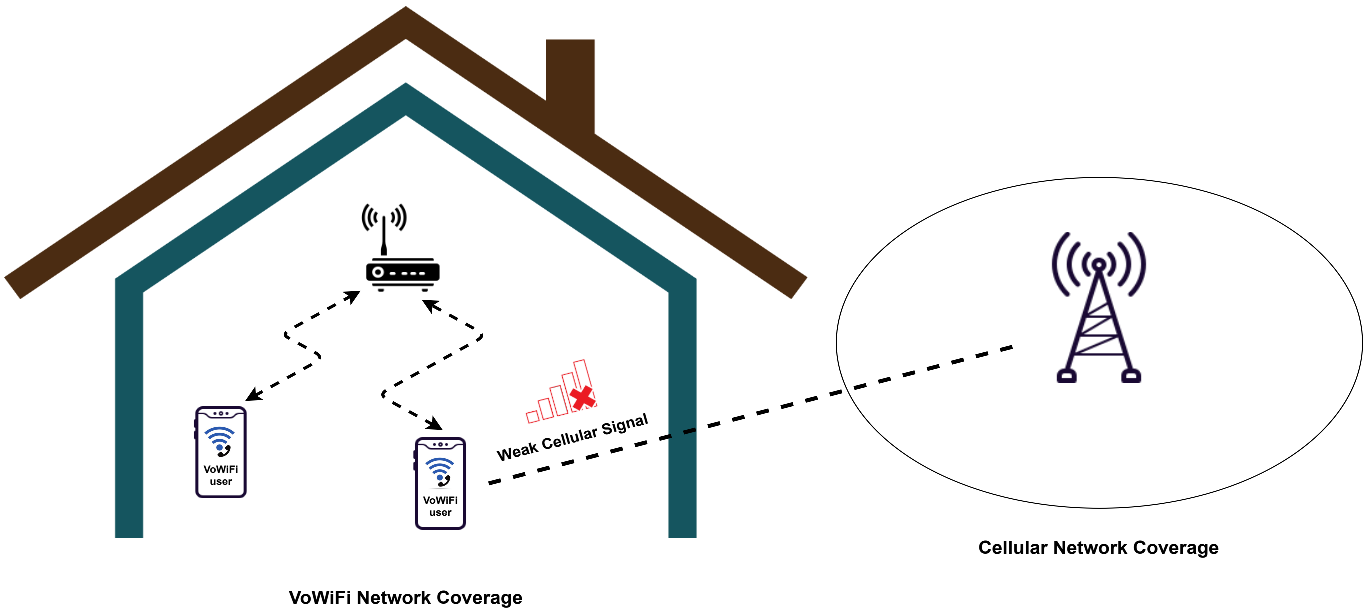

Fig. 1. VoWiFi scenario.

in [3] prioritized an AP by decreasing the length of DIFS and contention window size. As a result, call capacity was increased from ten to twelve stations. In [4], the authors have modified the IEEE 802.11 MAC protocol by minimizing the effect of AP bottleneck and increasing the VoIP transmission capacity. It was stated that the capacity of Voice over Wireless Local Area Network (VoWLAN) had been improved by 20%. To achieve a tighter bound on VoWiFi admission capacity, authors in [5] proposed a metamodel that utilizes formal empirical modeling techniques. According to this approach, considering G.711 voice codec the IEEE 802.11b standard WLAN AP has a 4-user VoIP call capacity limit. In Full-Duplex (FD) communications, the scheme described in [6] improved capacity by 14.3%. According to [7], using

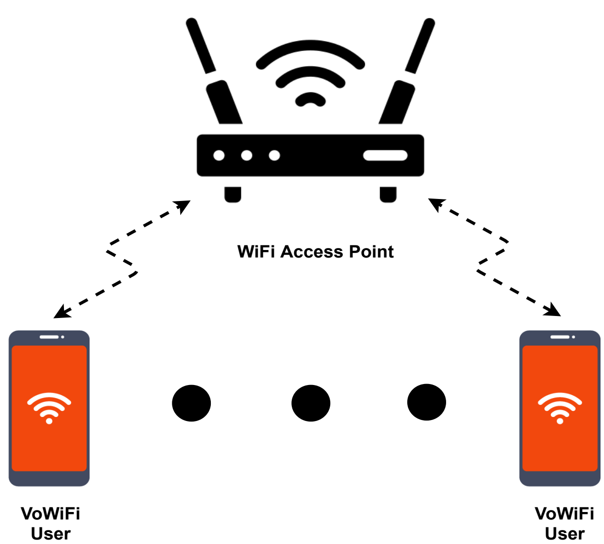

Fig. 2. Setup for VoWiFi service.

the G.711 and G.729 voice codecs for the IEEE 802.11b standard AP results in reduced latency, less packet loss and higher quality, resulting in increased VoIP capacity. We discovered most of these papers estimated VoIP call capacity without considering the newer WLAN standards such as IEEE 802.11ac/ax, Frame Check Sequence (FCS) in Layer 2 or the Data Link Layer and the cRTP protocol.

Work reported in [8], [9] estimated VoWiFi cell capacity considering Frame Check Sequence (FCS) in Layer 2 or the Data Link Layer and the cRTP protocol in newer WLAN standards such as IEEE 802.11ac/ax. In [8], cell capacity for VoWiFi service is estimated for IEEE 802.11ac standard WLAN AP. However, in this work the impact of retransmission is not investigated. In [9], cell capacity providing VoWiFi service is estimated using IEEE 802.11ax standard WLAN AP for CBR traffic without considering AIFS and retransmission techniques. Further, we observed that cell capacity providing VoWiFi service for IEEE 802.11ax is understudied. As a result, in this paper we have presented analytical models to estimate cell capacity considering AIFS and retransmission in the sixth-generation WLAN standard that supports VoWiFi. In the following sections, we have discussed our proposed analytical models.

III. VoWiFi Cell Capacity Estimation of WLAN AP

We have started by estimating the capacity of a WLAN AP for VoWiFi service using the basic Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Following that, we have calculated the cell capacity of a WLAN AP providing VoWiFi service using the RTS/CTS frames. Finally, we have investigated the effect of packet retransmission on VoWiFi cell capacity.

A. VoWiFi cell capacity estimation using the basic CSMA/CA

The total time needed by AIFS, Short Inter-frame Spacing (SIFS) and DIFS characterised by $\mathsf{T}_{\mathfrak{ifs}}$ is given in the following expression.

$$\mathsf{T}_{\mathfrak{ifs}} = \begin{cases} \mathsf{T}_{\mathfrak{difs}} + \mathsf{T}_{\mathfrak{sifs}}, & DIFS\ is\ used \\ \mathsf{T}_{\mathfrak{aifs}} + \mathsf{T}_{\mathfrak{sifs}}, & AIFS\ is\ used \end{cases} \quad (1)$$

where $\mathsf{T}_{\mathfrak{difs}}$ is the time for DIFS, $\mathsf{T}_{\mathfrak{sifs}}$ is the time for SIFS and $\mathsf{T}_{\mathfrak{aifs}}$ is the time for AIFS. Further, the following expression specifies the total time for all the headers denoted by $\mathsf{T}_{\mathfrak{l}}$.

$$\mathsf{T}_{\mathfrak{l}} = \begin{cases} \mathsf{T}_{\mathfrak{rtp}} + \mathsf{T}_{\mathfrak{udp}} + \mathsf{T}_{\mathfrak{ip}} + \mathsf{T}_{\mathfrak{mac}} + \mathsf{T}_{\mathfrak{ph}}, & Uncompressed \\ \mathsf{T}_{\mathfrak{crtp}} + \mathsf{T}_{\mathfrak{mac}} + \mathsf{T}_{\mathfrak{ph}}, & Compressed \end{cases} \quad (2)$$

where $\mathsf{T}_{\mathfrak{ph}}$ denotes the time required for physical frame header, $\mathsf{T}_{\mathfrak{mac}}$ denotes the time required for MAC frame header, $\mathsf{T}_{\mathfrak{ip}}$ denotes the time required for IP header, $\mathsf{T}_{\mathfrak{udp}}$ denotes the time required for UDP header, $\mathsf{T}_{\mathfrak{rtp}}$ denotes the time required for RTP header and $\mathsf{T}_{\mathfrak{crtp}}$ denotes the time required for cRTP header. Now, the time needed for transmitting a VoWiFi packet successfully with a frame interval of Φ denoted by $\mathsf{T}_{\mathbb{S}_\Phi}$ is given in the following expression.

$$\mathsf{T}_{\mathbb{S}_\Phi} = \begin{cases} \left(\frac{\mathsf{C}^{\mathfrak{b}} \times \mathsf{C}_{\Phi}^{\mathfrak{fi}}}{\mathsf{D}_{\mathfrak{ph}}}\right) + \mathsf{T}_{\mathfrak{l}} + \left(\frac{\mathsf{ACK}^{\mathfrak{size}}}{\mathsf{D}_{\mathfrak{ph}}} + \mathsf{T}_{\mathfrak{ph}}\right) + \mathsf{T}_{\mathfrak{ifs}} + \left(\mathsf{T}_{\mathfrak{slot}} \times \frac{\mathsf{CW}_{\mathfrak{min}}}{2}\right), \\ \quad \mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \le \Phi \le \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}\ and\ (\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \wedge \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}) \neq 0 \\ 0, \quad \mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \le \Phi \le \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}\ and\ (\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \wedge \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}) = 0 \end{cases} \quad (3)$$

where $\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}}$ is the minimum value of frame interval, $\mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}$ is the maximum value of frame interval required for a voice codec, $\mathsf{C}_{\Phi}^{\mathfrak{fi}} = \Phi$ is the frame interval of voice codec which ranges between $\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}}$ and $\mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}$, $\mathsf{C}^{\mathfrak{b}}$ is the bit rate of voice codec, $\mathsf{D}_{\mathfrak{ph}}$ is the physical data rate, $\mathsf{ACK}^{\mathfrak{size}}$ denotes the size of acknowledgement (ACK) frame, $\mathsf{CW}_{\mathfrak{min}}$ is the minimum size of contention window and $\mathsf{T}_{\mathfrak{slot}}$ is the slot time. Now, the number of VoWiFi calls can be accommodated in a WLAN AP denoted by $\mathsf{N}_{\mathfrak{call}}$ is presented using the following expression.

$$\mathsf{N}_{\mathfrak{call}} = \left\lfloor \frac{\mathsf{C}_{\Phi}^{\mathfrak{fi}}}{2 \times \mathsf{T}_{\mathbb{S}_\Phi}} \right\rfloor, \quad \mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \le \Phi \le \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}\ and\ (\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \wedge \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}) \neq 0 \quad (4)$$

B. VoWiFi cell capacity estimation with basic CSMA/CA using RTS/CTS frames

The time needed to successfully transmit a VoWiFi packet allowing RTS/CTS frames with a frame interval of Φ denoted by $\mathsf{T}_{\mathbb{S}(\mathfrak{rc})_\Phi}$ can be calculated using the following expression.

$$\mathsf{T}_{\mathbb{S}(\mathfrak{rc})_\Phi} = \begin{cases} \mathsf{T}_{\mathbb{S}_\Phi} + \left(\frac{\mathsf{RTS}^{\mathfrak{size}}}{\mathsf{D}_{\mathfrak{ph}}} + \mathsf{T}_{\mathfrak{ph}}\right) + \left(\frac{\mathsf{CTS}^{\mathfrak{size}}}{\mathsf{D}_{\mathfrak{ph}}} + \mathsf{T}_{\mathfrak{ph}}\right) + 2 \times \mathsf{T}_{\mathfrak{sifs}}, \\ \quad \mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \le \Phi \le \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}\ and\ (\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \wedge \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}) \neq 0 \\ 0, \quad \mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \le \Phi \le \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}\ and\ (\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \wedge \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}) = 0 \end{cases} \quad (5)$$

where $\mathsf{RTS}^{\mathfrak{size}}$ denotes size of the RTS frame and $\mathsf{CTS}^{\mathfrak{size}}$ denotes size of the CTS frame. Now, we can find the number of users utilizing the VoWiFi service in a WLAN AP by considering RTS/CTS frames denoted by $\mathsf{N}_{\mathfrak{call}(\mathsf{rc})}$ using the following expression.

$$\mathsf{N}_{\mathfrak{call}(\mathsf{rc})} = \left\lfloor \frac{\mathsf{C}_{\Phi}^{\mathfrak{fi}}}{2 \times \mathsf{T}_{\mathbb{S}(\mathfrak{rc})_\Phi}} \right\rfloor, \quad \mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \le \Phi \le \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}\ and\ (\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \wedge \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}) \neq 0 \quad (6)$$

C. Impact of packet retransmission on VoWiFi cell capacity

Average time of contention window represents the behavior of the system more closely. So, we have preferred the average time of contention window for performance analysis. Now, using average case of contention window the number of VoWiFi calls the WLAN AP supports considering retransmission denoted by $\mathsf{N}_{\mathfrak{call\_rt}}$ is given in the following expression.

$$\mathsf{N}_{\mathfrak{call\_rt}} = \left\lfloor \frac{\mathsf{C}_{\Phi}^{\mathfrak{fi}}}{2 \times ((\mathsf{n}+1) \times \delta + (\mathsf{T}_{\mathfrak{slot}} \times \frac{\mathsf{CW}_{\mathfrak{min}}}{2}) \times (2^{\mathsf{n}+1} - 1))} \right\rfloor, \quad \mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \le \Phi \le \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}\ and\ (\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \wedge \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}) \neq 0 \quad (7)$$

where $\delta = \left(\frac{\mathsf{C}^{\mathfrak{b}} \times \mathsf{C}_{\Phi}^{\mathfrak{fi}}}{\mathsf{D}_{\mathfrak{ph}}}\right) + \mathsf{T}_{\mathfrak{l}} + \left(\frac{\mathsf{ACK}^{\mathfrak{size}}}{\mathsf{D}_{\mathfrak{ph}}} + \mathsf{T}_{\mathfrak{ph}}\right) + \mathsf{T}_{\mathfrak{ifs}}$ and n is the number of retransmissions per packet. Similarly, the cell capacity of a WLAN AP providing VoWiFi service considering RTS/CTS frames and packet retransmission denoted by $\mathsf{N}_{\mathfrak{call\_rt\_rc}}$ can be obtained using the following expressions.

$$\mathsf{N}_{\mathfrak{call\_rt\_rc}} = \left\lfloor \frac{\mathsf{C}_{\Phi}^{\mathfrak{fi}}}{2 \times ((\mathsf{n}+1) \times \delta_{RC} + (\mathsf{T}_{\mathfrak{slot}} \times \frac{\mathsf{CW}_{\mathfrak{min}}}{2}) \times (2^{\mathsf{n}+1} - 1))} \right\rfloor, \quad \mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \le \Phi \le \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}\ and\ (\mathfrak{min}_{\mathsf{C}^{\mathfrak{fi}}} \wedge \mathfrak{max}_{\mathsf{C}^{\mathfrak{fi}}}) \neq 0 \quad (8)$$

where $\delta_{RC} = \left(\frac{\mathsf{C}^{\mathfrak{b}} \times \mathsf{C}_{\Phi}^{\mathfrak{fi}}}{\mathsf{D}_{\mathfrak{ph}}}\right) + \mathsf{T}_{\mathfrak{l}} + \left(\frac{\mathsf{ACK}^{\mathfrak{size}}}{\mathsf{D}_{\mathfrak{ph}}} + \mathsf{T}_{\mathfrak{ph}}\right) + \mathsf{T}_{\mathfrak{ifs}} + \left(\frac{\mathsf{RTS}^{\mathfrak{size}}}{\mathsf{D}_{\mathfrak{ph}}} + \mathsf{T}_{\mathfrak{ph}}\right) + \left(\frac{\mathsf{CTS}^{\mathfrak{size}}}{\mathsf{D}_{\mathfrak{ph}}} + \mathsf{T}_{\mathfrak{ph}}\right) + 2 \times \mathsf{T}_{\mathfrak{sifs}}$. Here, the time-out time for receiving the ACK or NACK is approximated with $\left(\frac{\mathsf{ACK}^{\mathfrak{size}}}{\mathsf{D}_{\mathfrak{ph}}} + \mathsf{T}_{\mathfrak{ph}}\right)$.

IV. Numerical Results

The frame format of PPDU for IEEE 802.11ax is illustrated in [9]–[11]. The system bandwidth (i.e. $\mathsf{D}_{\mathfrak{ph}}$) of IEEE 802.11ax is taken as 4803.92 Mbps. The expression to find the system bandwidth for IEEE 802.11ax is derived in [9]. We have taken G.729 voice codec having bit rate (i.e. $\mathsf{C}^{\mathfrak{b}}$) 8 kbps with a frame interval (i.e. $\mathsf{C}_{\Phi}^{\mathfrak{fi}}$) of 20 ms, $\mathsf{CW}_{\mathfrak{min}}$ as 15 and the rest of the parameters are summarised in Table I. The cell capacity providing VoWiFi service obtained for different WLAN standards estimated using (4) without considering RTS/CTS frames and (6) with RTS/CTS frames respectively are shown using Fig. 3. From Fig. 3, we observed that VoWiFi users supported in IEEE 802.11ax using AIFS is showing 4.81% increase compared to DIFS without considering RTS/CTS frames. Similarly, using RTS/CTS frames with AIFS in IEEE 802.11ax is showing 3.02% increase w.r.t. DIFS. Again, from Fig. 3 we observed that VoWiFi users supported in IEEE 802.11ax using AIFS without RTS/CTS frames is showing 219.35% increase compared to IEEE 802.11b, 60.27% increase compared to IEEE 802.11g, 44.9% increase compared to IEEE 802.11n and 0.97% increase compared to IEEE 802.11ac. Further, from Fig. 3 we observed that VoWiFi users supported in IEEE 802.11ax using AIFS with RTS/CTS frames is showing 180.35% increase compared to IEEE 802.11b, 73.72% increase compared to IEEE 802.11g, 24.86% increase compared to IEEE 802.11n and 1.18% increase compared to IEEE 802.11ac. To prevent

TABLE I
PARAMETERS USED.

Parameters	Size (in Bytes)	Time (in μs)
$T_{\mathfrak{rtp}}$	12	0.019
$T_{\mathfrak{udp}}$	8	0.013
$T_{\mathfrak{ip}}$	20	0.033
$T_{\mathfrak{crtp}}$	2	0.003
$T_{\mathfrak{mac}}$	40	0.066
$T_{\mathfrak{ph}}$	-	39.2
$ACK^{\mathfrak{size}}$	14	0.023
$T_{\mathfrak{slot}}$	-	9
$T_{\mathfrak{sifs}}$	-	16
$T_{\mathfrak{difs}}$	-	34
$T_{\mathfrak{aifs}}$	-	25
$RTS^{\mathfrak{size}}$	20	0.033
$CTS^{\mathfrak{size}}$	14	0.023

packet loss, we have applied the retransmission technique using (7) without considering RTS/CTS frames and (8) with RTS/CTS frames for CBR traffic. Using Fig. 4, we have shown the impact of packet retransmission on VoWiFi cell capacity for IEEE 802.11ax.

V. CONCLUSION

We developed analytical models to estimate the cell capacity of different generations of WLAN APs providing VoWiFi service. We observed that the cell capacity of WLAN AP supporting VoWiFi service obtained using AIFS with/without RTS/CTS frames is giving better results compared to DIFS. Further, we found that IEEE 802.11ax with/without RTS/CTS frames and using AIFS supports a greater number of users compared to DIFS while allowing retransmission.

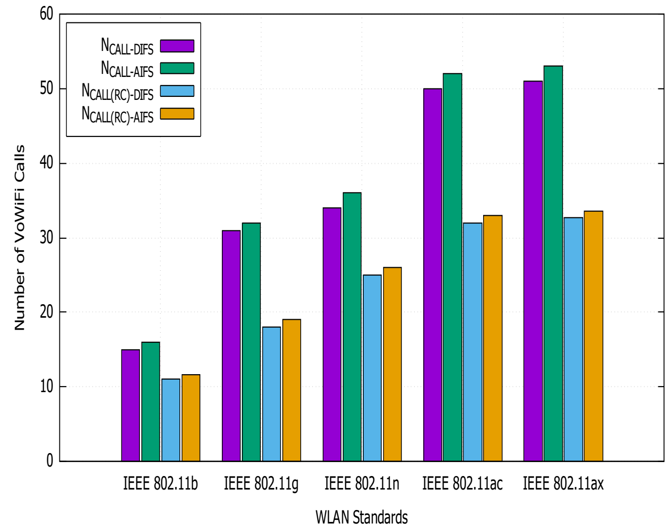

Fig. 3. Cell capacity in IEEE 802.11b/g/n/ac/ax providing VoWiFi service using G.729 voice codec.

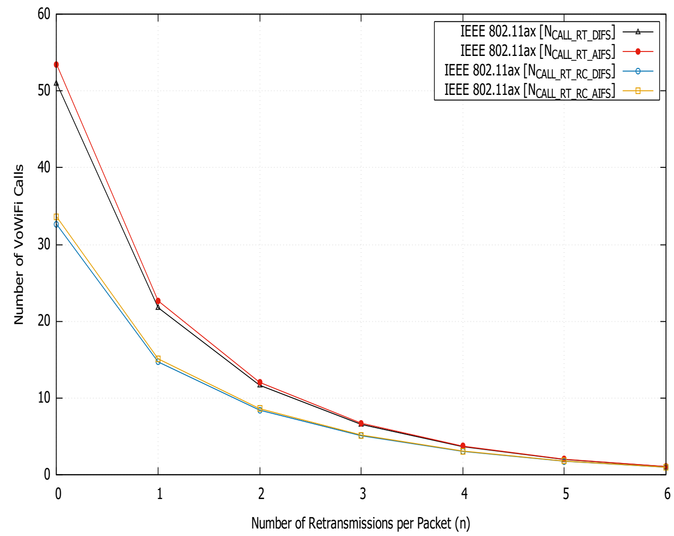

Fig. 4. Cell capacity in IEEE 802.11ax providing VoWiFi service considering the DIFS and AIFS under collision.

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