Design and Optimization of IEEE 802.11ad-based Dense Network in Cabin Environment

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Abstract—In this paper, we aim to design and optimize the performance of IEEE 802.11ad-based dense network in cabin environment. For a typical airplane model, we propose a suitable network deployment and build up the directional antenna model and path loss model. We also develop an electromagnetic algorithm to predict the in-cabin 60 GHz radio propagation characteristics and the channel model. Considering the blockage effects, we further investigate the link level and system level performance of IEEE 802.11ad networks for different modulations and different cabin regions. The simulation results validate that the IEEE 802.11ad network is applicable to the wireless in-flight entertainment and communication (WIFEC) services. Moreover, the adopted rate adaption scheme dramatically improves the robustness of IEEE 802.11ad networks, which achieves better performance than fixed modulation scheme.

Index Terms—IEEE 802.11ad networks; wireless in-flight entertainment and communications; performance optimization.

I. INTRODUCTION

In recent years, the IEEE 802.11a/b/g/n/ac-based wireless in-flight entertainment and communication (WIFEC) systems in the unlicensed 2.4 GHz and 5 GHz frequencies are being adopted in more and more commercial airplanes. Passengers may bring their own devices and use Bluetooth and WiFi for some wireless applications. Moreover, wireless sensor networks are also being explored for monitoring the aircraft structural health, temperature, humidity, etc [1]. It is easily foreseeable that the 2.4 GHz and 5 GHz bands are going to be congested in the aircraft, hence we are motivated to explore a new wireless system using another band to provide the WIFEC system, specifically, the IEEE 802.11ad network [2].

The IEEE 802.11ad network is regulated to operate in the 60 GHz millimeter wave (mmWave) band and capable of serving new wireless applications such as uncompressed high definition (HD) video streaming and ultra fast wireless file transfers with the demand for very high throughput (VHT) up to multi-gigabit per second [3]. In [2], four operating channels named Channels 1 to 4 are specified, and each of them has a 2.16 GHz bandwidth. The maximum data rate can reach at 6.75675 Gbps. However, the coverage range of 11ad system is only a few meters and it is easily affected by the blockage. This is because the 60 GHz mmWave signals suffer much more severe atmospheric attenuation and higher penetration loss than that in the widely-used 2.4 GHz and 5 GHz band [4]. To compensate the signal attenuation and provide robust communication link, the directional antenna technique is adopted by IEEE 802.11ad networks.

Although many existing works have studied the IEEE 802.11ad networks, they did not consider the in-cabin scenario. The aircraft cabin is much different from other indoor scenarios [5]. There is a high density clutter due to the furniture and seats, leading to merely any line-of-sight (LOS) transmission between transmitter and receiver locations. The cabin walls are usually metal-backed multi-layer dielectric structures, which is different from the normal office environment. Thus, the application of existing commercial software is hard to predict in-cabin 60 GHz radio channel so that the related performance is not common. To the best of our knowledge, this paper is the first work to investigate the performance of IEEE 802.11ad networks in a cabin environment. The main contributions of this paper are listed as follows:

- Develop an effective and efficient electromagnetic algorithm to predict the radio propagation characteristics in aircraft cabin;
- Use the inter cluster method to customize the in-cabin 60 GHz channel model;
- Conduct the link level performance study of the IEEE 802.11ad networks in aircraft cabin;
- Build an IEEE 802.11ad-compliant WIFEC network simulator to investigate the system level performance of IEEE 802.11ad networks for different modulation techniques and different cabin regions;
- Validate that the IEEE 802.11ad network is applicable to VHT WIFEC services and optimize its performance by using the rate adaption scheme.

The rest of this paper is organized as follows: Section II presents the airplane layout and network deployment. Then, the in-cabin 60 GHz radio propagation characteristics and channel model are derived in Section III. The performance evaluation is shown in Section IV. Finally, Section V concludes this paper.

II. AIRPLANE LAYOUT AND NETWORK DEPLOYMENT

The considered airplane physical layout, the seat arrangement and the partition of a typical airplane are shown in Fig. 1(a). It is clearly seen that this airplane has two aisles, two cabin monuments, and six zones (two business cabins and four economic cabins). Since the 60 GHz signal is hard to penetrate walls, we have to divide the airplane into four individual regions: Zone 1, Zone 2, Zone 3/4 and Zone 5/6. For each zone, we mount two access points (APs) on both
III. IN-CABIN 60 GHz SIGNAL PROPAGATION CHARACTERISTICS AND CHANNEL MODEL

A. Directional Antenna Model

The location of an AP deployed on the cabin wall is shown in Fig. 2. Thus, we can derive the gain of the antenna array pattern as follows.

We denote the location of the considered AP, i.e., the center of antenna array, by \((x_b, y_b, z_b)\) and that of a receiver STA by \((x_u, y_u, z_u)\) in 3D space. Moreover, the elevation angle and the azimuth angle are denoted by \(\theta\) and \(\phi\), respectively.

Suppose that each antenna array has \(N\) elements and all the elements have the same radiation pattern of \(R(\theta, \phi)\). Let \(r_{b,n} = (x_{b,n}, y_{b,n}, z_{b,n})\) and \(w_n\) denote the position and weighting factor of an arbitrary antenna element \(n\), respectively. Thus, the output signal \(r\) is given by

\[
r = R(\theta, \phi) \sum_{n=1}^{N} w_n \exp(-jkr_{b,n}).
\]  

(1)

In Eq. (1), the wave vector \(k\) is given by

\[
k = (k_x, k_y, k_z) = \frac{2\pi}{\lambda} (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta),
\]

(2)

and the weighting factor \(w_n\) is given by

\[
w_n = \exp(j(k_x^* x_{b,n} + k_y^* y_{b,n} + k_z^* z_{b,n}))
\]

\[
= \exp(j|k|(\sin \theta^* \cos \phi^* x_{b,n} + \sin \theta^* \sin \phi^* y_{b,n} + \cos \theta^* z_{b,n})),
\]

(3)

where \((\theta^*, \phi^*)\) denotes the target direction that the current antenna array points to.

Finally, the antenna gain \(G(\theta, \phi)\) can be calculated by

\[
G(\theta, \phi) = 20 \log_{10}|r|,
\]

(4)

and its pattern is drawn in Fig. 3 accordingly.
B. Path Loss Model

According to the Friss equation, the received signal strength (RSS) at an arbitrary STA, is given by

\[ RSS = P_{tx} + G(\theta, \phi) - \text{PathLoss}(d) + G_{rx}, \]  

(5)

where \( P_{tx} \) is the transmit power, \( G(\theta, \phi) \) in Eq. (4) and \( G_{rx} \) are the antenna gains at the transmitter side and the receiver side, respectively, \( d \) is the distance between them. Here, we assume that each STA is equipped with an omni-directional antenna, i.e., \( G_{rx} = 0 \) dBi.

Due to different numbers of STAs in different zones, APs 1 to 4 in Zone 1 and Zone 2 will be equipped with only one directional antenna and its main beam is pointing towards the centre of the aircraft. However, for AP 5 and AP 8 in Zone 3/4 and Zone 5/6, a 3-sector antenna is used to provide better quality of service (QoS) to as many passengers as possible in these regions. The main lobes of these three sectors are adjusted to point toward the left-corner, the centre and the right-corner of the corresponding zone, respectively. At each transmission, APs 5 to 8 select only one sector to communicate with its STAs based on the beamforming training results.

C. Prediction of In-cabin 60 GHz Radio Propagation

In this subsection, we propose an electromagnetic hybrid technique to predict the 60 GHz radio propagation characteristics in the aircraft cabin, which combines the integral equation (IE) method with the ray tracing (RT) technique.

1) IE method: The IE method is employed to model the transmitting antenna arrays as introduced in Section III-A. Normally, a microstrip antenna consists of conductor and dielectric objects which can be modeled by fictitious surfaces. Then, IEs are built up on these antenna surfaces and solved by standard method of moments (MoM) procedure. After that, the antenna parameters like three-dimensional (3D) radiation pattern will be determined accordingly.

2) Image based ray tracing technique: We also develop an image based ray tracing technique to model the 60 GHz radio propagation characteristics in aircraft cabin. The cabin walls, ceiling, and floor are modeled as multi-layer dielectric structures, where the cabin wall is considered as the glass fiber reinforced plastics (GRP), and the cabin ceiling and floor are considered as the carbon fiber reinforced plastics (CRP). Thus, the predicted reflections are computed accordingly.

Last, the predicted radio propagation characteristics will be shown in the performance evaluation part.

D. Customized In-cabin 60 GHz channel model

IEEE 802.11ad standard has considered three scenarios, including conference room, cubical environment and living room [6]. However, the cabin environment was not considered. In this subsection, we will use the inter cluster method to customize the 60 GHz channel model in aircraft cabin.

In IEEE 802.11ad channel model recommendation [6], it has been verified by several experimental measurements that the 60 GHz propagation channel is clustered. Therefore, we can obtain the inter cluster model parameters characterized by signal propagation paths as follows.

First, the realization of channel impulse responses is described by [6]

\[ h(t, \phi_{tx}, \theta_{tx}, \phi_{rx}, \theta_{rx}) = \sum_i A^{(i)} C^{(i)} (t - T^{(i)}), \]

\[ \phi_{tx} - \Phi^{(i)}_{tx}, \theta_{tx} - \Theta^{(i)}_{tx}, \phi_{rx} - \Phi^{(i)}_{rx}, \theta_{rx} - \Theta^{(i)}_{rx} \]  

(6)

where \( t, \phi_{tx}, \theta_{tx}, \phi_{rx}, \theta_{rx} \) are time, azimuth and elevation angles at the transmitter, and azimuth and elevation angles at the receiver, respectively; \( A^{(i)} \) and \( C^{(i)} \) are the gain and the channel impulse response for the \( i \)th cluster, respectively; \( T^{(i)} \), \( \Phi^{(i)}_{tx}, \Theta^{(i)}_{tx}, \Phi^{(i)}_{rx}, \Theta^{(i)}_{rx} \) are the time-angular coordinates of the \( i \)th cluster, respectively.

Second, based on the separation distance between the transmitting AP and the receiving STA, we classify the channel model into three scenarios: near, medium and far. The near scenario is illustrated in Fig. 4, where we show an example of the 1st order and 2nd order reflections among different clusters. Here, the 1st order reflection clusters come from walls, partitions, ceiling and floor, respectively, and the 2nd order reflection clusters come from wall-to-wall, floor-to-ceiling, and floor-to-wall, respectively.

Third, we generate in-cabin channel realizations for near scenario in Fig. 5 with consideration of both LOS and non-line-of-sight (NLOS) conditions. Obviously, NLOS case has higher average power attenuation and longer root-mean-squared (rms) delay spread than that of LOS case.

Last, in a similar way, we can generate the in-cabin channel realizations for medium and far scenarios accordingly.

IV. PERFORMANCE EVALUATION

In this section, we first evaluate the link level performance based on the in-cabin radio propagation characteristics and
channel model as derived in Section III. Then, we develop an event-driven 11ad-compliant WIFEC network simulator to evaluate the system level performance of the IEEE 802.11ad networks as deployed in Section II.

A. Link Level PER Performance

The system configurations in our physical (PHY) layer simulation are given by Table I. To support the transmission and reception of different types of frames, we study the control PHY modulation (i.e., modulation and coding set (MCS) 0) and the single carrier (SC) PHY modulations (i.e., MCSs 1-12) accordingly. Note that MCS 1-5 corresponds to the BPSK modulation, MCSs 6-9 corresponds to the QPSK modulation and MCSs 10-12 corresponds to the 16-QAM modulation [2].

Fig. 6 shows the packet error rate (PER) performance of Control PHY under near, medium and far scenarios. We can observe that to achieve 1% PER, the control PHY modulation requires very low signal-to-noise ratio (SNR) of around −9 dB for all scenarios. Fig. 7(a)-(c) shows the PER performance for SC PHY under near, medium and far scenarios, respectively. We can clearly see that the required SNR threshold for the same MCS increases as the transmission range increases from near to far. Moreover, as compared with the LOS condition, the NLOS performances for BPSK and QPSK modulations degrade only about 2-3.5 dB and 1.5-5 dB, respectively. However, for 16-QAM modulation, the NLOS performance severely degrades more than 9 dB.

For simplicity, we list the required SNR thresholds in Table II, where the maximum PER is targeted at 1%.

B. System Level Performance

1) Network Configurations: We use two YUV format video files [8] to simulate different types of WIFEC services such as video download from an arbitrary AP to its STAs. The first one is a standard definition (SD) video file named “Foreman” and the second one is a high definition (HD) video file named “Parkrun”. Here, “Foreman” has a total number of 300 frames with total size of 308 MB and frame rate of 30 frames per second (fps), and “Parkrun” has a total number of 500 frames with total size of 2.67 GB and frame rate of 25 fps. For transmission efficiency, the original files will be encoded into H.264 format [9] packets by the AP. At the receiver side, the STA will decode the received H.264 packets and recover them...
with error concealment techniques into the YUV file again to play individually.

For IEEE 802.11ad network configuration, we assume that each beacon interval (BI) is set to 100 ms, within which data transfer interval (DTI) is equally allocated to every STA as their service periods (SPs). The control frames such as beacon frames and beamforming training frames are transmitted by control PHY modulation, and the data frames are transmitted by SC PHY modulations. Moreover, the normal acknowledgement (ACK) policy is used and the MAC service data unit (MSDU) size is limited to 1472 bytes due to the length constraint of Ethernet frames. Other system configurations used in our simulations are summarized in Table III.

Furthermore, since 60 GHz radio signals are easily blocked by human body or trolley movement in aircraft cabin, we also consider the effects of blockage. According to [10], we can generate the blockage events by the assumptions that the mean time of blockage events is 0.5 second and the occurrence frequency is set to once per minute.

Last, we use AP 1 in the business cabin Zone 1 and AP 5 in the economic cabin Zone 3/4 to investigate the performance of IEEE 802.11ad networks. The related seat arrangements are introduced in Section II. Each STA will select only one AP.
IEEE standard for local and metropolitan area networks - part 11: STAs join in AP 5’s network, respectively.

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and different cabin zones.

Fig. 9. The achieved system level performance for different MCS values

to join its network based on the best received signal strength

under LOS condition as calculated by Eq. (5). By this network

selection criterion, 15 STAs join in the AP 1’s network and 62 STAs join in AP 5’s network, respectively.

2) System Performance: Based on the directional antenna model, pass loss model and predicted in-cabin radio signal propagation characteristics in Sections III, we draw the Figs. 8(a)-8(c) to show the RSS value (represented by SNR) at each STA when the corresponding AP is transmitting. As a result, for given SNR and MCS value, whether an on-going packet can be transmitted successfully or not will depend on the corresponding PER value as given in Figs. 6 and 7.

Considering different MCS values and different cabin zones, the achieved channel utilization rates and the average packet drop rates for SD and HD video services are shown in Fig. 9(a) and Fig. 9(b), respectively. Here, the channel utilization rate reflects the network load under the selected modulation, and the average packet drop rate reflects the QoS of video reception. Normally, the packet drop has two reasons: 1) The transmission times extend the packet retry limit, which is due to the fact that the RSS is too weak to meet the minimum SNR requirement of the selected modulation as listed in Table II. For example, the blockage occurs or the current adopted MCS value is too high. 2) The transmission time is beyond the packet delay constraint, which is due to the insufficient network capability. In other words, the AP cannot allocate sufficient SPs to so many STAs for the selected MCS and support their WIFEC services at the same time.

From Fig. 9, we can see that the SD service is well supported in both cabins, where the related channel utilization rate and average packet drop rate are quite low. This is because the number of generated packets for this service is not too much. The only exception is MCS 12, which results in high packet drop rate due to the higher SNR requirement as explained by Reason 1. However, for HD service, the channel utilization rate and the average packet drop rate dramatically increase, especially at lower MCS area (due to aforementioned Reason 2) and higher MCS area (due to aforementioned Reason 1).

To optimize the system level performance, we consider to implement the rate adaption (RA) scheme [2] by which the most suitable MCS value will be selected for the on-going transmission based on the received SNR of the previous transmission. From both Figs. 9(a) and 9(b), we can see that the RA scheme does achieve better balance between the network load and the QoS of video transmission than other fixed modulation schemes, which validates the fact that IEEE 802.11ad network is applicable to the VHT WIFEC system.

V. CONCLUSIONS

In this paper, we have studied the IEEE 802.11ad networks in cabin environment. For a typical airplane layout, we have proposed the suitable network deployment and predicted the in-cabin 60 GHz radio propagation characteristics as well as the channel model. We have validated that the IEEE 802.11ad network is applicable to the VHT WIFEC system. With consideration of blockage effects, we have studied the performance optimization by using the rate adaption scheme.

REFERENCES


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