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Interference impacts on 60 ghz real-time online video streaming in wireless smart tv platforms

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Abstract In this paper we provide a method for computing and estimating the impact of interference on real-time online 1080p@30Hz and 1080p@60Hz high-definition video streaming in 60 GHz wireless smart TV platforms. The analysis involves two different interference scenarios: 1) downlink interference from deployed 60 GHz access points to the associated mobile ad-hoc devices, and 2) uplink interference from randomly deployed 60 GHz ad-hoc mobile devices to their associated access points. With these interference scenarios, the interference impact on the quality of main 1080p@30Hz and 1080p@60Hz wireless high-definition video streaming with various simulation settings are measured and estimated in terms of signal-to-interference-plus-noise ratio.

Keywords Smart TV platforms · Video streaming · Interference · 60 GHz · IEEE 802.11ad

1 Introduction

Smart TV and related technologies and applications have received a lot of attention by consumer electronics companies and the research community, where many areas are explored including automatic video annotation [6], enhanced signal processing techniques for audio and video processing [19], human computer interaction (HCI) [11, 21], home entertainment with smart TV platforms [2], and so forth. Besides these directions, one of the most

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promising research topics related to wireless communications is rich media transmission from set-top box to smart TV wireless display—wireless smart TV platforms as can be seen in [3, 10, 12, 14, 22], a closely related trend to video communications and networks over randomly deployed wireless devices [1, 16, 23, 24].

To transmit 1080p@30Hz high-definition video streams in a real-time online manner over the wireless medium for smart TV platforms, 1.5 gigabit/s (Gbps) data rates are required as discussed in [7–9]. For that, a single 1080p video frame consists of 1080×1920 pixels and each pixel consists of 24 bits in an RGB format (8 bits for each red, green, and blue color representation). In addition, 30 frames are transmitted in a second for 1080p@30Hz, thus 1.5 Gbps is required for uncompressed 1080p@30Hz high-definition wireless video streaming. Similarly, approximately 3 Gbps is required for uncompressed 1080p@60Hz high-definition wireless video streaming. Among currently available wireless technologies, only 60 GHz wireless technology can support more than 1.5 Gbps or 3 Gbps data rates. This 60 GHz multi-Gbps wireless technology was initiated with the name of WirelessHD [3], which also aimed to enable the wireless and real-time 1080p high-definition video transmission from set-top box to wireless TV display. Because of the benefits of this multi-Gbps wireless technology, IEEE 802.11 wireless local area networks (WLANs) standard groups also organize 60 GHz standards named IEEE 802.11ad Vey High Throughput (VHT) [18], therefore 60 GHz mm-wave WLAN access points (APs) can be deployed for multi-Gbps services with associated mobile and wireless devices such as mobile smartphones, mobile laptops, tablets, and so forth. Despite this activity, less work is done on understanding the quality of 1080p@30Hz high-definition streaming for wireless transmission under interference conditions.

This paper analyzes the quality of 1080p@30Hz high-definition real-time online video streaming for wireless transmission from a set-top box to wireless TV display when there is interference from nearby IEEE 802.11ad-capable devices including APs, mobile smartphones, laptops, tablets, and so forth. As shown in [1], the impact of interference should be precisely measured in video-aware wireless networks for user satisfaction and quality-of-experience (QoE). For more precise analysis of the impact of interference, two separate interference scenarios are taken into account: 1) the downlink interference which occurs because of the transmission from IEEE 802.11ad APs to the associated IEEE 802.11ad-capable devices and, 2) the uplink interference which occurs because of the wireless transmission from IEEE 802.11ad-capable consumer electronics devices to the associated IEEE 802.11ad APs. Note that the uplink transmission mechanism involves transmit power control in each non-AP mobile wireless device.

This analysis is essential to justify the use of wireless smart TV platforms, and to support the quality of 60 GHz wireless video streaming against potential interference sources. If the generated interference by nearby wireless devices is too high, it negatively impacts the quality of wireless smart TV video streaming from set-top box to the wireless TV display, which would discourage users from adopting wireless smart TV over the traditional TV using HDMI cables for the connection between set-top box and wireless TV display. Thus, this research is worthy in addressing this essential problem, and is considered as a first step for the understanding of wireless smart TV platforms.

The remainder of this paper is organized as follows: Section 2 presents preliminaries for the computation of interference on 60 GHz indoor wireless video streaming including reference network models, path-loss models, and antenna radiation patterns in azimuth and elevation planes. Section 3 computes the maximum achievable rates of the main video streaming link when there is interference in 60 GHz wireless channels. Section 4 presents simulation results and Section 6 concludes this paper.

2 Preliminaries

This section describes a reference home network model (Section 2.1), reference 60 GHz IEEE 802.11ad path-loss models (Section 2.2), and reference 60 GHz IEEE 802.11ad antenna radiation patterns (Section 2.3), respectively.

2.1 A reference in-home network architecture

The reference in-home network architecture considered in this work is illustrated in Fig. 1. In this architecture, there is one main wireless 1080p high-definition video transmission from set-top box to wireless smart TV display. As presented in Section 1, 60 GHz mm-wave wireless technology is used for this transmission. Note that common systems may not be limited to this wireless transmission, since there may be several 60 GHz wireless communication systems within a single home. As shown in Fig. 1, there is one 60 GHz IEEE 802.11ad-enabled AP within the illustrated home. In addition, there are several ad-hoc 60 GHz IEEE 802.11ad-capable mobile and wireless consumer electronics devices, including mobile smartphones, laptops, tablets, and so forth. The transmission from AP to associated mobile devices is named *downlink transmission* and the transmission from mobile devices to AP is named *uplink transmission*, in this paper.

When the AP is transmitting data to one of the randomly deployed ad-hoc mobile devices, the radio propagation generates interference to the main video streaming wireless link from set-top box to wireless smart TV display. This is called the *downlink interference*. On the other hand, when the mobile platforms are transmitting data to the AP, the radio propagation also generates interference to the wireless high-definition video streaming from set-top box to wireless smart TV display. This is called the *uplink interference* in this paper.

Fig. 1 A reference in-home network model

2.2 Reference IEEE 802.11ad path-loss models

Because high carrier frequency wireless systems have notable wireless propagation characteristics, considering precise and standardized wireless models is important. IEEE 802.11ad path-loss models are defined for both line-of-sight (LOS) and non-line-of-sight (NLOS). Therefore, the IEEE 802.11ad path-loss model with LOS situation as follows [15]:

$$PL_{\text{LOS}}(d) = A + 20\log_{10}(f) + 10n\log_{10}(d) \tag{1}$$

in a dB scale where $A = 32.5$ dB which is a specific value for the selected type of antenna and beamforming algorithms, which depends on the antenna beamwidth but for the considered beam range from 60° to 10° the variance is very small—less than 0.1 dB. In Eq. 1, n refers to the path-loss coefficient where it is set to 2, and f stands for a carrier frequency in GHz, and is set to 60. Note that there is no shadowing effect in LOS path-loss model as presented in [15]. This LOS path-loss model is used for the wireless transmission from set-top box to wireless display because the radio link is generally LOS. As described in Section 2.1, the considered network model is indoor. Therefore, the IEEE 802.11ad path-loss model with NLOS situation is also considered for the nearby consumer electronics devices with 60 GHz radio. The corresponding model is formulated as follows [15]:

$$PL_{\text{NLOS}}(d) = A + 20\log_{10}(f) + 10n\log_{10}(d) + X_\sigma \tag{2}$$

$PL_{\text{NLOS}}(d)$ is in dB, where $A = 51.5$ dB is a value for the selected type of antenna and beamforming schemes, which depends on the antenna beamwidth and the variance is very small—less than 0.1 dB in the considered beam range from 60° to 10°. In Eq. 2, $n = 0.6$ and $f = 60$, where they are defined as above. Last, X_σ stands for the shadowing effects due to NLOS, which can be calculated by Gaussian distribution with zero mean and standard deviation σ, where $\sigma = 3.3$ dB. The IEEE 802.11ad path-loss model in NLOS has a randomness of X_σ, i.e., the average behaviors of IEEE 802.11ad NLOS path-loss model is also plotted.

Because we are considering the network model in Section 2.1 for an indoor environment, the average of IEEE 802.11ad NLOS path-loss model is used for formulating between APs and their associated mobile stations. In addition, the IEEE 802.11ad LOS path-loss model is used for formulating the path-loss between set-top box and wireless TV display because there are no obstacles between set-top box and the wireless TV display, in general.

2.3 Reference IEEE 802.11ad antenna models

The reference 60 GHz IEEE 802.11ad VHT antenna radiation pattern model is derived from the standard document approved by the International Telecommunication Union (ITU) [5]. According to that models, the antenna gain that depends on azimuth and elevation angles is represented as follows:

$$G(\varphi, \theta) = \begin{cases} G_{\max} - 12|x|^2, & 0 \le x < 1, \\ G_{\max} - 12 - 15\ln|x|, & 1 \le x, \end{cases} \tag{3}$$

where $G_{\max}$, φ, and θ represent a maximum antenna gain, an azimuth angle ($-180° \le \varphi \le 180°$), and an elevation angle ($-90° \le \theta \le 90°$), respectively. In this equation, x can be obtained as follows:

$$x = \Psi / \Psi_\alpha \tag{4}$$

where Ψ and Ψ_α can be computed as follows:

$$\Psi = \cos^{-1}(\cos\varphi\cos\theta), 0^\circ \le \Psi \le 180^\circ \tag{5}$$

and

$$\Psi_\alpha = \frac{1}{\sqrt{\left(\frac{\cos\alpha}{\varphi_3}\right)^2 + \left(\frac{\sin\alpha}{\theta_3}\right)^2}} \tag{6}$$

where φ_3 and θ_3 stand for the 3 dB half-power beam-width in azimuth and elevation planes (unit: degrees). Last, α in Eq. 6 can be calculated as follows:

$$\alpha = \tan^{-1}\left(\frac{\tan\theta}{\sin\varphi}\right). \tag{7}$$

According to this computation process, the reference high-directional antenna radiation patterns can be derived as shown in Fig. 2 (2D planes). Note that φ_3 and θ_3 are set to 45° in these figures because of the size limitation of home entertainment network systems. For the performance evaluation, various φ_3 and θ_3 values are considered. Figure 2 shows the separated plotting in terms of azimuth and elevation planes.

These antenna patterns are used for all consumer electronics devices equipped with 60 GHz mm-wave radio including set-top box, wireless display, IEEE 802.11ad-enabled devices (i.e., APs, mobile smartphones, laptops, and tablets).

3 Achievable rate computation

This section presents the procedure for achievable rate computation. First of all, the achievable rate R can be obtained as follows:

$$R = B\log_2(SINR + 1) \tag{8}$$

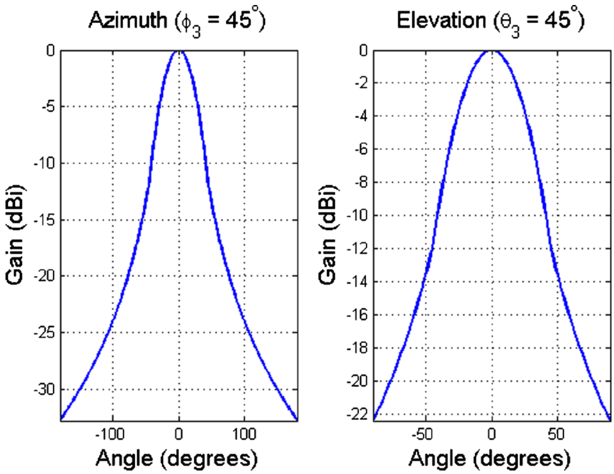

Fig. 2 60 GHz reference antenna radiation patterns in 2D azimuth and elevation planes where G_{max} is set to 0 dBi without loss of generality

where B stands for the bandwidth and this value is set to 2.16 GHz in the IEEE 802.11ad standard as presented in [7–9]. SINR in Eq. 8 stands for the signal-to-interference-plus-noise-ratio, which can be computed as follows:

$$SINR = \frac{S}{I + N} \tag{9}$$

in a linear scale where S stands for the received signal strength at the receiver of main video streaming (i.e., wireless high-definition display equipped with IEEE 802.11ad radio frequency (RF) front-end) from the transmitter of main video streaming (i.e., wireless set-top box equipped with IEEE 802.11ad RF front-end). In addition, I is the accumulated interference from nearby IEEE 802.11ad-enabled consumer electronics devices including mobile phones, laptop, and so forth. Last, N is a normalized noise factor in the air where this value is generally considered as a Gaussian distribution with 0 mean and 1 standard deviation.

Section 3.1 presents the numerical procedure to compute the signal strength of main video streaming from set-top box to wireless display, i.e., S, and Sections 3.2 and 3.3 explain the procedure for calculating uplink and downlink interference, i.e., I, respectively.

3.1 Main video streaming signal strength over 60 GHz

The received signal strength of wireless video streaming from set-top box to HDTV display can be computed as follows:

$$S = G_{\mathrm{TX}}^{\mathrm{main}} + P_{\mathrm{TX}}^{\mathrm{main}} - PL_{\mathrm{LOS}}\left(d_{\mathrm{RX}}^{\mathrm{TX}}\right) + G_{\mathrm{RX}}^{\mathrm{main}} \tag{10}$$

in a dB scale where $G_{\mathrm{TX}}^{\mathrm{main}}$ and $G_{\mathrm{RX}}^{\mathrm{main}}$ stand for the transmit and receive antenna gain of main 60 GHz 1080p high-definition wireless video streaming from set-top box (i.e., transmitter) to wireless display (i.e., receiver) and both are set to 22 dBi [20]. In addition, $P_{\mathrm{TX}}^{\mathrm{main}}$ is transmit power at the set-top box, and this is set to 14 dBm [17]. Last, $PL_{\mathrm{LOS}}\left(d_{\mathrm{RX}}^{\mathrm{TX}}\right)$ is a path-loss model from the set-top box to the wireless TV display. This path-loss model is for LOS as formulated in Eq. 1 because there are no obstacles between set-top box and wireless TV display. In general, the distance between set-top box and wireless display is around 5 meters in home entertainment networks, i.e., $d_{\mathrm{RX}}^{\mathrm{TX}} = 5$.

3.2 Downlink interference

The downlink interference is defined as follows. As shown in Fig. 1, the IEEE 802.11ad-enabled AP is a source for downlink high-volume data transmission toward the associated stations including mobile smartphones, laptops, tablets, etc. Thus, the multiple transmit antennas of the AP are pointing towards the receivers of associated mobile devices. Assume that there are no antenna misalignments in this interference analysis and simulation. Then, the interference from each transmit antenna of the AP can be calculated as:

$$I_i^{\mathrm{Donwlink}} = G_{\mathrm{TX}}^{\mathrm{AP}}\left(\varphi^+, \theta^+\right) + P_{\mathrm{TX}}^{\mathrm{AP}} - PL_{\mathrm{NLOS}}\left(d_{\mathrm{RX}}^{\mathrm{AP}}\right) + G_{\mathrm{RX}}^{\mathrm{main}}\left(\varphi^*, \theta^*\right), \tag{11}$$

in a dB scale where $P_{\mathrm{TX}}^{\mathrm{AP}}$ stands for the transmit power of IEEE 802.11ad AP, and it is set to 10 dBm, i.e., 10 mWatt [20]. In addition, $PL_{\mathrm{NLOS}}\left(d_{\mathrm{RX}}^{\mathrm{AP}}\right)$ is a path-loss model from the AP to the wireless TV display. This path-loss model is for NLOS as formulated in (2) because there are potential obstacles or penetration loss between the AP and the wireless smart TV display in indoor wireless networks. $G_{\mathrm{TX}}^{\mathrm{AP}}\left(\varphi^+, \theta^+\right)$ is the antenna radiation gain from IEEE 802.11ad AP towards the receiver of main video streaming, i.e., wireless smart

TV display, while it is aligned with its associated mobile stations. While the antenna of the IEEE 802.11ad AP is facing its associated mobile station, the aligned 60 GHz receive antenna beam generates interference to the receive antenna at wireless smart TV display as shown in Fig. 3. Similarly, $G_{\text{RX}}^{\text{main}}(\varphi^*, \theta^*)$ is the receive antenna gain at the wireless smart TV display from downlink interference. While the receive antenna is facing the transmit antenna, the receive antenna beam overhears interference occurred by the transmission from IEEE 802.11ad AP to its associated mobile devices as shown in Fig. 3.

After calculating individual downlink interference, the overall downlink interference can be obtained by adding the individual downlink interference as follows:

$$I = \sum_{\forall i} I_i^{\text{Downlink}}, \tag{12}$$

which is measured in a linear scale where i stands for the index of all given wireless links of downlink interference.

3.3 Uplink interference with power control

The uplink interference is defined as follows in this paper. As illustrated in Fig. 1, the non-AP IEEE 802.11ad-capable mobile platforms are the sources of wireless transmission to their associated IEEE 802.11ad AP. Then, the interference from mobile platforms to the antennas at the AP can be calculated as follows:

$$I_i^{\text{Uplink}} = G_{\text{TX}}^{\text{STA}}\left(\varphi^+, \theta^+\right) + P_{\text{TX}}^{\text{STA}} - PL_{\text{NLOS}}\left(d_{\text{RX}}^{\text{STA}}\right) + G_{\text{RX}}^{\text{main}}\left(\varphi^*, \theta^*\right), \tag{13}$$

in a dB scale, where $PL_{\text{NLOS}}\left(d_{\text{RX}}^{\text{STA}}\right)$ is a path-loss model from the mobile stations to the wireless TV display. This path-loss model is for NLOS as formulated in (2) because there

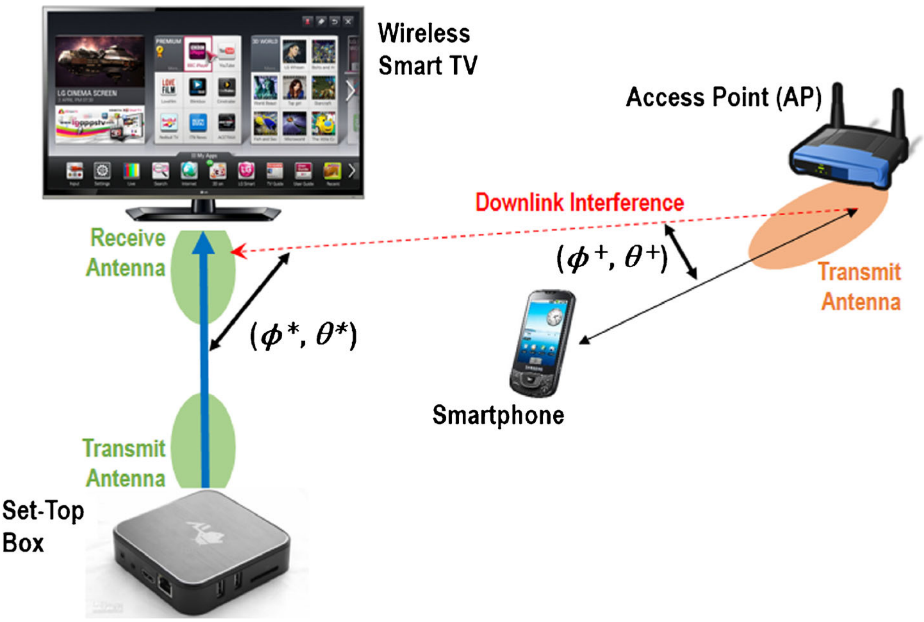

Fig. 3 Downlink interference scenario

are potential obstacles or penetration loss between the mobile stations and the wireless smart TV display. $G_{\mathrm{TX}}^{\mathrm{STA}}\left(\varphi^{+},\theta^{+}\right)$ is the antenna radiation gain from IEEE 802.11ad non-AP mobile station towards the receiver of the main video streaming, i.e., wireless smart TV display, while it is aligned with its associated IEEE 802.11ad AP. While the antenna of the IEEE 802.11ad mobile station is facing its associated AP, the aligned 60 GHz receive antenna beam generates interference to the receive antenna at the wireless smart TV display as shown in Fig. 4. In addition, $G_{\mathrm{RX}}^{\mathrm{main}}(\varphi^{*},\theta^{*})$ is the receive antenna gain at the wireless smart TV display from uplink interference, and this receive antenna at the wireless smart TV display is aligned with the transmit antenna at the transmitter of the video streaming, i.e., set-top box. While the receive antenna is facing the transmit antenna, the 60 GHz receive antenna beam overhears interference occurred by the transmission from 60 GHz IEEE 802.11ad-capable consumer mobile stations to their associated 60 GHz IEEE 802.11ad AP as can be seen in Fig. 4.

Last, $P_{\mathrm{TX}}^{\mathrm{STA}}$ in Eq. 13 stands for the transmit power of IEEE 802.11ad non-AP mobile stations to their associated IEEE 802.11ad AP. In the case of uplink interference, uplink transmit power control at non-AP stations is introduced. The considered uplink transmit power control for computing $P_{\mathrm{TX}}^{\mathrm{STA}}$ is adopted from the LTE device uplink power control that can be formulated as follows [25]:

$$P_{\max}^{\mathrm{STA}}\cdot\min\left[1,\max\left\{R_{\min},\left(\frac{PL_{\mathrm{NLOS}}\left(d_{\mathrm{RX}}^{\mathrm{STA}}\right)}{PL_{x-ile}}\right)^{\gamma}\right\}\right] \tag{14}$$

in a linear scale, where $R_{\min}=P_{\min}^{\mathrm{STA}}P_{\max}^{\mathrm{STA}}$ in a linear scale which is equal to $P_{\min}^{\mathrm{STA}}-P_{\max}^{\mathrm{STA}}$ in a dB scale. The $P_{\min}^{\mathrm{STA}}$ and $P_{\max}^{\mathrm{STA}}$ are set to -40 dBm and 24 dBm in this paper. This $R_{\min}$ stands for the minimum power reduction radio to prevent the mobile devices with good channels to do video streaming at very low power level. In Eq. 14, PL_{x-ile} is the x

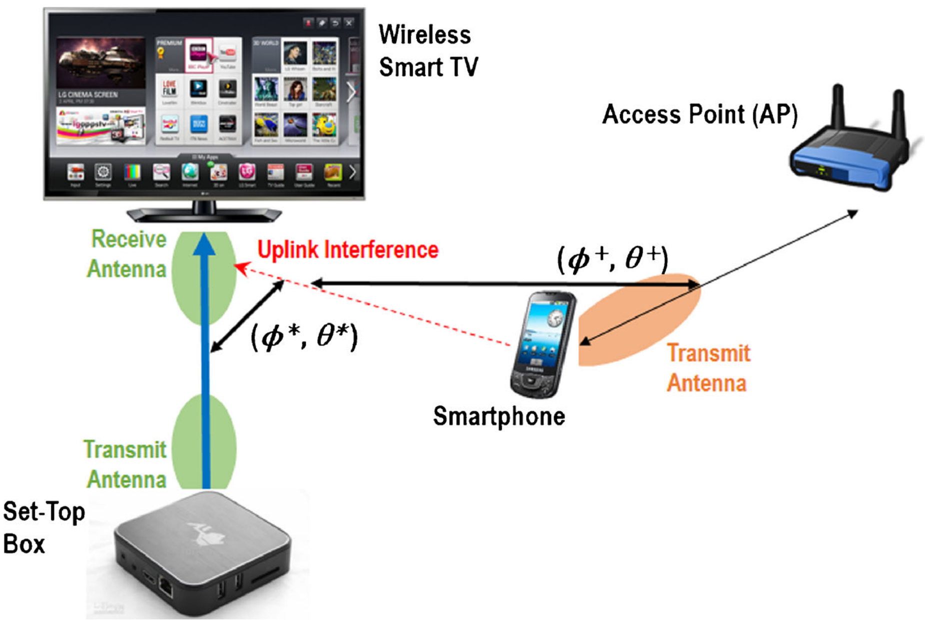

Fig. 4 Uplink interference scenario

percentile path-loss including shadowing effects and it is set to 98 dB. In Eq. 14, γ stands for the balancing factor for the mobile devices with good channels and the mobile devices with bad channels where $0 < \gamma \leq 1$.

After calculating individual uplink interference, the overall uplink interference can be obtained by adding the individual uplink interference as follows:

$$I = \sum_{\forall i} I_i^{\text{Uplink}}, \tag{15}$$

in a linear scale where i stands for the index of all given wireless links of uplink interference.

4 Simulation study

This section provides intensive simulations with the given radio characteristics in Section 2 and the computational procedures of the achievable data rate of the main video streaming wireless link from set-top box to wireless smart TV display in Section 3. Section 4.1 describes the network topology for this interference simulation study. Based on the given topology in Section 4.1, the impacts on the quality of high-definition video streaming from downlink interference and uplink interference are presented in Section 4.2 and Section 4.3, respectively. Because of the randomness of locations of the mobile associated devices and APs, the azimuth and elevation angle directions of antenna radiation patterns are also random. Therefore, Monte Carlo simulation was performed for evaluating the impacts of interference. For the Monte Carlo simulation, 100 different random deployments are considered and eventually the results are averaged.

For the two different uplink and downlink interference scenarios, the quality of main video streaming link is measured in terms of (i) various numbers of associated mobile stations in each AP, (ii) various numbers of APs, and (iii) various transmit power at APs (only for downlink interference simulation).

4.1 Simulation topology

The basic simulation topology is shown in Fig. 5.

As can be seen in Fig. 5, the size of the network is 15×12 square meters, and the main video streaming link is located at the center of the network with the distance of 5 meters. In addition, the IEEE 802.11ad APs are uniformly deployed around the corners of the network. Last, the mobile devices which are associated with the APs are randomly deployed within the network.

4.2 Achievable rates with downlink interference

This section discusses the impacts of downlink interference on the main video streaming wireless link from the set-top box to wireless TV display.

For the first part, the interference impacts on the achievable rates of the main video streaming link are measured while the number of associated mobile devices in each AP are varying from 1 to 9. Note that 3 APs are deployed in the reference in-home network. For the system parameter settings, the transmit and receive antenna gains of the main streaming wireless link are 22 dBi, the transmit power at the set-top box is 14 dBm, the φ_3 and θ_3 of all given devices including set-top box, wireless TV display, mobile devices, and APs are 60°. The transmit powers at APs and mobile devices are 10 dBm, the transmit and receive

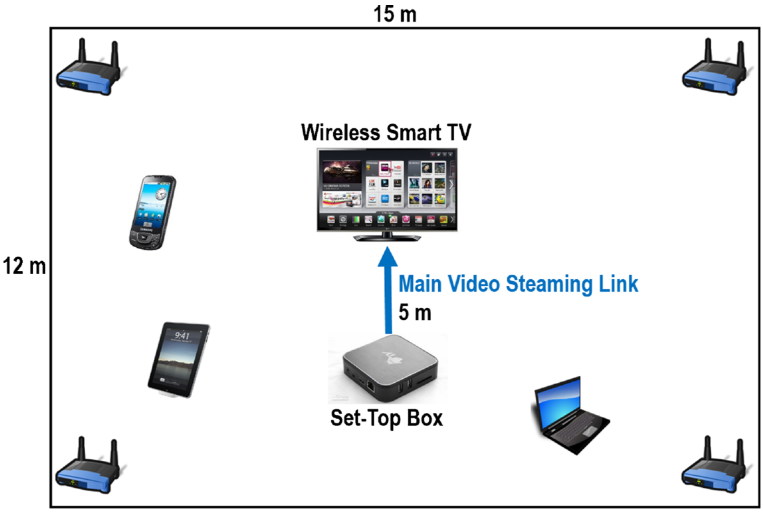

Fig. 5 Basic simulation topology

antenna gains of APs and mobile devices are all 10 dBi. Last, the heights of set-top box and wireless TV display are 0.3 meter, the heights of APs are 3 meters, and the heights of mobile devices are 1.5 meters. Then, the simulation results are as shown in Fig. 6.

As shown in Fig. 6, if the number of the associated mobile devices is equal to or less than 5 in all given 3 APs (totally 15 mobile stations), uncompressed 1080p@30Hz video streaming is possible. Even if the number is equal to or less than 9, we can stream 1080p@30Hz video signals without any loss using entropy coding. Note that entropy coding can compress video signals up to 50 % without information/quality loss [4]. Similarly, 1080p@60Hz

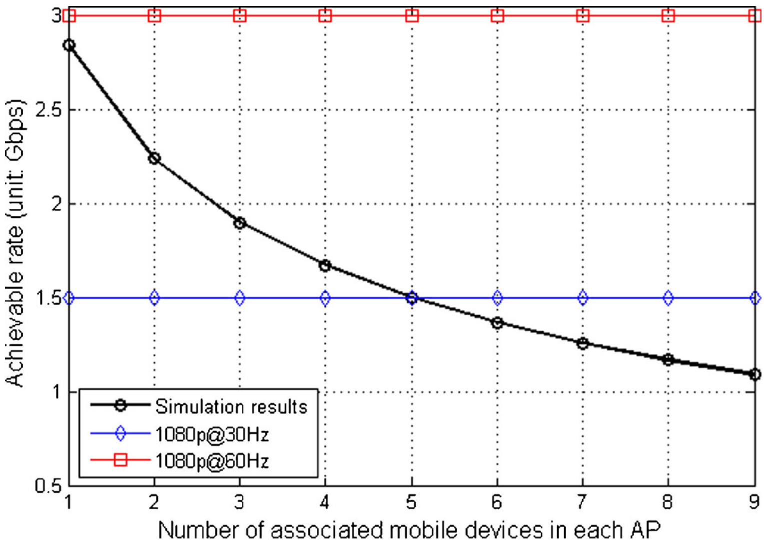

Fig. 6 Main video streaming quality degradation due to the downlink interference with various number of associated mobile devices in each AP

video signals can be streamed until the number of associated mobile devices in each AP (where the number of APs is 3) is 5 without data/quality loss using entropy coding. If the number of associated mobile devices in each AP exceeds 5, then the wireless TV display starts to show the loss of video streaming qualities.

Next, the simulation is performed with various numbers of APs where each AP is associated with 3 mobile devices. The other settings are same as in the previous simulation. The simulation result is shown in Fig. 7.

As shown in Fig. 7, if the number of APs is equal to or less than 2, 1080p@60Hz can be streamed without compression. In addition, if the number of APs is equal to or less than 5, 1080p@60Hz with lossless entropy coding and uncompressed 1080p@30Hz video streaming are available. If there are more than 5 and less than 9 APs, the quality loss over 1080p@60Hz will happen and lossless 1080p@30Hz with entropy coding is available. Interestingly, the achievable rate when the number of APs was 3 is smaller than the achievable rate when the number of APs was 4. As shown in Fig. 8, if there are three APs in the network one of the APs (i.e., AP3 in the left side of Fig. 8) will be very near the wireless TV display (i.e., receiver of the main streaming wireless link) which can generate more interference impacts. Therefore, it is possible to generate more interference impacts even with APs according to the deployment geometry and settings.

According to the various settings of transmit powers at APs, achievable rates can be varied as shown in Fig. 9. For this simulation, 3 APs are deployed in the network and each AP is associated with 3 mobile devices. If the transmit powers at APs are equal to or less than 12 dBm, uncompressed 1080p@30Hz video streaming and lossless 1080p@60Hz with entropy coding are available. In addition, if the transmit powers at APs are between 12 dBm and 18 dBm, lossless 1080p@30Hz video streaming with entropy coding is possible. However, 1080p@60Hz video streaming will start to have noise and quality degradation. If the transmit powers at APs are more than 18 dBm, then 1080p@30Hz video streaming will also start to have quality degradation over the main video streaming wireless link.

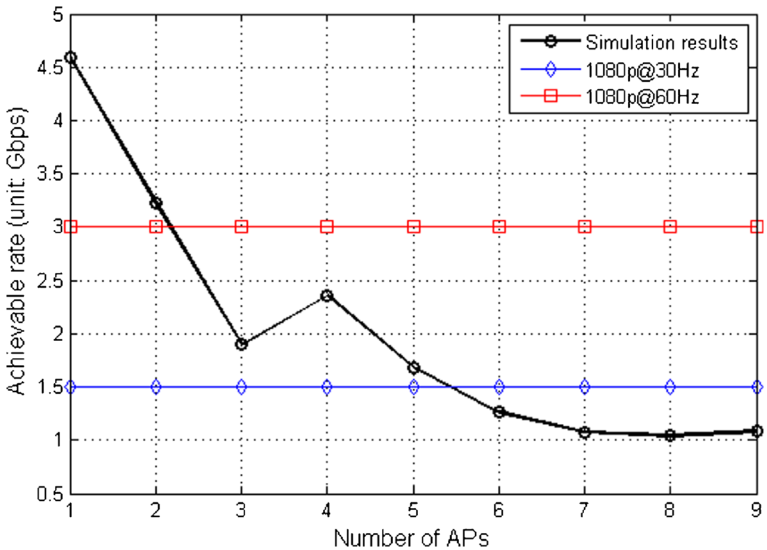

Fig. 7 Main video streaming quality degradation due to the downlink interference with various number of APs

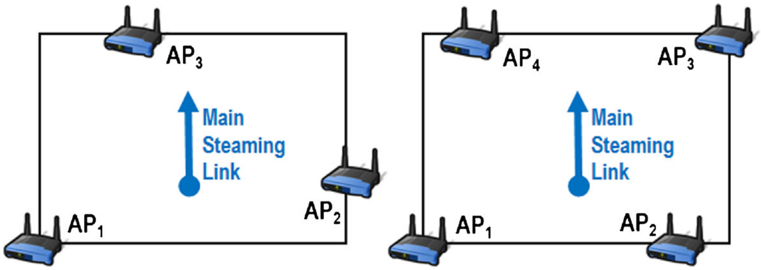

Fig. 8 Network topology when the numbers of APs are 3 (left) and 4 (right), respectively

4.3 Achievable rates with uplink interference

This section discusses the impacts of uplink interference, i.e., interference occurred by the transmission from mobile devices to their associated APs, to the main wireless video streaming from set-top box to wireless display.

First of all, the interference impacts on the achievable rates of the main video streaming link are measured while the number of mobile devices in each AP are varying from 16 to 24. In addition, 3 APs are deployed in the network and the transmit power at each AP is set to 10 dBm. The transmit power of main video streaming transmitter, i.e., set-top box, is set to 14 dBm and the transmit and receive antenna gains at the main link are set to 22 dBi. The transmit and receive antenna gains in APs and mobile devices are 10 dBi.

In addition, to be used in the power control mechanism at the mobile stations, the maximum transmit powers are set to 10 dBm and the minimum transmit powers are set to −40 dBm. Then, the received power at the main video streaming link, i.e., interference on the main link, can be reduced according to the transmit power control.

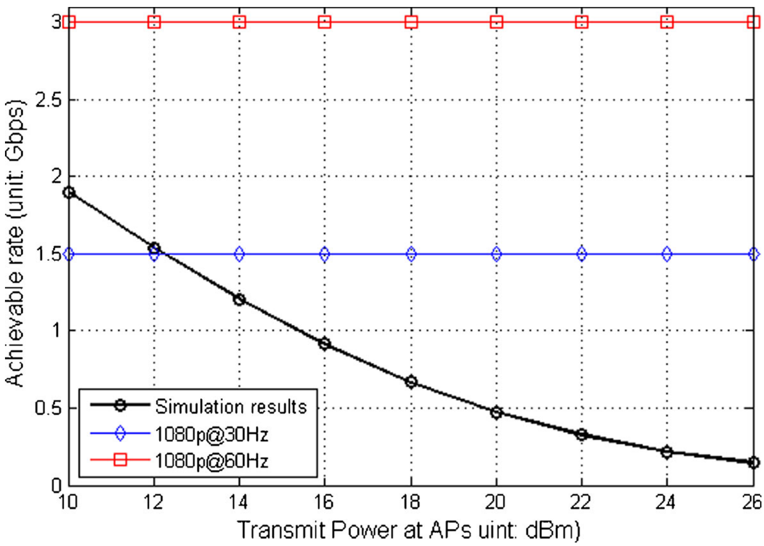

Fig. 9 Main video streaming quality degradation due to the downlink interference with various transmit power settings at APs

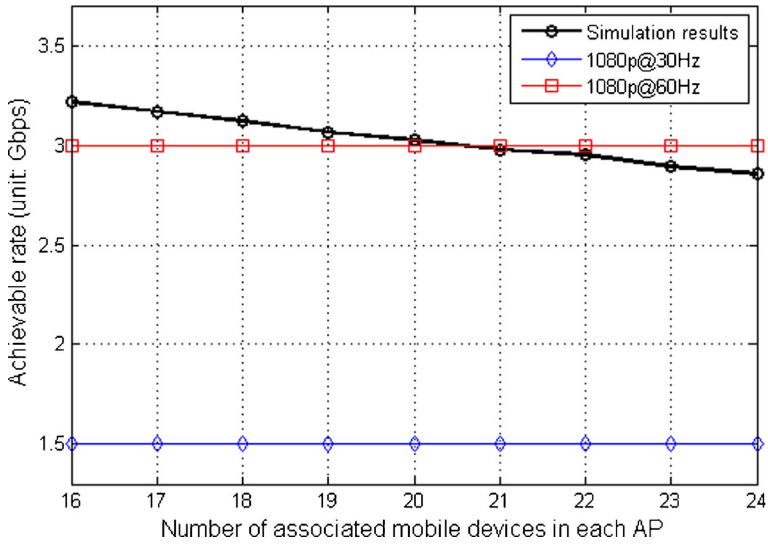

Fig. 10 Main video streaming quality degradation due to the uplink interference with various number of associated mobile devices in each AP

As shown in Fig. 10, even when there are around 20 devices in each AP, the interference impacts are not harmful in terms of the quality degradation over the main video streaming wireless link. If the number of associated mobile devices in each AP is equal to or less than 20, uncompressed 1080p@60Hz and 1080p@30Hz video streaming are possible. Moreover, even if the number of associated mobile devices is more than 20, it is still possible to provide

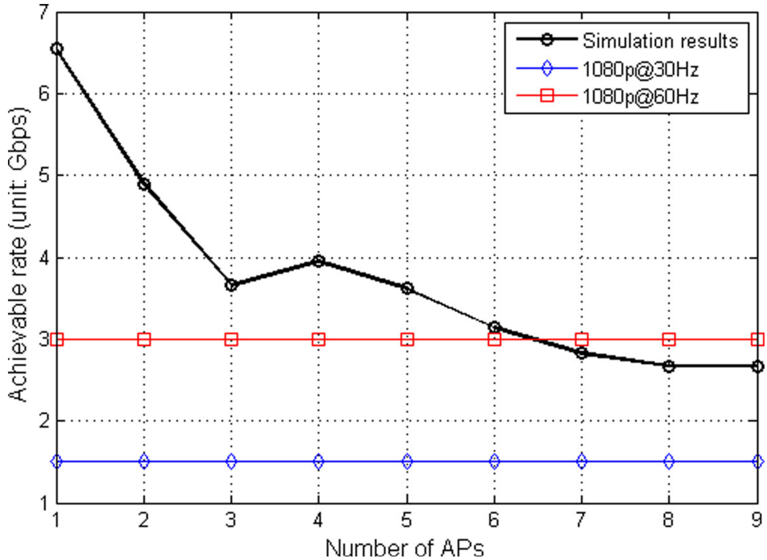

Fig. 11 Main video streaming quality degradation due to the uplink interference with various number of APs

reasonable qualities because the entropy coded 1080p@60Hz and 1080p@30Hz without compression are available.

In Fig. 11, the impact of uplink interference on main video streaming wireless link when the numbers of APs varies between 1 and 9 is simulated. In this simulation, each AP is associated with 10 mobile devices. As can be seen in Fig. 11, all simulation results show that 1080p@30Hz uncompressed video streaming is possible. 1080p@60Hz uncompressed video streaming is also possible when the number of APs is equal to or less than 6. In addition, 1080p@60Hz with entropy coding is available until the number of APs is 9. Therefore, all simulation results have no quality degradation due to lossy video coding.

5 Discussions

The simulated and presented results provide the baseline interference impacts, i.e., there is no consideration of interference suppression methods and particular modulation and coding schemes. Therefore, the communication system engineers can numerically estimate the baseline interference amounts as presented in this paper, and then they can design suitable interference suppression methods, modulation schemes, and coding techniques.

In mobile environments (e.g., train wagon, bus, ferry, etc), additional factors should be considered, including the time required for beamforming training. As discussed in Section 2.3, the considered 60 GHz antenna patterns are quite directional. Thus, finding the maximum SNR directions between TX and RX takes a lot of time which is quite challenging in mobile service supports. Thus, this factor should be additionally considered along with interference impact calculation. More details about this fast beam training in 60 GHz wireless systems are presented in [13].

6 Conclusions and future work

This paper computes and estimates the impacts of interference on 60 GHz multi-Gbps wireless high-definition real-time online video streaming from set-top box to wireless HDTV display. For the computation of interference impacts, standardized path-loss models and practical high-directional antenna radiation patterns are used. In addition, two differentiated interference scenarios are considered: the downlink and uplink. As can be seen in the simulation results, 1080p@60Hz and 1080p@30Hz video streaming without quality degradation is possible with uncompressed video streaming and lossless entropy coding, in general.

As a future research direction, various antenna types can be considered in addition to the standardized reference antenna radiation patterns studied in this work. Furthermore, hybrid indoor and outdoor network scenarios are to be considered because IEEE 802.11ad APs can be deployed outdoor as well.

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