Interference-Free Coexistence among Heterogenous Devices in the 60 GHz Band

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Abstract. With its abundant bandwidth and worldwide availability, the 60 GHz band has been considered as a promising solution to provide multi-Gbps wireless transmission. Different standard bodies and industrial interest groups start various projects to develop technologies in the 60 GHz band for applications such as high-definition (HD) and fast file transfer. However, until now very little efforts are made to ensure interference-free coexistence between these technologies. In this paper, we investigate the interference problem in the 60 GHz band. The ECMA-387 standard is used as a study case to illustrate how some simple techniques can mitigate the interference among heterogenous devices in the 60 GHz band. We conduct both mathematical analysis and simulations to demonstrate the performance of these simple techniques and identify some problems for future improvements.

Keywords: heterogenous, interference, coexistence, wireless PANs.

1 Introduction

In the last decade, data rates and file sizes of multimedia applications have increased substantially. These applications drive the data rate beyond the megabit-per-second (Mbps) level to a formidable gigabit-per-second (Gbps) level. Take high definition (HD) video as an example. The raw data rate of a full HD video with a resolution of 1920*1080 pixels is as high as 2.98 Gbps.[1] In order to support transfer of such high-date rate videos between consumer electronics, High Definition Multimedia Interface (HDMI) was developed. The HDMI cable can transfer uncompressed HD video within a distance of 10 meters at a rate of 4.7 Gbps.

In addition to HD videos, many other applications including bulk file transfer, system backup and computer ducking stations can benefit from multi-Gbps transmission. Although these applications generally do not require strict quality of service (QoS) as HD videos, the transfer time is always a crucial performance metric. For example, consider synchronizing an 80G-iPod with the music library in a personal computer. It takes more than 20 minutes if using a USB 2.0 cable (at a full speed of 480 Mbps). However, it takes only 3 minutes if using the latest USB 3.0 cable (up to 4.8 Gbps).

[1] The refreshing rate is 60 frames per second, and each pixel is represented by 24 bits.

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Although many "wired" solutions (e.g., HDMI or USB 3.0) are developed to support multi-Gbps transmission, doing so over a wireless link is never an easy task. In principle, one can increase the transmission rate of a wireless link by increasing (1) the spectrum efficiency, and/or (2) the transmission bandwidth. By using the advanced techniques such as orthogonal frequency division multiplexing (OFDM) and multi-input multi-output (MIMO), one might be able to "squeeze" out 15 bits per second per Hertz [1]. However, even with such high spectrum efficiency, a bandwidth of 200 MHz is needed to achieve a 3-Gbps transmission rate. One can find that the real challenge to achieve multi-Gbps wireless transmission is to allocate a sufficient amount of bandwidth in the already-crowded wireless spectrum.

Lately, the 60 GHz band becomes an attractive solution to multi-Gbps wireless communications. The 60 GHz band has a common 3.5 GHz bandwidth worldwide, up to 9 GHz in Europe, and up to 7 GHz in North America and Japan. Figure 1 shows the spectrum availability in these regions. Thanks to its abundant bandwidth and worldwide availability, the 60 GHz band can provide multi-Gbps transmission with a much relaxed spectrum efficiency, which leads to a simpler hardware design. For example, one can use a bandwidth of 2 GHz in the worldwide 60 GHz band, with a spectrum efficiency of 1.5 bits per second per Hertz, to "easily" achieve a data rate of 3 Gbps.

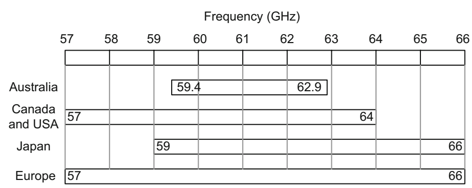

Fig. 1. Spectrum availability around 60 GHz band

1.1 Multiple Competing Standards

In views of the promising potential in the 60 GHz band, different standard bodies and interest groups have started various projects for 60-GHz communications. These projects include WirelessHD developed by the WirelessHD Consortium [2], IEEE 802.15.3c developed by the IEEE 802.15 Task Group 3c [3], WiGig developed by WiGig Alliance [4], IEEE 802.11ad developed by the IEEE 802.11 VHT Study Group [5], and finally, the ECMA-387 [7] developed by the Ecma International TC48.

WirelessHD targets on streaming uncompressed full-HD audio and video at a distance of 10 meter. WirelessHD specifies two physical (PHY) modes: High Rate PHY (HRP) and Low Rate PHY (LRP). HRP adopts the OFDM and provides a throughput of over 3 Gbps (when using 16-QAM) for video streaming. LRP also adopts the OFDM but only supports up to 40Mbps transmission for lower power consumption. The LRP is used for transmitting and receiving control messages and cannot be used when there is video streaming in vicinity.

IEEE 802.15.3c is designed for general wireless personal area networks (PANs) and supports data rates from 1 Gbps to more than 5 Gbps. IEEE 802.15.3c defines three PHY modes, including Single Carrier mode (SC PHY), High Speed Interface mode (HSI PHY), and Audio/Visual mode (AV PHY). SC PHY uses single carrier with adaptive modulations to achieve a date rate of up to 5.28 Gbps. On the other hand, HSI PHY and AV PHY (dedicated for video streaming) adopt the OFDM to provide data rates of 5.77 and 3.8 Gbps, respectively.

IEEE 802.11ad is designed for wireless local area networks (LANs) and aims to support at least 1 Gbps transmission at a range of at least 10 meters. As a member of the 802.11 family, IEEE 802.11ad relies on a so-called Fast Session Transfer to provide "*a seamless transfer of an active session from the 60 GHz band to the 2.4/5 GHz band, and vice versa.*" This function allows devices to switch among different PHYs for either higher transmission rates (in 60 GHz band), or extended ranges and better reliability (in 2.4/5 GHz band) depending on the network environment.

The ECMA-387 standard supports multi-Gbps wireless transport for both bulk data transfer and multimedia streaming. In order to support theses applications, the ECMA-387 standard defines three device types: Types A, B, and C, each with a different level of capability and hardware complexity. According to ECMA-387, Type A devices support both single carrier block transmission (SCBT) and OFDM to provide more than 6 Gbps transmission at 10 meters for full-HD video streaming and Wireless PAN applications. Type B devices use a simpler single carrier modulation to support a lower data rate (3.175 Gbps) at 3 meters. Type C devices use an even simpler single carrier modulation (OOK and 4-ASK) to support point-to-point data exchange without QoS guarantees. Type C devices only communicate within a range less than 1 meter using a data rate of up to 3.2 Gbps.

1.2 Challenges – Interference among Heterogenous Devices

As one can see from the above discussion, different solutions have been developed to enable a wide range of applications in the 60 GHz band. On one hand, we can find the best solution for each application. On the other hand, devices based on different solutions will be collocated in the same 60 GHz band. Since these solutions adopt different PHY-layer technologies, network architectures and channelization, the collocated devices inevitably will interfere with each other. This problem is referred to as interference among heterogenous devices in this paper.

Interference among heterogenous devices is not a unique problem in the 60 GHz band. Take 2.4 GHz ISM band as an example. The WiFi, Blutooth and ZigBee devices can interfere with each other when using overlapping frequency bands. However, interference in the 60-GHz band could be a a much serious problem compared to that in 2.4 GHz band for the following reasons. First, the number of channels in the 60 GHz band is much less than in the 2.4 GHz band. In the 60 GHz band, the channel bandwidth is generally between 1 to 2 GHz in order to support multi-Gbps transmission. As a result, only 3 or less channels can be defined. In the 2.4 GHz band, devices usually have more than 10 channels to operate (e.g., 11 channels for WiFi, or 16 channels for ZigBee devices). With less channels available, devices in the 60 GHz band have more difficulties to avoid interference from other heterogenous devices.

Second, the maximum allowed power in the 60 GHz band is much higher than in other unlicensed bands. The Equivalent Isotropically Radiated Power (EIRP) in the 60 GHz band can be as high as 40dbm. With such a transmission power, along with the use of directional antennas, the interference among heterogenous devices in the 60 GHz band simply cannot be ignored as it is in the 2.4 GHz band.

Finally, both HD video streaming and bulk data transfer are high-duty cycle applications. Even with the multi-Gbps transmission rates, the wireless link can easily be fully-loaded by a single high-duty cycle application. In order to reduce overhead and fully utilize the link capacity, most of the existing 60 GHz solutions adopt the master-slave architecture with a reservation-based channel access. Unlike the widely-adopted, contention-based channel access in the 2.4 GHz band (e.g., carrier sense multiple access used by WiFi or ZigBee devices), devices using the reservation-based channel access do not perform energy detection before accessing a channel. As a result, heterogenous devices in the 60 GHz band do not have the chance to avoid each other in time domain as WiFi and ZigBee devices.

In this paper, we investigate the interference among heterogeneous device in the 60 GHz band. Instead of harmonizing the physical-layer signal formats, we approach this problem from the perspective of the medium access control (MAC) layer. We will use the ECMA-387 standard as our study case and show how heterogenous devices may be able to coexist with each other without a common PHY layer.

The rest of this paper is organized as follows. In Section 2, we give an introduction to the mechanisms for interoperability and coexistence in the ECMA 387 standard. In Section 3, we examine different interference scenarios, and identify some potential problems when using the ECMA-387 solutions. In Section 4, we analyze and simulate the identified problems using OPNET Modeler. Finally, we conclude our work in Section 5.

2 Case Study: ECMA-387

The ECMA-387 standard is an all-purpose standard that supports a wide range of applications in the 60 GHz band. To accommodate various applications while taking into account device complexity, the ECMA-387 standard defines three device types, each for some specific applications. The devices of different types use different PHY modes and network architectures, and thus, treat each other as heterogenous devices. To address this issue, several mechanisms are specified in the ECMA-387 standard for inter-operation and coexistence among these devices. In this section, we give a detailed description of these mechanisms and explain the design rationale.

2.1 Heterogeneous Devices: Three Device Types

ECMA-387 defines three types of devices, namely the advanced Type A device, the second simple Type B device, and the simplest Type C device. The target applications of Type A devices include HD video streaming and general applications in a Wireless PAN. The target applications of Type B devices are point-to-point, short-range (1-3 meters) video streaming and data transfer. Type C devices target the point-to-point fast file download in less than 1 meter. Among these three types of devices, Type A devices are considered as the “high end, high performance” device; Type B devices are considered as “economic” devices, and the Type C devices are considered as the “low-end” cheap devices.

Each type of devices uses a basic PHY mode specifically designed for that type. These basic PHY modes are mode-A0, mode-B0, and mode-C0 for Type A, Type B, and Type C devices, respectively. The mode-A0 PHY uses SCBT with BPSK and provides 0.397 Gbps within 10 meter transmission ranges. The mode-B0 uses SC with DBPSK and provides 0.794 Gbps within 1 to 3 meter transmission ranges. The mode-C0 uses SC with OOK and provides 0.8 within less than 1 meter ranges. If a pair of communicating devices belong to the same device type, they communicate using the PHY mode of the device type.

In addition to supporting its own basic PHY mode, a device is also required to support the basic PHY modes of less advanced devices. For example, a Type A device is required to support both mode-B0 and mode-C0 PHYs while a Type B device is required to support the mode-C0 PHY. These additional requirements facilitate the inter-operation among heterogeneous devices without incurring too much PHY complexity to the more advanced Type A and Type B devices. For example, a Type A device can then communicate with Type B devices using the mode-B0 PHY, and communicate with Type C devices using the mode-C0 PHY. Similarly, a Type B device can communicate with Type C devices using the mode-C0 PHY.

Based on the above designs in the ECMA-387 standard, the mode-C0 PHY seems as a common PHY for all devices. With this common PHY, devices of different types may exchange information with each other to avoid interference. Unfortunately, the transmission range of the simple mode-C0 PHY is only around 1 meter. Therefore, devices that are beyond this range cannot communicate using the mode-C0 PHY and may still interfere with each other. As we will explain later, the ECMA-387 relies on a dual-beacon protocol to address the interference among homogeneous devices.

2.2 Interoperability

In the ECMA-387 standard, interoperability is referred to as data communication between heterogeneous devices. To enable inter-operation, devices of different types form a Master-Slave Pair (MSPr). In the MSPr, the more advanced device is the master device while the simpler device is the slave device. For instance, in an MSPr established by a Type A device and a Type B device, the Type A device is the master and the Type B device is the slave. In an MSPr established by a Type B device and a Type C device, the Type B device is the master and the Type C is the slave.

Data transmission in an MSPr is carried out by exchange of poll frames between the master and slave devices. In the poll frames, the master device specifies the time for the slave device to transmit/receive the data as well as the time to receive the next poll frame. The slave device follows the timing provided in the poll frame and transmits/receives during the specified interval. The timing structure of an MSPr is shown in Figure 2. Since the simpler slave device does not support more advanced PHY modes, transmission of polls and data frames must use the basic PHY mode of the slave device. As a result, the transmission rate and range of an MSPr is limited by the capability of the slave device. For example, the transmission range of a Type A-C MSPr cannot exceed 1 meter. This is an unfortunate compromise due to the tradeoff between the performance and complexity.

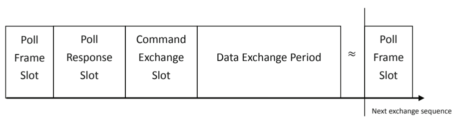

Fig. 2. Timing structure of a Master Slave Pair (MSPr)

2.3 Coexistence

Devices of different types in the ECMA-387 may interfere with each other when they are collocated in the same channel but not in the inter-operation mode. Figure 3 shows an example of how two independent pairs of Type A devices and Type B devices interfere with each other. Here, the two Type A devices use the mode-A0 PHY for their communication while the two Type B devices use the mode-B0 PHY. One can see that the Type A device X and the Type B device Y interfere with each other as their antennas point to each other. The ECMA-387 addresses the interference problems differently depending on the devices involved in the interference. For interference that involves Type A and Type B devices, a Dual-beacon Protocol is adopted. For interference that involves Type C devices, a channel sensing mechanism is adopted. These two approaches are detailed in the following two subsections.

Dual-beacon Protocol. The ECMA-387 standard requires Type A and Type B devices to send beacons periodically using their own basic PHY modes. The purposes of beacon transmission are two-fold. First, the beacons are used by the devices of the same type to synchronize with each other. Second, a device declares in the beacons its reservation of the channel time. Once receiving the reservation information, devices of the same type can avoid interfering with that device by honoring its reservation. The timing structure established by the beacons is shown in Figure 4. With this timing structure, an advanced device can

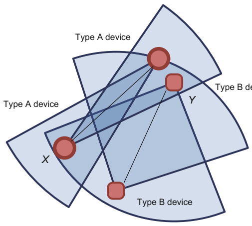

Fig. 3. Coexistence between the AA-BB communicating pairs

communicate with another advanced device of the same type while communicating with a simpler device via the MSPr. For example, as also shown in Figure 4, Type A device X reserves time block 1 to communicate with Type A device Y, and reserves time block 2 to inter-operate with Type C device Z. Since the beacons from devices of different types use different PHY modes, a Type-B device cannot receive and decode the mode-A0 beacons to synchronize and honor the Type A device's reservation. On the other hand, a Type A device is able to receive and decode the mode-B0 beacons and thus may avoid interfering with the Type B devices. However, the transmission range of the mode-B0 PHY is only 3 meters. As a result, a Type A device that is more than 3 meters from a Type B device is still unaware of the Type B device's reservation and thus cannot avoid interfering with the Type B device.

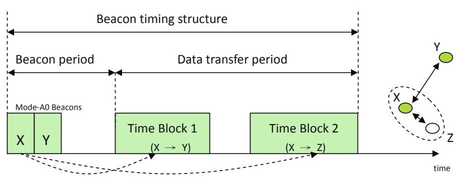

Fig. 4. Timing structure established via transmission and reception of beacons

To address the interference between the Type A and Type B devices, the ECMA-387 standard requires a Type B device to send mode-A0 beacons as well. However, the Type B device does not need to receive and decode the mode-A0 beacons. The mode-A0 beacon is transmitted solely for the Type A devices to avoid interfering with the Type B devices. Since the transmitter of a mode-A0 PHY is much simpler compared to the receiver of a mode-A0 PHY, this additional requirement does not incur too much hardware complexity to the second simple Type B device. The transmission of both mode-A0 and mode-B0 beacons by the Type B devices is referred to as Dual-beacon protocol in the ECMA-387 standard.

The timing structure of the Dual-beacon Protocol is illustrated in Figure 5. Each Type B device sends a mode-A0 beacon right after the mode-B0 beacon.

The mode-A0 beacon sent by a Type B device contains identical information as the mode-B0 beacon. With these information, a Type A device can honor a Type B device's reservation and coexist with the Type B device even they are 10 meters apart.

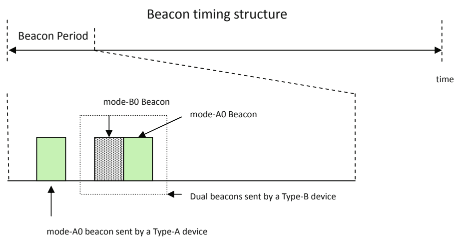

Fig. 5. Timing structure in Dual-beacon Protocol

Channel sensing with prioritized access. Type C devices are considered as the lowest-level devices in the ECMA-387 standard. In order to reduce the hardware complexity, the Type C device are not to required to transmit and receive beacons. For two Type C devices to communicate with each other, an MSPr is established with one Type C device being the master device and the other being the slave device.

Without transmission and reception of any beacon, a Type C device may interfere with the Type A and Type B devices as well as being interfered by these devices. The ECMA-387 standard addresses this issue by requiring a Type C device to transmit only when the channel is free of non-Type C transmission. To achieve that, a Type C device scans the channel for a duration that is long enough to determine that the channel is free of non-Type C transmission, before starting an MSPr. In addition, a Type C device aperiodically ceases transmission to scan for non-Type C transmission after the MSPr is established. Both the master and slave Type C devices must perform the scans to minimize the interference. When detecting non-Type C transmission, the master Type C device suspends the MSPr for an additional period of time. If the channel is free of non-type C transmission after the suspension, the master device restarts the MSPr. If a slave Type C device detects non-Type C transmission, it informs the master Type C device. The master Type C device reacts as if the non-Type C transmission is detected by itself.

The aforementioned rules make the Type C devices in the ECMA-387 standard as the lowest priority devices in terms of channel access. Given that the Type C devices targets on the low-cost application with no QoS guarantee, sacrificing the performance of the Type C devices seems not a bad option (at least from the viewpoint of the ECMA-387 standard).

Synchronization issues. The Dual-beacon protocol enables a Type A device to honor a Type B device's reservation and thus to avoid interfering with the Type B device. To achieve such interference-free coexistence, these devices must synchronize with each other. Otherwise, the timing information in the beacons for channel reservation is useless.

Synchronization between devices using the Dual-beacon Protocol is a tricky issue. Given that the Type B devices can only transmit (not receive or decode) the mode-A0 beacons, the Type B devices are unable to use the mode-A0 beacons from the Type A devices for synchronization. The ECMA-387 standard specifies unique rules to address the synchronization problem of the Dual-beacon Protocol. These rules are listed as follows.

1) A Type-A device X shall synchronize to the slowest Type B device, unless the Type-B device is one of the salve devices in X's MSPr.
2) A Type-A device indicates itself as a forced synchronized device in the beacons if it synchronizes to a Type B device or a forced synchronized device.
3) A non-forced synchronized device X shall synchronize to a forced synchronized device Y, unless Y is already forced to synchronize to X.
4) A forced synchronized device shall not synchronize to another forced synchronized device.
5) A device indicates itself as a forced synchronized device in the beacons if it synchronizes to a forced synchronized device.
6) A Type A device X shall synchronize to the slowest Type A device Y, if there is no Type B device or forced synchronized device other than X's slave devices.
7) A slave device shall synchronize to its master device in the MSPr.
8) A device indicates itself as a forced synchronized device in the beacons if it is a slave device in an MSPr.
9) A Type B device X shall synchronize to the slowest Type B device Y, if X is not a slave device and there is no forced synchronized device other than X's slave devices.

The forced synchronization is designed to address the case when a device detects another device but finds out that device cannot synchronize with itself (i.e., one-way communication between Type A and Type B devices). Although these rules solve most of the synchronization problems in the ECMA-387 standard, we show in the next section that there still exist some problems that need further consideration.

3 Synchronization Problems for Interoperability and Coexistence

The ECMA-387 standard defines synchronization rules for interference-free coexistence among heterogenous device. In this section, we thoroughly examine these rules in different network scenarios. We focus on the scenarios with communication pairs formed by Type A devices and Type B devices. The Type C devices are the lowest-priority devices and have little impact on the performance of Type A and Type B devices. The scenarios of our interests are further categorized into four cases, and are denoted as AA-BB, AA-AB, AB-BB, and AB-AB, respectively.

3.1 Case I: AA-BB Pairs

The logic topology of Case I is shown in Figure 6. Since the two Type B devices are not the slaves of any device and do not understand the mode-A0 beacons, they simply synchronize to each other according to Rule no.9. The two Type A devices are forced to synchronize to the Type B devices directly or indirectly, depending on whether or not receiving the mode-A0 beacons from the Type B devices. If yes, the Type A device is forced to directly synchronize to the Type B device according to Rule no.1. Otherwise, the Type A device is forced to synchronize to another forced synchronized Type-A device according to Rule no.3. Note that if none of the Type A devices is a forced synchronized device, it means that both of the Type A devices are outside the coverage of the Type B devices. Thus, the two pairs, AA and BB, do not interfere with each other and do not need to synchronize to each other.

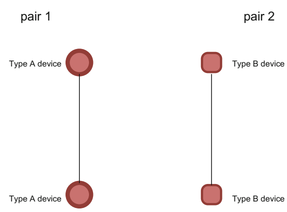

Fig. 6. Case I: AA-BB pairs

3.2 Case II: AA-AB Pairs

The logic topology of Case II is shown in Figure 7. Since the Type B device is the slave of its master Type A device, the Type B device is forced to synchronize to that Type A device according to Rule no.7. If any of the two Type A devices in the AA-pair is in the coverage of the Type B device, these two Type A devices will be forced to synchronize to the Type B device according to Rule no.3. If any of the Type A devices in the AA pair is also in the coverage of the Type A device in the AB-pair, the Type A device in the AB-pair will also be forced to synchronize to the Type A devices in the AA-pair according to Rule no.3.

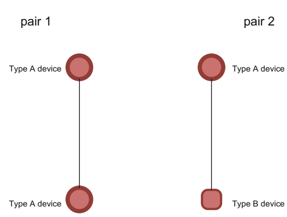

Fig. 7. Case II: AA-AB pairs

If none of the Type A devices in the AA-pair is in the coverage of the Type A device of the AB-pair, these two Type A devices are synchronized to the Type A device of the AB-pair via the Type B device.

If none of the two Type A devices in the AA-pair is in the coverage of the Type B device, these two Type A devices along with the Type A device in the AB-pair synchronize with each other according to Rule no.6.

3.3 Case III: AB-BB Pairs

The logic topology of Case III is shown in Figure 8. Again, the Type B device in the AB pair is forced to synchronize to its Type A master device according to Rule no.7. If any of the Type B devices in the BB-pair is in the coverage of the Type B device in the AB pair, then both of the Type B devices in the BB-pair will synchronize to the Type B device in the AB-pair according to Rule no.3. If the Type A device in the AB pair is also in the coverage of any of the Type B devices in the BB-pair, the Type A device is then forced to synchronize to the Type B devices in the BB-pair according to Rule no.3. If the Type A device in the AB-pair is not in the coverage of any of the Type B devices in the BB-pair, then the Type B devices in the BB-pair indirectly synchronize to the Type A device via the Type B device in the AB-pair.

If none of the Type B devices in the BB-pair is in the coverage of the Type B device in the AB-pair, the Type A device in the AB-pair is forced to synchronize to the Type B devices in the BB-pair according to Rule no.1. The Type B device in the AB-pair then indirectly synchronizes to the Type B devices in the BB-pair via the Type A device.

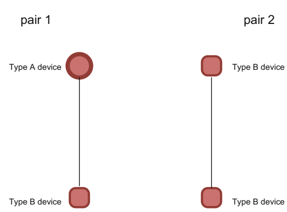

Fig. 8. Case II: AB-BB pairs

3.4 Case IV: AB-AB Pairs

The logic topology of Case IV is shown in Figure 9. In this case, both of the Type B devices are forced to synchronize to their own master Type A devices according to Rule no.7. If none of the Type A devices receives the mode-A0 beacons from each other or from the Type B device in another AB-pair, then the two Type-B devices are the only forced synchronized devices. Based on Rule no.4, these two Type B devices do not synchronize with each other even if they are in the coverage of each other. As a result, the four devices cannot synchronize with each other, and the interference-free coexistence between these two AB-pairs are compromised.

Note that if any additional link other than the links shown in Figure 9 is established , these four devices will be able to synchronize to each other. In the next section, we will give a thorough mathematical analysis on how frequently the case shown in Figure 9 may occur given that the devices use directional antennas. We will also show how clock drifting affects the synchronization using the OPNET-based simulations.

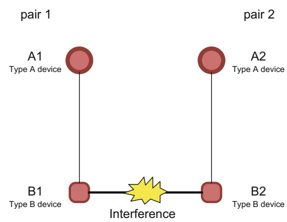

Fig. 9. Case IV: AB-AB pairs

4 Simulation and Analysis

To better evaluate the impact of synchronization on coexistence, we consider realistic network topologies that may lead to the logic topologies illustrated in Section 3. We first consider the scenario shown in Figure 9, as our earlier discussion suggests that there exists a non-zero probability that devices may not synchronize with each other. Our first objective in this section is to evaluate how frequently this scenario can occur by deriving a probability upper bound.

4.1 System Setup

We consider two AB pairs, each forming a MSPr and randomly located in a given area. The transmission range of each Type A device is 10 meters, and the transmission range of each Type B device is 3 meters, based on the ECMA-387 standard. The beam width of the Type A devices varies from 15 to 90 degrees (array antennas), while the beam width of the Type B devices is fixed at 90 degrees (fixed antenna). These settings reflect the differences in device complexity.

The distance between the two Type B devices is randomly distributed between 0 meter to 3 meters so that the Type B devices are in the coverage of each other. The antennas of the two Type B devices are randomly oriented. Each Type A devices is located in the coverage of its own slave Type B device. Since we assume that the MSPr has been formed, the antenna of each Type A device is pointed toward the slave Type B devices. The system setup is illustrated in Figure 10.

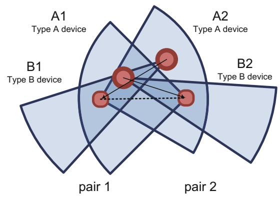

Fig. 10. System setup

4.2 Probability Upper Bound

As mentioned in Section 3, synchronization in Case IV is not a problem as long as there exists a link — other than the link between the Type B devices — between the two AB pairs. Denote the event that there exists a link between device i and j as L_{ij}. The probability that these two AB pairs cannot synchronize to each other can be obtained by

$$P_{no-sync} = P[L_{B_1B_2}] * P[L'_{A_1A_2} \cap L'_{A_1B_2} \cap L'_{A_2B_1} | L_{B_1B_2}]. \tag{1}$$

We first calculate the probability $P[L_{B_1B_2}]$. The event $L_{B_1B_2}$ occurs when the two Type B devices point their antennas to each other. Therefore, we have

$$P[L_{B_1B_2}] = P[B_1 \to B_2] * P[B_2 \to B_1], \tag{2}$$

where the event $B_i \to B_j$ represents that Type B device i points its antenna to Type B device j. Given that the antenna of a Type B device is randomly oriented with a beam width of 90 degrees and the location of the Type B devices are randomly selected, one can calculate $P[B_i \to B_j]$ by

$$P[B_i \to B_j] = \int_0^{2\pi} \int_{\phi}^{\phi-2\pi} \frac{\pi}{2} \frac{1}{2\pi} \, d\theta \, d\phi = \frac{1}{4}. \tag{3}$$

With Eq. (3), the probability $P[L_{B_1B_2}]$ can then be calculated by

$$P[L_{B_1B_2}] = \frac{1}{4} * \frac{1}{4} = \frac{1}{16}. \tag{4}$$

To calculate $P[L'_{A_1A_2} \cap L'_{A_1B_2} \cap L'_{A_2B_1} | L_{B_1B_1}]$, we first rewrite the probability as

$$\begin{aligned} &P[L'_{A_1A_2} \cap L'_{A_1B_2} \cap L'_{A_2B_1} | L_{B_1B_2}] \\ &= 1 - P[L_{A_1B_2} | L_{B_1B_2}] - P[L_{A_1B_2} | L_{B_1B_2}] \\ &- P[L_{A_2B_1} | L_{B_1B_2}] + P[L_{A_1B_2} \cap L_{A_2B_1} | L_{B_1B_2}] \\ &+ P[L_{A_1A_2} \cap L_{A_2B_1} | L_{B_1B_2}] + P[L_{A_1A_2} \cap L_{A_1B_2} | L_{B_1B_2}] \\ &- P[L_{A_1A_2} \cap L_{A_1B_2} \cap L_{A_2B_1} | L_{B_1B_2}]. \end{aligned} \tag{5}$$

By closely examining these events, one can find that only $P[L_{A_1A_2}|L_{B_1B_2}]$, $P[L_{A_1B_2}|L_{BB}]$, $P[L_{A_2B_1}|L_{B_1B_2}]$, and $P[L_{A_1B_2} \cap L_{A_2B_1}|L_{B_1B_2}]$ have non-zero values. In other words, the other events cannot occur with any given orientation and locations of the devices. Thus, Eq. (5) can be further simplified as

$$\begin{aligned} &P[L'_{A_1A_2} \cap L'_{A_1B_2} \cap L'_{A_2B_1}|L_{B_1B_2}] \\ &= 1 - P[L_{A_1A_2}|L_{B_1B_2}] - P[L_{A_1B_2} \cup L_{A_2B_1}|L_{B_1B_2}]. \end{aligned} \tag{6}$$

$P[L_{A_1B_2} \cup L_{A_2B_1}|L_{B_1B_2}]$ in Eq. (6) is very difficult to be obtained. Therefore, instead of finding the exact value of $P[L'_{A_1A_2} \cap L'_{A_1B_2} \cap L'_{A_2B_1}|L_{B_1B_2}]$, we calculate its upper bound by

$$\begin{aligned} P[L'_{A_1A_2} \cap L'_{A_1B_2} \cap L'_{A_2B_1}|L_{B_1B_2}] \leq \\ 1 - P[L_{A_1A_2}|L_{B_1B_2}]. \end{aligned} \tag{7}$$

Finally, the upper bound of $P_{no-sync}$ is obtained by

$$P_{no-sync} < \frac{1}{16} * (1 - P[L_{A_1A_2}|L_{B_1B_2}]). \tag{8}$$

Figure 11 illustrates the upper bound of $P_{no-sync}$ for different beam widths of the Type A devices. It can be found that the probability linearly decreases with the increase of the beam width. The result seems contracting the intuition as the larger the beam width, the more chances that there exist additional links between the AB pairs so that devices can synchronize with each other. However, it is noted that the probabilities are plotted based on Eq. (8). Therefore, the larger the beam width, the larger the value of $P[L_{A_1A_2}|L_{B_1B_2}]$, and, thus the smaller the upper bound.

Another important observation in Figure 11 is that the maximum of the upper bound is only 0.06, which occurs when the beam width of the Type A device is 15 degrees. Note that $P_{no-sync}$ is the "conditional" probability that two AB pairs lose the synchronization given that their Type B devices are in the coverage of each other (within a 3 meter range). If we take into account the cases where the Type B devices of the AB pairs are outside the coverage of each other, the probability of two AB pairs losing synchronization with each other (so that they interfere with each other) will be even smaller.

4.3 Simulation Results

We conduct OPNET-based simulations to evaluate the impact of clocking drifting on synchronization in realistic network environments. The synchronization procedure is implemented as follows. When a device receives a beacon from another device, it extracts the timing information in the beacon and determines the start time of the beacon timing structure of the beacon transmitter. By comparing the start time of all neighbors with its own start time, the device can determine the amount of relative drifting and then adjust the local clock according to the rules in Section 2.3. If the device should synchronize to a slower-clock

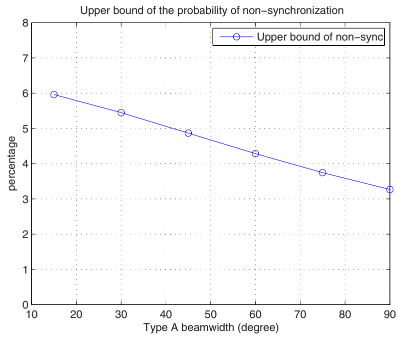

Fig. 11. Probability upper bound: Lack of synchronization in Case IV

device, it delays the start time in his next beacon timing structure. If the device should synchronize to a faster-clock device, it advances the start time in his next beacon timing structure.

We consider Case I and Case II in Section 3. The physical topology and clock drifts for each case are given in the following subsections.

Case I: AA-BB pairs. Figure 12 shows the physical topology and the coverage of each device. Based on the setting, A2 is in the coverage of B1 and B2 (and vice versa). The result network connectivity is shown in Figure 13. The arrows in the figure represent the relation in terms of clock adjustment between devices. An outbound arrow represents that a device may synchronize to the device to which the arrow points. Figure 13 shows that A1 synchronizes to A2, A2 synchronizes to either B1 or B2, and either B1 synchronizes to B2 or B2 synchronizes to B1 depending on their clock drifts. In this simulation, the clock drift of A1, A2, B1, and B2 are randomly set as 9.9 ppm, 4.32 ppm, -4.7 ppm, and 6.35 ppm. The length of the beacon timing structure is set as 256 milliseconds. Therefore, the total clock drift within one beacon timing structure can be calculated as +2.54 microseconds (us) for A1, +1.11 us for A2, -1.20 us for B1, and +1.63 us for B2.

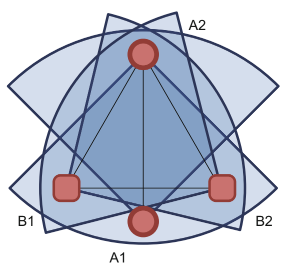

Fig. 12. Topology of Case I: AA-BB pairs

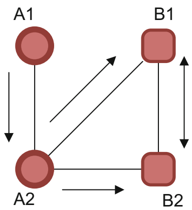

Fig. 13. Logic links and synchronization relationship in Case I

The differences between the start times of the four devices are shown in Figure 14. Here, we use B2's start time as the reference. One can find that the start times of the four devices are not perfectly aligned due to the clock drifting. However, they do not drift away with the time. Figure 14 shows that B1 is faster than B2, but the difference never exceeds 3.2 us. On the other hand, A1 is always slower than B2 but the difference never exceeds 2.2 us. The simulation shows that these four devices are synchronized as expected.

Figure 15 shows the clock adjustment of each device at the beginning of each beacon timing structure. Since the clock resolution is 1 us in our simulation, the adjustment must be a round off of the actual difference of devices's start times. For example, B1 delays its clock either 2 or 3 us in order to synchronize to the slowest device B2. The figure shows that A1 tries to synchronize to A2, A2 tries to synchronize to B1 while B1 tries to synchronize to B2.

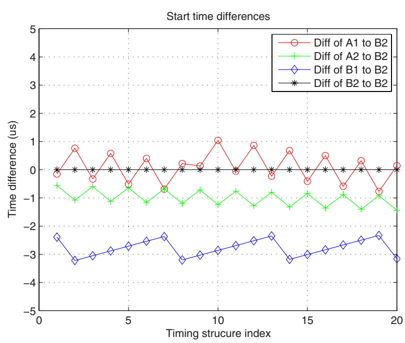

Fig. 14. Start time differences between devices in Case I

Case II: AA-AB pairs. Figure 16 shows the physical topology and the coverage of each device. Based on the setting, A2 is also in the coverage of A3 and B1 (and vice versa). The resulting network connectivity is shown in Figure 17. We can find that in this case, A1 should synchronize to A2, A2 should synchronize to B1 (i.e., the slave of A3), B1 should synchronize to its master device, and finally A3 should synchronize to A2. In other words, every device should adjust

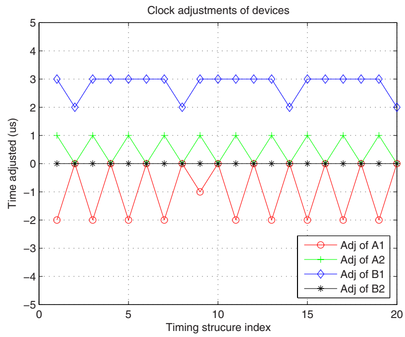

Fig. 15. Clock adjustment in Case I

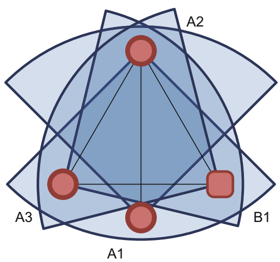

Fig. 16. Topology of Case II: AA-AB pairs

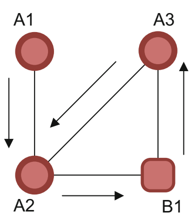

Fig. 17. Logic links and synchronization relationship in Case II

its local clock. This is quite different from the previous case where B2 is the clock reference of all other devices.

In this simulation, the clock drift of A1, A2, B1, and B2 are randomly set as 1.49 ppm, 4.5 ppm, 9.66 ppm, and 7.74 ppm. The length of the beacon timing structure is still 256 milliseconds. Therefore, the total clock drift within one beacon timing structure can be calculated as +0.38 us for A1, +1.15 us for A2, +2.47 us for A3, and +1.98 us for B1.

The differences between the start times of the four devices are plotted in Figure 18. Here, we use A3's start time as the reference. One can find that the start times of the four devices are again not aligned due to the clock drifting.

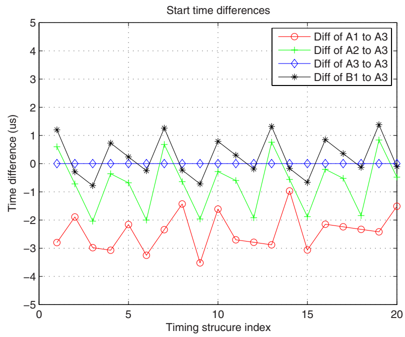

Fig. 18. Start time differences between devices in Case II

However, they still do not drift away with the time even though not a single device (such as B2 in Case II) can be used as the absolute clock reference. We can find that the maximum difference between the devices's start times never exceeds 4 us.

One interesting observation from Figure 18 is that all of the curves change in a similar way. For example, when the difference between B1's and A3's start times decreases/increases (the 'star' line), the difference between A1's and A3's start times (the 'square' line) decreases/increases as well, with a possible delay of 256 ms. The same situation can be found for the difference between A2's and A3's start times. The observation verifies the so-called circular synchronization as we pointed out earlier in this section.

5 Conclusions

In this paper, we investigated the interference among heterogenous devices in the 60 GHz band. The ECMA-387 standard was used as our study case to demonstrate how interference-free coexistence can be achieved without imposing too much complexity on simple devices. The Dual-beacon Protocol of the ECMA-387 protocol was thoroughly investigated, especially from the aspect of synchronization between heterogeneous devices. Our numerical and simulation results show that with a probability of more than 0.94, the heterogenous devices using the ECMA-387 standard can coexist without interfering with each other.

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