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Improving the Bluetooth and Wi-Fi Coexistence Issue using a Canceller

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11. 15. 2013

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[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Thesis Title

Name

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ABSTRACT

Bluetooth and Wi-Fi are two common wireless technologies today and are especially prevalent in smart phones. Although these two technologies are convenient, if the two are used simultaneously, performance degradation, such as throughput and communication valid distance, occurs.

This paper presents a simple and effective solution for resolving the in-device coexistence problem between Wi-Fi and Bluetooth. The main idea is to introduce a canceller in the circuit to cancel out the in-device interference when Wi-Fi and Bluetooth radios operate simultaneously in one device. Based on the testbed, extensive experiments were carried out to validate the performance of the proposed scheme. Our results show that the proposed solution gives substantially better performance than existing methods. Our results show that our proposed scheme provides more isolation to use AFH mechanism in small devices than current techniques. Our proposed approach, entitled the hybrid arbitrator, can significantly improve the performance of both of Wi-Fi and Bluetooth.

Keywords- coexistence, AFT, Hybrid Arbitrator, Bluetooth, Wi-Fi, Canceller

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Ⅰ. INTRODUCTION

Recent advances in wireless communication are aimed toward to make our life a lot more comfortable and efficient. These wireless technologies use different radio frequencies in order to avoid interference. But the radio frequency, being under strict government control, is a limited resource. For example, it is owned by the government for public and military uses, or it is sold to service provider to offer cellphone service. However, there is unlicensed band reserved for industrial, scientific and medical purposes. It is called ISM band, which is freely used world-wide. Therefore, many wireless technologies were developed using ISM band. This development has led to a crowded ISM band with heterogeneous wireless protocols. When heterogeneous protocols work simultaneously, these interfere with each other. Eventually, each protocol fails to work properly, which is known as the coexistence problem [1]. Typical examples are Bluetooth and Wi-Fi., which are both integrated onto a single smart phone, one of the most popular mobile devices. Thus, the degradation in Wi-Fi and Bluetooth performance might occur when these operate simultaneously which is called self-interference. In this paper, we focus on this self-interference coexistence problem. Furthermore we anticipate this problem will become more common in the future, because smartphones increasingly include more functions. Therefore spatial allocation will be smaller and more interference will occur. Future products like Google Glass, iWatch, and SAMSUNG Galaxy Watch use Bluetooth communication with a smartphone and have Wi-Fi module. Figure 1 show limitation of space of current smartphone and new device.

Fig. 1. Latest mart devices

There has been much progress from past researches to resolve this. The IEEE 802.15.2 recommends *collaborative mechanisms*: Packet Traffic Arbitration (PTA), Alternating Wireless Medium Access (AWMA), and Deterministic Spectral Excision (DSE) and *non-collaborative mechanisms*: Adaptive Packet Selection and Scheduling (APSS) and Adaptive Frequency Hopping (AFH) [1]. Among them, AFH mechanism is the most widely used method for avoiding interference. Bluetooth takes all the evasive action by itself using AFH which is based on Frequency Division Multiplexing (FDM). It measures the whole channel noise power. If some channel noise power is lager then threshold, then it is registered as a bad channel and it is excluded from the hopping sequence [2]. But it cannot solve the coexistence problem alone, when spatial isolation is not enough. When Wi-Fi signal transmission and Bluetooth reception are operated at the same time in a small device, the number of Bluetooth bad channels will increase and SINR will decrease because of the self-interference. Bluetooth will eventually stop working and When Wi-Fi signal reception and Bluetooth transmission operate at the same time, the result will be the same.

A few years ago, the paper on full duplex wireless communication was published. According to this paper, they made full duplex wireless communication system with self-interference cancelling technique using two transmission antennas and one receiving antenna

[3]. After one year, they improved their design to use only one transmission antenna and one receiving antenna [4]. They divide two transmission paths, one path goes to transmission antenna and another path goes to balun and then to the noise canceller (QHX-200) which reverses the original signal and tune the signal level; the sum of these two path signals become zero at the receiving antenna. This technique is known as, "Full duplex" Since then, more research was carried out using this technique: research of improving medical implant device security [5], research of improving Wi-Fi backoff mechanism [6], research which one access point (AP) work like few APs at same time using only one antenna [7], and so on.

In this paper, we present a simple and effective solution for resolving the self-interference coexistence issue of Wi-Fi and Bluetooth using self-interference cancelling technique in line with latest research findings. Our main contributions are as follows:

• This is useful to the terminals which is co-located various wireless protocol to minimize self-interference by improving spatial isolation. Furthermore, we prove increasing performance by measuring real throughput at the testbed.

• It able to commercialization immediately with reasonable size to apply to small devices without making any changes to existing wireless protocol.

• This is a new approach method in the physical (PHY) layer for resolving coexistence problem, and is different from existing solutions.

The remainder of the paper is organized as follows. Section II provides an overview of Wi-Fi and Bluetooth, and then summarize existing solutions for coexistence of Wi-Fi and Bluetooth. Key limitation of existing solutions are explained in Section III. Section IV, introduces a novel mechanism, called the hybrid arbitrator, for improving the in device coexistence performance of Wi-Fi and Bluetooth. Extensive experiments and performance validation of the proposed scheme is included in Section V. The conclusion appears in Section VI.

Ⅱ. Background

The basics of Wi-Fi and Bluetooth are introduced in this section, followed by current solutions to coexistence.

2.1 Bluetooth

Bluetooth wireless technology provides cable-free connection for a wide range of computing and telecommunication devices. It is a license-free standard open for anyone to use. The standard is established by the Bluetooth Special Interest Group (SIG) [2]. Bluetooth specification describes how the technology works and its profiles detail how specific applications work to ensure interoperability.

Bluetooth uses the 2.4 GHz ISM band (from 2,402 MHz to 2,480 MHz), which is divided into 79 channels of 1 MHz bandwidth. Bluetooth performs frequency hopping spread spectrum (FHSS) with a nominal hopping rate of 1,600 hops per second. Gaussian frequency-shift keying (GFSK) modulation was the only modulation scheme available at first. Bluetooth 2.0+EDR introduced $\pi/4$-DQPSK and 8DPSK modulations. According to Bluetooth specification, the data rate is 1-24Mbps with different modulation. Transmission power is 0, 4, and 20 dBm depending on the power class 1, 2, and 3 [2].

Bluetooth provides point-to-point and point-to-multipoint connections as well as ad-hoc networking capabilities. The device that initiates the connection is called the master, while the rest are called slaves. A master can create two types of logical links with a slave device as follows:

•*Asynchronous Connection Less (ACL):* ACL provides a data connection with best effort bandwidth.

•*Synchronous Connection Oriented (SCO):* SCO provides real time connection with a guaranteed bandwidth, which is usually used for voice applications.

In relation to the two link types, 14 basic rate packet types are defined, which are split into four segments and categorized according to how many occupy time slots. These are shown in Table 1.

Table 1: Basic packet type

1	Common packets	POLL, NULL, ID, FHS
2	Single slot packets	SCO: HV1, HV2, HV3, DV ACL: DM1, DH1
3	ACL 3 slot packet	DM3, DH3
4	ACL 5 slot packet	DM5, DH5

Figure 2 shows that one, three, and five-slot packets are available for dynamic usage. Longer packets are used to increase the throughput, which leads to more time for transmitting data but less time for re-tuning the synthesizer.

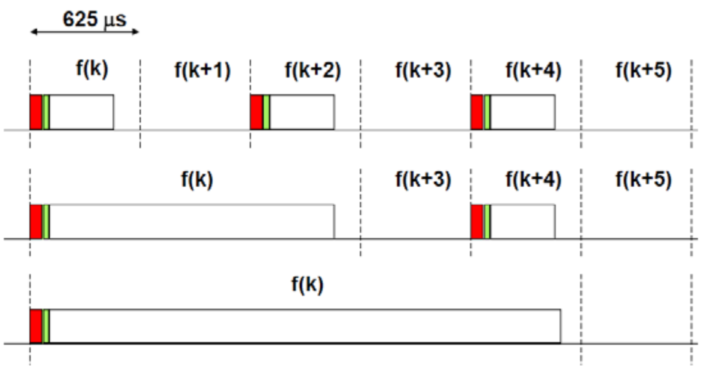


Fig. 2. Three types of packet type

Each packet type has a different level of error correction code (CRC), different payload size, header size, transmission and receiving rate, and forward error correction (FEC) as shown in Tables 2 and 3.

Table 2: ACL packets

Type	Payload Header (bytes)	Payload (bytes)	FEC	CRC	Symmetric Max. rate (kb/s)	Asymmetric Max. rate (kb/s)	
						Forward	Reverse
DM1	1	0-17	2/3	yes	108.8	108.8	108.8
DH1	1	0-27	no	yes	172.8	172.8	172.8
DM3	2	0-121	2/3	yes	258.1	387.2	54.4
DH3	2	0-183	no	yes	390.4	585.6	86.4
DM5	2	0-224	2/3	yes	286.7	477.8	36.3
DH5	2	0-339	no	yes	433.9	723.2	57.6
AUX1	1	0-29	no	no	185.6	185.6	185.6

Table 3: SCO packets

Type	Payload Header (bytes)	Payload (bytes)	FEC	CRC	Symmetric Max. rate (kb/s)
HV1	na	10	1/3	no	64
HV2	na	20	2/3	no	64
HV3	na	30	no	no	64
DV	1 D	10+(0-9) D	2/3 D	yes D	64+57.6D

In accordance with the Bluetooth version upgrade, many additional types of packets are added to the standards such as eSCO packets and EDR ACL packets.

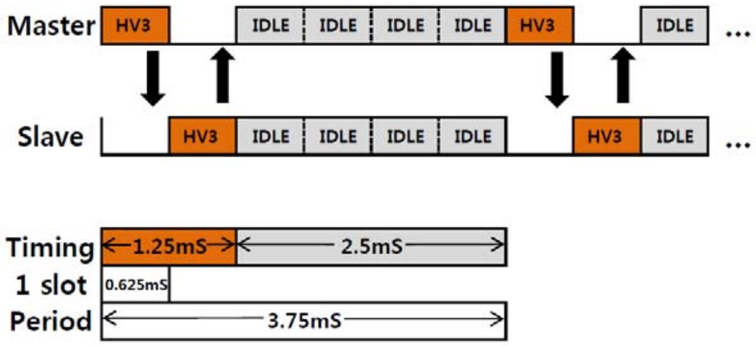


Fig. 3: SCO: HV3 packet timing

Figure 3 shows HV3 packet timing. In the figure, a master and a slave in SCO connection, respectively, consume one slot of 625 μs in a total period of six-slot time. This leaves four slots available for either ACL transmission or Wi-Fi. [8, 9, 10]

2.2 Wi-Fi

Wi-Fi is used as a synonym for WLAN (Wireless Local Area Network). 802.11 is a set of standards for WLAN. These standards provide the basis for wireless network products using the Wi-Fi brand. 802.11b,g,n which is a PHY layer protocol, uses the 2.4GHz ISM band and obeys the rules and regulations of the US Federal Communications Commission (FCC). It uses direct-sequence spread spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM) signaling methods. Normally 802.11 divides into 13 channels spaced 5 MHz apart, from 2.4000GHz to 2.4835GHz. 802.11b is based on DSSS with the 22MHz bandwidth (with 2MHz guard band) and has a maximum data rate of 11 Mbit/s. 802.11g is based on OFDM with the 20MHz bandwidth and has a maximum physical layer bit rate of 54 Mbit/s. 802.11n added Multiple-Input Multiple-Output Antennas (MIMO) technology and normally uses the 20MHz or 40MHz bandwidth. It operates at a maximum data rate of 600 Mbits/s with a maximum of three non-overlap channels: 1, 6 and 11. Equivalent Isotropically Radiated Power (EIRP) in the EU is limited to 20 dBm (100 mW), which allows for a communication range of about 100 meters. Table 4 is a summary of 802.11 PYH layer protocols [11, 12].

Table 4: 802.11 protocols

802.11 protocol	Release	Freq. (GHz)	Bandwidth (MHz)	Data rate per stream (Mbit/s)	Allowable MIMO streams	Modulation	Approximate outdoor range (m)
—	Jun-97	2.4	20	1, 2	1	DSSS, FHSS	100
a	Sep-99	5	20	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM	120
		3.7					5,000
b	Sep-99	2.4	20	1, 2, 5.5, 11	1	DSSS	140
g	Jun-03	2.4	20	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM, DSSS	140
n	Oct-09	2.4/5	20	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2	4	OFDM	250
			40	15, 30, 45, 60, 90, 120, 135, 150			250
ac DRAFT	~Feb 2014	2.4/5	20	up to 87.6	8		
			40	up to 200			
			80	up to 433.3			
			160	up to 866.7			

The 802.11 MAC protocol is based on Distributed Coordination Function (DCF) to share the medium access. The DCF relies on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). In a network, each mode accesses the medium in a contention manner by random delays to avoid collision. Figure 4 shows how each node works in a CSMA/CA mechanism.

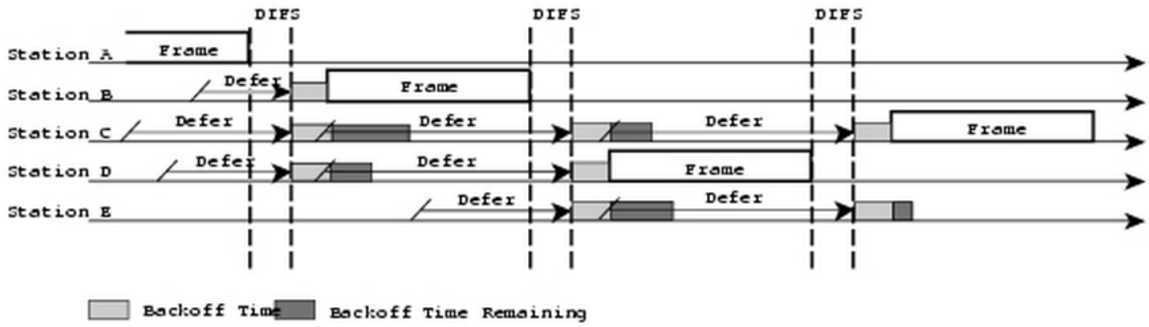


Fig. 4: CSMA/CA Example

If a station has data to transmit, each station will randomly choose a backoff number from 0 to a minimum contention window (CWmin). It then waits until the channel is free for a DIFS interval. If the channel is still free, the random backoff number which indicates the number of slot time will be decreased and one slot time is 20 μs. When one station reaches 0, it transmits its data. When the channel becomes busy, the random backoff number remains the same until the channel becomes free. If a channel becomes free, it repeats decrementing the backoff number until the data is transmitted. If a collision occurs during this process, stations which failed transmitting would select another backoff number from 0 to 2^n*CWmin. Where n is the number of continual collision and maximum n is 5 which is called CWmax.

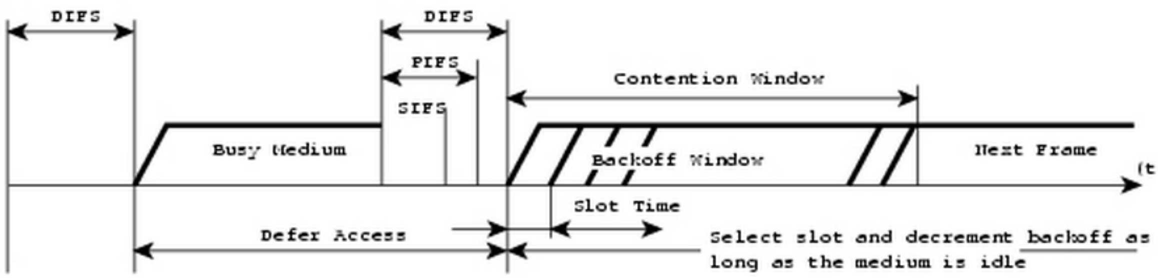


Fig. 5: Interframe Spaces (IFSs)

Interframe spaces allow 802.11 to control which traffic gets first access to the channel once the carrier sense declares the channel to be free.

802.11 currently defines three interframe spaces:

- Short interframe space (SIFS) =10 µs
- Point (coordination function) interframe space (PIFS) SIFS + 1 x slot time = 30 µs
- Distributed (coordination function) interframe space (DIFS) 50 µs SIFS + 2 x slot time = 50 µs

SIFS

Important frames such as acknowledgments wait for the SIFS before transmitting. There is no random backoff when using the SIFS, as frames using the SIFS are used in instances where multiple stations would not be trying to send frames at the same time. The SIFS provides a short and deterministic delay for packets that must go through as quickly as possible. The SIFS is not available to data frames. Only 802.11 management and control frames use SIFS.

PIFS

An optional portion of the 802.11 standard defines priority mechanisms for traffic that uses PIFS. There is no random back mechanism associated with PIFS, as it relies upon a polling mechanism to control which station will transmit. The option is not widely adopted due to the associated overhead and lack of flexibility in its application.

DIFS

Data frames wait for the DIFS before beginning the random backoff procedure that is part of the DCF. This longer wait ensures that traffic using the SIFS or PIFS timing will always get an opportunity to send before any traffic using the DIFS attempts to send [13].

Today's devices mostly support Enhanced Distribution Channel Access (EDCA), an enhanced version of DCF. This adds Quality of Service (QoS) by allocating different inter-frame spaces in accordance with QoS levels.

The 802.11 Frame, shown in the following figure, contains control information used for defining the type of 802.11 MAC frame and providing information necessary for IP and MAC addresses, bit error checks, QoS, and so on.

The payload can contain transmission data from 0-2312 bytes. Throughput comprises the payload size without any control data. According to this payload size, total throughput will be different because of the overhead. Therefore, a large payload size is more efficient than a small one.

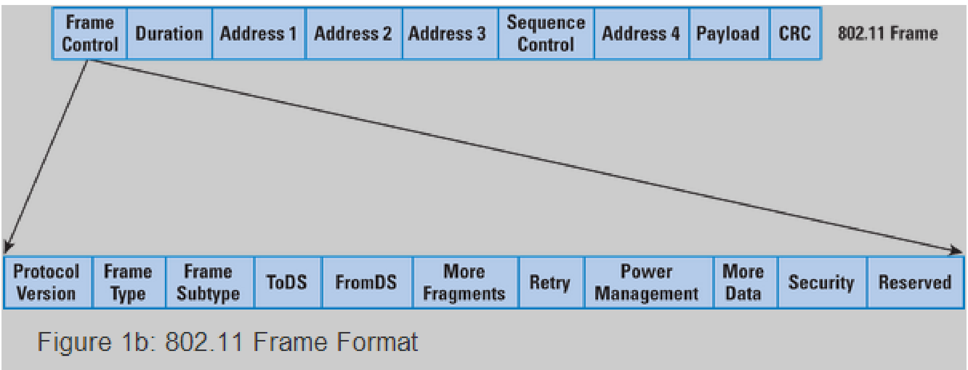


Fig. 6: 802.11 Frame Format

Ⅲ. Existing solutions and limitations

3.1 Existing solutions for coexistence of Wi-Fi and Bluetooth

There are two types of coexistence solutions: collaborative and non-collaborative. The collaborative mechanism described in IEEE 802.15.2 is intended to be used when Wi-Fi and Bluetooth are co-located in a device. Collaborative mechanisms require Bluetooth and Wi-Fi protocols to exchange information for accessing the medium. Non-collaborative mechanisms let Bluetooth and Wi-Fi work independently to avoid interference. Both mechanisms were designed to mitigate interference [1, 14].

•*Collaborative mechanisms:*

1. PTA: When Bluetooth and Wi-Fi attempt to transmit at the same time, a transmit request is submitted to an arbitrator for approval. The arbitrator may deny a transmit request to avoid collision. The PTA mechanism dynamically coordinates sharing of the medium base on the traffic load of Wi-Fi and Bluetooth. The arbitrator needs to know the traffic priority of each packet. Figure 7 shows its mechanism.

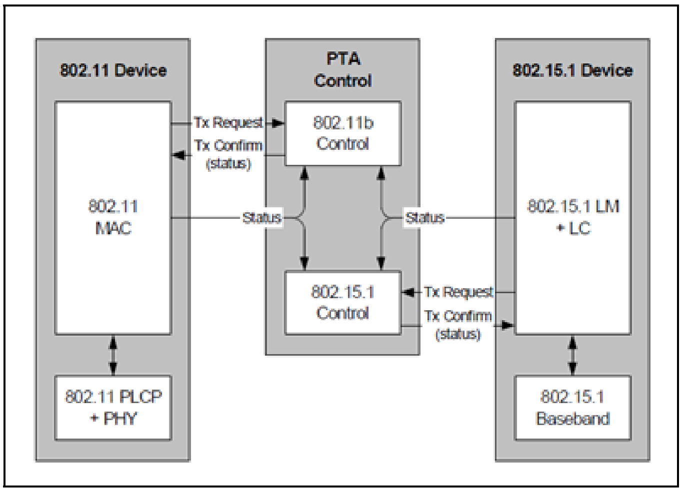


Fig. 7: PTA mechanism

2. AWMA: This is a simple procedure that divides the time interval for transmission and reception into Bluetooth interval and Wi-Fi interval. For this mechanism to work, Wi-Fi

nodes must connect to the same AP and the Bluetooth device must be in master mode. In addition, the AP has to support this technique.

3. DSE: This is PHY layer technique. The Wi-Fi receiver has a programmable notch filter to notch out the narrow-band Bluetooth interferer. But for this technique to work, the Wi-Fi receiver needs to know the frequency hopping pattern as well as the timing of the Bluetooth transmitter. In addition, signal processing adds significant complexity to Wi-Fi receivers.

•*Non-collaborative mechanisms:*

1. AFH: The Bluetooth 1.2 specification includes AFH to avoid interference by allowing a channel to be classified as “good” or “bad”. “Bad” channels are avoided and replaced in the hopping sequence by pseudo-randomly selecting out of the available “good” channels. Figure 8(a) is a collision situation without adopting AFH and (b) shows the AFH mechanism in action.

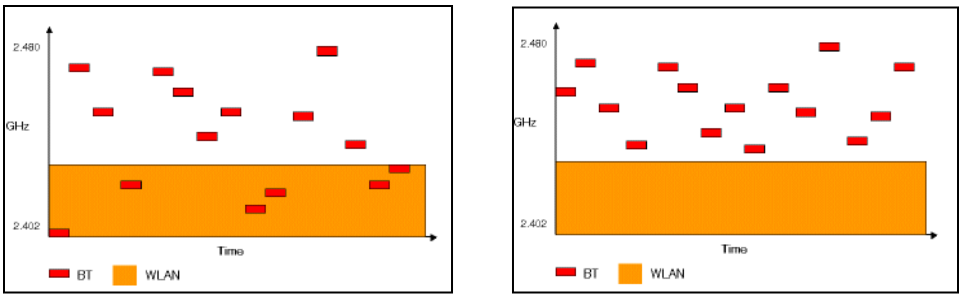


Fig. 8 (a) Collision without AFH (b) Using AFH

2. APSS: Bluetooth provides a variety of packet types with various payload lengths and forward error correction (FEC) options. APSS enables controlling these packet types, payload lengths, and FEC. For instance, it uses shorter packets and drops the FEC when

interference occurs. This can actually improve throughput compared to larger packets. But this mechanism is an inappropriate technique for Bluetooth voice applications.

It is recommended that coexistence schemes are implemented, either separately or in combination with other coexistence schemes for additional performance improvements [1].

3.2 Limitation of existing coexistence solutions

As mentioned earlier, both collaborative and non-collaborative solutions have limitations in the application. PTA is only helpful when both protocols are in transmission mode. AWMA is not used well because of compatibility issues and complexity. DSE is also complex. APSS is not suitable to Bluetooth SCO link. AFH needs isolation between both protocols. Among these solutions, AFH alone or in combination with other solutions are the most widely used. This section will focus on the limitation of existing solutions such as AFH- and TDM-based solutions. AFH offers good performance because it does not use a time-share method, but it requires sufficient isolation. It correlates with the relative strengths of the signals to determine how much isolation is required. On the other hand, a TDM-based solution is not as simple. When Bluetooth operates with synchronous link, Wi-Fi has to use the remaining time to avoid interference. Wi-Fi transmission is simple such as PTA, but in the case of reception, we cannot guarantee that Wi-Fi data will arrive in the remaining time. In this case, it depends on the Wi-Fi data transmission length, and Bluetooth duty cycles how much performance degrades if there is no special regulation with the AP [15, 16, 17].

3.2.1 TDM-based solutions

In the PTA mechanism, when Bluetooth and Wi-Fi attempt to transmit the at same time, a transmit request is submitted to the PTA for approval. The PTA may deny a transmit request to avoid collision. The PTA mechanism dynamically coordinates sharing of the medium base on the traffic load of Wi-Fi and Bluetooth. In addition, it supports Bluetooth SCO (Synchronous connection-oriented) link. If the PTA receives requests from Wi-Fi and Bluetooth at the same time, it prioritizes transmissions based on simple rules which depend on the packet type and load. For example, an SCO packet will have higher priority than a Wi-Fi common data packet. But the PTA mechanism considers that both protocols are transmissions. On the other hand, AWMA leads to complexity.

If Wi-Fi data is received at the SCO packet timing, collision occurs. Because we cannot control Wi-Fi received packets without adding communication with the AP. Wi-Fi has to know the receiving timing from the AP. For this mechanism, AP needs additional protocol or upgrade. In addition, it offers lower performance than operating each Wi-Fi and Bluetooth; it is time sharing. Furthermore, it needs scheduling according to load traffic and SCO packets.

3.2.2 FDM-based solutions

The Bluetooth specification version 1.2 includes AFH. It is a non-collaborative technique that allows Bluetooth devices to detect and avoid interference. In AFH, channels are classified as a good or bad by noise power level. Bad channels are then avoided in the hopping sequence when both Bluetooth and Wi-Fi operate at the same time. Figure 2 illustrates AFH operation to avoid collisions. On the other hand, the key factor of AFH's performance is the relative signal strength between Wi-Fi and Bluetooth. Wi-Fi devices must have high output power to support reliable high data rate transmission and long distance propagation. In devices where Wi-Fi is co-located with Bluetooth Class 2 or Class 3, the Wi-Fi transmitter has approximately +20 dB higher output power than Bluetooth. This difference in signal strength yields performance degradation of both Wi-Fi and Bluetooth in AFH [17].

•*Wi-Fi transmission and Bluetooth reception:*

Figure 9(a) shows the 802.11g spectrum mask and the Bluetooth spectrum of accumulated hopping when Wi-Fi transmits its signal and Bluetooth receives data from the master. The Wi-Fi transmission signal interferes greatly with the Bluetooth receiving signal in situations that lack isolation, such as smartphones. Even though the receiving signal for Bluetooth is high enough, the Wi-Fi signal and its sideband lobe affect the Bluetooth signal, which leads to poor SINR (Signal to Interference plus Noise Ratio) and throughput in Bluetooth. When the Bluetooth receiving signal level is weaker, eventually, Bluetooth not work. On the other hand, the Wi-Fi transmission signal is clean because Bluetooth avoids the Wi-Fi channel with the AFH mechanism. In this case, the AFH mechanism is bad for Bluetooth.

•*Wi-Fi reception and Bluetooth transmission:*

Figure 9(b) shows the spectrum when a signal is received by Wi-Fi and transmitted by Bluetooth. The Wi-Fi received signal is also bad because the Bluetooth transmission noise affects the Wi-Fi signal.

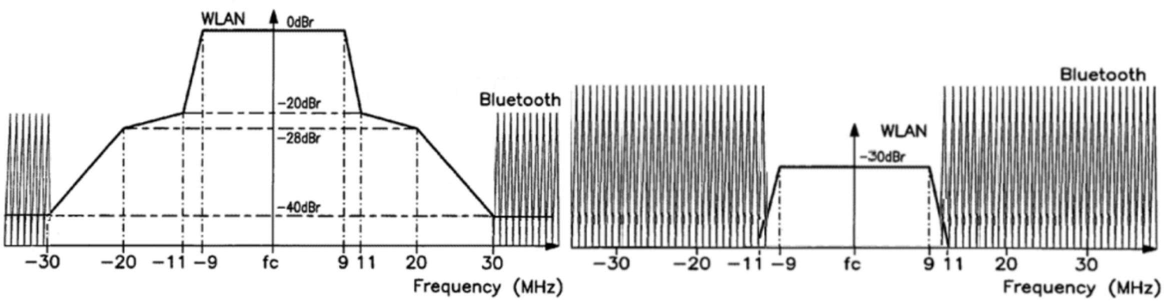


Fig. 9(a): Wi-Fi TX/Bluetooth RX (b) Wi-Fi RX/Bluetooth TX

Ⅳ. Proposed scheme

As explained in the previous section, the most widely adopted scheme, AFH, suffers from performance degradation, especially in the case of Wi-Fi TX/Bluetooth RX and Wi-Fi RX/Bluetooth TX. Furthermore, this phenomenon will become more severe when the spatial separation is insufficient, such as with portable devices. In this paper, a novel mechanism called the Hybrid Arbitrator is proposed. The Hybrid Arbitrator can effectively cancel the self-interference. The proposed Hybrid Arbitrator scheme can be used on top of AFH in order to significantly enhance the performance of AFH.

4.1 Canceller

Let H(t) denote the self-interference channel between the TX antenna and the RX antenna. Through this channel H(t), transmitted (?) signal x(t) interferes with RX. Here, we express H(t) by introducing a certain time delay Δ and a negative (?) gain of α, which is expressed as follows:

$$\mathrm{x(t)} * \mathrm{H(t)} = \alpha \cdot x(t-\Delta)$$

Where "*" denotes the convolution operation. This interference signal affects the quality of the receive signal. In order to remove this interference signal, we place a reverse channel between the TX and the RX antennas, which is called the canceller. The effect of the canceller, denoted by -H(t), is as follows:

$$\mathrm{x(t)} * \mathrm{H(t)} + \mathrm{x(t)} * \left(-\mathrm{H(t)}\right) = \mathrm{x(t)} * \left(\mathrm{H(t)} - \mathrm{H(t)}\right)$$

$$= \mathrm{x(t)} * 0 = 0$$

Here, we split the transmit signal, x(t), by a coupler. One signal goes into the antenna for propagation and the other to the canceller path. The sum of the TX interference signal and the signal after the canceller becomes zero at the receiving antenna. Figure 10 shows this canceller mechanism.

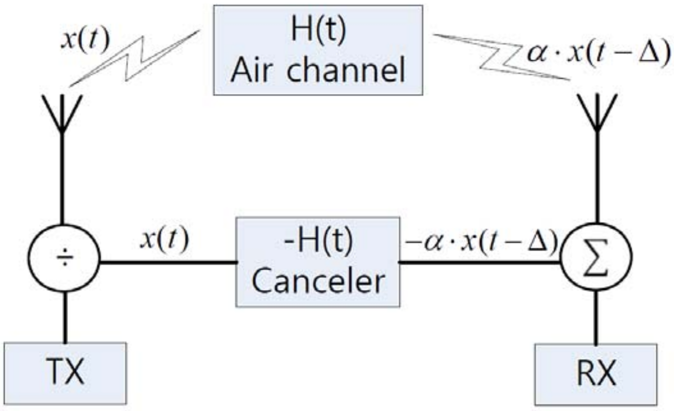


Fig. 10: Mechanism of the canceller

4.2 Cancellation channel setting

An efficient reverse channel requires a correct value of Δ and -α. The algorithm that can find Δ and -α is as follows:

1. First check the center frequency of the TX signal. This is denoted as Tx_center_freq.

2. α is fixed at 1, Δ changes from 0 to 1/Tx_center_freq. When the received signal power is smaller in the RX part than in the Δ shifted (?) value it is fixed.

3. The gain α is changed when the received signal power is smaller than the fixed value of α.

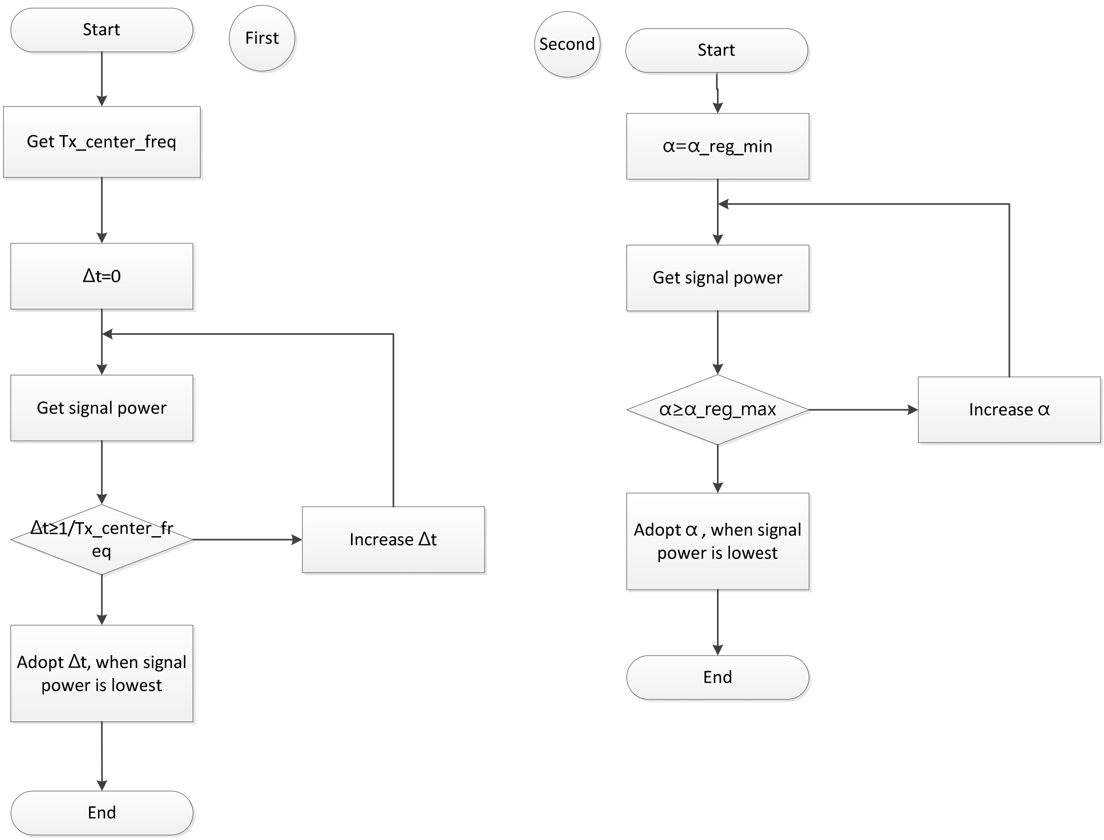


Fig. 11: Algorithm of finding Δ and - α

4.3 Hybrid arbitrator

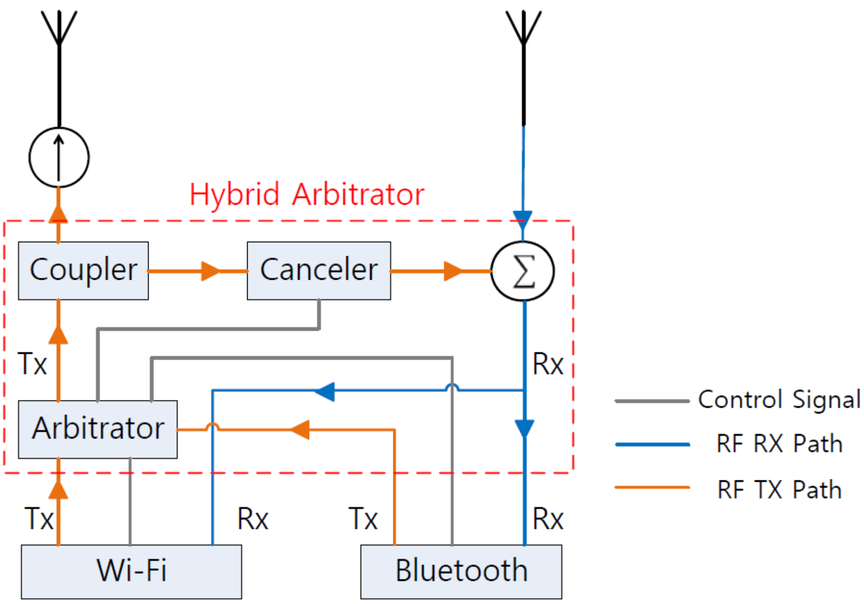


Fig. 12: A diagram of the hybrid arbitrator

Figure 12 shows the proposed Hybrid Arbitrator that applies the proposed canceller on top of AFH and PTA mechanisms. Wi-Fi and Bluetooth RF TX endpoints are tied to an arbitrator. This arbitrator can have information on whether Wi-Fi and Bluetooth are enabled as well as TX or RX operating mode by using the control signal. According to the operation mode of each Wi-Fi and Bluetooth, the arbitrator operates as described in Table 5.

Table 5: Operation mode of the hybrid arbitrator

Wi-Fi	Bluetooth	Mode of the hybrid arbitrator
TX	TX	AFH or PTA
TX	RX	AFH with Interference Cancelation
RX	TX	AFH with Interference Cancelation
RX	RX	Idle
work	off	Idle (Wi-Fi work as MI-MO)
off	work	Idle

1. Operating in WLAN TX Bluetooth TX: When both Bluetooth and WLAN transmit data, the Hybrid Arbitrator chooses TX operation using PTA according to situation.
2. Operating in WLAN TX Bluetooth RX: While WLAN uses one antenna for transmission, Bluetooth can receive not just the data but also self-interference from another. But, such an issue can be resolved by using an internal canceller so that AFH can be utilized. A canceller can be used on top of AFH.
3. Operating in WLAN RX Bluetooth TX: In WLAN RX and Bluetooth TX, AFH is used with a canceller.
4. Operating in WLAN RX Bluetooth RX: FDM-based AFH is used in WLAN and Bluetooth transmitter.
5. Operating in Bluetooth off: WLAN operates MI-MO with two available antennas when the Bluetooth is off.
6. Operating with WLAN off: Bluetooth operates alone.

Ⅴ. Experimental

We implemented a test bed and carried out extensive experiments. First, we measured the performance of the canceller. Then, we performed experiments to validate the performance of the proposed scheme under various conditions.

5.1 Canceller performance

First, we measure the canceller's performance. 'How much self-interference can be cancelled?' is a key factor for this proposal.

5.1.1 Canceller Arrangement

To implement the canceller, we arranged the canceller as shown in Figure 13. We used some key component for the canceller such as a commercial coupler, a transformer, and a noise canceller (QHX-220). The end point of the RF transmission signal connects to the RF TX in Figure 13. The coupler divides the RF transmit signal into two paths. One path connects with the transmit antenna with 90% power path and the other with the transformer with 10% power. The transformer reverses the received signal and passes it to the noise canceller, which adds the amplitude gain and delay. Then, it is combined with the self-interference signal which comes from the RX antenna.

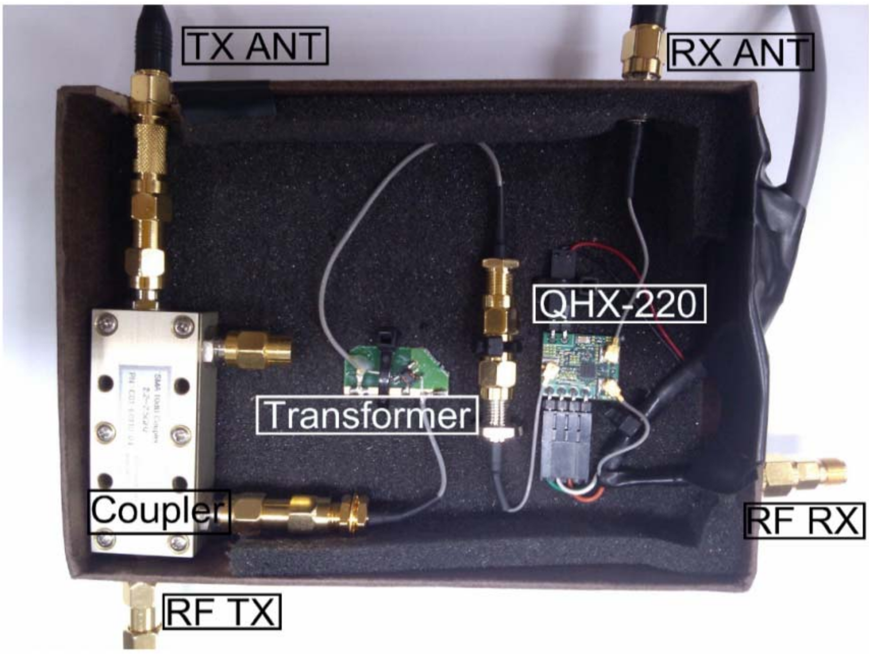
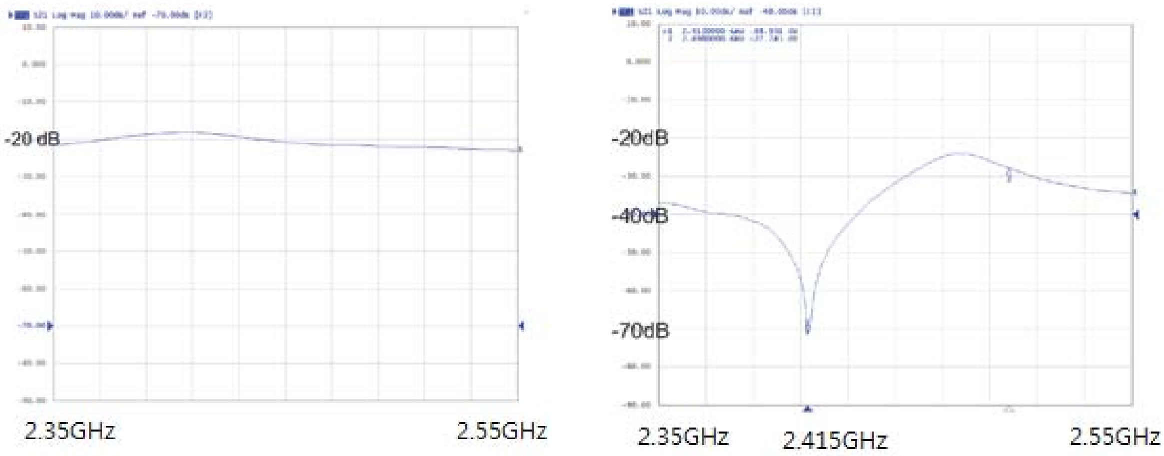


Fig. 13. Canceller test bed

5.1.2 Measurement of cancellation performance according to frequency

To know the bandwidth coverage and the frequency features, we tested the cancellation performance according to frequency by using a network analyzer.

First, we fixed the distance between the TX antenna and the RX antenna at three centimeters. This is a reasonable distance for small portable devices. Then, we connected the network analyzer with the TX antenna as Port A and the RX antenna as Port B. From Port A, the RF signal transmits as 0 dB power and Port B measures the receive signal strength from 2.35 GHz to 2.55 GHz, which corresponds to the channel H(t) as air channel. In Figure 14 (a) we show, the signal strength is about -20 dB with measuring frequency range. And then we applied the canceller between the TX and RX RF paths. We tuned the QHX-220's delay and amplitude for maximum cancellation at Wi-Fi channel 1 (2.412GHz). As in Figure 14 (b), the signal is canceled and its strength at the minimum is almost -70 dB at 2.415 GHz but its bandwidth is too small to cover the Wi-Fi bandwidth. The results show that the canceller can effectively cancel out the self-interference once the channel is properly identified.



(a) (b)

Fig. 14 Network analyzer measurement, (a) measurement of S21 without canceller, (b) measurement of S21 with canceller

5.1.3 Measurement of active cancellation performance using spectrum analyzer

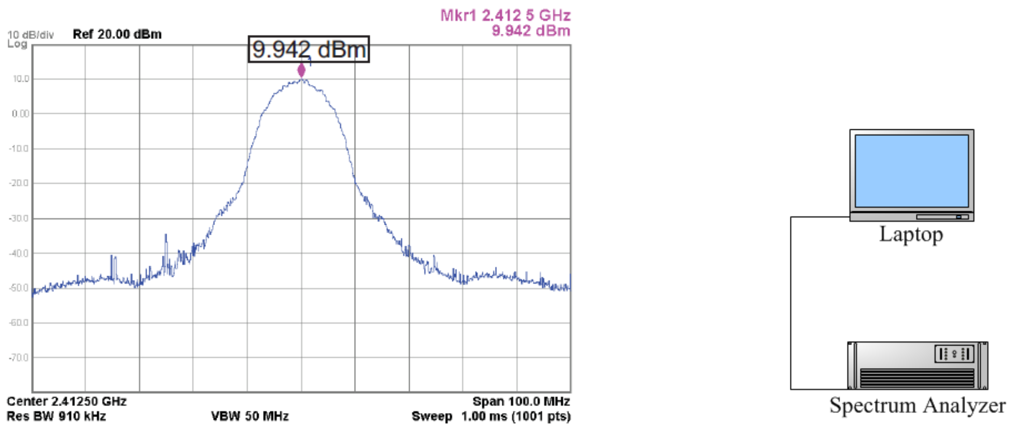
As with the previous measurement, the peak cancellation point was almost -70dB, but the bandwidth was too narrow to cover the Wi-Fi bandwidth. So, to find the Wi-Fi (wide band) cancellation performance, we directly measured the Wi-Fi transmit signal from a laptop by using a spectrum analyzer. A Lenovo E320 laptop was disassembled and the RF end-point of the Wi-Fi module was connected to an RF cable for an external connection and then reassembled with the laptop.

First, the laptop uploaded its data using Wi-Fi continuously and we measured the radio spectrum through the external RF cable connected to the spectrum analyzer. Figure 15 (a) shows the direct measuring result of transmission of Wi-Fi with the max-hold mode for 30 seconds. The peak transmit power is almost 10 dBm.

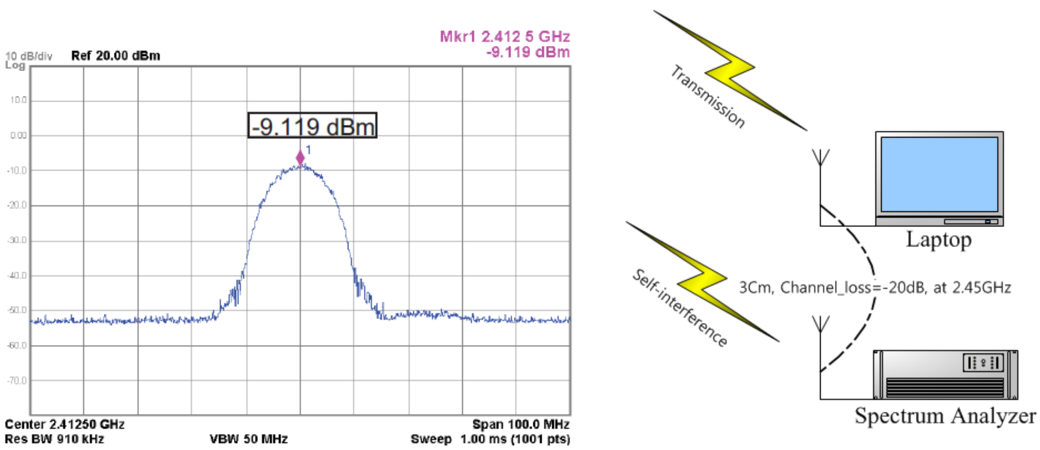
Second, we measured the spectrum of the interference. The Wi-Fi external RF cable was connected to the external antenna, which had a transmission antenna positioned next to the receiving antenna at a distance of three centimeters. The receiving antenna was connected to a spectrum analyzer. Figure 15 (b) shows the result. The air channel between the two antennas makes a loss of almost 20 dB.

Third, we added the canceller between the Wi-Fi transmission antenna and the receiving antenna. In Figure 15 (c), we show the result with the canceller. In the figure, the interference signal power is reduced by 15 dB compared to without the canceller. In fact, this power level corresponds to the case of a 21 cm distance between the TX antenna and the RX antenna without the canceller, which is shown in Figure 15 (d).

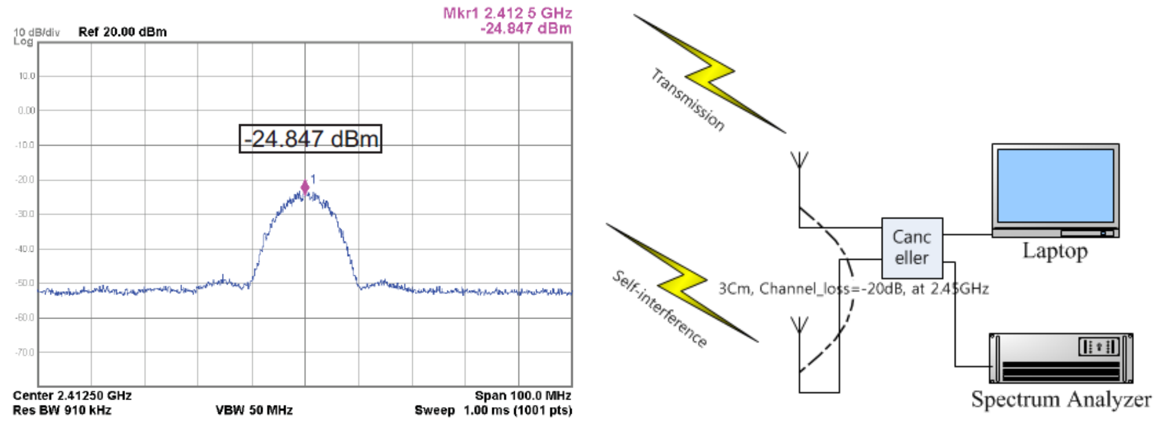
Consequently, applying the canceller gives a spatial gain from 21 cm to 3 cm, which is about 15 dB isolation.



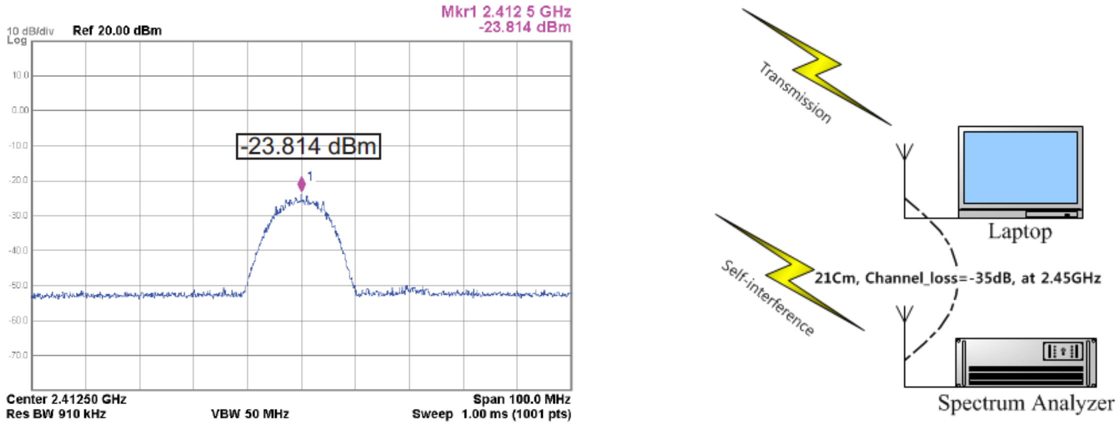
(a)



(b)



(c)



(d)

Fig. 15. Spectrum Analyzer measurement, (a)Wi-Fi TX spectrum, (b)Wi-Fi interference spectrum at RX antenna (c) Wi-Fi interference at RX antenna with canceller. (d) Wi-Fi interference spectrum at RX antenna at a distance of 21 cm.

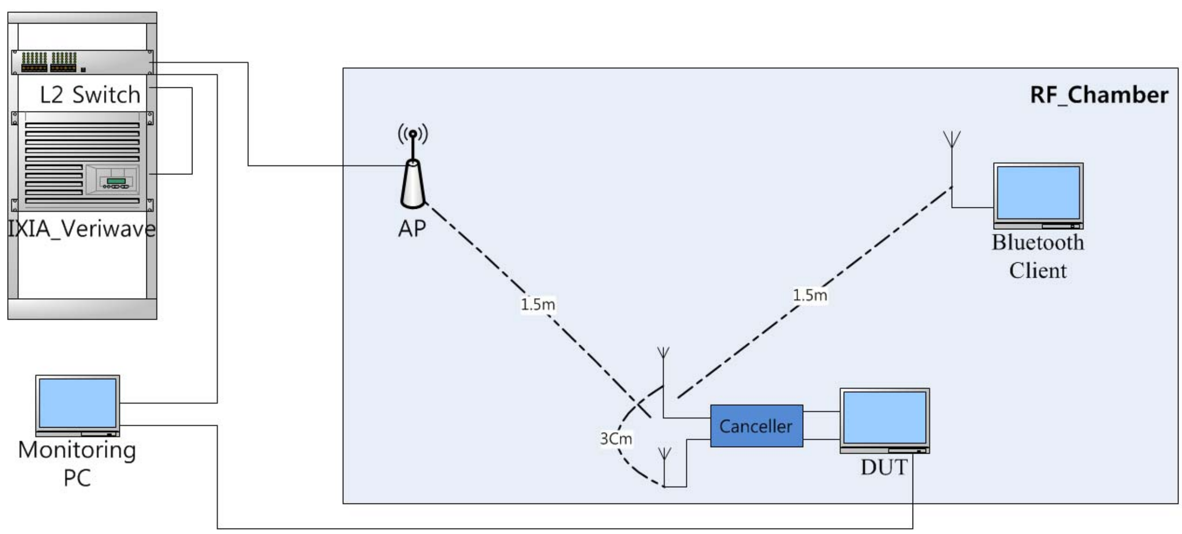
5.2 Measurement of real throughput

In the previous section, we showed the performance of the canceller when Wi-Fi transmits. In this section, we test the real throughput when Wi-Fi and Bluetooth operate at the same time.

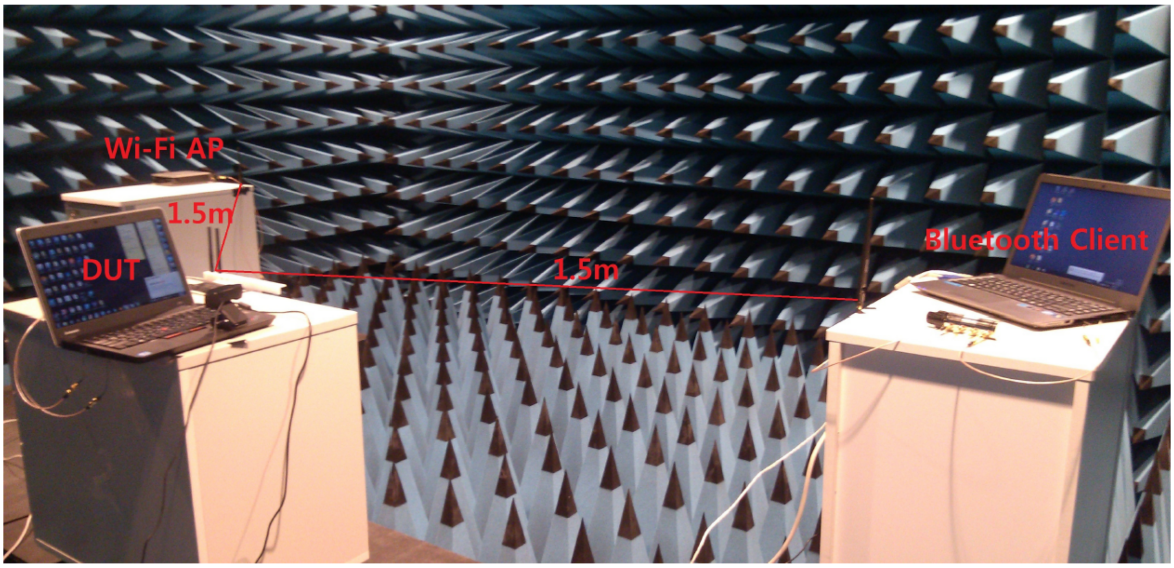
5.2.1 Organization of test bed

To make a reliable test result, we carried out the test in an RF chamber which blocks all frequency band noise. The overall setup is shown in Figure 16. First, we positioned the device under test (DUT) at the center of the RF chamber. A Wi-Fi AP was placed to the left of the DUT at a distance of 1.5m, then a Bluetooth client was positioned on the opposite side. The Bluetooth client was a laptop working in file transfer profile (FTP) mode with an EDR speed (3 Mbps in the PHY layer). We measured the Bluetooth throughput using Windows Bluetooth file transfer application with AFH mode. The Wi-Fi throughput was measured by IXIA Veriwave test 90 equipment. IXIA Veriwave test 90 connects with private networks that consist of an AP (Access Point, Cisco WAP4410N), Cisco Layer 2 switch (SG300-28), and a monitoring PC without an Internet connection. The Wi-Fi used channel 1 and 802.11n mode.

When we tested situations without the canceller, we connected two external antennas from the Wi-Fi module RF endpoint and the Bluetooth chip RF end pin. The distance between these two antennas was fixed at three centimeters and 1.5 cm. On the other hand, when we tested the canceller's performance, additionally, we connected the canceller between the RF path of Wi-Fi and that of Bluetooth. Originally, we wanted to test throughput according to distance between DUT and Wi-Fi or DUT and Bluetooth Client. However, we could not do so due to limitations of the RF chamber size. Instead, we added an RF attenuator to the AP and Bluetooth client.



(a)



(b)

Fig. 16. Test bed, (a) test bed block diagram, (b) real test bed

5.2.2 Case of Wi-Fi TX and Bluetooth RX

We carried out a measurement study in the following order. We installed a 30 dB attenuator to the Wi-Fi AP RF path and a variable attenuator to the Bluetooth client. Then, we measured the throughput of the Bluetooth and Wi-Fi while changing the variable attenuator value.

The result is given in Figure 17. Until the Bluetooth client's attenuation value is 20 dB, the case with the canceller gives a substantial performance improvement. In the 1.5 cm case, until 10 dB attenuation, Bluetooth works well. In the case without the canceller, poor performance is recorded. In the meantime, the Wi-Fi throughput is almost the same in all cases as follows: Wi-Fi throughput is 51.772 Mb/s, coexistence of Wi-Fi and Bluetooth with the canceller yields 51.727 Mb/s, while coexistence without the canceller transmits at 51.349 Mb/s.

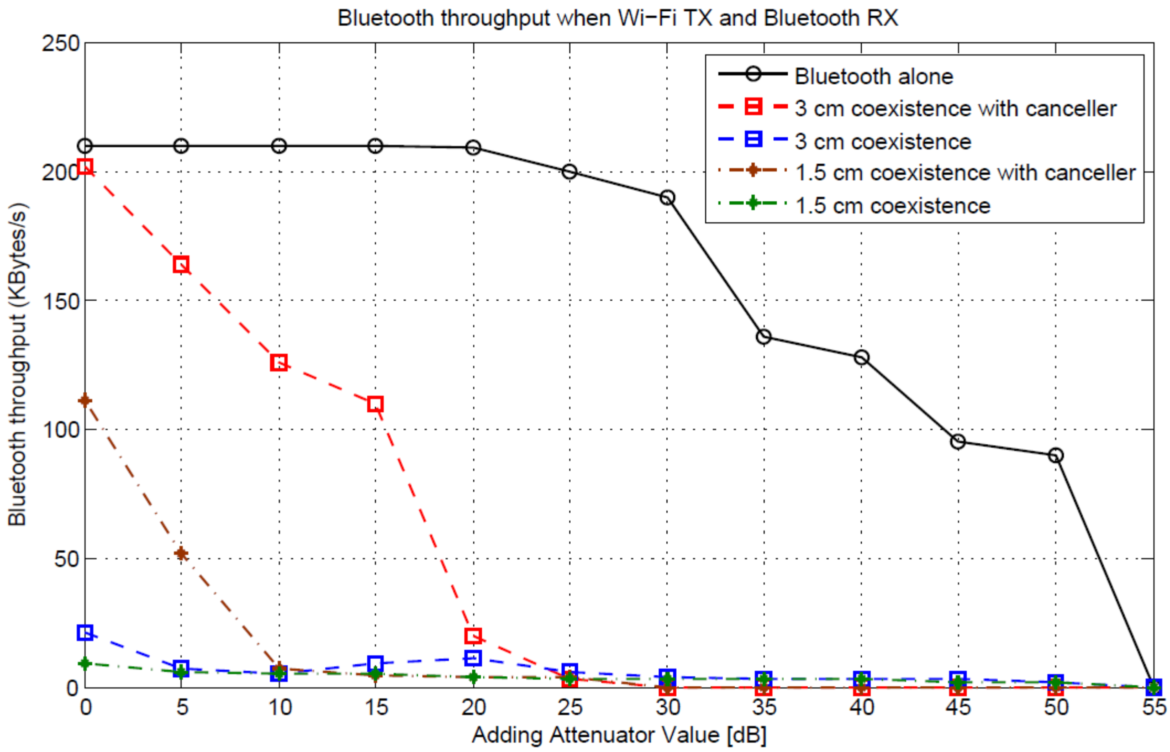


Fig. 17. Throughput of Bluetooth as a function of the attenuator value

5.2.3 Case of Wi-Fi RX and Bluetooth TX

We also tested the case when Bluetooth works as an uplink and Wi-Fi works as a downlink at the DUT. As shown in Figure 18, the case of coexistence with the canceller at a distance of three cm performs better from 0 dB to 10 dB than the case of coexistence without the canceller performs better after 10 dB. At 1.5 cm, the canceller is effective through the entire range of attenuation. In the meantime, Bluetooth throughput is nearly the same in all cases: Bluetooth by itself transmits at 234 KB/s, coexistence of Wi-Fi and Bluetooth with the canceller gives 209.8 KB/s, and coexistence of Wi-Fi and Bluetooth without the canceller results in 216.5 KB/s.

Further investigation into why the case with the canceller performs worse than the one without a canceller after 10 dB by using a spectrum analyzer is required. No isolator cause cancelation not only current transmission interference signal but also receiving signal through the TX antenna and canceller. When the receive signal is strong enough, the amount of cancelation of transmission interference is larger than the cancelation of the receiving signal. But the canceled received signal is insufficient to decode when the received signal is week. And 1.5 cm canceller gives better performance than three cm canceller. The setting of Δ and $-\alpha$ seems to be more suitable to the 1.5 cm canceller.

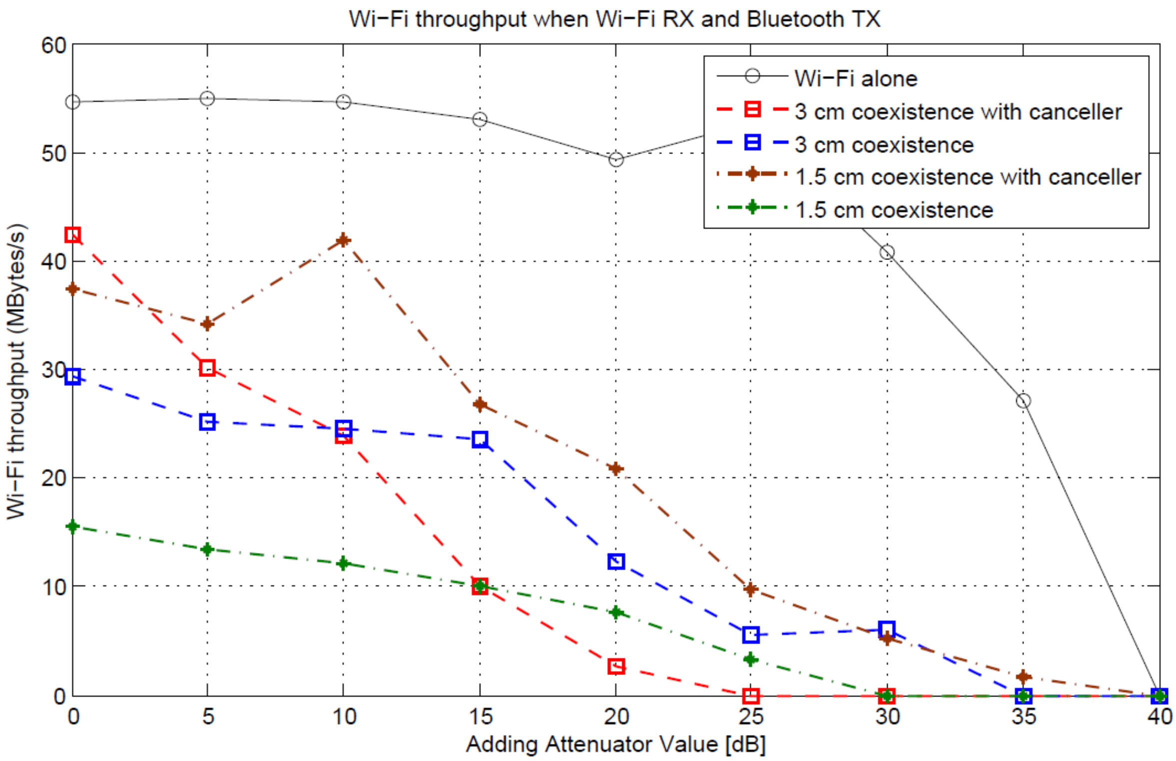


Fig. 18. Throughput of Wi-Fi as a function of the attenuator value

Ⅵ. Conclusion

This paper proposes a simple and effective solution for resolving the in-device coexistence problem of Wi-Fi and Bluetooth. In summary, we introduced a canceller that can cancel out in-device interference. Extensive experimental results show that the proposed approach can significantly improve the throughput performance in practice. This solution will be particularly viable for portable devices where Wi-Fi and Bluetooth radios coexist in a small space. There are several remaining issues for future research. One direction is to introduce an isolator in the circuit that is expected to further improve the communication performance as it will prevent the self-cancellation which also cancels out the original receiving signal.

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요 약 문

Canceller를 이용한 Bluetooth와 Wi-Fi 성능 향상

최근 스마트폰과 같이 한 단말기에 Wi-Fi와 Bluetooth 기능이 공존하는 기기가 많다. Bluetooth와 Wi-Fi는 같은 2.4GHz ISM band를 사용하는데 동시에 무선통신이 이루어지면 상호간섭으로 인하여 통신 유효거리, 통신속도 등 성능저하가 일어 난다.

이러한 문제를 해결하기 위하여 IEEE 802.15.2 표준이 있다. 이 표준에서는 PTA, AW-MA, DSE, APSS, AFH 기법을 소개하고 있는데 그 중 AFH 방법이 가장 널리 사용되고 있다. AFH 방법은 Bluetooth가 channel hopping sequence를 결정할 때, 전체 채널의 noise level을 검색하여 noise가 많은 채널은 bad channel로 등록하고 hopping sequence에서 제거하는 방법 이다. Wi-Fi의 한 개 채널당 bandwidth는 20MHz이기 때문에 Bluetooth가 사용하는 전체 bandwidth: 83.5MHz에서 20MHz를 뺀 나머지를 사용하면 될 것 같지만, 실제로 한 단말기내에서는 공간이 부족하여 Wi-Fi와 Bluetooth 안테나가 가까이에 있어 Wi-Fi가 송신신호를 내보낼 때, sideband lobe가 영향을 주어 Bluetooth SINR이 내려간다. 반대로 Bluetooth가 송신신호를 내보내고 Wi-Fi가 수신 상황일 때도 Bluetooth의 송신신호가 영향을 주어 Wi-Fi 수신 감도가 내려가게 된다.

이를 개선하기 위하여 본 연구에서는 Canceller를 이용하였다. 송신신호를 Coupler를 통하여 1%의 cancel 신호와 99% 송신신호로 나누어 송신 신호는 안테나를 통하여 방사 시킨다. 이때 cancel 신호는 위상 반전 및 delay를 이용하여 송신 신호의 위상과 반대되는 신호로 가공하고 수신안테나를 통하여 들어오는 자기 간섭신호와 합해져 간섭신호를 제거한다.

본 연구의 성능 검증을 위하여 실제 하드웨어를 설계하고 상용제품에 적용하여 적용 전 후의 성능을 실험하였다. 실험 결과 송신성능의 저하 없이 수신성능이 Bluetooth의 경우 약 50%, Wi-Fi의 경우 약 20% 성능향상이 있었다.

본 논문에서 제안한 기술은 공간적으로 작게 설계가 가능함으로 상업적으로 즉시 사용이 가능하며, 이전에 존재하지 않았던 새로운 간섭제거 방법을 소개하고 있다.

핵심어: canceller, AFH, Wi-Fi, Bluetooth

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