Harnessing Self-Cancellation for Coexistence of Wi-Fi and Bluetooth

Wonhong Jeon, Sungmin Han, Ji-Woong Choi, and Kyung-Joon Park

Department of Information and Communication Engineering
Daegu Gyeongbuk Institute of Science and Technology
Daegu, 711-873 Republic of Korea
Emails: {cwh4898, krcapt13, jwchoi, kjp}@dgist.ac.kr

***Abstract*—In this paper, we present a simple and effective solution for resolving the in-device coexistence problem of Wi-Fi and Bluetooth. The main idea is to introduce a canceller in the circuit in order to cancel out the in-device interference when Wi-Fi and Bluetooth radios simultaneously operate in the same device. Our proposed approach, entitled the hybrid arbitrator, can significantly improve the performance of both of Wi-Fi and Bluetooth. Based on our testbed, we carry out extensive experiments to validate the performance of the proposed scheme. Our results show that the proposed hybrid arbitrator gives substantially better performance than existing methods.**

***Keywords*— Full-duplex, AHT, Bluetooth, Hybrid Arbitrator, WLAN, canceller, coexistence**

I. Introduction

The recent advance in wireless communication has made our life a lot more efficient and comfortable. However, wireless bandwidth is a limited resource, and each government tightly controls its usage. Usually, the wireless bandwidth is owned by the government for public and military uses, and from time to time, some of the bandwidth is sold to service providers to provide certain services such as cellular service.

Exceptions are the unlicensed bands for industrial, scientific and medical purposes, so called the ISM bands, which are freely used worldwide. Hence, many wireless technologies have been developed based on the ISM bands, among which the most successful ones are Wi-Fi and Bluetooth. For example, the smartphones, the most popular mobile devices incorporate both Wi-Fi and Bluetooth typically in the same 2.4 GHz ISM band. Consequently, serious performance degradation can happen when both Wi-Fi and Bluetooth radios simultaneously operate, which is known as the in-device interference problem.

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

- The proposed scheme, called the hybrid arbitrator, can significantly reduce the in-device self-interference, which can be used on top of the existing adaptive frequency hopping (AFH) method in order to further enhance the overall system performance.
- We develop a testbed and carry out extensive experiments that empirically validate the performance of the proposed method.
- The proposed scheme is highly practical in the sense that it requires a simple extension of existing circuitry without modifying any wireless protocols.

In fact, there have been substantial amount of studies for resolving the self-interference problem. For example, the IEEE 802.15.2 Standard recommends collaborative mechanisms such as packet traffic arbitration (PTA), alternating wireless medium access (AWMA), and deterministic spectral excision (DSE) as well as non-collaborative mechanisms such as adaptive packet selection and scheduling (APSS) and adaptive frequency hopping (AFH) [1]. Among these schemes, the AFH mechanism is most widely used for avoiding interference. Bluetooth takes an evasive action by adopting AFH, which operates as follows: AFH first measures the noise level over the entire channels. If some of them are larger than a threshold, then register them as bad channels and exclude them from the hopping sequence [2].

However, AFH alone is often insufficient to resolve the coexistence problem between Wi-Fi and Bluetooth, especially when there is not enough spatial isolation. In particular, the two cases when one is in transmission while the other is in reception are critical because the receive signal is much weaker than the transmit signal due to channel attenuation. When the Wi-Fi radio is in transmission while the Bluetooth radio is in reception without enough isolation, the number of bad channels of Bluetooth may significantly increase and even prevent Bluetooth from proper operation due to the insufficient number of good channels. This is because, in this case, not only those channels occupied by Wi-Fi, but also adjacent ones may be considered as bad by AFH due to the relatively weak Bluetooth signal interfered with the leakage Wi-Fi signal at the sideband lobes. The case when Wi-Fi receives and Bluetooth transmits will also be an issue, though less serious.

Recently, a full duplex wireless communication system is implemented by applying the so-called *self-interference cancelling technique* with two transmit antennas and one receive antenna [3]. In their subsequent work, they improve their idea by using only one transmit antenna and one receive antenna [4]. In this work, they consider two transmission paths, i.e., one goes to transmit antenna and the other to the balun and then the noise canceller, which reverses the original signal and also tunes the signal level. The sum of these two signals will become zero at the receive antenna. More recently, there have been substantial studies by applying this technique: medical implant device security [5], a more efficient Wi-Fi backoff mechanism [6], a study on an access point (AP) that performs like several APs [7]. Here, we exploit the idea of self-interference cancellation and apply it to the in-device coexistence problem.

The remainder of the paper is organized as follows. In Section II, we provide an overview of Wi-Fi and Bluetooth, and then summarize existing solutions for coexistence of Wi-Fi and Bluetooth. We explain the key limitation of existing solutions in Section III. In Section IV, we introduce a novel mechanism, called the hybrid arbitrator, for improving the in-device coexistence performance of Wi-Fi and Bluetooth. We carry out extensive experiments and validate the performance of the proposed scheme in Section V. Our conclusion follows in Section VI.

II. Preliminaries

In this section, we introduce the basics of Wi-Fi and Bluetooth. Then, we explain existing solutions to their coexistence.

A. Bluetooth

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 the frequency hopping spread spectrum (FHSS) with nominally 1,600 hops per second.

Bluetooth provides point-to-point, 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 with two link types, 14 basic rate packet types are defined, which are split into four segments as categorized in Table I.

TABLE I
Basic packet types.

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

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 and less time for re-tuning the synthesizer. Each packet type has a different level of error correction and protection codes and different payload size [8]. 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.

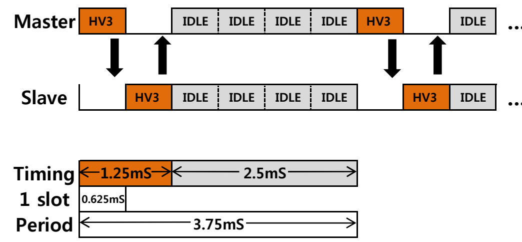


Fig. 1. SCO: HV3 packet timing.

Figure 1 shows HV3 packet timing. In the figure, a master and a slave in SCO connection, respectively, consume one slot of 625 us in a total period of six-slot time. This leaves four slots available for either ACL transmission or Wi-Fi [2], [9], [10].

B. IEEE 802.11

Wi-Fi is a commercial terminology for wireless technology based on IEEE 802.11. IEEE 802.11 is a set of standards for wireless local area network (WLAN). These standards provide the basis for wireless network products using the ISM brands. IEEE 802.11b/g/n use 2.4 GHz ISM band and obey the rules and regulations of US Federal Communications Commission (FCC). They use direct-sequence spread spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM) signaling methods. Normally, the ISM band for 802.11 is divided into 13 channels spaced 5 MHz apart, from 2.4000 GHz to 2.4835 GHz. 802.11b is based on the DSSS with 22 MHz bandwidth and has a maximum data rate of 11 Mbit/s. 802.11g is based on OFDM with 20 MHz bandwidth and a maximum physical layer bit rate of 54 Mbit/s. 802.11n adds multiple-input multiple-output antennas (MIMO) technology and 20 MHz or 40 MHz bandwidth. It operates at a maximum data rate from 54 Mbits/s to 600 Mbits/s. Among the 13 channels, non-overlapping ones are Channel 1, 6, and 11. In the EU, equivalent isotropically radiated power (EIRP) is limited to 20 dBm (100 mW), which can communicate within about 100 m [11], [12].

C. Existing solutions for coexistence of Wi-Fi and Bluetooth

Since Wi-Fi and Bluetooth typically share the same 2.4 GHz ISM band, their coexistence becomes a critical issue. In general, we can classify existing coexistence solutions into two classes, i.e., collaborative and non-collaborative ones. Collaborative mechanisms require information exchange between Wi-Fi and Bluetooth for channel access [1]. In the meantime, with non-collaborative schemes, Wi-Fi and Bluetooth independently operate and avoid interference. We can summarize the basic operation of typical coexistence schemes as follows:

- *Collaborative mechanisms*

1. PTA: When Bluetooth and Wi-Fi attempt to transmit at the same time, a transmit request is submitted to the arbitrator for approval. The arbitrator may deny a transmit request in order to avoid collision. The PTA mechanism dynamically coordinates the medium sharing based on the traffic load of Wi-Fi and Bluetooth. The arbitrator needs to know the traffic priority of each packet.
2. AWMA: This divides the time interval for transmission and reception either into that of Wi-Fi or Bluetooth. In order to enable this mechanism, Wi-Fi nodes must be connected to the same AP and Bluetooth device must be in the master mode. In addition, the AP has to support this technique.
3. DSE: This is a PHY layer technique, which introduces a programmable notch filter in the Wi-Fi receiver in order to notch out the narrow-band Bluetooth interferer. However, in this technique, the Wi-Fi receiver needs to know the frequency hopping pattern and the timing of the Bluetooth transmitter. Consequently, significant signal processing burden is added to Wi-Fi receivers.

- *Non-collaborative mechanisms*
  1. Adaptive frequency hopping (AFH): Bluetooth 1.2 specification includes AFH to further avoid interference. In this scheme, each channel is classified as good or bad so that bad channels are avoided and replaced in the hopping sequence by pseudo-randomly selection out of the remaining good channels.
  2. APSS: Bluetooth provides a variety of packet types with various payload lengths and forward error correction (FEC) options. APSS enables to control these packet types, payload lengths, and FEC. For instance, APSS uses shorter packets, drops the FEC when interference occurs. This can actually improve throughput compared to larger packets. But, this mechanism is inappropriate for Bluetooth voice applications.

In general, it is recommended that a combination of existing schemes can give additional performance improvement [13]–[15].

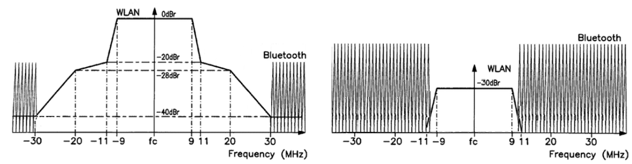
III. Limitation of Existing Coexistence Solutions

As already mentioned, both collaborative and non-collaborative solutions have their limitations. In this section, we explain the limitation of representative schemes.

A. AFH as a representative scheme for FDM based solutions

The Bluetooth specification version 1.2 supports AFH, which is a non-collaborative scheme that allows Bluetooth devices to detect and avoid interference. In AFH, channels are classified as good or bad, and bad channels are avoided in the hopping sequence when Bluetooth and Wi-Fi operate at the same time. Figure 2 illustrates AFH operation to avoid collisions.

A key issue for AFH performance is the relative signal strength between Wi-Fi and Bluetooth. Wi-Fi radios need high output power in order to support reliable data transmission, especially compared to Bluetooth. For example, if Wi-Fi is co-located with Bluetooth Class 2 or Class 3 capability, the Wi-Fi transmitter may have +20 dB higher output power than that of Bluetooth. This difference of the signal strength may yield performance degradation of both Wi-Fi and Bluetooth in AFH [16]. In particular, among the four cases of transmission and reception of Wi-Fi and Bluetooth, the following two cases are the most critical in terms of performance degradation.



(a) AFH: Wi-Fi TX / Bluetooth RX (b) AFH: Bluetooth TX / Wi-Fi RX

Fig. 2. Relative signal strength.

- *Wi-Fi transmission and Bluetooth reception*
  Figure 2 (a) shows the 802.11g spectrum mask and Bluetooth accumulated spectrum when Wi-Fi transmits its signal and Bluetooth receives data. As shown in the figure, Wi-Fi transmit signal severely interferes with the Bluetooth receive signal in lack of spatial isolation. Even when the Bluetooth receive signal is quite strong, the effect of the Wi-Fi signal and its sideband lobe is serious. Consequently, Bluetooth has poor signal to interference plus noise ratio (SINR) and throughput degradation. More seriously, as the level of the Bluetooth receive signal becomes weak, Bluetooth may not work at all. On the other hand, the Wi-Fi transmit signal is relatively unaffected because Bluetooth avoids the Wi-Fi channel by the AFH mechanism.
- *Wi-Fi reception and Bluetooth transmission*
  Figure 2 (b) shows the spectrum when Wi-Fi is receiving the signal and Bluetooth is transmitting. In this case, the Wi-Fi receive signal is also affected from Bluetooth transmission signal because the relative signal strength of Wi-Fi is weaker than Bluetooth. It also has sideband lobes. In addition, there is some possibility that the AFH mistakenly consider the Wi-Fi channel as good, which is not zero. which results in further performance degradation.

B. PTA and AWMA as a representative scheme for TDM based solutions

In the PTA mechanism, When Bluetooth and Wi-Fi attempt to transmit at the same time, a transmit request is submitted to PTA for approval. PTA may deny a transmit request in order to avoid collision. If PTA receives requests at the same time from Wi-Fi and Bluetooth, it prioritizes transmissions based on the packet type and the traffic load. For example, SCO packet of Bluetooth has higher priority than Wi-Fi common data packet [1]. However, the PTA mechanism only considers the case when both Wi-Fi and Bluetooth transmit.

On the other hand, AWMA requires a substantial level of complexity. If Wi-Fi data is received at SCO packet timing,

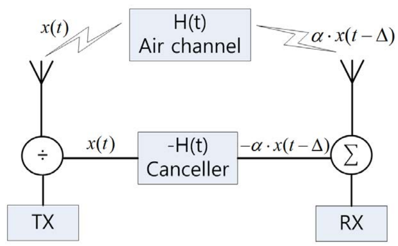


Fig. 3. A mechanism of the canceller.

collision is occurred. We are unable to control Wi-Fi receive packets without adding communication with AP. So, AP has to know Bluetooth SCO timing. Consequently, protocol update is required at the AP. In addition, AWMA gives worse throughput performance because of its intrinsic time-sharing nature. Furthermore, AWMA needs a scheduling algorithm according to the traffic load and SCO packets [16].

IV. Proposed scheme

As explained in the previous section, the most widely adopted scheme, AFH, suffers from performance degradation especially when 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 the case of portable devices. In this paper, we propose a novel mechanism, called the hybrid arbitrator, which 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.

A. Canceller

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

$$x(t) * H(t) = \alpha \cdot x(t - \Delta),$$

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. Here, the effect of the canceller, denoted by $-H(t)$, is as follows:

$$\begin{aligned} x(t) * H(t) + x(t) * (-H(t)) &= x(t) * (H(t) - H(t)) \\ &= x(t) * 0 = 0. \end{aligned}$$

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 receive antenna. Figure 3 shows this canceller mechanism.

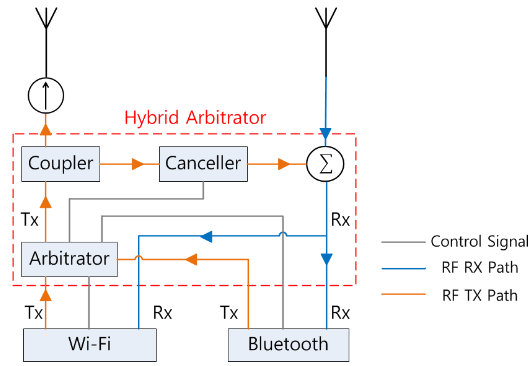


Fig. 4. A diagram of the hybrid arbitrator.

B. Hybrid arbitrator

Figure 4 shows the proposed hybrid arbitrator that apply the proposed canceller on top of AFH and PTA mechanisms. Wi-Fi and Bluetooth RF TX endpoints are tied by an arbitrator. This arbitrator can have information on whether Wi-Fi and Bluetooth are enabled as well as their operating mode of TX or RX by using a control signal. According to the operation mode of each Wi-Fi and Bluetooth, the arbitrator operates as Table 2. In the case of TX/TX, when each receiver's SINR is high enough, the arbitrator works as AFH. On the other hand, if the SINR is low, the arbitrator works as PTA. In the case of TX/RX, we can use the canceller on top of AFH. It should be noted that the hybrid arbitrator can only control the TX part. So, it has nothing to do in the case of RX/RX.

TABLE II
Operation mode of the hybrid arbitrator.

Bluetooth	Wi-Fi	Mode of the hybrid arbitrator
TX	TX	AFH or PTA
TX	RX	AFH with Interference Cancellation
RX	TX	AFH with Interference Cancellation
RX	RX	Idle

V. Experimental results

We implement a testbed and carry out extensive experiments. First, we measure the performance of the canceller. Then, we perform experiments to validate the performance of the proposed scheme under various conditions.

A. Canceller testbed

For implementation of a canceller, we use a commercial coupler, a transformer, and a noise canceller (QHX-220). The coupler divides the RF transmit signal into two paths. One connects with transmit antenna with 90% power path and the other with the transformer with 10% power path. The transformer reverses the received signal and pass it to the noise canceller, which adds the amplitude gain and delay. Then, it is combined with the self-interference signal. The overall canceller testbed is shown in Figure 5.

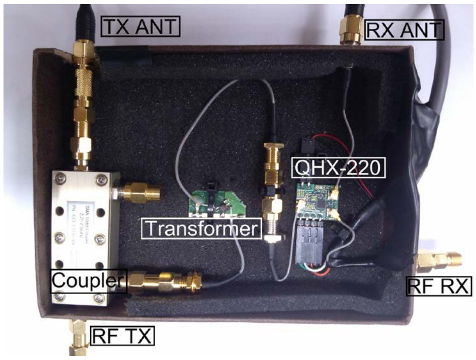


Fig. 5. Canceller testbed.

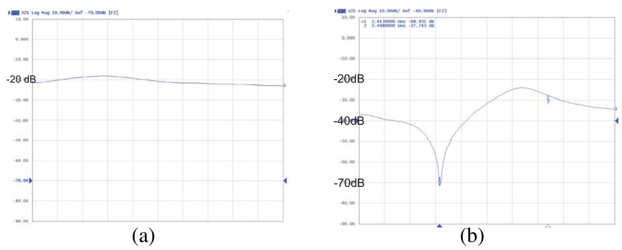


Fig. 6. Network analyzer: (a) Received interference signal and (b) received interference signal with our canceller.

First, we fix the distance between the TX antenna and RX the antenna with 3 cm. This is a reasonable distance for small portable devices. Then, we connect 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 shown in Figure 6 (a), the signal strength is about -20 dB. Now, we apply the canceller between the TX and RX RF paths. As in Figure 6 (b), the signal is cancelled and its strength at the minimum is almost -70 dB at 2.415 GHz. This results show that the canceller can effectively cancel out the self-interference once the channel is properly identified.

Now, we directly measure the Wi-Fi transmit signal from a laptop by using a spectrum analyzer. Figure 7 (a) shows the result with the max-hold mode for 30 seconds. The peak transmit power is almost 10 dB. We now measure the spectrum of the interference. The Wi-Fi transmit path from the laptop Wi-Fi module is connected with the external antenna, which is positioned next to the receive antenna with 3 cm distance. This receive antenna is connected with a spectrum analyzer. Figure 7 (b) shows the result. In Figure 7 (c), we show the result with the canceller. In the figure, the interference signal power is even reduced by 15 dB than that without the canceller. In fact, this power level corresponds to the case of 21 cm distance between the TX antenna and the RX antenna without the canceller, which is shown in Figure 7 (d). Consequently, we can conclude that to apply the canceller gives spatial gain from 21 cm to 3 cm, which is about 15 dB isolation.

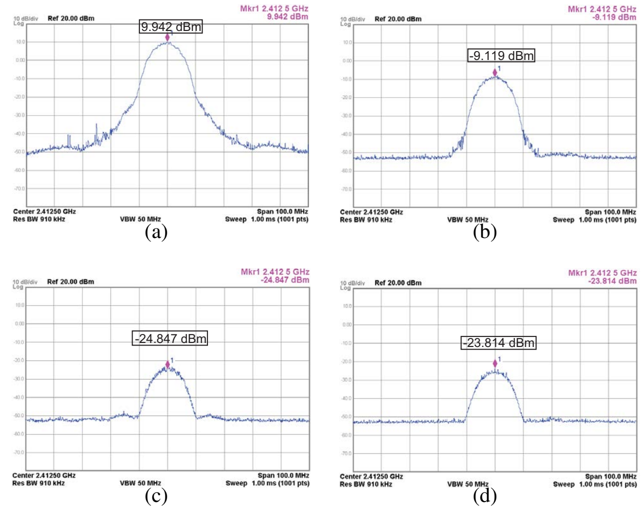


Fig. 7. Spectrum Analyzer: (a) Directly measuring the transmission signal, (b) Received interference signal after channel, (c) Received interference signal with canceller and (d) Received interference signal at 21cm distance.

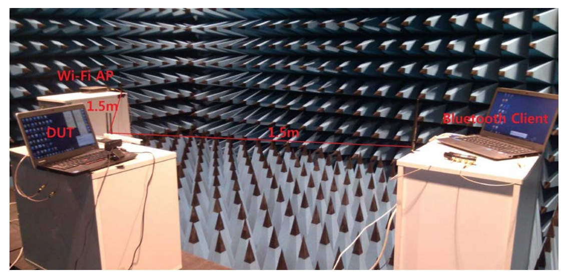


Fig. 8. Experimental environment in a RF chamber.

B. Case of Wi-Fi TX and Bluetooth RX

We show the performance when Wi-Fi transmits and Bluetooth receives. Our overall setup is shown in Figure 8. First, we position the device under test (DUT) at the center of the RF chamber Then, a Wi-Fi AP is located at the left side of the DUT and a Bluetooth client is positioned on the opposite side of the Wi-Fi AP. The Bluetooth client is a laptop working in the file transfer profile (FTP) mode with the EDR speed (3 Mbps in the PHY layer). We measure the Bluetooth throughput using the Windows Bluetooth file transfer application. The DUT is another laptop and work in the AFH mode. When we test the cases without the canceller, we connect two external antennas from the Wi-Fi module RF endpoint and Bluetooth chip RF end pin. The distance between these two antennas is fixed to 3 cm. On the other hand, When we test the canceller performance, we connect the canceller between the path of Wi-Fi and that of Bluetooth.

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

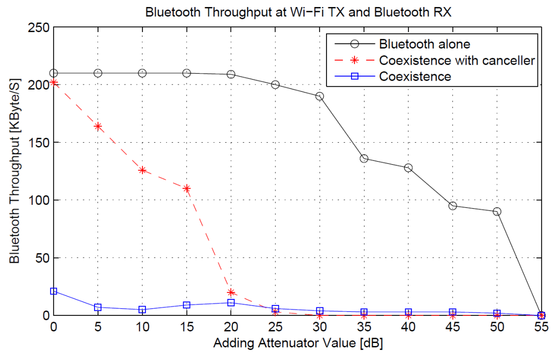


Fig. 9. Bluetooth throughput vs. channel attenuation.

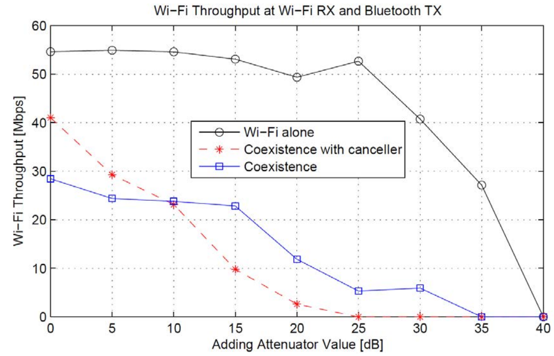


Fig. 10. Wi-Fi throughput vs. channel attenuation.

The result is given in Figure 9. Until Bluetooth client's attenuation value is 20 dB, The case with the canceller gives substantial performance improvement. After 30 dB attenuation, the Bluetooth is unable to perform file transfer. In the case without the canceller, we can see poor performance. In the meantime, the Wi-Fi throughput is almost the same in all cases as follows: Wi-Fi alone gives 51.772 Mb/s, coexistence of Wi-Fi and Bluetooth with the canceller gives 51.727 Mb/s, coexistence without the canceller gives 51.349 Mb/s.

C. Case of Wi-Fi RX and Bluetooth TX

We also test the case when Bluetooth works as uplink and Wi-Fi work as downlink at the DUT.

As given in Figure 10, the case of coexistence with the canceller is better from 0 dB to 10 dB and the case of coexistence without the canceller is better after 10 dB. In the meantime, the Bluetooth throughput is almost the same in all cases as: Bluetooth alone gives 234 KB/s, coexistence of Wi-Fi and Bluetooth with the canceller gives 209.8 KB/s, coexistence of Wi-Fi and Bluetooth without the canceller gives 216.5 KB/s.

We further look into why the case with the canceller gives poor performance compared to that without the canceller after 10 dB by using a spectrum analyzer. No isolator cause cancellation not only current transmission interference signal but also receiving signal through the TX antenna and canceller. When the receive signal is strong enough, amount of cancellation of transmission interference lager than cancellation of receive signal. But cancelled received signal is not enough to decoding when received signal is week.

VI. Conclusion and Future Work

In this paper, we propose a simple and effective solution for resolving the in-device coexistence problem of Wi-Fi and Bluetooth. In a nutshell, we introduce a canceller that can cancel out the in-device interference. Extensive experimental results show that the proposed approach can significantly improve the throughput performance in practice. We expect that our 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. We are currently working on a testbed to validate the idea.

VII. Acknowledgements

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