Coexistence of Collocated IEEE 802.11 and Bluetooth Technologies in 2.4 GHz ISM Band

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Abstract. In this paper, we investigate coexistence of collocated 802.11 and Bluetooth technologies in 2.4 GHz industrial, scientific, and medical (ISM) band. To that end, we show a time division multiplexing approach suffers from the "avalanche effect". We then provide remedies to avoid this effect and improve the performance of the overall network. For example, it is shown that a simple request-to-send (RTS) / clear-to-send (CTS) frame handshake in WLAN can avoid "avalanche effect" and improve the performance of overall network.

Keywords: medium access control, coexistence, wireless networks.

1 Introduction

We are witnessing a tremendous growth in wireless technologies. Different wireless technologies are now integrated in a single handheld device, allowing mobile users to access different networks simultaneously. Coexistence of these collocated technologies in the same device is an important problem that needs to be addressed in order to ensure smooth mobile user access to different networks. In this paper, we focus on the coexistence issues of collocated IEEE 802.11 and Bluetooth technologies. These technologies operate in 2.4 GHz band, with Bluetooth hoping in 79 MHz of the ISM band while 802.11 requiring 16 MHz or 22 MHz band (depending on whether 802.11b or 802.11g is used). Therefore, interference between these technologies greatly impacts the performance of both networks.

Most of the research/work has been focused on coexistence of these technologies when they are not collocated in the same device [1]-[9]. In [1], the authors propose two coexistence mechanism between 802.11 and Bluetooth that are based on scheduling techniques and result in interference mitigation between the two technologies. An improvement on the throughput for both 802.11 and Bluetooth has been shown at the expense of a small additional delay for data transfer. In [2] experimental results for the interference between IEEE 802.11b and Bluetooth technologies are presented; however, no remedies have been provided to mitigate the interference between these two technologies. Howitt in [3] present an analysis on the coexistence of WLAN and Bluetooth in UL band and derives

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a closed form expression for the collision probability in terms of the network and radio propagation parameters. However, in [6], the authors, for the first time, investigate the coexistence problem between 802.11 and Bluetooth technologies that are collocated in the same device and propose time-division multiplexing (TDM) coexistence solution. They analyse the performance of both technologies with and without the proposed coexistence solution.

In our paper, we investigate the coexistence between 802.11 and Bluetooth technologies collocated in the same device. Different from the work in [6], we show that TDM approach suffers from the "avalanche effect" (to be described in Section 1). We provide simple solutions to mitigate this undesired effect and further improve the performance of the overall network.

The remainder of the paper is organized as follows. In Section 1 we describe existing problem with TDM approach. Simulation setup is described in Section 2, while results follow in Section 3. Finally, we briefly discuss the impact of these results in Section 4 and we conclude our findings in Section 5.

In handheld devices where the Bluetooth and 802.11 radios are collocated, the interference problem becomes more severe due to the coupling and the distance between the radios, while for non-collocated case, this is less severe due to high-attenuation [6]. To mitigate this problem for the collocated technologies, in [6] the authors propose a time-division multiplexing (TDM) solution, where time is shared between the two technologies.

While TDM seems an attractive approach, it does suffer from the "avalanche effect", which greatly reduces the performance of both technologies. To explain the effect, consider the following scenario. Let assume that the network consists of an access point (AP), serving different stations (STAs) among which there is a combo STA (C-STA) that contains 802.11 and Bluetooth technologies collocated, as well as a Bluetooth slave device (see Figure 1, where AP is denoted as AP-STA0, and C-STA is STA1-Master). Note that we will use AP and C-STA throughout the paper, by implying AP-STA0 and STA1-Master.

According to the TDM scheme, the Bluetooth and 802.11 technologies in the C-STA will take turn in accessing the medium, thus transmit/receive operations. However, if AP has traffic to send to the C-STA, after n unsuccessfull transmitted packets it reduces the operational rate (physical data rate) to a lower value. Under this scenario, the time that it will take the same packet to be transmitted over the air will increase as the operational rate decreases. Therefore, the chances of the transmitted packet "colliding" with Bluetooth transmission/reception operation increases. Hence, the operational rate further decreases and the process continues till the AP transmission rate (to the C-STA) reaches the minimum operational rate. This is called the "avalanche effect", where the reduction in the operational rate increases the collision probability between 802.11 and Bluetooth operations and the increase in collision probability further decreases the operational rate. The operational rate during the "avalanche effect" is depicted in Figure 2. To be fair to the authors in [6], the "avalanche effect" is more observable when the network consists of many STAs served by the AP, while in their study, the authors concentrated on a single AP, single C-STA, and a Bluetooth device.

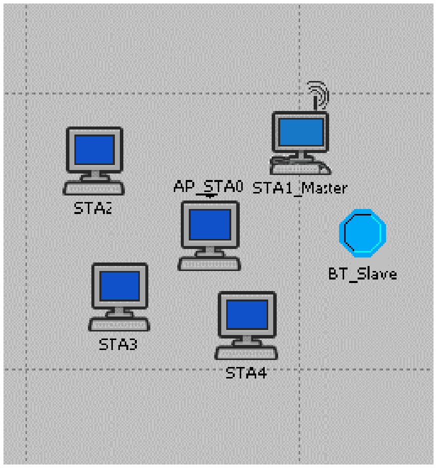

Fig. 1. Network under investigation

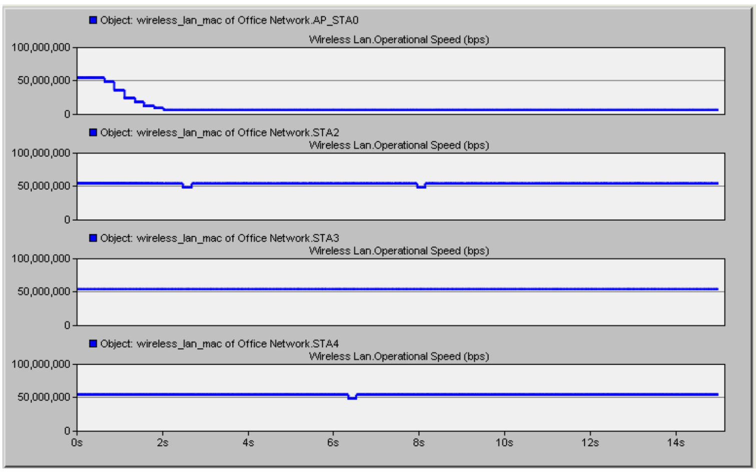

Fig. 2. Rate adaptation in the network under investigation

Next we describe the scenario and the simulation setup for "avalanche effect" investigation.

2 Simulation Setup

To investigate the impact of the "avalanche effect" on the performance of WLAN and Bluetooth networks as well as some of the proposed remedies for avoiding it, we consider the network depicted in Figure 1. In addition, we assume that the maximum data transmission rate in WLAN is 54 Mbps (belonging to 802.11g), while Bluetooth uses synchronous connection oriented (SCO) and asynchronous connection oriented (ACL) logical transports [9]. We also assume that Bluetooth carries voice traffic using HV3 packets, which carries 3.75 msec of speech at 64 kbps. Therefore, an HV3 packet is sent every 6 slots, where each slot consists of a 625 microsec duration [9]. While we could consider other logical transports for Bluetooth, as well as different packets, for illustration purposes, we focus on SCO and HV3 packets, which are the most common ones.

To evaluate the performance of the network, we use OPNET^{TM} simulations. We modified the code to implement rate adaption algorithm, which is based on the number of un-successfull/successfull transmission to decrease/increase the transmission rates. In addition, we enabled request-to-send (RTS) / clear-to-send (CTS) handshake between the AP and the C-STA. Thus, everytime that the AP gains access to the medium and has a data packet to transmit to C-STA, it starts with an RTS/CTS handshake. We also implement periodic/scheduled powersave negotiation between the C-STA and the AP, where the C-STA goes into powersave mode when Bluetooth transmit/receive operation is ongoing, and awakes when Bluetooth transmit/receive operation is off. The last two approaches can be used to avoid the un-necessary rate reductions. For example, when RTS/CTS handhshake is used, the C-STA does not reply to the AP with CTS if the remaining time duration from the end of CTS transmission frame is not sufficient to complete the data packet-ACK communication between the AP and the C-STA. Therefore, the AP assumes that there is a collision and hence, there is no drop in the operational rate. When periodic powersaving approach is used, the AP is aware of the time when C-STA is awake, therefore, data packet is sent only during this time and ensuring that the time required for data packet-ACK is smaller than the time remaining before the C-STA enters the powersave mode.

Next we report results obtained via our network simulations and discuss our findings.

3 Results

When Bluetooth is not present, for a 54 Mbps and saturated traffic load, the throughput is about 27 Mbps [10]. For Bluetooth HV3 traffic, the throughput is 64 Kbps. When both technologies are collocated on the same device, if HV3 traffic is given priority and it is protected, then WLAN throughput is expected to drop by about 33%. This is due to the fact that HV3 traffic occupies two 625 microsec slots for transmit/receive operation every 6 time slots. To better observe the impact of "avalanche effect" in WLAN/Bluetooth coexistence, we consider the network as in Figure 1 and traffic flows as depicted in Table 1. In our simulations we give priority to HV3 traffic and protect its transmission.

Figure 3 shows the performance of Bluetooth under the following:

- When rate adaption is not used; i.e., the AP does not decrease/increase the operational rate with the combo STA regardless of whether transmitted packets are successfull or not.
- With rate adaptation, where the AP decreases/increases the operational rate if the transmitted packets are un-successfull/successfull.

- RTS/CTS handshake and rate adaptation, where the AP starts with an RTS/CTS handshake with the C-STA before transmitting and data packet.
- Periodic powersave with rate adaptation, where the C-STA negotiates a periodic powersave time interval with the AP based on the Bluetooth transmit/receive cycles.

It is clear that rate adaption (RA) results in lower throughput for Bluetooth due to the fact that it increases the time that WLAN packet transmitted from the AP occupies over the air. Since the operational rate decreases and reaches its minimum operational value, the collisions between Bluetooth and WLAN transmission increases; hence, the Bluetooth throughput decreases. When RTS/CTS handshake, the collision probability decreases and Bluetooth performance is even better than that when RA is not used. This can be explained with the fact that RTS/CTS mechanism may not fully utilize the medium; e.g., CTS is not received and all the STAs in the WLAN network have to wait for a CTS timeout before they can start competing for the medium again. Periodic powersave approach results in slightly better Bluetooth performance and could be explained with the fact that better utilization during Bluetooth off period "pushes" the back-off times (for WLAN STAs) in the Bluetooth transmit/receive operations. To

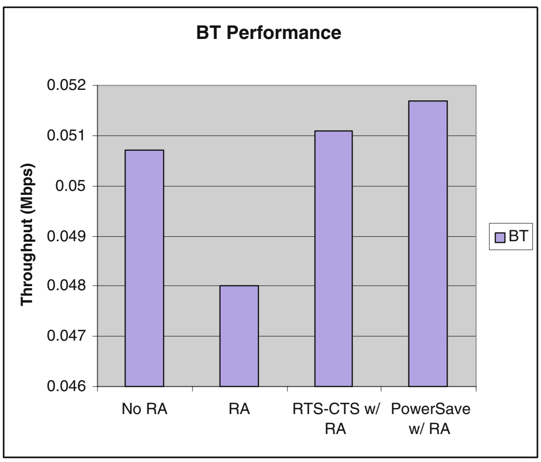

Fig. 3. Bluetooth performance for different approaches

Table 1. Traffic flows for the scenario depicted in Figure 1

Traffic flows	Offered Load	Traffic Type	PER	Max. Delay
AP-STA0->STA1	10 Mbps	Email attach.	N/A	Non-QoS
Blt-Master (STA1)->Blt-Slave	64 Kbps	HV3	5%	2.5 msec
STA2-> AP-STA0	30 Mbps	FTP	N/A	Non-QoS
STA4-> AP-STA0	2 Mbps	Stream. Video	10^{-4}	0.2 sec
STA3-> AP-STA0	0.096 Mbps	VoIP	5%	0.03 sec

achieve better Bluetooth throughput, one can incorporate adaptive frequency hoping (AFH) approach, where Bluetooth hops in the frequencies that do not overlap with WLAN channel. In our study, however, we do not consider AFH.

Figure 4 shows the performance of WLAN for different approaches as mentioned earlier. Again, it is clear that RTS/CTS and periodic powersave approach achieve a throughput of almost 3 times better than that of RA alone.

Figure 5 shows the performance of WLAN QoS flows for different approaches as mentioned earlier. It is clear that the throughput achieved for these flows meet QoS requirements for all approaches.

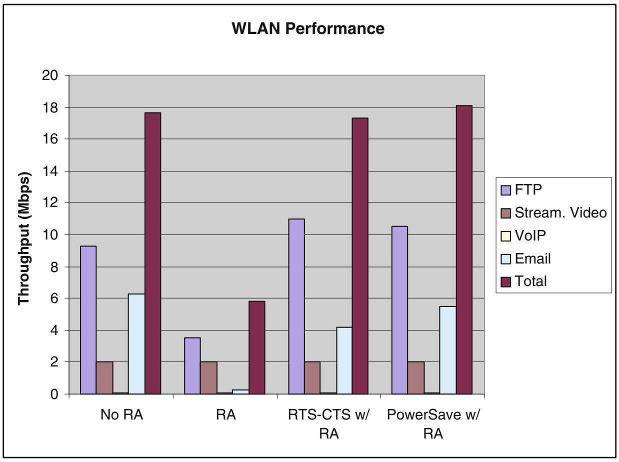

Fig. 4. WLAN performance for different approaches

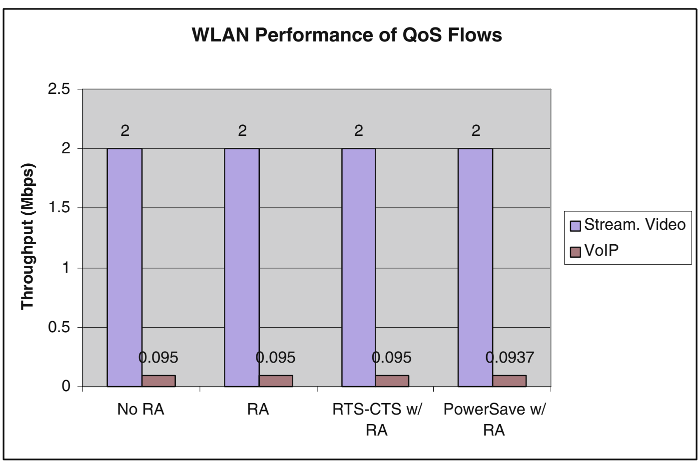

Fig. 5. WLAN QoS flows performance for different approaches

4 Discussions

We presented the "avalanche effect" as well as solutions that can avoid this undesirable effect. It is shown that the performance of the overall network improves when the proposed solutions are used.

It is worth mentioning here that one could consider scenarios that make use of different logical transports for Bluetooth as well as different packet types. Nevertheless, from the proposed solutions, RTS/CTS handshake will be more robust to different scenarios for the simple reason that periodic/scheduled powersave approach is valid if the traffic in Bluetooth technology has a known pattern.

Furthermore, out of band interference between WLAN and Bluetooth technologies were not considered; rather, only if the transmission/reception bands were overlapping, the interference was measured at each of the technologies.

As it is, the use of RTS/CTS and/or periodic/scheduled powersave mechanism would require changes in the AP/STA behavior, since current products do not associate these two approaches to coexistence. The need to have many different wireless technologies integrated in the same device is forcing standards and/or consortiums to design with coexistence issues in mind.

5 Conclusions

In this paper, we presented and discussed issues related to the collocated IEEE 802.11 and Bluetooth technologies coexistence in 2.4 GHz ISM band. Our results show that simple modifications to the AP/STA behavior in WLAN networks can mitigate the "avalanche effect" and improve the performance of both networks.

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