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An Overview and Assessment of Wireless Technologies and Co-existence of ZigBee, Bluetooth and Wi-Fi Devices

R. Challoo[a], A. Oladeinde[a], N. Yilmazer[a], S. Ozcelik[b], L.Challoo [c]

[a]*Department of Electrical Engineering and Computer Science*
[b]*Department of Mechanical and Industrial Engineering*
[c]*College of Graduate Studies and Department of Educational Leadership & Counseling*
Texas A&M University-Kingsville, 700 University Blvd., Kingsville, TX 78363, USA

Abstract

Wi-Fi, ZigBee and Bluetooth wireless communication systems utilize the Industrial Scientific and Medical-(ISM) Band, which results in a high mutual interference between these technologies since they all these systems operate at the same or very close frequency bands. The interference problem increases with an in-device Co-existence (technologies existing on same device). This is primarily due to the characteristics of each technology such as access mechanism, frame structure, peak transmit power and frequency of operation. This work describes the interference between the Wi-Fi mostly as an aggressor on Bluetooth and ZigBee wireless networks. So the experimental analysis of the coexistence of these three technologies in an assumed home environment is studied especially when ZigBee is enabled for a Home Automation Network where there could be close proximity of Wi-Fi and Bluetooth devices such as PDAs and mobile phones. The obtained result shows that there is severe degradation on ZigBee and Bluetooth packet transmission of packets as well as re-transmission of ZigBee packets when Wi-Fi is operating.

Keywords: Wi-Fi, ZigBee, Bluetooth, ISM, aggressor, Home Automation Network, PDAs

1. Introduction

ZigBee (IEEE 802.15.4) is establishing an enabling place for the Wireless Sensor Network (WSN) especially in the application of home automation network because of its low power and cost. Its lower power is vulnerable to other wireless technology that has higher power and working in same spectrum. It's among the wireless technologies that share the unlicensed ISM band used purposely for Personal WANs. However, the Bluetooth (IEEE 802.15.1) and Wi-Fi (IEEE 802.11) share the same unlicensed band with the ZigBee and experience mutual interference problem especially at close proximity. Adaptive Frequency Hopping, a spread-spectrum technique, was introduced to Bluetooth technology to mitigate the problem of interference between it and Wi-Fi and any other technology that exist in same spectrum [1]. According to [2], [3] IEEE 802.15.4 has a little impact on the IEEE 802.11 performance. However, IEEE 802.11 can have a serious impact on the ZigBee and Bluetooth performance if

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the channels allocation is not carefully taken into account. Mutual interference among these technologies is considered a topical issue especially among technologies that shares spectrum that are close enough to cause interference (< 50MHz channel separation). Research has been done to find the best practice to alleviate the interference among devices using technology in same spectrum. This paper describe existing work and experimental results on the IEEE 802.11 Wi-Fi standards, its interference with the ZigBee and the Bluetooth technologies in a home environment where ZigBee is enabled for a home automation while Wi-Fi and Bluetooth devises such as PDAs and mobile phones, gaming devices co-exist with it in same home.

2. Technology Overview

A quick overview of the three technologies was discussed. Aspects of the three technologies that are necessary for the full comprehension of this study were also discussed such as the number of channels, the transmission power, modulation type and the access scheme.

2.1 Wi-Fi

The IEEE 802.11 network is a specification of the Wireless Local Area Network (WLAN). In its low band mode, IEEE 802.11(b, g, n) transmit data from 11 Mbps and up to 54M bps and goes up to 32 meters indoors and 95 meters outdoor [11]. The IEEE 802.11n standard uses double the radio spectrum compared to 802.11a or 802.11g. However, IEEE 802.11a, c transmit data is up to Gbps and can exceed range by more than two times of the b and g technologies. Low band Wi-Fi transmits in the ISM 2.4 GHz band while the high band transmit in the 5 GHz band. A BPSK and QPSK digital modulation technique is used to transmit data up to 54 Mbps and each channel in the ISM band is 22 MHz wide and are overlapped. Any two channels whose channel numbers differ by five or more do not overlap. Wi-Fi's Enhanced Isotropic Radiated Power (EIRP) is limited to 20 dBm (100 mW) [11].

2.2 Bluetooth

The IEEE 802.15.1 standard is a proprietary open wireless technology standard for exchanging data over a short distance. It uses the short wavelength radio transmission ISM Band in the 2400-2480 MHz. It is desired for the Wireless Personal Area Network WPAN adopted solely to replace the cable technology. Bluetooth radio adopts the Frequency Hopping Spread Spectrum – FHSS. It occupies the entire ISM band thereby utilizing 79 channels with each channel at 1 MHz. A GFSK, EDR, $\pi/4$-DQPSK and 8 DPSK modulation formats are employed in the Bluetooth Technology. The transmit distance of this technology ranges with the transmit power. Class 1 device of output power of 100 mW transmit up to 100 meters while device of 25 mW output power transmit can reach up to 10 meters [11].

2.3 ZigBee

This specification was adopted for a low cost, low power digital radios and had found application in areas like home automation, telecommunication services, healthcare and remote control just to mention a few. Similar to the Wi-Fi and the Bluetooth technologies, ZigBee also operates in the ISM radio band. Data transmission rates of 250 Kbps [6]. ZigBee (IEEE 802.15.4) technology specifies the physical and medium access control layers for low rate wireless PANs and transmits up to 10 meters [7]. Sixteen channels are defined for this specification in the 2.4 GHz band but with a narrower band of 2 MHz and also do not overlap. So, up to sixteen ZigBee network can coexist in same area and at the same time. A latest ZigBee release supports frequency hopping in the "ZigBee Pro" Standard. This allows a ZigBee PAN to move from one channel to the other if overloading occurs in the former channel [6]. The communication model requires it to distribute work among many different devices which resides within individual ZigBee nodes which in turn forms a network.

2.4 Channel, Frequency and Modulations

ZigBee channel is 2 MHz wide, as opposed to a Wi-Fi channel which has bandwidth of 22 MHz.. The Bluetooth channel is 1MHz wide and occupies the whole available spectrum and possess high frequency hopping rate. Figure 1 shows the allocation of the ZigBee and Wi-Fi channels over the 2.4 GHz ISM band. The Wi-Fi individual channel overlaps four ZigBee channels while the three most used non-overlapping Wi-Fi channels are channels 1, 6 and 11 which leaves channels 25 and 26 of the ZigBee channels free of interference. Also, the maximum allowable transmit power of the Wi-Fi output which could be up to 100 times higher than the maximum allowed power of the ZigBee could also serve as a further aspect making the coexistence of Wi-Fi and ZigBee difficult.

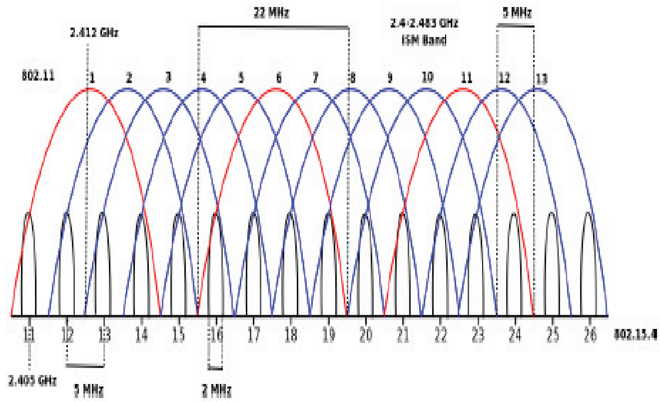

Figure 1: Allocation of ZigBee and Wi-Fi Channels over the ISM Band [11]

3. BLUETOOTH AND Wi-Fi INTERFERENCE CASES

If Bluetooth and Wi-Fi systems operate at the same time in close proximity as in the case of a mobile device then they will interact (collide) with each other, introducing an undesired effect called interference which deteriorates the overall performance of the wireless communication systems . The sidebands of each transmission must also be accounted for. Interference between Bluetooth and Wi-Fi occurs when either of the following is true:

- A Wi-Fi receiver senses a Bluetooth signal at the same time when a Wi-Fi signal is being sent to it. The effect is most pronounced when the Bluetooth signal is within the 22 MHz-wide passband of the Wi-Fi receiver.
- A Bluetooth receiver senses a Wi-Fi signal at the same time when a Bluetooth signal is being sent to it; the effect is most pronounced when the Wi-Fi signal is within the passband of the Bluetooth receiver.

It is worthwhile to note that neither Bluetooth nor Wi-Fi was designed with specific mechanisms to combat the interference that each creates for the other. As a fast frequency-hopping system, Bluetooth assumes that it will hop away from occupied channels, minimizing its exposure to interference. The Wi-Fi MAC layer, which is based on the Ethernet protocol, assumes that many stations share the same medium, and therefore, if a transmission fails, it is because two Wi-Fi stations tried to transmit at the same time. This report examines how this assumption drives system behavior that actually worsens the impact of Bluetooth interference.

4. ADAPTIVE BLUETOOTH SOLUTIONS

To alleviate the potential problems of interference in the ISM band, the Bluetooth SIG are discussing several adaptive technologies [8].

4.1 Adaptive Frequency Hopping

This involves a change in Bluetooth frequency hopping sequence to allow for more flexible use in the ISM band. Bluetooth device must hop through all 70 channels regardless of whether another technology that operates in the ISM band is already occupying a segment of the band. It introduces some degree of intelligence into the process so that the Bluetooth device would analyze the available spectrum and steer the transmission to those channels where interference would not be encountered or where it would not cause interference to other devices using occupying a portion of the band.

4.2 Transmission power control

This involves adapting transmit power of devices used in the ISM band. The reasoning behind this technique is based on common sense. Transmitting data at a power level above the minimum needed to meet a predetermined level of acceptable data integrity unnecessarily causes interference to other users in the band. Noting is gained by transmitting at a higher power level above the minimum needed which would result in interference with other devices in the area. The current Bluetooth standard calls for a poor receiver sensitivity level of -70 dBm. More sensitive receivers would allow for a reduction in the transmit power level while maintaining an acceptable signal-to-noise ratio which would enhance the system's co-existence performance. Adaptive power control could also reduce the overall power consumption by a Bluetooth device.

4.3 Adaptive Selection of Packet Type

The type of Bluetooth packets being transmitted also affects the co-existence performance. The packets can carry various payloads depending on the number of "slots" in the packet. Packets can occupy between one to five time slots according to Bluetooth specifications. While carrying 10 times as much data, a Bluetooth packets with five slots will remain on a certain channel at a certain frequency five times longer than would a one-slot packet, increasing the vulnerability of this packet to interference as well as increasing the chance with other sharing the frequency. A transmitter is capable of dynamic packet type selection would determine would determine where and when interference is present and adapt the Bluetooth packet type accordingly. So if a channel is acquired, more data can be transmitted while a shorter packet type could help ameliorate the condition when interference in the surrounding area reaches a point where packet corruption is unacceptable. Research has shown that shorter Bluetooth packets can improve data throughput in an environment with interference.

5. 802.11 SOLUTIONS

The 802.11 solutions are also similar to the Adaptive Bluetooth techniques. As previously described in section IV, three channels centered on channel 1, 6 and 11 are configured in figure 1 above**.** An 802.11 access point would typically be assigned to a certain channel and this would not change without the intervention by the LAN Administrator. However, dynamic channel selection would allow the access point itself to determine which channel is best suited for communication at any time. By detecting interference on a Wi-Fi channel, a channel with high noise content can be avoided. Multipath propagation and inter-Symbol interference are monitored and can form basis for dynamic channel selection.

Adaptive packet fragmentation is another technique used by Wi-Fi to cope with co-existence interference. This is because the length of 802.11b packets needed not be the maximum length for each transmission, fragmented of shortened packets can be used to overcome the effects of coexistence interference. With shorter packet length, less data must be retransmitted when a packet transmission fails because of interference.
Similarly, transmission power control can also minimize the interference caused to other users in the band. Here, the optimal transmission power would be the minimum level necessary to maintain a predefined level of data integrity.

6. ZigBee SOLUTIONS

The most difficult thing when trying to remedy the interference problem between ZigBee and other devices that share same spectrum is due to the difference in their physical layers. There are two ways for ZigBee devices to intervene between 802.11 and Bluetooth devices that operate with it in same spectrum. The first method is transmitting an 802.11 or a Bluetooth packet indicating that this packet would have an unusually long duration permitting ZigBee to transmit during this period in which other 802.11 or Bluetooth device would sleep. The second method would be the use of Request to Send (RTS) or Clear to Send (CTS) message to clear 802.11 or Bluetooth traffic. This works on the theory that sending out a CTS message will block all 802.11 or Bluetooth devices from transmitting for a specified period of time. Hence, the goal of the two solutions is to temporarily block out 802.11 or Bluetooth messages for a window of time large enough that ZigBee device can successfully transmit their messages thereby resolving interference issue [9]

7. COEXISTENCE TESTING

Since Bluetooth devices hop over 79 MHz of the ISM band, Wi-Fi devices require approximately 16 MHz of bandwidth to operate and ZigBee has sixteen networks in the ISM Band with 2 MHz bandwidth, the possibility of having Bluetooth, ZigBee and Wi-Fi products in same area without interference is low. Due to this interference, a coexistence test was run with actual ZigBee, Bluetooth and Wi-Fi products to determine their level of coexistence.

7.1 Testing Setup

The throughput testing was performed using a Wi-Fi access point and a station. Two laptops with Bluetooth enabled are used as a master and slave for the Bluetooth test while two devices using ZigBee are equally used. The test is intended to obtain the empirical data-throughput results corresponding to realistic scenarios.

A base-line test was performed to determine the maximum throughput for both the Wi-Fi and Bluetooth network. Figure 2 shows the baseline obtained for the Wi-Fi when data was transferred from the access point to the station at a specified distance. The result shows that the device maintains a connection speed in excess of 5.5 Mbps up to the maximum distance of 250 feet [10].

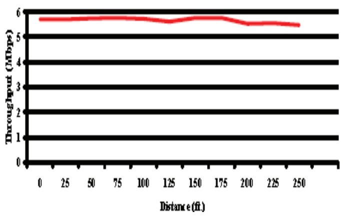

Figure 2: Wi-Fi Baseline Throughput [10]

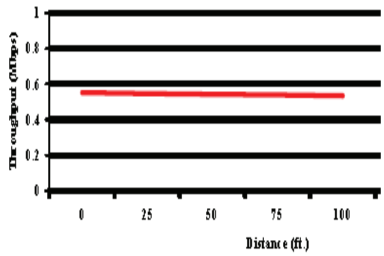

Figure 3: Bluetooth Baseline Throughput [10]

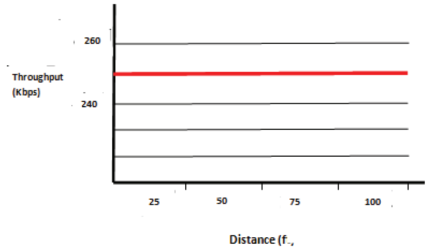

Figure 4: ZigBee Baseline Throughput [10]

The Bluetooth and ZigBee baseline throughput is shown in figure 3 and 4 respectively. Data was transferred from the Bluetooth master to the slave with no interference. The throughput is approximately 550 Kbps at the specified distance and 250 Kbps for ZigBee.

8. **EXPERIMENTAL RESULT**

The impact of Wi-Fi on an ongoing Zigbee transmission when the ZigBee network is set up on channel 11 - 14 while the Wi-Fi network is set up on channel 1 with a payload of 64-byte payload frames is very apparent. The frame error rate as shown in figure 5 of zigbee drops to a value of 0.45 and 0.73 with channel 13 being the less impared and 14 the most impared [11]. Hence the prensense of Wi-Fi is not totally destructive for ZigBee network. Very similar result would be registered for other channel combinations such as Wi-Fi channel 6 and ZigBee channels 16-19 and Wi-Fi channel 11 and ZigBee channels 21 -24. ZigBee loses a litle percentage of its frames. Conversely, the impact of ZigBee of a Wi-Fi connection is low. Wi-Fi is practically not affected by the activity of the ZigBee as shown in figure 6.

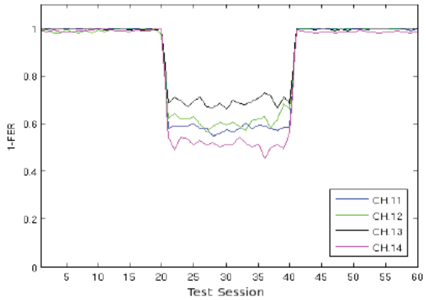

Figure 5: FER of ZigBee under the interference of Wi-Fi[11]

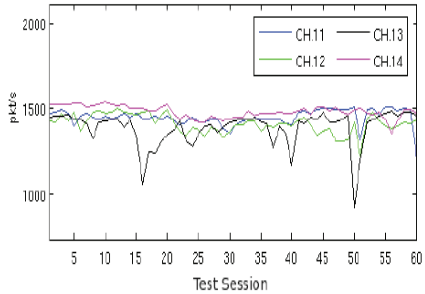

Figure 6: FER of Wi-Fi under interference of ZigBee [11]

The effect of Bluetooth over the ZigBee network is not noticeable. Its Frame Error Rate is only reduled by less than 10% [12]. Conversely, the effect of the ZigBee over the Bluetooth shows rather an unstable network, shown in figure 7, the degradation effect is not well noticed.

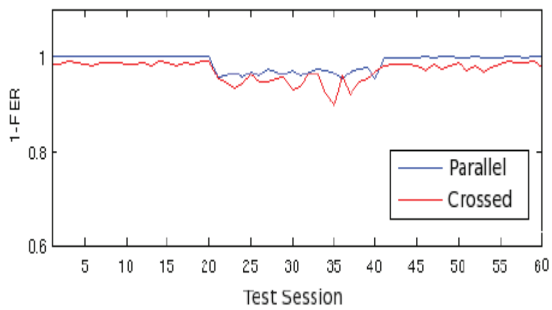

Figure 7: ZigBee effect over Bluetooth [11]

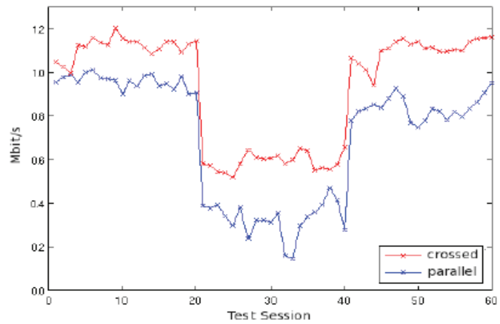

Figure 8: Bluetooth Effect over Wi-Fi [11]

The effect of Wi-Fi over Bluetooth shows a strong degradation of Bluetooth signal in Figure 8. Bluetooth goodput drops from 1.12 Mbps to 0.59 Mbps for TT –RR scenario and 0.95 Mbps to 0.30 Mbps for TR –RT scenario. This shows that the FHSS employed by the Bluetooth is less effective. As a consequence, the use of smart and adaptive hopping patterns techniques could indeed be a major contributor towards the achievement of robust Bluetooth connections in the vicinity of Wi-Fi devices. Wi-Fi has a great impact on both ZigBee and Bluetooth devices. The degradation on Bluetooth occurs as soon as Wi-Fi is activated whereas it occurs only when the Wi-Fi frame rate is increased in ZigBee.

9. CONCLUSION

To summarize, Wi-Fi devices are scarsely affected by the presence of other wireless technologies operating concurrently such as ZigBee and Bluetooth devices Conversely, Bluetooth and ZigBee suffers conspicously from the presence of Wi-Fi . ZigBee which was deemed to be interference free was heavily influenced by the Wi-Fi whose spectrum covers more than the classic four ZigBee channels. Hence ZigBee cannot only rely on the supportedly safe channels such as 15, 20, 25 and 26 [11]. The FHSS technique used by the Bluetooth did not reveal to be very effective in contrasting Wi-Fi interference. Also, the ZigBee system is much more sensitive to the position of the Wi-Fi transmitter than the Bluetooth. This means that while ZigBee networks can be deployed in a shared area by having ZigBee devices placed far from Wi-Fi radios, this is not true for Bluetooth networks which instead requires a more drastic seperation from Wi-Fi polluted areas.

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