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Simulation and Throughput Analysis of Multiple IEEE 802.15.1 Devices in Presence of Interference

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ABSTRACT

The increasing interest in wireless ad-hoc networks built by the portable devices equipped with short-range wireless network interfaces. IEEE 802.15.1 WPAN (Bluetooth) and IEEE 802.11b WLAN (Wi-Fi) are most popular and emerging wireless technologies. These technologies migrates wired system applications into the wireless domain. Applications includes, computing, sensing, and communication. In Bluetooth multichannel environment, the master essentially controls the channel. While accessing wireless medium, devices will encounter very high rate of interference, because of an absence of coordination between independent masters. Study of interference in multichannel environment is important because it affects the throughput of the wireless system.

This paper focus on the effect of co-channeled multiple Bluetooth devices on a carrier-sense multiple-access (CSMA)-based wireless local area network (WLAN). The CSMA protocol is considered for WLANs, and the probability of error of a WLAN packet is calculated in the presence of interfering Bluetooth packets. Simulations have been used to correlate the analytical results, which indicate that the presence of just one fully loaded interfering Bluetooth multiple devices reduces the throughput with longer packet transmissions.

General Terms

Performance, Design, Experiment, Verification

Keywords

Bluetooth, BER, Interference, Frequency hopping, Performance.

1. INTRODUCTION

Bluetooth (BT) is most promising wireless personal area network (WPAN) technology. The BT multiple device environments referred as piconet. In this, the Master essentially controls the channel [23]. Due to an absence of coordination between independent Masters while accessing the wireless medium, devices will encounter high packet interference if several BT devices are simultaneously operating in the same area. Since even a headset and a mobile phone can be connected with a BT link forming a piconet, it may not be unusual to find the independent piconets in jam-packed places like local trains, railway station, shopping malls, and so on. Study of packet interference gains importance because it affects throughput of a piconet [2][11][16].

El-Hoiydi [2] has presented a probabilistic model of interference of single-slot packets in a *homogeneous cluster* of piconets, i.e., all piconets are either of 79-hop type or of 23-hop type. Considering that all the portable devices can have a Bluetooth interface and people are highly mobile these days, it will not be uncommon to find a cluster of piconets of both the 79-hop and the 23-hop types in the same area. Naik et al. [12] have given a generalized model of interference of single-slot packets in a heterogeneous cluster of piconets. A heterogeneous cluster means all the devices in some piconets are of 79-hop type and all the devices in the rest of the piconets are of 23-hop types. (The reader may note that in our present study, a heterogeneous cluster does not include a piconet where the Master is of the 79-hop (or, 23-hop) type and a Slave is of the 23-hop (or, 79-hop) type.)

Table 1 summarizes the data rates obtained at the baseband level by using different types of packets. Packet types such as DM1 and DH1 occupy a single slot, and deliver a maximum data rate of 172.8 Kbps in both the directions forward or reverse. Moreover, data traffic is generally asymmetric in applications such as Internet browsing.

Table 1: Types of data packets with data rates

Type of data packets	Maximum Data Rate (Kbps)		
	Symmetric	Asymmetric	
		Forward	Reverse
DM1	108.8	108.8	108.8
DM3	258.1	387.2	54.4
DM5	286.7	477.8	36.3
DH1	172.8	172.8	172.8
DH3	390.4	585.6	86.4
DH5	433.9	723.2	57.6

The coexistence of WPANs and the associated interference characterization pose challenging research problems from different perspectives. First, the choice of a performance evaluation method (simulation, analytical, or empirical) to study the interference in collocated WPANs is partially dependent on the similarities between the WPAN protocols and the associated network characteristics (topology, transmission power, modulation schemes, packet structures, application characteristics, etc.). Generally, the complexity of performance evaluation for such environments increases when WPANs of heterogeneous radio characteristics are present, which makes computer-simulation techniques a preferred methodology. Analytical treatments, however, can readily provide first-order performance approximations in interference-affected scenarios but are more difficult to formulate when incorporating a diverse range of parameters in closed form [5].

The rest of this paper is organized as follows: In Section 2, we present some background on Bluetooth as well as a brief survey of related work. Section 3 explains the promising low power wireless technologies using the 2.4GHz ISM band. In Section 4, we develop system model in MATLAB Simulink of packet transmission in a Bluetooth piconet with a single slave. Section 5, we extend our results to multiple active slaves in a piconet to analyze the results of simulation. The throughput performance in the presence of BT interference along with the corresponding results is presented in Sections 6. Finally, conclusions vis-a-vis the research in this paper are drawn in Section 7.

2. RELATED WORK

Of the various radio access technologies, the mutual interference between BT and IEEE-802.11-based WLANs in the 2.4-GHz ISM band has attracted the greatest attention. The foremost reason for this research direction is the popularity of the two WPANs, which are being used and extensively deployed together (in millions) in a large number of countries around the world. In the following, we review the existing literature on the mutual interference scenario of BT and IEEE-802.11-based WLANs [22].

The research presented in [21], and [3][15] mostly relies on simulation frameworks or measured experimental results to study the coexistence between the two wireless systems. Punnoose *et al.* [21] rely on measurement results to evaluate the performance of an interfered BT link. In [11], the effect of mutual interference on both BT and IEEE 802.11b links is investigated, and measurements are also taken to validate the simulation results. In [3], simulation results are presented at bit level, highlighting the effect of IEEE 802.11b on BT. The authors present results from a coexistence test bed in [13] and [14], where the main aim is to validate the simulation models using measurements from a real-life test bed. The BT packet error probability due to IEEE 802.11b interference is given in [17] using a basic Physical (PHY) layer analytical model. The work reported in [18] and [19] presents a simulation environment for modeling IEEE 802.11 and BT interference based on detailed PHY layer and medium access control (MAC) layer models. Other papers, e.g., [6] and [8], propose coexistence mechanisms using different traffic-scheduling techniques that mitigate the interference between BT and IEEE 802.11b WLANs.

Analytically, issues on the BT-802.11 interference have been well presented in [5], and [8]. In [16], Howitt gives a closed-form solution for the probability of packet collision using a lognormal shadowing radio propagation model and considering adjacent band interference. However, only single-slot BT packets are considered in the analysis. The same author in [8] analytically examines the impact that an 802.11b network has on BT performance. The approach is based on empirical results to develop the analytical model under varying interference scenarios. The key assumptions in the analysis are single-slot BT packets and the consideration of a mean delay period between 802.11b packet transmissions. An integrated coexistence analytical model is given in [1], entailing various PHY and MAC aspects. However, the authors focus on a more combined approach and do not incorporate the probability of time coincidence between overlapping packets and the BT frequency-hopping guard time, which have a serious effect on the packet error rate. In [8], Ashraf *et al.* study the interference effect of a p-persistent carrier-sense multiple-access collision-avoidance (CSMA-CA) protocol on a BT piconet's throughput using a detailed CSMA model; but the opposite scenario of BT's interference on CSMA is not given any attention. More recently, in [5], Stranne *et al.* have proposed an energy-based interference analysis of heterogeneous WPANs and explored BT and IEEE 802.11b throughput behavior as an example. The work in [5] takes into account the basic path-loss model and adjacent channel interference; however, it is assumed that no intra system interference exists. From the CSMA-based WLAN point of view, this assumption implies that the packets are not lost due to channel contention between the CSMA users, which does not hold true particularly in high traffic conditions.

3. THE TECHNOLOGIES

3.1 Bluetooth

The BT protocol stack is illustrated in Fig 1 [10]. The BT specific protocols are SDP, L2CAP, Link Manager, Baseband, and the Bluetooth Radio. Our primary modeling focus is on the characteristics of the RF, Baseband, and L2CAP elements of the stack. Assuming maximum traffic density, it is the characteristics of these sub-layers that dictate network performance in the presence of mutual interference.

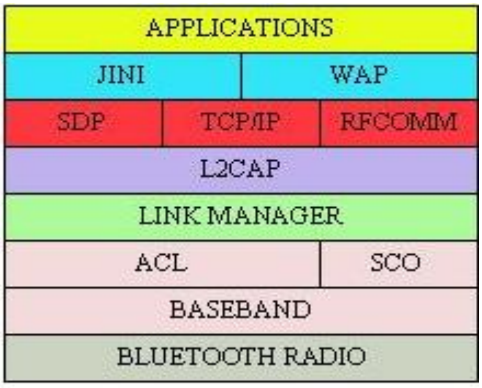

Fig 1: Bluetooth Protocol Stack

The BT Baseband sub-layer offers two data link layer transmission services, Asynchronous Connection Less (ACL) and Synchronous Connection Oriented (SCO). SCO is a symmetric point-to-point service in which the master transmits on reserved slots. The slave transmits in the following slot. This service was designed to support real time applications, especially voice. The ACL service utilizes a link level ARQ algorithm in which packets are retransmitted until a positive acknowledgement is received by the sender, insuring that ACL frames are not dropped in the physical channel [10].

Bluetooth Baseband utilizes optional Forward Error Correction for certain packet types. SCO supports 1/3 and 2/3 FEC, while ACL allows for 2/3 FEC only.

The Logical Link Control and Adaptation Protocol (L2CAP) handle application multiplexing, segmentation and reassembly (SAR), and group abstractions.

The Link Manager (LM), also called Link Management Protocol (LMP), is responsible for connection establishment, security, and control. LM messages are filtered out at the receiving node and are not sent up the protocol stack.

The Service Discovery Protocol (SDP) identifies services available by or through a Bluetooth device.

3.1.1 Piconet

The basic BT network topology (referred to as a piconet) is a collection of slave devices operating together with one master described in Fig 2. A piconet consists of at least two nodes: a master and anywhere from one to seven slaves. The master defines the piconet's pseudo-random frequency hopping sequence and transmission timing, derived from the master's 48 bit address and clock value. The master controls the channel by polling the slave(s) and is always the first to transmit in the TDD cycle. Each slave may only transmit after successful reception from the master [10].

3.1.2 Scatternet

Scatternet is a group of independent and non-synchronized piconets depicted in Fig 2 that share at least one common Bluetooth device. Bluetooth devices must have point-to-multipoint capability to engage in scatternet communication. There may be a maximum of 10 fully loaded piconets in a scatternet.

There can be only 2 to 8 Bluetooth devices talking to each other. This is called a piconet. Among these devices, there can be only one master device, all the rest are slave devices. A device can belong to two piconets meantime, serving as slaves in both piconet or a master in one and slave in another. This is called a bridging device [10]. Bridging devices connect piconets together to form a scatternet:

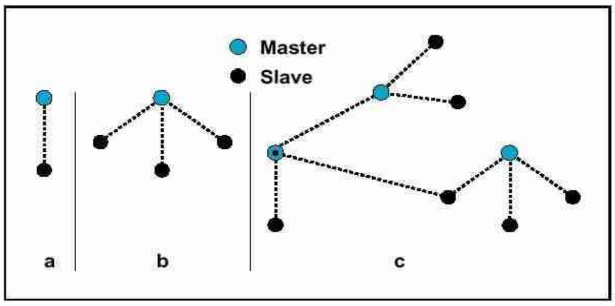

Fig 2: (a) Single slave piconet, (b) multiple-slave piconet and (c) scatternet

3.2 IEEE 802.11b

The IEEE 802.11 standard [20] defines both the physical (PHY) and medium access control (MAC) layer protocols for WLANs. In this sequel, we shall be using WLAN and 802.11b interchangeably. In this work, we focus on the 802.11b specification (DS spread spectrum) since it is in the same frequency band as Bluetooth and the most commonly deployed.

The basic data rate for the DS system is 1Mbps encoded with differential binary phase shift keying (DBPSK). Similarly, a 2Mbps rate is provided using differential quadrature phase shift keying (DQPSK) at the same chip rate of 11×10^6 chips/s. Higher rates of 5.5 and 11Mbps are also available using techniques combining quadrature phase shift keying and complementary code keying (CCK); all of these systems use 22MHz channels. The IEEE 802.11 MAC layer specifications, common to all PHYs and data rates, coordinate the communication between stations and control the behavior of users who want to access the network. The Distributed Coordination Function (DCF), which describes the default MAC protocol operation, is based on a scheme known as Carrier Sense Multiple Access, Collision Avoidance (CSMA/CA). Both the MAC and PHY layers cooperate in order to implement collision avoidance procedures. The PHY layer samples the received energy over the medium transmitting data and uses a clear channel assessment (CCA) algorithm to determine if the channel is clear. This is accomplished by measuring the RF energy at the antenna and determining the strength of the received signal commonly known as RSSI, or received signal strength indicator. In addition, carrier sense can be used to determine if the channel is available. This technique is more selective since it verifies that the signal is the same carrier type as 802.11 transmitters. In all of our simulations, we use carrier sense and not RSSI to determine if the channel is busy. Thus, a Bluetooth signal will corrupt WLAN packets, but it will not cause the WLAN to defer transmission [6].

4. SYSTEM MODEL & SIMULATION

MATLAB Simulink is the most dominant tool to examine the properties of the wireless network devices like Bluetooth and WLAN. This study models the RF components of the Bluetooth transceiver. A single-hop transceiver comprises of the binary data generator, GFSK and a pseudo-random number generator to achieve frequency hopping among 79 one-MHz wide frequencies bands over an AWGN channel, and the corresponding receiver.

The 802.11 is generated by a separate independent block which allows us to control precisely the rate of transmission, packet type and number of devices of 802.11.

The proposed model shown in Fig 3 enables performance evaluation of Bluetooth, piconet and scatternet in presence of interferences such as co-channel, 802.11 and concentrates on the modules responsible for measuring the important parameters of the system.

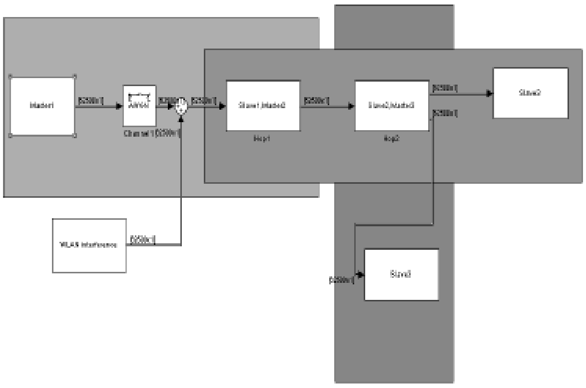

Fig 3: System model in MATLAB

In the model, we consider 'N' BT piconets co-existing independently in a certain closed physical environment. This leads to each piconet being suffered by N-1 potential interfering piconets. We assume that all nodes within a given piconet lie in the transmission range of all the other co-existing piconets. Thus, they are collocated sufficiently close in such a manner that if two or more piconets transmit a packet on the same frequency band at any instant, the corresponding colliding packets are considered corrupted and lost. All piconets use a frequency hop range of 79 frequency channels.

5. RESULTS AND DISCUSSIONS

Both BT and WLAN occupy a section of the 2.4 GHz ISM band. BT uses Frequency Hopping Spread Spectrum (FHSS) and is allowed to hop between 79 different 1 MHz-wide channels in this band. WLAN uses Direct Sequence Spread Spectrum (DSSS). Its carrier does not hop or change frequency and remains centered on one channel that is 22 MHz-wide. When a Bluetooth radio and a Wi-Fi radio are operating in the same area, the single 22 MHz-wide Wi-Fi channel occupies the same frequency space as 22 of the 79 Bluetooth channels which are 1 MHz wide.

When a Bluetooth transmission occurs on a frequency that lies within the frequency space occupied by a simultaneous Wi-Fi transmission, some level of interference can occur, demonstrated in Fig 4.

In this scenario, if WLAN device encounters interference from a Bluetooth transmission and subsequently slows its transmission rate; it will then spend more time than before transmitting a packet on a frequency available to Bluetooth, thus having the effect of increasing the likelihood of interference between BT and 802.11.

The BER is measured by varying the number of hopes of BT. The model is simulated for 5 hops and the BER is plotted as function of number of hopes of BT shown in Fig 5.

In our simulation, the performance of proposed system is also evaluated by plotting a graph of the Error Rate as a function of distance between transmitter and the interferer. Fig 6 describes, as the distance between transmitter and interferer increases the error rate decreases [25].

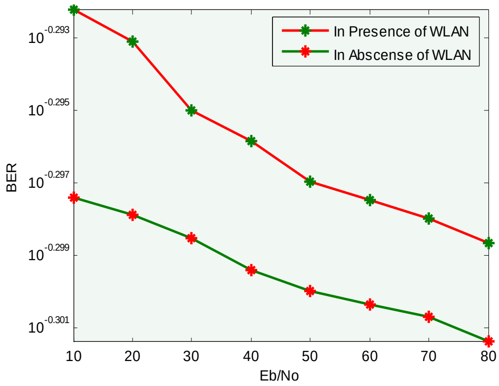

Fig 4: BER Vs En/No With and Without 802.11b

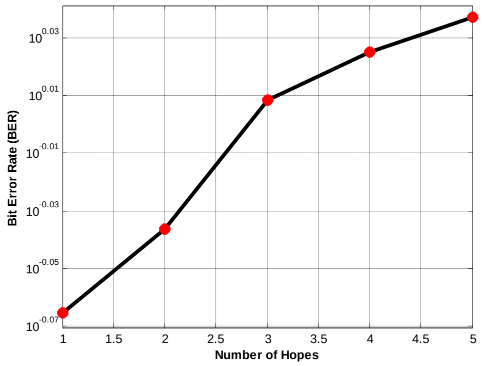

Fig 5: Plot of BER Vs No. of Hopes

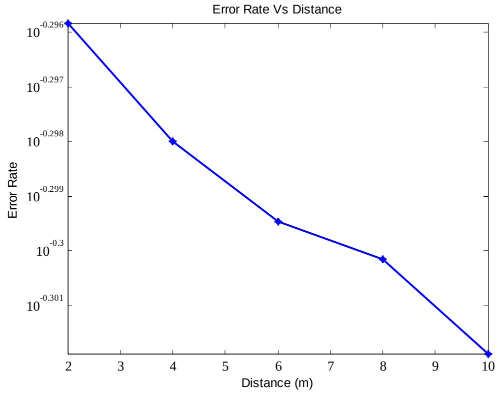

Fig 6: Error Rate Vs Distance from 802.11b

6. DELAY PERFORMANCE ANALYSIS

To analyze the delay performance of the proposed model, we used the methodology proposed by Gkelias *et al.* in [3] to calculate the CSMA/CA delay performance. Specifically, the model in [3] calculates the average end-to-end packet delay in a CSMA/CA network taking into account packet collisions within the CSMA nodes only. By integrating the probability of success of a WLAN packet in the presence of a single BT piconet into the framework, we analyze the effect of BT interference on CSMA packet delay characteristics.

Fig 7 depicts the delay performance of CSMA in the presence of N number of interfering BT piconets. The plot gives a quantitative *overview* of the effect of BT interference on the end-to-end packet delay of CSMA enabled WLAN networks.

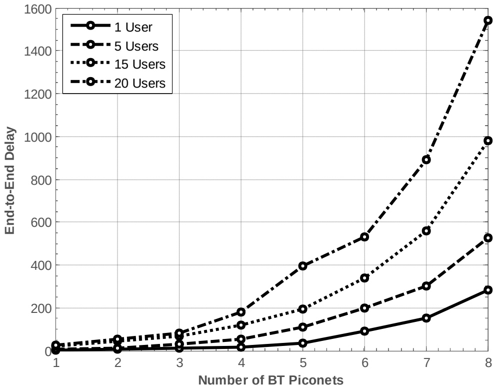

Fig 7: End-to-End CSMA delay as function of number of BT Piconets for different CSMA users

A more detailed analysis shows that, the end-to-end delay is increased for each interfering BT piconet. It can also be observed that the WLAN system becomes impractical for delay-critical applications in the presence of even one fully loaded BT piconet. However, if the BT piconets are lightly loaded, the normalized delay is increased moderately per interfering BT piconet.

In our simulation, a Wi-Fi interferer is modeled to demonstrate the performance degradation. As the distance of the interferer from the transmitting device increases the error rate of the system decreases and further, it improves the performance of the system.

7. CONCLUSIONS

The term coexistence is used to describe the scenario when the collocated WPANs practice no special procedures to mitigate or cancel the mutual interference but instead simply function as they would in an interference-free environment [22]. Under these conditions, technologies like BT, which employ FHSS, provide some resistance against the interference by constantly hopping to a new frequency channel. However, networks such as IEEE-802.11-based WLANs, which generally use the same frequency channel, are more prone to a constant source of interference.

We developed a MATLAB Simulink model for co-channel multiple BT devices on CSMA based WLAN. In this paper, we presented the performance of a CSMA-based WLAN has been shown to be severely degraded in the presence of a number of interfering BT piconets. In particular, the throughput and delay characteristics of the interfered CSMA-based WLAN have been analyzed, and results showed that an increase in BT piconet population causes an exponential decrease in the performance of the CSMA system. Specifically, for 5 CSMA users there is a reduction in its throughput can be observed in the presence of just one fully loaded BT piconet.

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