Bluetooth Performance with Bursty Noise and Traffic

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ABSTRACT

Bluetooth is a novel radio indoor wireless technology supporting short range portable devices Ad hoc intercommunication. The evaluation of its performance has been receiving more attention lately. In this paper a Personal Area Network (PAN) was set up using few Bluetooth devices to assess Bluetooth's Asynchronous Connection Less (ACL) service of overlapped devices operate in close proximity. Ad hoc connections in Bluetooth network have been assessed based on experimental and simulation study in the presence of burst noise and traffics of concurrent transmissions on unlicensed spectrum 2.4 GHz. Measurements and simulation based results are presented to investigate the performance metrics; delivery probability, load and latency. It has been found that burst losses can trigger lengthy retransmission timeout.

Keywords- Bluetooth; Personal Area Network;Asynchronous ConnectionLess ACL link; Piconets.

اداء البلوتوث مع ضوضاء وتدفق حزمي

الخلاصة

البلوتوث هي تكنولوجيا لاسلكية داخلية لدعم اتصالات مخصصة لظرف خاص وهدف خاص للتواصل بين الاجهزة المحمولة ضمن مديات قصيرة. تقييم اداءها لاقت انتباها كبيرا مؤخرا. في هذا البحث تم إنشاء شبكة المنطقة الشخصية (PAN) باستخدام عدة أجهزة بلوتوث لتقييم خدمة من نوع غير متزامن بدون رابط (ACL) لأجهزة متداخلة تعمل على مقربة. وقد تم تقييم اتصالات المخصص لظرف خاص وهدف خاص في شبكة البلوتوث على أساس دراسة تجريبية والمحاكاة في وجود حزمة ضوضاء ومرور من بث متزامن على الطيف غير المرخص 2.4GHz. وقياسات نتائج المحاكاة استنادا إلى التحقيق في مقاييس الأداء ؛ احتمال التجهيز ، الحمل والأختفاء. النتائج العملية و نتائج التحليل المحاكي تعرض لغرض دراسة مقاييس الاداء: احتمالية التوصيل والحمل والتاخير. ولقد وجدت ان الفقد الحزمي تستغرق وقت اطول لاعادة الارسال.

INTRODUCTION

Bluetooth is a short range up to 10m, or 100m (with a power boost) radio technology for wireless personal area networks operating in Industry Scientific and Medical (ISM) unlicensed spectrum 2.4 GHZ [1]. It emerges ad-hoc communications between portable computing devices such as laptops, PDAs, and cellular telephones. Originally, it is intended to provide a ubiquitous mechanism for wireless transfer of relatively small amounts of data and to replace cables in a range of applications that connect portable devices together. Bluetooth wireless technology allows seamless interconnectivity among devices. It is considered as low power and low-cost transceiver chips [1, 2].

Bluetooth network is composed of a number of piconets, each involves a master device and seven active slave devices at most; all data transfer take place through the piconet master. Due to the broadcast nature of wireless channel and low power level in range of 1mW-100mW, Bluetooth transceiver chips suffer from many source of interference as microwave ovens, 802.15.4 wireless sensor network and 802.11 WLAN operating on the same spectrum space and in the same environment. To combat multi-path and interference, Frequency Hopping Spread Spectrum FH/SS modulation is usually employed [2,3]. The evaluation of Bluetooth system and addressing approaches to develop and improve its performance have been received a lot of attention by the research community.

In [4], analysis of the Bluetooth physical layer is presented in a single room office environment that ensures line of sight propagation with interference between Bluetooth piconets themselves. Glomie et al. [5, 6] have investigated the coexistence performance of Bluetooth with 802.11 WLAN, while the authors in [7] present the negative impact of Bluetooth voice and data traffic on WLAN systems. Coexistence performance of Bluetooth, Zigbee and WLAN is investigated in [8]. Also, many works have depicted transmission control protocol performance of Bluetooth devices [9, 10], where the standard protocol leads to increase the latency and window size against the challenges of wireless channels.

The goal in this paper is to give additional insights on the TCP performance of Bluetooth traffic under different channel conditions, and to evaluate its efficacy when operates in close proximity to microwave ovens (microwave ovens are a primary user of the bandat 2.45 GHz) or other Bluetooth devices as an interference source. The work has focused on that specific common interferer that exists in close proximity of the Bluetooth transceiver in use while there is an obvious lack of using WLAN and/or wireless sensor network in the environments we live. Both measurement and simulation results are considered in this work. Agilent N4010A as a Bluetooth test set is used to provide measurements in accordance with RF test specification perform inquiry and establish a connection in test mode or normal mode [11].

In this work, the indoor channel model is considered. It is well known that propagation of radio waves inside a building is a very complicated process, and it depends significantly on topography the environment offer, e.g. line of sight or obstructed propagation. More, the indoor channel is time variant due to motion of people and equipment and is characterized by high path losses and large variations in losses. The indoor channel can less easily be captured in rough path loss exponents. While delay spreads are often much smaller than outdoors, the indoor systems often have to carry very high data rates, e.g. to support wireless multimedia computing. There are several causes of signal corruption in a wireless channel. The primary causes of attenuation are distance, penetration losses through walls and floors and multipathpropagation [12, 13].

The rest of the paper is organized as follow; Section II offers more details on Bluetooth radio system. Section III models the performance as the failure rate to reflect the main features of concern. Simulation based and some measurement based results are presented in section IV, to portray Bluetooth performance in terms of packet delivery probability, load and latency. Finally, we conclude the work in section V.

BLUETOOTH SYSTEM

This section gives brief overview of Bluetooth systems. Bluetooth describes how mobile phones, computers, and personal digital assistants (PDAs) can be easily interconnected using a short-range wireless connection. Such a network is called a piconet, in which a master employs round-robin mechanism to poll and serve the slaves. Time Division Duplexing is employed by which the master transmits to a slave in one time slot, and a slave transmits to the master in the next slot, as shown in Figure (1). Time Division Multiple Access (TDMA) is used to share the channel across multiple slave devices where the master determines which time slots each slave can occupy. Further, multiple piconets are combined into a larger scatternet, as presented in Figure (2). Device may act as master in one piconet and slave in another where the traffic can route across piconets to extend the range of Bluetooth. Each master of a piconet chooses a different FH schedule so that piconets can operate in the same area without interfering with each other. A channel is defined as a unique pseudo-random frequency hopping sequence derived from the master device’s 48-bit address and its Bluetooth clock value. Slaves in the piconet synchronize their timing and frequency hopping to the master upon connection establishment [2, 14].

Bluetooth defines not only a radio interface, but a whole communication stack that allows devices to find each other and advertise the services they offer. Two types of connection are being offered in piconet network: Synchronous Connection-Oriented (SCO), and Asynchronous Connection-Less (ACL). They differ by in payload length and Forward Error Correction (FEC) options. The application chooses the type to use, depending on the requirements of data rate and degree of error protection [1]. An SCO link provides guaranteed delay and bandwidth, apart from possible interruptions caused by the link manager protocol. A slave can open up to three SCO links with the same master, or two SCO links with different masters, while a master can open up to three SCO links with up to three different slaves. SCO links provide constant-bit-rate symmetric channels, making them suitable for streaming applications that require fixed symmetric bandwidth. ACL is proper for best-effort service as in IP networks, which have gained more importance as now a day's most of the applications, have moved to IP, and may carry bursty traffic [2, 15].

To combat multi-path and interference, Bluetooth employs FH/FSK of hop rate 1600 hops/sec and slot time 0.625 ms over specifically defined 79 hop channels each spaced by 1MHz. All the devices on a piconet are on the same channel at any particular moment. FH/SS is a method of transmitting radio signals by rapidly switching a carrier among many frequency channels, using a pseudorandom sequence known to both transmitter and receiver. Adaptive Frequency-hopping (AFH) is used in the physical layer of Bluetooth to improve the resistance to interference by avoiding using crowded frequencies in the hopping schedule where only good frequencies are used [2].

Therefore, AFH should be complemented by a mechanism for detecting good/bad channels. However, due to time variant wireless channel, AFH could also fail to avoid the interference.

PERFORMANCE MODEL

This section portrays the model has been set to investigate the performance. The ACL link is an asymmetric connection with Automatic Repeat Request (ARQ) procedure in case of packet errors. ACL service is a Pure Round Robin. All the slaves listen to downlink transmissions from the master and may reply with an uplink transmission immediately after being polled by the master. The master takes even-numbered slots, whilst slaves' packets are odd- numbered. Packets may span 1, 3 or 5 slot long and stay on the same frequency. The probabilities P_1, P_2, and P_3, are assumed for the three cases of packet length, respectively. Therefore, the ith moment of service time Ti is given as

$$T_i=1^i.P_1 + 3^i.P_2 + 5^i.P_3 \qquad \dots (1)$$

$P_1=1$ and $P_2=P_3=0$ for short packets length, $P_1= P_3=0$ and $P_2=1$ for medium length, and $P_1=P_2=0$ and $P_3=1$ for long packets length. The probability of service failure P_e^i is relevant to T_i and failure rate FR over the channel

$$P_e^i = T_i \, .FR \qquad \dots (2)$$

FR is a function of many factors; radio characteristics, SNR, packet size and number of piconets in the coverage area K. For this and for the reason that when a remote has too much data to send, the largest possible packet size is chosen. This work has focused on fixed packet size; the medium size.

Bluetooth devices frequency-hop in a pseudo-random sequence around 79 channels. Eachpiconet is synchronized to a frequency-hopping sequence defined by its master, and a piconet is arranged so that only one device is transmitting at any particular moment. Suppose that one piconet transmits on channel j. The second piconet's probability of colliding is 1/79. The probability that a Bluetooth slavesuccessfully creates a connection with the master or another slave in the Piconet (1-FR) is given by

$$P_s = 1 - FR = 1 - \frac{1}{79} \, .TR \, .(K-1) \qquad \dots (3)$$

TR is the traffic rate in terms of packet/slot, and takes a value between 0 and 1. (1/79) is the probability that the interfering piconet has chosen the same frequency as the piconet of interest.

Further, the performance of protocol stack is affected by the network topology. Possible and considered topologies presented in this work include either single or multiple wireless links located at the end of the path.

RESULTS

A. Measurement-based results

Different setups may be used for Bluetooth measurement tests. One way to test transmitter performance of a full functional Bluetooth deviceis to use a Bluetooth test set, such as the Agilent N4010A Figure (3).

An experimental study has been done to evaluate Bluetooth performance in a piconet, as it is illustrated in Figure (4). The test set Agilent N4010A and Bluetooth Device (BD) form a piconet where the tester acts as master and BD under test acts as slave. The test set establishes a link with the devices in either Normal or Test mode using the standard Bluetooth protocol.Within a specific slot time, the tester sends POLL packetsand BD confirm the reception by transmitting back a NULL packet carrying acknowledgment bit. The master is configured to send 300 bytes packets at a rate of10 packets/sec.

Based on some measurements of delivery probability at a slave with SNR=3dBin a piconetworks in an interference free area, Figure(5a) shows slight variation with an average probability of 0.5 and standard deviation 0.04. Figure 5b depicts the probability with an average of 0.5 and standard deviation of 0.29; depending on measurements at the slave coexist in close proximity with bursty interference such as microwave oven working in intermittent intervals, and SNR=6dB. Bursty signal might not reflect a change in SNR while it interferes with the flow transmits. During the idle period of the oven, higher delivery probability is observed.

The next scenario for the measurement is test the relation of the delivery probability with SNR Figure (6). Transmit power and transmit rate of the master and slave are set at 1mW and 1Mbps, respectively, where the salve moves around the master within 8 meters. SNR values are reported by the receiver’s card at different distance from the master and are presented on the x-axis. The *y*-axis shows the delivery probability. This experiment confirms that high SNR values > 10dB result in low loss rates and lower SNR values lead to intermediate loss rates. As is it obvious, predicting the success of a delivery depending on the SNR is hard for a wide range of values and suggesting that SNR is not the only factor determining the loss rate.

B. Simulation-based Results

1) System model: the performance has been assessed in different channel states using Qualnet simulation. The simulation code consists of several layered modules that are interconnected by simple interfaces for passing packets up and down along the layers, as is presented in Figure (7).

Wireless channel module includes RF model and interconnects all wireless nodes in a simulation scenario and interchanges frames among them. Physical layer module either gets the frames coming from the channel module where each is simply passed to the MAC module where all further handling is done, or pass the frames coming from MAC layer to the wireless channel. Most of the complexities are implemented in MAC layer; transmission and reception coordination, calculating back off time and collision management. Upper layers; transport or application layers generates the traffic data or digests the delivered data as the end point of connection.

The simulation code mainly uses thresholds to determine whether one frame is received correctly by the receiver with a probability $P_d \leq 1$. When multi-frames are received simultaneously by a device, the code calculates the ratio of the reference frame’s signal level to the total signal level of other frames plus the background noise with a probability $P_d \geq 0$. Signal strength of a frame is obtained by corresponding propagation model and distance between the transmitter and receiver Bluetooth devices.

2) Channel model*:* The indoor channel model considered in the simulation should reflect three scale effects; large, medium and small. Path loss model defines large scale effect to calculate the signal strength as a function of distance the signal cross. Shadow model introduces medium scale fluctuations and averages the signal level over a typically 40 wavelengths. Multipath fading has small-scale effect that leads to rapid fluctuations of the phase and amplitude of the signal if the vehicle moves over a distance. Large and medium scale effects are considered in the simulation study while, at this phase of the work, the fading effect is neglected. The attenuation in the transmitted signal γ is proportional to (β/d^4f^2), where β denotes a Gaussian random variable to reflect the variation of the received power at certain distance d.

In the typical scenario defined for Bluetooth, the fading process can be assumed flat on the 1 MHz bandwidth and constant for the entire duration of a data packet especially for relatively short packet length considered here.

3) Performance test*:* The first scenario includes one master node and 2 to 6 slaves to investigate the total traffic load of the Bluetooth system as the number of slave increases in a given area. The work considers a piconet in which the slaves create end-to end connections with each other, so that no traffic starts or ends at the master. The master transmits in even-numbered slots and the slaves transmit in odd-numbered slot according to a schedule has been set by the master. The master assigns time slot for each associated slave to transmit any request from its upper layers. Two associated slaves attain almost 0.35 of the channel capacity while four or six slaves achieve 0.52 and 0.75 of the maximum capacity, respectively as presented in Figure (8).

In the second scenario, an environment has been modeled with many obstacles and a number of Bluetooth devices distributed randomly in it to form up to 5 overlapped piconets, each involves up to 5 slaves. These devices are typically carried by hand and they are often operated while moving. The mobility is the main reason for time variance in the channel, thus it is required to be aware of these variance of the channel characteristics.

The performance of transport protocols can be affected by the number and distribution of wireless links. A piconet experiences interference when the transmission frequency of a packet in a piconet matches with that being used in one or more other piconets. Due to the mobility of Bluetooth devises, interference could extend to some slots duration and lead to negative impact that stays for longer period.

Figure (9) shows the packet error probability (PEP) and the target ACL packet for different numbers of piconet interferers with bursty traffic. The assessment considers the joint effect of noise, path loss, shadowing and interference from adjacent Bluetooth piconets. The number of potential interferes is given by the total number of adjacent piconets, since only one terminal at a time is allowed to transmit in each piconet. The curve is reflecting the collision probability with interfering piconets traffic that increases with larger number of piconets in the coverage area. As expected, PEP gets higher with larger packet size.

Finally, TCP performance is investigated in Bluetooth device against the bursty traffic from the interfering piconets (Figure10) since the majority of the traffic over Bluetooth networks belongs to TCP/IP family of protocols. TCP is a reliable transport protocol that performs well in fixed networks where any perceived packet due to error or buffer overflow is construed by a TCP sender as occurring due to buffer overflow. Wireless links are characterized by higher bit error rates and subsequently causes inefficiencies in TCP operation where congestion control procedures result in unnecessary window reduction, which causes a drop in the TCP load. The assessment considers the salves sends TCP traffic to the master and each TCP segment will be acknowledged with a single, empty TCP segment carrying only the TCP acknowledgement bit.

Figure (10) illustrates the impact of higher number of overlapped network in a piconet's load and latency. TCP sender waits for round trip time RTT to get back an acknowledgement to announce for correct delivery of the data bytes and then send the next bytes; otherwise TCP sender initiates congestion control mechanism to reduce window size or congestion avoidance using slow start mechanism and increases the back off timer exponentially to retransmit the lost bytes. TCP in such networks suffers from significant load degradation and high latency triggering a spurious timeout. An obvious reduction in load and increase in latency are recorded for five independent simulation runs to catch the average values and the variance.

CONCLUSIONS

Bluetooth links are short range wireless links that typically used with a good quality signal however; the transport protocol is affected when such links experience interference covering an area around the Bluetooth device. Based on measurement results in an indoor environment, it has been found that predicting the success of delivery process depending on SNR does not lead to correct result. However, high SNR values are relevant to low loss rates. Further, presence of burst interference results in a variation in the delivery probability with an average of 0.5 and standard deviation of 0.29. Though burstinterfering signal might not reflect a change in SNR.

Simulation-based results portray the impact of burst noise and traffic transmitted from other piconets on the same channel on the probability of collision in frequency and time overlap that subsequently assess the delivery at Bluetooth receiver. It has been found that bursty losses can trigger lengthy retransmission timeout and lack TCP performance through inefficient use of wireless channel; low load and long latency.

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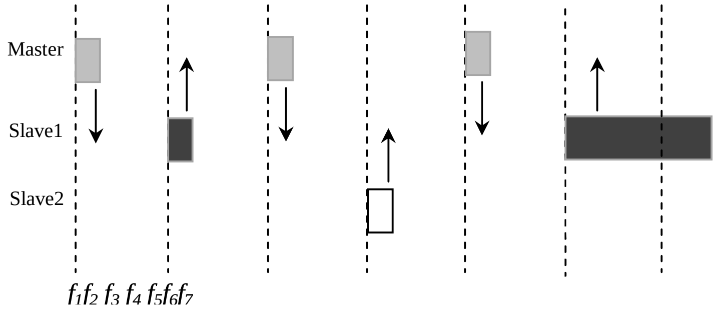


Figure (1) FH/TDD channel in a piconet. Each time slot on a different frequency according to frequency hopping schedule. The slots are centrally allocated by the master and alternately used for master and slave transmission. Packets may span multiple slots and stay on the same frequency.

Figure (2) Up to 7 slaves connects to a master in a piconet. Multiple piconets may overlap to form a larger scatternet.

Figure (3) The Agilent N4010A Test set.

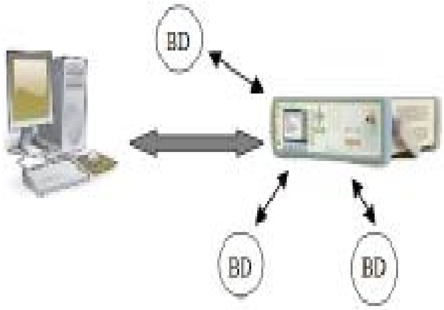
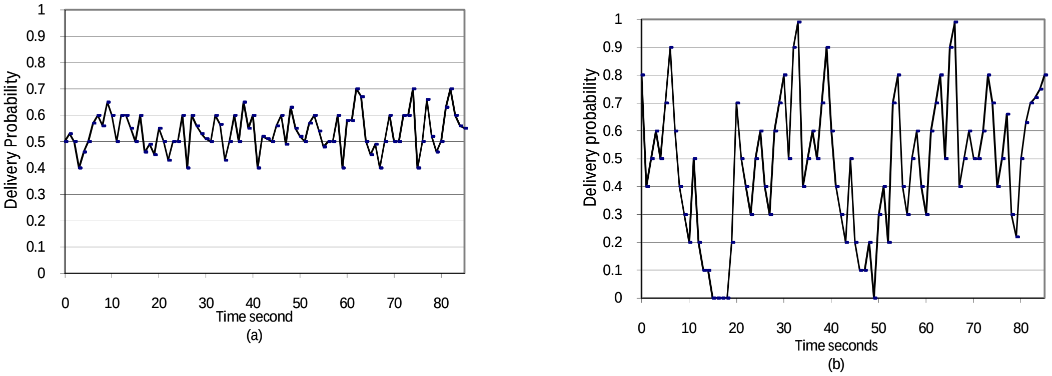


Figure (4) Test set consists of N4010A tester as a master and number of Bluetooth Devices BD to form a piconet.N4010A enables broad range of Measurements for evaluating Bluetooth Wireless format in the 2.4 GHz band.



(a)

(b)

Figure (5) Variation in delivery probability with time in a) an interference free area with an average of 0.5 and standard deviation of 0.04, b) presence of burst interference with an average probability of 0.5 and standard deviation of 0.29.

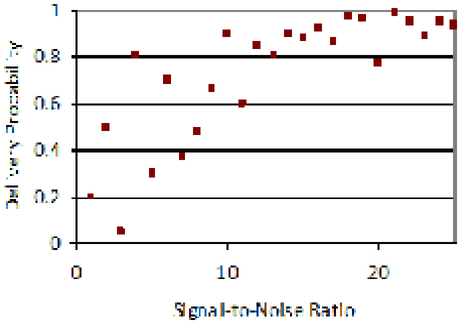


Figure (6) Variation in delivery probability versus SNR at a slave radio interface.

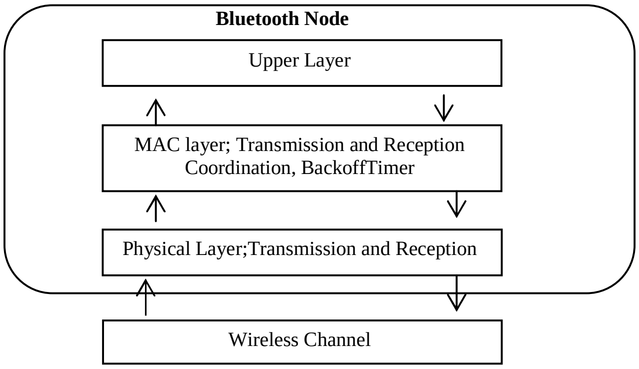


Figure (7) Layered modules in wireless simulation framework.

Figure (8)Normalized total load in a piconet with different number of slaves up to 6.

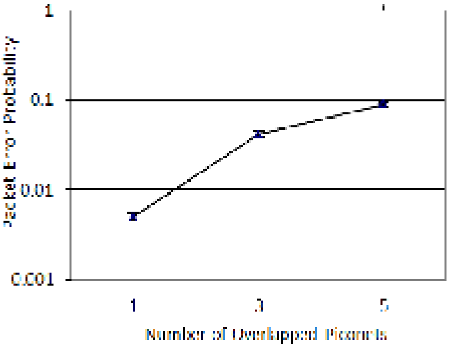


Figure (9) Packet Error Probability PEP at Bluetooth device with number of interfering piconets in the coverage area.

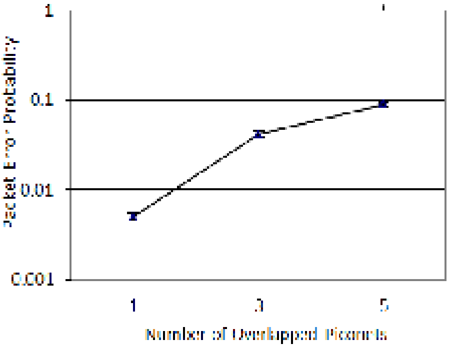


Figure (10) Load (solid line) and latency (discrete line) recorded by TCP protocol as a reaction of overlapping with different number of piconets in the coverage area.