Performance Evaluation in Time-Synchronized Multi-Piconet Bluetooth Environments

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***Abstract*— Multiple Bluetooth piconets operating in the globally available 2.4-GHz Industrial, Scientific and Medical (ISM) band are likely to co-exist in a physical environment, supporting applications such as wireless earphones, keyboards etc. An independently operating Bluetooth piconet will inevitably encounter the interference from collocated piconets, which results in individual piconet as well as overall network performance degradation. This paper shows that synchronization among co-existing Bluetooth piconets yields considerable performance improvements as compared to uncoordinated piconets.**

***Index Terms*— Bluetooth, multi-piconet, coexistence, synchronization.**

I. INTRODUCTION

Bluetooth is a technology using short-range radio links, forming a small network among communicating nodes called a piconet [1]. It is intended to replace the cable(s) connecting portable and/or fixed electronic devices. The usage of Bluetooth-enabled devices has increased enormously in recent years. This trend has facilitated an extensive deployment of low-power ad-hoc wireless communication links between different electronic devices to transfer data, synchronize information and even connect to the Internet through Bluetooth. In short, Bluetooth has served for the need of an increasingly mobile lifestyle by providing an independent Personal Area Network (PAN) to the individual end-user.

Based on the deployment of the Bluetooth technology on such a rapid scale, multiple Bluetooth piconets are likely to co-exist in a physical environment. A typical example of this can be portrayed as of a classroom where each student operates his/her own Bluetooth piconet to transfer or synchronize files. Hence, a typical classroom may easily have a large number (e.g. 100) of co-existing piconets, located within each other's transmission range and using the same 2.4-GHz Industrial, Scientific and Medical (ISM) band. Therefore, it becomes vitally important to investigate the problem of co-channel interference arising from other Bluetooth piconets and propose a feasible solution to mitigate it.

Mutual interference between Bluetooth piconets was investigated in [2] and [3], where the authors addressed the problem by presenting simulation results considering fully and partially loaded piconets. In [4], the author presented an upper bound on the packet error rate of a Bluetooth Asynchronous Connectionless (ACL) link under co-channel interference. The limitations in [4] were successfully removed in [5], in which different packet types and traffic models were integrated into the collision analysis. The analytical results were benchmarked against the results from simulations. In [6], the analytical approach of [5] was extended further by including the frequency-hopping guard time effect.

The aforementioned studies provide an analytical approach to the mutual interference problem in co-existing Bluetooth piconets. These studies, however, do not incorporate synchronization among piconets or propose any interference mitigation approach. The already published works emphasize the fact that a large number of co-existing piconets severely degrades the individual piconet or overall network performance in terms of higher packet error rates and lower aggregate network throughput. The aim of this paper is to quantify the potential gains that could be obtained by synchronizing different coexisting piconets. In this paper, we do not discuss or propose possible synchronization architectures, but rather emphasize on presenting results of an analytical framework to highlight the benefits that are obtained with synchronization in such mutual interference scenarios.

The rest of the paper is organized as follows. The Bluetooth system overview is described in Section II. The underlying interference model is discussed in Section III. In Section IV, the packet collision analysis considering synchronization among piconets is presented. Analytical results are then presented in Section V and conclusions are drawn in Section VI.

II. BLUETOOTH

The entire Bluetooth protocol architecture is defined in [1]. A brief summary will be presented in this section with special emphasis on its PHY layer characteristics and parameters. A Bluetooth piconet essentially uses a master/slave architecture in which the master controls the traffic flow. All Bluetooth devices have identical hardware properties so that the master is only selected when the network is successfully established. The unit initiating the connection acts as the master and can organize the channel access for up to seven other active units, which are called slaves. The master carries out the polling in a time-division duplex (TDD) manner.

Bluetooth uses frequency hopping spread spectrum (FHSS) to transmit data packets and frequency hop range in most countries covers 79 carriers of 1MHz bandwidth each. Binary baseband data is modulated using Gaussian frequency shift keying (GFSK) and the frequency synthesizer transmits each packet on a newly chosen frequency. The maximum hopping rate in a piconet is 1600 hops per sec. Moreover, the channel is divided into slots of length 625 μs. The actual data is transmitted in part of the total packet transmission time, e.g. 366 μs out of 625 μs in the case of single-slot packet transmission. The remaining time (259 μs, as shown in Fig. 1) is used to let the electronics stabilize to the next frequency hop, known as the frequency hopping guard time.

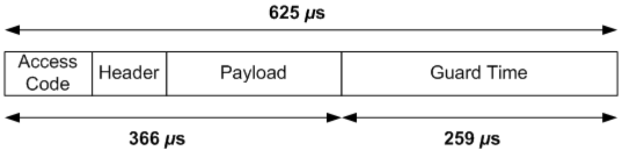


Fig. 1. Frequency hopping guard time illustration for 1-slot packet transmission.

Two physical links are supported in Bluetooth: ACL for data traffic and synchronous connection-oriented (SCO) for time-bounded voice communication. Three SCO packets are defined: HV1, HV2 and HV3. HV stands for high-quality voice. These packets are all single slot but vary in the amount of information they carry: HV1 carriers 10 bytes, HV2 carries 20 bytes and HV3 carries 30 bytes. The ACL link, on the other hand, allows 1, 3 and 5-slot data packets with the optional use of forward error correction (FEC). DM (medium-speed data) packets are all 2/3-FEC encoded to tolerate possible transmission errors. Not encoded by FEC, DH (high-speed data) packets are more error-vulnerable but can carry more information. DM1/DH1 packets occupy one time slot, while DM3/DH3 and DM5/DH5 packets occupy 3 and 5 time slots, respectively.

This paper focuses on performance improvements in ACL connections. Only DH1, DH3 and DH5 packets are considered as these packets do not use FEC and are more susceptible to channel impairments and interference.

III. INTERFERENCE MODEL

We consider N Bluetooth 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 piconets use a frequency hop range of 79 frequency channels. Also, they are collocated sufficiently close in such a manner that if two or more piconets transmit a packet within the same frequency band at any instant, the corresponding colliding packets are considered corrupted and lost.

As explained in the previous section, three types of ACL packets are considered here. Each of these packets has a certain probability of arrival associated with it. The arrival probabilities for 1, 3, and 5-slot packets are represented by ρ_1, ρ_3 and ρ_5, respectively. The idle time in the piconet is modeled by assuming a single-slot empty or dummy packet that does not carry any traffic but occurs with a certain probability. This is the same approach used by [5], [6]. The dummy packet is assigned the probability ρ_0 such that $\rho_0 = 1 - (\rho_1 + 3\rho_3 + 5\rho_5)$. We assume that all collocated piconets carry identical traffic with equal arrival probabilities ρ_1, ρ_3 and ρ_5. An extension of the presented analysis to the case of different arrival rates in all piconets is tedious but feasible.

IV. INTERFERENCE ANALYSIS WITH SYNCHRONIZATION

The performance of a Bluetooth network can be evaluated using various quantitative metrics such as packet error rate (PER), individual piconet throughput (S) and aggregate network throughput (Θ). The relevance of each performance metric is dependent on the specific network requirements. In this paper, the above-mentioned three measures of performance are considered for accentuating the effect of synchronization in collocated piconets. The respective equations for PER, S and are derived using a probabilistic treatment entailing different Bluetooth baseband parameters.

It is important here to elaborate what exactly we mean by synchronization in the context of this paper. As described in Section II, the transmission time is divided into slots of length 625μs. The packet transmissions within each piconet start at slot boundaries, centrally controlled by the master. With no coordination between two collocated piconets, an ongoing packet transmission in one piconet can be interfered by more than one packet from the other piconet. This is because the slot boundaries in the two piconets are not synchronized. The analysis presented hereafter is based on the assumption that the collocated piconets are time-synchronized in a manner such that slot boundaries of all the piconets overlap with each other.

We begin by considering two co-existing piconets X and Y. Each of these piconets can transmit a 1, 3 or 5-slot (DH1, DH3 or DH5) packet with respective probabilities ρ_1, ρ_3 or ρ_5. We focus our attention on the piconet X and derive the success probabilities $\Pr[s, i]$, for each of the three packet types i.e. $i = 1, 3,$ and 5, in the presence of interference from the piconet Y. For an ongoing transmission in X, the probability that piconet Y chooses another frequency (no collision) as the one chosen by piconet X is $P_0 = 1 - \frac{1}{79} = \frac{78}{79}$.

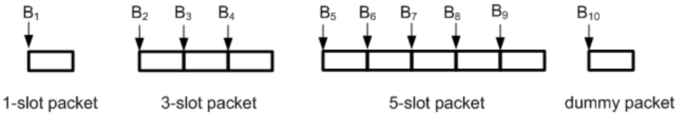


Fig. 2. Slot beginnings for different packet types.

We denote the starting slot boundary in each packet type as shown in Fig. 2, such that:

- B_1, B_2, and B_5 mark the beginning of a 1, 3, and 5-slot packet, respectively.
- B_3 and B_4 represent the beginnings of the second and third slots of a 3-slot packet, respectively.
- B_6, B_7, B_8, and B_9 denote the beginnings of the second, third, fourth, and fifth slots of a 5-slot packet, respectively.
- B_{10} corresponds to the beginning slot boundary of an empty or dummy packet.

All slot beginnings $B_j, j = 1...10$, have arrival probabilities associated with them. It is clear that the probability of occurrence of B_1 is ρ_1 per slot; the probability of occurrence for each of B_2, B_3, and B_4 is ρ_3; the arrival probability for each of B_5, B_6, B_7, B_8, and B_9 is ρ_5; and the probability of occurrence of B_{10} is ρ_0. To emphasize on the occurrence of a particular slot, we denote the arrival probability of B_j by $\xi(B_j), j = 1..10$. We also define $g(j)$ to be the number of slots that follows the slot beginning B_j and belongs to the same packet. As an example, $g(1) = 1, g(3) = 2, g(8) = 2$, and $g(10) = 1$.

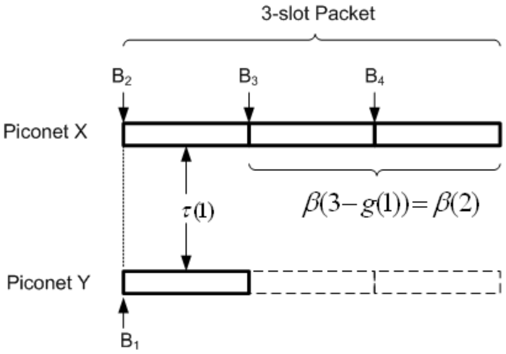


Fig. 3. Packet collisions in synchronized piconets.

Before we formulate the success probability $\Pr[s, i]$ of an i-slot packet, we present an example of packet collision for a 3-slot ($i = 3$) packet in piconet X as illustrated in Fig. 3. Since the two piconets X and Y are time-synchronized, the slot beginnings of transmitted packets in the two interfering piconets start at the same time instant. In Fig. 3, piconet Y transmits a 1-slot packet containing the slot beginning B_1, with probability ρ_1. The success probability for the first slot of the 3-slot packet would therefore be $P_0 = \frac{78}{79}$. We denote this probability function by $\tau(j)$, where j represents the jth slot beginning in Y's packet. Intuitively, if Y transmits the dummy packet (B_{10} with probability ρ_0), the success probability is simply 1. We can move on to consider the success probability of the remaining part ($i - g(1)$) of X's 3-slot packet. In Bluetooth, two consecutive packets are transmitted on two different frequencies. The next packet in Y could be either 1, 3, 5-slot or a dummy packet, but is transmitted on a different frequency with respect to the first one. In case, Y transmits a 1-slot packet next, the success probability of the second slot of X's packet will be $P_0 = 1 - \frac{1}{78} = \frac{77}{78}$. Else, if Y transmits a dummy packet next, the success probability will be 1 for the second slot of the X's packet. In both cases, we will then need to consider the success probability of the remaining last slot of X's packet. Thus, the success probability of the remaining portion of X's packet is solved recursively by defining a probability function $\beta(m)$. Intuitively, $\beta(m)$ is the success probability of the last m slots of X's packet, excluding the first slot.

Based on the aforementioned probability functions, we formulate $\Pr[s, i]$ as follows:

$$\Pr[\text{s,}i] = \sum_{j=1}^{10} \xi(B_j) \cdot \tau(j) \cdot \beta(i - g(j)), \tag{1}$$

where

$$\tau(j) = \begin{cases} 1 & \text{if } j = 10, \\ P_0 & \text{otherwise} \end{cases} \tag{2}$$

and $\beta(m)$ is defined for $k > 0$ as follows

$$\begin{aligned} \beta(m) = {} & \frac{\rho_0}{\rho_0 + \rho_1 + \rho_3 + \rho_5} \cdot \beta(m - g(10)) \\ & + \frac{\rho_1}{\rho_0 + \rho_1 + \rho_3 + \rho_5} \cdot \tilde{P}_0 \cdot \beta(m - g(1)) \\ & + \frac{\rho_3}{\rho_0 + \rho_1 + \rho_3 + \rho_5} \cdot \tilde{P}_0 \cdot \beta(m - g(2)) \\ & + \frac{\rho_5}{\rho_0 + \rho_1 + \rho_3 + \rho_5} \cdot \tilde{P}_0 \cdot \beta(m - g(5)), \end{aligned} \tag{3}$$

where $\beta(m) = 1$, for $k \leq 0$. In (1), we consider each type of slot beginning $(B_j), j = 1..10$, to appear in the first slot. The corresponding probability is $\xi(B_j)$. The function $\tau(j)$ gives the success probability for the first slot of X's packet and the function $\beta(m)$ accommodates the success of the remaining part of X's packet.

Equation (1) gives the probability of success for an i-slot packet in piconet X in the presence of the interfering piconet Y. X experiences interference from N-1 sources when there are N piconets co-existing. The PER_i for an i-slot packet in piconet X is thus given as:

$$PER_i = 1 - \Pr[\mathrm{s}, i]^{N-1}. \tag{4}$$

The throughput, S, for piconet X in an N-piconet environment is given as:

$$\begin{aligned} S = \rho_1 \cdot \Pr[\mathrm{s}, 1]^{N-1} \cdot R_1 + 3 \cdot \rho_3 \cdot \Pr[\mathrm{s}, 3]^{N-1} \cdot R_3 \\ + 5 \cdot \rho_5 \cdot \Pr[\mathrm{s}, 5]^{N-1} \cdot R_5, \end{aligned} \tag{5}$$

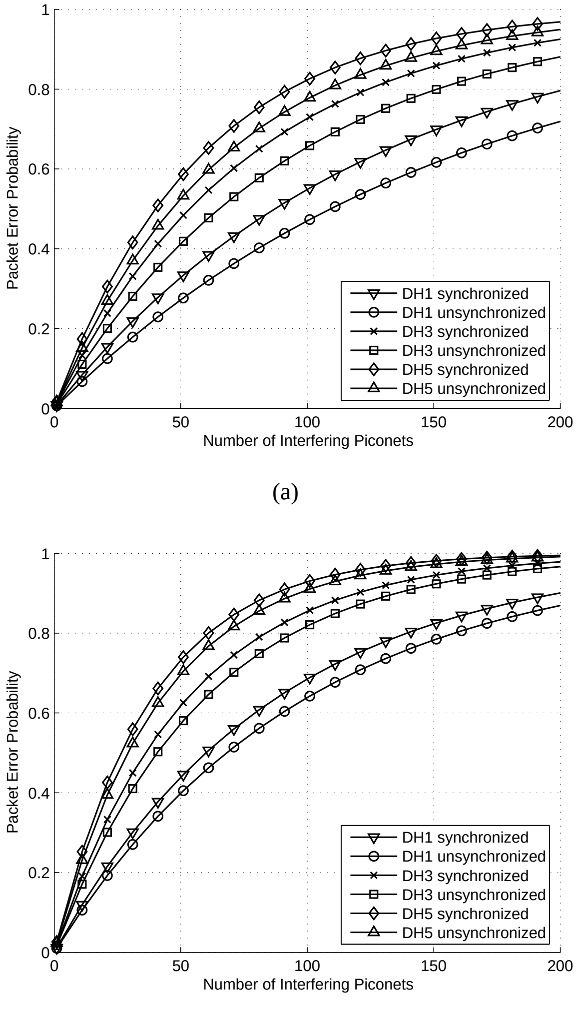
where $R_1(345.6), R_3(780.8)$ and $R_5(867.9)$ are the data rates (Kbps) for 1 (DH1), 3 (DH3), and 5-slot (DH5) packets, respectively (for example, 1464 bits are contained in a DH3 packet, therefore $R_3 = \frac{1464}{1875} = 780.8$ Kbps). The aggregate network throughput, Θ, of successfully transmitted packets in all the piconets is thus given as $\Theta = N \times S$.

V. Numerical Results

Based on the analysis presented in the previous section, several numerical results are shown, and the performance of synchronized transmissions is compared against unsynchronized transmissions in this section.

In Fig. 4, the PER performance of the synchronized transmissions is plotted against unsynchronized transmissions, as a function of number of piconets co-existing in a certain environment. DH1/3/5 packets are considered with equal arrival probabilities ($\rho_1 = \rho_3 = \rho_5$). In Fig. 4(a), a lighter uniform traffic load of 50% ($\rho_0 = 0.5$) is considered in all collocated piconets. There are a couple of common points to be considered here. Firstly, the PER increases as the number of piconets increases, reflecting an increased mutual interference. Secondly, smaller packets (DH1) have lower values for PER with respect to the longer packets (DH5). This is because they suffer fewer collisions due to their shorter time durations. As shown in the figure, synchronization delivers significant PER improvements for all the three packet types. For example, it offers 20% PER improvement for DH1 type packets when 150 piconets are existing together. It is worth considering here that improvement gaps increase as the number of piconets increases.

Fig. 4(b) depicts the PER performance of synchronized piconets for a higher traffic load of 80% ($\rho_0 = 0.2$). The PER is higher for all the three packet types with respect to the lighter traffic load of 50%. Even at heavier loads, the synchronization outperforms unsynchronized transmissions.

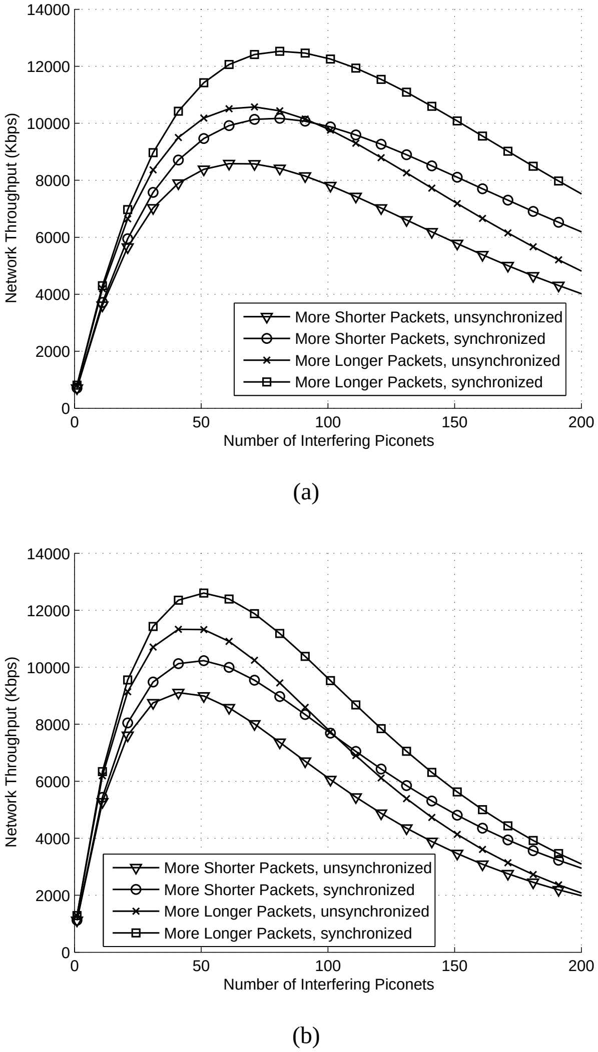


(a)

(b)

Fig. 4. PER comparison of synchronized and unsynchronized transmissions: (a) 50% traffic load, and (b) 80% traffic load.

Fig. 5 reports aggregate network throughput as a function of the number of interfering piconets. In Fig. 5(a), the traffic load is chosen as 50% ($\rho_0 = 0.5$). Two different arrival models are considered here. The ratio ρ_1:ρ_3:ρ_5 is set to 3:2:1 to reflect the case of more shorter packets in each piconet. Similarly, the ratio ρ_1:ρ_3:ρ_5 = 1:2:3 depicts the case of more longer packets. The graph shows that higher throughput is achieved with more longer packets. This is because, though longer packets are more vulnerable to collisions, they carry more data bits per slot ($R_5 >> R_1$). Also, the aggregate throughput reaches a maximum for a certain value of N and then drops as N increases. Synchronized transmissions generate approximately 30% more aggregate throughput for 100 interfering piconets. This improvement increases with increasing value of N.



(a)

(b)

Fig. 5. Aggregate network throughput comparison of synchronized and unsynchronized transmissions: (a) 50% traffic load, and (b) 80% traffic load.

VI. CONCLUSIONS

A mathematical analysis for synchronization in multi-piconet Bluetooth environments has been presented. It has been shown that synchronization yields excellent network performance improvements under varying traffic load conditions. As an example, it offers 26% network throughput improvement in the presence of 100 co-existing piconets.

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