

Performance of IEEE 802.11 WLANs in a Bluetooth Environment

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Abstract—Coexistence of different wireless systems that share the same frequency band is becoming one of the most challenging issue due to the wide-spread popularity of WLANs and to the rapid development of short-range radio systems. In this paper we consider WLANs based on the IEEE 802.11 standard and a short-range radio system based on Bluetooth specifications, which operate in the 2.4 GHz ISM frequency band. We present a model of the interference that IEEE 802.11 WLANs may experience either because of a voice or a data Bluetooth link. We derive results showing that by applying simple traffic shaping techniques, interference can be significantly reduced. In the presence of Bluetooth data traffic, WLAN packet error probability can be decreased by 19% at the expense of an additional average delay in Bluetooth packet transmission equal to 10 ms, or by 29% at the expense of a Bluetooth average packet delay equal to 110 ms.

I. INTRODUCTION

Wireless computing has experienced a enormous growth since it allows users to access network services without being tethered to a wired infrastructure. The two wireless systems that have experienced the most rapid evolution and wide popularity are the standard developed by IEEE for wireless local area networks (WLANs), identified as IEEE 802.11, and the Bluetooth technology. Both these systems operate in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band (i.e., 2.400-2.4835 GHz).

IEEE 802.11 WLANs are designed to cover areas as vast as offices or buildings. The fundamental building block of the network is the so-called Basic Service Set (BSS), which is composed of several wireless stations and one fixed access point. The access point provides connection to the wired network [1].

WLANs operate at bit-rates as high as 11 Mb/s and can use either a FHSS (Frequency Hopping Spread Spectrum) or a DSSS (Direct Sequence Spread Spectrum) [1]. In the case of FHSS systems, hopping sequences span over 79 channels, each one 1 MHz wide; while, DSSS systems use a 11-chip Barker sequence and their bandwidth is roughly equal to 20 MHz [2].

Bluetooth (BT) provides interconnection of devices in the user's vicinity in a range of about 10 m, and it could become an official standard if adopted by IEEE 802.15, which seeks to develop a standard for personal area networks.

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The basic architectural unit in BT systems is the piconet, composed of a *master* device and seven active *slave* devices at most, which are allowed to communicate with the master only [3].

Bluetooth can provide a bit-rate equal to 1 Mb/s. A FHSS scheme is used at the physical level; each master chooses a different hopping sequence so that piconets can operate in the same area without interfering with each other. Hopping frequencies range over 79 frequency channels in the ISM band, each of the channel being 1 MHz wide. The nominal hop dwell time is equal to 625 μ s. Sequences are created by generating several sub-sequences, each composed of 32 hops. The first sub-sequence is obtained by taking 32 hops at random over the first 64 MHz of the frequency spectrum; then the successive 32 MHz are skipped, and the next sub-sequence is randomly chosen among the following 64 MHz. The procedure is repeated until the hopping sequence is completed [4]. A TDD technique is used to transmit and receive data in a piconet: each packet transmitted in a slot corresponds to the minimum dwell time; slots are centrally allocated by the master and alternately used for master and slave transmissions. Fig. 1 shows the FH/TDD channel. Multislot packets can also be transmitted; in this case packets are sent by using a single frequency hop, that is the hop corresponding to the slot at which the packet started.

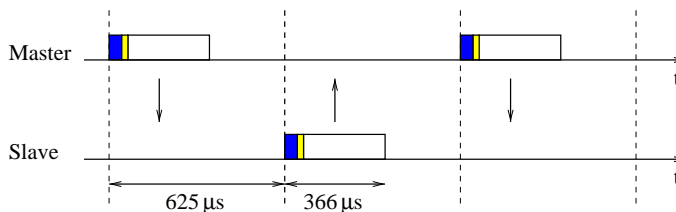


Fig. 1. The FH/TDD channel in Bluetooth.

Without any provisions, IEEE 802.11 WLANs and Bluetooth systems operating in the same environment will interfere with each other. Several IEEE and Bluetooth documents [5], [6], [7], [8] have already addressed this issue. However, the analysis presented in these documents is based on coarse assumptions and the proposed interference models are not suit-

able for a thorough study of the system dynamics.

In this paper, we first develop an accurate and flexible model to evaluate performance of a IEEE 802.11 WLAN in the presence of either a voice or a data Bluetooth link. We use this model to derive results in terms of packet error probability experienced in the WLAN system. Then, we apply traffic shaping techniques to the Bluetooth packet flow and we show that a significant reduction of the interference between WLANs and Bluetooth can be achieved. Although simple shaping mechanisms are considered here, useful insights are obtained. We believe that the development of appropriate traffic control algorithms is one of the key points to reduce interference among wireless systems implemented according to different specifications.

II. COEXISTENCE MODEL

We consider a IEEE 802.11 WLAN using a DSSS scheme and having a bandwidth equal to 20 MHz. Our reference scenario involves a BSS and a large number of BT piconets operating in a common area.

A BT transmitter interferes with the WLAN receiver because the interfering power from BT causes a decrease of the carrier to interference power margin, denoted by γ . Based on the results presented in [7], [8], the number of BT piconets that interfere with the BSS and the associated carrier to interference power margin can be determined from the following system parameters:

- distance between a WLAN station and the associated access point;
- interference range of the BT piconets;
- average density of BT piconets in the considered area;
- transmission power used in both the systems;
- signal attenuation factor due to propagation.

Given γ , the bit error probability at the WLAN receiver, denoted by p_e , can be computed. For instance, in the case of a WLAN system using a BPSK modulation and an uncoded DSSS signal, we have [9]

$$p_e = Q\left(\sqrt{2 \cdot \gamma \cdot L_c}\right) \quad (1)$$

where L_c is the number of chips per information bit.

In our reference scenario, we assume that B BT piconets are in the range of interference of the WLAN, each of them associated with a bit error probability equal to $p_e^{(i)}$ ($i=1, \dots, B$). In order to derive the probability that BT piconets actually interfere with the WLAN system, we must compute the probability, denoted by h_f , that a BT packet hops on the DSSS band. We approximate the number of BT channels to 80 (each channel corresponds to 1 MHz) and divide the BT frequency spectrum into four bands 20 MHz wide, as shown in Fig. 2. For the sake of simplicity, we consider that the DSSS band corresponds to the first 20 MHz. Considering the procedure used to generate the BT hopping sequences [4], we notice that by starting with a 32-hops sub-sequence taken at random from the first 64

channels, the same 64 channels will be used again after five sub-sequences have been selected. Through simple calculations, it follows that the first time a sub-sequence is selected, the 64 channels include all the DSSS frequency band; for the second sub-sequence 4 DSSS channels are used, for the third one 16 channels, and for the fourth and fifth sub-sequence all the DSSS band is included. Therefore, we have

$$h_f = \frac{1}{5} \cdot \left(\frac{20}{64} + \frac{4}{64} + \frac{16}{64} + \frac{20}{64} + \frac{20}{64} \right) = 0.25. \quad (2)$$

We notice that by applying this method, h_f can be calculated for any position of the DSSS band in the BT spectrum frequency.

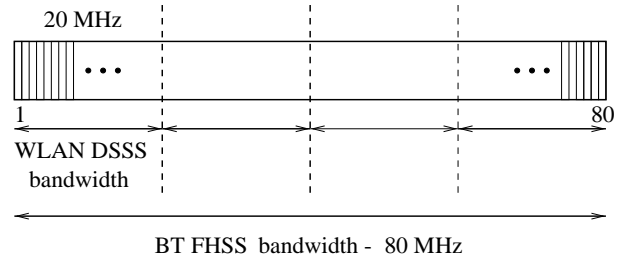


Fig. 2. Bluetooth and WLAN DSSS frequency bandwidth.

III. PERFORMANCE ANALYSIS

In this section we compute the packet error probability of a WLAN system due to Bluetooth interference; the impact of both a voice and a data BT link is investigated.

We denote the BT packet time interval (also called slot interval) by T_{BI} , the actual BT transmission time per packet by T_{BP} , and the WLAN packet time duration by T_W . Let x be the time from the beginning of the first overlapping BT packet interval to the beginning of the WLAN packet; x is a random variable uniformly distributed between 0 and T_{BI} .

The number of BT packet intervals that overlap the WLAN packet depends on x and can be derived as [6]

$$N(x) = \begin{cases} \left\lceil \frac{T_W}{T_{BI}} \right\rceil & \text{if } x \leq T_{BI} \cdot \left\lceil \frac{T_W}{T_{BI}} \right\rceil - T_W \\ \left\lceil \frac{T_W}{T_{BI}} \right\rceil + 1 & \text{else} \end{cases} \quad (3)$$

Fig. 3 shows an example with $N(x)=5$; variables T_i ($i=1, \dots, N(x)$) indicate the portion of the i -th BT packet that actually interferes with the WLAN packet. Observe that during the second packet interval, none BT transmission takes place and therefore T_2 is equal to 0. For the generic packet interval i ($i=1, \dots, N(x)$), we have that if none BT transmission occurs in interval i , $T_i = 0$; otherwise [6]

$$T_i = \begin{cases} \max(T_{BP} - x, 0) & i=1 \\ T_{BP} & i=2, \dots, N(x) - 1 \\ \min(x + T_W - (N(x) - 1)T_{BI}, T_{BP}) & i=N(x) \end{cases} \quad (4)$$

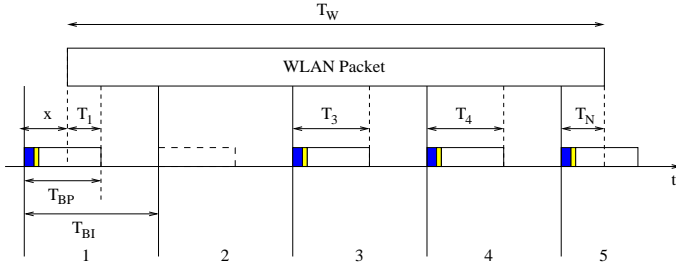


Fig. 3. Overlap of WLAN and Bluetooth packets.

In the following we will denote by $T_i^{(b)}$ the ratio T_i/T_b , where T_b is the bit time duration.

A. Bluetooth Voice Traffic

In a Bluetooth voice link, each phone call occupies the FH/TDD channel slot intervals according to a deterministic pattern.

Let us consider a fixed value for the offset x ; given x , the number of BT packet intervals overlapping a WLAN packet, $N(x)$, can be computed from (3). For $j=1, \dots, N(x)$, we define $\delta_v(j)$ as

$$\delta_v(j) = \begin{cases} 1 & \text{if a BT voice packet is transmitted in slot } j \\ 0 & \text{else} \end{cases} \quad (5)$$

Therefore, the mean number of bits per WLAN packet ‘hit’ by BT voice traffic, conditioned on the value of x , can be written as

$$S_{|x} = h_f \left(T_1^{(b)} \delta_v(1) + T_{BP}^{(b)} \sum_{j=2}^{N(x)-1} \delta_v(j) + T_N^{(b)} \delta_v(N(x)) \right) \quad (6)$$

By considering the ‘hit’ bits, that are actually in error, as i.i.d., the probability to correctly receive a WLAN packet is approximated by

$$P\{\text{correct WLAN packet} | x\} = (1 - p_e)^{S_{|x}}, \quad (7)$$

where p_e is the bit error probability associated to the interfering BT piconet. By deconditioning with respect to x , the packet error probability is

$$\epsilon = 1 - P\{\text{correct WLAN packet}\} = 1 - \int_0^{T_{BI}} (1 - p_e)^{S_{|x}} \cdot \frac{1}{T_{BI}} dx \quad (8)$$

B. Bluetooth Data Traffic

In the case of a BT data link, we assume that the traffic generated by each of the B interfering piconets is Poisson distributed with rate λ_i ($i=1, \dots, B$). Thus, the aggregated traffic generation process is Poisson distributed with rate $\lambda_a = \sum_{i=1}^B \lambda_i$, and the probability that K packets are transmitted over a time period equal to N BT packet intervals, is equal to

$$P_K = (\lambda_a N)^K e^{-\lambda_a N} / K! \quad (9)$$

The average bit error probability at the WLAN receiver, conditioned on a BT packet interfering with the WLAN, is

$$\bar{p}_e = \frac{\sum_{i=1}^B p_e^{(i)} \lambda_i}{\sum_{i=1}^B \lambda_i} \quad (10)$$

Let us now consider a fixed value for the offset x . By conditioning on having K BT transmissions over the $N(x)$ BT packet periods, the probability that all K transmissions occur in any of the $N(x)$ slots other than the first and the last one, is

$$p_{a-int}(x) = \frac{\binom{N(x)-2}{K}}{\binom{N(x)}{K}}; \quad (11)$$

the probability that among K transmissions one occurs either in the first or in the $N(x)$ -th BT packet interval is

$$p_{1-ext}(x) = \frac{\binom{N(x)-1}{K-1}}{\binom{N(x)}{K}}; \quad (12)$$

finally, the probability that of K transmissions one takes place in the first overlapping time interval and one in the $N(x)$ -th time period is

$$p_{2-ext}(x) = \frac{\binom{N(x)-2}{K-2}}{\binom{N(x)}{K}} \quad (13)$$

The mean number of bits per WLAN packet ‘hit’ by Bluetooth, conditioned on the value of x and on K transmissions over the $N(x)$ intervals, can be written as

$$S_{|x,K} = h_f \left[T_{BP}^{(b)} \cdot K \cdot p_{a-int}(x) + 2 \cdot T_{BP}^{(b)} (K-1) p_{1-ext}(x) + (T_1^{(b)} + T_N^{(b)}) p_{1-ext}(x) + T_{BP}^{(b)} (K-2) p_{2-ext}(x) + (T_1^{(b)} + T_N^{(b)}) p_{2-ext}(x) \right] \quad (14)$$

By deconditioning with respect to K , we have

$$S_{|x} = \sum_{K=0}^{N(x)} S_{|x,K} \frac{(\lambda_a N(x))^K e^{-\lambda_a N(x)}}{K!} \quad (15)$$

Similarly to the case of a BT voice link, we can write the WLAN packet error probability as

$$\epsilon = 1 - \int_0^{T_{BI}} (1 - \bar{p}_e)^{S_{|x}} \cdot \frac{1}{T_{BI}} dx \quad (16)$$

In the next section, we use the interference model described above to derive performance in terms of the WLAN packet error probability as the system parameters vary.

IV. RESULTS

We consider a WLAN system using a DSSS scheme and providing an instantaneous rate equal to 11 Mb/s. We assume that each WLAN packet is followed by an acknowledgment and information is streamed in a continuous manner; also we assume that data exchange is asymmetric, i.e., either the access point is sending data packets and the wireless station is sending acknowledgments or vice versa [10]. Fig. 4 shows the WLAN traffic timing in the case of payload equal to 1500 bytes.

The value of p_e at the WLAN receiver is set equal to 10^{-3} for any interfering BT piconets. We assume that the transmission of a WLAN packet fails either whenever the packet or the corresponding acknowledgment are not correctly received.

For the Bluetooth system, we set $T_{BI}=625 \mu\text{s}$ and $T_{BP}=366 \mu\text{s}$. In the case of voice traffic, we consider HV3-type link, i.e., for each active phone call a voice packet is transmitted in both directions every six time slots. In the case of data traffic, a DH1-type link is assumed, and therefore the shortest data packet (366 μs long) is used.

Fig. 5 shows the behavior of the WLAN packet error probability in the presence of an interfering BT voice link; curves are plotted for different values of the WLAN packet payload and for two different values of the BT traffic load. The WLAN packet error probability is quite high and increases as a larger payload is considered. However, we believe that a significant improvement in performance can be achieved if a traffic control algorithm is introduced in the WLAN system. As an example, we applied the following control mechanism: the transmission of a WLAN packet is delayed by a time period equal to T_{BI} whenever the previous packet transmission fails. In this case, we observed a reduction in the WLAN packet error probability equal to 10%.

Fig. 6 presents the WLAN packet error probability in the case of BT data traffic, as the WLAN payload and the BT aggregated traffic generation rate, λ_a , vary. As expected, the packet error probability increases as λ_a grows and a larger payload is considered. Again, in order to get better performance, we introduced a traffic shaping mechanism such that a BT transmitter can not send single packets over the channel but must always transmit burst of β packets.

Figs. 7, 8, 9, and 10 show the WLAN packet error probability and the average delay experienced by a BT packet when the traffic shaping mechanism described above is implemented. The average packet delay was calculated by considering the delay from the time instant at which a BT packet is generated to the time instant at which it is transmitted and by averaging over the number of BT packets that are transmitted during a WLAN

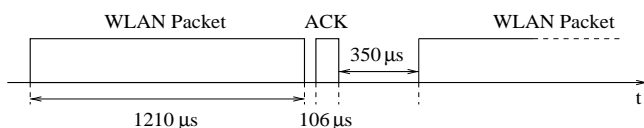


Fig. 4. Timing on a WLAN system for payload equal to 1500 bytes.

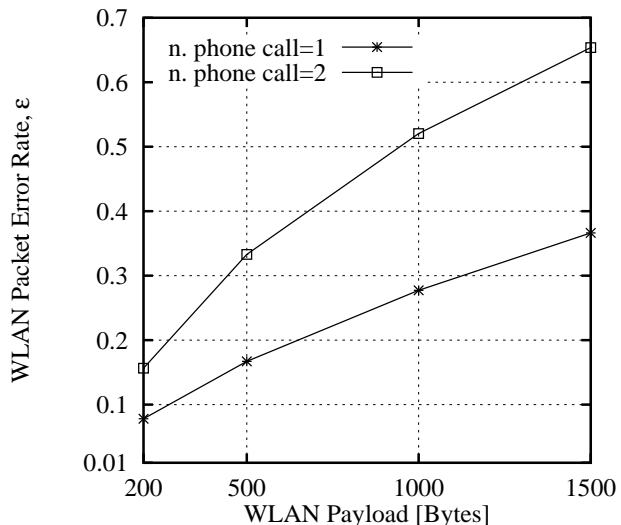


Fig. 5. Coexistence of a IEEE 802.11 WLAN and a BT voice link: Packet error probability of WLAN when one and two BT phone calls are active.

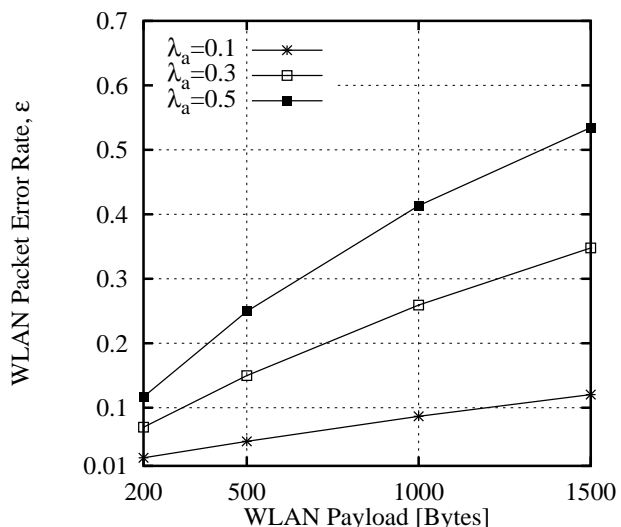


Fig. 6. Coexistence of a IEEE 802.11 WLAN and BT data traffic: Packet error probability of WLAN for different values of WLAN payload and BT traffic generation rate. No BT traffic shaping is implemented.

data stream of 1000 packets.

The results presented in Figs. 7 and 8 were obtained for different values of BT traffic rate λ_a and of burst size β . (A burst size equal to 0 corresponds to the case in which no shaping is used.) Looking at the plots, it can be seen that for $\lambda_a = 0.3$ and a burst size equal to 5, the packet error probability is 19% less than in the case in which no shaping is applied; whereas, the corresponding average delay introduced in the BT traffic is equal to 10 ms.

The results shown in Figs. 9 and 10 were obtained for $\lambda_a = 0.3$ and changing values of the burst size β . For a fixed value of β , curves were derived by varying the rate, denoted

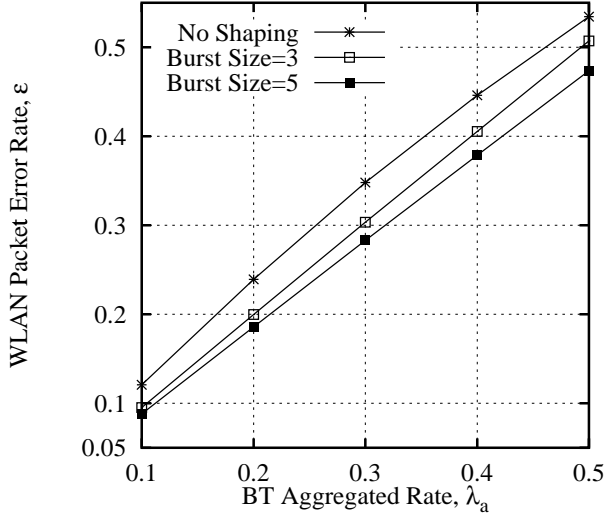


Fig. 7. Coexistence of a IEEE 802.11 WLAN and BT data traffic: Packet error probability of WLAN as the BT traffic generation rate, λ_a , varies. Shaping of BT traffic is implemented; results are shown for two different values of burst size and compared with the case when no shaping is adopted.

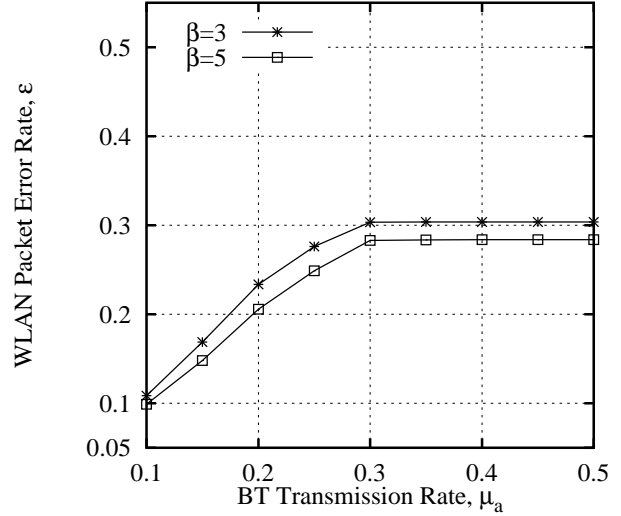


Fig. 9. Coexistence of a IEEE 802.11 WLAN and BT data traffic: Packet error probability of WLAN when the BT traffic generation rate, λ_a , is equal to 0.3 and the transmission rate over the BT channel varies.

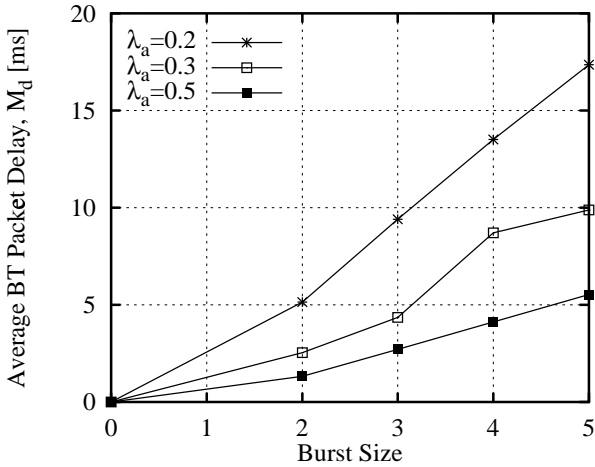


Fig. 8. Coexistence of a IEEE 802.11 WLAN and BT data traffic: Average delay of Bluetooth packets when traffic shaping is adopted as the BT traffic generation rate, λ_a , varies and for different values of burst size. Burst size equal to 0 corresponds to the case in which no shaping is implemented.

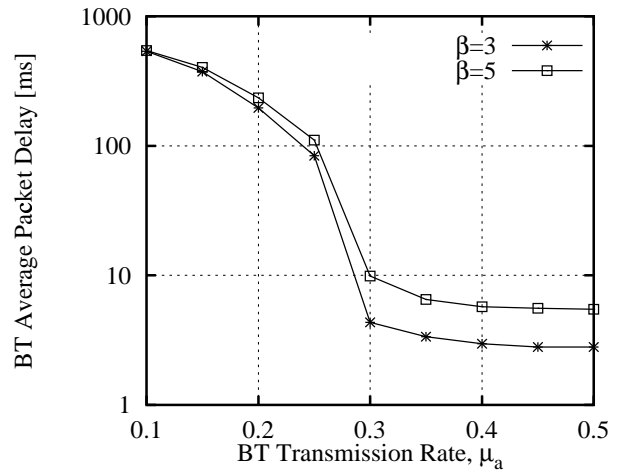


Fig. 10. Coexistence of a IEEE 802.11 WLAN and BT data traffic: Average delay of BT packets as the transmission rate over the BT channel and the burst size vary. The BT traffic generation rate, λ_a , is equal to 0.3.

by μ_a , at which traffic is transmitted over the BT channel. We notice that a great improvement is achieved in terms of WLAN packet error probability as values of μ_a smaller than the aggregated traffic generation rate, λ_a , are used; however, in this case the delay introduced in the BT packet transmission can be significant. With respect to the case in which shaping is not implemented, for $\mu_a = 0.25$ we obtain an improvement in terms of packet error probability equal to 20% for $\beta = 3$ and equal to 29% for $\beta = 5$; the correspondent average packet delay introduced in BT traffic is equal to 84 ms and 110 ms, respectively.

V. CONCLUSIONS

In this paper, we presented a flexible model for the computation of interference between IEEE 802.11 WLANs and Bluetooth systems. Both a voice and a data Bluetooth link were considered. Results showed that a high packet error probability may be experienced by a WLAN system when an interfering Bluetooth piconet is active.

We applied simple traffic shaping techniques to the Bluetooth data flow and a significant reduction of the WLAN packet error probability was obtained. In particular, by transmitting Bluetooth data traffic in a bursty manner, we can achieve a 19% improvement at the expense of an additional average delay in

Bluetooth traffic equal to 10 ms, or a 29% improvement at the expense of a Bluetooth average packet delay equal to 110 ms.

This suggests that by developing appropriate traffic control algorithms, interference among different radio systems operating in same environment and sharing same frequency band can be dramatically reduced. Clearly, control mechanisms defined at a high layer in the protocol stack have also the advantage to avoid modifications to the standard specifications of wireless systems.

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