Coexistence Mechanisms for Interference Mitigation between IEEE 802.11 WLANs and Bluetooth

Carla F. Chiasserini and Ramesh R. Rao

Abstract— **Different wireless systems sharing the same frequency band and operating in the same environment are likely to interfere with each other and experience a severe decrease in throughput. In this paper, we consider IEEE 802.11 WLANs and Bluetooth-based WPANs, which operate in the 2.4 GHz ISM bands. We propose two coexistence mechanisms based on traffic scheduling techniques, which mitigate interference between the two technologies. The proposed algorithms can be applied either when 802.11 and Bluetooth are able to exchange information as well as when they operate independently of one another. Results show that through the proposed coexistence mechanisms the interference between 802.11 and Bluetooth can be reduced and the throughput of the two systems is significantly improved at the expense of a small additional delay in the transfer of data traffic.**

I. Introduction

IN the next few years, pervasive deployment of smart wireless devices is expected. To make this vision a reality, devices must be able to share the same frequency band and move between different wireless systems without the need of any licensing procedure [1]. However, although the use of unlicensed bands facilitates spectrum sharing and allows for an open access to the wireless medium, it also raises serious challenges such as mutual interference between different radio systems and spectrum utilization inefficiency.

In this paper, we deal with the problem of mutual interference between two emerging wireless technologies: WLANs (Wireless Local Area Networks) and WPANs (Wireless Personal Area Networks). In particular, we consider IEEE 802.11 WLANs [2], [3] and short-range radio systems based on the Bluetooth (BT) specification [4], [5], or equivalently, IEEE 802.15 WPANs [6]. These systems will operate in the 2.4 GHz ISM (Industrial, Medical and Scientific) frequency bands, i.e., the unlicensed spectrum. BT uses a FHSS scheme, while IEEE 802.11 can either use a FHSS (Frequency Hopping Spread Spectrum) or a DSSS (Direct Sequence Spread Spectrum) technique. WLANs and WPANs are complementary rather than competing technologies, and many application models have been envisioned where it is necessary for Bluetooth and 802.11 to operate simultaneously and in close proximity [7]. In these conditions, interference between 802.11 and BT occurs whenever the interference energy is sufficient to cause a decrease of the signal to interference ratio at the receiver and the two systems transmissions overlap both in frequency and in time.

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According to the IEEE 802.15 Working Group, interference between 802.11 and BT causes a severe degradation of the systems' throughput when the distance between interfering devices is less than 2 m; a slightly less significant degradation is observed when the distance ranges between 2 and 4 m [8]. In order to mitigate such an effect, the IEEE 802.15 Working Group has created the Task Group 2 (TG2), which is devoted to the development of *coexistence mechanisms* [6], i.e., techniques that allow 802.11 and BT to operate in a shared environment without significantly impacting the performance of each other [9].

Two classes of coexistence mechanisms have been defined: collaborative and non-collaborative techniques [6]. With collaborative techniques it is possible for the BT network and the WLAN to exchange information to reduce the mutual interference; however, they can be implemented only when the BT and the 802.11 devices are collocated in the same terminal. With non-collaborative techniques there is no way to exchange information between the two systems and they operate independently. Examples of collaborative coexistence mechanisms are the scheduling scheme, so-called META (MAC Enhanced Temporal Algorithm) [10], and the TDMA (Time Division Multiple Access) scheme presented in [11]. META involves the use of a centralized controller, that monitors the BT and the 802.11 traffic and allows exchange of information between the two radio systems. The controller works at the MAC layer and allows precise timing of packet traffic, thus avoiding interference between the two collocated devices. A similar approach is used in [11], where a TDMA scheme is adopted to make transmissions of two collocated BT and 802.11 devices never overlap in time. This algorithm however can not be applied in the case of BT voice traffic, and both these schemes are unable to mitigate interference coming from non-collocated devices unless very restrictive assumptions are made on the network scenario [10], [11]. Also, since they totally orthogonalize transmissions of technologies that share the same radio spectrum, the systems' throughput will be significantly decreased as the number of wireless technologies operating in the unlicensed bands grows. An example of non-collaborative coexistence mechanism is the Adaptive Frequency Hopping technique [12], [13]. According to this scheme, frequency channels are classified as 'good' or 'bad' and hops are adaptively selected from the pool of 'good' channels. However, since the majority of current BT implementations perform the hop selection in hardware, this technique would imply a new release of BT devices.

In this paper, we propose two novel coexistence mechanisms, so-called OLA (OverLap Avoidance) schemes, which are based on simple traffic scheduling techniques. The first mechanism is to be performed at the IEEE 802.11 in the presence of a BT voice link, the second mechanism at the BT system in the case of a BT data link. The proposed algorithms have the following advantages: 1) they do not need a centralized traffic scheduler; 2) they can be implemented in collaborative or non-collaborative mode; 3) they are able to mitigate interference between collocated and non-collocated BT and IEEE 802.11 devices; 4) they have minor impact on the IEEE 802.11 standard and on the Bluetooth specification. Both the schemes are based on the assumption that 802.11 and BT can detect interference due to other technologies sharing the same environment. This assumption is trivially true in a collaborative setting, where information related to traffic transmissions can be directly exchanged between the interfering systems. In a non-collaborative setting, this information can be acquired through channel sensing and assessment of the received signal strength and of the packet loss rate. This is further discussed in Section III.

By applying the OLA mechanisms, in the case of a BT voice link we obtain an improvement of about 20% both in the 802.11 and the BT goodput, with an additional delay in the 802.11 data transfer of the order of tens of milliseconds. In the case of a BT data link, the goodput improvements are up to 50% for 802.11 and up to 24% for BT nodes, with a negligible increase in the BT data transfer delay.

The remainder of the paper is organized as follows. In Section II, we briefly describe the IEEE 802.11 and the BT technology, and introduce the model adopted to evaluate the mutual interference between the two network systems. Section III presents the proposed coexistence mechanisms; Section IV describes the considered simulation scenario. Results showing the obtained improvement in performance are presented in Section V. Finally, Section VI concludes the paper.

II. System Background

IEEE 802.11 WLANs cover a range of approximately 100 m and can operate at bit-rates as high as 11 Mb/s. We focus on systems that use the DSSS (Direct Sequence Spread Spectrum) scheme and consider their bandwidth to be roughly equal to 22 MHz [2], [14]. The fundamental building block of the network is the so-called Basic Service Set (BSS), which is composed of several wireless stations using the same spreading sequence and MAC function. Wireless stations can directly communicate with each other forming an ad-hoc network, or through a centralized access point, which also provides a connection to the wired network [2]. The two fundamental MAC schemes defined in the IEEE 802.11 standard are the DCF (Distributed Coordination Function) and the PCF (Point Coordination Function). The former is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol and allows for an asynchronous data transport; the latter is based on polling controlled by the access point and is able to support real-time traffic [3]. In this paper, only the DCF scheme is considered.

Bluetooth provides interconnection of devices in the user's vicinity; its typical use is in a range of roughly 10 m. 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 [4], [5]. Bluetooth can support up to three synchronous connection-oriented (SCO) links, for real-time services such as voice traffic, and asynchronous connection-less (ACL) links for non real-time applications, such as data traffic. The maximum throughput that can be provided is equal to 721 Kb/s. A FHSS scheme is used at the physical level with hop rate equal to 1600 hops/s; 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 channels being 1 MHz wide. The nominal hop dwell time is equal to 625 μs. A TDD technique is used to transmit and receive data in a piconet: each packet transmitted in a slot occupies 366 μs; slots are centrally allocated by the master and alternately used for master and slave transmissions. Master transmissions always begin at even slots (namely, in slots $2n$ with $n = 1, 2, \ldots$), slaves transmissions at odd slots (namely, in slots $2n + 1$ with $n = 1, 2, \ldots$). Fig. 1 shows the FH/TDD channel. The BT specification also allows for multi-slot data transmissions, i.e., for packets that occupy more than one slot (namely, three or five slots). In this case, packets are sent by using a single frequency hop, which is the hop corresponding to the slot at which the packet started.

In order to define mechanisms for the coexistence of IEEE 802.11 and BT devices operating in a common area, it is imperative to develop an appropriate model for their mutual interference.

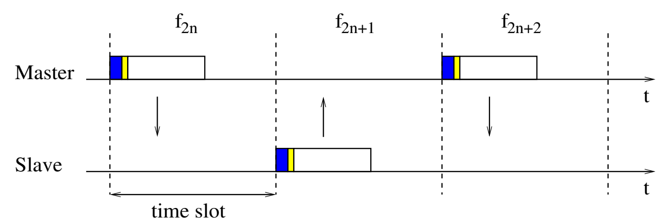

Fig. 1. The FH/TDD channel in Bluetooth.

A. Interference Model

Interference between IEEE 802.11 and BT arises whenever the interfering power from a BT (802.11) transmitter causes a significant decrease of the carrier to interference power margin at the 802.11 (BT) receiver [15], [16], [17], [18], [19]. By using the method presented in [17], [18], [19], the number of interfering devices and the associated carrier to interference power margin can be derived from the following system parameters: *(i)* distance between transmitters and receivers; *(ii)* average density of the transmitters in the considered spatial area; *(iii)* transmission power of the interfering systems; *(iv)* signal attenuation factor due to propagation.

In this work, we assume that the number of BT devices having sufficient power to cause interference to 802.11 is given, as well as the number of 802.11 stations that cause interference to BT. We compute the average number of symbols 'hit' because of a collision between 802.11 and BT as follows.

We denote the BT time slot by T_{BI}, the actual BT transmission time per slot by T_{BP}, and the 802.11 packet time duration

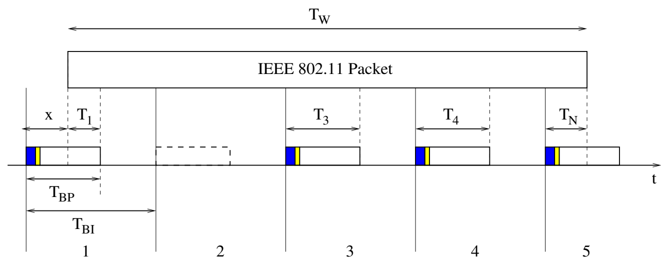

Fig. 2. Overlap between IEEE 802.11 and Bluetooth packets.

by T_W. Let x be the time period from the beginning of the first overlapping BT slot to the beginning of the 802.11 packet (x ranges in the time interval $(0, T_{BI})$). The number of BT slots that overlap in time the 802.11 packet depends on x and can be derived as [16]

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

Fig. 2 shows an example with $N(x)$=5 and packet length equal to one slot. Variables T_i $(i = 1, \ldots, N(x))$ indicate the portion of the $i-$th BT slot that actually interferes with the 802.11 packet. For the generic time slot i $(i = 1, \ldots, N(x))$, we have that if none BT transmission occurs in interval i, $T_i = 0$; otherwise [16]

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

Fixed the value of x, for $i = 1, \ldots, N(x)$ we define δ_i as the probability that BT traffic is transmitted in slot i.

By considering that the 802.11 stations use a DSSS scheme, the probability that BT and 802.11 overlap in frequency is equal to the probability that BT hops on the WLAN DSSS band. From the procedure used to generate the BT hopping sequences [5], it follows that the BT hopping on the WLAN band can be approximated by an i.i.d. process with parameter h_f. When no coexistence mechanism is applied, we can write [20]: $h_f = \frac{22}{79} = 0.278$, where 22 MHz and 79 MHz are the 802.11 and the BT bandwidth, respectively.

The average number of symbols 'hit' because of a collision between BT and 802.11 can therefore be written as

$$\eta_x = h_f \left(T_1^{(s)} \delta_1 + \sum_{i=2}^{N(x)-1} T_i^{(s)} \delta_i + T_{N(x)}^{(s)} \delta_{N(x)} \right), \quad (3)$$

where we denote by $T_i^{(s)}$ the ratio T_i/T_s $(i = 1, \ldots, N(x))$, with T_s being the symbol time duration. From (3), it is clear that in order to mitigate the mutual interference between BT and 802.11, we need to make either $N(x)$, h_f or δ_i $(i = 1, \ldots, N(x))$ small. A small $N(x)$ can be obtained by using short WLAN packets, which however increases the 802.11 transmission overhead. A small h_f requires reducing the probability that 802.11 and BT transmissions overlap *in frequency*. While, a small δ_i implies a low probability of overlap *in time* between the two systems' transmissions.

III. The OLA Coexistence Mechanisms

Based on the previous findings, we develop two coexistence algorithms, so-called OLA (OverLap Avoidance) mechanisms, which use simple traffic scheduling techniques at the MAC layer.

The first algorithm, denoted by V-OLA (Voice-OverLap Avoidance), is used in the case of BT voice links. This scheme avoids overlap in time between the BT voice traffic and the 802.11 data packets by performing a proper scheduling of the traffic transmissions at the WLAN stations. In a BT network, each SCO link occupies FH/TDD channel slots according to a deterministic pattern. Thus, a 802.11 station shall start transmitting when the BT channel is idle and adjust the length of the WLAN packet so that it fits between two successive BT transmissions. The second algorithm, denoted by D-OLA (Data-OverLap Avoidance), is suitable for BT data links. As described in Section II, the length of the BT packets can be equal to one, three or five time slots. In the case of multi-slot transmissions, packets are sent by using a single frequency hop, which is the hop corresponding to the slot at which the packet started. The key idea of the D-OLA algorithm, described in more detail below, is to use the variety of packet lengths that characterizes the BT system to avoid overlap in frequency between 802.11 and BT transmissions. Within each interfering piconet, the D-OLA algorithm induces the BT master device to schedule data packets with the proper duration (i.e., one, three or five slots) in order to skip the frequency locations of the hopping sequence that are expected to drop on the 802.11 band. The two proposed mechanisms are jointly applied when both voice and data links are active over the BT channel.

The proposed schemes are based on the assumption that both 802.11 and BT devices can detect interference due to other technologies sharing the same environment and using the same frequency band. This assumption is trivially true in a collaborative setting, where BT and 802.11 can directly exchange information related to their traffic transmissions. In a non-collaborative setting, this information can be acquired through channel sensing and assessment of the received signal strength and of the packet loss rate. This issue is further discussed below for each one of the proposed schemes.

A. The V-OLA Mechanism

In the case of BT voice traffic, slots are allocated according to a deterministic pattern; for instance, for each SCO connection using a HV3-type link [5], a single-slot packet is transmitted periodically in both directions every six time slots. Whenever a BT packet hops in the 802.11 frequency band, a 802.11 station in receive mode[1] senses the BT transmission as colored noise, i.e., as a signal with a specific behavior in time and in frequency. In a non-collaborative setting, a 802.11 station can detect the time intervals that are occupied by interfering transmissions, by monitoring the channel. If SCO and ACL links are

[1] 802.11 and BT are half-duplex systems (i.e., devices can not simultaneously transmit and receive).

simultaneously active on the BT channel, the D-OLA scheme is also applied and, as explained later, the probability that an ACL packet hops on the 802.11 band becomes negligible. This implies that a 802.11 station is likely to detect interference due to the BT voice traffic only. Due to the periodicity and the predefined time duration of the BT voice packets, the 802.11 device can easily estimate the interference pattern.

Whenever a 802.11 station is ready to transmit, it acts accordingly to the information acquired on the interference pattern. If the channel is idle and no interference is expected for a time period equal to the next $(i-1)$ BT slot duration, the 802.11 station transmits a data packet with payload size equal to the minimum of $(i \cdot 500)$ bytes and 1500 bytes. The minimum payload has been set to 500 bytes to make the corresponding 802.11 packet transmission time comparable to the duration of a single-slot BT packet. Conversely, if the channel is occupied by an interfering signal, the WLAN station can either *(i)* send a packet with a 500 bytes payload (Shortened Transmission (ST) mode) or *(ii)* refrain from transmitting (Postponed Transmission (PT) mode).

With the ST mode, the 802.11 transmission does not necessarily overlap in time with the BT packets because a 1-slot BT packet lasts just slightly longer than half the duration of one time slot. Besides, even in the case of time overlap, 802.11 and BT packets collide only if BT packets hop on the WLAN frequency band.

When a WLAN station refrains from transmitting, i.e., it acts in PT mode, the 802.11 transmission is postponed by computing a new backoff time. In this case, two opposite effects take place: on the one hand a lower overlap probability is achieved than in the case where a short packet is transmitted; on the other hand the WLAN stations' access delay increases and the WLAN channel utilization decreases with respect to the case where the ST mode is applied.

B. The D-OLA Mechanism.

We consider a BT data link and assume that the BT master devices are aware of which frequency channels are occupied by the interfering 802.11 stations. Since a 802.11 system does not typically moves from its 22 MHz frequency band, in a non-collaborative setting, a BT device can identify the frequency channels that are occupied by the WLAN by using any of the following methods [13]. *(i)* The BT device gradually acquires which channels are occupied based on the observed packet loss. *(ii)* The BT device assesses the received signal strength (RSSI) across the radio environment before it starts operating. *(iii)* The BT device transmits "test" packets across the frequency spectrum, observes the packet loss rate over the channels and discovers the band used by an interfering system.

Let us focus on the FH/TDD channel of one BT piconet. Recall that a master transmission always begins in even slots, while slaves can start transmitting in odd slots only. For the sake of simplicity, we assume that default data packets are 1-slot long. Let us denote by f_m the frequency location of the hopping sequence at the generic time slot m and let the current time slot be equal to $2n$.

Consider first that following f_{2n}, f_{2n+1} hops on the 802.11 band. Notice that f_{2n} and f_{2n+1} shall correspond to a master and a slave transmission, respectively. According to the D-OLA algorithm, if enough data are buffered at the master for the intended slave, the master schedules a multi-slot packet instead of a single-slot packet. In this way, frequency hop f_{2n+1} is skipped; for instance, if a 3-slot packet is sent, the next slave transmission will use f_{2n+3}. If not enough data are available, the master acts by default and sends a single-slot packet.

Next, assume that among the frequency locations following f_{2n}, f_{2n+2} hops on the 802.11 band. Notice that frequency location f_{2n+2} corresponds to a master transmission. In this case, at time slot $2n$ the master asks the slave, that will transmit in the next slot, to send a multi-slot packet so that f_{2n+2} is skipped. If the slave has enough data to send, let us say, a 3-slot packet, the slave transmission extends from slot $2n+1$ to slot $2n+3$ by using frequency f_{2n+1} only. The next slot allocated for the master transmission will therefore hop on frequency location f_{2n+4}. A similar mechanism is applied when default data transmissions use 3-slot or 5-slot packets.

The scheduling algorithm could also let the master (slave) refrain from transmitting in the time slot corresponding to a frequency that hops on the 802.11 band whenever there are not enough data in the buffer at the master (slave) to send a multi-slot packet. In this case, the collision probability is further reduced but the BT throughput decreases as well.

C. Remarks

The OLA schemes do not require a centralized controller since they do not perform a precise time scheduling of the 802.11 and BT packet traffic. They can either operate as collaborative or non-collaborative coexistence mechanisms and, hence, are able to reduce interference both in the case of collocated and non-collocated devices. If interfering systems other than BT and 802.11 are present, the beneficial effects of the OLA mechanisms still hold as long as 802.11 can estimate the interference pattern with sufficient accuracy.

The proposed algorithms have minor impact on the 802.11 standard and on the BT specification. According to the 802.11 standard, a station shall defer its transmission if it detects a busy channel during the Clear Channel Assessment (CCA) procedure. There are three different CCA modes [3]: *(i)* a busy channel is reported upon detection of any energy above a certain threshold; *(ii)* a busy channel is reported only upon detection of a DSSS signal, which can be either above or below the energy threshold; *(iii)* a busy channel is reported upon a DSSS signal with energy above the threshold. Thus, in the V-OLA mechanism, both the PT and the ST modes are compliant with the 802.11 standard, and can be implemented by using the appropriate CCA mode.

The current Bluetooth specification involves that BT devices dynamically adapt their hopping sequence to the interference conditions, by scheduling ACL packets with different length. Thus, the D-OLA scheme exploits a behavior of the BT devices already existing in the specification, and we do not need to change the procedure of hop selection that is performed in the hardware. In a BT piconet, however, the master can only indicate to the slaves the maximum number of slots to use; while, according to the D-OLA mechanism, a slave should interpret the indication from the master as the suggested packet length.

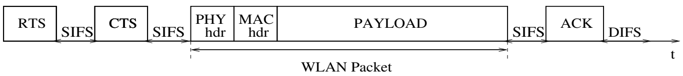

Fig. 3. Timing of a successful IEEE 802.11 packet transmission.

IV. Simulation Scenario

We consider an IEEE 802.11 ad-hoc network providing an instantaneous rate equal to 11 Mb/s and using the DCF MAC scheme. The number of active stations is assumed to be equal to 10. All the stations operate as a self-contained BSS and are able to directly communicate with each other; all stations are assumed to be asynchronous data users with a finite transmission buffer. The arrival of frames from a station's higher layer protocol to the MAC sublayer is modeled with exponential inter-arrival times and a truncated geometric distribution for the frame lengths [22]. The mean value of the truncated geometric distribution is set to 1500 bytes, while the maximum frame length is set to the maximum length of the MAC Service Data Unit (MSDU) established by the IEEE 802.11 standard (i.e., 2304 bytes). The parameter of the exponential distribution is fixed in such a way that the average 802.11 traffic load normalized to the channel capacity is equal to λ_w, a varying parameter in the simulations.

In order to reduce the complexity of the simulation model, the following further assumptions have been introduced: *(i)* possible values for the WLAN packet length, if not otherwise specified in the following, have been limited to 500, 1000 and 1500 bytes; *(ii)* the RTS/CTS mechanism is considered always active; *(iii)* no interference is considered from nearby BSSs using the same DSSS spreading sequence; *(iv)* propagation delay is neglected, which is a reasonable assumption due to the small distance between stations; *(v)* a two-state Markov model is used to represent the bit error process due to the effect of fading; in state *good* the bit error rate is equal to 10^{-10}, in state *bad* is equal to 10^{-5} [22]; the transition probability from *good* to *bad* is equal to 0.01, from *bad* to *good* is equal to 0.1.

A 802.11 transmission is considered to be successful if no collision occurs on the RTS frame and both the data packet and the corresponding acknowledgment sent by the receiver are correctly received. Fig. 3 shows the 802.11 traffic timing in the case of successful packet transmission. If a packet is not correctly received, retransmission will take place according to the backoff procedure defined by the IEEE 802.11 standard. The number of retransmissions before the packet is discarded from the station buffer is limited and set to the Long_Retry_Limit. The values of the IEEE 802.11 parameters used in the simulation model are listed in Tab. I.

For the Bluetooth system, we consider a single piconet where devices are polled by the master on the basis of a round-robin scheme. Each device has a finite transmission buffer; assumption *(iv)*, introduced above for the IEEE 802.11 simulation model, holds also for the BT network. The packet error process over the wireless channel is assumed to be Bernoulli, and the average packet error probability is set to 10^{-3}. We assume that BT voice traffic is transmitted by using a HV3-type link, which is expected to be the most popular link type for SCO services [8]. With the HV3-type link for each active connection a packet is transmitted in both directions every six time slots. In the case of data traffic, a DH1-type link is assumed to be the default operating mode, and therefore single-slot data packets are used. When the D-OLA scheme is applied, we consider that 1-slot and 3-slot packets are used; in the case of 3-slot packets, a DH-3 type link is adopted. Notice that in the HV3-, DH1- and DH3-type link, information in the payload is not FEC encoded [5]. The values of the Bluetooth system parameters are reported in Tab. II.

TABLE I
Parameters used in the simulation of the IEEE 802.11 system.

Parameter	Assigned Value
Long_Retry_Limit	10
Physical Header	144 bits
MAC Header	272 bits
Slot_Time	20 μs
SIFS	10 μs
DIFS	50 μs

TABLE II
Parameters of the Bluetooth system.

Parameter	Value
T_{BI}	625 μs
T_{BP} (1-slot packet)	366 μs
T_{BP} (m-slot packet)	625 μs in slot $i \leq m-1$ 366 μs in slot $i = m$

The arrival of data to a BT device's MAC sublayer is modeled with exponential inter-arrival times and a truncated geometric distribution for the data unit length. The mean value of the truncated geometric distribution is set to 1500 bytes, while the maximum data unit length is set to 2800 bytes, which corresponds to the the total information carried by 100 DH1 packets. The parameter of the exponential distribution is determined in such a way that the average Bluetooth traffic load normalized to the channel capacity is equal to λ_b, a varying parameter in the simulations. Packets that are not correctly received are retransmitted according to the fast-ARQ scheme [4], where the sender is notified of the transmission outcome in the first possible slot following the packet transmission.

We model the mutual interference between 802.11 and BT as described in Section II-A, and assume a non-collaborative setting.

V. Performance Results

Results showing the performance of the OLA mechanisms are derived by using the simulation scenario described in the previous section. While presenting the performance of the V-OLA scheme, we essentially consider a 802.11 BSS interfering with one BT piconet only. This assumption is motivated by the

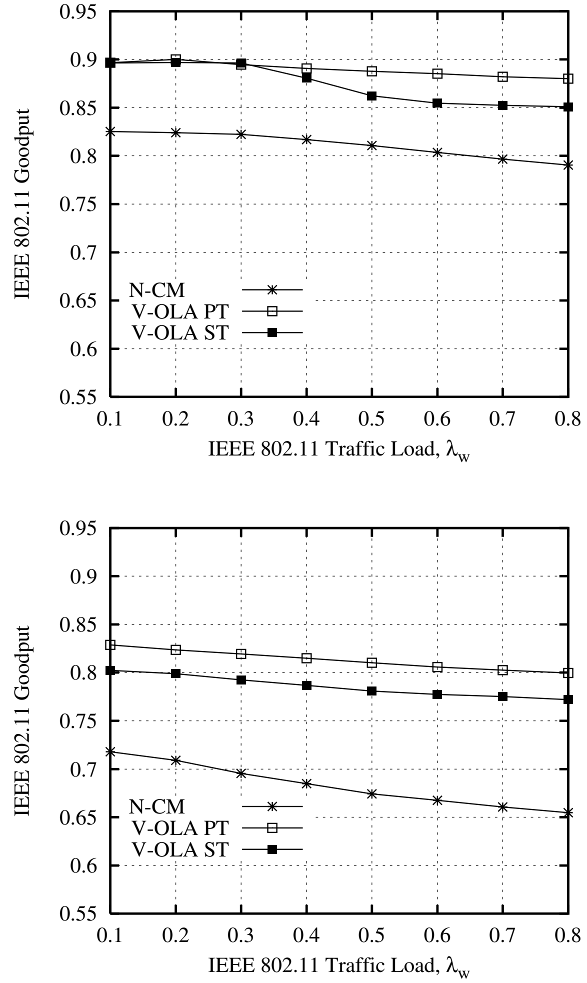

Fig. 4. IEEE 802.11 goodput when BT supports one SCO link (upper plot) and two SCO links (lower plot). Performance obtained through the V-OLA scheme and when no coexistence mechanism is applied (N-CM) are compared.

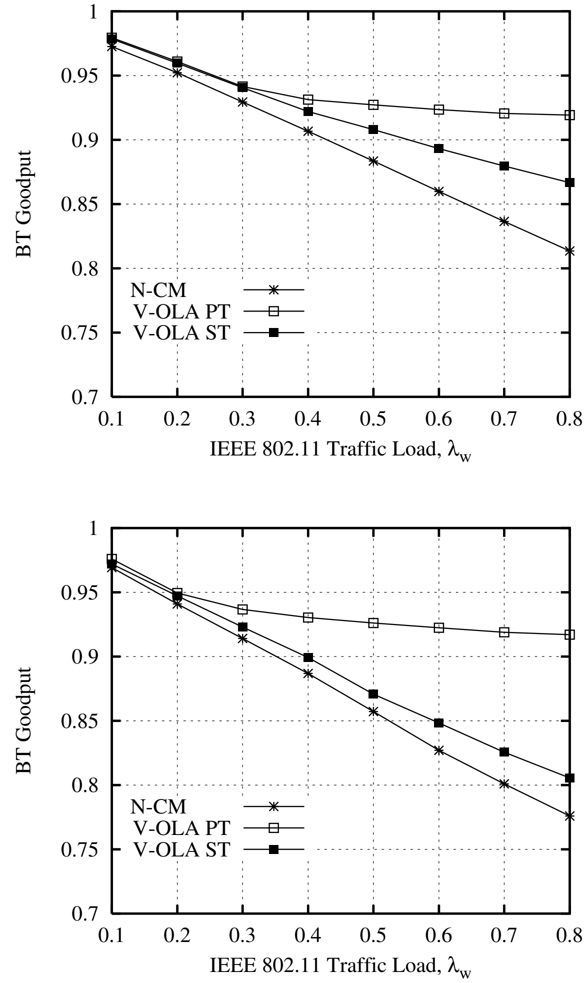

Fig. 5. BT goodput versus the IEEE 802.11 traffic load when BT supports one SCO link (upper plot) and two SCO links (lower plot). Performance obtained through the V-OLA scheme and when no coexistence mechanism is applied (N-CM) are compared.

fact that only BT devices, whose distance from the 802.11 receiver is less than 2 m, cause a severe degradation of the 802.11 throughput.

Fig. 4 presents the 802.11 goodput as a function of the 802.11 traffic load in the case where the BT channel supports one SCO link (upper plot) and two SCO links (lower plot). Performance of the V-OLA scheme in Postponed Transmission mode and in Shortened Transmission mode are compared with the results obtained in the absence of any coexistence mechanism (indicated in the figure by label N-CM). Goodput is defined as the fraction of transmitted information that is successfully transferred over the radio channel. As expected, the behavior of the 802.11 goodput slightly varies as the WLAN traffic load increases; while, by comparing the two plots in Fig. 4, we observe a significant reduction in the 802.11 goodput when we pass from one to two SCO links. However, in the case of one SCO link, by applying the V-OLA PT scheme we obtain an improvement of 10% with respect to the case where no coexistence mechanism is implemented; in the case of two SCO links the improvement is equal to 23%. When the V-OLA ST scheme is used, slightly worse performance than in the case of the V-OLA PT scheme is achieved. In fact, in ST mode the 802.11 stations do not stop transmitting during the BT busy slots and, thus, the probability to overlap BT voice packets is higher.

Fig. 5 shows the BT goodput as a function of the 802.11 traffic load for the two V-OLA schemes and in the absence of any coexistence mechanism. The upper and the lower plots refer to the case where BT supports one and two SCO links, respectively. Clearly, as λ_w grows, the BT goodput decreases due to the greater interference level. The improvement achieved by using the V-OLA PT scheme can be up to 15% in the case of one BT voice call and up to 20% in the case of two SCO links. In these plots, the gap between the performance obtained through the PT mode and the ST mode is much greater than in Fig. 4, due to the interference caused by unsuccessful RTS and CTS frames. This effect becomes more evident as the 802.11 traffic load grows and the number of BT idle slots decreases, i.e., the collision probability between WLAN stations increases.

Fig. 6 presents the behavior of the 802.11 average packet delay, with the packet delay being the period from the time instant at which a packet is generated to the time instant at which the packet is successfully transmitted. Results are presented

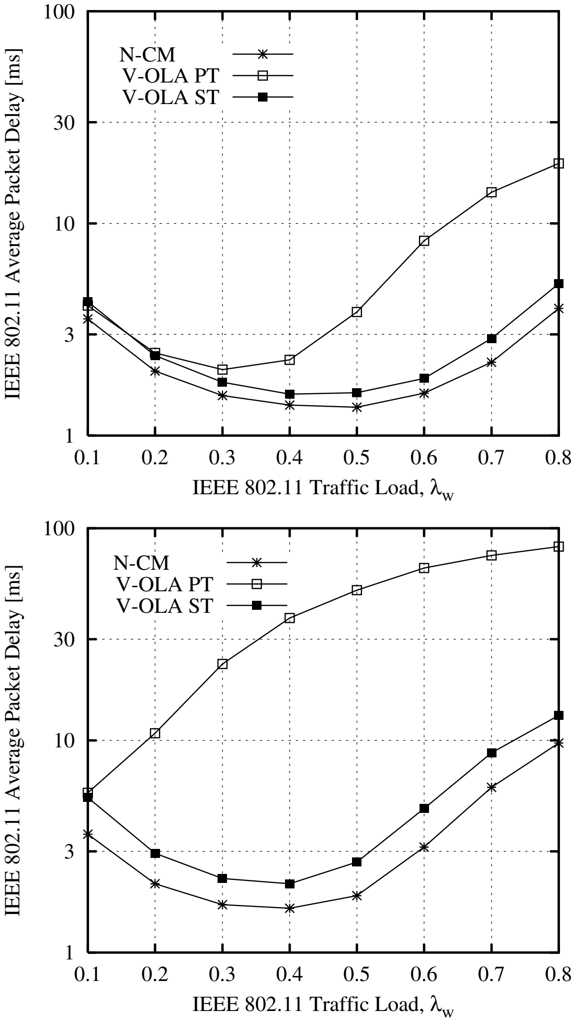

Fig. 6. IEEE 802.11 average packet delay versus traffic load λ_w in the presence of one SCO link (upper plot) and two SCO links (lower plot). Performance obtained through the V-OLA scheme and in the case where no coexistence mechanism is applied (N-CM) are compared.

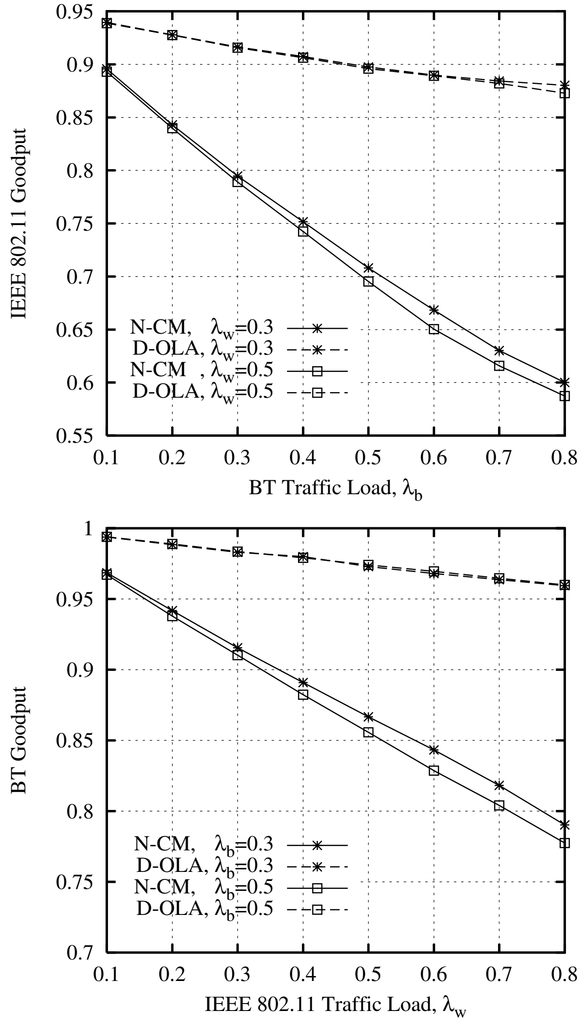

Fig. 7. Goodput of the IEEE 802.11 and the BT systems in the presence of BT data links. Performance obtained through the D-OLA scheme and when no coexistence mechanism is applied (N-CM) are compared.

as functions of the 802.11 traffic load for the PT and the ST schemes, and in the absence of any coexistence mechanism. For very low values of λ_w, the major delay contribution is due to the assumption that 802.11 packets must have a minimum payload equal to 500 bytes. For high traffic load, delay is mainly due to collisions between WLAN stations and, in the case of the PT mode, to the lack of BT idle slots. The delay obtained in the case of the ST mode is slightly greater than the delay experienced when none scheme is applied and remains low even when two SCO links are considered. When the PT mode is applied, a low delay is obtained only for one SCO link and λ_w less than 0.6. When two SCO links are supported and the number of BT idle slots decreases, for almost any value of λ_w the PT mode gives a delay one order of magnitude higher than in the case of the ST mode.

Figs. 7–9 compare the performance of the D-OLA scheme with the performance obtained in the absence of any coexistence mechanism. Results shown in Figs. 7 and 8 were derived by setting the payload of the 802.11 packets to be equal to 1500 bytes. The upper plot in Fig. 7 presents the 802.11 goodput as a function of the BT traffic load for $\lambda_w = 0.3$ and 0.5. In the case of the D-OLA scheme, the 802.11 goodput remains almost constant as the BT traffic load increases; while, when none scheme is implemented, a significant degradation is observed. The improvement in performance achieved through the proposed coexistence algorithm is as high as 50% for BT traffic load equal to 0.8. As expected, results slightly change as the 802.11 traffic load varies.

Similar considerations hold for the results presented in the lower plot in Fig. 7, where the BT goodput is shown as a function of λ_w and for different values of the BT traffic load. In this case, the improvement in performance obtained through the D-OLA scheme is equal to 24% for $\lambda_w = 0.8$.

Fig. 8 shows the BT average packet delay versus the BT traffic load, for $\lambda_w = 0.3$ and 0.5. For $\lambda_w = 0.5$, the delay experienced when the D-OLA algorithm is applied is slightly higher than the delay achieved in the absence of any coexistence mechanism; for $\lambda_w = 0.3$, the two curves overlap. This shows that the D-OLA scheme greatly mitigates the mutual interference between 802.11 and BT without causing a reduction in the BT throughput.

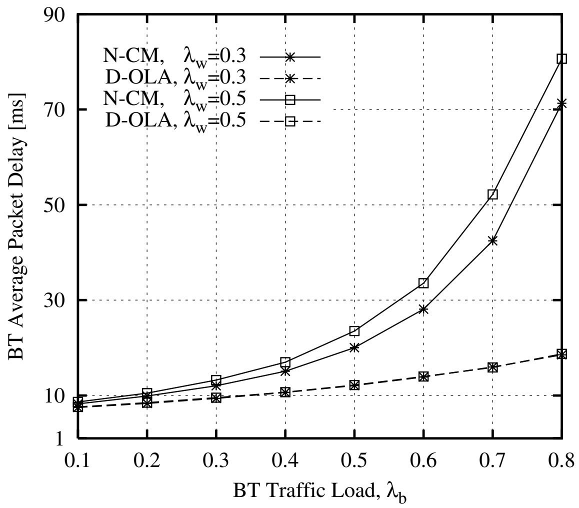

Fig. 8. BT average packet delay versus BT traffic load in the presence of BT data links. Performance obtained through the D-OLA scheme and when no coexistence mechanism is applied (N-CM) are compared for different values of the IEEE 802.11 traffic load.

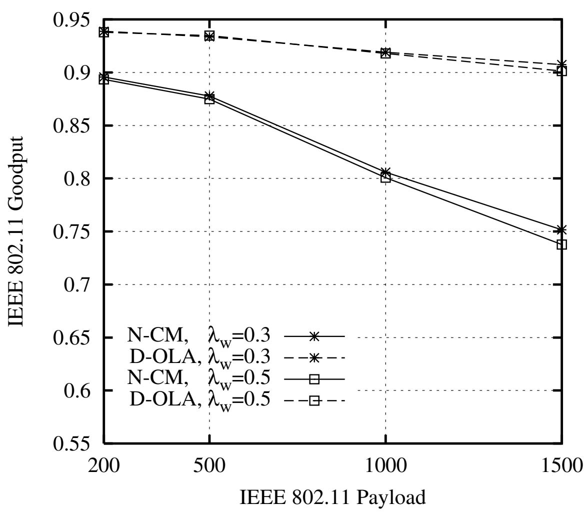

Fig. 9. IEEE 802.11 goodput versus the packet payload in the presence of BT data links and BT traffic load equal to 0.4. Performance obtained through the D-OLA scheme and when no coexistence mechanism is applied (N-CM) are compared for different values of the IEEE 802.11 traffic load.

Fig. 9 presents the 802.11 goodput as the payload of the 802.11 packet varies, for $\lambda_w = 0.3$ and 0.5. Results were derived from simulations where the 802.11 payload was fixed to a constant value. The plot confirms the improvement achieved through the D-OLA algorithm. As expected, when no coexistence mechanism is used, lower values of WLAN payload give higher 802.11 goodput since the packet error probability decreases. While, it is interesting to notice that in the case of the D-OLA scheme the WLAN payload has a negligible impact on the performance.

VI. Conclusions and Future Work

In this paper, the problem of mutual interference between different wireless technologies operating in the 2.4 GH ISM bands was addressed. We considered IEEE 802.11 WLANs and Bluetooth-based WPANs. Two different coexistence mechanisms based on traffic scheduling techniques were proposed: the former (named V-OLA scheme) to be applied at the WLAN stations to avoid overlap between 802.11 traffic and Bluetooth voice packets; the latter (named D-OLA scheme) to be executed at the Bluetooth devices to avoid overlap in frequency between 802.11 traffic and Bluetooth data packets.

The main advantages of the proposed mechanisms are the following: 1) they do not require a centralized traffic scheduler; 2) they can be implemented either when 802.11 and Bluetooth are able to exchange information (collaborative coexistence mechanism) or when they acquire this information by detecting interfering transmissions over the radio channel (non-collaborative coexistence mechanism); 3) they are able to mitigate interference between collocated and non-collocated Bluetooth and 802.11 devices; 4) they have minor impact on the IEEE 802.11 standard and the Bluetooth specification.

Results showing significant reduction in interference between 802.11 and Bluetooth obtained through the proposed mechanisms were presented. In the case of two Bluetooth voice connections, an improvement of about 20% both in the 802.11 and the Bluetooth goodput was achieved, while the additional delay introduced in the 802.11 data transfer was of the order of tens of milliseconds. In the case of Bluetooth data traffic, the 802.11 goodput increased by 50% for high Bluetooth traffic load; whereas, for high 802.11 traffic load, the Bluetooth goodput improved of 24% without showing a significant increase in the data transfer delay.

The capability of the proposed mechanisms to cope with interference caused by microwave ovens is under investigation. Other aspects that need to be addressed in future research are as follows.

1. Exploring the possibility to enhance the physical layer of unlicensed devices so that their ability to detect interference generated by other technologies is improved.
2. Performance evaluation of the proposed techniques when different Bluetooth packet types are used and when, in the case of the V-OLA mechanism, the minimum 802.11 payload is larger than 500 bytes.
3. Coexistence between Bluetooth and 802.11 systems that implement the PCF MAC scheme.
4. Performance study of the proposed techniques through experimental measurements.
5. Impact of the D-OLA mechanism on the interference between coexisting Bluetooth piconets.

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