Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2010, Article ID 473534, 11 pages
doi:10.1155/2010/473534

Research Article

Coexistence Mechanism for Colocated HDR/LDR WPANs Air Interfaces

Marco Monti,[1] Mauro De Sanctis,[1] Ernestina Cianca,[1] Marina Ruggieri,[1] and Ramjee Prasad[2]

[1] *Department of Electronic Engineering, University of Rome "Tor Vergata", Rome, Italy*
[2] *Center for TeleInfrastruktur, Aalborg University, Aalborg, Denmark*

Correspondence should be addressed to Marco Monti, marco.monti@uniroma2.it

Received 2 December 2009; Revised 5 August 2010; Accepted 22 September 2010

Academic Editor: Geert Leus

This paper addresses the issues of interference management among Low Data Rate (LDR) and High Data Rate (HDR) WPAN air interfaces that are located in close-proximity (up to 10 cm) and eventually on the same multimode device. After showing the noticeable performance degradation in terms of Bit Error Rate (BER) and goodput due to the out-of-band interference of an HDR air interface over an LDR air interface, the paper presents a novel coexistence mechanism, named Alternating Wireless Activity (AWA), which is shown to greatly improve the performance in terms of goodput of the most interference vulnerable air interface (i.e., the LDR air interface). The main difference of the proposed mechanism with respect to other collaborative mechanisms based on time-scheduling is that it synchronizes the transmission of the LDR and HDR WPANs at the superframe level instead of packet level. Advantages and limitations of this choice are presented in the paper. Furthermore the functionalities of the AWA mechanism are positioned in a common protocol layer over the Medium Access Control (MAC) sublayers of the HDR and LDR devices and it can be used with any standard whose MAC is based on a superframe structure.

1. Introduction

An increasing number of transceivers are needed to fulfill the communications need of the modern user, who wants to use a growing variety of applications anytime and anywhere. In most cases, these newly deployed transceivers operates in the same radio band and use antennas that are in close proximity to other transceivers. Sometimes those transceivers are located in the same wireless device.

These situations, where multiple air interfaces are positioned in the same multimode device, are referred to as colocated air interfaces. Colocated air interfaces create an increased level of system interference which can affect data transfer significantly by reducing goodput. This paper addresses the issue of the interference management among Low Data Rate (LDR, few kbps) and High Data Rate (HDR, hundreds of Mbps) WPAN air interfaces that are in close-proximity (colocated at a maximum distance of 10 cm) [1]. Recently, the issue of interference evaluation and management between Ultra Wideband (UWB) and narrowband systems has received a wide interest. An overview of coexistence issues between UWB and narrowband wireless communication systems is provided in [2]. The authors of [3] propose an analytical framework for coexistence in networks composed of both narrowband and UWB wireless nodes, based on fundamental tools from stochastic geometry. In [4] the bit error probability is analyzed for the case of a single UWB pulse interfering with a binary phase shift keying narrowband system, in an AWGN channel. Furthermore, many works can be found on the analysis of interference and on interference avoidance mechanisms for uncoordinated wireless devices that transmit over the same unlicensed bands [5, 6]. However, most of these works focus on the coexistence of short range wireless networks (i.e., Bluetooth, 802.15.1 and 802.15.4) and Wireless Local Area Networks (i.e., IEEE 802.11) [7].

No works can be found on the specific issue of interference between LDR WPAN and HDR WPAN colocated air interfaces, which is the focus of this paper.

In particular, the following two standards are considered: the European Standard, ECMA-368 [8], for low-power and multimedia capable HDR WPANs based on UWB, and the

IEEE 802.15.4 standard for LDR WPANs [9] based on spread spectrum communications. It is worth noting that while the IEEE 802.15.3a standard based on UWB for HDR WPANs [10] has been disbanded, the ECMA-368 is fully operational through the WiMedia Alliance. On the other hand, the IEEE 802.15.4 standard is operational through the ZigBee alliance. ECMA-368 and IEEE 802.15.4 are currently the most important and advanced standards for LDR and HDR WPANs.

As shown in this paper, when the distance between the LDR and HDR WPAN air interfaces is less than 10 cm, the LDR air interface experiences a noticeable performance degradation and it is completely unable to establish a reliable link when the distance becomes less than 5 cm. Therefore, a coexistence mechanism becomes of utmost importance to reduce the vulnerability of the LDR air interface with respect to the interference of the HDR air interface. In particular, after presenting a simulation analysis of the interference between ECMA-368 and IEEE 802.15.4, this paper proposes a novel collaborative coexistence mechanism between these two standards, named Alternating Wireless Activity (AWA). The AWA algorithm is based on the time-scheduling principle: the algorithm controls and synchronizes the access to the network of the devices associated to the LDR and HDR WPANs. The two interfering networks exchange information about the structure of the their superframe and no modification to the standards is required. As for any collaborative mechanism, their implementation is more straightforward if the two air interfaces are colocated in the same multimode device [7, 11].

With respect to the others collaborative time-scheduling coexistence mechanisms that can be found in literature [7], the AWA algorithm synchronizes the transmission of the LDR and HDR WPANs at the superframe level instead of alternating the transmission at packet level. The consequences of this feature are: the computation rate of the scheduler is reduced with respect to the per-packet scheduling mechanisms; the coexistence is guaranteed for all LDR and HDR nodes of the networks instead of a single pair of nodes.

The proposed mechanism allows to manage a trade-off between the improvement in the fairness of the system (also the most interference vulnerable air interface can work) and the reduction of the goodput of the less interference vulnerable air interface. In particular, the LDR air interface can increase its goodput to acceptable values with a variable reduction of the HDR duty cycle (from 6.25% to 50%). Finally, an improved version of this mechanism (IAWA) has been proposed, which allows a more flexible distribution of the fairness among the two air interfaces. With the IAWA, it is possible to decide more flexibly the proper distribution of transmission time between the two air interfaces and hence, decide what is the best trade-off between goodput of an air interface and fairness of the system.

It is worth outlining that the functionalities of the AWA mechanism are positioned in a common protocol layer over the LDR and HDR MAC sublayers, and, hence it can be used with every physical (PHY) layer. The AWA mechanism is presented together with its advantages and drawbacks.

The paper is organized as follows. Section 2 presents the application scenario and the interference scenario. Moreover, the PHY and MAC specification of ECMA-368 and IEEE 802.15.4 standards involved in the scenario are presented. Section 3 presents the interference analysis between the two radio technologies. In Section 4, after a brief overview on interference management mechanisms, the AWA coexistence mechanism and its improved version are presented. The performance in terms of goodput for both the LDR and HDR device, with and without AWA are also discussed. Conclusions are drawn in Section 5.

2. Application Scenario

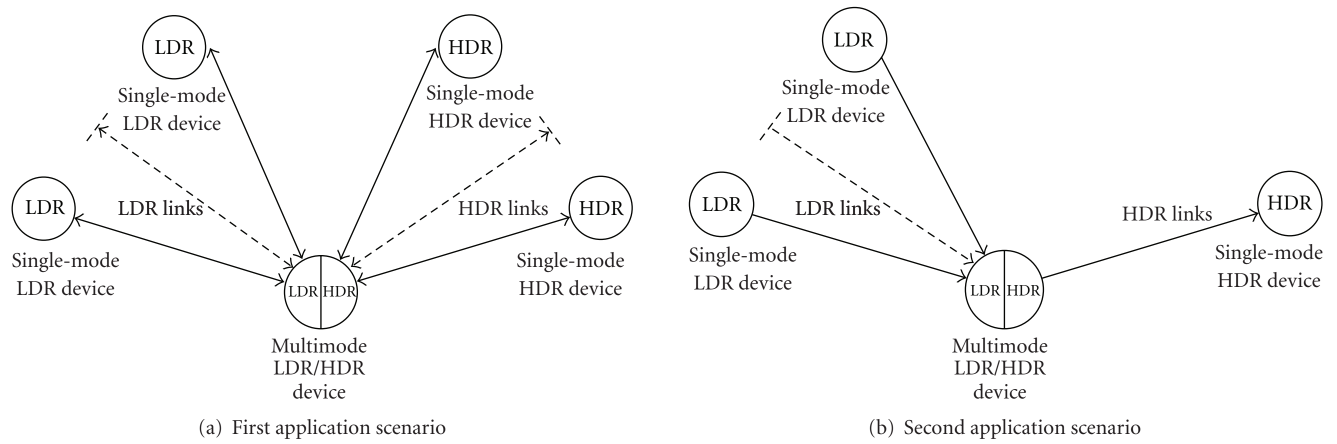
Simultaneous exploitation of different air interfaces does not necessarily mean that they simultaneously transmit and/or receive, but it means that both interfaces are powered on, have established a connection and have data to transmit or receive. The simultaneous exploitation of two air interfaces within one multimode device can be dictated by user needs. An example of multimode device is a notebook provided with a multimode LDR/HDR WPAN air interface. The first multimode application scenario include both LDR and HDR applications running on the same multimode device. In this scenario the multimode user device is connected via LDR links to single mode LDR devices (e.g., a mouse, a headphone, etc.) and via HDR links to single mode HDR devices (e.g., a printer, a mobile game player or a file repository). In this case the data flow of one single connection is independent from each other (see Figure 1(a)). The second example of application scenario includes a multimode device (i.e., translational bridge) capable of forwarding data received from a LDR connection to a HDR connection. In this case the data that flow through the HDR connection depends on the data that flow through the LDR connections (see Figure 1(b)).

In these application scenarios, the LDR WPAN transceiver and the HDR WPAN transceiver are located very close in the same multimode device, up to 10 cm of distance. In this paper we refer to this specific situation as colocated air interfaces, while usually this term has a more broad meaning which includes any air interface that is within the radio range of another air interface.

Because of the very short distance between the different transceivers colocated in a multimode device, the interference effects are very severe and specific analysis and management are needed.

2.1. Interference Scenario.

Additive interference is generated by an undesired signal which is added to the desired signal and it includes: cochannel interference and adjacent channel interference. Cochannel interference occurs when the interfering signal has the same carrier frequency of the useful information signal. Adjacent channel interference can be further categorized into in-band interference and out-of-band interference: in-band interference occurs when the center of the interfering signal bandwidth falls within the bandwidth of the desired signal; out-of-band interference



(a) First application scenario

(b) Second application scenario

Figure 1: Examples of application scenarios for multimode LDR/HDR WPAN devices.

occurs when the center of the interfering signal bandwidth falls outside the bandwidth of the desired signal. The latter type of interference can be experienced when transmitters and receivers operate close together in terms of the two main variables that determine their degree of isolation from each other: distance and frequency separation.

In order to show the effect of interference and the specific application of the coexistence algorithm we refer to two particular standards for LDR and HDR WPAN that are described in the following subsections.

2.2. ECMA-368 WPANs. The ECMA-368 standard is designed for high data rate, low-power and multimedia capable WPANs defining both the PHY (see Table 1) and MAC layers [8].

The ECMA MAC sublayer exploits a synchronized and totally distributed approach. A distributed beaconing scheme is used for time synchronization, network topology control and channel access coordination. There are no devices that act as central coordinator. Two medium access methods are foreseen:

(i) the reservation-based Distributed Reservation Protocol (DRP),

(ii) the contention-based Prioritized Channel Access (PCA).

The channel time resource is organized into superframes with a length that can reach a maximum of 65,536 μs. The superframe is divided in slots called Medium Access Slots (MASs) and in a superframe, a maximum of 256 MASs are accepted.

Each superframe starts with a Beacon Period (BP) which is the period of time declared by a device during which it sends or listens for beacons; BP extends over one or more contiguous MASs. Coordination of devices within radio range is achieved by the exchange of beacon frames. Periodic beacon transmission enables device discovery, supports dynamic network organization, and provides the basic timing for the network, carrying reservation and scheduling information for accessing the medium. The start of the first MAS in the BP, and the superframe, is called the Beacon Period Start Time (BPST), as shown in Figure 2.

Table 1: Summary of parameters considered for the standard ECMA-368.

Parameter	Value
Receiver sensitivity	−74.5 dBm
Receiver Maximum Input Level	−20 dBm
Output Power (Maximum)	−41.3 dBm/MHz
Number of bands (used)	14 (band group no. 1)
Channel Spacing	528 MHz
Effective Bandwidth	528 MHz
Data Rate	53.3, 80, 106.7, 160, 200, 320, 400 and 480 Mb/s
Symbol Rate	3.2 Msymbol/s
Total number of subcarriers	128
Modulation	QPSK, DCM

Every device transmit its beacon and listen to the remaining beacon slots sent by others devices belonging to network. The total BP length is variable and depends on the system overall layout. It is not allowed to use more than 96 beacon slots (32 MAS which corresponds to 8.129 ms) in each superframe. The rest of the MASs after the BP is the Data Period (DP) which is used to exchange data among devices.

The DRP provides a collision-free channel access, announcing future transmissions and thus allowing devices to coordinate their channel access. By means of the BP, devices can learn the MAS occupation status and make their own reservation. The reservation is announced by the owner device in its beacon and is identified with the start MAS number and the duration in unit of MASs. According to the standard, several types of reservation can be generated.

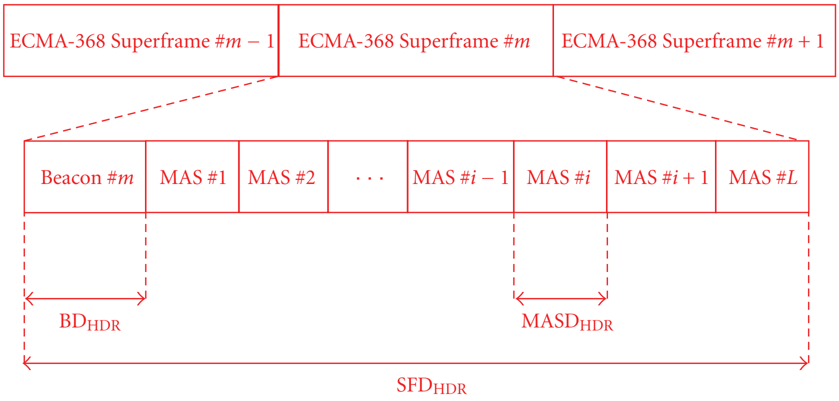


FIGURE 2: ECMA-368 MAC.

TABLE 2: Summary of parameters considered for the standard IEEE 802.15.4.

Parameter	Value
Center frequency	$f_c = 2405 + 5(k - 11)$ MHz $k = 11, 12, \ldots, 26)$
Receiver sensitivity	−85 dBm
Receiver Maximum Input Level	−20 dBm
Output Power (Maximum)	0 dBm
Number of Channels (used)	16 (nr. 26)
Channel Spacing	5 MHz
Effective Bandwidth	2 MHz
Data Rate	250 kb/s
Symbol Rate	62.5 ksymbol/s
Chip Rate	2 Mchip/s
Chip Modulation	O-QPSK

(i) Alien BP prevents transmission during MASs occupied by an alien BP.

(ii) Hard reservation provides exclusive access to the medium for the reservation owner and target; unused time should be released for PCA.

(iii) Soft reservation permits PCA, but the reservation owner has preferential access.

(iv) Private reservation provides exclusive access to the medium for the reservation owner and target.

(v) PCA reserves time for PCA. No device has preferential access.

2.3. IEEE 802.15.4 WPANs. The IEEE 802.15.4 standard is used for very low data rate, low-power and low-duty cycle WPANs and it addresses both the PHY (see Table 2) and MAC layers [9].

The central controller of the network called PAN coordinator can optionally bound its channel time by using a superframe structure (i.e., beacon-enabled PAN). A superframe starts with the transmission of a beacon frame. In a superframe enabled WPAN, the superframe can have an active and an inactive portion; the active portion is divided into 16 equally sized slots. Figure 3 shows the general structure of the 802.15.4 MAC superframe, which consists of four parts:

(i) the beacon frame, which is used to synchronize the devices associated to the WPAN, identify the WPAN and describe the structure of the superframe,

(ii) the Contention Access Period (CAP), where devices may communicate using a slotted CSMA/CA mechanism,

(iii) the Contention Free Period (CFP), where the access to the channel is controlled by the PNC, which assigns Guaranteed Time Slots (GTSs) for that communication in response to the request message. The PAN coordinator can allocate up to 7 GTS,

(iv) the inactive period, during which devices may enter a low-power mode.

The total duration of the superframe $\mathrm{SFD_{LDR}}$, also called Beacon Interval (BI), is computed as follows (in seconds):

$$\mathrm{SFD_{LDR}} = \mathrm{aBaseSuperframeDuration} \cdot \frac{2^{\mathrm{BO}}}{R_s} \tag{1}$$

where aBaseSuperframeDuration = 16 · 60 symbols, R_s = 62.5 ksymbols/s and the Beacon Order (BO) is constrained by: $0 \leq \mathrm{BO} \leq 14$; when BO = 15 the PAN coordinator will not transmit beacon frames. On the other hand, the duration $\mathrm{SAD_{LDR}}$ of the active portion of the superframe is computed as follows:

$$\mathrm{SAD_{LDR}} = \mathrm{aBaseSuperframeDuration} \cdot \frac{2^{\mathrm{SO}}}{R_s}, \tag{2}$$

where the Superframe Order (SO) is constrained by: $0 \leq \mathrm{SO} \leq \mathrm{BO}$. The duration of the inactive portion of the superframe is here denoted as $\mathrm{SID_{LDR}}$ and the following equation hols: $\mathrm{SFD_{LDR}} = \mathrm{SAD_{LDR}} + \mathrm{SID_{LDR}}$.

3. Impact Assessment of the Out-of-Band Interference

In this section, the performance degradation due the interference occurring between two WPAN devices, one HDR and

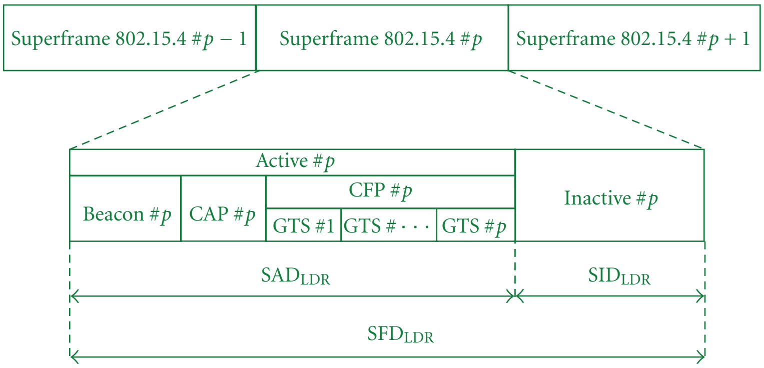


Figure 3: IEEE 802.15.4 MAC superframe structure.

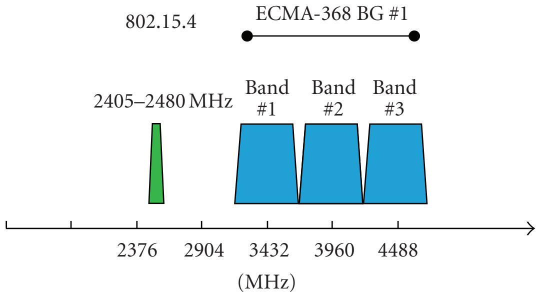


Figure 4: Frequency separation between the considered standards.

one LDR device, is assessed through simulations. As previously discussed, we consider the following two standardized air interfaces for WPANs: ECMA-368 for HDR WPAN device and IEEE 802.15.4. The specific transmission parameters for the two standards are summarized in Tables 1 and 2, while the respective transmission bands and frequency separation are shown in Figure 4. The IEEE 802.15.4 simulation chain is based on OQPSK modulation transmitting at 250 kbps and occupying channel number 26 at 2480 MHz. The ECMA-368 simulation chain uses UWB with QPSK modulation transmitting at 200 Mbps and occupying the Band Group 1, that has a lower frequency of 3168 MHz, thus the minimum frequency distance is 688 MHz.

In the scenario of interest for this paper, where both HDR and LDR WPANs air interfaces operate simultaneously in close proximity and the two specific standards have separate center frequencies, out-of-band interference arises. A passband simulator has been developed for the complex evaluation of the impact of this out-of-band interference between colocated ECMA-368 and IEEE 802.15.4 air interfaces. We assume line-of-sight conditions with negligible multipath. The simulated channel is an AWGN channel with free space path loss. When the distance d between the two air interfaces is such that the far-field hypothesis can be considered valid, the following formula for the path loss has been used [8, 9]:

$$P_l = 45 + 20 \cdot \log(d), \tag{3}$$

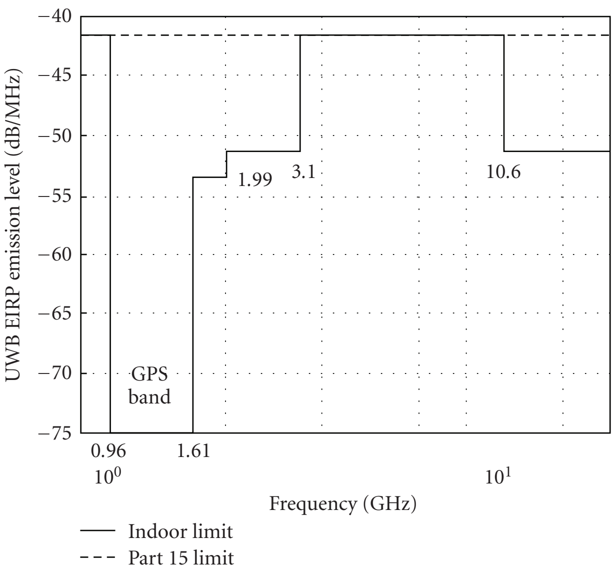


Figure 5: FCC spectral mask for indoor UWB use.

where P_l is expressed in dB. However, when the distance is such that the far-field hypothesis is no longer valid, the following formula for the path loss in the near-field has been used [12, 13]:

$$P_l = 45 + 20 \cdot \log(d) + 3.5 \cdot \log(d). \tag{4}$$

Considering a two-half wavelength dipole, the near-field region is limited at a distance of 6 cm [14].

Before showing the results of the evaluation of the impact of the interference, it helps to have a rough idea of the distance between the HDR interferer and the LDR receiver above which the LDR air interface does not experience this interference as the interference level is below the receiver noise floor. Let us consider the power spectral mask for indoor UWB devices as approved by FCC, which is shown in Figure 5. If we consider that the HDR UWB interferer has a constant power spectral density along the 2 MHz bandwidth of the LDR air interface, the effective power P_{eff} (in dBm)

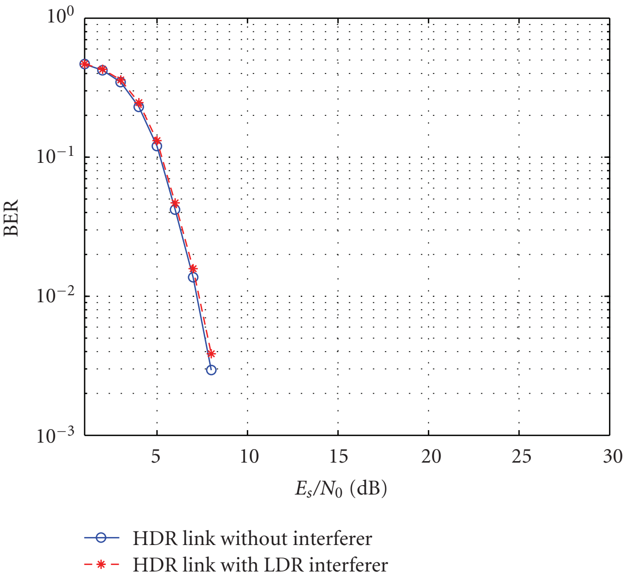


Figure 6: Interference effects of an IEEE 802.15.4 interferer on an ECMA-368 link. The distance between the interferer and the intended receiver is set to 10 cm.

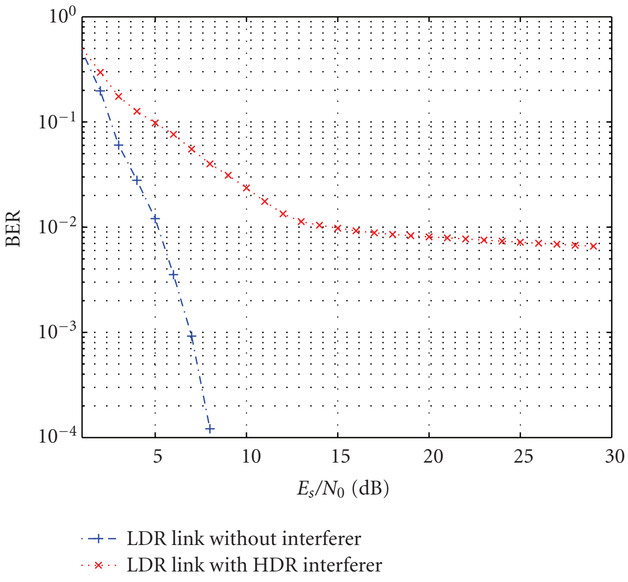


Figure 7: Mutual interference effects of an ECMA-368 interferer on an IEEE 802.15.4 link. The distance between the interferer and the intended receiver is set to 10 cm.

emitted from the HDR transmitter, at the frequency f of 2.48 GHz can be at the maximum equal to [15]:

$$P_{\text{eff}} = \left[-51.3 + 87 \cdot \log\left(\frac{f}{3.1}\right)\right] + 10 \cdot \log(B_{\text{eff}}), \quad (5)$$

where B_{eff} is the effective bandwidth of the LDR receiver (2 MHz). Assuming the interference power equal to the receiver sensitivity S (in dBm) and considering (5) and (3) the following equation holds: Considering a LDR receiver sensitivity of $S = -85$ dBm and solving for d the distance at which the received power equals the receiver sensitivity S of the LDR receiver is 14.6 cm. This means that above 14.6 cm of distance the LDR receiver will not experience the interference from the HDR device because it is below the noise floor. On the other hand, simulations have shown that when the the interferer is at a distance lower than 6 cm (near-field interference scenario) already at a distance of 5 cm the BER saturates to 0.5. Therefore, when they are too closely located, even when the center frequencies of the LDR and HDR air interfaces are enough separated and strict limitations to the transmission power are imposed, severe performance degradation is experienced.

In the following simulation results, we have assumed that the interferer is placed at 10 cm from the intended receiver and several distances between the intended transmitter and the intended receiver are considered, which corresponds to different values of energy per symbol to noise E_s/N_0.

Figures 6 and 7 show the BER versus E_s/N_0 curves for both the 802.15.4 and the ECMA-368 air interfaces, with/without the interferer. From Figure 6 is evident that the interference effects generated from an IEEE 802.15.4 interferer on a ECMA-368 link are negligible while from Figure 7 a considerable impact was generated from a ECMA-368 interferer on an IEEE 802.15.4 link. In Figure 8, the performance degradation of the IEEE 802.15.4 link with/without an ECMA-368 interferer is shown in terms of goodput, that is, the number of bits successfully received per second. The goodput can be derived from the Packet Error Rate (PER), denoted by p, as follows:

$$\lambda = r \cdot \epsilon \cdot (1 - p) \quad (6)$$

where r is the transmission bit rate (in bit/s), and ϵ is the duty cycle. The goodput has been evaluated assuming a packet length of 512 bytes. In presence of an interferer, we can state that the goodput does not exceed 10% of the maximum link capacity, even with very high SNRs. This noticeable goodput reduction justifies the need of a proper coexistence mechanism.

4. Interference Management Mechanisms

The simplest approach to solve interference problems is to assign orthogonal subchannels in the available spectrum so that the resources are equally shared. With the increasing number of devices and technologies the resources have become limited and therefore these resources have been assigned to more than one user/technology. Nowadays the primary issue in the design of wireless ad-hoc networks is the management of the interference that transmissions generate at nearby receivers.

In the following subsections we propose a novel coexistence mechanism based on an efficient superframe-by-superframe time division alternate transmission which does not waste radio resources such as power and frequency.

4.1. AWA Coexistence Algorithm. The proposed coexistence mechanism is here named Alternating Wireless Activity (AWA). It works by controlling and synchronizing the

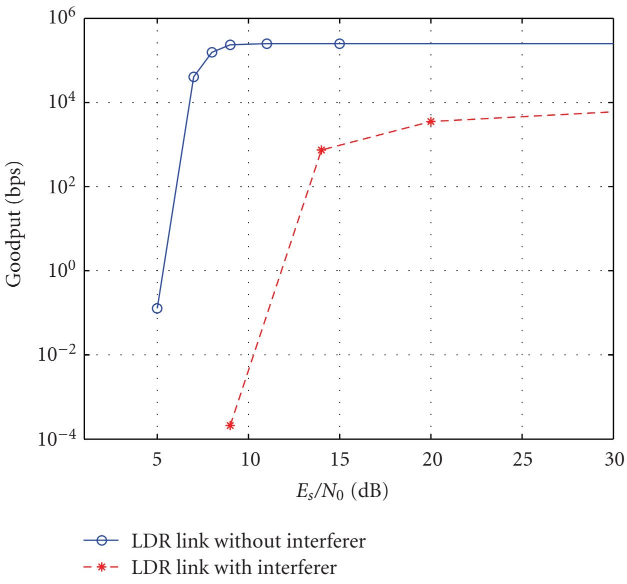


FIGURE 8: LDR link goodput without and with interference placed at 10 cm distance from the LDR receiver. The distance between the interferer and the intended receiver is set to 10 cm.

access to the network of the two air interfaces that are requested to coexist. Its functionalities are positioned in a common protocol layer over the two MAC sublayers. For sake of simplicity, in this Section the proposed mechanism is presented for the specific ECMA-368 and IEEE 802.15.4 and it makes use of the ECMA-368 DRP with hard reservation and the inactive period of the IEEE 802.15.4. However, it is worth noting that the same algorithm could be also applied to any other alternative PHY as long as the MAC has a superframe structure. Since no other ECMA-368 air interfaces are transmitting during the hard reservation, one or more MASs can be allocated to an IEEE 802.15.4 WPAN that will not be interfered by any ECMA-368 air interface. On the other hand, since no IEEE 802.15.4 air interfaces are transmitting during the inactive portion of the superframe, this inactive portion will be synchronized to overlap the entire ECMA-368 superframe except the ith MAS (or more MASs) that is overlapping with the active portion of the IEEE 802.15.4 WPAN. In this case the ECMA-368 WPAN will not be interfered by any IEEE 802.15.4 air interface.

The synchronization of the ECMA-368 and IEEE 802.15.4 superframes is shown in Figure 9. The ith MAS of the mth ECMA-368 superframe is allocated to the active portion of the pth IEEE 802.15.4 superframe. The inactive portion is virtually divided into two parts: the mth ECMA-368 superframe starts simultaneously to the second part of the inactive portion of the $(p-1)$-th IEEE 802.15.4 superframe, while the the mth ECMA-368 superframe ends simultaneously to the first part of the inactive portion of the pth IEEE 802.15.4 superframe. The duration of the first part of the inactive portion of the pth IEEE 802.15.4 superframe is denoted as $\mathrm{SID}_{\mathrm{LDR}}^{p'}$, while the second part of the inactive portion is denoted as $\mathrm{SID}_{\mathrm{LDR}}^{p'}$. The synchronization of the two superframe sequences allows to free from interference all ECMA-368 and IEEE 802.15.4 devices associated to the common LDR/HDR dual-mode device. The AWA mechanism is a collaborative coexistence mechanism, in fact in order to achieve this synchronization the ECMA-368 air interface and the IEEE 802.15.4 WPAN controller are expected to exchange information.

There are two restrictions to the exploitation of the AWA coexistence algorithm.

(i) There must be a dual-mode HDR/LDR WPAN device within the common coverage area of the ECMA-368 and IEEE 802.15.4 WPANs and it will allow the exchange of synchronization information between the two MACs.

(ii) The IEEE 802.15.4 WPAN must be beacon enabled with an active and an inactive period.

(iii) Hard Reservation must be used.

Under these restrictions, the steps of the algorithm are listed in the following:

(1) The dual mode device reserves one or more MASs for a virtual transmission; these MASs will be used from the IEEE 802.15.4 WPAN.

(2) The coordinator of the IEEE 802.15.4 WPAN sets the superframe duration equal to the superframe duration of the ECMA-368 WPAN. Therefore, the superframe periodicity is the same for both ECMA-368 and IEEE 802.15.4 WPANs.

(3) Under the assumption that all the private MASs allocated to the IEEE 802.15.4 WPAN are pseudostatic, the following equation holds:

$$\mathrm{MASD}_{\mathrm{HDR}}^{(m)} = \mathrm{MASD}_{\mathrm{HDR}}^{(m+1)}. \tag{7}$$

Furthermore the position of the pseudostatic time slot (i.e., ith MAS) of the mth ECMA-368 superframe is equal to the position of the pseudostatic time slot (i.e., ith MAS) of the $(m+1)$-th ECMA-368 superframe.

(4) For the synchronization of the two networks, the following equations will hold:

$$\mathrm{SFD}_{\mathrm{HDR}}^{(m)} = \mathrm{SFD}_{\mathrm{LDR}}^{(p)}, \tag{8}$$

$$\mathrm{MASD}_{\mathrm{HDR}}^{(m)} = \mathrm{SAD}_{\mathrm{LDR}}^{(p)}, \tag{9}$$

$$\mathrm{SID}_{\mathrm{LDR}}^{p'} = \mathrm{SID}_{\mathrm{LDR}}^{p+1'}, \tag{10}$$

$$\mathrm{SID}_{\mathrm{LDR}}^{p''} = \mathrm{SID}_{\mathrm{LDR}}^{p+1''}. \tag{11}$$

Because of the constraint on $\mathrm{SFD}_{\mathrm{HDR}}$, which is: $0 < \mathrm{SFD}_{\mathrm{HDR}} \leq 65535 \cdot 10^{-6}$ seconds, and the constraint on $\mathrm{SFD}_{\mathrm{LDR}}$ computed by (1) where $0 \leq \mathrm{SO} \leq \mathrm{BO} \leq 14$, (8) can only be satisfied with $\mathrm{BO} = 1, 2$. Furthermore, in order to use the inactive portion, possible values of BO and SO are: $(\mathrm{BO}, \mathrm{SO}) = (1, 0)$, $(\mathrm{BO}, \mathrm{SO}) = (2, 0)$ and $(\mathrm{BO}, \mathrm{SO}) = (2, 1)$ which provide a LDR duty cycle of 50%, 25% and 50%,

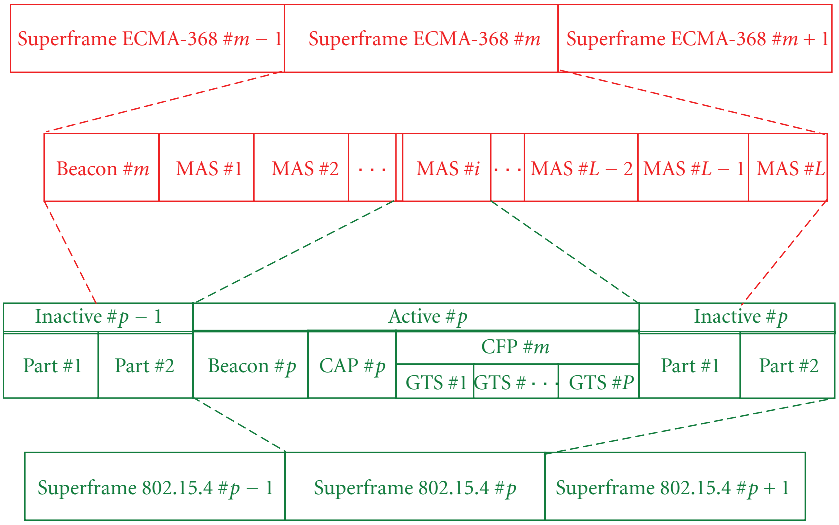


Figure 9: Interaction of the superframe structures for the AWA coexistence mechanism.

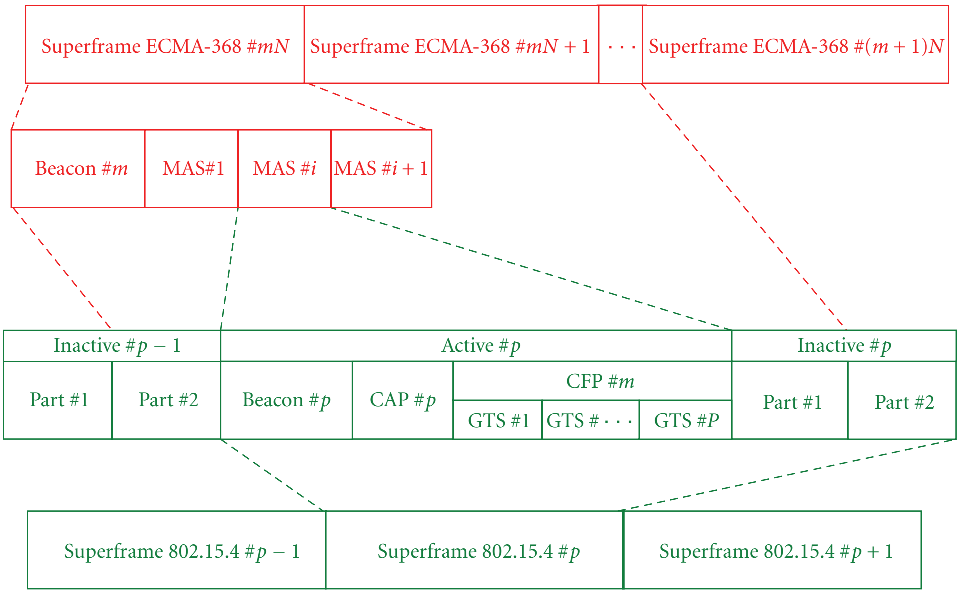


Figure 10: Interaction of the superframe structures for the improved AWA coexistence mechanism.

respectively, see Table 3. It is worth noting that the duty cycle of the HDR network is complementary to the duty cycle of the LDR network.

In situations where the duty cycle of the HDR network will be higher than 75% (i.e., the LDR duty of cycle lower than 25%), an improved version of the AWA mechanism should be considered.

4.2. Improved AWA Coexistence Mechanism. In the Improved version of the AWA (IAWA) coexistence mechanism, the private MAS for LDR is not allocated once per superframe, but it is allocated once per N superframes. In other words, the private MAS is allocated during the superframe no. mN, while it will skip the private MAS allocation for the next $N-1$ HDR superframes. The synchronization of the ECMA-368 and IEEE 802.15.4 superframes is shown in Figure 10.

In the basic version of the AWA mechanism, the dual mode device computes the superframe structure once per superframe. With this improved version, the dual mode device will compute the superframe structure once per N superframes.

With IAWA it is possible to overcome the duration limit of the superframe, then also other duty cycle solutions are available, like 12.5%, 6.25% and 3.125%, see Table 4.

It is worth noting that, for both AWA basic mechanism and its improved version, no modifications to the ECMA-368 and IEEE 802.15.4 MAC standards are required. As proof of concept, the two simulators of the standards ECMA-368 and IEEE 802.15.4 developed for the interference study, have

Table 3: 802.15.4 timings for a data rate of 250 kbps with AWA.

(BO, SO)	Timings	Symbols	Duration	Size
(BO, SO) = (1, 0)	SFD_{HDR}	1920	30.72 ms	7680 bit
	SAD_{LDR}	960	15.36 ms	3840 bit
	Time Slot	60	0.96 ms	240 bit
	Max. CFP	520	8.32 ms	8 slot
Duty Cycle = 50%				
(BO, SO) = (2, 0)	SFD_{HDR}	3840	61.44 ms	15360 bit
	SAD_{LDR}	960	15.36 ms	3840 bit
	Time Slot	60	0.96 ms	240 bit
	Max. CFP	520	8.32 ms	8 slot
Duty Cycle = 25%				
(BO, SO) = (2, 1)	SFD_{HDR}	3840	61.44 ms	15360 bit
	SAD_{LDR}	1920	30.72 ms	7680 bit
	Time Slot	120	1.92 ms	480 bit
	Max. CFP	1480	23.68 ms	12 slot
Duty Cycle = 50%				

Table 4: 802.15.4 timings for a data rate of 250 kbps with IAWA.

(BO, SO)	Timings	Symbols	Duration	Size
(BO, SO) = (3, 0)	SFD_{HDR}	7860	122.88 ms	30720 bit
	SAD_{LDR}	960	15.36 ms	3840 bit
	Time Slot	60	0.96 ms	240 bit
	Max. CFP	520	8.32 ms	8 slot
Duty Cycle = 12.5%				
(BO, SO) = (4, 0)	SFD_{HDR}	15360	245.76 ms	61440 bit
	SAD_{LDR}	960	15.36 ms	3840 bit
	Time Slot	60	0.96 ms	240 bit
	Max. CFP	520	8.32 ms	8 slot
Duty Cycle = 6.25%				
(BO, SO) = (5, 0)	SFD_{HDR}	30720	491.52 ms	122880 bit
	SAD_{LDR}	960	15.36 ms	3840 bit
	Time Slot	60	0.96 ms	240 bit
	Max. CFP	1480	23.68 ms	12 slot
Duty Cycle = 3.125%				

been integrated in a finite state machine model of the IAWA. It is important to underline that the functionalities of this mechanism are above the MAC sublayer, hence, it can also be used with every alternative PHY layer of ECMA-368 and IEEE 802.15.4 WPANs.

The simulation results of the IAWA coexistence algorithm, compared to the case with interference and without IAWA (duty cycle 100%), are shown in Figure 11 in terms of goodput of the LDR link. The goodput is plotted for different values of the duty cycle. For any value of Es/N_0, the goodput is always higher by using the IAWA coexistence mechanism. This increase of the goodput with IAWA with respect to the case without IAWA is more evident when the SNR becomes low. In fact, when the SNR is low, the received power of the interference signal is much higher than the power of the wanted signal. As already discussed, this improvement is achieved to the detriment of the goodput of the HDR link which is decreased with the complement of the duty cycle of the LDR link. As a consequence the fairness of the multimode LDR/HDR device is increased by using the IAWA algorithm.

4.3. Advantages and Limitations. Several coexistence mechanisms based on TDMA have been proposed in literature for the coexistence between different wireless networks [7, 11]. These coexistence mechanisms were based on the application of the TDMA principle at the packet level or at the slot level which means that the time resource is assigned to one of the two nodes of the two networks for each transmitted packet or for each transmission slot. Therefore, these coexistence mechanisms allow the coexistence only between the two nodes associated, respectively, to the first wireless network and to the second wireless network that share a common coexistence scheduler. The difference between the proposed AWA/IAWA coexistence mechanism and other coexistence mechanisms based on TDMA is that our mechanism applies the TDMA synchronization at the superframe level. This means that the channel resources that are shared by the two wireless networks are assigned to one portion of one or more superframes of the networks. As a consequence, the advantages with respect to other TDMA coexistence mechanisms can be summarized as follows.

(i) The allocation to different devices/networks is performed for every superframe, thus lowering the computation rate of the scheduler for the resource allocation with respect to other mechanisms based on slot or packet TDMA.

(ii) The sharing of resources between the two wireless networks can be managed through the duty cycle setting in order to adapt the resource allocation to the different QoS requirements or the traffic load of the two wireless networks.

(iii) The coexistence is guaranteed for all LDR and HDR devices associated to the unique LDR/HDR controller which applies the AWA/IAWA coexistence mechanism. In fact, the two sets of nodes of the two wireless networks are synchronized with the LDR/HDR network controller that sets the superframe structures of the LDR and HDR networks. In this case the interference between each node and any other node is prevented. This is not true in case of slot or packet TDMA coexistence mechanisms since the coexistence is guaranteed only to the pair of devices applying the slot or packet TDMA mechanism.

(iv) The AWA/IAWA coexistence mechanism can be applied to any pair of wireless networks which perform the transmission organized into superframes, for example, IEEE 802.15.3, IEEE 802.15.4, ECMA-368, IEEE 802.11, IEEE 802.16, IEEE 802.22, ETSI HIPERLAN/2.

In the particular case analyzed in this paper, the AWA/IAWA coexistence mechanism does not require any modification to the standards IEEE802.15.4 and ECMA-368. However, there are some limitations to the use of the AWA/IAWA mechanism. First of all, the coexisting wireless networks that wants to use the AWA/IAWA algorithm must allow to allocate slots or active/inactive portions of time within the superframe. In other terms, if within the superframe we can only use contention-based multiple access schemes, the AWA algorithm cannot be used. Moreover, as it is a collaborative mechanism, there should be a multimode device which acts as central controller for the two wireless networks. This is a consequence of the collaborative feature of the algorithm.

Finally, it is worth outlining that it is a time-scheduling based algorithm and as such, the performance improvement in terms of goodput depends on the interference level (i.e., the distance) between the air interfaces. Therefore, its use is more suitable in case of high interference levels (which is the case of colocated air interfaces).

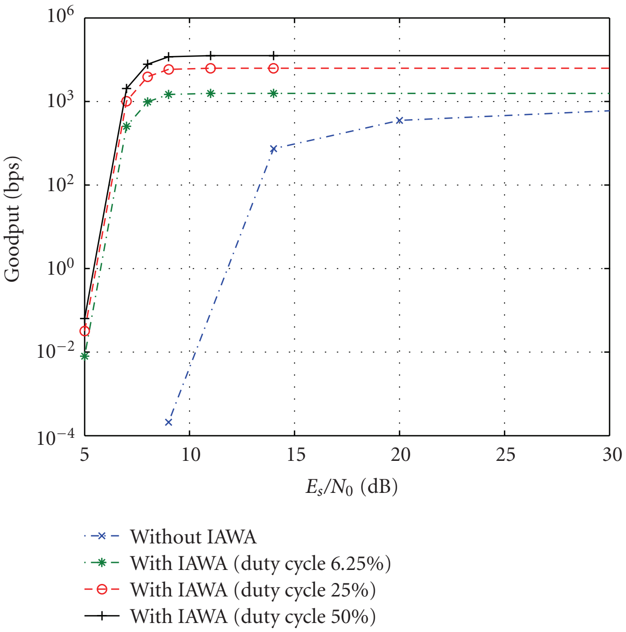


FIGURE 11: Goodput of the IEEE 802.15.4 link using the IAWA coexistence mechanism with different Duty Cycles. The distance between the interferer and the intended receiver is set to 10 cm.

5. Conclusion

In this work, the issue of the interference among Low Data Rate (LDR) and High Data Rate (HDR) WPAN air interfaces that are located in close-proximity (up to 10 cm) and eventually on the same multimode device is addressed. We considered IEEE 802.15.4 and ECMA-368 standards. Simulations have shown that IEEE 802.15.4 links are affected by ECMA-368 interference when the distance is less than 10 cm. Therefore, a collaborative coexistence mechanism named AWA has been proposed for managing the simultaneous operation in close proximity of two complementary WPANs. The AWA mechanism achieves perfect coexistence by controlling and synchronizing the access to the network of the HDR and LDR air interfaces. It is worth noting that the synchronization of the two LDR and HDR superframe sequences allows to free from interference all LDR and HDR devices associated to the common dual-mode LDR/HDR WPAN controller. The proposed algorithm allows the LDR air interface to work with acceptable value of goodput with a controlled reduction of the goodput of the HDR air interface.

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