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A new role-switching mechanism optimizing the coexistence of bluetooth and Wi-Fi networks

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Abstract Unlicensed ISM band is used by various wireless technologies. Therefore, issues related to ensuring the required efficiency and quality of operation of coexisting networks become essential. The paper addresses the problem of mutual interferences between IEEE 802.11b transmitters (commercially named Wi-Fi) and Bluetooth (BT) devices. An optimization approach to modeling the topology of BT scatternets is introduced, resulting in more efficient utilization of ISM environment consisting of BT and Wi-Fi networks. To achieve it, the Integer Linear Programming approach has been proposed. Example results presented in the paper illustrate significant benefits of using the proposed modeling strategy.

Keywords Bluetooth, IEEE 802.11b · Interference · Coexistence, ILP optimization · Minimization of interferences

1 Introduction

We have been witnessing a very fast development of various wireless technologies and network devices making use of the common unlicensed ISM band (the abbreviation for Industrial, Scientific and Medical), e.g. Bluetooth (BT) [3], IEEE 802.11b (Wi-Fi) [8] or IEEE 802.11g. As a result, it becomes more and more difficult to provide transmission parameters that can guarantee the quality of services required by coexisting networks. This is especially true of network devices operating in a close vicinity around other devices belonging to different independent networks, very often based on different technologies and functional solutions.

Several coexistence algorithms have been proposed to provide for higher operational efficiency of diverse technological solutions working within the same area. These approaches can be divided into two groups [9]:

– collaborative mechanisms, requiring information exchange between Bluetooth devices and IEEE 802.11b and,
– non-collaborative mechanisms, which can be adapted separately by 802.11b and/or Bluetooth devices without a direct collaborative system (like e.g. AFH [4]—Adaptive Frequency Hopping algorithm).

Collaborative algorithms are well investigated in [9]. Example techniques that facilitate the coexistence of various technologies, are based on prediction of propagation conditions. For instance, in [4], the *Interference aware BLUEtooth Segmentation mechanism (IBLUES)* has been introduced. It uses a dynamic BT frame selection scheme (depending on the propagation conditions), and relies upon the theoretical determination of the probability of successful transmission of frames and the queuing tasks analysis. Owing to such information, the algorithm takes decisions concerning the choice of a frame format between those defined in specification [3], according to which the data will be transferred (e.g. DM1, DM3, DM5).

In [10], a new coexistence mechanism, related to the management of a Bluetooth network topology has been proposed. This mechanism, named *Interference Aware BLUEtooth Scatternet (RE)configuration Algorithm* (IBLUEREA),

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is based upon the idea of the switching functionality built in BT devices. Generally, BT devices more frequently operating in the ISM band, should be moved further from IEEE 802.11b devices and other BT piconets as well as from each other. It can be achieved via changing functionalities of piconet/scatternet devices (from master to slave or vice versa). The IBLUEREA algorithm leads to electing a BT device operating as a master device (in a given piconet) when such a device causes, and is exposed to, little interference, compared to other BT piconet devices.

In this paper, we propose a more systematic approach to the problem of coexistence of different BT and Wi-Fi devices, operating in a certain area and utilizing ISM resources. The paper extends the idea presented in [10], and formulates a more general optimization problem of coexistence of BT and Wi-Fi networks. To strengthen the concept of a coexistence mechanism, the Integer Linear Programming approach has been introduced. The solutions lead to optimal topology, in terms of location of BT devices in a complex ISM environment. The issue is to minimize the mutual interferences in order to maximize the transmission efficiency and quality.

The paper is organized as follows. Section 2 illustrates the idea of modeling the complex ISM environments. Section 3 formulates the optimization problem. Section 4 describes the simulation environment, and Sect. 5 presents the benefits of using the optimization strategy, leading to minimization of interference. Some exemplary topology scenarios are investigated via simulation experiments. Conclusions and remarks complete the paper.

2 Modeling the ISM environment

While analysing the efficiency of utilization of a given ISM environment, a lot of factors, like the number of coexisting various technology devices, their parameters, propagation conditions, etc., need to be taken into consideration. In order to estimate with a required accuracy the efficiency of a given ISM environment, the influence of all interfering devices on prospective receivers located within their range need to be accounted for.

Bluetooth specification [3] precisely determines the rules of formation and maintenance of piconets as well as the rules of joining and leaving the active network by a device. Devices within one piconet may take on the superior as well as the inferior role. Superior status—master—is assigned to the device that initiated the process of piconet creation. Switching (changing) of master and slave functionalities is possible with regard to the BT network devices.

A master device manages the transmission within a piconet. On the other hand, a slave device wishing to communicate with another station, sends data first to the master device that redirects it to an appropriate recipient. More complex BT networks—called scatternets—can be also created in which a number of piconets are connected.

Some useful mathematical tools have been invented that can describe those network structures. In [5], the general principles of scatternet description (in the form of matrices) have been presented. The authors also proposed metrices making the aggregated (and standardized) link capacity determination in scatternet possible. The metrices are of little significance when tackling the interference issue, which has only been mentioned in this article. Moreover, those metrices do not enable the analyses of interference coming from other systems. In [7], an original methodology and key metrices necessary for determination of interaction between Bluetooth scatternets and IEEE 802.11b network devices have been presented.

The coexistence mechanism, proposed in [10], allows for an efficient and effective reconfiguration of a Bluetooth network topology. This mechanism, named *Interference Aware BLUEtooth Scatternet (RE)configuration Algorithm* (IBLUEREA), is based upon the idea of performing master functions by those BT devices more frequently using the ISM band and closer to receivers/transmitters of other wireless technology devices (e.g. 802.11b) and BT piconets. IBLUEREA accepts switching (changing) of device functionalities from master to slave, and vice versa and operating as a master (in a given piconet) is only permitted to a device that causes, and is exposed to, little interference, compared to other BT piconet devices and networks using other technologies. In order to ensure minimum interactions between BT and Wi-Fi devices, IBLUEREA uses a new approach for modeling the complex ISM environments.

In each piconet, data transmission is managed by the master node. The master node thus uses the ISM band the most frequently (assuming that a given piconet contains more than one slave node). Therefore, it is possible to improve the transmission quality in a Wi-Fi network (as well as in a BT network) by assigning the master functionality to the BT node that is located far from the Wi-Fi receiver. This is explained in Fig. 1.

Figure 1 shows two hypothetical scenarios. In the left part of Fig. 1, a master BT node is located close to a Wi-Fi receiver. In a second scenario, shown in the right part of Fig. 1, the functionality of a master node is assigned to a device located farther from 802.11 receiver. Simulations were to analyze the number of frames received without errors in the regarded networks. It was observed that by reconfiguring the BT piconet, the number of frames received without errors in a Wi-Fi network was increased by 21%. The improvement in a BT network was marginal (1%). However, when analyzing other scenarios, a greater improvement of transmission quality in a BT scatternet may be achieved.

In this paper, a formal optimization problem of coexisting BT and Wi-Fi networks is formulated.

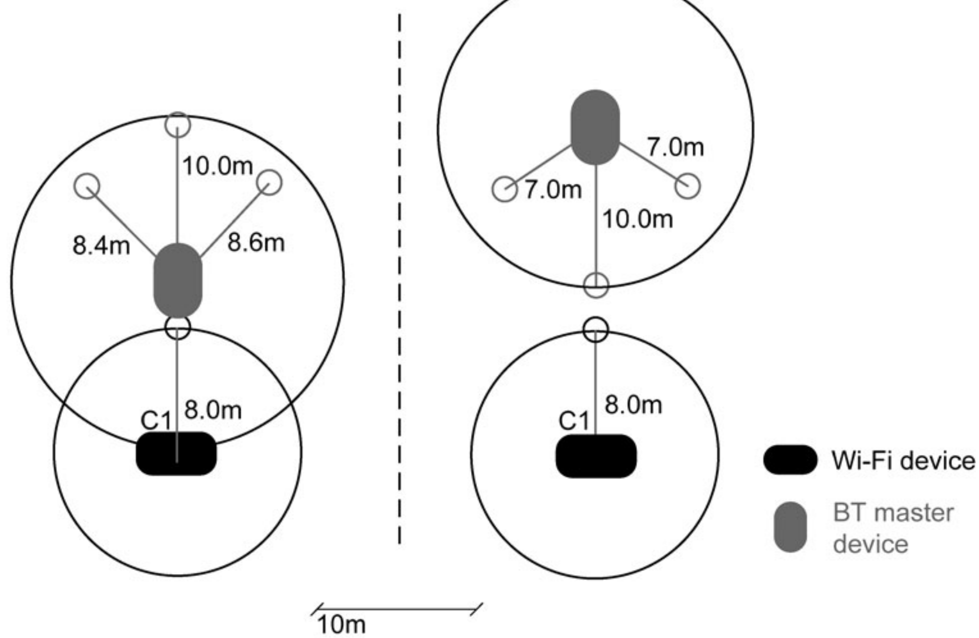

Fig. 1 Example topologies of BT networks with various functionalities of BT nodes

3 Optimization problem

We assume the coexistence of M networks with static placement of nodes (i.e. no mobility is considered). In each BT network, we need to choose one node as a master node. However, each choice has a certain impact on the performance of other networks.

In this section, we propose the Integer Linear Programming model to determine the optimal placement of master nodes in coexisting networks with the objective to minimize the mutual interference between networks i.e., maximize the transmission efficiency and quality. For that purpose, the set of following constants and variables is introduced:

constants

$d_{a_m,a'_{m'}}$ measure of a negative influence between networks m and m' in the case where node a is a master node in network m and node a' is a master node in network m'

V_m number of nodes in network m

M number of potentially interfering Bluetooth networks (piconets)

variables

$J_{a_m,a'_{m'}}$ equals 1, if node a is a master mode in network m and node a' is a master node in network m'; 0 otherwise

Our primary goal is to find the optimal placement of master nodes in BT networks, such that it minimizes the total mutual negative influence of coexisting networks, defined as:

$$F = \sum_{m} \sum_{m'} \sum_{a} \sum_{a'} (d_{a_m,a'_{m'}} \cdot J_{a_m,a'_{m'}}) \tag{1}$$

subject to

constraints assuring that there is only one master node in each BT network

$$\sum_{a} \sum_{a'} (J_{a_m,a'_{m'}}) = 1$$

$$m = 1, 2, \ldots, M; m' = 1, 2, \ldots, M; m \neq m' \tag{2}$$

where $J_{a_m,a'_{m'}} \in \{0, 1\}$.

We may optimize the network configuration assuming various efficiency parameters, e.g. the average number of frames received with errors at all the nodes in a network S. In the remaining part of the paper, we will assume that the values of $d_{a_m,a'_{m'}}$ are calculated as:

$$d_{a_m,a'_{m'}} = \frac{1}{n^S} \sum_{x \in N^S} f(x) \tag{3}$$

where $f(x)$ is the sum of probability values of receiving frames with errors at a node $x \in N^S$ (estimated with regard to all other nodes interfering with k), calculated as:

$$f(x) = \sum_{\substack{k=1 \\ k \neq x}}^{N} f^k(x); \quad x, k \in N^S \tag{4}$$

Formula (3) expresses the average frame error rate calculated for all coexisting n^S nodes belonging to the network S. Next, we will try to minimize the value defined by (3).

We are interested in finding the representation of $Y_r \in \Re$ for which the sum of average probabilities of receiving frames with errors at all the nodes from a network S_r is minimized. Therefore, the optimal placement of master nodes may be calculated as follows:

$$K^*(Y_r) = \min_{Y_r \in \Re} K(Y_r) \tag{5}$$

Taking into account the previously assumed definitions, formula (5) may be rewritten as:

$$K(Y_r) = \min \frac{1}{n^S} \sum_{x \in N^S} (f(x)) \tag{6}$$

The coefficients $f^k(x)$ in formula (4), depend on the frame error rate at nodes belonging to S and are defined as:

$$f^k(x) = (1 - P_{S(k,x)}) \cdot \upsilon_{k,x} \tag{7}$$

where $P_{S(k,x)}$ conditional probability of successfully receiving a frame at node x assuming the occurrence of interference from node k, $\upsilon_{k,x}$ reflects the intensity of interferences between nodes x and k as well as the frequency of using the ISM band by node x.

The probability $P_{S(k,x)}$ can be written as follows:

$$P_{S(k,x)} = \sum_N P_S(P_E|n) \cdot P_C(n, N) \tag{8}$$

where $P_C(n, N)$ probability of a collision of a given technology frame with n other technology frames out of N possible collisions (frequency analysis), $P_S(P_E|n)$ the probability of a successful reception of a IEEE 802.11b frame (Bluetooth), which was subject to a collision (time analysis).

In order to calculate the probability $P_S(P_E|\ n)$, it is important to determine the bit error rate P_E, in two cases: with and without collisions. Formulas describing the bit error rates have been presented in [9].

It is easy to see that any node interfering with node k uses the ISM band only at certain timeslots. Similarly, any node x being interfered by other nodes also transmits data only at certain timeslots. While calculating the values of $\upsilon_{k,x}$, we will thus determine the respective upper bounds for certain collisions (assuming that all the networks are mutually independent).

We will now investigate in detail all possible scenarios of collisions, in which nodes k and x may be the master and slave devices, respectively, in a BT as well as in a Wi-Fi network. Assuming that node k is a master node ($k \in M^S$) and interferes with a given node $x \in S^x$ ($x \in M^S$), we may assume that it transmits once every two frames. Therefore, the element $\upsilon_{k,x}$ (for scenarios where a master node interferes with other master node) takes the form:

$$\underset{a_{k,x}\neq 0}{\forall}\ \underset{k\in M^S}{\forall}\ x \notin S^k,\ x \in M^S \Rightarrow \upsilon_{k,x} = \frac{a_{k,x}}{2} \cdot \frac{a_{x,k}}{2} = \frac{1}{4} \tag{9}$$

However, if we investigate the scenario in which a master node $k \in M^S$ interferes with other slave node $x \in S^x$ ($x \notin M^S$), then $\upsilon_{k,x}$ may be given as:

$$\begin{aligned}\underset{a_{k,x}\neq 0}{\forall}\ \underset{k\in M^S}{\forall}\ x \notin S^k,\ x \notin M^S \Rightarrow \upsilon_{k,x} &= \frac{a_{k,x}}{2} \cdot \frac{a_{x,k}}{2\cdot(n^x-1)}\\ &= \frac{1}{4\cdot(n^x-1)}\end{aligned} \tag{10}$$

where n^x denotes the number of nodes in S^x i.e., the BT scatternet including node x.

We will now investigate the scenario in which the interfering node k is a slave node ($k \in S^k, k \notin M^S$), i.e. it may interfere with other nodes $x \in S^x (k \neq x)$, according to its frequency of transmitting the data in scatternet S^k. In this case, $\upsilon_{k,x}$ may be written as:

$$\begin{aligned}\underset{a_{k,x}\neq 0}{\forall}\ \underset{k\notin M^S}{\forall}\ x \notin S^k,\ x \in M^S \Rightarrow \upsilon_{k,x} &= \frac{a_{k,x}}{2\cdot(n^k-1)} \cdot \frac{a_{x,k}}{2}\\ &= \frac{1}{4\cdot(n^k-1)}\end{aligned} \tag{11}$$

In the case where node k interferes with another slave node, $\upsilon_{k,x}$ takes the form:

$$\begin{aligned}&\underset{a_{k,x}\neq 0}{\forall}\ \underset{k\notin M^S}{\forall}\ x \notin S^k,\ x \notin M^S \Rightarrow \upsilon_{k,x}\\ &= \frac{a_{k,x}}{2\cdot(n^k-1)} \cdot \frac{a_{x,k}}{2\cdot(n^x-1)} = \frac{1}{4\cdot(n^k-1)\cdot(n^x-1)}\end{aligned} \tag{12}$$

where n^k and n^x denote the numbers of nodes in networks S^k and S^x, respectively.

In the case of nodes that are used to connect the Bluetooth network bridges, we assume the formulas (11)–(12), taking into consideration that any bridge device may interfere with all the networks it connects, even though it is not exchanging data with these particular networks.

We will denote by $N^{Wi\text{-}Fi}$ the set of Wi-Fi nodes in network S. Assuming that Wi-Fi nodes use the CSMA/CA technique, the impact of any 802.11 device $k \in N^{Wi\text{-}Fi}$ on other technology devices $x \notin N^{Wi\text{-}Fi}$(BT here) may be described by the following formulas:

$$\begin{aligned}\underset{k\in N^{Wi\text{-}Fi}}{\forall} x \notin N^{Wi\text{-}Fi},\ x \in M^S \Rightarrow \upsilon_{k,x} &= \frac{a_{k,x}\cdot a_{x,k}}{2\cdot n^k}\\ &= \frac{1}{2\cdot n^k}\end{aligned} \tag{13}$$

Table 1 Possible settings of parameter $v_{k,x}$

Type of interfering node k	Type of a node x being interfered	$v_{k,x}$
master BT	master BT	$\frac{1}{4}$
master BT	slave BT	$\frac{1}{4\cdot(n^x-1)}$
master BT	Wi-Fi	$\frac{1}{2\cdot n^x}$
slave BT	master BT	$\frac{1}{4\cdot(n^k-1)}$
slave BT	slave BT	$\frac{1}{4\cdot(n^k-1)\cdot(n^x-1)}$
slave BT	Wi-Fi	$\frac{1}{2\cdot(n^k-1)\cdot n^x}$
Wi-Fi	master BT	$\frac{1}{2\cdot n^k}$
Wi-Fi	slave BT	$\frac{1}{2\cdot(n^x-1)\cdot n^k}$

n^k, n^x the numbers of nodes in networks S^k and S^x, respectively, i.e. in scatternets containing nodes k and x

n^k number of nodes IEEE802.11b of a Wi-Fi subnet, such that includes the node k

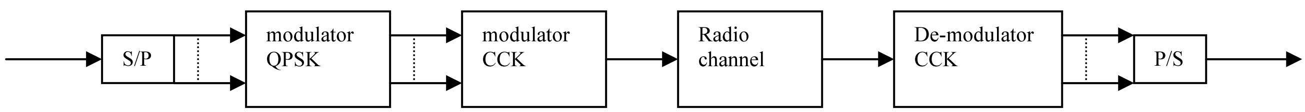

Fig. 2 Functional scheme of implemented transmission environment (IEEE 802.11b). *QPSK—Quadrature Phase-Shift Keying* modulation, *CCK—Complementary Code Keying* modulation used in IEEE 802.11b standard, *S/P*—serial/parallel converter, *P/S*—parallel/serial converter

$$\underset{k\in N^{Wi\text{-}Fi}}{\forall} x \notin N^{Wi\text{-}Fi},\ x \notin M^S \Rightarrow v_{k,x} = \frac{a_{k,x}\cdot a_{x,k}}{2\cdot(n^x-1)\cdot n^k} = \frac{1}{2\cdot(n^x-1)\cdot n^k} \tag{14}$$

where n^k is number of IEEE802.11b devices in a Wi-Fi subnetwork that contain the interfering node k.

In order to analyze the influence of BT devices on other technology devices (here Wi-Fi), we modify the formulas (13)–(14) by a pair-wise exchange of k and x indices. The set of possible values of parameter $v_{k,x}$ is illustrated in Table 1.

4 Simulations environment

To illustrate the benefits of the optimum location of BT scatternet devices co-existing with Wi-Fi devices, a dedicated network simulator was used. In this simulator, channel models with either additive white Gaussian noise (AWGN) or with fading, have been implemented. In the second case, the Rice model [12], with small-scale fading, and no obstacles between transmitter and receiver was applied. The simulator uses a simplified implementation of a non-zero mean value compound Gaussian process with parameters measured in the real office environment [1].

Due to the fact that the main sources of disturbances in investigated networking environments were the transmitters of other systems (BT and Wi-Fi, respectively), the Gaussian noise was accepted at a relatively low (usually treated as standard) level of −95 dBm, according to commonly accepted characteristics of “good” channels [13].

There are many models of indoor signal attenuation, both statistical as well as taking into account the geometrical shapes of rooms. For the simulation purposes, a statistical model described in [11] has been selected. According to this model, signal attenuation PL (dB) over a distance d (m), can be expressed as follows:

$$PL(d) = \begin{cases} 40.0 + 20\lg(d), & d \le 8 \text{ (m)} \\ 58.5 + 33\lg(d/8), & d > 8 \text{ (m)} \end{cases} \tag{15}$$

The network simulator used in modeling included the basic functionality of physical and MAC layers (IEEE 802.11 standard), as well as the physical (RADIO) layer of the Bluetooth standard. The implementation was performed subject to certain simplifications. The most important elements of the implemented environment are described later in this section. In particular, the structure of the analyzed transmission environment (802.11b) is presented in Fig. 2.

Data incoming from the MAC layer (at 11 Mbps) are grouped in the S/P converter into 8-bit sequences. The pairs of bits are then input to QPSK modulation. Sets of four QPSK symbols are next concatenated appropriately in the CCK modulator to obtain a codeword consisting of 8 symbols of a signal transmitted into the radio channel at 11 Mbps. The receiver utilizes the same simplified algorithm to obtain the 8-bit sequence as was used to generate the received CCK codeword. Decoded sets of bits are then utilized to form a frame passed to the upper layers at the receiving node.

On the other hand, in the implementation of 802.11b receivers, a simplified algorithm proposed in [2], has been used for decoding the CCK signals (*Complementary Code Keying*).

In the case of IEEE 802.11b environment, we assumed that in a each simulation scenario:

– the network nodes did not change their location,
– the parameters of transmission channel were constant. In particular, the bandwidth of a single radio channel was set to 22 MHz.

Additionally, in simulation experiments it was assumed that network devices generate and constantly exchange CBR (*Constant Bit Rate*) type of traffic. CBR is a stream of constant-length frames being generated by the source node, using the constant interspaces (i.e. at constant transmission rate). Parameters of the used CBR model included:

– maximum bit rate: 11 Mb/s (IEEE 802.11b standard),
– frame length: 1500 B.

The data and ACK frames transmitted with errors were retransmitted using the ARQ *Stop and Wait* algorithm. The maximum power of IEEE 802.11b transmitter was set to 100 mW.

When analyzing the interferences from a Bluetooth system, it was necessary to determine the probability of time-frequency collisions and the relative power levels for both the signals at the input of the 802.11 receiver. For the sake of simplicity, the GFSK modulation scheme was replaced by BPSK, since the latter has lower computational complexity (the same approach has been used in [6]).

Regarding the BT networks, the following assumptions were made:

- data transmission was performed with the use of collisionless TDD (*Time Division Duplex*) scheme. BT frames were transmitted between master and slave devices according to the assumed timeslot pattern (i.e. even and odd timeslots for master→slave and slave→master transmission, accordingly),
- the transmission channels were selected using the FHSS method (*Frequency Hopping Spread Spectrum*) in a random manner. The selection of the carrier frequency was based on the formula: $f = 2.402$ GHz $+ k$ MHz, where $k = 0, 1, 2, \ldots, 78$,
- the data of each transmitting node fit in a timeslot of a length 625 µs (1/1600 s). Transmission breaks (i.e. periods with no data transmission) were used to stabilize the frequency after selecting a next transmission channel. Therefore, the real time of channel utilization was equal to $\tau_{BT} = 366$ µs,
- the bandwidth occupation of a single channel was set to 1 MHz,
- data transmission was performed by means of asynchronous connections without retransmission, using DH1 frames (each carrying 366 bits of data). A single DH1 link used a single channel of a piconet (CBR source),
- in each piconet, data transmission was performed between the master node and one of the slave nodes,
- Class 3 devices were in use (the with maximum power of 1 mW; 0 dBm).

Simulations were performed for the case of several randomly generated network topologies. Simulation scenarios were prepared to analyze the typical network configurations met in real environments. In all cases, the reconfiguration scenarios were to ensure the optimal location of BT master nodes, minimizing the value of the objective function (1), formulated in Sect. 3. The results of simulation experiments, presented below, were obtained on the basis of 30 simulation runs lasting 10 s each (warm-up periods were disregarded).

5 Example results

Taking into account the assumptions from Sect. 3, optimum network topologies were sought, leading to minimization of mutual interferences (at the same time minimizing the average FER value).

The analyzed network topologies are depicted in Fig. 3. Figure 3a shows an example BT scatternet, which may be referred to as the initial solution Y_1. The second one (Fig. 3b) presents the result of making use of the Bluetooth network structure reconfiguration algorithm (the network configuration with optimum placement of master BT nodes according to the assumed criterion (1)).

In the analysed case, 1500B-long 802.11b frames and DH1 BT frames (generated by CBR sources) were transmitted. The respective distances between network devices are determined by the distance scale presented in the bottom left corner of Fig. 3.

The influence of the AFH algorithm on the network performance was also investigated. Example results are presented in Fig. 4. The respective lengths of 95% confidence intervals are shown in Table 2. The modeling performed for the fading channel (the Rice model) for the initial configuration from Fig. 3a proved that the proposed algorithm ensures:

– 57% improvement of the average FER value—regarding the Wi-Fi network transmission,
– 15% improvement of FER—regarding the AFH mode of BT devices and Wi-Fi networks.

The same strategy, regarding the topology (re)configuration, has also been employed to measure the performance of coexisting piconets, as presented in Fig. 5 (example 2). Additionally, the effects of utilizing the Adaptive Frequency Hopping algorithm by BT devices in presence of different channel models were investigated. In Fig. 5a, the original

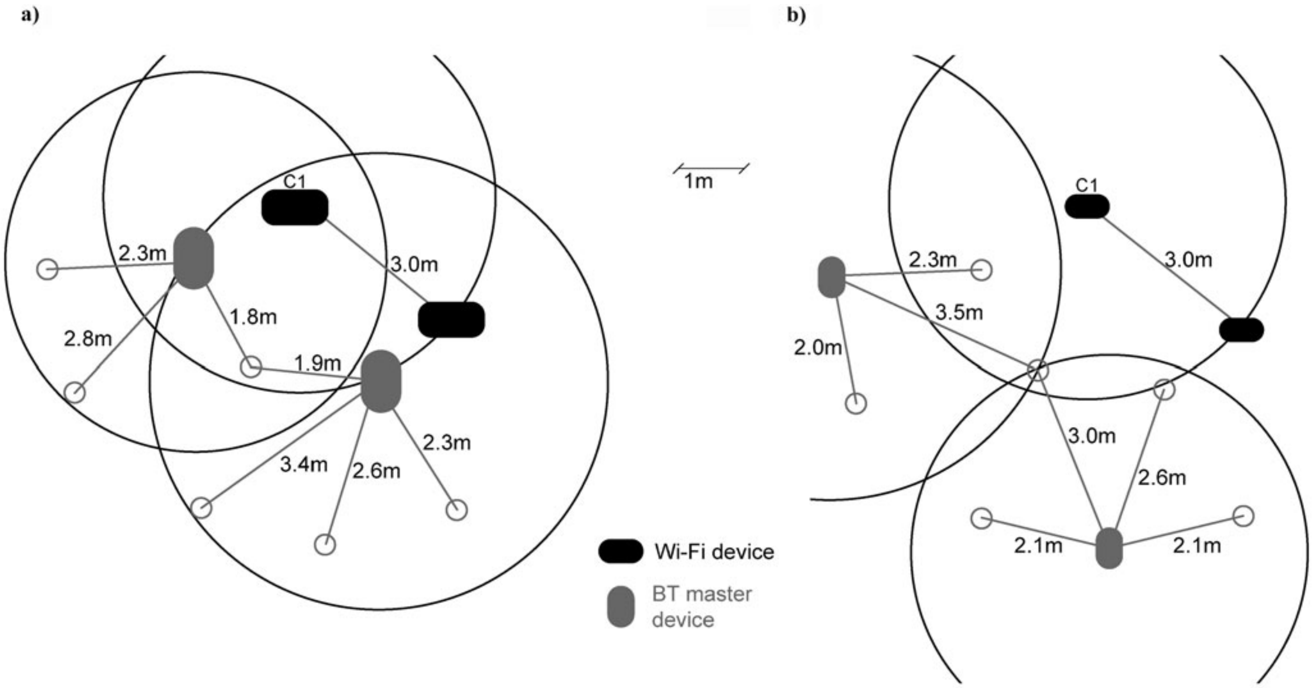

Fig. 3 Example illustration of IBLUEREA algorithm: network topology (**a**) before and (**b**) after reconfiguration

Fig. 4 Average Frame Error Rates (FER) for Bluetooth (class II devices) and 802.11b nodes (example 1—Fig. 3; AWGN channel with Rice fading)

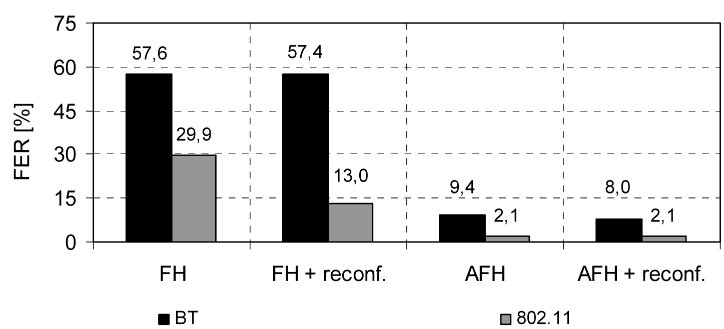

Table 2 Lengths of the 95% confidence intervals for the average FER values

	FH BT	FH 802.11	AFH BT	AFH 802.11
before reconfiguration	0.46%	0.70%	0.41%	0.31%
after reconfiguration	0.54%	0.38%	0.38%	0.23%

configuration of piconets with three Wi-Fi nodes is presented, whereas in Fig. 5b, the situation after reconfiguration is shown. In both diagrams, distances between piconet devices are indicated.

The results of experiments for the two considered channel models (AWGN and Rice fading) are presented in Fig. 6. The respective lengths of 95% confidence intervals are shown in Table 3.

The second example scenario actually describes and investigates the problem of mutual interferences between BT scatternets. As shown in Fig. 6, the use of the reconfiguration algorithm and the strategy to change the role of nodes may also have a very positive impact on the efficiency of ISM band utilization by devices employing the AFH algorithm (a 71% improvement in BT frame loss was observed).

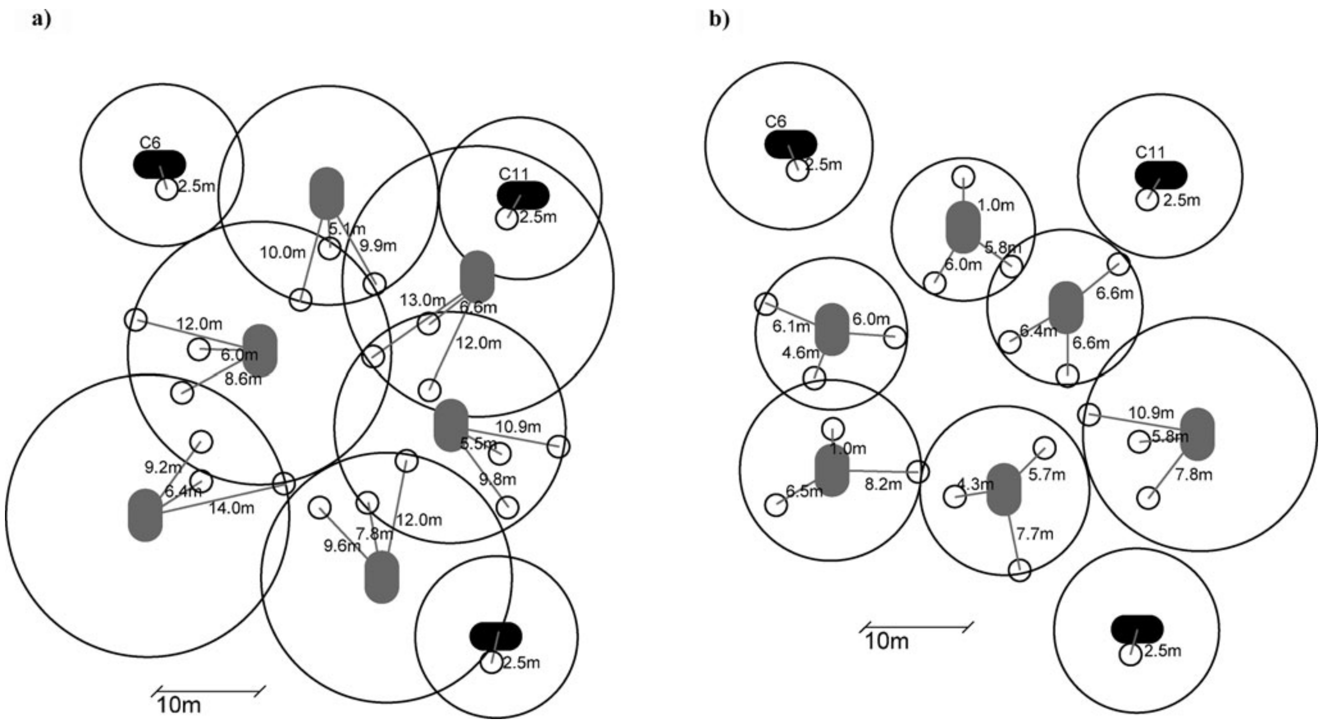

Fig. 5 Example illustration of the proposed the coexistence algorithm minimizing the mutual interferences: (**a**) topology before reconfiguration, (**b**) topology after executing the algorithm

Fig. 6 Average FER values for Bluetooth (class II devices) and 802.11b network devices (example 2—Fig. 5)

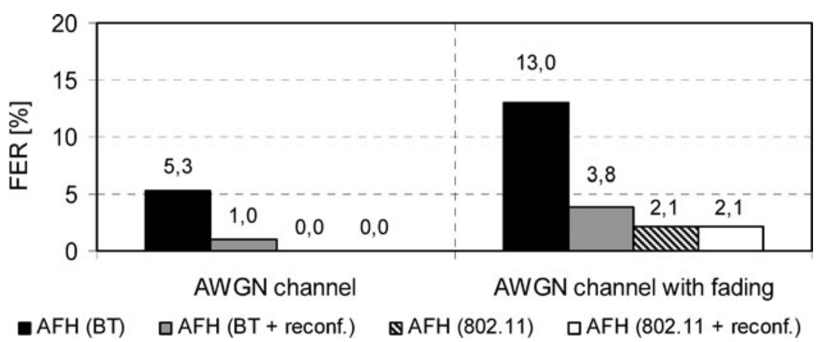

Table 3 Lengths of the 95% confidence intervals for the average FER values

	AFH BT	AFH BT + reconf.	AFH 802.11	AFH 802.11 + reconf.
AWGN channel	0.18%	0.10%	–	–
AWGN channel with fading	0.43%	0.16%	0.18%	0.29%

It may be of great importance especially in the case of sensor networks formed by large sets of Bluetooth devices. For modeling scenarios with AFH mechanism, the Wi-Fi technology does not benefit by using the algorithm. This is reasonable, since BT devices do not utilize the Wi-Fi band due to the AFH algorithm.

6 Role-switching mechanism vs. distance criterion

In the context of the proposed solution, one may query the validity of creating such complex models to find the optimal location of nodes in a network. Below, we present two extreme cases that justify the need for utilizing more complex techniques.

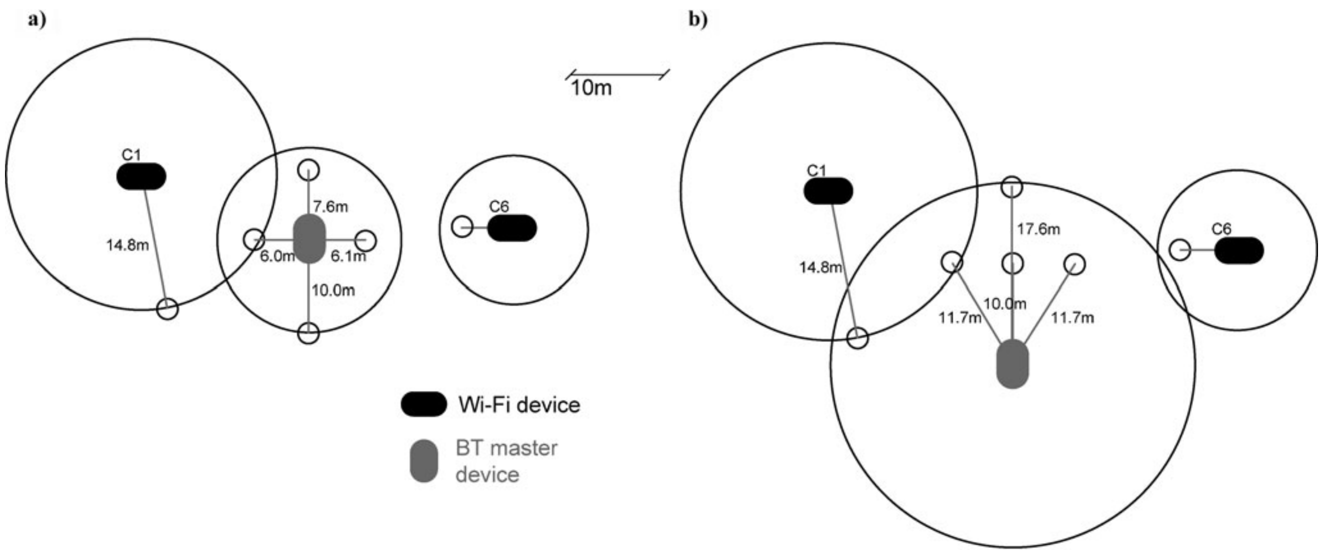

Fig. 7 Comparison of the proposed coexistence algorithm minimizing the mutual interferences, and the criterion based on maximizing of distance between BT devices

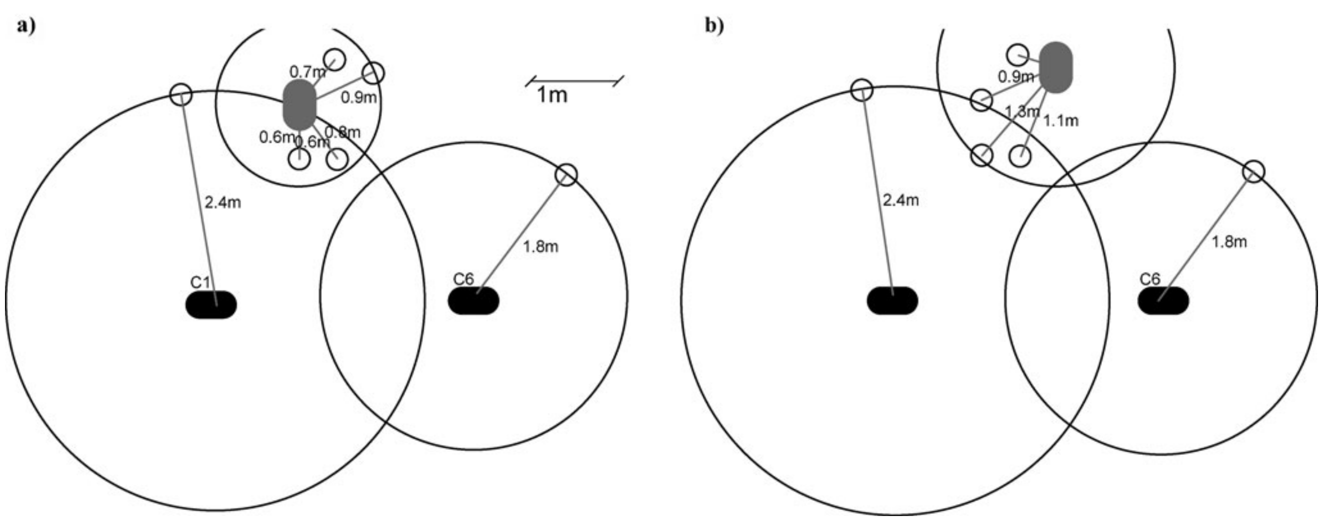

Fig. 8 Comparison of a criterion based on minimizing of distance between BT devices and the proposed the coexistence algorithm minimizing the mutual interferences

Table 4 Average FER values for Bluetooth (class II devices) and 802.11b network devices (example 3—Fig. 6; AWGN Channel)

	Role-switch mechanism	Min distance criterion
Wi-Fi FER avg.	1.4%	2.7%
BT FER avg.	42.9%	56.1%

Table 5 Average FER values for Bluetooth (class II devices) and 802.11b network devices (example 4—Fig. 7; AWGN Channel)

	Role-switch mechanism	Min distance criterion
Wi-Fi FER avg.	0.0%	0.0%
BT FER avg.	48.4%	56.7%

6.1 Role-switching mechanism vs. max distance criterion

In the first case we will compare the introduced criterion with a model aimed at finding the maximum sum of distances between BT devices.

The role-switching mechanism resulted in creating the topology shown in Fig. 7a, which implied that the summary distance between devices was equal to 29.7 m. Other mechanism (aimed at finding the maximum distance between BT devices—Fig. 7b) returned the topology with the summary distance between devices equal to 51 m. In terms of the frame error rate (FER), the average improvement of 47% and 23.5% was achieved in Wi-Fi and BT networks, respectively, when using the role-switching mechanism, compared to the results for the min-distance criterion.

The last example proved that the objective to maximize the distances between devices does not always improve the transmission quality. Therefore, we will now check whether minimizing the summary distance between master and slave nodes in a BT network could improve the performance. For that purpose, we will investigate the scenario from Fig. 8.

6.2 Role-switching mechanism (IBLUEREA) vs. min distance criterion

In the example from Fig. 8, the objective to minimize the summary distance between master and slave nodes resulted in a topology, for which this sum of distances between nodes is equal to 3 m. On the other hand, the role-switching mechanism resulted in a topology with the respective summary distance equal to 3.8 m. Therefore, in the latter case, the improvement in terms of FER of 24% in a BT network was observed.

The application of both objectives (maximization or minimization of distances) is not possible without additional knowledge concerning the characteristics of investigated network. The role-switching mechanism uses this information to predict the propagation conditions as well as to estimate the probability of transmitting frames without errors.

7 Conclusions

The paper presents the advantages of using the role-switching mechanism for creation and modification of BT scatternets. Simulation results show that the advantage of the algorithm is the possibility to reduce mutual interference between BT and 802.11b networks. The results also show that the algorithm may be used together with other mechanisms even during formation of BT scatternets and may contribute to the improvement of coexistence mechanisms (such as the AFH algorithm).

To conclude, the role-switching mechanisms may yield a significant improvement in transmission quality for complex scenarios of coexistence of various technologies using the ISM band.

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