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Interference Aware Bluetooth Scatternet (Re)configuration Algorithm IBLUEREA

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Abstract. The paper presents a new algorithm IBLUEREA, which enables reconfiguration of Bluetooth (BT) scatternet to reduce mutual interferences between BT and Wi-Fi (IEEE 802.11b) networks operating on the same area. IBLUEREA makes use of proposed procedure for modelling ISM environment around a given BT scatternet. The mechanism is based on estimation of the probabilities of successful (unsuccessful) frame transmissions. This determination is useful to take a decision concerning co-existence of technologies which operate in the same ISM band (here Bluetooth and IEEE 802.11b).

Keywords: Bluetooth, IEEE 802.11b, interference, co-existence

1 Introduction

The number of various wireless technologies and network devices making use of ISM band (e.g. Bluetooth (BT) [2], IEEE 802.11b (Wi-Fi) [7] or IEEE 802.11g) is growing very fast. Due to this, it becomes more and more difficult to provide transmission parameters that can guarantee the quality of services required by co-existing networks. This specially refers to specific network devices operating in a close vicinity around other devices belonging to different independent networks, very often based on different technical and functional solutions.

In order to provide for a higher operational efficiency of a number of technological solutions working within the same area, coexistence mechanisms have been worked out [1]. Such mechanisms can be divided into two groups [1]:

- Collaborative mechanisms, requiring information exchange between IEEE 802.11b and Bluetooth devices.
- Non-collaborative mechanisms, which can be adopted by 802.11b and/or Bluetooth devices without a direct collaborative system.

Apart from the mechanisms presented in [1], examples of different collaborative algorithms can be found in the literature. Isolated examples of solutions facilitating the co-existence of various technologies can be traced, which are based on predicting the propagation conditions variability. For example, in [4] has been presented *Interference aware BLUEtooth Segmentation mechanism* which is based upon a dynamic BT frame choice (depending on the propagation conditions). This method relies upon the theoretical determination of the probability of successful frames transmission and the queuing tasks analysis. Based on such information IBLUES "undertakes" decisions concerning the choice of a frame (from those defined in specification [2]), through which the data will be transferred (e.g. DM1, DM3, DM5).

In this article a new coexistence mechanism has been presented which is correlated to the management of Bluetooth network topology. This mechanism has been named *Interference Aware BLUEtooth Scatternet (RE)configuration Algorithm* (IBLUEREA). IBLUEREA algorithm is based upon the idea of switching functions performed by those BT devices which more frequently operate in ISM band (i.e. masters) and are close to receivers/transmitters of other technology solutions (e.g. 802.11b) and BT piconets. IBLUEREA involves operating as a master (in a given piconet) for a device which simultaneously causes, and is susceptible to, little interference (comparing to other BT piconet devices and networks using other technologies). For this analysis, IBLUEREA uses a new model for comparing the efficiency of usage of ISM band.

Chapter 2 describes the above-mentioned procedure for modelling the efficiency of ISM environment. Theoretical basis of this model have been illustrated with a simple example illustrating its mechanism.

Chapter 3 presents the idea behind the IBLUEREA algorithm. Chapter 4, in turn, presents the benefits of using this algorithm. Some exemplary topology scenarios have been subject of simulations tests.

2 ISM environment modelling

While making comparisons regarding the efficiency of given ISM environments, among others, the number and function of co-existing various technology devices 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 the receivers located within their range need to be accounted for.

In [6] the general principles of scatternet description (in the form of matrixes) have been presented. The authors also suggested metrics, thanks to which the aggregated (and standardized) link capacity determination in scatternet is possible. The metrics are of little significance while tackling the interference issue, which has only been mentioned in this article. Moreover, those metrics do not enable the analyses of interference coming from other systems. Below, it has been presented the original methodology and key metrics necessary for co-existence of the Bluetooth scatternet and IEEE 802.11b network effectiveness determination.

Let us assume that a scatternet with the topology presented in Fig. 1 has been created. Devices 1 and 4 operate as masters. Piconet 1 includes slave devices with numbers 2 and 3. Whereas piconet 2 includes slaves 3 and 5. Slave no. 3 acts as a bridge between the two piconets.

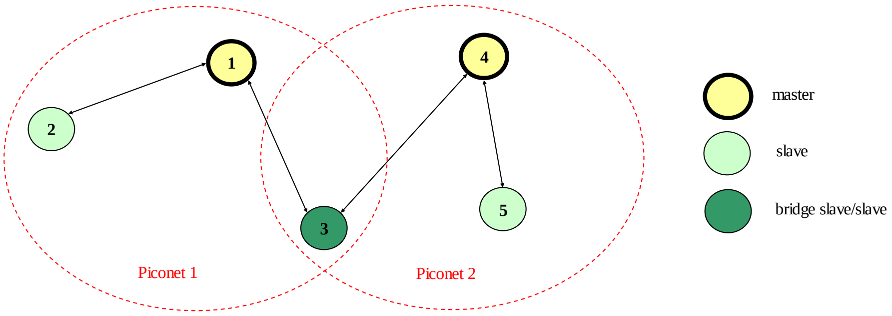

Fig. 1. An example of scatternet consisting of two BT piconets.

In order to illustrate the co-existence mechanism, Fig. 2 presents also an example of ISM environment, with possible mutual interference areas of the Bluetooth piconet and the coexisting IEEE 802.11b network. It has been assumed that the mutual interference areas are those where given technology transmitters have a substantial negative impact on the receivers of other BT piconets or 802.11b network (for example, frame error rate can, in theory, exceed a given threshold value).

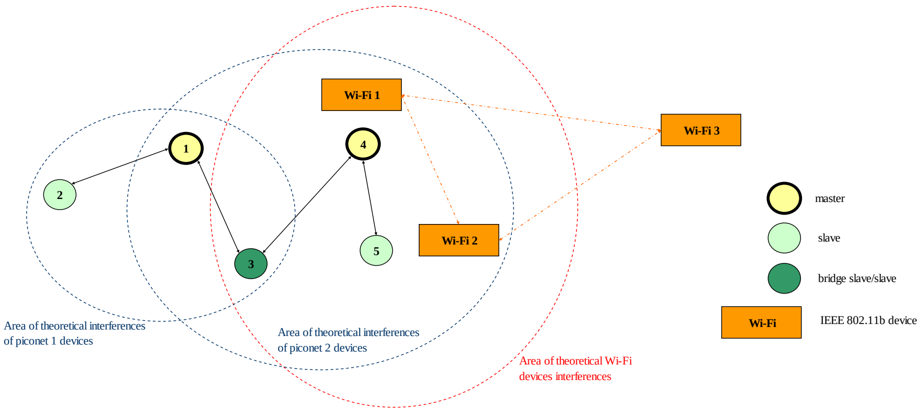

Fig. 2. Example of Bluetooth and Wi-Fi mutual interference areas

In accordance to the above illustration:

- Piconet 1 can potentially interfere the transmission of device 3, in case when it operates as an element of piconet 2[1],
- Piconet 2 jams the transmissions between 1 and 3 devices (piconet 1) and interferes the receptions at IEEE 802.11b: Wi-Fi 1 and Wi-Fi 2,
- IEEE 802.11b network interferes the transmissions of BT: 3, 4 i 5,
- Wi-Fi 3 is beyond interference over BT scatternet.

1 To simplify the analyses, it has been assumed that if a device belongs to a given piconet, it should affect the interference area under examination. In fact, the interference range of each individual device with another one should be examined.

Thus the ISM environment, defined in such way, can be formally presented using the interference matrix $\mathbf{A}_{(B+W)x(B+W)}$:

$$A_{(B+W)\times(B+W)} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \textbf{(1)}$$

where B is the number of BT scatternet devices; and W is the number of Wi-Fi network devices.

Columns of matrix **A** represent subsequent numbered: BT scatternet devices, and following IEEE 802.11b network devices. Each element $a_{i,j}$ of the matrix is created in the following way: if a given device *i* potentially interferes device *j*, then $a_{i,j}$ equals 1 (otherwise 0). Therefore, rows *i* of matrix **A** represent interfering devices, whereas columns *j* – the devices being interfered.

Matrix **A** presented in (1), informs which devices can cause interferences with other.

Let's mark additionally with: *m* – the master group, *s* – slave group (belonging to given masters) and *b* – group of bridge devices for a given scatternet. For the network presented in Fig. 2, those sets are: *m*={1;4}, *s*={(2,3);(3,5)} and *b*={3}.

Let's mark by p_i a set of all devices of the Bluetooth piconet, within which the device *i* operates.

To estimate the impact of each interfering device *i* over *j* we will create matrix **X.** This matrix specifies the theoretical estimation of intensity of devices' operation in ISM band. Let us also assume that all devices have queued tasks (traffic load = 1). The method of setting $x_{i,j}$ elements of matrix **X** has been presented below.

Each master device $i \in$ m ($i \in p_i$) interfering a given device $j \in p_j$, accordingly to the abovementioned assumptions, manages piconet p_i by polling one by one all devices which belongs to the piconet, therefore:

$$\forall_{a_{i,j}\neq 0,\, i\in m} \forall j \in p_j : x_{i,j} = \frac{a_{i,j}}{2} \quad \textbf{(2)}$$

Whereas slave device $i \in$ s ($i \in p_i$), interferes transmission of other devices at the frequency of calling up device *i* within piconet p_i, that is:

$$\forall_{a_{i,j}\neq 0,\, i\in s} \forall j \in p_j : x_{i,j} = \frac{1}{2 s_i} \quad \textbf{(3)}$$

where s_i means the number of slaves within piconet p_i.

For Bluetooth bridges $i \in b$ we assume formula (2), remembering that the bridge device can interfere all networks it connects, and within which it is not currently operating.

For determination of BT devices influence on other technology devices (here 802.11b) we assume also formulas (2)-(3).

Level of interference of 802.11b devices (influencing other devices operating in the same band - here BT devices) can be estimated with the assumption that the CSMA/CA method causes the even use of ISM band:

$$\underset{i,j \notin m \vee s}{\forall} x_{i,j} = \frac{a_{i,j}}{L_{i,j}} \tag{4}$$

where: $L_{i,j}$ – number of IEEE 802.11b devices in a given Wi-Fi network[2].

The formulas (2) - (3) relate directly to a BT scatternet, whereas (4) to IEEE 802.11b network. Using the relations from (2) to (4), matrix **A** can be modified, which now transforms to matrix **X**, presented as (5).

$$\boldsymbol{X}_{(B+W)x(B+W)} = \begin{bmatrix} 0 & 0 & 1/2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/4 & 0 & 0 & 0 & 0 & 0 \\ 1/4 & 0 & 0 & 1/4 & 1/4 & 1/4 & 1/4 & 0 \\ 1/2 & 0 & 1/2 & 0 & 0 & 1/2 & 1/2 & 0 \\ 1/4 & 0 & 1/4 & 0 & 0 & 1/4 & 1/4 & 0 \\ 0 & 0 & 1/3 & 1/3 & 1/3 & 0 & 0 & 0 \\ 0 & 0 & 1/3 & 1/3 & 1/3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

Each of the possible interferences of $a_{i,j}$ (or respectively $x_{i,j}$) features a given frame error rate, which can be specified for each situation under analysis. Therefore, it is possible to create matrix $\mathbf{B}_{(B+W)x(B+W)}$ – successful frame transmission probability matrix. The elements of matrix **B** have been described in the following way:

$$b_{i,j} = x_{i,j} \cdot (1 - P_{S(i,j)}) \tag{6}$$

where:

$P_{S(i,j)}$ – The probability of a successful frame reception by device *j*, in case of a potential interference from device *i* (and other propagation conditions).

2 Right assumption for all Wi-Fi devices, in particular those whose transmission do not affect Bluetooth scatternet efficiency (that is located in a significant distance from BT devices), but using ISM band within a given BSS.

The probability of $P_{S(i,j)}$ can be in general written as follows:

$$P_{S(i,j)} = \sum_{N} P_S(P_E \mid n) P_C(n,N) \quad \textbf{(7)}$$

where:

$P_C(n,N)$ – probability of given technology frame collision with n other technology frames (or the same technology for Bluetooth piconet) out of N possible collisions (frequency analysis),

$P_S(P_E \mid n)$ – respectively the probability of a successful reception of IEEE 802.11b frame (Bluetooth), which was subject, or was not, of a collision (time analysis).

Within $P_S(P_E \mid n)$ probability it is important to specify the bite error rate, P_E, in case of a collision and in lack of collision. The relations of the bite error rates have been presented in [1].

For the created matrix **B** its metric β can be determined, which represents standard average efficiency measure of coexisting networks:

$$\beta = \frac{1}{2}\alpha_1 + \frac{1}{2}\alpha_2 \quad \textbf{(8)}$$

where:

- α_1 – standardized BT network efficiency measure:

$$\alpha_1 = \frac{\sum_{i=1}^{B}\sum_{j=1}^{B} b_{i,j}}{\sum_{i=1}^{B}\sum_{j=1}^{B} a_{i,j}} \quad \textbf{(9)}$$

- α_2 – standardized IEEE 802.11b network efficiency measure :

$$\alpha_2 = \frac{\sum_{i=B+1}^{B+W}\sum_{j=B+1}^{B+W} b_{i,j}}{\sum_{i=B+1}^{B+W}\sum_{j=B+1}^{B+W} a_{i,j}} \quad \textbf{(10)}$$

Measure β is a numerical representation of the standardized sum of interference frequency affecting the devices within a given network (given technology solution), simultaneously allowing for the successful transmission probability (despite such interference). Having parameter β it is possible to specify the efficiency of the coexisting BT and IEEE 802.11b networks (and not only) as far as their mutual interferences are concerned. Metric β is a measure for comparing the efficiency of the complex ISM environments[3]. The lower the value of $\beta \geq 0$, the lower the interference ratio (mutual interferences) of a given ISM environment by various technologies.

[3] A constraint of this method is the lack of allowing for the traffic analysis. This method can be extended by elements of e.g. the link average capacity within given network. For the purposes of the study of interference ratio, the analysis has been focused upon the model aspects irrespective of the traffic generated within given networks.

Optimal (created) ISM environment is a such one which ensures a minimum value of β (criterion function).

Based upon the above described ISM environment efficiency comparison method, the reconfiguration (creation) of co-existing networks is possible. It would provide the lowest mutual interference ratio. The algorithm enabling such function has been presented in the following chapter.

3 Nature of IBLUEREA algorithm

IBLUEREA algorithm, which is based upon the above described ISM environment efficiency method, is a suggested reconstruction mechanism for Bluetooth scatternet. The idea behind IBLUEREA relies upon the changes of functions fulfilled by a device (master, slave, bridge). IBLUEREA decisions are taken upon ISM environment features (the above described criterion function), which encompasses the analysis of potential interferences coming from different transmitters.

IBLUEREA algorithm contains the following operations cycle, preceded by the use of a mechanism generating scatternet of a minimal number of piconets[4]:

1. BT master devices control the usage of ISM band[5] and have information on the topology within a given scatternet,
2. In case of recognition of a complex ISM environment[6], BT masters chose from them an IBLUEREA coordinator (or the device which identified the complex ISM environment becomes the coordinator).
3. The coordinator triggers the procedure of establishing parameter β_1, that is a standardized efficiency of coexisting networks (for the existing topology), simultaneously determining the network reconfiguration possibility to provide for the lowest possible interference ratio (β_2 for a new topology); information for the coordinator come from other BT devices, which determinates the frame successful transmission probability.
4. Upon collecting information from all BT master devices and the devices of other technologies (here Wi-Fi), the coordinator takes a decision on a possible network reconfiguration according to the new functions assigned.

IBLUEREA operating mechanism has been presented in Fig. 3 as a simple sequence of operations.

4 e.g. *Law, Mehta and Siu* mechanism [5].

5 Sensing the channel can be done e.g. every 30 time slot.

6 Complex ISM environment is such one which includes minimum two piconets (3 devices each) and a Wi-Fi transmitter.

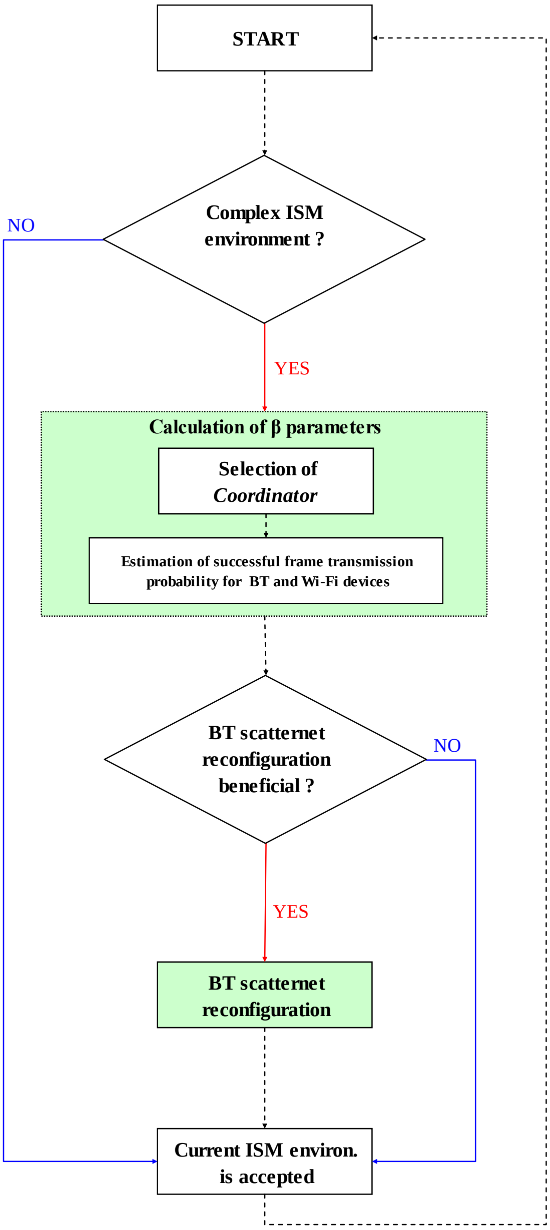

Fig. 3. IBLUEREA algorithm.

Each Bluetooth piconet is a subject of reconfiguration in order to provide for a function for such master device which is logically located as far as possible from the interference source and/or can be in the least a source of interferences itself (here 802.11b network or other BT piconets). The coordinator appoints the new master device upon a BT frame successful transmission probability (within a given piconet).

The decision of the scatternet reconfiguration takes place when the minimal (lower[7]) parameter β_2 is found (in relation to measure β_1, resulting from the current ISM environment).

To illustrate the algorithm mechanisms, examples of its functioning have been presented further on (see Fig. 4).

4 Example of IBLUEREA functioning

In order to assess IBLUEREA usefulness, let us consider some scenarios of Bluetooth and 802.11b networks operation.

Fig. 4 gives examples of theoretical topologies. The first one is a result of a BT scatternet exemplary formulating. The letter case envisages the use of IBLUEREA algorithm for Bluetooth network reconfiguration.

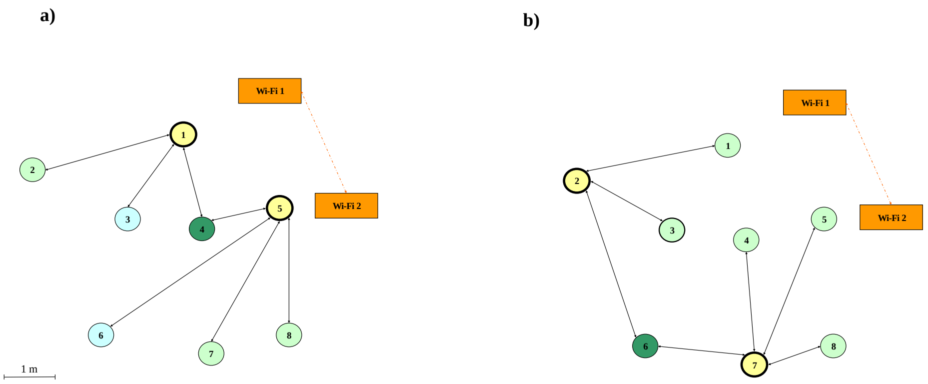

Fig. 4. Illustration of functioning of IBLUEREA algorithm: a) topology before reconfiguration, b) topology after IBLUEREA algorithm effecting changes.

Let us assume that the subjects of our study are frames of 1500B for 802.11b and DH1 frames for Bluetooth (generated by constant bit rate source). By establishing parameters β for the quoted scenarios we receive respectively: $\beta_a = 0{,}26 > \beta_b = 0{,}21$. Measure β_b simultaneously specifies the minimum value of the parameter to be obtained in a such ISM environment (under the accepted comparison model).

The calculation of parameter β is necessary for taking the decision whether the suggested reconfiguration is likely to bring about expected benefits of ISM band efficiency enhancement through co-existing networks or not. It could be especially useful for highly complex ISM environments, in which in a relatively close vicinity coexist a significant number of various technologies and devices.

To illustrate the effect of IBLUEREA mechanism exemplary results of simulations[8] for a complex ISM environment are presented below.

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7 Considerations concerning the search for only lower measures β can be a result of the implementation of IBLUEREA algorithm itself.

8 It has been additionally assumed that 802.11b use two channels to enhance their throughput. It corresponds with the two independent Wi-Fi networks scenario.

Table 1 presents the results of simulation measurements for four cases (example 1). The coexistence of BT and 802.11b network was analysed which did not have coexistence mechanism triggered (FH – Frequency hopping BT) and using the AFH mechanism (Adaptive Frequency Hopping) [1] – see Fig. 4A. For the purposes of comparison a situation was analysed in which the topology was reconfigured as a result of IBLUEREA algorithm functioning (which corresponds with Fig. 4B).

Tab. 1. Average frame error rate of Bluetooth (class II devices) and 802.11b networks (example 1 - AWGN channel)

	Mechanism used			
	FH	AFH[9]	FH + IBLUEREA	AFH + IBLUEREA
Average BT FER [%]	57.0	3.9	56.8	2.4
Average 802.11 FER [%]	20.5	0.0	9.3	0.0

As presented in Tab. 1, making use of IBLUEREA mechanism (upon the analysed example) facilitates the efficiency of coexisting Bluetooth and 802.11b networks both for the scenario where no coexistence mechanism was used (FH), and where Bluetooth network triggered the AFH mechanism. As presented in the example, the efficiency with triggered AFH was increased. It needs to be stressed out that in a situation where in a close vicinity function various technology solutions, using various transmission techniques, the use of only AFH algorithm can be hindered.

To illustrate the benefits of IBLUEREA algorithm also using AFH algorithm let us analyse a more complex ISM environment (example 2). Let us assume that the ISM environment consists of 3 independent 802.11b networks and 4 BT piconets (20 class II devices) scattered over the radius of 10m. We are examining two scenarios: in the first master devices are equally located within 4m from the centre and in the letter within 9m. Table 2 compares ISM environment efficiency using AFH mode.

Tab. 2. Average frame error rate of Bluetooth (class II devices) and 802.11b networks (example 2 - AWGN channel)

	Mechanism used	
	AFH	AFH + IBLUEREA
Average BT FER [%]	12.5	4.0
Average 802.11 FER [%]	0	0

In the scenarios from the second example, in fact, the issue relating the mutual BT piconet is being examined. As shown in Tab. 2, making use of IBLUEREA algorithm can have a positive impact on the enhancement of ISM band efficiency through the use of AFH devices. It can be particularly useful for sensor networks comprising of a large number of Bluetooth devices.

9 For simplicity reasons, it has been assumed that only channels used by 802.11b network are avoided. Therefore mutual interferences only from BT piconets are possible.

5 Summary

This paper presents a new IBLUEREA mechanism based upon the use of a new model comparing the efficiency of ISM environment usage. It has been proved that IBLUEREA can facilitate the coexistence mechanisms in use (including AFH mechanism [1]).

An advantage of IBLUEREA algorithm is its potential to reduce mutual interferences of BT and 802.11b networks. It needs to be stressed out that IBLUEREA algorithm can be implemented together with other mechanisms (e.g. Law, Mehta and Siu algorithm [5]), even at the BT scatternet formation stage. A disadvantage of such an algorithm is the necessity of information exchange between coexisting technologies and additional LMP frames exchange (in Bluetooth). Moreover BT network needs to allow for the time slot to sensing the ISM band usage.

In future works, the authors plan to compare IBLUEREA mechanism while using chosen algorithms for Bluetooth network formation.

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