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Challenges of eWALL Wireless Interoperability

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Abstract Due to development of different technologies there has been significant improvement in quality of life. As a result of that, average person's lifetime duration has been increased. That triggers the problem of independent living of senior citizens. One of the main concerns of the world today is how to enable senior citizens to live independently. As a response to that, systems like eWALL are being developed. eWALL for Active Long Living is a FP7 funded project and it aims to develop system which will enable elderly people to live independently. These systems consist of a large number of sensors which make wireless sensor network. In this paper, different wireless technologies that can be used for communication in systems that are designed to support independent living of elderly people, have been described. The most important focus is at wireless personal area network technologies, like ZigBee, Bluetooth, Bluetooth Low Energy and wireless local area network technologies (e.g., Wi-Fi). There are many obstacles in designing wireless sensor network and most of them concern energy efficiency and interoperability of different technologies that are being used for communication. The main challenge in the current technology world is tremendous increase of use of various wireless devices and technologies, which can cause relatively high interference, so that the wireless devices can stop working. Using cognitive radio in solving the interoperability problem of different wireless technologies in wireless sensor networks has become interesting research topic. In this paper, research on interoperability of different wireless technologies is presented. Using Spectrum Engineering Advanced Monte Carlo Analysis Tool wireless sensors network in home environment was modelled. Interference based on devices layout and activity was investigated. Also, possible improvements that can be made with cognitive radio are investigated and obtained results are given in this paper.

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1 Introduction

Smart home environments are being developed as a response to growing number of elderly people. These environments (e.g. eWALL) consist of a large amount of sensors, which all communicate using different WPAN and WLAN technologies. A great number of sensors and devices in home environment can cause interference which is harmful for communication quality. In order to improve communication quality, interoperability between WPAN and WLAN technologies needs to be achieved. In this paper SEAMCAT simulation tool was used for conducting research of interference in home environments. We modelled a home environment where two kinds of technologies were combined: WPAN and WLAN. The following WPAN technologies were used: ZigBee, Bluetooth, Bluetooth Low Energy; used WLAN technology was Wi-Fi at 2.4 GHz. The goal was to examine interference between the technologies. The method for interference examination has been based on devices and sensors layout and their activity. Also, in order to decrease interference in smart home environments, cognitive radio rises as a possible solution. Cognitive radio was first introduced by Mitola [1]. Cognitive radio [2] is aware of its environment and based on the changes in environment, it can change its parameters (e.g. modulation, transmit power). Today, it represents a wireless communication technology that allocates scarce radio spectrum intelligently and increases spectrum utilization efficiency. In SEAMCAT, cognitive radio devices were simulated in order to compare their performance to non-cognitive radio devices in terms of interference. The paper is organized as follows; in Sect. 2, overview of related work and smart home environments projects is shown. Technologies that are being used in wireless sensor networks for systems that enable elderly people to live independently, are presented in Sect. 3. Section 4 deals with concept of interoperability in wireless sensor networks and also discusses interference in wireless sensor networks. In Sect. 5, description of used propagation model is given. In Sect. 6, SEAMCAT simulation tool was described. Results obtained by SEAMCAT simulation tools are given in Sect. 7, together with comparison of cognitive radio devices and non-cognitive radio devices performances in wireless sensor networks. Conclusions are given in Sect. 8.

2 Related Work (Smart Home Environments; EU projects)

With the technology development, quality of life gets improved. One of the main scopes of todays technology development is enabling elderly people to live independently and more comfortably. To ensure these requirements, smart home environments are being developed. Over the last couple of years, the number of projects related to smart home environment that enable elderly people to live more independently has been increasing. eWALL for Active Long Living is one of them and it is EU funded project. This project started in November of 2013 and lasts until November of 2016. Table 1 shows an overview of the projects within EU.

Table 1 Overview of projects related to smart home environment [3]

Project name	End-users	Services	Technology
Mobiserv EU FP7 Project [4]	Older adults with mobility problems	Robot monitors user's behaviour	Robot
	Informal caregivers	Reminders for eating, medication and socializing	Smart textiles for vital signs monitoring
	Medical experts	Caregivers customize Robots reminders	Optical recognition of eating, drinking and emotion
		Communication with caregivers and alerts caregivers and alerts for emergencies	Sensor inside home
Long Lasting Memories (EU FP7) [5]	Older adults cognitively healthy or with mild cognitive decline	Cognitive exercises	Wii peripheral devices for physical training
		Physical exercises ADL monitoring	Brain fitness gradior software
			eHome monitoring system
ISISEMD EU CIP ICT-PSP project (HP, AAL) [6]	Older adults with MCI	Reminders for ADL and medication	Web-based platform
	Formal caregivers	Home environment monitoring (doors, cookers, lights, bed)	Server side: J2ee-based web portal and a set of services
	Informal caregivers such as relatives	Fall detection	Client side: large touch screen PC domotic sensor wearable fall detection and GPS device
		Outdoors geo localization	
		Memory training	
		Video communication	
		Emergency button	
		Web-portal for caregivers for reminders configuration and remote monitoring	
Dem@Care [7]	Older adults with MCI	ADL recognition	Werable sensors: Physiological: WIMU, DTI-2
	Informal caregivers	Automatic assessment of cognitive situation (early Alzheimer, MCI, healthy) from short vocal exercises	Life-logging: SenseCam
	MCI clinicians	Personalized adaptive feedback	Audio-visual: wearable mic, GoPro camera
		Lifestyle monitoring: sleep, exercise, sociability, mood, eating	Ambient senors: Gear 4 Sleep Clock
		Intelligent decision support	Static cameras: Sony Kinect, ASUS RGB-D Bench, ark ADL datasets
IS-ACTIVE (EU, AAL) [8]	COPD patients in GOLD stages II and III	Physical activity monitoring and coaching in every-day life	Inertial activity sensors
	Caregivers	Virtual community	Intelligent coaching system on smartphone
			Gaming environment sensors

Table 1 continued

Project name	End-users	Services	Technology
Just Checking (Just Checking Ltd) [9]	Older adults living at home	In-home monitoring	Five sensors in every room
	Relatives, friends who are physically absent	Older adult doesn't interact with the system family receives alerts	Carers: PC/Smartphone/ Tablet to access the web platform Older adults: no input to the system

3 Wireless Technologies in Systems Enabling Independent Elderly Living

In this section, review of different technologies (e.g. ZigBee, Bluetooth, Bluetooth Low Energy, Wi-Fi) that are being used in houses with the deployed systems for surveillance and independent living of elderly people, is given. Also, examples of how these technologies are being used in smart home environments are given.

3.1 ZigBee

ZigBee [10] was developed as a standard for applications that require a low data rate wireless networking, low battery power consumption and low running costs. However, the standard provides great flexibility in compare to the other network types, with reliable and secure communication. ZigBee is a technological standard, based on the IEEE 802.15.4 standard, which is created specifically for control and sensor networks. In Industrial, Scientific, Medical (ISM) band,the data rate is limited to 250 kbps in the global 2.4 GHz, 20 kbps in the 868 MHz band used in Europe, and 40 kbps in the 915 MHz band used in North America and Australia. The ZigBee standard is built on top of the IEEE 802.15.4 standard and it is created by ZigBee Alliance organization [10]. Figure 1 shows ZigBee channels and frequencies.

3.2 Bluetooth

Bluetooth is a radio standard for short-range communication which enables a connection to be made between Bluetooth [11] devices. Bluetooth is a standard of data and speech

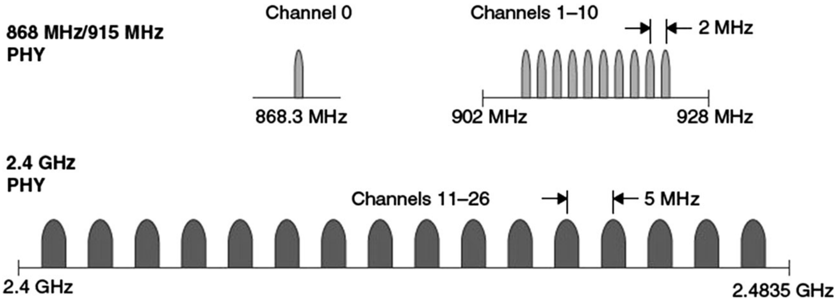


Fig. 1 ZigBee channels and frequencies

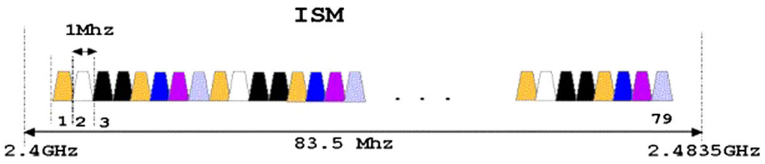


Fig. 2 Bluetooth channels and frequencies

transmission which is characterized by low price and low consumption. Bluetooth is used for short range data transmission up to 10 m. Possible transmission powers for Bluetooth are: 1 and 100 mW. With greater transmission power (e.g. 100 mW) it is possible to achieve communication range up to 100 m. IEEE 802.15.1 work group is in charge of Bluetooth standard development. With Bluetooth standard it is possible to achieve transmission rates up to 1 Mbps. This standard uses frequency range from 2.4 to 2.4835 GHz. In Fig. 2 Bluetooth channels and frequencies are shown.

3.3 Bluetooth Low Energy

Bluetooth Low Energy (BLE) [12] is an ultra-low powered feature of Bluetooth 4.0 wireless radio technology. This technology has a different protocol stack from the classic or standard Bluetooth technology. Bluetooth Low Energy still operates in the same ISM frequency band as standard Bluetooth. However, it uses a different frequency-hopping spread-spectrum (FHSS) scheme. Standard Bluetooth devices hop at a rate of 1600 hops per second over 79 channels with 1-MHz-width. Bluetooth Low Energy FHSS employs 40 channels of double size, i.e., 2-MHz-wide channels, to ensure greater reliability over longer distances. With standard Bluetooth, data rates of 1, 2, or 3 Mbit/s can be achieved, while BLEs maximum achievable rate is 1 Mbit/s. This technology has a range of up to 50 m and it is used for connectivity of devices such as PC, mobile phone, laptop or other Bluetooth enabled products. This facilitates a wide range of applications in healthcare [13], built in security [14], and ad-hoc networking [15]. Devices using Bluetooth Low Energy wireless technology are expected to consume a fraction of the power of classic Bluetooth products. Power consumption of standard Bluetooth devices is equal to 1 W, while of Bluetooth Low Energy devices is equal to 0.01–0.05 W. Products are meant to operate more than a year on a button cell batterywithout recharging. Thus, the BLE technology ensures continuous communication of sensors such as thermometers with other devices like mobile phones. In Fig. 3 Bluetooth Low Energy channels and frequencies are shown.

3.4 WLAN Technologies (Wi-Fi)

Wi-Fi stands for Wireless Fidelity [16]. Generally, it refers to any type of IEEE 802.11 Wireless Local Area Network [16]. All Wi-Fi standards use the unlicensed radio spectrum and these standards utilize spread spectrum wireless communication techniques to ensure reliable operation in RF environments. In Wi-Fi spread spectrum radios, three different spreading or modulation techniques are used: Direct Sequence Spread Spectrum (DSSS) [17], Complementary Code Keying (CCK) [17] and Orthogonal Frequency Division Multiplexing (OFDM) [17]. The IEEE 802.11 consists of different standards and the most common are the following standards [16]:

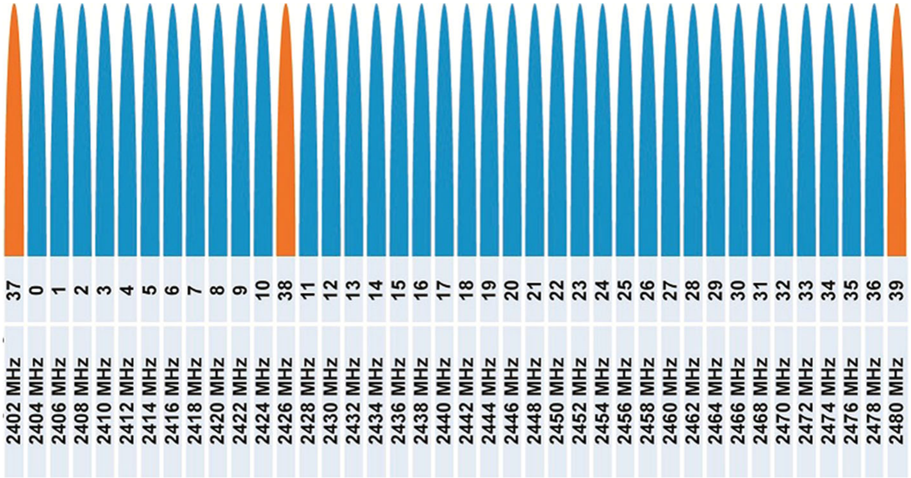


Fig. 3 Bluetooth low energy channels and frequencies

- IEEE 802.11a—The IEEE 802.11a standard is capable of providing high speeds up to 54 Mbps and it uses 5GHz ISM band.
- IEEE 802.11b—The IEEE 802.11b standard uses 2.4 GHz ISM frequency band. Even though it provides speeds up to 11 Mbps which is less than IEEE 802.11a speeds it is used more often, due to the cheaper equipment necessary for 2.4 GHz ISM band. Typical range of IEEE 802.11b standard is 30 m indoor.
- IEEE 802.11g—The IEEE 802.11g standard is introduced in 2003. It uses the 2.4 GHz ISM band, same as IEEE 802.11b standard. The difference is that IEEE 802.11g standard provides speeds up to 54 Mbps, which makes it more popular than above mentioned IEEE 802.11 standards.
- IEEE 802.11n—The IEEE 802.11n standard was introduced in July 2009. This standard provides speeds up to 600 Mbps. It uses DSSS, CCK and OFDM, 20 and 40 MHz channel width. This standard uses 2.4 and 5 GHz frequency band same as above mentioned standards.

In Fig. 4 IEEE 802.11b/g channels and frequencies are shown.

All of the above described technologies are being used in smart home environments either for remote data transfer, sensing or control [18, 19]. Smart home environments can use Bluetooth technology in different ways. One possibility is to embed appliances with Bluetooth radio transceivers and use that technology to communicate with a home server that is accessible by the user. This enables monitoring and control operations to be conducted by the user. Also, another possible application is the establishment of Bluetooth

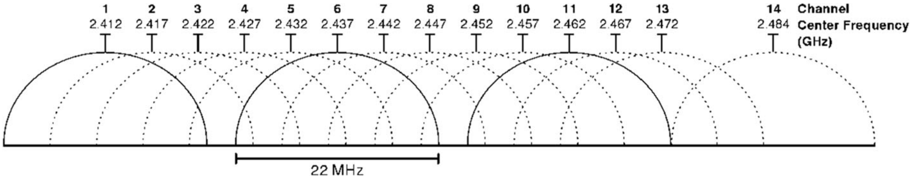


Fig. 4 WLAN channels and frequencies

enabled sensor networks that can track the well being of people with disabilities. The issue with using Bluetooth technology in smart home environments is its security vulnerability. Also, ZigBee technology was described as one of the technologies used in smart home environments. Possible applications of ZigBee technologies are in personal healthcare. This technology can be used for personal monitoring [20, 21]. Furthermore, ZigBee technology can be used in residential/light commercial control and in consumers electronic [22]. Wi-Fi standards also have an important role in smart home environment communication. Over the past years, Wi-Fi standards like IEEE 802.11b/g and IEEE 802.11n have evolved [23, 24]. The latter supports high data rates, and therefore is expected to be used in consumer electronics applications (e.g. video streaming in smart home environments) [25]. In conclusion, all of the above described technologies are used in smart home environments either for body area network (BAN), where these networks consist of different healthcare monitoring devices [26], or for WSN (surveillance, security systems and energy management), or for personal area network (PAN) [27] where they are used for multimedia.

4 Interoperability and Interference Challenges

One of the biggest challenges in wireless sensor networks is interoperability. Interoperability is defined as an ability of devices to communicate and exchange data effectively [28]. In wireless sensor networks interoperability can be defined on three levels: technical, syntactic and semantic level. In the technical level interoperability focuses on transparent network connectivity between sensor nodes, including the establishment of the communication at physical layer and medium access layer. Technical level can be improved using global and open standardization. Standards of importance for the studied case are: IEEE 802.15.4, IEEE 802.15.1 and IEEE 802.11. In each case sensor node employs a specific PHY and MAC layer to manage radio transmissions. In Fig. 5 interoperability levels are shown.

In this paper, interoperability was examined on the technical level, which means that our primary goal was to study interference, as a major issue in achieving interoperability. Namely, the expected future very high number of sensors in our local environment will result in interference, and thus, in reduction of interoperability or operability itself.

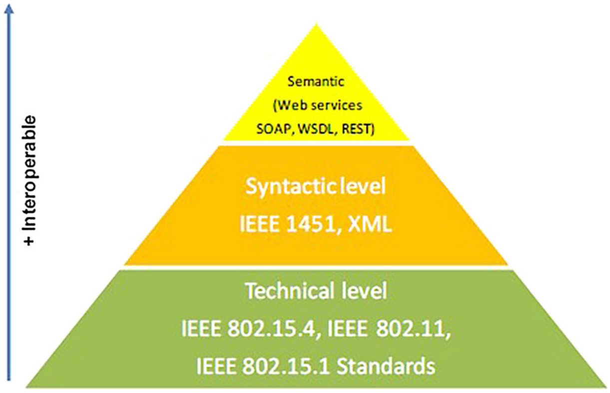


Fig. 5 Interoperability levels [29]

SEAMCAT simulation tool enables us to examine probability of interference between different technologies. Interference calculation engine (ICE) is used for calculation of interference probability. In order for this engine to be able to calculate interference probability, interference criteria need to be defined. Out of the four possible criteria [C/(I + N) carrier to interference and noise ratio; (N + I)/N noise and interference to noise ratio; I/N interference to noise ratio; C/I carrier to interference ratio], the C/I has been chosen as the main criterion. By comparing the criteria to the samples of wanted (dRSS) and unwanted (iRSS) signals, probability of interference is calculated. The probability of interference of the victim receiver is calculated as [30]:

$$p_I = 1 - p_{NI} \tag{1}$$

where p_I is probability of interference and p_{NI} is probability of non-interference of the receiver. There are different approaches of calculating interference probability. When C/I criterion is considered, p_{NI} can be calculated as follows [30]:

$$p_{NI} = \frac{P\left(\frac{dRSS}{iRSS_{comp}} > \frac{C}{I}, dRSS > sens\right)}{P(dRSS > sens)} \tag{2}$$

where $dRSS$ is desired received signal at victim receiver, $iRSS_{comp}$ is computed interfering signal at victim receiver, C/I is interference criterion and sens is victim receiver sensitivity. From equation above it can be seen that probability of non-interference equals to probability that $dRSS$ and $iRSS_{comp}$ ratio is greater than interference criterion (C/I) with condition that $dRSS$ has to be greater than receiver sensitivity. Similarly, when C/(I + N) criterion is considered, p_{NI} can be calculated as follows [30]:

$$p_{NI} = \frac{P\left(\frac{dRSS}{iRSS_{comp}+N} > \frac{C}{I+N}, dRSS > sens\right)}{P(dRSS > sens)} \tag{3}$$

When (I + N)/N criterion is considered, p_{NI} can be calculated as follows [30]:

$$p_{NI} = \frac{P\left(\frac{iRSS_{comp}+N}{N} > \frac{I+N}{N}, dRSS > sens\right)}{P(dRSS > sens)} \tag{4}$$

When I/N criterion is considered, p_{NI} can be calculated as follows [30]:

$$p_{NI} = \frac{P\left(\frac{iRSS_{comp}}{N} > \frac{I}{N}, dRSS > sens\right)}{P(dRSS > sens)} \tag{5}$$

Figure 6 shows signal levels which are used to determine the occurrence of interference.

In Fig. 6a situation when there is no interference and the victim is receiving the desired signal with a margin. In this case the victims signal level is equal to sum of sensitivity and wanted signal margin. In Fig. 6b signal levels when interference is occurring are shown. The interference adds to the noise floor. The difference between the wanted signal strength and the interference signal, measured in dB, defines the signal to interference ratio. If interference is avoided, the ratio is greater than the required C/I threshold.

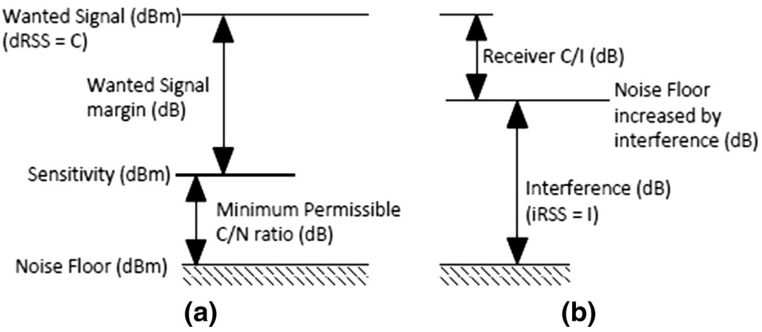


Fig. 6 The signal levels used to determine whether or not interference is occurring [30]

5 Extended Hata Propagation Model

In this chapter, extended Hata model is described. Extended Hata propagation model [31] is an empirical model designed for mobile radio applications in cluttered environment. The model ensures calculation of path loss in an urban environment. The model is extended by correction factor for sub-urban and rural environments. Extended Hata model is used for distances up to 40 km and antenna heights within the range of 1–200 m. Extended Hata propagation model can be divided into three sections [31]:

- Distances up to 40 m: Free space propagation,
- Distance from 40 to 100 m: interpolation between values L40 and L100,
- Distances 100 m: Extended Hata.

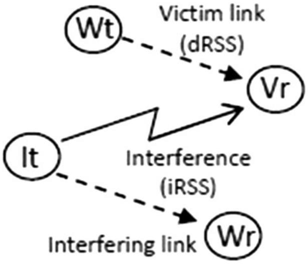
Table 2 gives description and default values of Extended Hata model parameters.

Table 2 Extended Hata propagation model parameters [31]

Parameter	Description and values
Variation	Variation in the path loss takes into account The uncertainty of building design, furniture, room size, etc
General environment	Environment of the propagation: urban, rural, suburban
Local environment (receiver)	Environment of the receiver antenna: outdoor, indoor
Local environment (transmitter)	Environment of the transmitter antenna: outdoor, indoor
Propagation environment	Environment of the propagation: below roof, above roof
Wall loss (indoor–indoor)	Default value 5 dB
Wall loss std dev (indoor–indoor)	Default value 10 dB
Wall loss (indoor–outdoor)	Default value 10 dB
Wall loss std dev (indoor–outdoor)	Default value 5 dB
Loss between adjacent floor	Default value 18.3 dB
Empirical parameters	Default value 0.46
Size of the room	Default value 4 m
Height of each floor	Default value 3 m

Fig. 7 Typical victim and interferer scenario for a Monte Carlo simulation trial

Fig. 8 Terminology used in SEAMCAT



6 SEAMCAT Simulation Tool

Interference investigation between WPAN and WLAN technologies was performed by SEAMCAT simulation tool [32]. In this chapter, a description of SEAMCAT simulation tool is given. SEAMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool) is a statistical simulation model that uses Monte Carlo analysis method to determine the potential interference between different radio communication systems [32]. SEAMCAT is a useful tool for sharing and compatibility studies on different equipment operating in the same or adjacent frequency bands, as well as for performing different evaluations (e.g., evaluation of different systems transmit and receive masks, evaluation of limits such as unwanted emissions, blocking and intermodulation levels). In this paper, SEAMCAT is used for investigation of coexistence and interference of different technologies. The Monte Carlo method is a statistical methodology for the simulation of random processes by randomly taking values from probability density function. With this method, SEAMCAT generates the desired and interfering signal levels at a victim receiver, and therefore probability of interference can be calculated. In this simulation tool, radio system parameters are defined by user as either constant or variable. In order to get reliable results, a large number of samples/events are applied in simulation. In most cases, number of samples is higher than 20,000. In Fig. 7 typical victim and interferer scenario for a Monte Carlo simulation trial is shown [30].

Figure 8 explains the terminology used in SEAMCAT [30].

Table 3 Relative position of sensors in relation to victim link receiver position

Sensor	Position in relation to victim link receiver position
ZigBee1	(2, 2 m)
ZigBee2	(−2, 2 m)
ZigBee3	(−4, −4 m)
Bluetooth 1	(4, 0 m)
Bluetooth 2	(0, −4 m)
Bluetooth low energy 1	(−4, 0 m)
Bluetooth low energy 2	(2m, −2 m)

7 Interference Probability Results

In this section, simulation was done using SEAMCAT software tool [32] in order to obtain results for interference of devices using Bluetooth Low Energy, ZigBee and Bluetooth technology. Wireless sensor network in home environment has been modeled by SEAMCAT simulation tool. Interference was investigated based on devices layout and activity. Also, possible improvements that can be made with cognitive radio are investigated. In order to investigate interference probability, wireless sensor network in home environment was modelled. ZigBee, Bluetooth and Bluetooth Low Energy sensors were placed in a room with size 10 by 10 m. Wi-Fi is used as a victim link, and ZigBee, Bluetooth and Bluetooth Low Energy were used as interfering links. Relative position of sensors is defined in dependency on victim link receiver and it is given in Table 3.

Based on Table 3, sensor layout in a room of size 10 by 10 m is given in Fig. 9.

In Fig. 9, ILT represents Interference Link Transmitter and ILR represents Interference Link Receiver of used sensors while Wi-Fi Tx represents transmitter of the Wi-Fi (victim) link and Wi-Fi Rx represents receiver of the Wi-Fi link. In Table 4 simulation parameters of interfering links are given.

Simulation parameters of victim link are given in Table 5.

In the first simulation, probability of interference is shown for chosen sensor layout. Simulation results are shown in Fig. 10.

It can be seen that probability of interference is rather high. It depends on transmitter power and position of sensor in relation to victim receiver and transmitter (Wi-Fi). The highest interference probability is obtained for a ZigBee sensor, and the lowest interference probability is obtained for one of the Bluetooth Low Energy sensors. Nevertheless, interference probability values are very similar. Due to high interference probability values, next step is simulation of given sensors layout with cognitive radio devices, where interference probability of those devices will be compared to interference probability of above simulated device. In SEAMCAT, cognitive radio devices refer to white spaces devices [33]. With spectrum sensing, these devices try to detect presence of protected services (i.e. Wt- wanted transmitter) in each of the potentially available channels. Spectrum sensing involves conducting a measurement within potentially available channel. Based on conducted measurement, it can be determined whether any protected service is present and transmitting. Additionally, detection threshold value, which is a key parameter for spectrum sensing, needs to be set up. If cognitive radio devices don’t detect any emission above threshold value, they are allowed to transmit. Therefore, when threshold

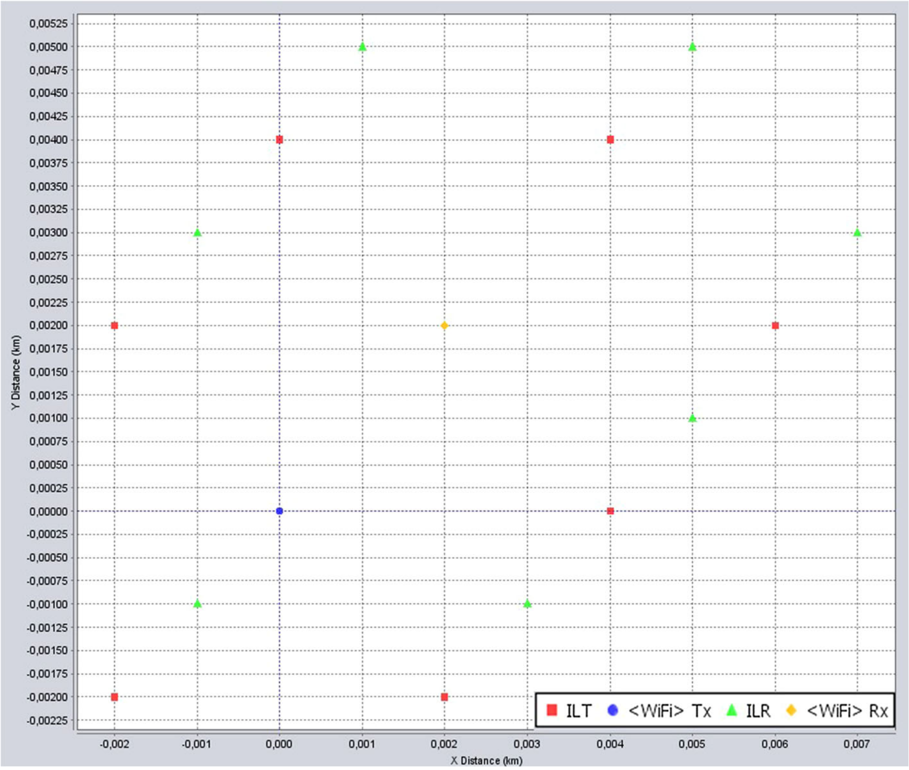


Fig. 9 Terminology used in SEAMCAT

Table 4 Relative position of sensors in relation to victim link receiver position

	ZigBee	Bluetooth	Bluetooth low energy
Power (Tx)	0 dBm	0 dBm	10 dBm
Antenna gain (Tx/Rx)	0 dBi	0 dBi	0 dBi
Frequency	2.4–2.483 GHz	2.4–2.4835 GHz	2.4 GHz
Sensitivity	−99 dBm	−71 dBm	−70 dBm
Propagation model	Extended Hata (Urban, Indoor)	Extended Hata (Urban, Indoor)	Extended Hata (Urban, Indoor)
Room size	10 × 10	10 × 10	10 × 10
Distance between Tx and Rx	1.41 m	1.41 m	1.41 m
Density of Tx	3	2	2

value is set to values much higher than the sensing received signal strength (sRSS), cognitive radio devices are allowed to transmit in any channel [34]. If a mean value of sRSS is chosen for threshold value, devices using white spaces can transmit in some channels. In other channels they are blocked. When the threshold value is set to value much

Table 5 Relative position of sensors in relation to victim link receiver position

Simulation parameter	Wi-Fi
Power (Tx)	20 dBm
Antenna gain (Tx/Rx)	0 dBi
Frequency	2.412–2.484 GHz
Sensitivity	−74 dBm
Propagation model	Extended Hata (Urban, Indoor)
Room size	10 × 10
Distance between Tx and Rx	2.828 m
Density of Tx	1

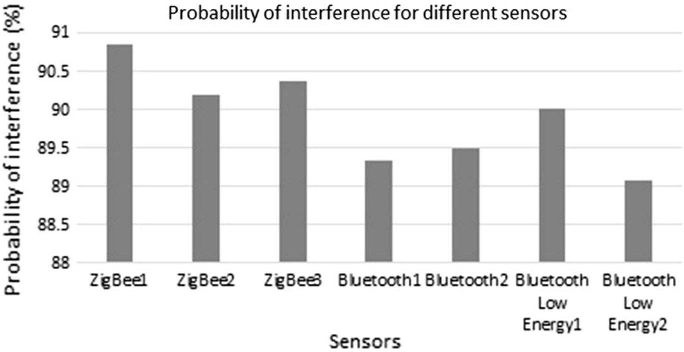


Fig. 10 Probability of interference depending on Tx density

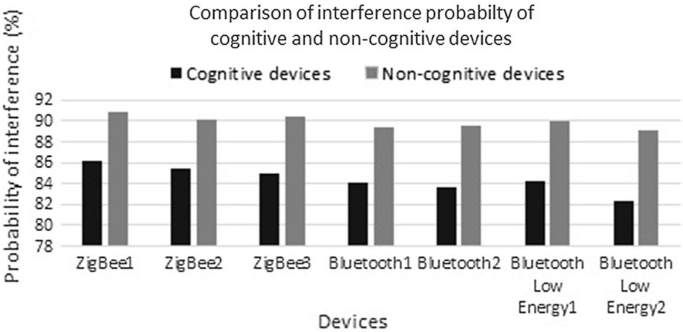


Fig. 11 Comparison of interference probability of cognitive and non-cognitive devices Threshold = −76 dBm

lower than sRSS level, all devices are blocked and can't transmit. In this paper, two different threshold values are chosen, and interference probability for these devices is compared to interference probability when non-cognitive radio devices are used. First threshold value of −76 dBm is chosen. That is a mean value of sensing received signal strength (sRSS). Figure 11 shows comparison of probability of interference for cognitive and non-cognitive radio devices.

From Fig. 11 it can be seen that when threshold value of −76 dBm is chosen, interference probability lowers. Interference is lower for 5–7% for all devices. Similar to non-cognitive devices, the highest interference is obtained by one of the ZigBee devices, and the lower interference is obtained by one of the Bluetooth Low Energy devices. Probability Density Function (PDF) of the frequencies used by cognitive devices is shown in Fig. 12.

From Fig. 13 it can be seen that when threshold value of −100 dBm is chosen, interference probability lowers. Interference is lower for about 45% for all devices. Interference probability is similar for all of the cognitive devices, and is around 50%. In Fig. 14 Probability Density Function (PDF) of the frequencies used by cognitive devices is shown. It can be seen that due to the lower threshold value more devices are blocked and can't transmit which results in lower interference.

Also, probability of interference in dependence on number of active transmitters per hour was investigated. For purpose of this simulation, new devices layout was used. In Table 6 parameters of interfering links for this simulation are given. Victim link parameters weren't changed.

Interference probability in dependence on number of active transmitters per hour is shown in Fig. 15.

For this simulation density of 50 Tx was used. Not all of them were active all the time. Depending on number of active transmitters, interference probability was determined. In

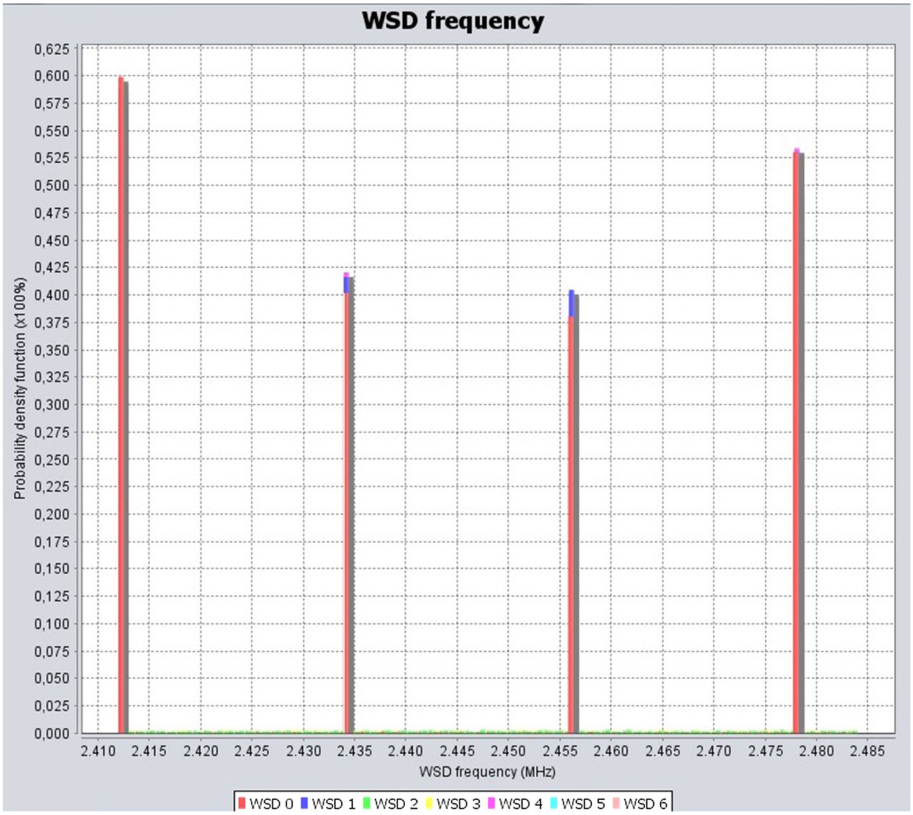


Fig. 12 Probability density function (PDF) of the frequencies used by cognitive radio devices

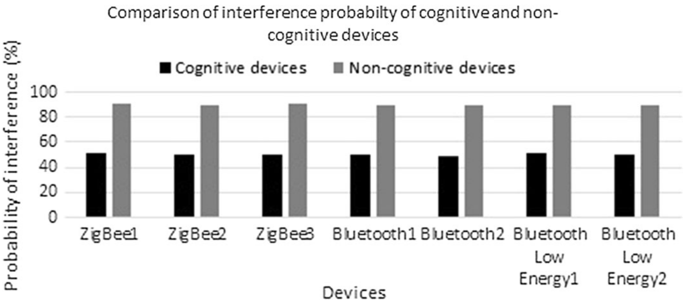


Fig. 13 Comparison of interference probability of cognitive and non-cognitive devices Threshold = −100 dBm

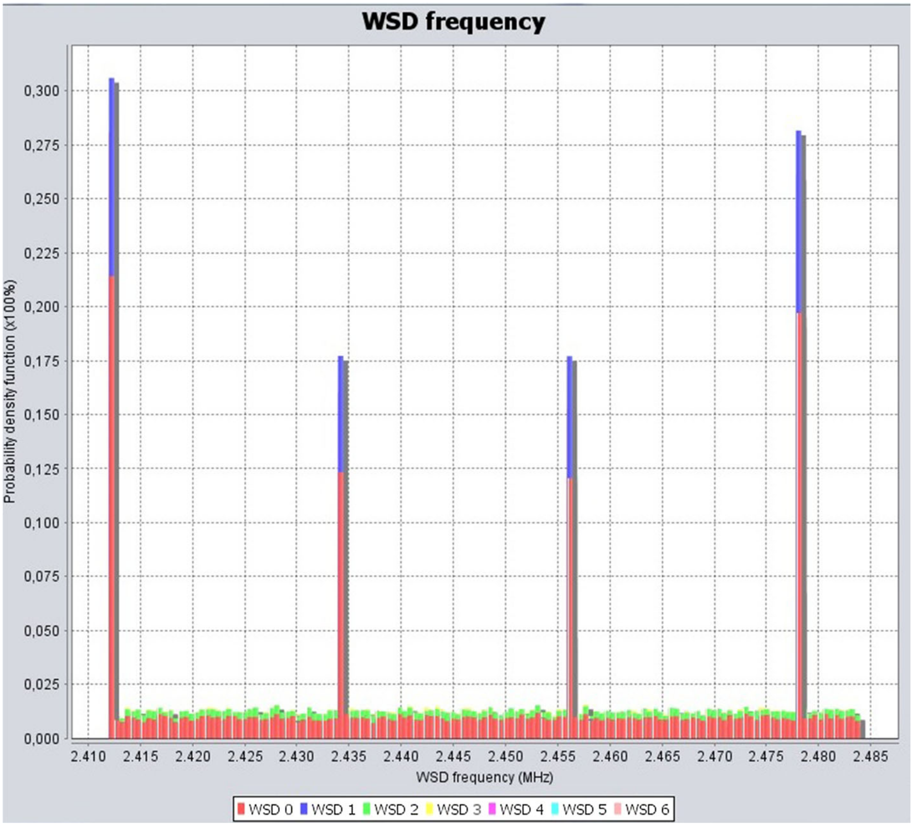


Fig. 14 Probability density function (PDF) of the frequencies used by cognitive radio devices

this scenario, the Closest interferer mode was used for devices layout. In the Closest interferer mode, there is only one interfering transmitter. That interfering transmitter is randomly placed in a circular area. Simulation radius for that area is derived from users density. From Fig. 15 it can be seen that the greater the number of active interferers is, the interference probability is higher. For only one active transmitter, interference probability

Table 6 Relative position of sensors in relation to victim link receiver position

	ZigBee	Bluetooth	Bluetooth low energy
Power (Tx)	0 dBm	0 dBm	10 dBm
Antenna gain (Tx/Rx)	0 dBi	0 dBi	0 dBi
Frequency	2.4–2.483 GHz	2.4–2.4835 GHz	2.4 GHz
Sensitivity	−99 dBm	−71 dBm	−70 dBm
Propagation model	Extended Hata (Urban, Indoor)	Extended Hata (Urban, Indoor)	Extended Hata (Urban, Indoor)
Room size	10 × 10	10 × 10	10 × 10
Simulation radius	0.1 km	0.1 km	0.1 km
Density of Tx	50	50	50
Acitivity (1/h)	1, 5, 10, 30, 50	1, 5, 10, 30, 50	1, 5, 10, 30, 50

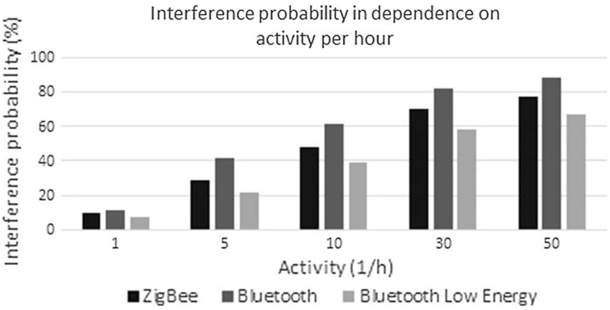


Fig. 15 Interference probability in dependence on active transmitters per hour

is between 76,64% for Bluetooth Low Energy to 11,443% for Bluetooth. When the number of active transmitters reaches 50, interference probability goes from 67,019% for Bluetooth Low Energy to 88,0% for Bluetooth, which is also the highest interference probability gained in this scenario. Thus, the highest interference is achieved for Bluetooth, while the lowest is achieved for Bluetooth Low Energy.

8 Conclusions

In this paper, interoperability problem in wireless sensor networks has been presented. Due to many different technologies that are coexisting in the expected future personal environment, interference raises as an important issue. In order to avoid interference in dense wireless sensor network, which will become part of every household with the elderly independent living system development, possibility of using cognitive radio devices is investigated. Also, interference dependency on devices activity is examined. As it was expected, with greater number of active devices, interference probability gets higher. The highest interference probability value was obtained for Bluetooth and equals to 88,08% when all 50 devices are active in 1 h. For purposes of simulation of cognitive radio devices and interference probability examination, new layout of devices has been constructed. It consists of three ZigBee devices, two Bluetooth and two Bluetooth Low Energy devices. The goal was to investigate interference when non cognitive radio devices were used and compare those results to the case with the used cognitive radio devices. Two scenarios were considered with cognitive radio devices. The first, when the threshold value is set to -76 dBm and the second, when the threshold value is set to -100 dBm. In the first case, there are slight improvements in interference probability: namely, compared to the case with the non-cognitive devices, interference probability is lower in this case for 5–7% for all devices. Also, interference probability values are different for each cognitive radio device. The highest interference is obtained with one of the ZigBee devices, and the lowest with one of the Bluetooth Low Energy devices. This is not the case when threshold value is set to -100 dBm. In this case, there is a significant improvement in interference probability. Interference for cognitive radio devices is about 50% and is similar for each used device. The results obtained in this paper clearly show that there is a problem with interference in smart home environment. This problem can be avoided or significantly reduced by using cognitive radio techniques. Hence, our next goal is to conduct future research on using cognitive radio in smart home environments.

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