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Cooperation of wireless networks IEEE 802.15.4 and IEEE 802.11b/g – introduction and measurements

***Abstract**. Article shows a description of influence of transmission in IEEE 802.11b/g standard (commonly called Wi-Fi) on transmission in IEEE 802.15.4 standard identified with ZigBee specification. The measurement verification of influence of Wi-Fi on ZigBee is presented. This type of measurement can be useful in WSNs because they are often collocated near to wireless computer networks which may cause disturbances in data transmission.*

Streszczenie.** Artykuł przedstawia wpływ transmisji prowadzonej w standardzie IEEE 802.11b/g (popularnie nazywanym Wi-FI) na transmisję w standardzie IEEE 802.15.4 utożsamianym z ZigBee. W artykule przedstawiono pomiary różnych parametrów sieci pokazujące wpływ Wi-Fi na ZigBee. Tego typu pomiary mogą być przydatne w sieciach pomiarowych, które narażone są na zaburzenia pochodzące od obecnych prawie wszędzie bezprzewodowych sieci komputerowych **(Współdziałanie sieci IEEE 802.15.4 i IEEE 802.11b/g).

Keywords: wireless transmission, IEEE 802.15.4, IEEE 802.11, measurements, delay, SINR.
Słowa kluczowe: transmisja bezprzewodowa, IEEE 802.15.4, IEEE 802.11, pomiary, opóźnienie, SINR.

Introduction

Many wireless technologies used to build local or personal area networks (WLANs, WPANs) operate into the 2.4 GHz ISM band [1]. IEEE 802.11 (here use alternatively: 802.11, Wi-Fi) is a set of media access control (MAC) and physical layer (PHY) specifications for implementing wireless local area network (WLAN) computer communication. IEEE 802.15.4 (here use alternatively: 802.15.4, ZigBee) is a standard created and maintained by consultants which specifies the physical layer and media access control for low-rate wireless personal area networks. It is the basis for the ZigBee, ISA100.11a, WirelessHART, MiWi, and Thread specifications, each of which further extends the standard by developing the upper layers which are not defined in IEEE 802.15.4 [2].

Coexistence of devices functioning on these standards is obligatory in scenarios such as smart homes, wireless body area networks etc. [4, 5]. Since these technologies work in the unlicensed ISM band, there is no regulatory body to prioritize channel access when the devices are collocated. This results in permanent channel access by devices but at the same time leads to interference issues. Coexistence mechanism is very important in such scenarios to avoid loss of valuable information such as human occupancy, physiological parameters or information about home safety [5].

Interference adversely affects technologies under operation, in terms of packet loss which leads to increase in the number of retransmissions that eventually reduce the effective data rate. This calls a need to avoid interference and coexistence. Most works explore either the interference [6, 7] or coexistence scenarios [8] but not both, and the mathematical model is not always introduced.

Detection, measurement and possible suppression of the coexistences between ZigBee and Wi-Fi networks are studied in [9] and [10]. In other works, particularly [11] and [12], attention is devoted to the investigation of the ZigBee transmission performance, operated in the unlicensed ISM band where different Wi-Fi network configurations are provided.

In [13] the impact of Wi-Fi to ZigBee in a limited range was studied, but it was proven that transmission through two ZigBee nodes is affected by transmission between access point and a computer in IEEE 802.11b/g standard. That investigations were important for new model of delays based on delta functions. This paper shows more detailed measurements that will be used to improve delta function model in future.

IEEE 802.11b/g and IEEE 802.15.4 overview

In this section, we give a brief overview about the MAC sublayers of IEEE 802.11b/g and IEEE 802.15.4, with relevant details on CCA modes.

IEEE 802.11b/g

Wi-Fi is a local area wireless technology and it includes the IEEE 802.11b/g standards for WLAN networks. It is commonly used to provide wireless connection at home and in the office, and allows the electronic devices to communicate over a computer network. Wi-Fi services are provided in the 2.4 GHz (ISM) band, where 14 RF channels are allocated, each with a bandwidth of 22 MHz. The maximum data rates in the IEEE 802.11b/g standards are 11 Mbit/s and 54 Mbit/s, respectively.

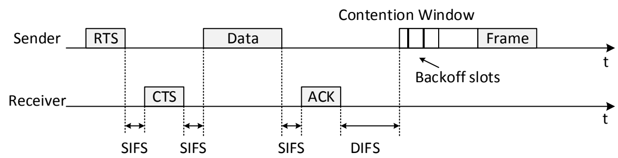

Fig.1. Messages and delays defined in the 802.11MAC protocol

The IEEE 802.11b/g MAC employs the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. CCA (Clear Channel Assessment) is used in the physical layer to determine the channel occupancy [14]. CCA performs Energy Detection (ED), or Carrier Sense (CS), or a combination of the two, i.e., CCA shall report a busy channel upon detection of any energy above the ED threshold, or a signal with the known features, e.g., the modulation and spreading characteristics, or a known signal with energy above the ED threshold. ED is a universal mechanism that can be deployed in all systems without requiring any knowledge of the type of underlying modulation scheme employed at the physical layer [15]. Before initiating a transmission, an IEEE 802.11b/g node senses a channel using either ED or CS. If the channel is sensed idle for a Distributed coordination function Inter-Frame Space (DIFS) time interval the node will transmit a packet. Otherwise, the node defers its transmission. As the channel becomes idle for a DIFS time interval, the node generates a random backoff delay based on an integer uniformly chosen in a Contention Window (CW), i.e., $[0,W]$, where W is the size of the CW.

Figure 1, which presents the key features of the 802.11 MAC protocol through a timing diagram, helps understand how Wi-Fi nodes use the wireless medium. The 802.11 standard specifies using CSMA/CA with ACKs as the MAC protocol, optionally with the addition of RTS/CTS packets [16]. The protocol also specifies the SIFS and DIFS intervals when nodes should defer using the medium.

IEEE 802.15.4

ZigBee is a wireless networking specification, based on IEEE 802.15.4. It is designed for communication scenarios, when low cost, low power and low data throughput (from 20 kbit/s to 250 kbit/s) are the most important requirements [17]. There are two versions of IEEE 802.15.4 CSMA/CA: slotted and unslotted. In this paper, we discuss only the popular unslotted one. Similarly to 802.11, also 802.15.4 devices employ the CSMA/CA channel access algorithm and the DSSS modulation.

Sixteen channels are defined for worldwide use in the 2.4 GHz band. However, differently from 802.11, they are much narrower (just 2 MHz) and do not overlap, so that up to sixteen 802.15.4 networks can easily coexist in the same area. There is also no support for dynamic channel selection.

In IEEE 802.15.4 WSNs, the channel is sensed only during a CCA period rather than during both a CCA and a backoff period, like in IEEE 802.11b/g WLANs. The standard specifies that either ED or CS (or both) is used to check the channel state, but does not provide precise algorithms. If the channel is sensed busy during the CCA period, the size of CW in IEEE 802.15.4 WSNs doubles, and when the number of the channel access attempts exceeds *macMaxCSMABackoffs*, the maximum number of backoffs the CSMA/CA algorithm will attempt before declaring a channel access failure, the pending packet is discarded [18].

Coexistence of IEEE 802.11b/g and IEEE 802.15.4

Coexistence defined as the ability of one system to perform a task in a given shared environment where other systems can or cannot work under the same set of rules.

Both IEEE 802.15.4 and IEEE 802.11b/g use CSMA/CA as their MAC channel access mechanism. A station should sense state of the medium before transmitting data. If the medium is sensed free, the station is allowed to send. While the medium is busy the station will postpone its transmission.

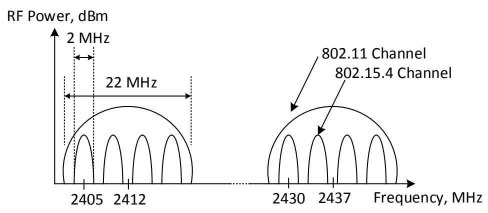

Fig.2. Transmission channels for IEEE 802.11 and 802.15.4

Figure 2 shows the allocation of the ZigBee and Wi-Fi channels over the 2.4 GHz ISM band. Single 802.11 channel completely overlaps with four ZigBee channels. The three most used non-overlapping Wi-Fi channels are 1, 6, and 11. In this case, two ZigBee channels should be free from interference from Wi-Fi transmissions, i.e. ZigBee channels 25 and 26. However, there is no assurance that using channels 25 and 26 solves the interference problem. For example, two channels might not be enough to allow coexistence among several geographically overlapping PANs.

Table 1 compares some of the technical specifications of both Wi-Fi and ZigBee. An issue that makes coexistence of Wi-Fi and ZigBee difficult is the different allowed transmission power. The maximum Wi-Fi output power can be up to 100 times higher than the maximum allowed ZigBee transmission power (100 mW vs.1 mW).

Table 1. IEEE 802.15.4 and IEEE 802.11b/g parameters

Parameter	IEEE 802.15.4	IEEE 802.11b	IEEE 802.11g
Transmit Power, dBm	0	20	20
Bandwidth, MHz	2	22	22
Transmit Rate, Mbps	25	6	54
Backoff Unit	320	20	9

The characteristics of both networks differ greatly, resulting in an asymmetric coexistence problem. To begin with, the output power of 802.15.4 devices is typically as low as 0 dBm [4], whereas the output power of 802.11b devices is usually 15 dBm or above. Next, although both techniques require a listen-before-send prior to every transmission, the sensing slot for 802.11b networks is 20 μs while for the 802.15.4 it is much larger – at 320 μs [19].

Also timing between IEEE 802.15.4. and IEEE 802.11b/g is different. Table 2 summarizes the duration of the DIFS, SIFS, and backoff slots for 802.11b and 802.11g. There are also shown the maximum and minimum packet sizes for 802.11b, 802.11g, and 802.15.4.

Table 2. Packet and interval durations for IEEE 802.15.4 and IEEE 802.11b/g

Parameter	IEEE 802.15.4	IEEE 802.11b	IEEE 802.11g
SIFS	–	30 μs	10 μs
DIFS	–	50 μs	28 μs
Slot time	320 μs	20 μs	9 μs
Initial CW	1–32	0–31	0–31
Min length packet	352 μs	202 μs	194 μs
Max length packet	4,256 μs	1,906 μs	542 μs

Measurements methodology

In order to measure accurately how Wi-Fi and ZigBee interfere with each other, we try to find a place where there are not any other devices working in the same frequency band, except the ones used in the experiments. Before each experiment, we had scanned each channel of 2.4GHz band carefully to ensure there were no other Wi-Fi/ZigBee devices active in the vicinity.

A test-bed was established to investigate the potential interference effect of IEEE 802.11b/g on IEEE 802.15.4. The basic network topology is shown in Fig. 3. There are two Wi-Fi nodes and two ZigBee nodes in total. The distance between the Wi-Fi nodes is d_M, and d means the distance between the ZigBee and Wi-Fi nodes.

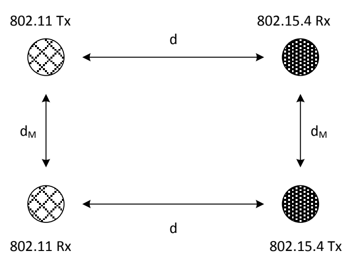

Fig.3. Basic network topology for experiments

In this work, saturated IEEE 802.11b/g interference is always assumed, which means there is always an IEEE 802.11b/g packet available for transmission. This corresponds to the presence of the worst-case of interference.

The 802.11 network in this experiment consists of an 802.11b/g access point and a laptop equipped with an 802.11 wireless radio configured in infrastructure mode. This laptop generates a stream of 1,500-byte TCP segments. Another laptop, connected to the D-Link access point through an Ethernet cable, acts as the traffic sink for the Wi-Fi network. The 802.15.4 network consists of X-Bee nodes. A dedicated sender sends one max-size packet (i.e., 128 bytes of payload) every 100 ms. The sender's transmit power is set to 0 dBm and the packets are sent to the broadcast address.

The 802.15.4 receivers are configured to accept packets with CRC errors, while the transmitted packets have a predefined byte pattern to enable off-line bit error analysis for corrupted packets. Each receiver logs the entire packet contents for all incoming packets by transmitting them to a dedicated PC over its serial interface. Additionally, ZigBee node logs transmission delay, number of send and received packets like in [13].

We examine the impact of different levels of 802.11 interference on the packet reception ratio (PRR) by varying the distance d between the 802.15.4 and 802.11 nodes. We run four sets of experiments with d = 1, 5, 10, 20, 40 meters. For each value of d, we repeat the experiment using 802.11b and 802.11g radios.

Transmission model

In [13] and [23] there was shown that transmission in wireless systems can be described by a delta function model:

(1) $$g_{\boldsymbol{B}}(\tau_{\boldsymbol{B}}) = a_0 g_{\boldsymbol{A}}(\tau_{\boldsymbol{B}} - b_0) + a_1 g_{\boldsymbol{A}}(\tau_{\boldsymbol{B}} - b_1) + \ldots + a_k g_{\boldsymbol{A}}(\tau_{\boldsymbol{B}} - b_k),$$

which is the sum of duplicates of the probability density function $g_A(\cdot)$ properly moved in time by the constant values b_0, b_1, …, b_k and multiplied by the constant coefficients a_0, a_1, …, a_k, which describe the probability of occurring the succeeding retransmissions. Eq. (1) is the probabilistic model of the total communication delay in a situation when disturbances affect the transmission, which causes the necessity of retransmissions.

Measurements results

We used four parameters additionally to RSSI, delay and LQI, to analyse our measurements.

1. SINR – signal to interference plus noise ratio (SINR) which can be defined as [20]:

(2) $$SINR = \frac{P_s}{P_n + P_i},$$

where P_s – is the power of the desired signal, P_n is the noise power, P_i – is the power of the interferer.

2. Path Loss – the path loss model represents the power loss between transmitter and receiver and is given by [21]:

(3) $$PL(d) = \begin{cases} 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) & for\ d \le d_0 \\ 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 40\log_{10}\left(\frac{d}{d_0}\right) & for\ d > d_0 \end{cases}$$

where: d – distance between 802.11 transmitter and 802.15.4 receiver, d_0 – length of line-of-sight between antennas (here over 20 m).

3. PRR – packet reception ratio – number of received packets to all transmitted packets.

During measurements we identify three types of 802.15.4 packet reception events: packets that are received correctly, packets that fail the CRC tests due to corrupted bits, and packets that are lost (i.e., transmitted but never received). Figure 5 presents the relative percentages for each of these three events for different values of d. As expected, 802.15.4 PRR (Fig. 4) is significantly reduced due to 802.11 interference, especially when the two networks are closer to each other. As d increases, the 802.15.4 PRR improves since the 802.11 interference becomes progressively weaker.

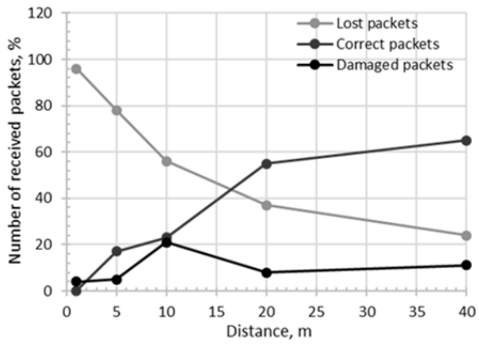

Fig.4. PRR for IEEE 802.15.4 under IEEE 802.11 interference

Consequently, we measured the signal to interference ratio SINR that is estimated for different distances between ZigBee receiver and the Wi-Fi transmitter. The ZigBee transmitter is placed at 1 meter distance of its receiver while the distance of Wi-Fi transmitter is increased gradually from 1 meter to 40 meters and the Wi-Fi is working at 11 Mbps data rate (Fig. 5).

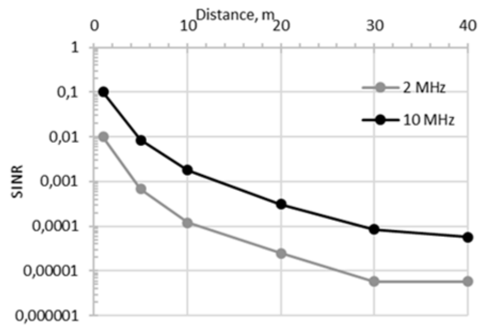

Fig.5. SINR versus distance and frequency shift of Wi-Fi channels from ZigBee transmission channel

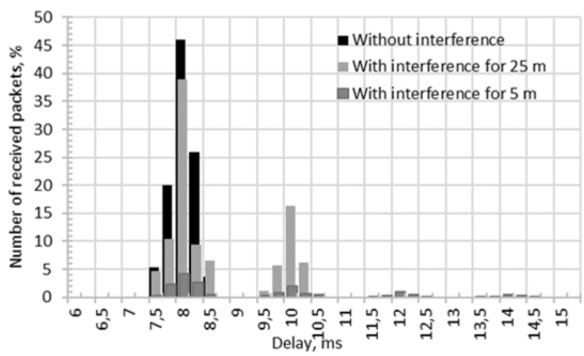

Fig.6. Delay histogram for IEEE 802.15.4 under and without Wi-Fi interference for distance of 5 meters between Wi-Fi and ZigBee

During measurements we also examined transmission delay for ZigBee nodes in absence of interference and with influence of Wi-Fi transmission. The result is shown on figure 6. The interference has a huge impact on transmission delay. If d is increasing, the interference is lowest so the delay is much smaller and a PRR is also increasing. Such a histogram can be described by mathematical delay model. For each histogram the model takes the form:

a) without interference:

(4) $$g_{\boldsymbol{B}}(\tau_{\boldsymbol{B}}) = 1 \cdot g_{\boldsymbol{A}}(\tau_{\boldsymbol{B}} - 8{,}1),$$

b) with interference for 25 meters

(5) $$g_{\boldsymbol{B}}(\tau_{\boldsymbol{B}}) = 0{,}68 \cdot g_{\boldsymbol{A}}(\tau_{\boldsymbol{B}} - 8{,}1) + 0{,}32 \cdot g_{\boldsymbol{A}}(\tau_{\boldsymbol{B}} - 10{,}2),$$

c) with interference for 5 meters

$$g_B(\tau_B) = 0{,}10 \cdot g_A(\tau_B - 8{,}1) + 0{,}04 \cdot g_A(\tau_B - 10{,}2) + + 0{,}02 \cdot g_A(\tau_B - 12{,}2) + 0{,}01 \cdot g_A(\tau_B - 14{,}1), \tag{6}$$

where g_B is the distribution of packets delay τ_B, and g_A is the pattern distribution for each histogram mode, here is the normal distribution.

Figure 7 shows a measured path loss between two 802.15.4 nodes and a path loss obtained from model (3). In regions beyond d_0 (line of sight) the second part of model is more adequate. Also we noticed that our measurements shows greater path loss what may be caused by specific condition of experiment (a long corridor).

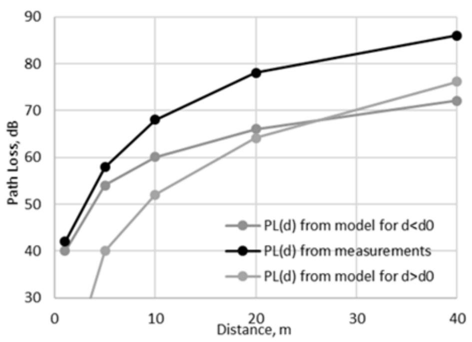

Fig.7. Path loss from measurements and model

We notice that our investigations are correlated with those in [22]. We know that transmission power of IEEE 802.11b and 802.15.4 nodes are different. The difference in transmitter power and receiver sensitivity leads to different ranges L1, L2. The L1 in our experiment is between 20 and 25 meters what the measurements of SINR have shown. Then the number of lost packets drops and the transmission parameters are very similar to obtained without interference. In L1 region the shorter timing gives IEEE 802.11b/g nodes priority over IEEE 802.15.4 nodes to access the channel and therefore causes major impossibility to get access to the channel for ZigBee. The ZigBee can sense the channel only when it is idle by the time t_{idle} when CCA mechanism is working what means:

$$t_{idle} \geq \mathrm{CCA} = \mathrm{DIFS} + t_{bo} \tag{7}$$

where t_{bo} is a random period of time called backoff time. This is also a condition of applicability of delta function model from [13] in areas with major 802.11 interference.

Conclusions

In this paper, we studied the coexistence performance of IEEE 802.15.4 WSNs under IEEE 802.11b/g interference. Paper presents investigations and measurements of a few parameters used to describe performance of IEEE 802.15.4 networks. Further research will be associated with region L1 and L2, where influence of interference is different. Consequently, the coexistence model will be introduced into delta function model of transmission delays.

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