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Abstract Wireless sensor networks have been more and more deployed for monitoring and controlling real environments. However, because of sensor nodes' limitations, their radios are more susceptible to noise and interference than in other wireless technologies. These are critical factors in the rigorous industrial environment, whose effects may not be the same on all channels of a sensor network. In this paper, we present some experimental studies about the characteristics of IEEE 802.15.4 channels in ISM band. We are particularly interested in the differences of implementing wireless sensor networks in academic and industrial environments. A common problem of wireless sensor network implementations is that most of them are purely academic or initially prepared in laboratory. Our study shows that it is very difficult to predict the quality and stability of the different channels in sensor networks, as the environment conditions greatly influence the network performance. Empirical approaches are suitable methods for choosing the appropriate channels to deploy WSNs in noisy environments. We conduct several tests in both laboratory and in a real world environment, particularly in an oil refinery as this is our case study in the context of the FP7 GINSENG project (Ginseng 2010).

Keywords Channel quality · IEEE 802.15.4 · Signal strength · Wireless sensor networks

1 Introduction

Wireless Sensor Networks (WSNs) offer a diversity of applications in most fields, including health-care, environmental monitoring, military and smart homes. However, the concept of designing and connecting many small and low cost devices leads to nodes in WSNs having limited processing and communication capabilities as well as limited memory and energy resources. Therefore, one of the main concerns in this area is to design and deploy sensor

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networks with great energy efficiency and high reliability. To do so, there are several power-saving protocols but the quality and stability of wireless channels also greatly contributes to this goal. Each wireless communication standard usually supports a set of discrete channels, allowing a wireless network to utilize a single channel or a subset of these channels. In reality, most of the wireless networks, including WSNs, are deployed using the default or a random channel since most (non-technical and technical) people assume that all channels in a standard have similar quality, i.e., they have identical characteristics (reliability, signal strength, etc). However, a defining characteristic of wireless communication is the variations of the signal strength over time and over frequency [1] which leads to the strength of a radio signal usually being unsteady and lossy. Furthermore, the radio frequency (RF) wave is influenced by multiple factors such as interference, noise, multi-path, shadowing, etc. These factors affect the error rate, delay, and signal strength in the WSNs and therefore, the reliability and the quality of service. Consequently, it is necessary to have the mechanisms to evaluate and measure the quality and the stability of a wireless channel. Although there are numerous models for theoretically predicting the channel variations over time and over frequency, it is very difficult to have an applicable model for accurately estimating and evaluating the reliability and characteristics of different channels in a wireless standard. As a result, experimentation could be considered as the most suitable method for measuring and evaluating the differences between channels in a wireless network.

IEEE 802.15.4 [2] was intended to be the key enabler for low complexity, ultra low power consumption, and low data rate wireless connectivity among inexpensive fixed, portable and moving devices. It was proposed as a standard for WSNs. IEEE 802.15.4 networks utilize three RF (radio frequency) bands: 868–868.6, 902–928 and 2,400–2,483.5 MHz; these are referred to as 868, 915, and 2,450 MHz bands, respectively. The 2,450 MHz band is commonly known as the Industrial, Scientific and Medical (ISM) band. The frequency bands, modulation techniques, and data rates of IEEE 802.15.4 (2006) is described in Table 1.

As shown in Table 1, IEEE 802.15.4 at frequency bands 868 and 915 MHz could utilize binary phase shift keying (BPSK), amplitude shift keying (ASK), or Orthogonal Quadrature Phase Shift Keying (O-QPSK) modulation while the ISM bands (2,450 MHz) only utilize O-QPSK modulation. This standard divided the available spectrum in the three bands into a total of 27 channels [2]:

- channel $k = 0$, at the frequency of 868.3 MHz
- channels $k = 1 \ldots 10$, at frequencies $906 + 2(k - 1)$ MHz
- channels $k = 11 \ldots 26$ in the ISM band, at frequencies $2{,}405 + 5(k - 11)$ MHz. Channel allocation in the ISM band is illustrated in Fig. 1a.

Table 1 Frenquency bands and data rates of IEEE 802.15.4

PHY (MHz)	Frenquency band (MHz)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbols/s)
868/915	868–868.6	BPSK	20	20
	902–928	BPSK	40	40
868/915	868–868.6	ASK	250	12.5
	902–928	ASK	250	50
868/915	868–868.6	O-QPSK	100	50
	902–928	O-QPSK	250	62.5
2450	2400–2483.5	O-QPSK	250	62.5

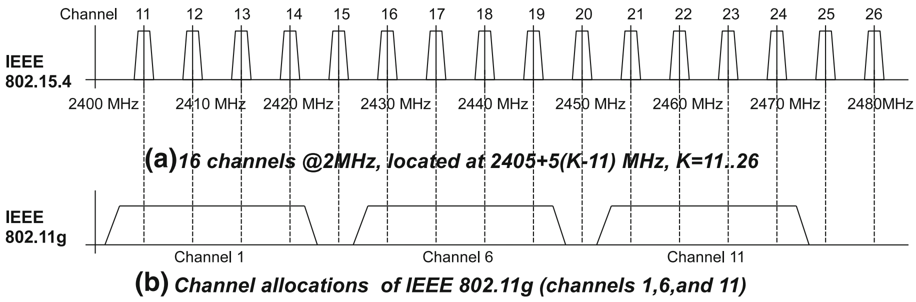


Fig. 1 Interference between IEEE 802.15.4 and wireless networks (IEEE 802.11g)

The PHY protocol of IEEE 802.15.4 can handle packets with the payload up to 127 bytes each. IEEE 802.15.4 networks support two main types of topologies: peer-to-peer and star. These networks can operate in beacon-enabled mode, which utilizes the slotted CSMA-CA access mechanism, or beaconless mode, which utilizes the unslotted CSMA-CA access mechanism. In the beacon-enabled mode, contention-free access can be provided by the coordinator, i.e., the nodes can request a guaranteed time slot (GTS) of appropriate duration and the coordinator decides whether to accept or reject the request [2,3].

As the ISM band is the most common used band and supported by most sensor vendors. In this paper, we did our experiments on sensor networks operated on the channels of this band. Since ISM band is also the home of other wireless network protocols (e.g., bluetooth, IEEE 802.11b,g), IEEE 802.15.4- based sensor networks frequently co-exist with other wireless networks, affecting each others quality and stability, but the effects of this interference may not be the same on all wireless channels. We are experiencing this problem in the context of the FP7 European Project GINSENG [4] where we are deploying a real-world implementation of a WSN at Galp Energias refinery, Portugal. While at first we started by using the default channel (e.g., channel 26), we soon discovered that the hazardous refinery environment (containing various metallic structures) greatly influenced our networks performance, which was very good in our early laboratory prototypes. This issue brought to our attention several questions: do the different channels of IEEE 802.15.4 have the same quality? How are they affected by factors such as interference and noise? How different are academic environments from real scenarios? In order to find the answers to these questions, we decided to conduct an empirical study about the characteristics of the channels of IEEE 802.15.4 in different environments. The main contribution of this work is to propose an experimental procedure for studying the characteristics of different channels of IEEE 802.15.4. In addition, different metrics (RSSI, loss rate, delay) of different channels of IEEE 802.15.4 in different environments were measured and analyzed. The results of this study showed that the performance and reliability of the IEEE 802.15.4 channels are channel-specific, location-dependent. As a matter of fact, it is necessary to do the empirical study of the deployed environment before selecting a channel or channels. As far as we know this is the first time that WSNs are being used in critical environments like refineries. From the scientific point of view this is very important because refineries represent one of the most critical industrial environments. This study was conducted in the context of FP7 GINSENG [4] project, whose main objective is to apply a performance controlled Wireless Sensor Network to control the GALP oil refinery.

The rest of this paper is organized as follows. Section 2 presents some backgrounds and related work. After that, Section 3 describes the experiment environments. Then, Sections 4, 5 and 6 describe the results of the experiments in the clean environments, the real world environments and the multi-motes sensor network, respectively. Section 7 discusses our point of view about the results. And, finally, Section 8 presents some conclusions.

2 Related Work

Wireless communication is very useful and flexible but, on the other hand, it is also susceptible to noise, interference, multi-path, obstacles, among other problems. In WSNs, because of the limited battery of sensor nodes, it is required that the radios transmit at very low power. Therefore, the effects of the above factors are more severe than in other wireless networks.

The major studies in wireless communication use radio propagation modeling [5,6], which models the behavior of radio wave propagation signals in different environments. Although these models help to predict the quality and reliability of wireless networks, it is required to have the knowledge to choose the right model for a specific environment. Therefore, the accuracy of this method is limited since different models give different results. In addition, in some environments, it is very difficult to find a suitable propagation model.

In wireless communication, the Received Signal Strength Indication (RSSI) is the measurement of the power level presented in the received signal. It is often used in localization [7,8] and in mobility algorithms. In addition, in [9] RSSI and LQI (Link Quality Indicator) were used to study the spatial and temporal characteristics of IEEE 802.15.4-compliant sensor network in a specific environment. In this study, the RSSI and LQI were measured at different locations in a specific room. The measured information could be used to predict the performance at any location in the room. A similar work was performed by Doherty et al. [10], which studied quality and stability of different channels and also compared the RSSI with the stability of channel paths. However, in this study it was difficult to understand the quality and reliability levels of different channels since it only studied these characteristics for a particular real-world environment (i.e., the printing factory in Berkeley, California) and did not present a comparison with other environments with different conditions. Furthermore, the characteristics of channels could be affected by internal interference (i.e., other sensor nodes in the same network).

3 Experiment Environments

In our experiments, we used TelosB hardware [11] and Contiki Operating System [12], as these are the platforms used in the GINSENG project. The XMAC protocol [13], a low power MAC protocol for wireless sensor networks, was employed in our empirical study since it is the most used protocol in WSNS. It is MAC protocol with duty-cycled (i.e., it uses awake, sleep intervals) for WSNs. It reduces latency and energy consumption by letting the senders send a short preambles with target address. When a receiver wakes up and receives a preambles with target address equals to its address, the receiver will send an early ACK to inform the sender that the receiver is ready to accept a packet. The short preamble saves energy at the transmitter and receiver with low latency. In addition, XMAC protocol does not support retransmission in case of packet errors (e.g., by collisions or interferences). In our experiments, the XMAC was set to turn on the radio to check the channel at the rate of 8 Hertz (i.e., 125 ms). The transmitted power in the experiments were set to 0 dBm (i.e., 1 milliwatt).

3.1 Test Locations

In order to study the characteristics of channels, different environments have been selected to perform the experiments. The first location was a room without the interference from other ISM wireless networks. The second location was an open space also without the presence of other ISM wireless networks. These two environments were considered "clean environments" since there were no interferences from other wireless networks, no obstacles, and no obvious sources of noises. The third environment was our laboratory at Informatics Department of the University of Coimbra, populated by many IEEE 802.11g wireless networks that operate on the channels 1, 6 and 11. The interference between these wireless networks and the IEEE 802.15.4 standard is shown in Fig. 1. The final and the main location was an industrial environment at the Sines refinery, Galp Energia, Portugal. While there are no other wireless networks that interfere with the IEEE 802.15.4 within the refinery, there is a considerable amount of signal noise caused by several types of machines and pumps that work 24 h a day.

3.2 Study Method

In our study, the following data was collected to study the characteristics of different channels of the IEEE 802.15.4 standard:

- Channel number
- Message sequence number
- Received Signal Strength (RSSI) of each packet
- Delay time (the time it takes to transfer a packet from sender to receiver)

In order to avoid internal interference among sensor nodes, a simple sensor network with two motes was setup to gather the necessary data. One mote acted as BaseStation and was connected to a computer to collect and record the data for post-processing and analysis. This mote also controlled which channel the sensor network should operate on and when it would switch to a different channel. Although the communication between two motes cannot represent the traffic model of a typical real multi-node WSN, it is enough to study the characteristics of channels of IEEE 802.15.4 standard (i.e., the main objective of the work in this paper). In addition, we also did some experiments with a multi-node sensor network (1 BaseStation and 3 motes) to see how the internal interference affects performance of the sensor network. The increase in the number of sensors influence the number of collisions, therefore, influence the RSS, loss rate, etc.

Since the major objective of the experiments in this paper is to study the characteristics of channels of the IEEE 802.15.4 based-sensor networks, the uniform traffic model is used. Although it is unrealistic traffic model, uniform traffic model is enough for studying the metrics for understanding the characteristics of IEEE 802.15.4 based-sensor networks. In this simple sensor network the BaseStation broadcasts a request message to the other mote every second (this schedule can be changed), which includes the message sequence number for tracing and computing the loss rate. When receiving this request message the mote measures the received signal strength, adds it to the message and sends it back to the BaseStation. In order to calculate the round-trip time between the BaseStation and the other mote, the BaseStation records both the time it sends a request message as well as the time when it receives the returned message.

Both nodes start with a predefined channel and the BaseStation employs a timer for switching to a different channel. When the timer expires, the BaseStation calculates the new channel on which the network should operate and then broadcasts a switching channel message. After waiting for 15 s, the BaseStation switches to the new channel and it continues to broadcast the request message. In our tests, the timer for switching channel was set to 5 min.

4 The Characteristics of Channels in Clean Environments

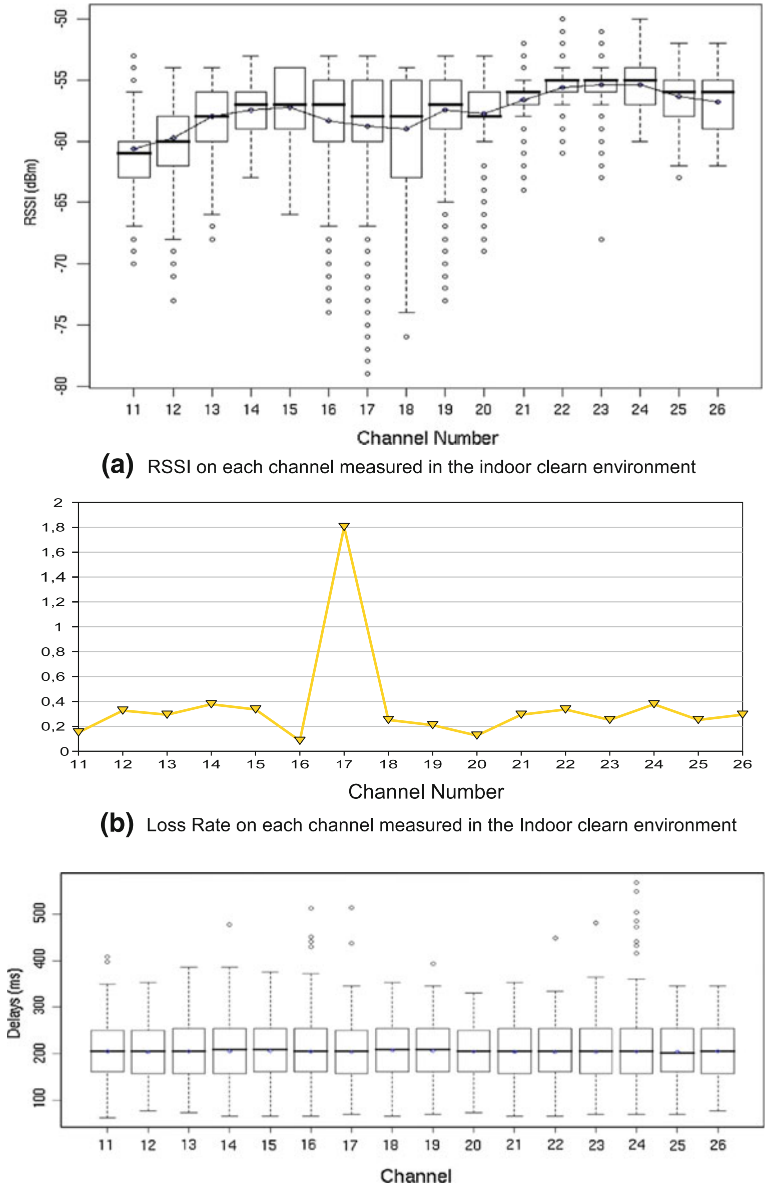
In the first two experiments we intended to study the characteristics of the IEEE 802.15.4 based-sensor networks in a clean environment, with no interference from other ISM wireless network sources and no obstacles.

For the indoor environment, we did the experiments for 20 h and the results are depicted in Fig. 2. As shown in Fig. 2a, the received signal strength of channels varies according to a sine function. It begins with a low RSSI then alternatively increases and decreases. As we can see, the RSSI of channels 11 and 12 were lower than that of the rest. In addition, some middle channels (e.g., 17 and 18) have outliers with rather low signal strength (<−75 dBm) that might affect the loss rate. As shown in Fig. 2b, some channels have higher packet loss rate than the others, especially channel 17.

The Fig. 2c shows the delay of transmission on each channel. Although the average delay was not much different among channels, some channels had outliers that may cause by collision and therefore packet loss. Although the network is simple and only comprises two nodes, packet collisions still occurs. Since the communication between two motes is two-way the collision could occur. When a packet was delayed at the received mote, the response packet sent from the received mote could probably collide with a new packet sent by the BaseStation. The delay was caused by the processing or by the duty cycled of X-MAC protocol. In addition, the large packet delay could also be caused by the quality of antena. As simplistic design philosophy and the constraints of sensor nodes, its radio often has minimum complexity (quality). Moreover, the antennae of sensor nodes are anisotropic and RSS of radio is very susceptible to the environment, a small change in position of the sensor node could result in a large variance in RSSI values. These factors lead to the instability of sensor radio. As we see from this figure, the channels with highest loss rate usually had the lowest signal strength with a larger variation (i.e., standard deviations) and/or outliers in signal strength or delay. For example, in case of channel 17, its signal strength had many outliers with very low value (<−75 dBm) as well as various outliers in delay. Consequently, its loss rate was very high. Similarly, despite having good signal strength, channel 24 had several outliers in delay, resulting in a loss rate higher than that of in other channels.

To study the variation of signal strength over time in different channels of IEEE 802.15.4 based sensor networks, a continuous experiment over 12 h was performed. In this experiment, the sensor network switched to new channel every 5 min, which means that each channel was measured nine times (t1…t9). Figure 3 shows the temporal variation of signal strength for each channel at different periods. The RSSI at each period is the mean of the measurements over 5 min. As we can see, some channels (e.g., 17, 18, and 19) had a greater variation than others. The varying behavior of the received signal strength over time shows that the reliability of some channels is not stable. For instance, as shown in Fig. 3, the signal strengths of channels 17 and 18 were very good at some periods but very poor at others.

In addition to the indoor clean environment, we also did some experiments with the outdoor clean environment (i.e., no interference sources from other ISM wireless networks and no obvious noise sources). As depicted in Fig. 4a, similarly to the indoor clean environment, some channels (e.g., 11,12, 13, and 14) had lower RSSI values than others. In addition, the channels with low RSSI usually have more packet loss, taking as an example the channels



(a) RSSI on each channel measured in the indoor clearn environment

(b) Loss Rate on each channel measured in the Indoor clearn environment

(c) Delay time on each channel measured in the Indoor clearn Environment

Fig. 2 The measurement results in the clean indoor environment

11, 13, and 15 as shown Fig. 4b. As presented in Fig. 4c, the differences in delays were not clear in this case.

The next section presents the experiment study of the characteristics of IEEE 802.15.4 channels in noisy and real environments.

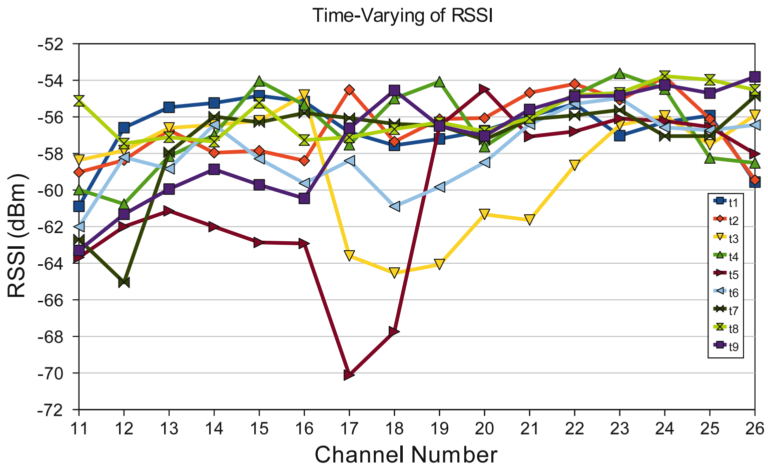


Fig. 3 Time varying of RSSI in clean indoor environment

5 The Characteristics of Channels in Real World Environments

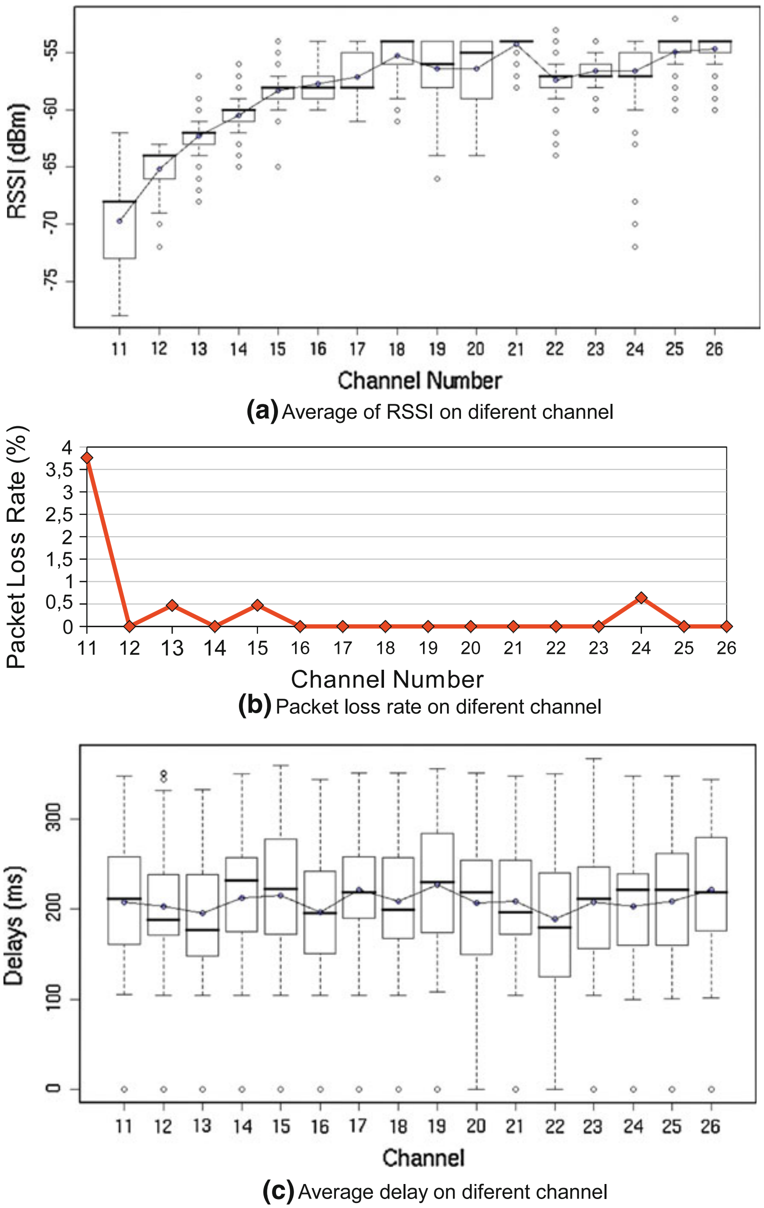
5.1 Effects of Interference of ISM Wireless Networks on IEEE 802.15.4

To study how the interference from other ISM wireless networks affects the IEEE 802.15.4 based sensor networks, we did numerous experiments at our laboratory building. The interference between the many IEEE 802.11g wireless networks present in our laboratory and an IEEE 802.15.4 based network is described in Fig. 1. From this figure, we can guess that the channels 15, 20, 25, and 26 potentially have better quality (signal strength, loss rate, delay, etc) and reliability than the others. Figure 5 shows the results of our experiments over 10 continuous hours.

As shown in Fig. 5a, besides the non-interfered channels, some other channels also have acceptable quality and reliability such as 16, 17, 19 and 21. We can also see that the best channels (high signal strength, less loss rate, and short delay time) are not the non- interfered ones. In terms of RSSI, channel 22 was the best, but in terms of loss rate channel 16 and 19 were the ones with the greatest performance. Similarly to the clean environment results depicted in Fig. 2, some initial channels (e.g., 11, 12 and 13) presented very bad results concerning quality and loss rate.

5.2 IEEE 802.15.4 in Noisy Environments

The final environment where we did experiments was the Sines Refinery, Galp Energia, Portugal. This is the environment where we have deployed the real world sensor networks as a part of GINSENG project [4], for monitoring and controlling the physical environment. As shown in Fig. 6, the results are not easy to predict. Although the RSSI of the first channel (channel 11) is better than in the other channels, in accordance to environments previously studied, its loss rate is high due to some sporadic, very low RSSI values (outliers). This means that the variation of this channel is high leading to instable results. From Fig. 6a, we also see that channels 16, 18, and 19 are more stable than the others since their signal strength is less spread (less variance). Channel 23 is the worst in term of both signal strength and loss rate.



(a) Average of RSSI on diferent channel

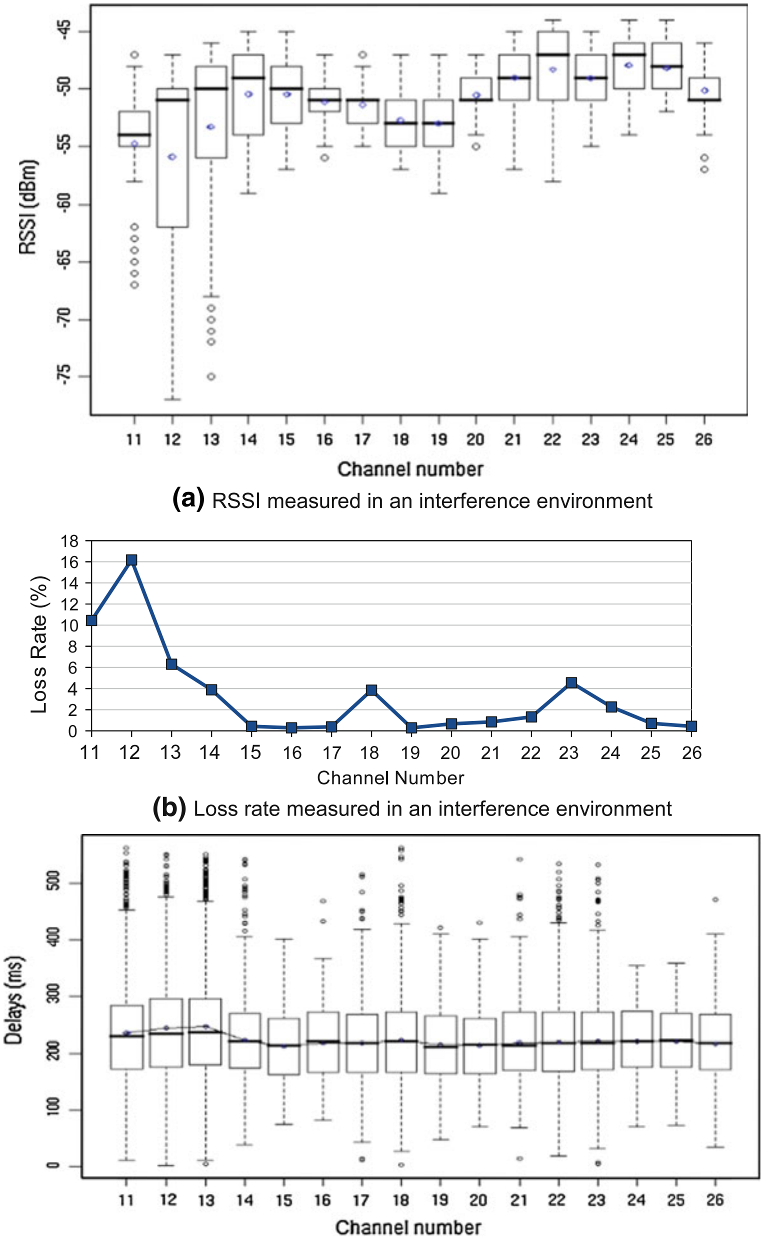
(b) Packet loss rate on diferent channel

(c) Average delay on diferent channel

Fig. 4 Measurement results from outdoor clean environment

6 The Characteristics of Channels in Multi-motes Sensor Network

To see how the internal interference influence the characteristics of IEEE 802.15.4 based sensor network, we did a numerous experiments with a four-motes sensor network in three different environments. The Fig. 7 shows the results of these experiments. As we can see from this figure that the internal interference significantly influences the loss rate. This was



(a) RSSI measured in an interference environment

(b) Loss rate measured in an interference environment

(c) Loss rate measured in an interference environment

Fig. 5 Measurement results from an interference environment

caused by the collision. However, the influence was not the same on all channels. In term of RSSI, channels 14, 15, 21, 22, and 23 seem better than the others. In term of delays, channels 13, 14, 17, 18, 20, 21 and 22 are better. Concerning loss rate, channel 14, 22 and 23 are better. From these results, we could see that channel 14 and 22 are more stable (good performance with less variance).

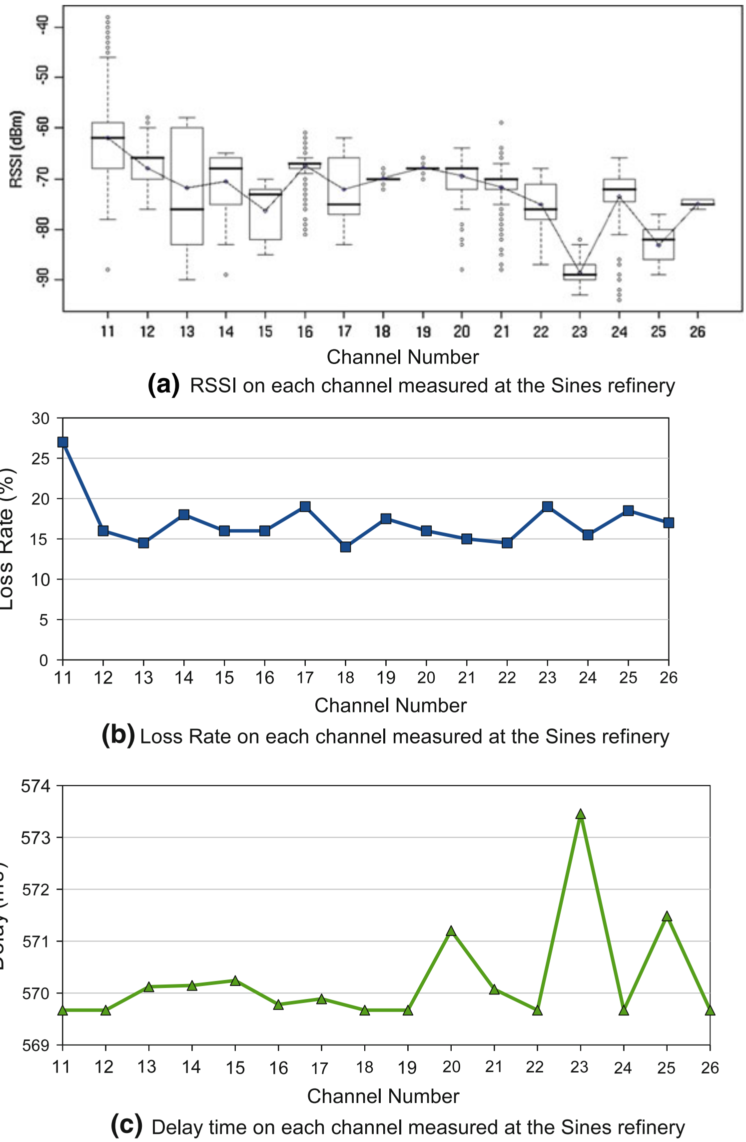


Fig. 6 Measurement results in real environment

7 Discussion

The Fig. 8 compares the means of the RSSI and loss rate values for the various IEEE 802.15.4 channels in different environments. From these results we can recognize that channels 11, 12 and 23 were not stable since their RSSI and loss rate values were in some cases good and in others very bad. Over the various experiments the channels 14, 16, 20 and 22 have proven to be the most stable, whereas channels 15, and 21 were also acceptable.

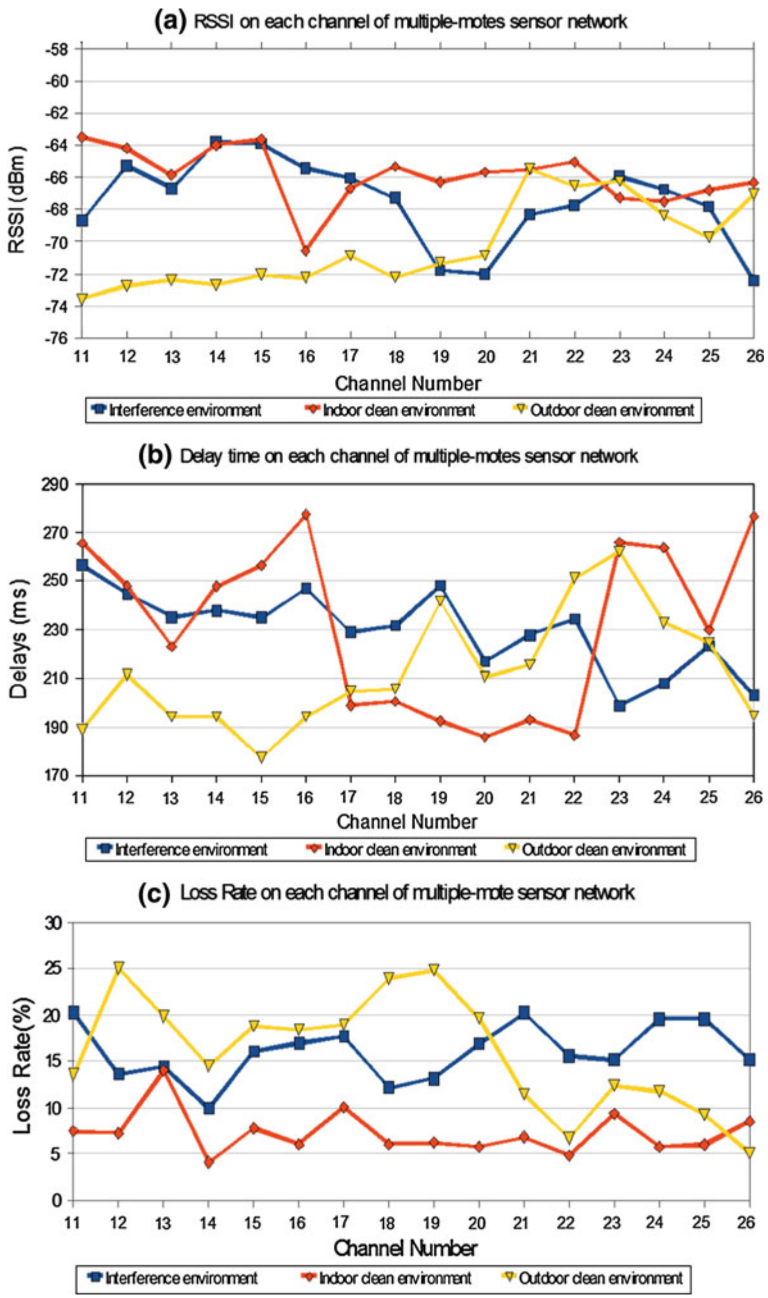


Fig. 7 Measurement results with a four motes sensor network

From the experiment results over the different environments we could make some remarks about the characteristics of channels in the IEEE 802.15.4 based sensor networks:

– The channels in the IEEE 802.15.4 ISM standard do not have the same quality and reliability. In addition, noise and interference affect each channel differently.

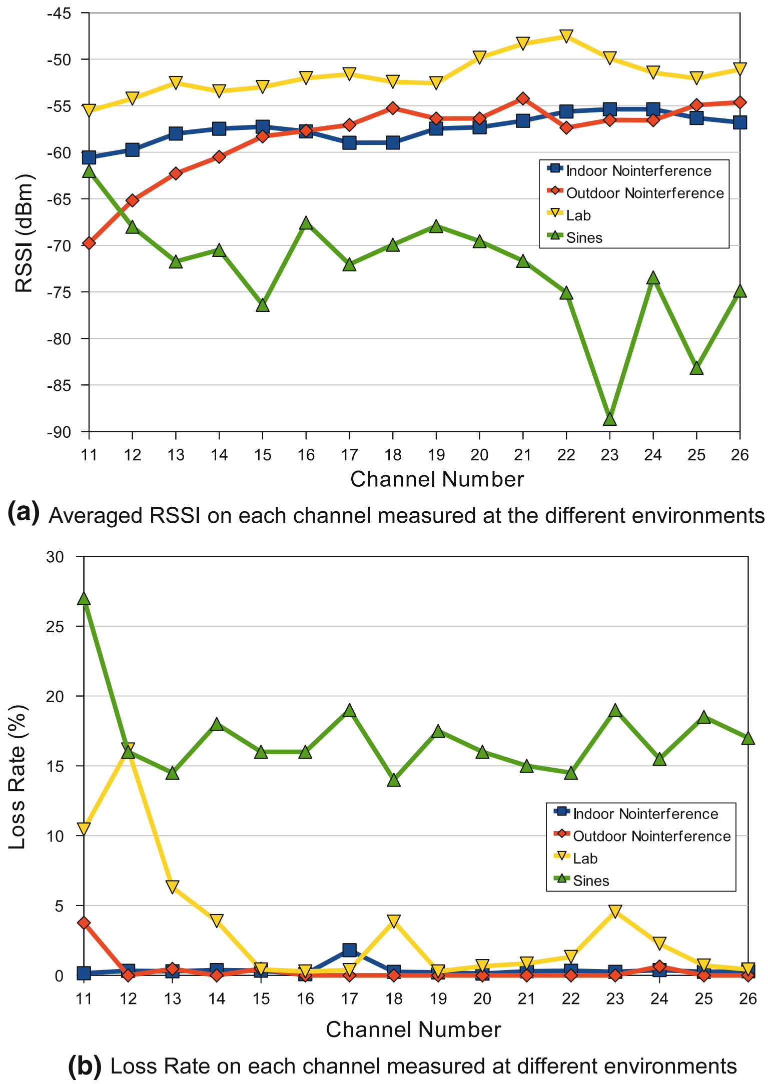


Fig. 8 Comparison among different environments

– In clean environments or in the presence of known interference sources, by using radio propagation modeling it is possible to use choose a-priory the appropriate channels for deploying a wireless sensor network. However, in environments with noisy sources, the propagation models cannot be used to accurately estimate the characteristics of wireless channels, making the task of selecting the best channels very difficult without an empirical study.

8 Conclusion

In this paper, we described several empirical studies about the characteristics of different channels of IEEE 802.15.4 in different environments. From these studies, we recognized that the channels in the same standard have different signal strengths and packet loss rates. Furthermore, the characteristics of channels also depend on the deployment environment. We also recognized that the difference in signal strength of different channels within a wireless standard has significant impact on the performance and on the reliability of the wireless communication.

From the results of our experiments, we can conclude that when deploying a wireless network, especially sensor networks, it is necessary to have an experimental evaluation phase, where the behavior of different wireless channels in the deployment environment is analyzed in order to select the most suitable one(s).

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