Channel quality of IEEE 802.15.4 based sensor networks

Thanh-Dien Tran[1], Ricardo Silva[2], David Nunes[3], Jorge Sa Silva[4]

Department of Informatics Engineering
University of Coimbra
Polo II - Pinhal de Marrocos, 3030-290 Coimbra, PORTUGAL
Email: [1]than@dei.uc.pt, [2]rnsilva@dei.uc.pt, [3]dsnunes@student.dei.uc.pt, [4]sasilva@dei.uc.pt

***Abstract*—** Channel quality of wireless networks is a topic considered by most of the network practitioners and researchers. There are several factors that affect the quality of a wireless channel, and therefore, the reliability of data delivery. Therefore, an understanding of the characteristics of a wireless channel is an essential part in the design, analysis and deployment of any wireless system. This paper establishes an empirical study of some of the major characteristics of IEEE 802.15.4 based sensor networks. The metrics used were received signal strength, loss rate and packet delay. The proposed study can be useful for selecting the most appropriate channel when deploying a wireless sensor network.

***Index Terms*— Channel Quality, Signal Strength, Wireless Sensor Networks**

I. Introduction

Wireless communication is one of the most important communication methods in use today. It is present everywhere and is used in many systems, from personal home networks to enterprise environments. Currently, there are many different standards for wireless communication with different ranges of coverage from a few meters up to several kilometers or even further. 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 Wireless Sensor Networks (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 [16]. The strength of the radio signal is usually unsteady and prone to losses. Furthermore, there are several factors that affect the quality of a wireless channel such as noise and interference. Thus, it is necessary to find a mechanism to evaluate or measure the quality of a wireless channel. Although there are numerous models for theoretically predicting the channel variations over time and frequency, it is very difficult to have an applicable model for accurately estimate and evaluate the reliability of a wireless channel. As a result, experimentation can be considered as the most suitable method for measuring and evaluating the characteristics of channels in a wireless network.

In a real environment, we encountered problems when deploying a sensor network on some specific wireless channels of IEEE 802.15.4. After being faced with these issues, we have concluded that the wireless channels in a standard do not have similar features after all (reliability, signal strength, etc). Therefore, we decided to design and establish an empirical study on characteristics of IEEE 802.15.4 based sensor networks. We do not intend to propose a propagation model for estimating the features of WSNs but instead, we only try to propose a method for empirically study the characteristics of wireless channels. Our proposed study could be used to select the appropriate channels for deploying a wireless sensor network or other wireless networks.

The rest of this paper is organized as follows. Section II presents some backgrounds and related work. After that, Section III describes the experiment environments and the proposed study model. Then, Section IV shows the results of the experiments. Section V discusses our point of view about our study on the signal strength of wireless channels. Finally, Section VI presents some conclusions and future work.

II. Backgrounds

Wireless Sensor Networks (WSNs) offer a diversity of applications in most of the 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 capability in processing and communication as well as limited memory and energy resources. Therefore, one of the main concerns of design and deployment of sensor networks is energy efficiency. There are multiple factors that affect the power consumption in WSNs, e.g., collision, interference, packet overhead, idle listening, overhearing, etc. In addition, the quality of a channel also contributes to the energy efficiency of the network. In order to theoretically estimate the different metrics of a wireless channel, several radio propagation models have been studied and proposed. The next subsection presents a short discussion of some common radio propagation models.

A. Radio Propagation Models

The modeling of the propagation channel is the process of creating models for a wireless channel with the primary purpose of predicting the received signal strength at the end of the link. Thus, a correct understanding of the propagation channel is a vital prerequisite for understanding the performance of wireless communication systems. In wireless communication, when the electromagnetic waves propagate from a transmitter to a receiver, its strength is affected by several factors including the three basic propagation mechanisms: reflection, diffraction, scattering. These three basic propagation mechanisms constitute the three main groups of the wireless channel propagation models: path loss, shadowing, and multipath fading [11]. Among these three independent groups of models only path loss is a deterministic effect because it depends only on the distance between the transmitter and the receiver. The other two are non-deterministic and depend on the wireless network's deployment environment. Currently, there are many propagation models proposed for predicting the strength of the received signal, ranging from simple models such as the free space path loss model, two ray ground, and simplified path loss model, to more complex and empirical models such as Young, Okumura, Hata and Nakagami [12], [11]. In simple models, theoretical mathematical models are used to estimate the signal strength whereas empirical models are based on extensive measurements to create the formula for estimating the signal strength.

TABLE I
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

The next subsection presents a short discussion about the IEEE 802.15.4 standard and its channels.

B. IEEE 802.15.4

IEEE 802.15.4 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 [6], [13]. It was proposed as a standard for WSNs. Currently, most sensor devices and networks support this standard. IEEE 802.15.4 networks utilize three RF (radio frequency) bands: 868 to 868.6 MHz, 902 to 928 MHz and 2400 to 2483.5 MHz; these are referred to as 868, 915, and 2450 MHz bands, respectively. The 2450 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) are described in Table I.

As shown in Table I, in IEEE 802.15.4 frequency bands at 868 and 915 MHz can utilize binary phase shift keying (BPSK), amplitude shift keying (ASK), or Orthogonal Quadrature Phase Shift Keying (O-QPSK) modulation while the ISM bands (2450 MHz) only utilize O-QPSK modulation. This standard divides the available spectrum in the three bands into a total of 27 channels [6]:

- channel k = 0, at the frequency of 868.3 MHz
- channels k = 1..10, at frequencies 906 + 2(k 1) MHz
- channels k = 11 . . 26 in the ISM band, at frequencies 2405 + 5(k 11) MHz. Channel allocation in the ISM band is illustrated in Fig. 1.

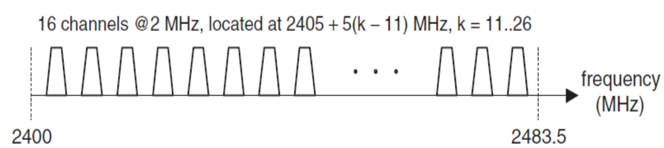

Fig. 1. Channel allocation of 2450 MHz band (IEEE2006)

The PHY protocol of IEEE 802.15.4 can handle packets with a payload up to 127 bytes each. IEEE 802.15.4 networks support two main topology types: 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 un-slotted 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 [6], [8].

Considering that the ISM band is the most commonly used band and that it is supported by most sensor vendors, our experiments focus on sensor networks that operate on channels belonging to it. The next section presents the overview of GinMAC, which was used in our experiments.

C. MAC Protocols and GinMAC

MAC protocol plays an important role in most types of networks especially wireless networks. MAC protocol is the part of the overall network functionality that deals with problems of achieving efficient, fair, and dependable access to the medium shared by a number of different devices [15]. One fundamental function of MAC protocol is to avoid collisions, i.e., interferences caused by two or more nodes transmitting at the same time. Three typical MAC protocol types have been proposed for wireless communication: time division multiple access (TDMA), code division multiple access (CDMA), and contention-based protocols like CSMA-CA.

In WSN, minimizing energy to prolong the network life time is a primary goal. “The design of the MAC protocol should prevent energy wastage due to packet collisions, overhearing, excessive retransmission, control overheads, and idle listening”[18]. Therefore, one of the main requirements of protocols for WSNs is to implement algorithms that provide energy efficiency while at the same time guaranteeing reliability, good performance, etc. Numerous MAC protocols have been proposed that try to achieve the requirements mentioned above, including: low power reservation-based MAC (TDMA) [7], B-MAC (CSMA) [9], CC-MAC (CSMA-CA) [14], S-MAC (CSMA-CA) [17], Z-MAC (TDMA/CSMA) [2], and TRAMA (TDMA/CSMA) [10].

The course of the GINSENG Project resulted in the development of a new Time Division Multiple Access (TDMA) MAC protocol [4], the GinMAC [5], which guarantees reliable and timely data delivery. The main goal of GinMAC is to provide a reliable and energy efficient control for wireless sensor networks that achieves good performance. A WSN that employs GinMAC is a multihop system with a predimensioned virtual tree topology and hierarchical addresses. The three main features of GinMAC are [3]: ***Off-line dimensioning***, i.e., the traffic patterns and channel characteristics are known before deployment; ***Exclusive TDMA***, i.e., a slot used by one node cannot be re-used by other nodes in the network; ***Delay Conform Reliability Control***, i.e., it supports delay bounds of D_S *(time to send data to sink)* and D_A (*time commands sent from the sink to actuators*) while achieving very high data transport reliability.
The main advantage of GinMAC is its assurance of good performance and reliability, i.e., losses and delivery delays are within acceptable limits at all times. In GinMAC, each node is aware of its position in the tree and knows the slot numbers assigned to its child nodes (to handle sensor data messages) and parent node (to handle sink data messages). This allows a node to transfer its data in a collision-free mode and the behaviour of network to be deterministic. In addition, the tree structure of WSNs is automatically built based on the node identification and the routing is automatically provided by GinMAC.
The preliminary prototype of the GinMAC protocol is implemented for the Contiki operating system. Currently, it has been deployed and evaluated in the industrial process control and automation of the Petrogal oil refinery at Sines (Portugal), under the GinSeng project. This example application performs real-time monitoring of industrial operations such as leakage detection, measurement of pressure in the pipes, fluid levels and also of the overall environment.

The next section details the testbed environments as well as the proposed model that was used in our experiment study.

III. The Proposed Study

This section presents the testbed environments and our experiment model for studying some characteristics of IEEE 802.15.4 based sensor networks.

A. TestBed environments

In our experiment study, two testbeds were set up: one single-hop WSN and one multi-hop WSN. The single-hop testbed environment is very simple, including one Base Station and only a few sensor nodes. The multi-hop sensor network environment is used as our testbed for the Ginseng Project [3] at FCTUC (Faculty of Sciences and Technology of the University of Coimbra, Portugal). This testbed comprises one Base Station and 15 sensor nodes (T-mote Sky nodes) that form a tree structure as depicted in Fig. 2. The testbed utilizes the ISM band of the 802.15.4 standard and employs the GinMAC protocol. One of the features of GinMAC is that the internal nodes automatically forward the received packets to the next hop until those packets reach the leaf node or Base station.

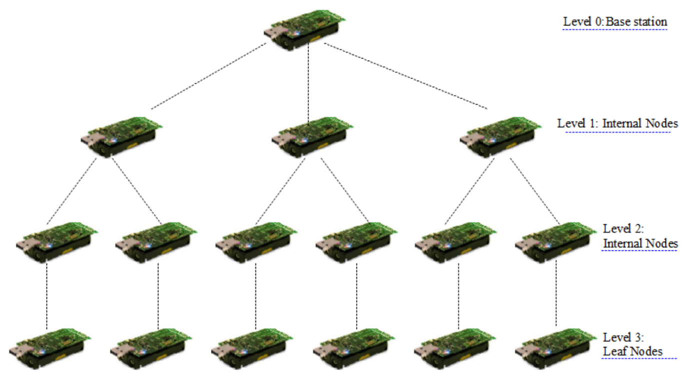

Fig. 2. Multi-hop experiment environment

The following subsection presents our proposed model for studying the characteristics of wireless channels.

B. Experiment model

In order to measure the characteristics of the wireless channels of IEEE 802.15.4 based sensor networks, we proposed an automatic channel switching model. In this model, the base station controls which channel the network will operate on and when it should switch to different one. The workflows of the base station and regular nodes are shown in Fig. 3 and Fig. 4, correspondingly.

The Base-Station starts with a predefined channel, which is set manually in the code or at installation time. As described in Fig. 4, after setting the default (start) channel, the Base-station initializes two schedules: the first one, which is fired periodically every ***tr*** time units, consists on sending request messages and the second schedule, which is fired periodically every ***tsc*** time units, is used for sending the channel switching requests. When the ***tsc*** event occurs the Base-station calculates the new channel on which the sensor network should operate and then broadcasts the channel switching messages three times, to insure that all nodes receive the request. In order to make the system work smoothly, after sending the channel switching messages the base-station will stop the schedule ***tr*** and wait for 15 seconds. After that, it will switch to the new channel and restart the ***tr*** schedule to continue the measuring process.

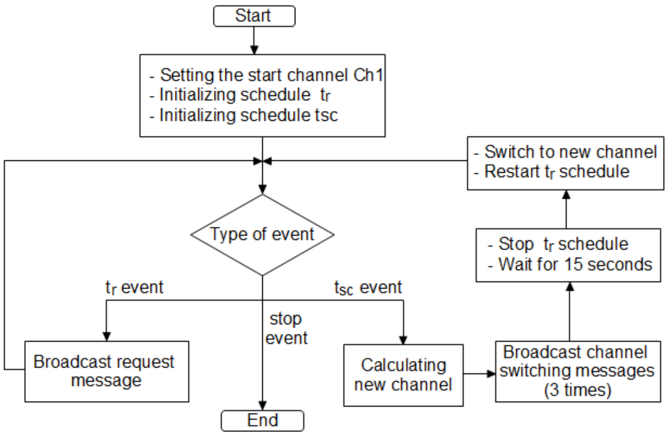

Fig. 3. Workflow of Base-station

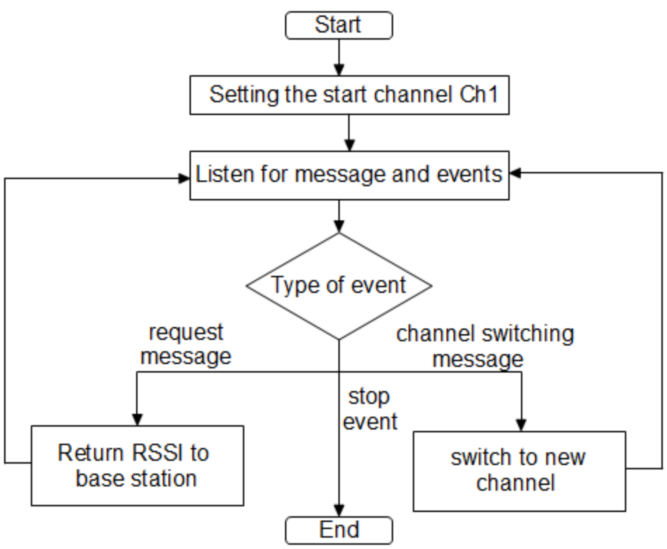

Fig. 4. Workflow of Nodes

Like the base-station, all the other nodes in a sensor network start with a predefined channel, which is set manually in the code or at installation time. The predefined channel on the nodes and base-station must always be the same. After booting, the nodes start listening for the messages and other events on the pre-defined wireless channel. When receiving request messages from the base-station, the node will get the RSSI of those messages and return this information to the base-station. If it receives a channel switching message, it will switch to the indicated channel, and start to listen on this new channel. This process is repeated indefinitely.

One issue with this model is that if during the experiment a node fails, then it is very difficult for that node to rejoin the network. This means that we have to restart all nodes (including the base station) and re-test.

IV. Experiment Results

In order to investigate the characteristics of IEEE 802.15.4 based sensor networks, we established several experiments in the above environments. In each experiment, the based station broadcasts the request message every two seconds (***tr***=2 seconds). All the other nodes, when receiving a request message from the base station, will get the RSSI values and the delay of that message and return them to the base-station.

As described in the section above, the base-station controls the channel on which the sensor network operates. In our experiments, the schedule for channel switching was 15 minutes, i.e., the base-station broadcasts the channel switching message every 15 minutes (***tsc***=15 minutes) leading the entire sensor network to operate on a new channel.

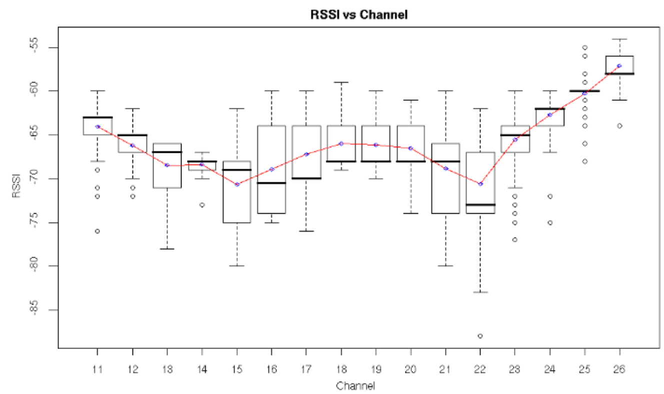

Fig. 5. RSSI vs Channel on a single-hop sensor network

The measurement results of RSSI values on different channels are presented in Fig. 5, for the single-hop sensor network, and in Fig. 6, for the multi-hop sensor network. As we can see on these two graphs, even with the same conditions (distance, noise, etc) there are different impairments in the received radio signals on different channels. In our experiment, in the case of the single-hop sensor network, without outside interference, channels 15 and 22 are the worst in terms of strength of the received signals. Channels 11, 13, 21, and 23 also include outliers and weak signals that may affect the quality of communication in sensor networks.

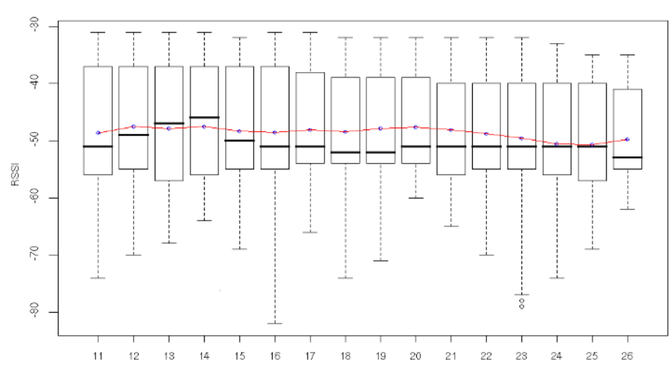

Fig. 6. RSSI vs Channel on a multi-hop sensor network

As shown in Fig. 6, in the case of the multi-hop network, channels 11, 16, 24, and 25 suffer from a greater impairment in the strength of received radio signals than other channels. Also, channels 13, 15, 18 and 23 present some outliers and weak signals that may affect the overall channel quality of the sensor network. In the experiments performed in the multi-hop network, we also conducted measurements of the delay of packets and of the loss rate on each channel. These measurements are depicted in Fig. 7 and in Fig. 8, respectively.

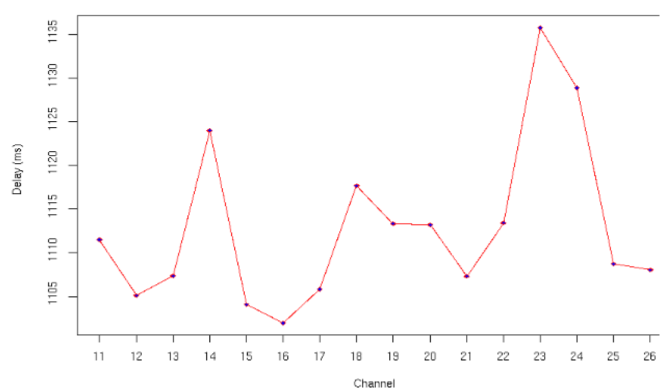

Fig. 7. Average Delay vs Channel on a multi-hop sensor network

As shown in these two figures, in most cases the channels that have high packet delays also have high packet loss rate (e.g., channel 11, 14, 24, and 25). Comparing with Fig. 6, the channels that have weaker received signal strengths (i.e., the smaller RSSI values) also have high delay and loss rate.

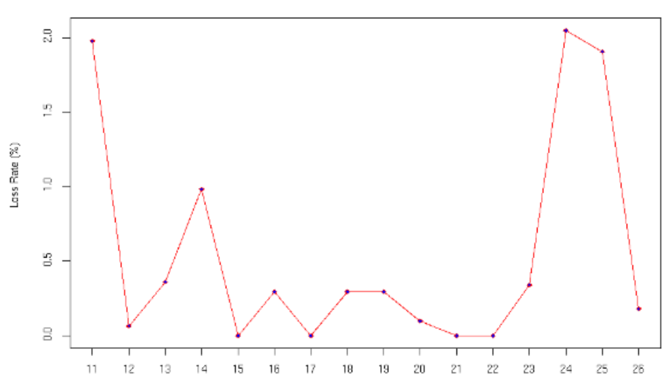

Fig. 8. Loss Rate vs Channel on a multi-hop sensor network

V. Discussion

From the above experiment study, we have acquired some useful knowledge about the characteristics of wireless channels.

The first remark is the relation between the frequency range and the signal strength. Many people believe that "usually, the channel impairments are worst at the lowest and highest end of allowable frequency range" [1]. However, throughout our experiment study we discovered that this claim is not always correct, i.e., in most experiments, the lowest and highest ends of the frequency range in IEEE 802.15.4 do not possess the weakest received signal's strength.

The second remark is the relation between wireless communication and deployment environment. While comparing Fig. 5 and Fig. 6 we recognized that the measurements of RSSI values for different channels in the two experimental cases do not fully match each other. From these results, we could deduce that the quality of wireless channels also depends on deployment environment. Environment factors such as noise and interference play an important role in the impairment of the radio signal.

Currently, there are many radio propagation models (both simple and complex) that try to theoretically calculate the signal strength at the receiver. However, these models usually produce non-reliable results when used for comparisons of different channels in a standard. Therefore, it is very difficult or maybe even impossible to guess the quality of different channels in a standard without experimental measurements. As a conclusion, in order to make a sensor network operate smoothly and reliably in the deployment environment, it is necessary to empirically evaluate the characteristics of the channels in order to select the best ones for the network.

VI. CONCLUSION

In this paper, we proposed a method for empirical study of the characteristics of wireless channels. The main points of this model are the fact that the Base-station controls the channel on which the entire network should operate and the mechanism for nodes to automatically switch between channels in a standard.

We also established numerous experiments on 802.15.4 compliant sensor networks. From these experiments, we recognized that the channels in the same standard have different signal strengths and other features that affect the channel quality. Furthermore, the characteristics of channels also depend on deployment environment. We also recognized that the difference in signal strength of different channels in a standard has a significant impact on the performance as well as on the reliability of the wireless communication.

From the results of the experiment, we could conclude that when deploying a wireless network, especially sensor networks, it is necessary to have an experimental evaluation phase of wireless channels in the deployment environment in order to select the most suitable channel(s).

As a future work, we will establish more experimental studies with different wireless networks and protocols to detect other factors that may affect the quality of a wireless channel.

ACKNOWLEDGMENT

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