New Channel Access Approach for the IEEE 802.15.4 Devices in 2.4 GHz ISM Band

Tolga Coplu and Sema F. Oktug

Abstract The number of indoor wireless communication devices and technologies employing the ISM band is increasing day by day. As a consequence, co-existence is a big challenge for tiny, IEEE 802.15.4-based and resource-constrained devices. In this paper, 2.4 GHz ISM band aggregated traffic is analyzed and a novel channel access approach is proposed based on the cognitive radio concepts in order to increase free channel access performance. The performance is evaluated by using the real-world RF signal strength measurements of an indoor IEEE 802.15.4 node with the presence of many IEEE 802.11 interferers. The performance evaluation gives promising results considering free channel access performance.

Keywords Co-existence · Cognitive radio · IEEE 802.15.4 · IEEE 802.11 · Channel access

1 Introduction

We are facing a limited bandwidth when communicating indoor wirelessly. In the 2.4 GHz Industrial, Scientific and Medical (ISM) band, the variety and the number of devices have a huge impact on the efficient use of the available bandwidth. As a result, co-existence raises a big challenge especially for the low power devices.

There are very valuable studies on the 2.4 GHz ISM band co-existence to mitigate the interference [1–5]. These studies especially focus on the co-existence of IEEE 802.11 and IEEE 802.15.4 technologies, because of their asymmetric interference

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patterns, as stated in [5, 6]. In all these techniques, the main principle is to decrease the conflicting resources. Since 2.4 GHz ISM band communication technologies are generally channel based, channel is one of the most important resources. Thus, many of the schemes in the literature propose dynamic or adaptive channel selection for better co-existence performance. Second, time is also a very valuable resource. In wireless media, there is no effective and fully utilized communication under co-existence. Therefore, determining free time slots has a key role for inner channel interference avoidance. Finally, space is another resource. Unfortunately, it cannot be effectively used since communicating devices do not have controlled mobility. However, there are important transmit power control schemes in the literature for interference mitigation.

In this work, we focus on boosting 2.4 GHz ISM band inner channel co-existence performance by using the cognitive radio concepts. The authors consider the IEEE 802.15.4 devices as the secondary users in the cognitive radio networks and the IEEE 802.11 devices as the primary users and introduce a new scheme for the channel access to be used by the IEEE 802.15.4 devices. The performance of the introduced scheme is studied under various real-life IEEE 802.11 traffic traces and promising results are obtained.

This paper is organized as follows: The analogy between ISM band co-existence and the cognitive radio concepts is given in Sect. 2. Section 3 presents the impacts of aggregated IEEE 802.11 traffic on the channel access performance of IEEE 802.15.4 devices. In Sect. 4, a new channel access scheme is explained in detail. Section 5 gives the performance evaluation of the proposed scheme using a testbed. Finally, Sect. 6 concludes the paper by giving future directions.

2 Motivation

In cognitive radio, the users are classified as primary and secondary users [7, 8]. Primary users have higher priority over secondary users in terms of communication due to a license mechanism. Unlike in the cognitive radio communications, there is no defined priority access mechanism in license-free ISM bands but a spontaneously occurring privileged access due to different output power of devices. For example, an IEEE 802.11 device interferes with a nearby IEEE 802.15.4 device communication and prevents its channel access or successful transmission whereas the IEEE 802.15.4 device has no such effect on the IEEE 802.11 communication [6].

At this point, it is practical to make an analogy with cognitive radio and adapt its priority-based user differentiation concept in the ISM band co-existence problem. Within the scope of this paper, the nodes suppressing the communication of the neighboring nodes are going to be called as ISM Primary Users (ISM-PU) and the aggregated heterogeneous traffic generated by these ISM-PUs is going to be called as Aggregated ISM-PU Traffic. On the other hand, the nodes affected by the aggregated ISM-PU traffic are going to be called as ISM Secondary Users (ISM-

SU). However, there are some domain specific differences between these two cases. Unlike in cognitive radio:

- The number of ISM-PUs is not restricted to one,
- ISM-PUs are not static. They may lose their ISM-PU characteristics in time because of mobility or change in Radio Frequency (RF) output power (vice versa),
- Devices using the same or different kinds of communication protocols can be the ISM-PU of the device that is of interest. For example, either an IEEE 802.11 or an IEEE 802.15.4 device can be the ISM-PU of an IEEE 802.15.4 device interested,
- Primary and secondary terms are not global. A node may not be the ISM-PU of all its neighbors.

Evaluating all the items above, it is hard to fully adapt cognitive radio concepts to the ISM band. However, primary and secondary user concepts have been motivating and also convenient for the proposed scheme in this paper.

3 The Analysis of Aggregated ISM-PU Traffic

In this work, a testbed is designed to analyze the interaction between ISM-PU and ISM-SU nodes. It is well known that the IEEE 802.11 devices are the major interferers in the 2.4 GHz ISM band [9–11]. Therefore, as ISM-PUs, we use IEEE 802.11g wireless access points and laptops connected to these access points. As ISM-SUs, the 2.4 GHz IEEE 802.15.4-compliant hardware is used. Then, the RF Signal Strength (RFSS) measurements of the communication channel, which is the main factor for both Clear Channel Assessment (CCA) and Received Signal Strength Indicator (RSSI) values, were recorded by using the 2.4 GHz IEEE 802.15.4-compliant products in different RF channels.

In our test scenario, two IEEE 802.15.4-compliant products, one of which configured as a transmitter node and the other as a receiver node, communicate periodically at an interval of 10 ms. In this setup, the transmitter node measures two consecutive CCA values, and then transmits these measurements to the receiver node with a unique packet ID. The transmitter node logs the same packet on a computer via serial wired communication. If the packet is received seamlessly, the receiver node inserts calculated RSSI value to the packet and sends the packet to a computer via serial wired communication. Note that, packet loss rate can be obtained by comparing the packet ID logs of the transmitter and the receiver nodes. The measurements were done for two different scenarios: with an ISM-PU idle (no IEEE 802.11 interference) communication channel and with an ISM-PU busy communication channel, respectively. A schematic representation of the testbed is shown in Fig. 1.

The logged CCA and RSSI measurements are presented in Fig. 2. The results show that when the channel is ISM-PU idle, the mean of CCA measurements is −85 dBm and the variance is 5 dBm. Since the RSSI measurements are about −55 dBm, the calculated SIR value is approximately 30 dBm. For such SIR values, packet loss is

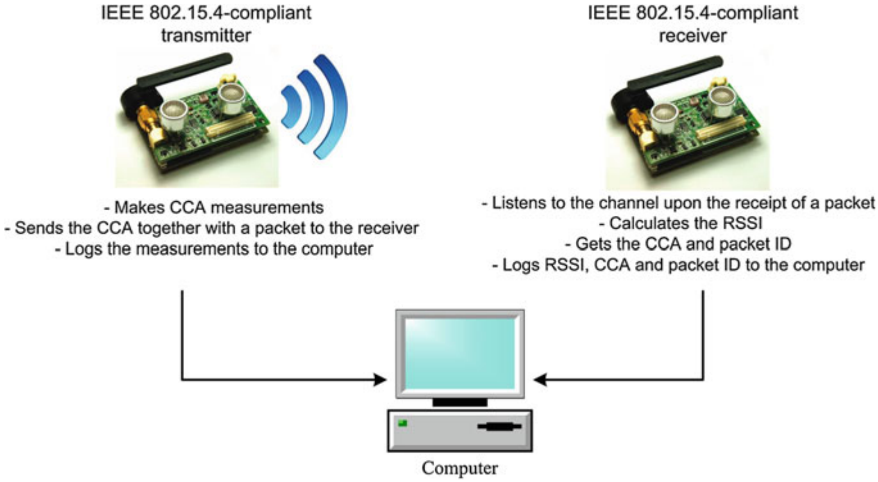

Fig. 1 A schematic representation of the testbed

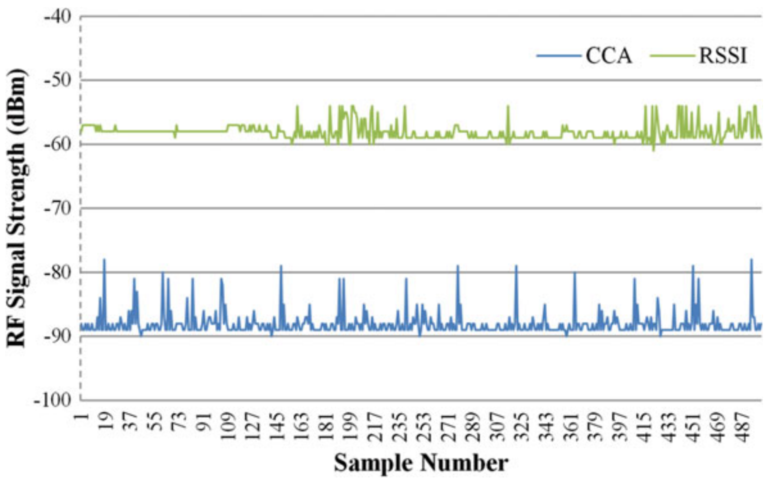

Fig. 2 500-sample snapshot of CCA and RSSI measurements for the ISM-PU idle scenario

not anticipated except for some particular environments. As expected, no packet loss is observed in the first scenario.

In the second scenario, called the ISM-PU busy scenario, the same testbed is used as in the first scenario. However, at this time, the ISM-PU devices around the laboratory are enabled. In this environment, neither the number of ISM-PUs nor the traffic pattern generated by them was manipulated. The traffic of the ISM-PU devices was a result of daily user activities in the offices around. Here, our goal is to examine the impact of real-world aggregated background IEEE 802.11 traffic on the IEEE

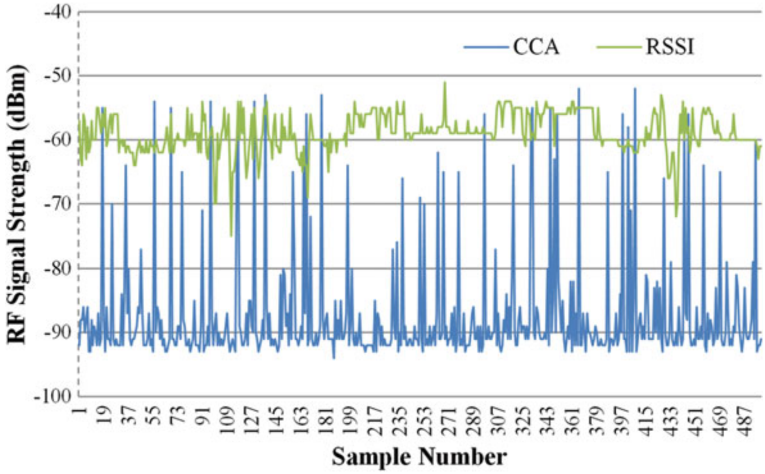

Fig. 3 500-sample snapshot of CCA and RSSI measurements for the ISM-PU busy scenario

802.15.4-compliant nodes. The CCA and RSSI measurements of the ISM-SU nodes are shown in Fig. 3. In these tests, the following points are observed:

- The CCA measurements, in the ISM-PU busy scenario, have high variance as seen in Fig. 3, which is due to the presence of ISM-PU traffic,
- Variations in the CCA values for different samples observed in the measurements is reasonable, since there are multiple ISM-PUs,
- A detailed analysis of the CCA and RSSI measurements reveal that only in 7.20 % of the observation period, there is ISM-PU traffic which forces SIR values to be below 10 dB and this causes a packet loss value of 6.94 %. Note that 10 dB threshold is selected because in the literature it is shown that 10 dB is a critical value for the IEEE 802.15.4 standard to have a successful communication [12].

Considering the fact that the communication channel is already ISM-PU idle for 92.8 % of the time, the high packet loss rate of 6.94 % indicates that the periodic channel access used in the testbed is not efficient enough.

4 Using High Autocorrelation Lag Values for Predicting the Aggregated ISM-PU Traffic Signals

In the previous chapter, the impact of co-existing Aggregated ISM-PU Traffic on ISM-SU is investigated using real-world RFSS traces. The testbed results showed that, in the environment, the ISM-SU packet loss ratio is close to the busy channel to free channel ratio. The main cause of such a result is that the channel access scheme cannot detect the co-existing interference literally. With this motivation, the

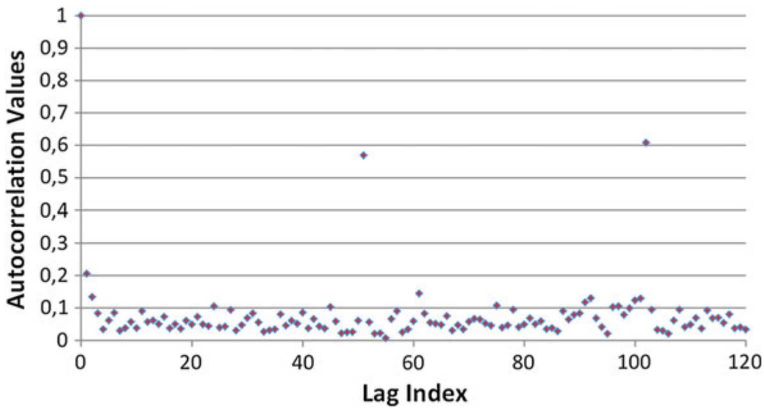

Fig. 4 Autocorrelation coefficients calculated for various lag values for ISM-PU busy scenario

CCA measurements gathered from the testbed are studied and then, a heuristic-based channel access scheme is proposed.

The periodic patterns of the co-existing traffic will be investigated in order to locate free channel access instants. In this approach, first, autocorrelation coefficients for varying lag values are calculated from CCA traces to detect the repeated patterns of the ISM-PU communication. The autocorrelation coefficients for the ISM-PU busy scenario are depicted in Fig. 4. This figure shows that the autocorrelation coefficients of some lag values are rather higher than the others. This is the cyclostationary feature effect of the ISM-PU communication. The proposed scheme assumes that for these high autocorrelation lag values, it is highly probable that there is co-existing ISM-PU traffic in the environment. At these instants, channel access of the ISM-SU should not be allowed.

It should be noted that there is more tha one ISM-PU in the environment. Thus, clustering these ISM-PUs according to the lag values would be beneficial for ISM-SUs to utilize the free bandwidth. However, as explained in the previous section, the ISM-SUs cannot measure the signal strength values of the ISM-PU communication properly which makes such a clustering impossible. Therefore, we propose to design a filter by using weighted autocorrelation lag values. This filter is going to be used by ISM-SU in order to predict the future ISM-PU interference.

In the proposed scheme the autocorrelation values, c_k, for different lags, k, are calculated as given in (1) whereas the maximum and the minimum signal strength values of the whole trace are given in (2) and (3), respectively.

$$C_k = \frac{\sum_{t=1}^{N-k}(q_t - \overline{q})(q_{t+k} - \overline{q})}{\sum_{t=1}^{N}(q_t - \overline{q})(q_t - \overline{q})} \qquad K = 1, \ldots, K \tag{1}$$

$$C_{\text{MAX}} = |\max(c_k)| \qquad K = 1, \ldots, N \tag{2}$$

$$C_{\text{MIN}} = |\min(c_k)| \qquad K = 1, \ldots, N \tag{3}$$

where q_t is the measured CCA value at index t, N is the total number of CCA samples and K representing the maximum lag value used in the algorithm. In order to determine the channel access instant for an ISM-SU, a simple filter, f_i, is designed as given in (4).

$$f_i = \frac{c_i - c_{\text{MIN}}}{c_{i\text{MAX}} - c_{\text{MIN}}} \qquad i = 1, \ldots, K \tag{4}$$

This filter value is applied to (5). For those values exceeding the control parameter T_{THR}, there is a probable ISM-PU traffic in the channel. At these instants where (5) returns busy channel, ISM-SU access to the channel should be prevented.

$$ChannelAcess(n + (i \times f_s^{-1})) = \begin{cases} free, & f_i \leq T_{\text{THR}} \\ busy, & f_i > T_{\text{THR}} \end{cases}, \quad i = 1, \ldots, N \tag{5}$$

where n indicates the current instant, f_s is the sampling frequency of the CCA measurements and T_{THR} is the decision threshold of the proposed scheme. For those values exceeding the control parameter T_{THR}, there is probable ISM_PU communication in the channel. Consequently, T_{THR} has a direct impact on the aggressiveness of the predictions made.

5 Performance Evaluation of the Scheme Proposed

The performance of the proposed scheme is compared with two other channel access schemes and results are given in Table. 1. In Scheme 1, every 10th sample on the test trace is selected. If the CCA value of this sample is below −75 dBm, this is recognized as a free channel access. Scheme 2 differs from Scheme 1 in terms of sample selection where the sample is selected according to uniform distribution within every 10-sample interval. Finally, in the proposed scheme, the channel access is scheduled to the instant with the lowest weight value.

It is obvious that the proposed scheme is highly capable of detecting ISM-PU traffic in the environment. However, we should keep in mind that there are instants where we predict ISM-PU traffic although the channel is free. This is the False Positive (FP) situation for our scheme. On the other hand, False Negative (FN) occurs

Table 1 Comparative free channel access performance of the proposed scheme

	Scheme 1	Scheme 2	Proposed scheme
# of free channel access	1851	1846	1979
# of busy channel access	149	154	21
% of free channel access	92.55 %	92.3 %	98.95 %
% of busy channel access	7.45 %	7.7 %	1.05 %

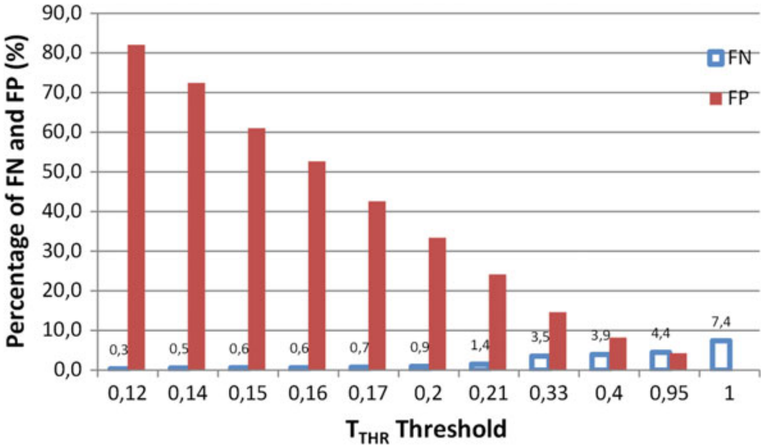

Fig. 5 The percentage of FNs and FPs for varying T_{THR} values

at the instants when the channel access is allowed although the channel is busy. In Fig. 5, the performance of the proposed scheme is evaluated based on the FN and FP rates of the channel access predictions for varying T_{THR} values where $N = 5000$, $K = 120$ and the ISM-PU traffic in the environment is occupying approximately 0.074 erlang (E). Figure 5 proves that free channel access prediction probability is inversely proportional to T_{THR}.

6 Conclusions

In this paper, 2.4 GHz ISM band aggregated traffic is analyzed, by using the adapted cognitive radio concepts. Then, a novel channel access scheme for the IEEE 802.15.4 devices is proposed. The performance of the introduced scheme is studied under various real-life IEEE 802.11 traffic logs. It is observed that the technique introduced gives promising results under the real world test traces, which motivates us to decrease the complexity of the scheme proposed and embed it to the IEEE 802.25.4 nodes as a future work.

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