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Methodology of cooperative spectrum sensing and dynamic access to the channels in WSN

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ABSTRACT

Cognition into wireless sensors is a current paradigm to improve the performance of wireless sensor networks (WSN) and the efficient use of the radio frequency spectrum. The classic static allocation of the radio frequency bands causes coexistence problems or underutilization of resources. This issue could be addressed using cognitive sensors with dynamic spectrum allocation. Therefore, a novel methodology for cooperative spectrum sensing and dynamic access to the channels (MSDAC) for a cluster of a WSN is proposed in this article. The MSDAC proposal aims the asynchronous coordination and communication between the cluster sensors in a simple way based on reinforcement-learning for home automation applications. Additionally, a set of experiments are formulated to evaluate and to compare the proposal. The experiments are based on a case study with a wireless local area network acting as primary user and a secondary network with burst traffic formed by IEEE 802.15.4 devices performing the MSDAC. The results show an improvement in the message delivery ratio and in the coexistence capability when MSDAC is used. In addition, the lowest amount of message retransmissions causes a reduction in the sensor active time when compared with other approaches, which is beneficial for energy saving.

1. Introduction

The efficient use of the radio frequency (RF) spectrum is fundamental to allow the development of more complex and optimal wireless systems. The RF spectrum is divided into channels using a static allocation model, where each channel is intended for exclusive use of a primary user (PU) in a specific region. The primary users can use these channels partially, allowing inactivity periods or white spaces (WS). In contrast, some bands have higher competition by the limited RF resources, e.g., the Industrial Scientific and Medical (ISM) band. The current static allocation leads to an unbalanced use of the RF spectrum (some bands present coexistence problems and channels of other bands are underutilized). An additional dynamic allocation using cognitive radio (CR) has been proposed to overcome the unbalanced use of the RF spectrum [1]. In this model, the secondary users (SU) will be able to use the WS dynamically under certain restrictions aimed to protect PU communications.

In addition, the WSN [2] are becoming more important in home automation applications to monitor or to change physical variables of a home area network (HAN). However, these networks work in a highly congested band (ISM) whereby the performance can be degraded by a wide variety of devices from different technologies [3]. An emerging approach is the integration of cognitive capabilities into sensor devices to perform dynamic spectrum access (DSA) for WS exploitation [4]. The key implications of this integration are an improvement of the WSN performance and a more efficient use of RF resources, or yet a higher coexistence capability when the ISM band is used [5]. This integration has several challenges related to overhead, collisions, spectrum sensing, PU protection, security, self-organization, energy consumption, hardware complexity, computational processing and other implicit restrictions of wireless sensor devices.

The current standards for WSN are classified in two categories according to the medium access control (MAC) used: random access [6] or access by time slots [7]. These standards are inflexible related to spectrum management, have synchronization requirements and do not consider the DSA concept to avoid harmful interference. For instance, the channel hopping in [7] is called "blind" because the conditions of channels are not considered.

Several works have studied the application of the DSA concept in a WSN that would take the role of secondary network. Some approaches use a network performing DSA through a common control channel (CCC) [8,9]; however, the search for a dedicated channel in the primary spectrum for WSN coordination is difficult and higher hardware complexity is needed. Similarly, a CCC is used by [10] to define an opportunistic channel selection scheme in a cognitive WSN. In the in-band signaling [11], the control messages travel in the same channels of data, which is more appropriate for the sensor device limitations. These strategies are frequently

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used for DSA implementation over WSN; however, the network can present complex signaling with high synchronization requirement. A cognitive WSN is proposed in [12] using simultaneous wireless transfer of information and power to optimize the energy consumption of relay nodes; however, the results are simulated and the time slot access has higher synchronization requirements.

A centralized scheme using ant colony optimization for a cognitive WSN is proposed in [13]. This scheme is simulated with unrealistic parameters and it needs more PU cooperation and higher exchange of control messages. Spectrum sharing for WSN is proposed through a strategic bargaining game [14] and a Bertrand game [15]. However, a continuous cooperation of the primary networks can be especially difficult to achieve in WSN. A cross-layer optimization based on Bayesian networks for cognitive WSN is proposed in [16]; however, a simulated evaluation and a partial discussion of the used centralized topology are unfavorable topics. In several methods [8,11,17,18], the dynamic access to the channels for a WSN is driven by communication rewards, e.g., the message delivery ratio (DR) over the time. Unfortunately, the spectrum sensing is not used by the sensor devices which must perform exploration in all channels to ensure that learning is done in the entire operating band. These methods cannot learn from all channels neither take advantage of the best channel at the same time (the learning process is serial over time).

The spectrum sensing is considered in [19] for DSA in WSN. In this scheme, the sensing is an individual task where each wireless sensor must supervise all channels without any cooperation. It implies complex processing for sensors with energy and hardware limitations. The cooperative spectrum sensing is more adequate to mitigate the impact of multipath fading, shadowing and receiver uncertainty issues [20]. In [21], the rewards of energy saving are used to feed a learning algorithm in a WSN and a cooperative spectrum sensing is performed. A cooperative spectrum sensing with IEEE 802.15.4 devices is also proposed in [22], but unfortunately a CCC is needed. A subset of nodes is used to form a cooperative multichannel sensing [23] in order to balance the residual energy of sensors and to maximize the network lifetime. In [23], the evaluation is simulated and the signaling is complex since the decision fusion is performed by a centralized coordinator. A reinforcement learning based clustered cooperative channel sensing is developed in [24]. The channel availability, sensing energy cost and channel impairment are considered. In contrast, the requirement of CCC and synchronization are some weaknesses of [24].

The sensing measurements to feed the learning in the sensor devices, the spectrum handoff and other MAC issues are not considered by the previous approaches. Additionally, the analysis is theoretical or simulated without addressing critical implementation and evaluation issues for the development of WSN with DSA. Few works address the spectrum handoff and other MAC issues; however, they show a range of disadvantages: synchronization requirement [8], higher complexity of the spectrum handoff [25] or higher complexity of the algorithms for channel selection [26]. The major part of these works are theoretical except [27], which presents an experimental evaluation. Nevertheless, the learning in the WSN needs an offline training, reducing the capacity of the network to react dynamically to the RF changes.

Thus, an open issue in WSN is the integration of the concepts: DSA, asynchronous coordination with simple signaling scheme, sensor device simplicity, multi-channel sensing learning, cooperation between cluster sensors and experimental evaluation. In this context, a methodology of cooperative spectrum sensing and dynamic access to the channels (MSDAC) for a cluster of a WSN that considers the traditional sensor restrictions is proposed in this work. A learning by cooperative spectrum sensing at cluster to identify the situation of channels is defined and a mechanism for dynamic access to the channels is proposed to allow asynchronous coordination. The behavior of the proposed methodology is evaluated and compared using an experimental case study. The comparative methodologies are: a method using rewards by access (MRA) (e.g., [8] or [17]), a blind channel hopping (BCH) similar to [7] and a fixed-channel approach commonly used in WSN (e.g., ZigBee). The results are good in terms of dynamic allocation of the channels, DR and coexistence capability, and a decrease in the time dedicated to message retransmissions is observed.

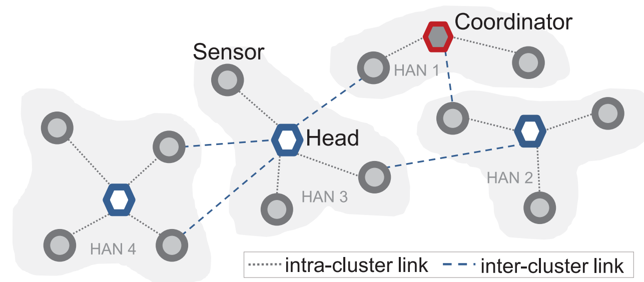

Fig. 1. WSN divided in clusters.

This paper is organized into six sections. Section 2 describes the proposed methodology. Section 3 describes the comparative methodologies. Section 4 shows the case study and the characteristics of the networks. Section 5 presents and analyzes the obtained results in the experiments and Section 6 shows the conclusions.

2. The MSDAC methodology

The following subjects are presented in this section in order to explain the MSDAC: application and network topology; general description of MSDAC; sensing and learning mechanism; dynamic access to the channels (DSA mechanism); and the work contributions.

2.1. Application and network topology

The WSN model used in this work is represented in Fig. 1. The network is divided in clusters, where each cluster consists of a head node and a set of sensors.

Residential automation in [28] is considered as application for the proposed network with each cluster representing a HAN, e.g., an apartment (see Fig. 1). In this scenario, the cluster sensors measure and send data of the HAN (e.g., temperature, illumination or humidity) to the head node. The head collects this information for controlling the air-conditioning system or the illumination system. The information collected by the head also could be sent remotely to a server to implement an IoT scheme (Internet of Things). A sensor acts as transmitter (TX) and the head is the receiver (RX). The head is the central element of a HAN and it is fed through a power supply source, while sensors are battery powered. The communication processes take place mainly within the cluster. Intra-cluster links are used to achieve this goal and the communication between clusters is performed by the inter-cluster links. The head node may be connected directly to internet or linked to sensors of neighboring clusters to perform the inter-cluster communication; however, these issues are not the focus of this paper. In our application, the cluster head solves the control loop with its sensors without sending or receiving information to the WSN coordinator; however, some configuration messages can be exchanged seldom using the inter-cluster links (distributed automation). The exchange of home automation data in the intra-cluster links is higher than the data exchanged between clusters, in average, we assume that the 95% of traffic is intra-cluster.