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Dynamic spectrum access with packet size adaptation and residual energy balancing for energy-constrained cognitive radio sensor networks

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ABSTRACT

We demonstrate an improvement in energy efficiency and network lifetime for the cluster-based multi-channel cognitive radio sensor network (CRSN). The improvement roots from two techniques proposed in dynamic spectrum access. The first technique exploits packet size adaptation: varying the packet size to adapt the transmission over the state-varying channel. This is to efficiently utilize the battery of sensors by having the most appropriately sized packets successfully transmitted, in accordance with the instantaneous channel conditions. The second technique focuses on channel assignment with awareness of the residual energy of sensors, such that sensors can spend their energy in a balanced way. This helps to prolong the network lifetime, compared to the random channel pairing approach. As all those techniques rely on the estimates of channel states and their performance is tied with the estimation accuracy, we theoretically derive a polynomial-time resolvable expression for the maximum-likelihood (ML) estimator PMF function. In light of this expression, the impact of channel estimation accuracy on network performance is thereby illustrated.

1. Introduction

The rapid growth of wireless services leads to the demand for a solution to spectrum scarcity and under-utilization of the licensed bands. Therefore, the Federal Communications Commission (FCC) allows unlicensed users to access the temporarily unused spectrum in an opportunistic manner (Akyildiz et al., 2009). Cognitive radio technology employed in traditional wireless networks improves spectrum utilization by allowing unlicensed users to access the licensed spectrum bands in an opportunistic manner which ensures that mutual interference between unlicensed and licensed users remains at an acceptable level. Cognitive radio technology can also be used in wireless sensor networks (WSNs). Existing WSNs are traditionally characterized by fixed spectrum allocation over crowded bands and lack the ability of adjusting its radio configuration to the dynamic operating environment (Akan et al., 2009; Goh et al., 2010). The event-driven nature often generates bursty traffic, which increases the probability of collision and the rate of packet loss. Cognitive radio allows opportunistic spectrum access to multiple available channels, which gives potential advantages to WSNs by increasing the communication reliability and improving the energy efficiency. Promising applications of cognitive radio sensor networks (CRSNs) were proposed in Akan et al. (2009), Goh et al. (2010), Vijayand et al. (2011), Liang et al. (2011), Zhang et al. (2011), Maleki et al. (2011) and Li et al. (2011).

Similar to a traditional WSN, a CRSN consists of a large number of low-cost low-power sensors with limited battery energy. In the CRSN, each sensor is equipped with a cognitive radio, which enables dynamic spectrum access and adaptation of its operating parameters. A sensor selects the most appropriate channel once an available band is identified and vacates the band when the transmission of a primary user (PU) is detected. One of the most important challenges for designing communication and networking protocols of a CRSN is the inherent energy constraint of the low-capability sensors with non-rechargeable batteries. Following are the two issues related to spectrum access protocols in a CRSN.

First, sensors have to analyze the sensing results and make decisions about the best available channel and the corresponding operating parameters. Since the spectrum access of sensors should not cause any interference to PUs, incorrect estimation of spectrum availability would result in unnecessary energy consumption by collisions and packet losses. A precise model and an estimator of the PU behavior are thus needed for sensors to manage

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coexistence with PUs. The PU behavior has been usually assumed to follow the Markov model, which provides the information for the prediction of future states based on its historical observations. However, additional power consumption is imposed by PU behavior estimation. Therefore, an accurate estimation method with low complexity is desired for a CRSN.

Second, since multiple sensors may try to access the same spectrum, a spectrum sharing mechanism is needed to coordinate multiple simultaneous transmissions. Most of the studies in traditional cognitive radio networks focus on Quality of Service (QoS) performance such as delay and throughput, which does not address the concern of an energy-constrained CRSN. In such a CRSN, there are two important metrics related to energy constraints for proposing an appropriate opportunistic spectrum access scheme. One is the total energy consumption needed to successfully transmit a certain amount of information bits. It should be reduced to help sensors to transmit as much information as possible during their lifetime. The other one is the network lifetime, which can be defined as the time duration from sensor deployment to the instant of network not functioning when the first sensor dies or a certain number of sensors die (Chen and Zhao, 2005). In this paper, not functioning refers to the death of the first sensor. The average wasted energy, which is defined as the total unused energy in the network when it dies, should be reduced in order to prolong the network lifetime (Chen and Zhao, 2005). Thus, the residual energy of all the sensors in the network need to be kept around the same level with a balancing scheme so that the wasted energy is minimized when the first sensor dies. In this way, the network lifetime is maximized.

1.1. Related work

There were many existing works studying dynamic spectrum access problems in cognitive radio networks (Akyildiz et al., 2009; Zhao and Sadler, 2007; Le and Hossain, 2008; Rashid et al., 2009; Akin and Gursoy, 2011; Gelabert et al., 2010; Chen and Wyglinski, 2009; Xiao et al., 2009; Tumulura et al., 2011; Zhao et al., 2007; Luo et al., 2008; Chen and Kwong, 2009; Long et al., 2008; Zhu et al., 2013; Haldar et al., 2013; Chen et al., 2013; Ren and Wang, 2013). However, all these papers focused on QoS performance, such as throughput and packet loss rate, without the consideration of the energy efficiency and network lifetime for spectrum access in cognitive radio networks. In Le and Hossain (2008), an OSA-MAC protocol based on IEEE 802.11 DCF model was proposed for opportunistic spectrum access. It analyzed saturation throughput of the system and sensing accuracy for QoS ensurance of PUs. In Rashid et al. (2009), the authors evaluated the data link layer QoS performance of cognitive users, such as average throughput and packet loss rate. In Akin and Gursoy (2011), effective capacity of cognitive radio channels was studied under QoS constraints and channel uncertainty, in which the transmitter is unaware of the channel fading coefficients. In Tumulura et al. (2011), a frame-based opportunistic spectrum scheduling scheme was implemented to maximize the aggregate throughput of all secondary users (SUs). In Zhu et al. (2013), two dynamic spectrum access algorithms are proposed with the performance measures of termination probability, blocking probability and traffic throughput. In Haldar et al. (2013), a novel probabilistic model is introduced for classification based on the occupancy of its nearby channels. The performance is evaluated by blocking probability, spectrum utilization and throughput.

There were also many studies addressing the energy constraints in WSNs. In Ci et al. (2005), a link adaptation mechanism with an adaptive frame size was proposed at the MAC layer to improve energy efficiency. In Gao et al. (2009), an optimization model for energy-efficient spectrum access was formulated to minimize the energy per bit for each single user. In Wang et al. (2006), a realistic power consumption model for WSN devices was proposed to derive the conditions for minimum power consumption in data transmissions. In Chen and Zhao (2005), residual energy information and channel state information were considered for lifetime-maximizing MAC protocols. However, these studies were based on ordinary WSNs and they did not need to consider the impacts of PU behavior in a cognitive radio network.

A few recent papers, such as Akan et al. (2009), Goh et al. (2010), Vijayand et al. (2011), Liang et al. (2011), Zhang et al. (2011), Maleki et al. (2011), Li et al. (2011), Tian et al. (2013), He et al. (2013), propose the integration of cognitive radio into the wireless sensor network. In Akan et al. (2009) and Goh et al. (2010), the basic concept of a CRSN is introduced which includes the main advantages and design challenges. In Vijayand et al. (2011), a framework of approaches to cognition in sensor networks is provided. Zhang et al. (2011) and Maleki et al. (2011) focus on reliable and energy-efficient spectrum sensing technique for CRSNs. Liang et al. (2011) analyzes the delay performance of a CRSN for supporting real-time traffic. In Tian et al. (2013), a novel QoS-aware spectrum access algorithm with power allocation are developed for both non-cooperative and cooperative users, which maximizes spectrum utilization and minimizes power consumption. He et al. (2013) minimizes the cost function which considers both the energy consumption and the packet loss rate when the controller decides whether a cognitive user should access the channel or not. We investigate the dynamic channel access protocols for a multi-channel cluster-based CRSN. In our previous work (Li et al., 2011), the total residual energy of the whole network was considered as the metric for channel assignment. In this paper, we further improve the energy efficiency by packet size adaptation and prolong the network lifetime by residual energy balance.

The performance of dynamic spectrum access is greatly affected by PU behavior, which is widely accepted to follow the Markov model in recent studies (Zhao et al., 2007; Rashid et al., 2009; Tumulura et al., 2011; Luo et al., 2008; Chen and Kwong, 2009; Long et al., 2008). In Zhao et al. (2007), Rashid et al. (2009) and Tumulura et al. (2011), the transition probabilities are assumed to be known to the SU. However, in real applications, it is almost impossible for an SU to obtain these parameters in advance. It has to estimate the PU behavior based on the current observations. Maximum Likelihood (ML) estimation (Lee et al., 1968) is used for estimating the transition probabilities of the Markov chain in Luo et al. (2008) and Chen and Kwong (2009). However, the performance of the ML estimator has not been analyzed. Long et al. (2008) analyzes the relationship between the estimation accuracy and the number of samples. However, the result of the paper only applies to the case where the number of samples is very large. In this paper, we derive a polynomial-time resolvable expression of the probability mass function for the ML estimator. This theoretically connects the estimation accuracy and the sample window size.

1.2. Our approach

In this paper, we investigate dynamic spectrum access issues for a multi-channel CRSN. PU behavior is modeled as a two-state Markov chain and its transition probabilities are estimated using ML estimation. We derive the probability mass function (PMF) of the ML estimator to evaluate its performance (estimation accuracy) indicated by the variance of the distribution. For spectrum access protocols, the packet size is adaptively selected according to the time-varying channel conditions. The goal for doing that is to improve energy efficiency in data transmission. Along with packet