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Estimating the medium access probability in large cognitive radio networks

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ABSTRACT

During the last decade we have seen an explosive development of wireless technologies. Consequently the demand for electromagnetic spectrum has been growing dramatically resulting in the spectrum scarcity problem. In spite of this, spectrum utilization measurements have shown that licensed bands are vastly underutilized while unlicensed bands are too crowded. In this context, Cognitive Radio Network emerges as an auspicious paradigm in order to solve those problems. The main question that motivates this work is: what are the possibilities offered by cognitive radio to improve the effectiveness of spectrum utilization? With this in mind, we propose a methodology, based on configuration models for random graphs, to estimate the medium access probability of secondary users. We perform simulations to illustrate the accuracy of our results and we also make a performance comparison between our estimation and one obtained by a stochastic geometry approach.

1. Introduction

The widely extended use of wireless technologies in our everyday lives (e.g. mobile phones, sensors, laptops), together with the prediction that the mobile data traffic will increase 8-fold between 2015 and 2020 [2], have shifted the attention and efforts of many researchers all over the world towards the study of Cognitive Radio Networks (see for example [11,24,25,27]). This concept is not new, and was first introduced by Mitola [19] in 1999. Cognitive Radio represents a promising technology which, based on dynamic spectrum access, strives at solving two important problems: spectrum underutilization and spectrum scarcity.

In this paradigm we can identify two classes of users: primary and secondary. Primary users (PUs) are those for which a certain portion of the spectrum has been allocated to (often in the form of a paid contract). Secondary users (SUs) are devices which are capable of detecting unused licensed bands and adapt their transmission parameters for using them.

The fundamental concept behind Cognitive Radio Networks (CRNs) is to allow SUs to use the licensed resource in the absence of PUs in order to improve the spectrum utilization. The key requirement in this context is that the PUs ought to be as little affected as possible by the presence of SUs. In the ideal case, PUs would use the network without being affected at all by SUs, which will in turn make use of whatever resources are left available.

Let us define the Medium Access Probability (MAP) as the mean number of concurrent transmissions that take place in a network divided by the total number of nodes. Given the network and the PUs utilization, one of the main performance metrics of interest here is naturally the MAP of SUs. This value measures the portion of spectrum "wasted" by PUs and which may be leveraged by SUs.

Many works like [5–7,17,23] have demonstrated that mathematical techniques such as stochastic geometry [26] and random graphs [9,28] are excellent tools in order to predict diverse wireless network performance metrics. They are specially useful to model interactions between nodes in large random networks. This randomness may include node positions, node mobility, fading, or traffic (stochastic arrivals and departure).

Stochastic geometry allows to study the average behavior over many spatial realizations of a network whose nodes are placed according to some spatial probability distribution. Generally, the location of the nodes are assumed to be a realization of an homogeneous Poisson point process (PPP). Moreover, and for particular cases, these probabilistic models may include other factors such as propagation models, transmitting power, receiving sensitive, antenna radiation patterns, signal polarization, and power/interference thresholds. The articles [18,21,22] are the most representative examples of the use of stochastic geometry in cognitive radio networks. The authors obtained closed formulas for bounds of some performance metrics (such as MAP) in different CRNs contexts. However, in some scenarios the obtained bounds

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are very conservative. Moreover, in more general cases (e.g. when the processes involved are not Poisson or when the fading variables are not independent), determining these bounds is a difficult task, if not impossible.

On the other hand, since we are interested in the MAP, many network characteristics (e.g. propagation models, transmitting power, etc.) can be abstracted into a (random) graph. Vertices in the graph represent nodes (or links) of the wireless network, and two nodes (or links) are connected by an edge when they cannot transmit simultaneously (as a consequence of the medium access mechanism, or the spectrum sensing capabilities of SUs). Then, the study of these structures provides an alternative route in order to predict performance metrics such as the MAP. In particular, recently the authors of [8] proposed a methodology for very general random graphs (characterized by the node's degree distribution), and they proved that some key properties of the system can be captured by ordinary differential equations. Authors of [7] applied this method in a wireless environment (RTS/CTS CSMA network) and obtained accurate results in the estimation of the MAP, whereas the methodology was further refined and simplified in [10].

In this paper, we consider two large wireless networks, one composed by PUs and the other by SUs. We are interested in estimating the MAP of SUs. To this end, we choose an approach based on random graphs and we extend the methodology developed in [8,10] to the context of CRNs. In particular, the main difficulties that arise in this work are related to the interaction between both networks. However, we show that the methodology yields differential equations for which explicit solutions may be obtained. With our proposal, we show that it is possible to calculate an analytic approximation of the MAP (both for PUs and, most importantly, SUs) in an arbitrary large heterogeneous random network.

As a further contribution of this article, we perform a comparison between the approximation presented here, based on random graphs, with that based on a stochastic geometry approach. To perform the comparison we will refer to [21], where the authors studied an analogous problem and they obtained a bound of the MAP of SUs. We also analyze how conservative this bound is in some representative scenarios. On the one hand, these comparisons will be performed on those scenarios where a stochastic geometry approach is valid and possible. On the other hand, we will show that the approach presented here is more general than the one that uses spatial models, analyzing their performance in real network scenarios (e.g. when the involved processes are not necessarily Poisson).

The rest of the paper is structured as follows. In Section 2 we introduce our hypotheses and the main characteristics of the considered MAC protocol. In Section 3 we present our main results, in particular we show the MAP estimation using a random graph approach based on [8]. In Section 4 we validate our results presenting numerical examples in several scenarios. In Section 5, we give an introduction of the stochastic geometric model proposed in [21] and we compare their results with our MAP approximation in representative cases. Finally, we conclude and discuss future work in Section 6.

2. Context and assumptions

This work bears on the analysis of a general scenario where there is a primary wireless network coexisting with a secondary one. In this context, SUs try to exploit the unused licensed spectrum, so the MAC protocol should provide mechanisms to give SUs a way to detect the primary spectrum holes.

In particular, we work with the Cognitive-CSMA model introduced in [21] where Carrier Sensing (CS) is used for spectrum sensing and for interference control. In this mechanism, the following principles are verified:

- each PU has a protection zone,
- no SU can transmit inside the protection zone of a PU,
- time is slotted,
- each time slot consists of three phases: primary sensing, secondary sensing and transmission.

During the primary sensing phase, all PUs sample an independent and identically distributed random variable that represents its backoff timer. When the time indicated by its backoff timer is elapsed, the tagged PU checks whether the channel is free (by means of the CS mechanism mentioned before), and if so immediately begins transmitting. In other words, a PU will transmit during a time-slot if and only if its timer is the smallest among all its primary contenders.

Once the primary phase is over, and the corresponding PUs are transmitting, the secondary sensing phase begins. Similarly to the previous phase, all SUs sample a backoff timer, after which time they transmit if the channel is free. The difference in this case is that the CS mechanism has to evaluate the presence of both SUs and, most importantly, PUs. Note that the protection zone of the PUs is thus implicitly defined by the ability of SU's CS mechanism to detect the presence of PUs. All in all, a SU will transmit if and only if it is not in the protection zone of an active primary user and its timer is the smallest among its secondary contenders. In this context, the MAP is defined as the probability that a user be granted the right to transmit in a time slot.

Naturally, the determination of the protection zone and contender transmitters is strongly related with the nodes' positions and propagation conditions (i.e. path-loss and fading variables). In our present context, and similarly to [21], we will assume that the CS will evaluate the channel as busy if the signal of any other node is received with an energy above a certain threshold. This threshold may be different for secondary and primary nodes.

Finally, and regarding traffic, we will assume that all SUs are saturated, i.e. have a packet ready to be sent in every time slot. This assumption stems from the fact that we are interested in estimating the capacity of SUs to exploit the resources left by the PUs (i.e. the MAP of SUs).

3. Random graphs and configuration algorithm

3.1. Preliminaries and motivation

As we mentioned above, at any time-slot, and given the nodes' position and propagation conditions, we may determine the protection zone of each PU and all contending nodes. This, together with the backoff timers, will in turn determine which nodes will be allowed to transmit. Note however that what is actually required to determine which nodes will transmit is precisely which pairs of nodes are contenders, and which SUs are in the protection zone of each PU (as opposed to the complete nodes' position and detailed propagation conditions).

The discussion above suggests that the network may be abstracted to a graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$ (the so-called interference graph), where the set of vertices represent the primary and secondary nodes, and the edges model the interference between any two nodes. In other words, if a transmission of node s triggers the CS of node r, then an edge from node s to r will exist. Note that in the particular case where s is a PU and r a SU, then an edge will exist if r is in the protection zone of s.

We will further assume a symmetric channel among PUs and SUs, meaning that the edges between nodes of the same type of user are bidirectional. Note however that the edges between a PU and a SU are directional, since the former are not affected by the