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Channel selection using a multiple radio model ☆

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ABSTRACT

How can a group of distributed secondary users make rendezvous on one among a set of available channels, whose exact content is a priori unknown to the participants? Let us assume that secondary users scan the set of channels, attempting to make rendezvous with each other. Each user has several radios that are concurrently used to achieve rendezvous. We propose two rendezvous algorithms for users equipped with several radios each. We study in detail the multiple user case and the asymmetric case, where the users have different but overlapping channel sets. The performance of the algorithms are analyzed and evaluated through simulation. Equations modeling the worst case performance and expected performance are developed.

1. Introduction

The demand for wireless continues to grow. Wireless traffic is increasing. Devices, such as smart phones and tablets, are numerous and bandwidth hungry. The numbers of wireless users, devices and applications are all booming as occupants of some of the segments of the radio spectrum. Radio spectrum is a limited natural resource. Lack of available radio spectrum is an issue with respect to the introduction of new applications. Indeed, the radio spectrum from 9 KHz to 275 GHz has been entirely allocated to various services. In theory, there is no room for new services and accommodating growth. This is dubbed the *spectrum crunch* problem. Nevertheless, not all allocated bandwidth is currently being intensively used. For instance, a limited number of frequencies allocated to television, space exploration and defense are occupied every-time, everywhere. Measurement experiments observed a remarkably low usage of the radio spectrum. For example, McHenry (2006) has concluded that over 80% of the allocated spectrum is unused. The cognitive radio paradigm aims at improving the radio spectrum usage efficiency and support of the expected growth of wireless traffic.

Opportunistic spectrum access is a cognitive radio approach. It works on the assumption that certain radio bands are allocated to a primary service (e.g., television) and a secondary service (e.g., computer networks). There are primary users and secondary users. A secondary user cannot cause harmful interference to the transmissions of a primary user. Opportunistic spectrum usage is a medium access model for secondary users. Primary users may access the wireless medium anytime. Secondary users must always monitor activities of primary users. They can only use residual air time. Secondary users must relinquish channels to primary users when the latter become active. Spectrum utilization can be improved by opportunistically transmitting in spectrum holes. An important question is: where are the spectrum holes? There are two approaches for finding them: database and sensing. In the database approach (Ishizu et al., 2012; Sun et al., 2012), secondary users query a database to find channels that are available for their operation. This approach requires a database-server infrastructure and a communication protocol between the secondary users and servers. In the sensing approach, secondary users observe the spectrum. They uncover unoccupied channels.

To be able to network together, secondary users meet and agree on one common channel. In the sequel, it is assumed that the secondary users are synchronous. Time is divided in slots of equal length. A rendezvous occurs within one time slot. There are two conditions for a successful rendezvous: a successful protocol handshake and being on the same channel during a time slot. These two conditions can be considered separately. They can be modeled individually and independently. The probability of a successful rendezvous is the product of the probability of a

☆This work is an extended and revised version of our former paper that developed a solution for a two-user, two-radio per user model (Barbeau et al., 2014a).

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successful protocol handshake and probability of being on the same channel during a time slot. The focus of this paper is on the latter aspect. We address the problem of finding a common channel by secondary users, on which they can network. The problem of finding and selecting a common channel can be approached using either a central controller, a dedicated common control channel or a distributed blind rendezvous technique. A blind rendezvous technique may use channel scanning. Each secondary user scans a set of channels looking for a rendezvous with a peer. Participating users may all have a common channel set, in the symmetric case, or a different, but non disjoint channel set, in the asymmetric case. The goal is to make the secondary users rendezvous on a common channel in a minimum number of time slots.

The problem addressed specifically in this paper is enabling communications for a group of secondary users by making rendezvous on an available channel. We assume that each secondary user scans the set of channels, attempting to make rendezvous with other secondary users. Time is divided into equal length intervals called time slots. During one time slot, each user is tuned into one or several channels, simultaneously. Two or several users make rendezvous when they are all tuned into a common and same channel during a time slot. Most of the research works conducted so far on this problem assume a single radio per user. We assume that each user has several radios that are concurrently used to achieve rendezvous with other users. With the current software-defined radio technology, multi-radio operation is perfectly doable.

Three cognitive radio paradigms have been identified (Kolodzy, 2005), namely, underlay, overlay and interweave. They refer to the model of spectrum usage by secondary users with respect to primary users. In the underlay model, secondary users are allowed to transmit until interference created to primary users remains below a threshold (Cormio and Chowdhury, 2010; Mesodiakaki et al., 2013, 2015). In the overlay model, because of their transmission technique, secondary user transmissions have no impact on the performance of primary users. In the interweave model, secondary users detect non-occupied spectrum segments and use them to communicate. The work presented in this paper falls into the interweave category.

We present two rendezvous algorithms, with a *bidirectional* behavior, for users that have $2k$ radios each, where k is a non-null positive integer. The algorithms differ in the way they are initialized. In the first algorithm, *2k-point algorithm*, each user picks $2k$ random starting channels. In the second algorithm, *k-point algorithm*, each user chooses k random starting channels. Let m be the number of available channels (assumed to be an odd number without loss of generality). The performance of our algorithms is determined by the Time-To Rendezvous (TTR) measure. We study first the two-user symmetric case, which means that the two users share exactly the same channel set. For the two-user symmetric case, the first algorithm achieves worst case performance in $m-1$ time slots. The second algorithm achieves worst case performance in $(m-1)/2$ time slots, but at the expense of an additional constraint, i.e., users must start running the algorithm at the same time slot. Their expected performance is almost the same, $\lceil \frac{m}{2k+1} \rceil$ or $\lceil \frac{m}{2k+2} \rceil$ time slots, asymptotically in k. Next we study, the more general multiple-user asymmetric case, which means that users may hold different channels sets, but with at least one channel in common. Equations modeling the worst case performance and expected performance are developed for all cases.

In Section 2, we review related work. We study a randomized algorithm in Section 3. The bidirectional algorithm exploiting several radios per user is described in Sections 4 and 5. We compare the theoretical performance of our algorithms with related algorithms in Section 6. Simulation results are presented in Section 7. We conclude with Section 8.

2. Related work

The problem of finding and selecting a common channel, by secondary users, can be approached using either a central controller, a dedicated common control channel or a distributed blind rendezvous technique. The blind rendezvous technique may use channel scanning. Each secondary user scans a set of channels looking to make rendezvous with a peer. Participating users may have a common channel set, under the symmetric model, or different, but non disjoint, channel sets, under the asymmetric model. The performance of the channel scanning algorithms is evaluated using the TTR metric. In the two users case, from the moment both users are running, it is the number of time slots required to achieve rendezvous. An algorithm with a finite maximum TTR is said to be *guaranteed rendezvous*. Related work includes the random channel and orthogonal-sequence-based algorithms of Theis et al. (2011) and DaSilva and Guerreiro (2008). The random channel algorithm visits all channels in a random order. For each time slot, a channel is selected among the available channels with uniform probability. The user is tuned on to that channel for the whole time slot. Rendezvous is not guaranteed. The asynchronous user ring-walk algorithm has been proposed by Lin et al. (2012) and Liu et al. (2010). Preference is given to channels with low interference to primary users. Rendezvous is not guaranteed to take place. Bahl et al. proposed an approach for WiFi/802.11 networks (Bahl et al., 2004). Rendezvous is guaranteed to take place under the symmetric model. Krishnamurthy et al. (2008) proposed a two-phase algorithm. The first phase is for neighbor discovery. It is conducted on common local channels. In the second phase, a global common channel is determined among the participating users. Bian et al. (2009), Bian and Park (2011), and Bian and Park (2013) use a quorum principle. Rendezvous is guaranteed. They have a solution for a two-channel case. Yang et al. (2010) have proposed an algorithm based on the k-shift-invariant concept that guarantees rendezvous. Lin et al. (2011, 2013) and Liu et al. (2012) authored the (enhanced) jump-stay rendezvous algorithm. It is designed for multiple users with guaranteed rendezvous. The modular clock algorithm was originally proposed by Theis et al. (2011). It is based on the ideas initially introduced by DaSilva and Guerreiro (2008). It is analogous to the jump-stay rendezvous algorithm, but the stay pattern is not performed (Barbeau et al., 2014b). Two-node rendezvous is guaranteed when they scan using different step increments. Practical evaluations of the modular clock algorithm, and random algorithm, have been conducted by Robertson et al. using the GNU radio framework (Robertson et al., 2012). More recent related contributions include the ones described in the papers of Chang and Huang (2013), Reguera et al. (2014), Gu et al. (2013) and Chang et al. (2014).

All the aforementioned works assume a single radio per user. In this paper, we assume that each user has two or more radios that can be used simultaneously to achieve rendezvous. Yu et al. (2013) have conducted research in that direction. They proposed the *role-based parallel sequence* (RPS) algorithm where users are equipped with multiple radios. In fact, each user has one dedicated radio and several general radios. The dedicated radio stays on a specific channel for a number of time slots. Then, switches to another one in a round-robin manner. The remaining general radios scan all the available channels, in parallel. For example, when a user has k general radios, k channels are simultaneously scanned per time slot. All available channels are scanned in a *parallel round-robin manner*. The number of radios may vary from user to user. The