DOCTORAL THESIS

Rendezvous for cognitive radio networks

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Abstract

With the traditional static spectrum management, a significant portion of the licensed spectrum is underutilized in most of time while the unlicensed spectrum is over-crowded due to the growing demand for wireless radio spectrum from exponential growth of various wireless devices. Dynamic Spectrum Access utilizes the wireless spectrum in a more intelligent and flexible way. Cognitive radios are a promising enabler for Dynamic Spectrum Access because they can sense and access the idle channels. With cognitive radios, the unlicensed users (SUs) can opportunistically identify and access the vacant portions of the spectrum of the licensed users (PUs). In cognitive radio networks (CRNs), multiple idle channels may be available to SUs. If two or more SUs want to communicate with each other, they must select a channel which is available to all of them. The process of two or more SUs to meet and establish a link on a commonly-available channel is known as *rendezvous*.

1) **Multiple Radios for Fast Rendezvous in CRNs:** The existing works on rendezvous implicitly assume that each cognitive user is equipped with one radio (i.e., one wireless transceiver). As the cost of wireless transceivers is dropping, this feature can be exploited to significantly improve the rendezvous performance at low cost. We investigate the rendezvous problem in CRNs where cognitive users are equipped with multiple radios and different users may have different numbers of radios. We first study how the existing rendezvous algorithms can be generalized to use multiple radios for faster rendezvous. We then propose a new rendezvous algorithm, called *role-based parallel sequence* (RPS), which specifically exploits multiple radios for more efficient rendezvous. Our basic idea is to let the cognitive users stay in a specific channel in one *dedicated radio* and hop on the available channels with parallel sequences in the remaining *general radios*. We prove that RPS provides guaranteed rendezvous (i.e., rendezvous can be completed within a finite time) and

derive the upper bounds on the maximum time-to-rendezvous (TTR) and the expected TTR. The simulation results show that i) multiple radios can cost-effectively improve the rendezvous performance, and ii) the proposed RPS algorithm performs better than the ones generalized from the existing algorithms.

2) **Efficient Channel-Hopping Rendezvous Algorithm Based on Available Channel Set:** All the existing rendezvous algorithms that provide guaranteed rendezvous (i.e., rendezvous can be achieved within finite time) generate channel-hopping (CH) sequences based on the whole channel set. However, some channels may be unavailable (e.g., being used by the licensed users) and these existing algorithms would randomly replace the unavailable channels by the available ones in the CH sequence. This random replacement is not effective, especially when the number of unavailable channels is large. We design a new rendezvous algorithm, called *Interleaved Sequences based on Available Channel set* (ISAC), that attempts rendezvous on the available channels only for faster rendezvous. ISAC constructs an odd subsequence and an even subsequence and interleaves these two subsequences to compose a CH sequence. We prove that ISAC provides guaranteed rendezvous. We derive the upper bounds on the maximum time-to-rendezvous to be $O(|C^1||C^2|)$ ($|C^1| \leq Q, |C^2| \leq Q$), where $|C^1|$ and $|C^2|$ are the numbers of available channels of two users and Q is the total number of channels. Extensive experiments are conducted to evaluate ISAC.

3) **Adjustable Rendezvous in Multi-Radio CRNs:** We propose an *Adjustable Multi-Radio Rendezvous* (AMRR) algorithm which exploits multiple radios for fast rendezvous based on available channels only. Suppose that a cognitive user is equipped with R radios. Our basic idea is to partition the radios into two groups: k *stay radios* and $(R-k)$ *hopping radios*. The user stays on specific channels in the stay radios while hops on its available channels parallelly in the hopping radios. We prove that the maximum time-to-rendezvous (MTTR) of AMRR is upper-bounded by $O(\frac{|C^1||C^2|}{R_1R_2})$, where $|C^1|$ and $|C^2|$ are the numbers of available channels of two users and R_1 and R_2 are the numbers of radios of the two users. This bound meets the

lower bound of MTTR of any deterministic rendezvous algorithm when two users are equipped with the same number of radios (i.e., $R_1 = R_2$). AMRR is *adjustable* in giving its best performance on either MTTR or E(TTR) by adjusting value of k. Simulation results show that AMRR performs better than the state-of-the-art.

4) **Cooperative Rendezvous in Multi-User CRNs:** The existing rendezvous algorithms implicitly assume that only one pair of users send handshaking messages for rendezvous at a time. In practice, more than one pair of users may go through the rendezvous process at about the same time and their handshaking messages may collide with each other. As a result, the rendezvous performance would degrade. We propose to turn this disadvantage (i.e., multiple users cause multiple access interference to each other) into an advantage (i.e., multiple users *cooperate* with each other for fast rendezvous). Specifically, we propose a *Cooperative Rendezvous Protocol* (CRP) where multi-pair users are cooperative to relay the channel information to speed the rendezvous efficiently. If one user gets the channel information of its intended rendezvous user, it can change the channel set and only hop on the commonly-available channels between itself and its intended rendezvous user. CRP can be applied in conjunction with any existing rendezvous algorithm. We prove that CRP can decrease the expected time-to-rendezvous (TTR). The simulation results show that: i) When there are multiple pairs of users, the rendezvous performance is significantly degraded because of collision, and ii) CRP can effectively counteract the collision and significantly improve the rendezvous performance.

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