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Opportunistic network coding for secondary users in cognitive radio networks

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In cognitive radio networks (CRNs), secondary users (SUs) may employ network coding to pursue higher throughput. However, as SUs must vacate the spectrum when it is accessed by primary users (PUs), the available transmission time of SUs is usually uncertain, i.e., SUs do not know how long the idle state can last. Meanwhile, existing network coding strategies generally adopt a block-based transmission scheme, which means that all packets in the same block can be decoded simultaneously only when enough coded packets are collected. Therefore, the gain brought by network coding may be dramatically decreased as the packet collection process may be interrupted due to the unexpected arrivals of PUs.

In this paper, for the first time, we develop an efficient network coding strategy for SUs while considering the uncertain idle durations in CRNs. At its heart is that systematic network coding (SNC) is employed to opportunistically utilize the idle duration left by PUs. To handle the uncertainty of idle durations, we utilize confidential interval estimation to estimate the expected duration for stochastic idle durations, and multi-armed bandits to determine the duration sequentially for non-stochastic idle durations, respectively. Then, we propose a coding parameter selection algorithm for SNC by considering the complicated correlation among the receptions at different receivers. Simulation results show that, our proposed schemes outperform both traditional optimal block-based network coding and non-network coding schemes, and achieve competitive performance compared with the scheme with perfect idle duration information.

1. Introduction

Due to the pressing demand of efficient frequency spectrum usage, cognitive radio networks (CRNs) have spurred a wide range of research interests because they can improve spectrum utilization of the limited spectrum resources [1]. The key idea in CRNs is to allow *secondary users* (SUs) share the spectrum simultaneously with the *primary users* (PUs), as long as they do not harm the transmissions of PUs [2]. As a result, a critical challenge for SUs in CRNs is how to efficiently utilize the "scarce opportunities" for higher performance.

In recent years, network coding [3] has emerged as a promising technology to achieve higher performance in wireless networks. By combining multiple input packets into one packet algebraically before forwarding, network coding is able to achieve the multicast capacity [3]. Due to its huge benefits, network coding is not only applied in multi hop scenarios, but also in single hop broadcast scenarios, which has been extensively studied in [4–7], etc. Intuitively, network coding can also be utilized to improve SUs' performance, e.g., the efficiency of SUs utilizing the "scarce opportunities" may be greatly increased.

Network coding has the potential to improve SUs' performance in CRNs. However, it is not easy to extend the previous studies of network coding to SUs in CRNs. To begin with, network coding usually adopts a block-based transmission (e.g., [8–10], etc). That is, the data packets in the same block can be recovered only when at least the number of block size coded packets are collected at the receivers. The block size must be carefully predetermined according to the current available time, since the block size is directly related to the throughput gain [10]. However, in the context of CRNs,

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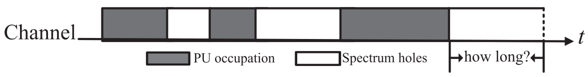

Fig. 1. The "spectrum holes" are limited and *uncertain*.

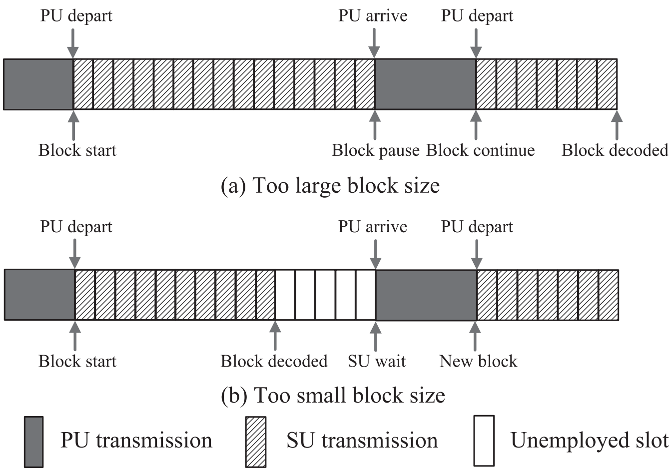

Fig. 2. The block size selection is challenging due to the *uncertain* idle duration.

SUs can only opportunistically explore the "spectrum holes" on PU channels for data transmissions. As shown in Fig. 1, these "spectrum holes", which are the available transmission time for SUs, are usually *uncertain* in the sense that SUs' transmissions may be interrupted by PUs at any time. Due to this uncertainty, it is challenging to apply network coding in SUs' data transmission.

Take Fig. 2 as an example. In Fig. 2(a), a block with too large size cannot be decoded in the current idle duration and have to be resumed in the next idle duration, which depends on the activity of PUs. Since the activity of PUs is uncertain and may be unpredictable sometimes, the packet delay (decoding & waiting) may be extremely large, which is unacceptable to delay-sensitive traffic. On the contrary, if the SUs choose a too small block size (see Fig. 2(b)), the block may be decoded long before the current idle duration ends. However, as put in [10], small block size cannot bring great throughput gains. Therefore, the coding scheme as well as the block size selection should be reconsidered and carefully designed with consideration of the uncertain idle durations in CRNs.

In this study, we aim to develop an efficient network coding scheme for SUs to achieve the promising performance gains in CRNs. *To our best, this is the first work to study how to leverage network coding to improve SUs' performance while considering the uncertain idle durations.* The key issue in the problem of network coding for SUs is to determine the block size k before each round of data transmission. According to [33–36], the optimal block size k^* is determined by several factors, among which a major one is the number of time slots I that is available for transmission. Thus, we propose to estimate I first, and then choose k^* based on the estimated I. Besides, to jointly consider the estimation of I and the selection of k^*, we employ systematic network coding (SNC) in the coded data transmission to reduce the negative effect from the inaccurate estimation.

To summarize, our main contributions are as follows.

1. We propose two idle duration selection algorithms for SUs to estimate the duration of available transmission. For the case where the idle duration is stochastic, we employ confidential interval estimation (CIE) to estimate the idle duration on average. For the non-stochastic case, we model the idle duration selection problem into a non-stochastic multi-armed bandits (MAB) problem [21] and propose a MAB-based algorithm to sequentially select the idle durations.
2. We develop a block size selection algorithm for SNC to adaptively determine the proportion of the number of coded packets and uncoded packets to be transmitted. We analytically show that the algorithm can be addressed in $O(NI^4)$ time, where N is the number of SU receivers and I is the estimated duration of available transmission.
3. We generalize our approach framework to incorporate multiple PU channels. To handle the uncertain idle durations under multiple PU channels, we discuss how to modify the CIE-based algorithm for stochastic idle durations and the MAB-based algorithm for non-stochastic idle durations, respectively. We also theoretically analyze the performance of the modified two-dimensional MAB algorithm.
4. Our simulation results show that, the gain of our proposed scheme over the non-network coding transmission policy and optimal random linear network coding scheme is up to 1.48× and 1.85× under stochastic idle durations, and 1.2× and 1.75× under non-stochastic idle durations, respectively. Besides, compared to the scheme with perfect idle duration information, our scheme achieves high steady utilization, around 90% for stochastic idle durations, and 88% for non-stochastic case, respectively.

The rest of this paper is organized as follows. The related work is reviewed in Section 2. Section 3 describes the model and problem formulation. In Section 4, we present two algorithms to handle the uncertainty of the available time for SUs, while a block size selection algorithm for SNC is developed in Section 5. Section 6 discusses how to extend our algorithms when there are multiple PU channels. The performance evaluation is conducted via extensive simulations in Section 7. Section 8 presents the discussion. Finally, Section 9 concludes the paper and discusses the future work.

2. Related work

The related studies can be generally categorized into the following four aspects: learning-based dynamic spectrum access in CRNs, characterization and modeling of PU behavior in CRNs, utilization of network coding in CRNs, and network coding for real-time traffic.

2.1. Learning-based dynamic spectrum access in CRNs

Our work is sort of learning the primary user environment in CRNs. There has been a rich body of studies on dynamic spectrum access in CRNs in existing works. SUs need to conduct a learning process to select good channels since channel availability and quality is unknown to SUs. Existing works study this problem from a sequential decision perspective by multi-armed bandits (MAB) approaches, or from a game theoretic perspective by equilibrium convergence.

Shu and Krunz [11] propose a throughput-optimal decision scheme for stochastic homogeneous channels. The proposed scheme uses a threshold to distinguish good channel and bad channel. For the case of pre-allocated ranks for SUs and non such prior information, Anandkumar et al. [12] proposes two distributed learning and allocation schemes respectively. Li et al. [13] studies the joint channel sensing, probing and accessing problem in CRNs when channel states are non-stochastic, and presents an almost throughput optimal scheme with the help of MAB.

Moreover, some works study dynamic spectrum access from an adaptive, game theoretic learning perspective. Maskery et al. [14] models the dynamic channel access problem as a non-cooperative game for stochastic homogeneous channels, and derives the probability of channel contention by CSMA mechanism.