Computer Communications 79 (2016) 9–21

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

TCPJGNC: A transport control protocol based on network coding for multi-hop cognitive radio networks[☆]

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A R T I C L E I N F O

Article history:
Received 12 November 2014
Revised 28 August 2015
Accepted 26 December 2015
Available online 31 December 2015

Keywords:
Cognitive radio networks
TCP
Network coding

A B S T R A C T

Cognitive radio (CR) has emerged as a promising solution to enhance spectrum utilization. In cognitive radio networks (CRNs), the secondary users (SUs) can opportunistically exploit frequency bands when the primary users (PUs) do not occupy the bands. However, TCP performance in CRNs may suffer from significant degradation due to this feature. In this paper, we investigate the limitations of TCP in multi-channel multi-radio multi-hop CRNs, and propose a novel transmission control protocol called TCPJGNC (TCP Joint Generation Network Coding, JGNC) based on network coding. In TCPJGNC, we dynamically adjust the number of packets involved in network coding according to the wireless communication environment to achieve better decoding probability. In the meantime, a coding scheme based on JGNC is provided which can reduce the number of retransmissions in TCPJGNC. In addition, we modify the TCP mechanism to fit into CRNs by considering the features of CRNs. An analysis of approximate expected throughput in TCPJGNC is provided and the simulation results indicate that TCPJGNC can significantly improve the network performance in terms of throughput, bandwidth efficiency and average end-to-end delay. To the best of our knowledge, TCPJGNC is the first transmission control protocol for multi-hop CRNs from a network coding perspective.

1. Introduction

With the demands of wireless technologies and applications, more and more spectrum resources are needed. Meanwhile, with the current spectrum allocation policy, all of the spectrum bands are exclusively allocated for licensed users (i.e., primary users PUs), and violation from unlicensed users (i.e., secondary users SUs) is not allowed. This is the main factor that leads to spectrum underutilization. The Federal Communications Commission (FCC) has indicated that temporal and geographical variations in the utilization of the assigned spectrum range from 15 to 85% [1]. Dynamic spectrum access [2] is proposed to solve the critical problem of spectrum scarcity. This new research area foresees the development of cognitive radio networks (CRNs).

The cognitive radio (CR) [3] principle has introduced the idea to exploit spectrum holes (i.e., bands) which result from the proven underutilization of the electromagnetic spectrum by modern wireless communication and broadcasting technologies. The exploitation of these holes can be accomplished by the notion of CRNs. CRNs have emerged as a prominent solution to improve the efficiency of spectrum usage and network capacity. In CRNs, the SUs can opportunistically exploit frequency bands when the PUs do not occupy the bands. Most of the research work that has been conducted in CRNs concentrates on the two lower layers, tackling PHYsical (PHY) layer and/or media access control (MAC) layer issues, including the definition of effective spectrum sensing, spectrum decision and spectrum sharing techniques [4,5]. Except for a few routing algorithms, the network layer protocols for CRNs are in the nascent stages of development [6–10]. Until very recently, the research community has started to realize the potentials of enhancing transmission control protocol (TCP) in multi-hop CRNs which can improve the performance of CRNs. TCP in CRNs exhibits similarities with the TCP in multi-channel multi-hop ad hoc networks/mesh networks, but with the additional challenge of having to deal with the dynamic behavior of the PUs, and their effects on changing spectrum opportunities (SOPs) of SUs. Some efforts have been taken to improve the TCP performance in CRNs through optimizing the lower-layer parameters [11–16] or modifying TCP itself [17–19]. Slingerland et. al. [11] evaluated the performance of TCP on CRNs. They considered different TCP variations including

☆ Part of this work was presented at IEEE Globecom 2011 [26].

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http://dx.doi.org/10.1016/j.comcom.2015.12.007

TCP NewReno [20] and TCP Vegas [21]. It was shown that the time taken by SUs in sensing mode affects the throughput of the TCP connections. Issariyakul et. al. [12] evaluated the performance of TCP NewReno on CRNs. They considered a new type of loss called service interruption loss, due to the existence of PUs. Their simulation results showed that there is an optimum number of channels for SUs to achieve maximum aggregate throughput. The optimum number of channels depends on the number of PUs and also the number of SUs on the network. In refs. [13,14], a scheme that optimizes TCP throughput without making changes to TCP was proposed. To achieve higher throughput in TCP Reno [22], their scheme optimized the low-layer parameters of the network, such as modulation and coding scheme in the physical layer, and frame size in the data-link layer. Similarly, Wang et. al. [15] investigated the TCP throughput performance enhancement for CRNs through lower-layer configurations. They studied the impacts of lower-layer parameters (e.g., packet error rate, queue length, spectrum sensing accuracy), PUs activities and channel conditions on the TCP throughput. However, they did not modify the congestion control mechanism in TCP Reno to respond to PU activities and spectrum sensing. Also they treat all types of losses as congestion losses in the scheme. Sarkar and Narayan [16] designed, implemented, and evaluated a transport protocol for CRNs. They augmented their protocol with TCP and TCP Westwood [23]. Their protocol handles temporary disconnections caused by spectrum sensing. Also, their protocol handles frequent bandwidth variation as the connection moves from one channel to another. However, they did not consider disconnection caused by PUs arrival.

On the other hand, from the perspective of modifying TCP itself, Felice et. al. [17] evaluated the performance of TCP over cognitive radio ad hoc networks (CRAHNs). They studied different TCP variations including TCP Reno, TCP NewReno and TCP Vegas by considering the impact of three factors on different TCP variants: (i) spectrum sensing cycle, (ii) interference from PUs and (iii) channel heterogeneity. Moreover, they analyzed the impact of CRAHNs characteristics over the route formation process, by considering different routing metrics and route discovery algorithms. Similarly, Chowdhury et al. [18,19] designed a transport protocol for CRAHNs. They modeled the transport protocol as a six-state system. Some of the events that cause the system to change state are route failure, congestion notification, node mobility, and spectrum change. However, it requires retransmissions from lower layers when data collision and loss of channel errors occur.

Network coding (NC) [24] has emerged as a promising technology to improve the performance of communications, especially in wireless networks. NC was originally proposed by Ahlswede et. al. in 2000, which allows intermediate nodes in the network to encode multiple packets together and forward more than one packet during a transmission. Using NC can enhance the performance of the wireless networks [25–27]. As we know, in traditional TCP, it uses feedback to acknowledge received packets in order. While incorporating NC into TCP, the feature is missing due to sending the linear combination of some original packets. TCP/NC [27] is one of the earliest TCP implementations which could incorporate NC with minor changes in the current protocol stack. However, in TCP/NC, source node transmits random linear combination of packets currently in the congestion window; it will be inefficient when the wireless environment changes, especially in multi-hop CRNs. In addition, in CRNs, due to the spectrum sensing and PUs activities, the available channels are instable. It will be more likely to drop packets than traditional wireless networks. Thus, the TCP performance of SUs will degrade when using the traditional TCP over CRNs. Therefore, designing a new TCP protocol for CRNs from a NC perspective is an urgent issue.

In this paper, we first study the characteristics of CRNs that lead to an obvious degradation in TCP performance, and then introduce the JGNC; finally, we evaluate the performance of incorporating JGNC in TCP over CRNs. We aim to improve the TCP performance from modifying TCP itself, rather than optimizing the lower-layer parameters as most of previous work. To the best of our knowledge, this is the first work studying NC incorporation with TCP in multi-hop multi-channel multi-radio CRNs.

The main contributions of this paper can be summarized as follows.

(1) We analyze decoding probability in wireless networks, which depends on the probability of linearly independent and packet loss rate. We also derive the decoding probability of JGNC in multi-channel multi-radio multi-hop CRNs, which considers PU activity.

(2) Considering the channel uncertainty in CRNs, we propose a novel TCP protocol TCPJGNC based on JGNC. In TCPJGNC, the number of the packets involved in network coding operation can be changed according to the wireless environment (packet loss rate) and redundancy factor. Also, we discuss the coding scheme of JGNC in TCP, which is set according to the changing ratio of ACK and the rank of the matrix consisting of the received packets' coding coefficient. In addition, we derive the expectation of the number of retransmissions in TCPJGNC, which is smaller than that of classical TCP and TCP/NC. TCPJGNC can significantly reduce the retransmissions and provide a higher decoding probability, and then enhance the TCP performance in multi-hop CRNs.

(3) We modify the TCP mechanism to fit into CRNs, by considering slow start, spectrum sensing state, spectrum changing state and presence of PUs, and give novel methods to calculate the effective window, retransmission time-out (RTO) and Round-Trip Time (RTT) for CRNs, respectively. In addition, an analysis of approximate expected throughput in TCPJGNC is provided.

(4) We present simulation results to evaluate the throughput, bandwidth efficiency and average end-to-end delay benefits of TCPJGNC under different network settings (e.g., PU activity, sensing time, and spectrum changing).

The rest of this paper is organized as follows. In Section 2, we first describe the system model considered in this study, and then analyze the challenges from four aspects: PU behavior, spectrum sensing, spectrum changing, and TCP itself in TCP performance over CRNs. We introduce the JGNC in Section 3. In Section 4, we describe our scheme TCPJGNC in detail, and give a throughput analysis model in Section 5. Simulation results are provided in Section 6. Section 7 concludes this paper.

2. System model and TCP's challenges in CRNs

2.1. System model

We now describe the model used in this paper for TCP performance analysis in CRNs. In our previous work [7], we assume an interweave model [28], i.e., the SUs in the CRNs can only transmit data when the PUs are not active. In this paper, we consider a time slotted multi-hop cognitive radio network with num_s SUs and num_p PUs. Each node (including SU and PU) is equipped with the same number of radios. We assume half-duplex on each radio. Each SU is capable of sensing the locally available channels and has the capability of channel changing at packet level for data transmission. On each given channel, PU activity is modeled as a Poisson process in which the lengths of both periods are exponentially distributed with rate λ_{busy}(the channel is occupied by the PU) and λ_{idle}(the channel is available for the SU), respectively.

A time-slotted model for SU is assumed, with a fixed slot duration T. Each slot consists of a sensing period with duration