Ad Hoc Networks 36 (2016) 177–188

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Modeling of rate-based congestion control schemes in cognitive radio sensor networks

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ARTICLE INFO

Article history:
Received 28 November 2014
Revised 25 June 2015
Accepted 29 June 2015
Available online 6 July 2015

Keywords:
Cognitive radio sensor networks
Rate-based congestion control
Steady-state rate distribution

ABSTRACT

Performance evaluation of transport layer protocols in cognitive radio sensor networks (CRSNs) is useful to provide quality-of-service for real-time reliable applications. This paper develops an analytical framework to model the steady-state sending rate of collecting cognitive radio (CR) sensors in rate-based generic additive-increase multiplicative-decrease (AIMD) and additive-increase additive-decrease (AIAD) congestion control schemes. Evolution process of sending rate is modeled by a discrete time Markov chain (DTMC) in the terms of queue length. We model the queue length distribution of a CR node by a semi-Markov chain (SMC) with assuming general probability density functions (PDFs) of input rate and attainable sending rate of the node. These PDFs are derived based on the parameters of MAC and physical layers and CRSN configuration. The proposed models are verified through various simulations.

1. Introduction

Cognitive radio technology is highly used as a capable tool to alleviate the spectrum underutilization problem and provide dynamic spectrum access (DSA) in wireless networks [1]. In this way, a CR-equipped node uses unlicensed spectrum bands opportunistically based on CR basic operations: spectrum sensing, decision and handoff [2]. Licensed users in cognitive radio networks are called primary users (PUs) which have priority to access the licensed bands [1]. CR users can use the licensed bands in the absence of PUs. If a primary user is appeared in the licensed band, CR user leaves the spectrum immediately [1]. Cognitive radio technology can be used in wireless sensor networks (WSNs) to overcome spectrum shortage problem and reserve the limited resources of sensors in WSNs [3]. Wireless sensor networks with CR-equipped sensor nodes are called cognitive radio sensor networks (CRSNs) [3]. With regard to the application, opportunistic spectrum access (OSA) feature of sensor nodes in CRSNs can decrease the collision and retransmission probabilities in the environments with bursty traffic which is common in sensor networks. Moreover, adaptive spectrum access of CR sensors in dynamic wireless channels increases the transmission efficiency which leads to less power consumption [3].

Primary users' activities and unique features of CRSNs such as spectrum sensing and spectrum mobility affect the performance of MAC, routing and transport layer protocols. Disregarding these effects may lead to the violation of main objectives of CRSNs. Hence, the performance evaluation of the protocols of MAC, network and transport layers with regard to CR-related parameters is crucial for CRSNs. In this paper, we focus on the performance evaluation of transport layer in CRSNs.

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http://dx.doi.org/10.1016/j.adhoc.2015.06.009
1570-8705/

The performance of transport layer protocols is important in the QoS of various applications in CRSNs. However, there is a limited amount of work on the performance evaluation of transport layer protocols in CRSNs. Most of previous studies [4–14] concentrated on the simulation-based performance evaluation of transport layer protocols. However, analytical investigation is required to model the performance of congestion control schemes in CRSNs for the following motivations: (1) transport-level delay (delay overhead of transport layer protocols) depends on the sending rate of source nodes in this layer. Sending rate of collecting CR sensors is controlled through the rate-based congestion control schemes by considering the congestion status of CR nodes in the network. (2) In real-time reliable applications, it is necessary to consider delay and reliability. Modeling the transport layer sending rate and congestion probability in CRSNs helps to investigate analytically real-timeness and reliability which makes better QoS provisioning in different applications. To the best of our knowledge, there is no analytical framework to calculate the sending rate distribution of CR source sensors based on the queue length distribution and MAC delay overhead of CR nodes in the current literature.

In this paper, an analysis of rate-based generic AIMD and AIAD congestion control schemes in CRSNs is presented. The main contributions are the following:

- An analytical model is proposed for the sending rate distribution of collecting CR sensors. The simulation experiments verify the sending rate model.
- In order to model the distribution of sending rate in the transport layer of collecting CR sensors, a stochastic congestion model is proposed. In this way, the queue length of CR nodes is assumed to be the congestion detection parameter. The queue length distribution of a CR node depends on the distribution of input rate and attainable sending rate of the node. Usually, the queue length distribution of a node is modeled by assuming that arrivals follow a Poisson process and the service time of a node has an exponential distribution. However, these assumptions are not always applicable. We do not make any assumption about the input and attainable sending rate distribution of CR nodes. Therefore, a semi-Markov chain (SMC) is proposed to model the queue length distribution of different nodes in CRSN.
- In order to accomplish the SMC, the probability density functions (PDFs) of input and attainable sending rates of different CR nodes are derived. These PDFs are calculated based on the proposed models of CR attainable sending rate on the channel, the delay overhead of MAC-layer and the CRSN configuration.

The rest of this paper is organized as follows. Section 2 reviews the related work addressing the performance evaluation of transport layer protocols in CRSNs and CRNs. Also, this section describes the congestion control schemes in WSNs. In Section 3, system model of the CRSN is defined. Section 4 models the sending rate distribution of a collecting CR sensor in the CRSN. Stochastic model of congestion in the CRSN is explained in Section 5. Analytical results and verifications are presented in Section 6. Finally, in Section 7, conclusions are presented.

2. Related work

In this section, we review the current research studies in the literature addressing the performance evaluation of transport layer protocols in CRNs and CRSNs. Furthermore, we review the congestion control schemes and explain the main modules of transport layer in WSNs.

2.1. Performance evaluation of transport layer protocols in CRSNs and CRNs

In [4], the performance of existing congestion control schemes is studied over cognitive radio sensor networks to reveal the CRSN challenges for transport layer protocols. Authors in [5] investigate the challenges of real-time transport over CRSNs in the different spectrum environments of smart grid. In [15], the optimality of simple rate adjustment techniques is investigated in CRSNs. In [16], the stochastic backlog and delay bounds of generic AIMD congestion control schemes in CRSNs are modeled based on stochastic network calculus (SNC) [17]. Ref. [16] models the backlog and delay bounds with the given sending rate distribution (probability mass function) of source nodes in CRSNs through moment generating function (MGF)-based theories in SNC. However, there is no modeling of sending rate distribution of CR source sensors based on queue length distribution and the attainable sending rate of MAC layer in CRSNs that is the main contribution of this study.

Although CRSN is a new research area to be studied for performance evaluation of transport layer protocols, there is a significant amount of research on evaluating the performance of TCP over cognitive radio networks (CRNs). In [6], TCP efficiency and throughput over CRNs are studied. The impact of primary users' traffic, the number of wireless channels and sensing period on the throughput of TCP is investigated in [7]. In [8], the behavior of TCP throughput, round trip time (RTT) and congestion window size are studied based on sensing frequency, primary users' traffic and the heterogeneity of channels. In [9], a transport protocol for cognitive radio ad-hoc networks is proposed. Furthermore, the impact of sensing time on TCP throughput is considered. Also, the effect of alternations in the available bandwidth of CR users on the behavior of TCP congestion control is studied. Authors in [10] discuss the TCP performance degradation in CRNs through considering the congestion window size, RTT behavior and retransmission timeout (RTO). In [12], TCP throughput is evaluated based on primary users' activities and the number of available wireless channels. An equation-based transport protocol for cognitive radio networks is proposed in [13]. Authors in [14] evaluate TCP end-to-end delay, throughput and packet drop probability with regard to packet size, sensing time, sensing accuracy and activities of primary users. However, most of studies have focused on the simulation-based performance evaluation of transport layer protocols in CRNs.

2.2. Congestion control schemes

In the literature, different transport layer protocols have been proposed for WSNs. The papers [18,19] comprehensively review the transport layer and congestion control