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TFRC-CR: An equation-based transport protocol for cognitive radio networks

Abdulla K. Al-Ali *, Kaushik Chowdhury

Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115, USA

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ABSTRACT

Reliable and high throughput data delivery in cognitive radio networks remains an open challenge owing to the inability of the source to quickly identify and react to changes in spectrum availability. The window-based rate adaptation in TCP relies on acknowledgments (ACKs) to self trigger the sending rate, which are often delayed or lost owing to intermittent primary user (PU) activity, resulting in an incorrect inference of congestion by the source node. This paper proposes the first equation-based transport protocol based on TCP Friendly Rate Control for Cognitive Radio, called as TFRC-CR, which allows immediate changes in the transmission rate based on the spectrum-related changes in the network environment. TFRC-CR has the following unique features: (i) it leverages the recent FCC mandated spectrum databases with minimum querying overhead, (ii) it enables fine adjustment of the transmission rate by identifying the instances of true network congestion, as well as (iii) provides guidelines on when to re-start the source transmission after a pause due to PU activity. TFRC-CR is evaluated through an extensive set of module additions to the ns-2 simulator which is also released for further investigation by the research community.

1. Introduction

Cognitive radio (CR) networks enable opportunistic use of available licensed spectrum to reduce the pressure on the unlicensed ISM bands in the 2.4 GHz and 5 GHz range. While the main functional blocks of spectrum sensing, switching, and sharing have experienced rapid strides over the past decade [1], work on higher layers of the protocol stack, such as the transport layer that is essential for realizing large scale practical deployments, remains in a nascent stage.

To date, the work on CR transport protocols has been based on the TCP window behavior, where the acknowledgment packets (ACKs) sent by the receiver determine the state of congestion within the network [2,15,21]. This self-clocking mechanism of TCP is highly susceptible to the observed round trip time. With periodic interruptions caused by the primary user's (PU) appearance or large scale bandwidth fluctuations, this mechanism by itself is unable to distinguish true congestion from PU induced spectrum changes. These works that directly adapt TCP for CR networks rely on comprehensive information from the underlying layers, as well as the intermediate nodes of the data path route. While there are distinct merits in a cross-layer approach, such a design violates the traditional end-to-end paradigm associated with the transport layer.

In window-based transport protocols, the problem of reliance on ACK timing is exacerbated in CR networks because nodes pause their transmission when they are engaged in sensing or channel switching. This, in turn, results in varying round-trip time estimates (in the case of TCP) rendering the self-clocking nature ineffective. The frequency and reliance on the ACKs for window based transmissions also lead to reverse path performance

* Corresponding author.
E-mail addresses: al-ali.a@husky.neu.edu (A.K. Al-Ali), krc@ece.neu.edu (K. Chowdhury).

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impact on the forward DATA path. In TCP, this can amount to 10–20% of the data stream rate as demonstrated in [4]. This paper presents a fresh perspective on the design of CR-specific protocols using an equation-based approach, wherein the concept of the congestion window in classical TCP is eliminated, and instead, an equation is devised as a function of the effective packet loss rate. This equation is not dependent on the time variance of the returning ACKs, and hence, the source transmission rate is less impacted by temporary disruptions in the flow.

The authors of [4] also report that CSMA/CA at the link layer results in bursty end-to-end flows when coupled with TCP at the transport layer. We independently verify this in Fig. 1 for a three node network where no congestion is introduced. The observed increase in TCP throughput may not only cause a potential adverse impact to the CR network through congestion, but also to the PUs by interfering with their packet delivery performance. Instead, the equation based TCP Friendly Rate Control (TFRC), a representative of the broader class of equation based transport protocol [3], remains stable, and in the absence of any other external stimulus, avoids the bursty transmissions seen in TCP.

Our approach towards transport protocol design for CR follows a new direction of using an equation based control, hitherto unexplored in the current literature. For this, we use the TFRC as the departure point. We not only adapt the state-action behavior of TFRC, but also modify the actual rate control equation leading to our new design for CR that we name as TFRC-CR. The main features of this new protocol are as follows:

- It allows the TCP source to integrate with designated spectrum databases, as mandated by the FCC in a recent ruling [5]. This limited (and required) interaction with the database totally removes any need of feedback from the intermediate nodes or from the underlying layers. Thus, TFRC-CR reverts back to the classical end-to-end paradigm associated with the transport layer.
- It intelligently polls the spectrum database only when needed, by identifying a possible PU arrival event based on the observed trend in packet losses, i.e., it does not consume the back-end system resources used for interacting with the database. Current regulations from FCC specify database polling at least once every 60 s for Mode I devices (more on that in Section 5), and our aim is to increase the access frequency only when a critical need is detected.
- It enhances the speed of response by distinguishing between spectrum change and true congestion. Hence, the transmission rate is almost never penalized unless the need is justified. Likewise, the rate of increase in the transmitted segments when new spectrum becomes available is much higher than that possible in the classical window based TCP, owing to the immediate effect of the rate equation.
- It modifies the TFRC rate control equation by changing the definition of the loss-event interval. This change allows the protocol to utilize the bandwidth more efficiently by having a higher and more accurate sending rate and throughput.

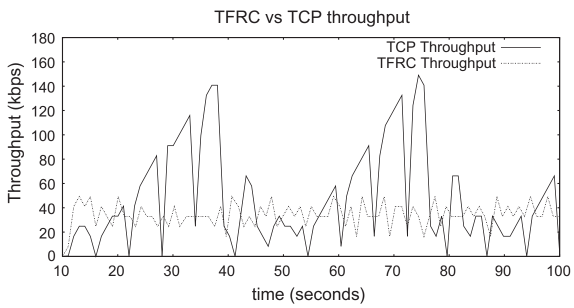

Fig. 1. Throughput comparison between TCP and TFRC in a 3-hop chain ad hoc network.

The rest of this paper is organized as follows: Section 2 gives the related works in the area of transport protocol design for CR. The preliminary background of TFRC and the motivation for adapting it for CRs is described in Sections 3 and 4. In Section 5, we describe the proposed protocol (TFRC-CR) in detail. Section 6 gives results from our comprehensive simulation study, and finally, we conclude our paper in Section 7 with pointers to future research.

2. Related work

While transport layer research in wireless networks has received considerable attention over the past decade, protocols focused specifically on CR networks are still in a nascent stage.

By minor modifications of the information contained in the feedback acknowledgments (ACKs) sent by the destination, such as by falsely advertising a receive window of 0 in Freeze TCP [6] when an impending hand-off is detected, the TCP source can be prevented from transmitting. The single end-to-end connection can be split into the wired (sender to base station or BS, when such an infrastructure support exists) and wireless (BS to the wireless node) planes, as shown in WTCP [7]. In Addition, some protocols explore tuning the sender's transmission rate through explicit notifications (TCP EFLN) [8] and via selective retransmissions of lost packets (TCP SACK) [9]. While each of these approaches have merits, they were not originally designed with the aim of licensed or primary user (PU) protection, sudden large-scale bandwidth fluctuations, and periodic interruptions caused by spectrum sensing and channel switching.

More specific to cognitive radio, various measurement studies have demonstrated the need for a new transport protocol for cognitive radio networks (CRNs) [13–15]. In particular, the suitability of TCP for CR networks, given its widespread use, has been explored in [13–17]. The work in [15] proposes modifications to TCP and introduces three different protocols: cogTCP, cogTCPE and cogTCPW. The *knowledge module* common to all of the above is linked to the transport protocol that leverages information from the link and physical layer such as sensing times and esti-