Transport Control Based on Spectrum Switching Detection in Cognitive Radio Ad Hoc Networks

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Abstract. Cognitive Radio is an intelligent wireless communication technology which can improve the radio spectrum utilization through opportunistically accessing the vacant portions of the spectrum. Due to the time-varying spectrum availability, a cognitive node has to perform spectrum switching frequently, which causes severe delay and high packet loss. Therefore, network protocol design for cognitive radio ad hoc networks (CRAHNs) should address this issue to ensure reliable end-to-end packet delivery. In this paper, we first propose a novel spectrum switching detection scheme for CRAHNs in which intermediate nodes monitor the variation of the Round-Trip Time (RTT) and the arrival interval time of packets to detect the spectrum switching over succeeding links. Based on the scheme, a new transport control mechanism is then designed to deal with spectrum switching in CRAHNs. We implement the proposed mechanisms on a USRP2-based testbed. The experiment results demonstrate that the mechanisms can detect the spectrum switching and improve end-to-end throughput by up to 45%.

Keywords: Cognitive radio, ad hoc networks, spectrum switching, transport control.

1 Introduction

A Wireless ad hoc network (WANET) is characterized by its self-organized nature that does not rely on any infrastructure and centralized administration. In WANETs, each node can dynamically select proper routing with multiple hops to forward data to its destination. Currently, WANETs are often limited to operate on industrial, scientific and medical (ISM) frequency bands. With the rapid development and deployment of wireless networks, ISM bands have become increasingly congested [1], [3]. Cognitive Radio (CR) technology is believed to be an intelligent wireless communication technology for improving the radio spectrum utilization by opportunistically exploiting the existence of spectrum holes. In CR networks, the CR users are capable of utilizing these licensed bands unoccupied by the primary users (PUs) while not causing

X. Zhang and D. Qiao (Eds.): QShine 2010, LNICST 74, pp. 1–15, 2011.
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interference to the primary service. It is envisioned that the CR technology can enhance the capacity of wireless networks by expanding the range of current wireless networks and making better use of spectrum resources. In traditional WANETs, the mobility of intermediate nodes and inherent wireless channel instability are the key factors that jeopardize the reliable end-to-end delivery of data. While in cognitive radio ad hoc networks (CRAHNs), since the CR users have to evacuate the licensed band once PUs return, some other issues, such as spectrum sensing, spectrum switching and awareness of the PUs' activities, are the major problems that account for unreliable data delivery[2], [3]. In particular, in CRAHNs, when PUs arrive, CR users have to give up the current channel and trigger the spectrum switching. In this process, CR users search for a set of available channels on various spectrum bands through spectrum sensing and negotiate with each other to get a mutually acceptable channel to recover the link between them. From the standpoint of end-to-end transmissions, there is a temporary link breakage on the path during the spectrum switching that could cause high packet loss and large delay. Thus, in CRAHNs, how to detect the spectrum switching in time and react to it efficaciously is a challenge to ensure reliable end-to-end data delivery.

In this paper, we first attempt to find an efficient spectrum switching detection scheme. Since spectrum switching causes a temporary link breakage, during this time, all packets have to be buffered in intermediate nodes and cannot be delivered to source or destination nodes. Therefore, Round-Trip Time (RTT) and arrival interval time of these delayed packets should manifest greater value than their counterparts in normal transmissions. Along an end-to-end path, the intermediate nodes near the links performing the spectrum switching can obtain more accurate information in time than the source node. We resort to these intermediate nodes to monitor RTT and arrival interval time of packets and design a spectrum switching detection scheme based on these two parameters. Based on this scheme, we then propose a new transport control protocol which prevents source nodes from injecting more packets into the network during the spectrum switching process in order to alleviate MAC layer contentions and packet bursts.

The rest of the paper is organized as follows. Section 2 reviews related work in this area. In Section 3, we describe our system model. A new MAC protocol is proposed in Section 4, which has been implemented on our testbed. Section 5 elaborates the spectrum switching detection scheme. A new transport control mechanism is introduced in Section 6. In Section 7, we describe our testbed and analyze the experiment results. Section 8 concludes our work.

2 Related Works

Considerable work has been done on transport control protocols (TCPs) to explore the reason for message loss. Ramani and Karandikar [4] employ Explicit Congestion Notification (ECN) to differentiate whether the loss is caused by congestion or not. Casetti et al. [5] introduce the TCP Westwood scheme relying on end-to-end bandwidth to discriminate the cause of packet loss (congestion or degraded wireless channel). Brakmo, Malley and Peterson [6] monitor the changes in the estimated amount of extra data in the network based on an explicit congestion model between throughput and RTT. Barman and Matta [7] assume that the variations in RTT and packet loss are correlated. By estimating the average RTT, TCP is able to distinguish the loss owing to congestion from that due to unreliable wireless transmissions. Biaz and Vaidya [8], Tobe et al. [9] investigate a set of ‘‘loss predictors” involving interval-arrival time and Relative One-way Trip Time (ROTT) to predict the underlying packet loss reasons. However, Cen, Cosman, Voelker [10] have pointed out that the classification indicators, as described above, are constrained by the network topology and each indicator can only be effective in certain topologies.

In wireless networks, data deliveries are plagued by problems such as high bit error rate (BER), route failure, multipath routing and network partition. Apart from these problems, dynamic spectrum access is another serious problem in CRAHNs which leads to route disruption. For example, route disconnection and longer packet RTT may be incurred if an intermediate node on the route is engaged in spectrum sensing or switching. A window-based transport protocol for CRAHNs called TP-CRAHN is first proposed by Chowdhury, Felice and Akyildiz [2], using the ECN mechanism to determine the loss causes. If the time lag contained in ECN is within the threshold Lmax (Lmax = 1.5× RTT in [2]), and no prior action has been taken on an earlier ECN from the same node, TP-CRAHN assumes that congestion occurs; while any further delay (i.e., time lag > Lmax) indicates that the path was temporarily disconnected due to a spectrum sensing or channel switching event. However, TP-CRAHN is just one modified TCP scheme which enables intermediate nodes to send or piggyback ECN to notify the source node. Felice, Chowdhury and Bononi [11] exploit a CRAHN model integrating three impact factors: spectrum sensing cycle, interference from PUs and channel heterogeneity. The performances of different TCP variants in CRAHNs are evaluated under this model using NS-2. Simulation results show that existing TCP schemes proposed for wireless ad hoc networks might not work well over CRAHNs. Sarkar and Narayan [12] propose another modular architecture chartered two modules: knowledge module and cognitive module. The approach is separated from standard transport protocols and adapts better to the unique characteristics of cognitive radio networks.

3 System Model

In our model, each CR node is equipped with a single transceiver that is capable of tuning to any channel among a licensed spectrum set. We assume that activities over the licensed channels can be described as two states, ON and OFF. The ON (Busy) state represents the channel is being used by PUs. The OFF (Idle) state indicates that the channel is free of PU activities.

In CRAHNs, a CR user needs to detect whether any PU appears on current channel before it gets ready to transmit or receive data packets. As shown in Fig. 1, if PU_{C3} occupies channel C3, CR user 3 has to suspend its transmission and starts a spectrum sensing operation. Spectrum sensing procedure searches for available channels over various spectrum bands that are not occupied by PUs. When CR user 3 finishes spectrum sensing and obtains a new available channel set, it triggers spectrum switching operation to negotiate with its neighbors to guarantee a mutually acceptable channel. If the spectrum switching succeeds, the link breakage is recovered and data transmission resumes. In this paper, we address three issues: an implementable medium

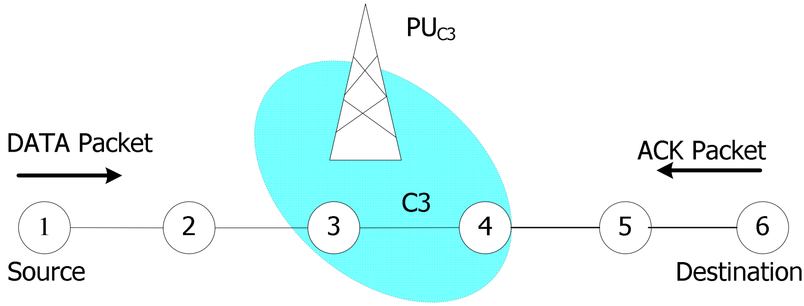


Fig. 1. PU occupies its licensed channel

access control (MAC) mechanism, an efficient spectrum switching detection scheme, and a reliable transport control scheme, in CRAHNs. In the following sections, we will elaborate these three design issues, respectively.

4 An Implementable MAC Protocol

In CRAHNs, CR users are capable of transmitting data on different channels via dynamic spectrum access. The CR MAC layer should provide an efficient mechanism considering two issues: (i) sensing the channel to detect the presence of PUs and switching to another available channel when PUs appear on the current channel; (ii) sharing the channel with neighboring CR users with a tolerable interference level to PUs [13]. MAC protocol design is a challenging issue in CRAHNs. IEEE 802.22 makes a standardization effort, while other MAC protocols are specially designed for various environments and applications. In our study, we attempt to design an implementable MAC protocol to balance between the limitation of hardware support and the performance of the protocol. To this end, we adopt a random access methodology based on carrier sense multiple access with collision avoidance (CSMA/CA).

Our implementable MAC is a special application of CSMA/CA in CRAHNs, as shown in Fig. 2. Due to the dynamic spectrum access, the MAC mechanism employs two types of channels, a common control channel and data channels. Two neighboring CR users exchange RTS/CTS to carry out handshake on the common control channel. If the process is successful, they turn to a data channel negotiated in advance and perform spectrum sensing to determine if any PU occupies the channel. Guaranteeing the absence of PUs at that time, two CR users can complete the data frame transmission. If any PU is active on the data channel, CR users have to give up the current channel and trigger spectrum switching to find another idle channel. Then, CR users negotiate a common idle channel to rebuild a new data channel.

Consider a network in which all nodes are deployed at the same distance to its neighboring nodes. Every node can only communicate with its one-hop neighbors, sense the transmissions of its two hop neighbors, and cannot detect other nodes. When a node is transmitting a packet on a channel, all nodes within its sensing range cannot transmit over the same channel. A chain topology is shown in Fig. 3. Assume there is

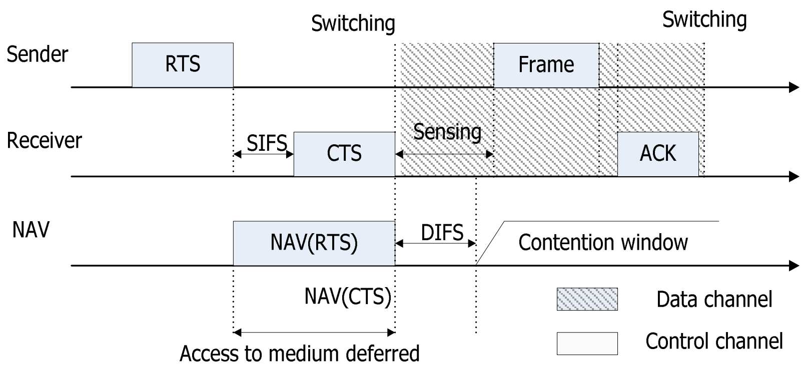


Fig. 2. An implementable MAC protocol

only one channel available. If node 1 and node 2 are exchanging RTS/CTS, node 3 may detect it and hence cannot transmit or receive any packet. It will wait for a time interval of NAV (Network Allocation Vector). However, node 4 is a hidden terminal to the RTS transmission. It is possible that node 4 considers the channel to be idle and attempts to transmit to node 5. The transmission between node 4 and node 5 may collide with the reception at node 2 and cause packet loss.

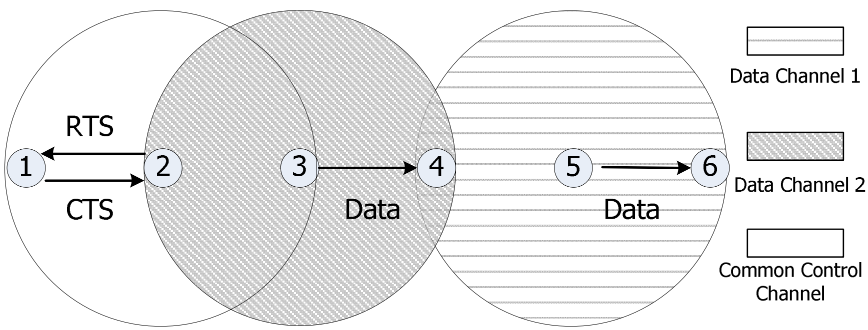


Fig. 3. A chain topology

Chen et al. [14] show that the bandwidth-delay product (BDP-UB) of a path can be upper bounded by *kN* with $k = 1/5$, where *N* is the number of round-trip hops. Our proposed MAC protocol utilizes one control channel and several data channels. We assume that there are enough available channels in the network and each link on an end-to-end path is built on a different data channel. Therefore, CR users only contend to access the common control channel. Although any pair of nodes can communicate on a different data channel simultaneously, as shown in Fig. 3, the BDP-UB of the path in CRAHNs cannot exceed $L/2$ (ideally, every two neighboring nodes compose a pair and transmit data simultaneously), where *L* is the length of the path.

5 A Spectrum Switching Detection Scheme

Since the link congestion leads to packet loss and timeout, TCP variants propose to control congestion window size to alleviate the congestion on the path. The conventional TCP approaches decrease the window size multiplicatively if the network is congested, e.g. the AIMD algorithm. This method is both costly and inefficient in multihop wireless networks. Especially in CRAHNs, since the CR users have to evacuate the licensed band once PUs return, some other issues, such as spectrum sensing, spectrum switching and awareness of the PUs' activities, are the major factors that account for unreliable data delivery. Thus, in CRAHNs, how to detect the spectrum switching in time and react to it efficaciously is a big challenge to ensure reliable end-to-end data delivery.

In particular, the appearance of PUs may cause spectrum switching which results in packet loss and path breakage in CRAHNs. The path breakage due to the spectrum switching is a new cause of packet loss and congestion for CRAHNs. For example, as shown in Fig. 1, the data channel between node 3 and node 4 is occupied by a PU. If the PU_{C3} appears on channel C3 and interrupts the data transmission between node 3 and node 4, the two nodes have to trigger spectrum switching to negotiate a new data channel. During this period, node 3 and 4 cannot communicate with other nodes. Source node 1 is unaware of the situation and will keep injecting packets into the network. As a result, node 2 will queue many packets and cannot transmit them to the next hop, node 3. When the spectrum switching between node 3 and 4 succeeds and the path recovers, the heavy traffic load at node 2 could lead to severe contentions, thus causing high packet loss.

The spectrum switching occurs frequently due to the dynamic spectrum access which greatly affects the performance of end-to-end throughput. In CRAHNs, predicting the spectrum switching and reacting to it as quickly as possible are critical to improving the end-to-end transmission throughput. In conventional transport layer control mechanisms, a source node needs a long time to learn the change of a path. Moreover, the information obtained by the source node becomes less accurate as the path length increases.

Compared with the source node, the intermediate nodes near the links performing spectrum switching, called detection nodes in this paper, can get more accurate information and react to the occurrence of spectrum switching effectively. It is important that the detection node could choose some appropriate features to detect the spectrum switching. In this paper, we investigate whether RTT and packet arrival interval time can be used as the indication of the spectrum switching. RTT measured at an intermediate node is defined as the time interval between the data packet arrival time and its corresponding ACK packet arrival time. Packet arrival interval time is defined as the interval between successive packets arrived at the intermediate node. During the process of end-to-end transmission, there are two types of packets, forward data packets and reverse ACK packets which are necessary to the reliable transmission. In general conditions, the throughput of data flow and ACK flow could be stable and have less sudden changes. In these situations, RTT and packet arrival interval time of these two types of packets are small and within a certain range. In CRAHNs, the occurrence of the spectrum switching could cause sudden increase of RTT and packet arrival interval time. As Fig. 3 shows, the link between node 3 and node 4 is unavailable because PU_{C3} occupies channel C3. During the temporary path breakage, forward data packets and reverse ACK packets cannot be exchanged between node 3 and 4. Instead, they are buffered in the queues of intermediate nodes near node 3 and 4 until the spectrum switching finishes and the link is recovered. In this process, significant delay occurs on these buffered packets. Consequently, RTT and arrival interval time would demonstrate greater values beyond the normal range. This shows the distinct features of the spectrum switching. Therefore, we observe the RTT and packet arrival interval time at the intermediate nodes on the path to unveil the effect of the spectrum switching on these two factors.

6 A New Transport Control Mechanism

CRAHN differs from existing networks in that CR users access the spectrum opportunistically. If two nodes in different types of networks attempt to realize data transmission, a transport control mechanism across heterogeneous networks is necessary. In general, the end-to-end connection mechanism could control the whole path, but it needs to modify existing protocols or create a new protocol to make it compatible with the two types of networks. This method is costly and inefficient. Every transport control mechanism can only work efficiently in certain situations. The cross-network mechanism considering all factors of different networks is too complicated and difficult to deploy. A feasible approach is to divide the end-to-end connection into separated connections at the border of any two different networks. As Fig. 4 shows, an end-to-end connection from node S to node 4 is established. Node 1 at the border of the CRAHN can be selected as the interface between two networks. The approach also makes the transport control mechanism of CRAHN transparent to the other network. Therefore, the nodes in the left side network can apply its original transport control mechanism without modifications. All the packets destined to node 4 are received, buffered and acknowledged by node 1. In the view of node 2, 3 and 4, node 1 is like a source node of the path.

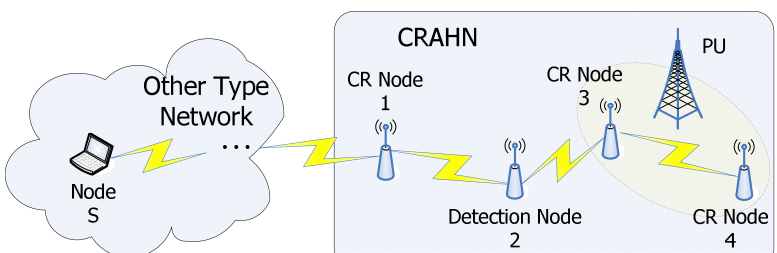


Fig. 4. End-to-end transmission

In CRAHNs, detection nodes are used to assist detecting the spectrum switching. As Fig. 4 shows, detection node 2 is near the link needing the spectrum switching. It can obtain accurate information of changes on the link through monitoring RTT and packet arrival interval time. Based on the discussion in Section 5, node 2 can monitor the arrival interval time of reverse ACK packets to detect the spectrum switching happened on its succeeding nodes, e.g. node 3 and 4. For the path without spectrum switching, the packet arrival interval time is within a certain range. If it suddenly grows beyond the range, probably spectrum switching has happened over the path. When receiving an ACK packet, the detection node starts a timer and waits for the next packet. If the timer expires and the next packet does not arrive, the detection node concludes that the spectrum switching has occurred and sends a message to inform node 1. We will find proper thresholds of RTT and packet arrival interval that indicate the spectrum switching has occurred. Node 2 can piggyback the message in ACK packet to node 1. Being aware of spectrum switching, node 1 runs a simple flow control mechanism to deal with it. The mechanism employs a fixed window transmission which is constrained by BDP-UB. Node 1 can either monitor RTT and packet arrival interval time to detect the spectrum switching or get more accurate information from node 2. When node 1 believes that the spectrum switching occurs, it checks data packets that are not acknowledged. If the number of these packets is greater than 2, node 1 will not send packets until it recognizes that the spectrum switching finished. In order to deal with ACK packet loss, the mechanism also employs retransmission timeout. The retransmission timeout does not increase exponentially as that in TCP when retransmission happens, because the spectrum switching and MAC contention are the main reasons for packet loss rather than the congestion in CRAHNs.

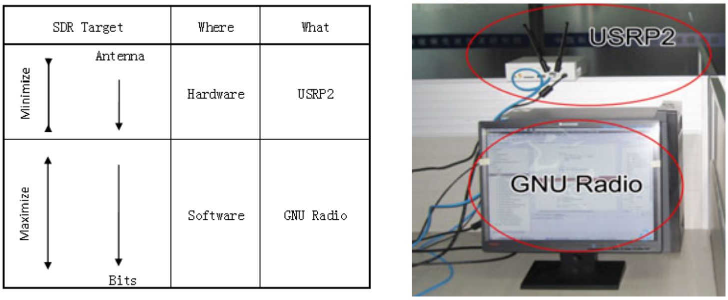
7 Experiment Environment and Results

In this section we demonstrate the variation of RTT and packet arrival interval time at intermediate nodes during spectrum switching in CRHANs based on the experiments. Our testbed is built with software defined radio devices. We analyze the experiment results and prove the efficiency of the spectrum switching detection scheme. The transport control mechanism based on the detection scheme also runs on our testbed and manifests a higher throughput than conventional TCP in CRAHNs.

7.1 Testbed Description

The software defined radio is used to create a flexible radio platform with software instead of traditional hardware to perform signal processing. The ideal software defined radio platform would use as little hardware as possible and let software deal with all of the processing. The receiver might have just an antenna connected to an analog-to-digital converter (ADC). Samples would then be read from the ADC and software would handle all signal processing, as shown in Fig. 5(a) [15]. Our testbed is built based on the GNU Radio and the 2nd version of Universal Software Radio Peripheral (USRP2), as shown in Fig. 5(b).

GNU Radio is a signal processing package with a free software development toolkit and provides an open-source library of common signal processing blocks [16]. The 2nd version USRP offers higher performance than the original USRP which leads us to choose USRP2 as a component of our testbed.



(a) (b)

Fig. 5. (a) Software defined radio design principle. (b) USRP2 and GNU Radio

7.2 Experiment Results

Each USRP2 is equipped with one transceiver and communicates with bandwidth of 0.5Mbps. We implement our MAC protocol based on GNU Radio that runs on USRP2. In order to study the influence of spectrum switching on the path, we set fixed routing table at every node from the source node to the destination node. In this experiment, the CR node communicates over frequency range from 2.4 to 2.5 GHz divided into 9 channels. The channel set C is {2.40GHz, 2.41GHz,…,2.48GHz} in which 2.48GHz is used for the common control channel and the others are data channels. The channel division guarantees that every link is allocated a different data channel with others over a connected path. A flow runs over a 3-hop chain topology as shown in Fig. 4. The link between node 3 and node 4 is subject to the appearance of PUs. In the experiment, PU appears periodically which leads to the spectrum switching of node 3 and node 4. As a detection node, node 2 records the RTT and packet arrival interval of the packets.

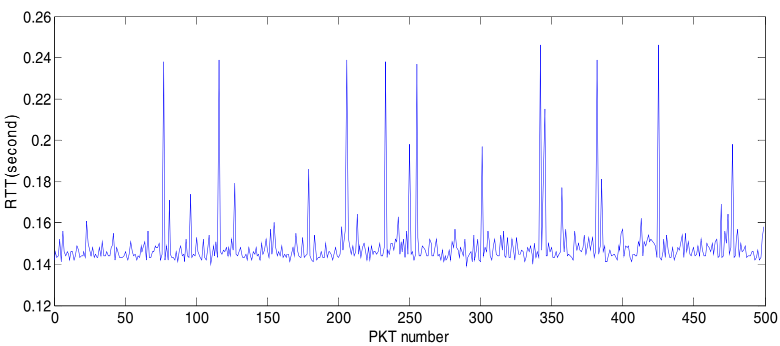


Fig. 6. RTT at detection node (no PU)

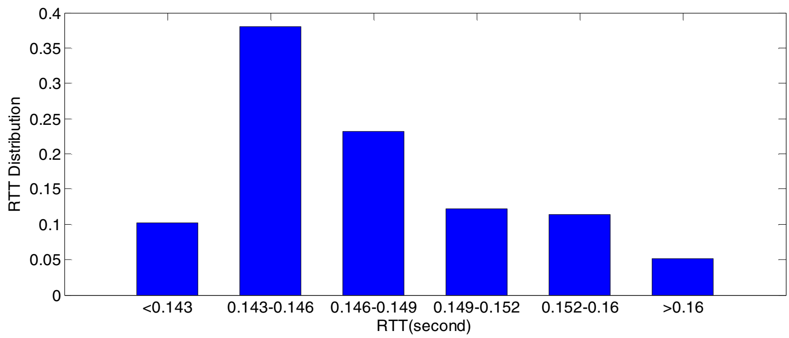


Fig. 7. RTT distribution in various time ranges at detection node (no PU)

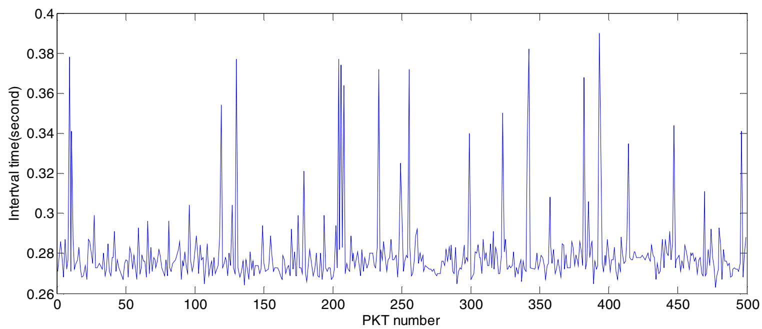


Fig. 8. Packet arrival interval time at detection node (no PU)

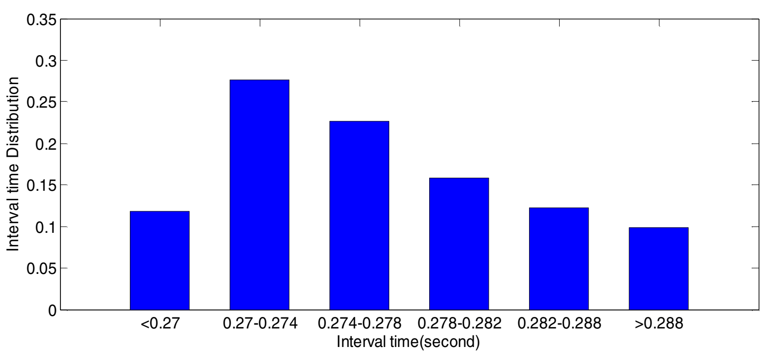


Fig. 9. Arrival interval time distribution in various time ranges at detection node (no PU)

We need to explore the distributions of the RTT and packet arrival interval time without spectrum switching as the benchmark for the comparison in various conditions. Fig. 6 manifests the RTT values of 500 packets at detection node with no PU. Most of these values are limited in a narrow range which is shown more evidently in Fig. 7. Almost 85% values of RTT are distributed in the range from 0.143 seconds to 0.16

seconds. Only 5% values are greater than 0.16 seconds which are demonstrated as spikes in Fig. 6. We investigate the packet arrival interval time under the same condition. As can be seen in Fig. 8, the values of the packet arrival interval remain relatively stable. Fig. 9 shows that about 90% of packet arrival intervals are below 0.288 seconds and the max value is about 0.39 seconds. Notice that a few spikes in Fig. 6 and 8 appear irregularly. They are caused by unreliable wireless channel condition. According to the experimental results of Fig. 6-9, we can conclude that the distributions of RTT and packet arrival interval time are relatively stable without spectrum switching.

We explore the impact of the spectrum switching on RTT and packet arrival interval time on various conditions. In the scenario, we set the sensing time to 0.2 seconds. PU arrives every 6 seconds in the experiment. As can be seen in Fig. 10 and Fig. 11, the values of RTT and packet arriving interval time experience sharp changes. These peaks in the two figures manifest that some packets are seriously impacted by the spectrum switching and have greater values of RTT and packet arrival interval time which are easily distinguished from normal values. Differed from these greater RTT values incurred by performing spectrum switching, many values of packet arrival interval time are less than normal values. When the spectrum switching finishes and the link recovers, certain node continuously sends packets buffered in its queue which leads to lower packet arrival interval time.

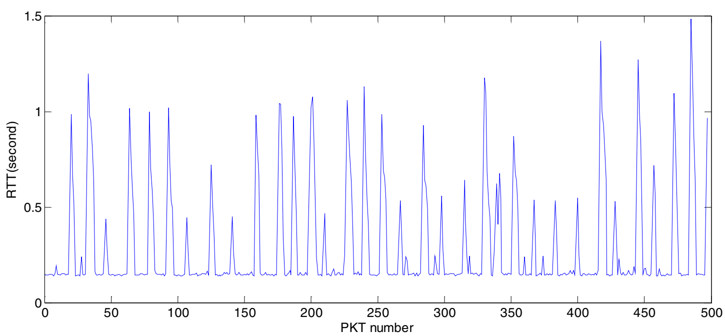


Fig. 10. RTT at detection node (sensing time is 0.2 seconds, PU arrives every 6 seconds)

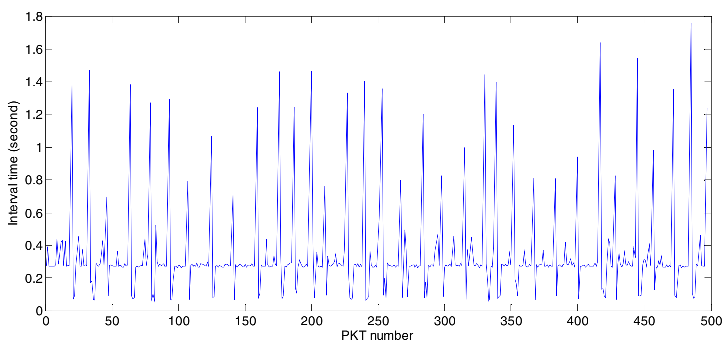


Fig. 11. Packet arrival interval time at detection node (sensing time is 0.2 seconds, PU arrives every 6 seconds)

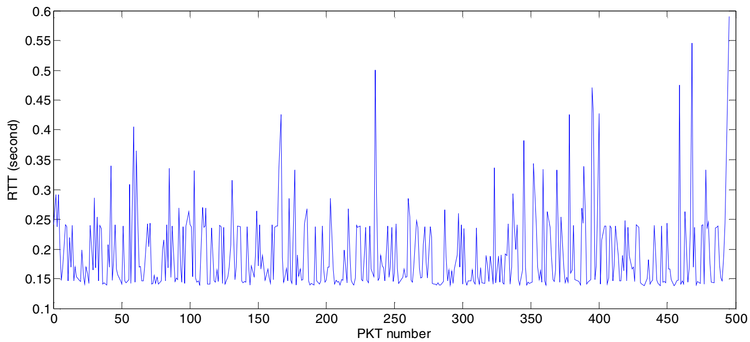


Fig. 12. RTT at detection node (sensing time is 0.2 seconds, PU arrives every 3 seconds)

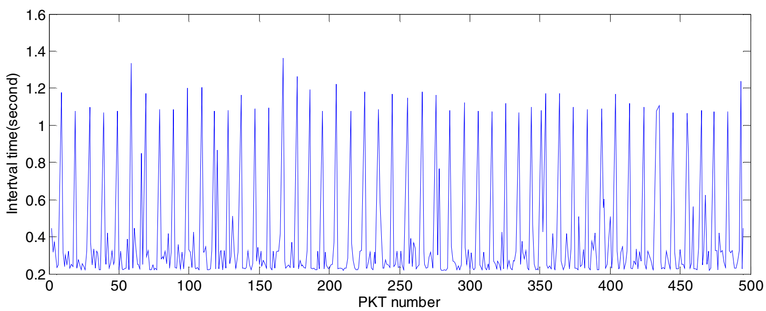


Fig. 13. Packet arrival interval time at detection node (sensing time is 0.2 seconds, PU arrives every 3 seconds)

In Fig. 12 and 13, we set the sensing time to 0.2 seconds and let a PU arrive every 3 seconds. Frequent spectrum switching causes the RTT of some packets increasing abruptly and also leads to longer packet delay and more serious MAC contention which are explicitly demonstrated by spikes in Fig. 12. These regular peaks shown in Fig. 13 manifest that packet arrival interval time can indicate frequent spectrum switching.

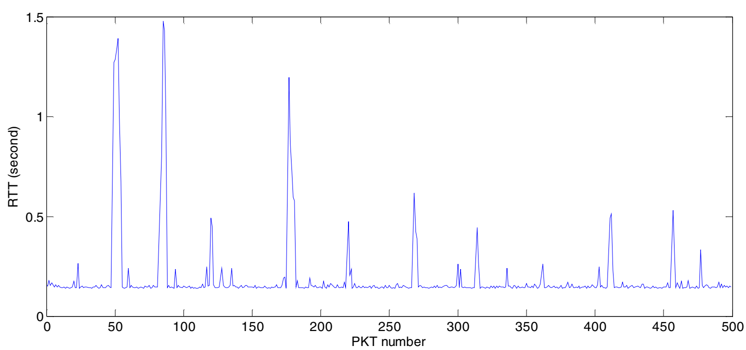


Fig. 14. RTT at detection node (sensing time is 0.1 seconds, PU arrives every 15 seconds)

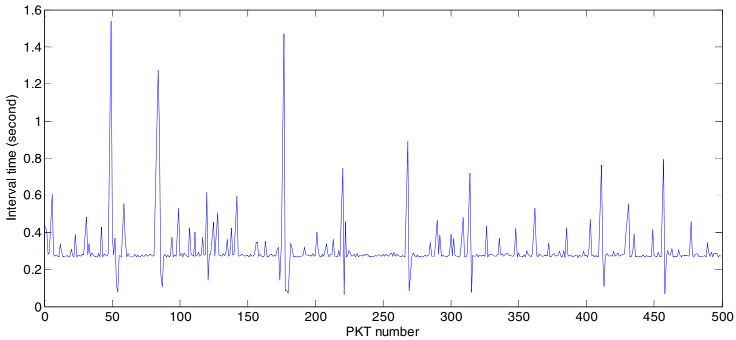


Fig. 15. Packet arrival interval time at detection node (sensing time is 0.1 seconds, PU arrives every 15 seconds)

We further adjust the sensing time from 0.2 seconds to 0.1 seconds and let a PU arrive every 15 seconds. As shown in Fig. 14 and 15, while the sensing time becomes shorter, these peaks still can indicate the occurrence of the spectrum switching. There are some spikes in the two figures which are caused by the variation of wireless channel condition even when no spectrum switching happens. As can be seen from Fig. 6-15, the packets affected by the spectrum switching experience longer RTT and packet arrival interval time compared with packets in normal transmissions. It is evident that the detection of spectrum switching via these two factors at intermediate nodes is reasonable and feasible in CRAHNs.

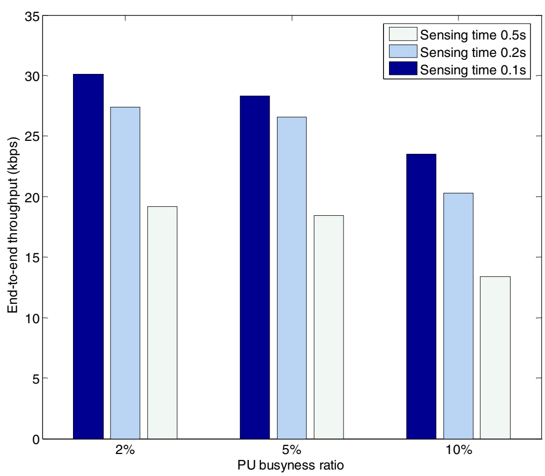


Fig. 16. End-to-end throughput in various conditions

According to the above analysis of the experiment results, the detection scheme depending on monitoring the variations of RTT and packet arrival interval time can indicate the spectrum switching accurately. Based on the scheme, we run the transport control mechanism discussed in Section 6 on our testbed. Fig. 16 shows the end-to-end throughput with respect to various sensing time and PU busyness ratio. With short sensing time (e.g. 0.1 seconds or 0.2 seconds), the differences of throughput are relatively small. The total time of the spectrum switching includes sensing time and negotiation time which is uncertain. When the sensing time is short, the negotiation time dominates the total time of spectrum switching. However, when the sensing time increases (e.g. 0.5 seconds), the ratio of the sensing time to the total time rises. Therefore, there is a noticeable decline of the end-to-end throughput. PU busyness ratio can also affect the throughput along the path. Frequent PU arrivals increase the number of spectrum switching. So the source node has to restrain from sending too many packets. Compared to the throughput under the other two PU busyness ratios, the throughput drops visibly when the PU busyness ratio is 10%. We also compare the throughput between our transport control mechanism and TCP. In Fig. 17, our mechanism achieves higher throughput than TCP by up to 45%. The reason is that our mechanism can detect the occurrence of the spectrum switching and slow down injecting packets into the path to avoid MAC layer contentions and packet bursts.

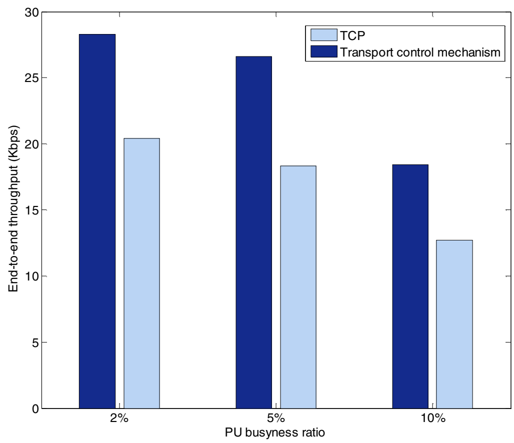


Fig. 17. End-to-end throughput (sensing time is 0.2 seconds)

8 Conclusions

In this paper, we first study the detection of the spectrum switching via RTT and packet arrival interval time in CRAHNs. The proposed novel detection scheme resorts to the intermediate node to monitor the changes of these two factors which can indicate the occurrence of the spectrum switching. Based on the scheme, a new transport control mechanism is designed for CRAHNs. We implement the system on our testbed and collect experiment data for analysis. The experiment results demonstrate that the proposed mechanisms can detect the spectrum switching and improve end-to-end throughput efficiently.

Acknowledgments. This work was supported by the National Natural Science Foundation of China under grant No. 60903192.

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