An Application-Oriented Routing Protocol for Multi-hop Cognitive Radio Networks

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***Abstract*—A challenge for routing in cognitive radio networks is the intermittent connection due to the occupying and releasing licensed channels of primary users. To solve this problem, the routing protocol will choose the most stable channel (the channel with the longest average length of idle period) to build up the stable path. This approach, however, can lead to the increase of channel competition between cognitive users since the most stable channels are preferred to be utilized by all cognitive users. In this paper, an application-oriented routing protocol is proposed. The main motivation is to reduce the channel competition between cognitive users by finding the appropriate path according to the application of cognitive users. Simulation results show that our proposed routing protocol reduces the loss ratio and increases the throughput significantly.**

***Index Terms*—cognitive radio; application-oriented; routing; stability**

I. Introduction

In wireless communication, the most valuable resource is the radio spectrum. However, according to recent studies[1][2], while the assigned spectrum (licensed spectrum) is under-utilized in various geographical locations and time, the unlicensed spectrum is always overloaded because of the growth of wireless services. To reduce the waste of licensed spectrum usage and provide more available spectrum resource for unlicensed users, an efficient way is allowing unlicensed users to opportunistically access the licensed spectrum without penalizing Quality of Service (QoS) of licensed users. Cognitive Radio (CR) [3] is envisaged as the sufficient technology that aims to flexibly use wireless radio spectrum. Each node in the Cognitive Radio Network (CRN) is equipped with a cognitive radio which has capabilities of sensing the busy channel, reconfiguring the radio parameters and switching to another channel. Due to the information collected during the sensing process, the CR users will use the idle licensed channel during vacant time and immediately release the channel whenever CR users detect any use of licensed users on this channel.

One of the most important problems in routing in multi-hop CRN is the intermittent connection. Unpredicted operation of primary users (PU) prevents secondary users (SU) from having a stable usage of the licensed spectrum. The intermittent connection will lead to frequent route corruptions whose consequence is that the re-routing process must be called several times, increasing transmission delay and packet loss. Although there are many routing protocols proposed for CRN, only few of them tackle the intermittent connection problem. There are two possible methods used to solve the problem of intermittent connection: corruption avoidance method and corruption reaction method. In the corruption reaction method [4][5], the proposed routing protocols define mechanisms to recover the route in case that the route is corrupted. Therefore, network can avoid the performance degradation whenever the route is corrupted due to the coming back of primary users. In the corruption avoidance method, the proposed routing protocols [6]-[11] define mechanisms to select the most stable route in order to avoid frequent changes of route and improve network performances. By considering the spectrum stability as the metric in the routing protocol, nodes will select the most stable link for each hop and obtain the most stable route.

The above channel selection algorithm [6]-[11] is designed with cross layer approach in which the channel information is collected by lower layers and used by network layer for routing decision. Even though this channel selection algorithm can help nodes to choose the most stable channel, it still leads to some problems. Firstly, by forcing all CR nodes in an area to operate over the most stable channel, the competition among CR nodes for the same channel resources will cause contention and collision problems in which the consequence will be an increase of end-to-end delays or a decrease of throughput. Secondly, the stable-channel approach will under-utilize the ability of operating on different channels which cognitive radio offers. Therefore, a novel spectrum allocation strategy is needed to provide better spectrum utilization in CRN.

As each application has its own traffic pattern which decides the transmission behaviour, the channels can be allocated to CR users according to their application types. For example, with Constant Bit Rate (CBR) Voice over IP (VoIP) applications or Delay Tolerant Network-liked applications in which the transmissions usually happen in short period of time, the channels which are not stable and often idle will be the appropriate candidate channels. Therefore, taking into account the type of applications, we can provide better channel allocation strategy in which the channel competition or interference

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will be reduced. In this paper, we introduce the Application-Oriented Stability (AOS) metric which helps nodes using unreliable and non-elastic delay applications to choose the channels which can be used more frequently even though these channels are not stable. The most stable channel (the channel with the longest average length of idle period) will be reserved to the nodes using reliable and elastic delay applications. By this channel allocation strategy, radio spectrum resource is utilized more efficiently and network performance will be improved.

The remainder of this paper is organized as follows. In Section II, we discuss works related to stable routing in cognitive radio network. Section III will study channel usage pattern according to application and describe the network model. In Section IV, we analyse the Application-Oriented Stability metric in detail and present the application-oriented routing protocol. Simulation results are illustrated in Section V. Finally, Section VI concludes this paper and figures out the future work.

II. Related work

Some stability routing techniques in cognitive radio network already exist. In [8], the authors first define the maximum link hold-time as the maximum length of available period before a cognitive link is considered to be failed. After that, the authors expressed the link hold-time as a function of the maximum link hold-time and the primary user usage pattern. The route hold-time then will be derived as the accumulated hold-time of links which compose the route. Finally, the routing metric based on the route hold-time and end-to-end throughput is proposed. Sharma et *al.* propose in [7] a new routing metric for multihop cognitive networks. This new metric includes the stability factor, also known as the average channel availability time which is calculated as weighted moving average of previously measured availability times and the time measured in the current measurement duration. Same remarks apply on [9][10], where the proposed routing metric is based on the channel utilization which depends on the average duration of available period of the channel. [6] proposes a collaborative strategy for route and spectrum selection in cognitive radio networks. The routing metric includes the spectrum stability factor used to gauge the variation of the spectrum. In [11], the authors use a threshold to decide whether the channel is stable. The channel will be considered as stable if its average available time is larger than the threshold. Otherwise all unstable channels will be excluded from the spectrum opportunity.

Our work differs from the previous proposals in two aspects: first, taking into account the application of cognitive users when allocating the channel using our stability parameter, and second, considering the length variance of idle periods which can lead to the wrong channel selection.

III. Network Model and Traffic Analysis

A. Network Model

We consider a cognitive radio network composed of primary users and cognitive users. Primary users are nodes which hold licenses for specific spectrum bands, and can occupy their assigned spectrum. Therefore, primary users will be provided a reliable communication environment regardless of time and space. Cognitive users use opportunistically the licensed channels to send their data when they detect the disappearance of primary users. We assume that all cognitive users are equipped with cognitive radios which have abilities of reconfiguring transmission parameters and scanning the channels for opportunistic transmission.

We also consider that each primary channel will follow an ON-OFF model in which channel alternates between state ON (active) and state OFF (inactive) [12]. An ON/OFF state models a time slot in which the primary user is or is not occupying a channel. The cognitive users can utilize the OFF time slot to transmit their own signals. Suppose that each channel changes its state independently. The ON-OFF channel model is depicted in Figure 1. The channels are assumed to

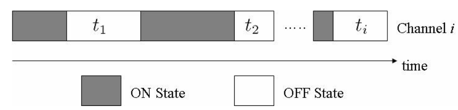

Fig. 1. The channel state for *i*th channel

be organized in two separate channel sets: a common control channel (CCC) and a set of data channels. All cognitive users in the network will use the CCC to send packets for contending the data channel or to exchange local information and routing control information. The set of data channel is used for data communication. Each data channel has bandwidth w. We also assume that all sensing information are accurate.

B. Traffic Analysis

In this section, Voice over IP (VoIP) on behalf of unreliable and non-elastic delay applications and File Transfer Protocol (FTP) on behalf of reliable and elastic delay applications will be studied through different topologies and channel patterns in order to find the most appropriate channel pattern for each type of application.

To study the impact of channel idle time on the performance of VoIP and FTP, we deploy different test cases which are different in the number of nodes (Figure 2). The detail of basic parameters used in each test case are described in Table I. Beside that, in each test case, ON-OFF model is used to model the channel availability at each node.

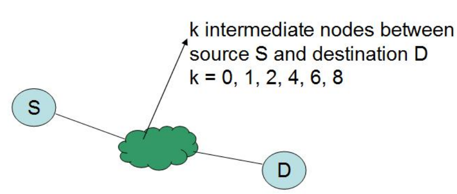

Fig. 2. Network topology of test cases

In each test case, we first create an UDP/CBR(VoIP) connection from source node to destination node and keep data

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TABLE I
SIMULATION PARAMETERS

Parameter	Value	Comments
Flat Grid	1000x1000	Simulation space. Here, a flat field 1000mx1000m
Node	MobileNode	The PU/SU that is recognized in ns-2 as a mobile wireless node
Bandwidth	2Mbps	The bandwidth of wireless network
Stack delay	9.5-10.5ms	A delay that allows a packet to go through OSI stack at node in ns-2
Propagation model	Two-Ray Ground	A propagation model supported by ns-2 to simulate the signal propagation
Interference model	Thermal Threshold	If a packet power is lower than a minimum threshold (set fixed), packet will get dropped
UDP/CBR rate	64kbps	Rate for application UDP/CBR
TCP/FTP	varied	Rate which claims as much as possible from the remained bandwidth
Duration	300s	A runtime for data transfer in a test case
Protocol overhead	5%-10%	Extra information exchanged between nodes besides data transfer (e.g. routing packets of Routing layer used to establish path for data from source to destination)
Data in UDP packet	160 bytes	Data in each UDP packet
UDP loss ratio accepted	3%	Loss ratio is acceptable to application
MAC layer	AOS-MAC	A modified version of $MAC_8 02.11$ supported by ns-2. AOS-MAC is implemented to allow the secondary users to transfer data on the licensed channel transparently to primary users
UDP traffic	UDP/CBR	UDP constant bit rate at 64kbps
Data in TCP packet	512 bytes	Data in each TCP packet
TCP traffic	TCP/FTP	The rate of FTP traffic is varied (FTP claims the bandwidth as much as possible)

transferring continuously in 300ms. All nodes in the network will choose the channel using the same criteria (e.g. the most stable channel which its length of idle time is varied for testing purpose) for data transmission. After that, we vary the length of channel idle time and observe the network performance which is shown through the throughput. We then create TCP/FTP connection and follow the same procedure as we did in case of UDP/CBR(VoIP) connection. The simulation is repeated 20 times for each test case.

The results are shown in Figure 3. The length of channel idle period (the OFF period) is varied from 2.1ms to 18.7ms. From Figure 3(a), two observations are deduced. Firstly, the network throughput will reach its maximum value and keep stable when the length of channel idle time reaches a threshold value. For instance, in the case there are 6 cognitive hops in the network, the network throughput will achieve its maximum value (78kps) when the length of channel idle time reaches the value of 15ms. Then the network throughput still stay at the maximum value even though the length of channel idle time continues to increase. Secondly, the threshold value of length of the channel idle time will be increased when there are more cognitive users in the networks. If cognitive users use the stability metric for channel selection, there are more channel competition when there are more cognitive users in the network. Hence, the consequence is that the length of channel idle time need to be increased in order to achieve the maximum value of network throughput.

The above observations are also applicable in case that application is FTP (Figure 3(b)). However, there is a difference between both cases. The difference is that, to achieve the threshold value of network throughput, the length of channel idle time in case of FTP need to be much longer than the length of channel idle time in case of VoIP. For example, from Figures 3(a) and 3(b), in the case of there are 2 cognitive users in the network, network throughput will achieve the maximum value when the length of channel idle time in case of VoIP and in case of FTP is equal to or greater than 4ms and 16ms respectively. In case there are 6 cognitive users in the network, the length of channel idle time in case of VoIP needs to be equal to the threshold value of 17ms for the convergence of network throughput. With FTP, the length of channel idle time must be much longer.

With the above observations, it is obvious that the channels composed to built up the path should be allocated according to the application of cognitive users.

IV. APPLICATION-ORIENTED ROUTING

In this Section, the Application-Oriented Stability (AOS) parameter is described in detail, and a routing protocol using AOS as a routing metric is provided.

A. Application-oriented stability

This section will present the AOS parameter. The objective of AOS is to help CR nodes to find appropriate channels for transmitting data according to CR nodes' application type. For FTP application, CR nodes will look for the most stable channel. For VoIP application, CR nodes will look for the channel which are idle frequently even though these channels are not the most stable channel.

The AOS parameter is composed by two components: stability S and total idle time I. The stability S describes the average length of idle time period in which the unlicensed users can access the channel. This component presents the stability of the channel. The total idle time I is calculated by summing up all the idle periods of channel from the time when CR node joins the network, starts to sense the surrounding environment and obtains the available information about the channel. By considering the total idle time I in conjunction with the stability S, we can identify the channels which are vacant frequently and has biggest total idle time. If we have a channel pattern as Figure 1, the stability S and the total idle time I will be derived as follow:

The stability:

$$S = \alpha S + (1 - \alpha)t_i \quad (1)$$

where t_i is the length of the ith idle period of the channel in the current measurement duration and α is the smooth factor The average available time of the channel S is calculated as the weighted sum of the past S and the current measured

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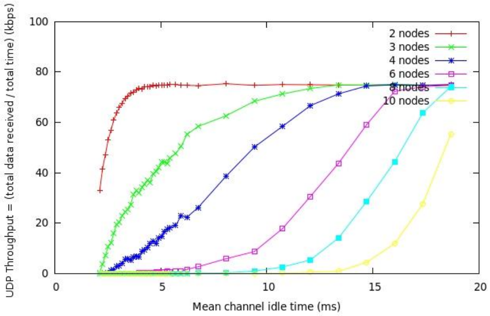
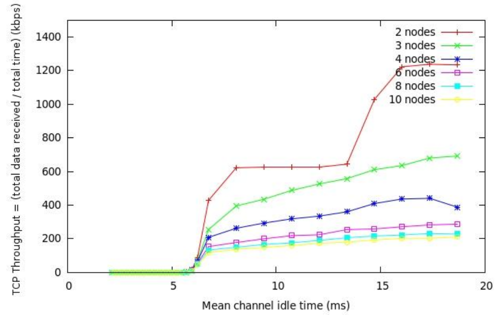


(a) VoIP Throughput



(b) FTP Throughput

Fig. 3. The relationship between the throughput of VoIP, FTP and the idle length of channel

length of the idle time period of the channel. Each time the channel changes from the OFF state to the ON state, the value of stability component is re-calculated and updated. The most stable channel will have the largest value of S

The total idle time:

$$I = \sum_{i=1}^{N} t_i \tag{2}$$

where t_i is the length of the ith idle period of the channel. N is the number of idle period from the time when CR node joins the network, starts to sense the surrounding environment and obtains the available information about the channel until the current measurement.

The total idle time of the channel I is calculated as the total idle time from the time when node joins the network, senses the surrounding environment and obtain the first information about the channel until the measurement time. Each time the channel changes from the OFF state to ON state, the value of idle level component is re-calculated and updated.

As the objective of AOS parameter is helping CR nodes to choose the appropriate channel according to CR nodes' application type, the AOS parameter will be defined as follow:

$$AOS = \left[\frac{c}{S} + \frac{1-c}{\frac{I}{S}\ln I}\right] + \sqrt{\frac{1}{N}\sum_{i=1}^{N}(t_i - S)^2}, \quad S \geq S_{threshold} \tag{3}$$

where c is the application indicator. c will equal to 0 if the application is VoIP and equal to 1 if the application is FTP. $S_{threshold}$ is the lower bound for S. The lower bound of S will guarantee that the channel will be normally available in a period of time that is enough to ensure CR nodes will transmit a packet successfully

The first part of AOS is defined to find the most appropriate channel for applications. With FTP application ($c = 1$), the most stable channels will be preferred. With VoIP application ($c = 0$), the preferred channels are the channels which are less stable than the most stable channels, but the idle frequency is high. The second part of AOS is used to avoid the variation in length of channel idle periods. Otherwise, the large variation in length of channel idle periods can cause the wrong channel selection.

Based on the AOS parameter, path metric will be derived as follow:

$$M = \sum_{i \in P, j \in C_i} AOS_{ij} \tag{4}$$

Where P is the end-to-end path. M is the path metric. C_i is the set of available channels for Cognitive Node i belonging to the path P

B. Application-Oriented Routing

In this section, we introduce our protocol using on-demand routing approach. When an application of CR node demands to transmit data, CR source node will initiate route discovery by broadcasting route request packet on CCC. After that, each intermediate node along the routes to destination will add the AOS information of channels into the route request packet in sequence. Whenever route request packets reach the destination node, destination node will use AOS information of channels to calculate the metric of each path and choose the path with minimum metric as the route of source node to the destination node.

Based on Ad-hoc On-Demand Distance Vector (AODV) routing protocol in NS-2 (version 2.31) [13] and CRN Simulator [14], Application-Oriented Routing Protocol (AORP) is implemented. Route REQuest (RREQ) packet format, route discovery and route selection are modified to implement AORP

1) Route Request Packet Format: To implement AORP, the RREQ packet needs to be modified to carry all information along the path which allow destination node to choose the appropriate path for source node. Each RREQ will contain complete information about a path between the source node and destination node: the address of intermediate node, the incoming channel used to communicate with its precedent node, the outgoing channel used to communicate with its successor node and the AOS value of the path associated with the intermediate node's outgoing channel. Beside that, the source node or intermediate nodes use neighbour IP address to send RREQ packets to its neighbours. In addition, the application indicator c is also added to help intermediate node and destination node calculate the value of AOS and choose the appropriate path for source node according to the source node's application. The format of RREQ packet is depicted in Figure 4.

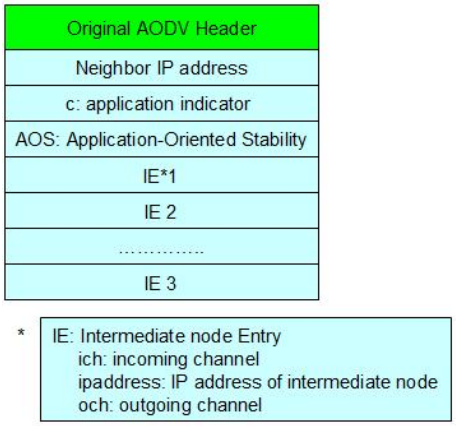


Fig. 4. Route Request Packet Format

2) Route Discovery: When an application of CR node demands to transmit data and CR node has not the route to the destination, source node will initiate multiple RREQ packets and send a RREQ packet to each neighbours on CCC. Each RREQ packet will contain the AOS value of the channel which has the minimum value of AOS among the common channels between source node and its neighbour. Whenever each intermediate node along the paths to destination receives a RREQ packet, it uses the Intermediate node Entry (IE) to check whether the RREQ packet is already forwarded by it. If the RREQ packet is not forwarded by the intermediate node yet, the intermediate node will create multiple the RREQ packets. The number of RREQ packets is equal to the number of its neighbours. For each pair of intermediate node and its neighbour, the intermediate node adds its address into the RREQ packet, puts the channel used to communicate with its precedent node in the incoming channel field of RREQ packet, puts the channel with the minimum value of AOS in the outgoing channel field of RREQ packet and updates the AOS value. Finally, the intermediate node sends the RREQ packets to its neighbours on CCC.

3) Route Selection: When the destination node receives a new RREQ packet, it will follow the below procedure to handle this packet:

Step 1: If there does not exist a path from the source node to destination node, then choose the route stored in RREQ and go to step 3, else go to step 2.

Step 2: If there exist a path from the source node to destination node, then compare the AOS value of existing path with the AOS value stored in the arrived RREQ. If the AOS value of existing path is less than or equal to the AOS value stored in RREQ, then ignore the RREQ packet, else update the path from source node to destination node to the new path stored in the arrived RREQ.

Step 3: Destination node sends ROUTE REPLY packet on licensed channel in unicast mode.

V. Simulation Results

We study the proposed metric Application-Oriented Stability (AOS) through a simulation using ns2. The ON-OFF model and the AOS metric will be implanted in the MAC layer and Routing layer respectively. A MAC (named AOS-MAC) is modified from MAC IEEE 802.11 supported by ns2. AOS-MAC is implemented to allow secondary users (SUs) to transfer data on the channel transparently to primary users (PUs). In order to do this, SUs only send traffic in OFF periods and do not access the licensed channel in ON periods when PUs are present.

Two test cases are designed to validate the proposed ON-OFF model and the AOS metric. Throughout the simulations, we consider all topologies created in a flat area of $1000m \times 1000m$. In each test case, a number of intermediate nodes are placed between source node and destination node. Each intermediate nodes has its own accessible channel list. In addition, two connections TCP/FTP and UDP/VoIP are kept to maintain data transfer during the running time of the scenario.

To evaluate the performance of AORP, together with AORP, we will implement another routing protocol S-AODV. S-AODV is a modified version of AODV in which the most stable channel will be selected for data transmission. The routing metric of S-AODV is $\frac{1}{S}$ (S is presented in Formulation (1)). We then compare the network performance in the case that routing protocol is AORP with the network performance in the case that routing protocol is S-AODV.

Initially, test cases will be executed by using the S-AODV and then, will be run again by using AORP. The numerical results are collected, computed and analysed to deduct the performance obtained by using S-AODV and AORP. The performance of test cases are evaluated by two parameters throughput and packet loss. These parameters are mainly affected by the end-to-end (e2e) delays between source and destination because throughput is calculated by total packets in bytes over the duration of data transfer, while packet loss is counted by a delay time-out mechanism in TCP/FTP or a play-out delay threshold in UDP/VoIP application. In summary, the e2e delay affects directly to total packets sent successfully in a duration of data transfer which is set fixed (300s) in test cases. When e2e delay increases, less packets can reach to the destination. For ease to follow, below is the topologies of all test cases. Nodes in orange are source node and destination node of VoIP connection and nodes in blue are source node and destination node of FTP connection while the other nodes in white are the intermediate nodes. VoIP application is run with constant bit rate 64kbps. FTP is run with variable rate which claims the bandwidth (maximum 2Mbps) as much as possible. Channels with odd identifiers (1, 3, 5, etc.) should be preferred by VoIP application while channels with even identifiers (2, 4, 6, etc.) should be preferred by FTP application. In the work of AORP, the quality of channel will be associated to AOS.

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Typically, the smaller the identifier is, the better the quality of the channel is.

Details for each test case result will be provided from Figure 7 to Figure 8 and Table II

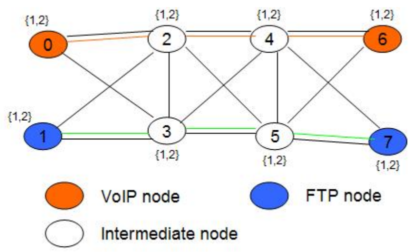

Fig. 5. 2 connections VoIP and FTP with less channel diversity in data flow

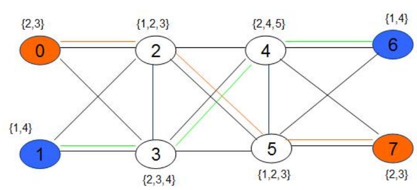

Fig. 6. 2 connections VoIP and FTP with channel diversity in data flow

TABLE II
TRAFFIC FLOW IN EACH TEST CASE

Test case	Traffic flow in case that routing protocol is AORP
Test case 1	VoIP traffic from node 0 to node 6 through node 2, 4 via channel 1 FTP traffic from node 1 to node 7 through node 3, 5 via channel 2
Test case 2	VoIP traffic from node 0 to node 7 through node 2, 5 via channels 3-1-3 FTP traffic from node 1 to node 6 through node 3, 4 via channels 4-2-4

In test case 1 and test case 2 (Figures 5 and 6), the performance of S-AODV is improved by AORP. This happens because by using S-AODV, all applications will try to use the most stable channels which have the largest average idle periods. Therefore, due to the AOS-MAC, all nodes have to compete with one another to take the channel and send the packet on the same channel. As the consequence, some packets might wait for a certain time before MAC is free again for being sent. This drawback could introduce the additional processing delay and increase the e2e delay, thus, increase the packet loss and reduce the performance for both VoIP connections and FTP connections. Compared to case with AOS, the applications will try to use the channels which are preferred to their needs. With the difference of preferred channel, nodes will not need to compete channels for data transmission and packets will not wait much for MAC to get free. Consequently, the AOS could lead both types of connection (VoIP and FTP) to the better performance.

However, in the concern of AORP, the diversity of channels could also give benefit to packets from the same flow. The throughput in Test case 2 (Figure 8(b)) is better than the throughput in Test case 1 (Figure 7(b)) because the path chosen in Test case 2 is composed by different channels while the path chosen in Test case 1 is composed by the same channel. The packets on path composed by different channels can avoid the channel competition and intra-flow interference caused by the transmission of packet belonging to the same flow. The channel competition and intra-flow interference would also introduce the additional processing delay, thus, reducing the throughput as shown in Test case 1.

Regarding the total packet loss (Figure 7(a) and Figure 8(a)), the number of total lost packets is reduced significantly by using the AORP routing protocol instead of S-AODV. In case of S-AODV, all cognitive nodes are forced to use the most stable channel. In addition, the VoIP application is set to run with a low bit rate 64kbps while FTP application is set to claim the bandwidth as much as it can. According to this configuration, the packets of VoIP application would be sent out the channel later than packets of FTP application. As the consequence, these packets suffered from the additional processing delay (mentioned in previous paragraphs) and the packet e2e delay will exceed the play-out delay threshold of VoIP application. This play-out delay violation will cause packets to get dropped at destination and hence increase the packet loss of VoIP application, resulting in the increase in the total number of lost packets. On the contrary, in case of AORP, VoIP traffic and FTP traffic are separated on flows which have different interest of channels. By this way, there is no channel competition between nodes relaying VoIP traffic and nodes relaying FTP traffic. Therefore, the total packet loss is reduced dramatically.

VI. CONCLUSION AND FUTURE WORK

In this paper, we have proposed an application-oriented routing protocol in cognitive radio network. We studied the transmission behaviour of VoIP and FTP applications to figure out the appropriate channel for each type of application. Based on this study, the application-oriented stability metric and application-oriented routing protocol are proposed to find an appropriate path according to the application running in cognitive nodes. Through simulations, the application-oriented routing protocol was shown to outperform S-AODV. In the future, we envisage to investigate more applications' transmission behaviour to provide more efficient channel allocation and route composition schemes. We also consider channel bandwidth in conjunction with application-oriented stability parameter to find path satisfying the demand of cognitive users' applications. Additionally, the scenarios with more concurrent traffic flows will be examined to verify the scalability of AORP.

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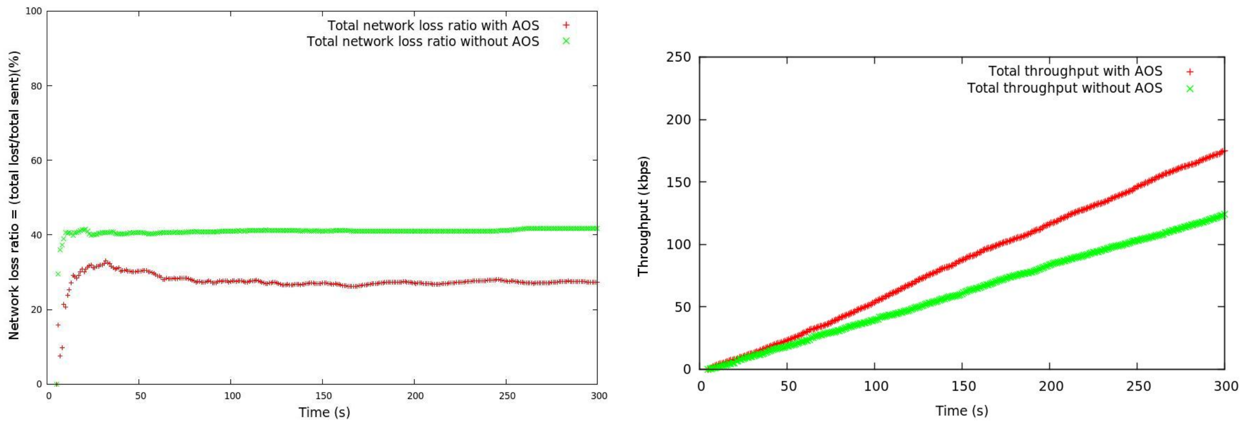
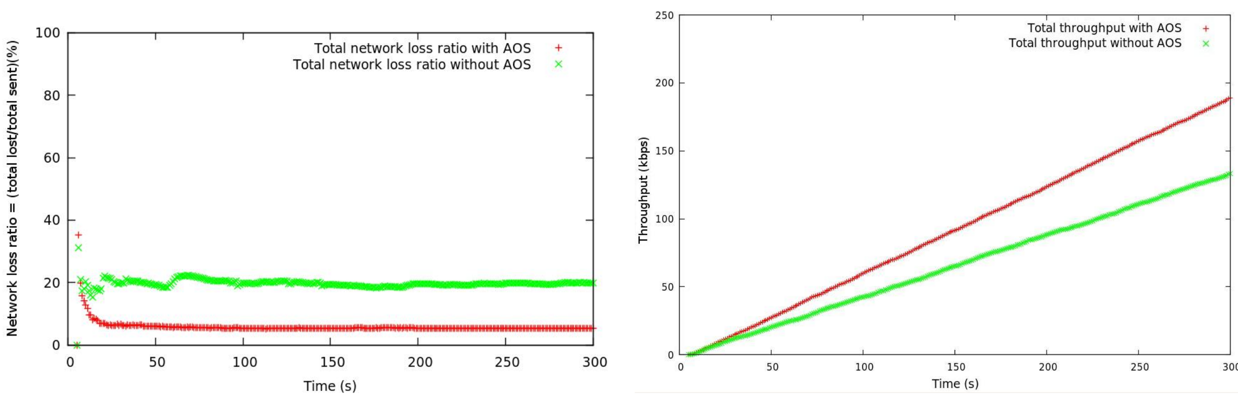


(a) Test case 1 - Loss

(b) Test case 1 - Throughput

Fig. 7. Test case 1 - No channel diversity



(a) Test case 2 - Loss

(b) Test case 2 - Throughput

Fig. 8. Test case 2 - Channel diversity

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