A Multipath Routing and Spectrum Access (MRSA) Framework for Cognitive Radio Systems in Multi-radio Mesh Networks

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ABSTRACT

Cognitive Radio (CR) techniques to dynamically utilize the frequency spectrum is under hot discussion recently. In particular, wireless mesh networks along with CR techniques may play a vital role in spectrum-scarce situations, which are the target environments of this paper. In CR systems, the most crucial issue is how to detect and mitigate the appearance of primary users. To minimize the effect of "onset" of primary users, we propose to use multipath routing assuming that multiple radios are equipped at each station. Using multipath and multiradio in wireless mesh networks shows that the performance (e.g. end-to-end throughput) is substantially more resilient to the dynamic behavior of primary users than other choices. The proposed routing and spectrum access framework seeks to reduce the contention and interference among stations in perspective of traffic load balancing.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols—*Routing Protocols*; C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communications*

General Terms

Algorithms, Design, Management

Keywords

Cognitive Radio, Multipath, Multiradio, Routing, Spectrum Access, Wireless Mesh Network

1. INTRODUCTION

Cognitive Radio (CR) techniques are recently gaining more and more attention [1] [2] [3] [4]. The fixed spectrum allocation policy allows only licensed users to access the allocated frequency band(s). However, spectrum usage census exhibits a large variation in both temporal and spatial dimensions. This inefficient usage can be overcome by a new communication paradigm, CR techniques. CR or dynamic spectrum access technologies opportunistically utilize spectrum holes or white spaces, which mean frequency bands that show a lack of activities of licensed users. A CR station is capable of switching between bands (or channels) in the environments of dynamic spectrum usage by measuring the propagation characteristics, signal strengths and transmission quality of different bands. Research efforts on CR networks cover a wide range of areas, including spectrum analysis, channel estimation, spectrum sharing, medium access control (MAC), and routing.

Wireless mesh networks have suffered from bandwidth scarcity, and hence they can leverage CR techniques to enhance the performance such as throughput. However, higher end-to-end throughput due to CR techniques comes with the cost of vacating a band if a licensed user appears in that band. Thus, in CR mesh networks, how to access the spectrum and how to route traffic should be jointly considered. Note that nodes, users and stations are interchangeably used in this paper.

In CR networks, all the users are classified into two groups, primary users (PUs) and secondary users (SUs). PUs are licensed users, who are authorized to use licensed bands whenever they want. SUs are CR users that can use frequency bands as long as they are not utilized by PUs. Once a PU starts using a band, which has been used by SUs, SUs should stop using the band. A band (or channel) is defined as a unit of frequency allocation throughout this paper and we assume that there are multiple non-overlapping bands in the spectrum pool.

When a SU uses a particular channel, it may share the channel with other SUs. In such cases, the channel contention and interference will be severe. This motivates us to employ multiple radios, each of which can be tuned to a different band. In this paper, we assume each SU is equipped with another radio for signaling traffic, which is not subject to PUs' preemption. Hence, every SU is assumed to have $1 + n$ radios: 1 radio for signaling traffic and n radios for data traffic.

If we apply any of prior routing proposals for mesh networks into CR environments, there will be severe degradation at primary users' interruption. Thus, we propose to use multiple paths, so that the "onset" of PU traffic will affect only one path at a time. That is, other unaffected paths will still keep forwarding packets.

This paper is organized as follows. In Section 2 we discuss related work and how we motivate our work. Section 3 details the proposed multipath routing protocol and spectrum access (MRSA) framework. We demonstrate our proposal by typical examples as well as comprehensively ample simulation tests. Also we present simulation results in Section 4. And finally we conclude our paper in Section 5.

CoRoNet' 09 September 21, 2009, Beijing, China

2. RELATED WORK AND MOTIVATION

Over the past few years, many research efforts have been made on PHY, MAC, and network layers in CR networks, especially on how to sense PUs' communications, how to coordinate channel switching among CR stations, how to route packets stably and efficiently and so on. Previous papers ([5] and [6]) proposed frameworks in CR mesh networks. In these frameworks, a SU station uses only a single radio and only a single path is set up between two SUs. Recently, how to design an adaptive routing protocol in CR mesh networks that can dynamically utilize the available radio resources is actively discussed. For instance, SORP [7] and CARD [8] are routing proposals in CR mesh networks, but they use only one path.

To the best of our knowledge, there have been no multi-path routing proposals in CR networks.Existing multi-path routing protocols in wireless mesh networks or mobile ad-hoc networks (MANETs) may not be able to adapt to CR environments since they neither consider the dynamic spectrum availability nor the imbalanced coexistence between PUs and SUs. To name a few routing proposals in MANETs, SMR [9] is a multi-path routing protocol, which splits data traffic into multiple maximally disjoint paths. MP-DSR [10] is an multi-path routing proposal based on DSR. SMR and MP-DSR use only one channel, which results in substantial inter-path and intra-path contention and interference.

We first list some design issues as follows: 1) inter-path contention and interference must be minimized to fully utilize multipath routing; 2) the proposed MRSA framework should overcome the interruption of PUs with minimal degradation; 3) the traffic load of each flow should be distributed over multiple radios as well as multiple paths for load balancing purposes.

With these objectives in mind, we propose a new multipath routing and spectrum access (MRSA) framework for CR mesh networks, where each node is assumed to have multiple radios. The contributions of our work are as follows. First, we define the concept of "spectrumwise disjointedness" between multiple paths to achieve high throughput. That is, if multiple paths do not have any contending/interfering bands between one another, these paths are spectrumwise disjoint. Thus, even if two paths have a station in common, they can be spectrumwise disjoint if they use different bands (on the different radios) at the common station. Second, we propose an opportunistic framework that combines multipath routing and dynamic spectrum access, which seeks to find out multiple paths and to decide frequency bands for each link of the paths so as to achieve as much "spectrumwise disjointedness" as possible. Last, we discuss how to adapt to PU's interruption by local recovery; Detecting the onset of PU's traffic, a SU switches to another available band by exchanging control information with neighbor(s).

Fig. 1 illustrates how SUs should behave dynamically as PUs show up. There are six SUs (S1, S2, ..., S6), each of which is equipped with four radios for data traffic at four bands (b1, b2, b3, and b4) in the spectrum pool. For sake of simplicity, each radio is fixed to one of the four bands with no overlapping. Two PUs (P1 and P2) are using some of their licensed bands in vicinity for some duration. P1 affects S1 and S2, and P2 affects S5 and S6 (indicated by gray dashed arrows). S1 is communicating with S6 over two paths: $S1 \rightarrow S2 \rightarrow S3 \rightarrow S6$ and $S1 \rightarrow S4 \rightarrow S5 \rightarrow S6$. When two paths are being set up, P2 is using b3, which is not selected by the SUs around P2. There is no intra-path and inter-path contention and interference since the two paths are spectrumwise disjoint. At the beginning, S1 forwards packets for S6 over two links: (1) band b2 for next hop S2 and (2) band b4 for next hop S3. At time t_0, P1 suddenly starts its communications on band b2, and hence S1 should vacate band b2 and move to band b3.

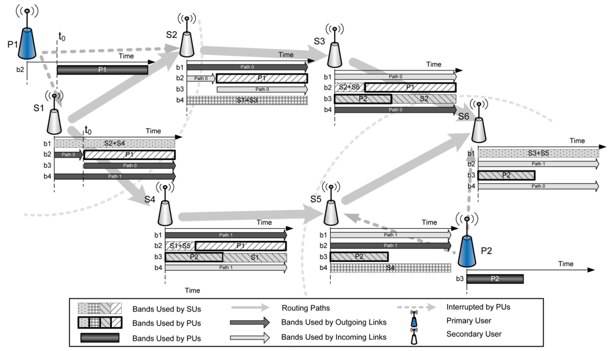


Figure 1: An illustration of multipath routing in a CR mesh network.

3. MULTIPATH ROUTING AND SPECTRUM ACCESS (MRSA) FRAMEWORK

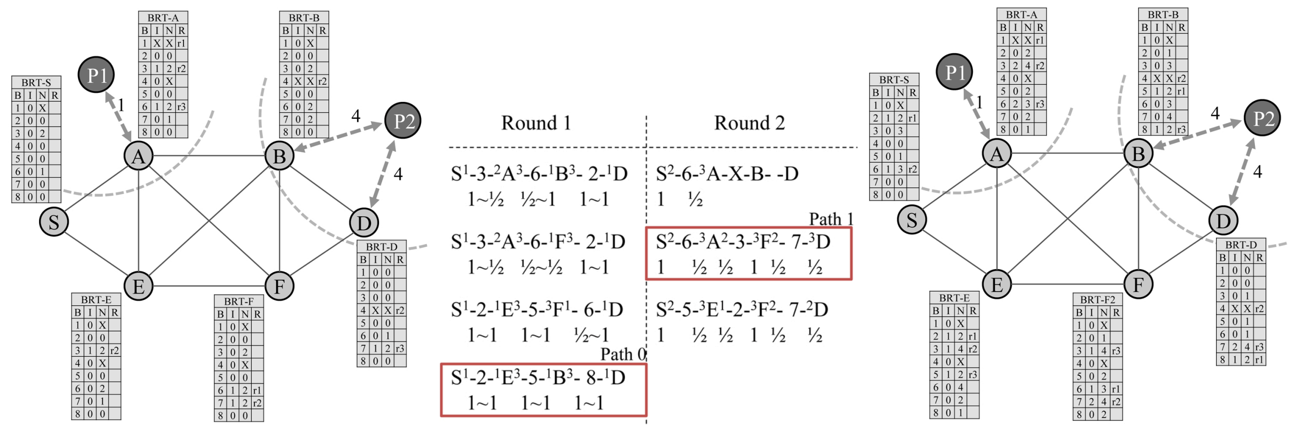
3.1 Preliminaries

We assume that there are N bands for data traffic in the spectrum pool. Signaling traffic can be delivered over these bands together with data traffic, but that typically requires broadcasting signaling traffic on all the available bands in worst case. Thus, instead, we assume another band for signaling traffic, like ISM band. Therefore, there are total $1 + N$ bands: b_0 for signaling traffic and $b_1, b_2, ..., b_N$ for data traffic. Likewise, each station has $1 + M$ radios: one radio (r_0) is fixed to b_0 and the other M radios ($r_1, r_2, ..., r_M$) are using the subset of N bands, where $M \leqslant N$. $A^2 \overset{4}{\longleftrightarrow} {}^1B$ denotes the transmission link between A's radio r_2 and B's radio r_1 on band b_4. N_{path} is the number of multiple paths to set up, which is assumed to be decided by applications.

In the literature on multi-path routing *topologywise disjoint paths are the paths that share no common station except the source and the destination. We also define* spectrumwise disjoint paths, which are the paths that may share a common station but different bands are assigned for the links around the common station. This means that two topologywise overlapping paths can have no inter-path contention and interference if the radios of the common stations are tuned to difference channels. Normally, bands in the spectrum pool is ample, but often radios are the scared resource. Hence, multiple flows may have to share the same radio. We assume that each radio in use can work only in shared mode. That is, multiple flows use the same band at the same radio, and therefore the link bandwidth will be shared. It will be very inefficient for a radio to switch between two or more bands for individual flows due to the switching and synchronization overhead.

3.2 MRSA Illustration

Firstly the the operation of the MRSA framework will be illustrated and evaluated based on the example in Fig. 2(a) where there are six SUs, and 8 bands are used for data traffic. Each SU has 3 radios for data traffic. The radio and band for signaling traffic is skipped. Currently there are two flows in the topology, $A^3 \overset{6}{\longleftrightarrow} {}^1F^2 \overset{7}{\longleftrightarrow} {}^3D$ and $A^2 \overset{3}{\longleftrightarrow} {}^2E$. The links among SUs are depicted in solid lines and two PUs (P1, P2) are around this network. The communications of PUs are detected by SUs, which are drawn as dashed arrows. Here P1 and P2 use bands 1 and 4, respectively. A band and radio usage table (BRT) of each SU is shown for every SU. Column B is the band index, and column I means how many flows of the station itself are using a particular band. Column N



(a) Original Topology (b) Two Path Selection (c) After Multipath Discovery

Figure 2: An Example of Route Discovery and Selection

shows how many flows of the station itself or its 1-hop neighbors are using this band. Column R shows which radio is tuned to a particular band. Once a PU starts transmissions over a band and a nearby SU detects PU's communication activities. The detecting SU marks that band by X in column I of its BRT and broadcasts that information over the signaling band (b_0). Once the neighbor station receives that message, the corresponding band in column N of the BRT in the neighbor will also be marked as X. On the signalling band b_0, every station will exchange column I with its 1-hop neighbors periodically by broadcasting hello messages. When a station receives a hello message from all of its neighbors, it will modify column N of its BRT by the sum of all the I columns from its 1-hop neighbors.

3.3 Routing Discovery

The routing module in the framework adopts the routing discovery procedure of DSR. Source S initially broadcasts an RREQ with a new RREQ_ID containing its own BRT. Note that all the control traffic (e.g. for router discovery) will be transmitted over the control band b_0 through radio r_0. An intermediate station receives an RREQ and forwards the RREQ based on following strategy for the destination to find out multiple candidate paths: (1) if the RREQ_ID is new, it attaches its BRT to the incoming RREQ and rebroadcasts the RREQ. (2) if the RREQ_ID is not new, which means an RREQ with same RREQ_ID is already processed, and if its hop count (from the source) is no larger than that of previous RREQ with same RREQ_ID, it attaches its BRT to the incoming RREQ and rebroadcasts the RREQ. Note that RREQs with same RREQ_ID can be rebroadcast at each intermediate station up to N_{path} times. (3) all RREQs in the other cases will be dropped. Every time a station forwards an RREQ, its station ID and BRT will be encapsulated into the header, and finally each RREQ will arrive at the destination with the collected information of all the stations along a candidate path.

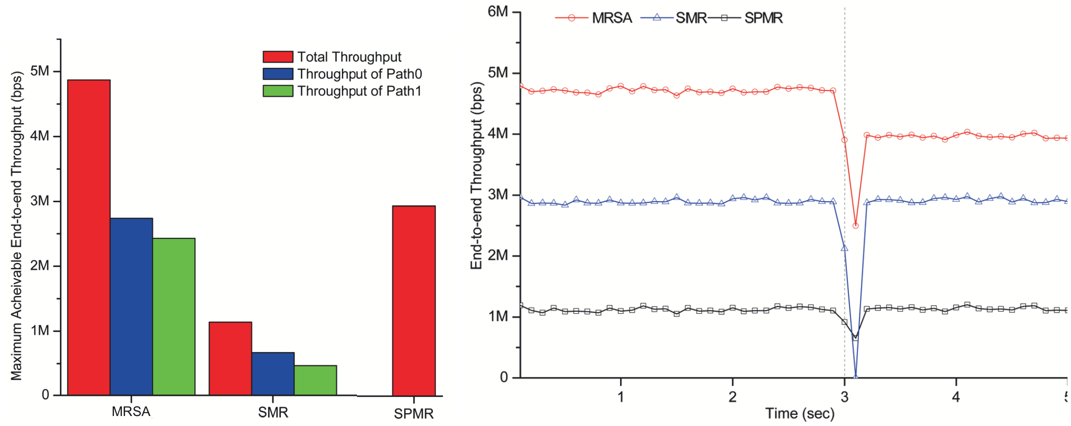
The destination will receive RREQs with the same RREQ_ID but different paths for a designated period. For each candidate path, we have to assign the band and radio of its links first. Then the destination will evaluate all the candidate paths by their available bandwidth capacity, to be detailed later. The band and the radio for each link for a candidate path will be selected according to Algorithm 1, similar to the algorithm in [11] and [12] Let P and Q denote the transmitter and the receiver of each link, respectively. Algorithm 1

Algorithm 1 Band Selection Algorithm for Each Link

Ignore every row whose N column value is X in either station
if (P has idle radio R^P, Q has idle radio R^Q) **then**
  find all bands with I=0 both at P and Q;
  $B \leftarrow$ the band with lowest sum of N value at P and Q;
  P tunes R^P to B;
  Q tunes R^Q to B;
end if
if (P has idle R^P, Q has none)or(P has none, Q has R^Q) **then**
  //suppose P is the one who has idle radio, Q has none;
  find all bands with I=0 at P and I≥1 at Q;
  $B \leftarrow$ the band with lowest sum of N value at P and Q;
  $R^Q \leftarrow$ the radio already tuned to B at Q;
  P tunes R^P to B;
  Q keeps R^Q tuned to B;
end if
if (P and Q have no idle radio) **then**
  if ∃(bands with I≥=1 both at P and Q) **then**
    find all bands with N≥1 both at P and Q
    $B \leftarrow$ the band with lowest sum of N value at P and Q;
    $R^P \leftarrow$ the radio already tuned to B at P;
    $R^Q \leftarrow$ the radio already tuned to B at Q;
    P keeps R^Q tuned to B;
    Q keeps R^Q tuned to B;
  else
    No solution, skip this path;
  end if
end if

operates in a greedy manner as follows. Algorithm 1 prefers to use an idle radio if any, and otherwise, it selects a radio that is already used to forward packets of other flow(s). In that case, Algorithm 1 always makes the radio work in shared mode. Also in selecting a band in each link, the destination should try to avoid using the same band that is already selected within two hops in order to reduce intra-path contention and interference.

We apply Algorithm 1 to the network in Fig. 2(a) and we get the 4 candidate paths in Fig. 2(b). Then, we evaluate each candidate path in terms of the minimum bandwidth capacity of the radios of all the nodes in the path, assuming the existing flows and the current flow get the fair share, which is called the *bandwidth share*.



(a) End-to-end Throughput (b) Throughput is decreased when a PU appears at 3 seconds

Figure 3: Example Simulations

For instance, suppose there are 2 flows going through a given radio, then the bandwidth share of the radio is 1/2. If it is an idle radio, the bandwidth share is 1. The bandwidth share of a candidate path is the smallest one among the bandwidth shares of all of its links. Therefore, the first selected path, Path 0, has the bandwidth share of 1, as shown in the left part in Fig. 2(b). After that, the destination will change related entries in all the BRTs. Then it starts a new path selection for the second path among the remaining candidate paths, as shown in the right part of Fig. 2(b). If there are multiple paths with the same bandwidth share, we choose the one with smallest number of joint nodes with Path 0, and then try to choose the path with smaller hop count. More paths can be iteratively selected In the same manner if $N_{path} > 2$. Fig. 3.1 shows the BRTs of all the nodes after the two paths for the flow are determined. Finally, the two established paths in the example are $S^1 \overset{2}{\longleftrightarrow} {}^1E^3 \overset{5}{\longleftrightarrow} {}^1B^3 \overset{8}{\longleftrightarrow} {}^1D$ and $S^2 \overset{6}{\longleftrightarrow} {}^3A^2 \overset{3}{\longleftrightarrow} {}^3F^2 \overset{7}{\longleftrightarrow} {}^2D$. Whenever the destination selects Path 0 or Path 1, the corresponding RREP is replied. While the RREP is relayed to the source, each intermediate station will store its path/radio/band information, and its BRT will be also updated.

3.4 Data Striping Issues

In our framework, a simple data striping mechanism like SMR [9] is adopted, which divides data packets into multiple paths equally and transmits them in a round robin fashion over the multiple paths. We assume that packets will be buffered and reordered at the destination. We consider extending the data striping mechanism in proportional to the actual goodput of each path as future work.

3.5 Route Maintenance and Recovery

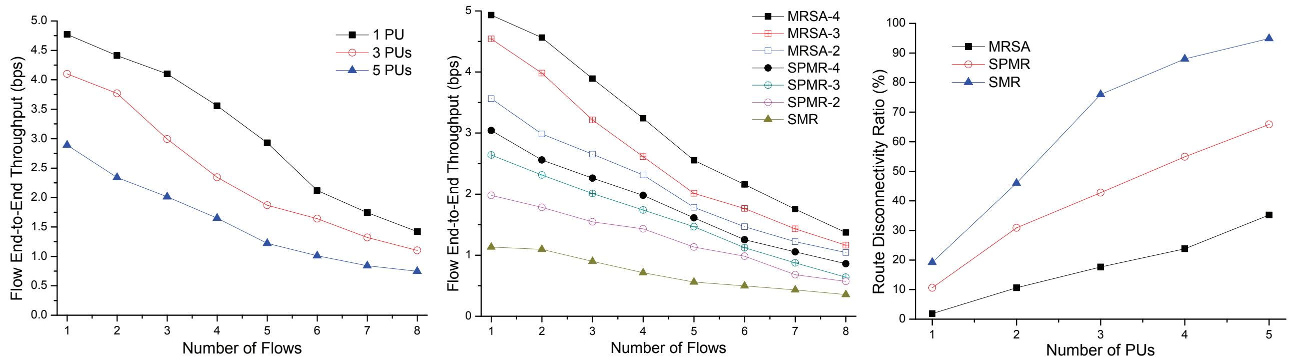
Overcoming the sudden onset of PUs is the responsibility of the route recovery process, which is critical in the MRSA framework since PUs will frequently interrupt ongoing flows of SUs. For this purpose, the RERR message in DSR is extended to recover an interrupted link by a PU. We assume that only one band will be interrupted at a time. When a SU detects PU's interruption, which is the monitoring functionality of CR systems, it will perform local recovery as follows. The detecting SU will be called the initiator. The RERR message sent by the initiator includes its new BRT, where the interrupted band in column I is marked as X. This RERR message will be forwarded to the source immediately to notify the link breakage. Then the source will transmit packets over the other selected paths until the broken path is recovered. Also another RERR message will be broadcast to 1-hop neighbor from the initiator, and then all the stations that receive the RERR message will check their BRTs to figure out whether they are using the interrupted band with the initiator. If so, the neighbor station will run Algorithm 1 with its own BRT with the BRT of the initiator in the RERR message for the interrupted link. Then it will modify its BRT, and reply to the initiator to notify the newly selected radio and band. The initiator then will send a new RREP with the new radio/band information to the source. The source will resume the data striping over the multiple paths as soon as the broken path is recovered.

4. EVALUATION

4.1 Simple Topology

We evaluate MRSA on the simple topology in Fig. 2(a) in NS2 [14], based on the CRCN simulator [13]. We use IEEE 802.11a at basic rate 6Mbps with saturated UDP traffic. Each station has 1 radio for signaling and 3 radios for data traffic. The mesh network has 1 band for signaling and 8 CR bands in the spectrum pool for simplicity. We compare MRSA with two reference schemes: (i) Split Multi-path Routing (SMR) [9] uses multiple paths but a single radio, and (ii) we devise another scheme that uses a single path, but each station has multiple radios, which is denoted by SPMR. Each simulation run is carried out for 100 seconds, and the end-to-end throughput of three schemes from S to D is shown in Fig. 3(a). Recall that there are already two existing flows as mentioned in Section 3.2.

The total throughput of path 0 (S-A-F-D) and path 1 (S-E-B-D) is around 4.9 Mbps. The throughput of path 0 is higher than that of path 1, because Path 0 is selected with bandwidth share 1 at the first time, and Path 1 has to use the remaining bandwidth capacity shared with other flows in the network. SMR can only achieve 1.1 Mbps throughput, since SMR suffers from inter-flow contention/interference and inter-path as well as intra-path contention/interference due to the single radio constraint. Total throughput of two paths of MRSA is notably higher than that of SPMR. Therefore by utilizing multiple radios, and by optimally assign non-overlapped channels for paths, our scheme has better performance on throughput than other related protocols



(a) End-to-end throughput of MRSA as the number of PUs increases

(b) Throughputs of MRSA, SMR, SPMR with varying numbers of radios

(c) The ratio of disconnected flows increases as the number of PUs increases

Figure 4: Random Topology Evaluation

4.2 Interruption in Simple Topology

With the same network topology, the route recovery is tested. In the middle of packet delivery over multiple paths (at 3 seconds in simulation time), a PU (P3) starts communications over band b_5 and E detects the interruption of P3. Thus the link $E^3 \overset{5}{\longleftrightarrow} {}^1B$ is interrupted. E will initiate the local recovery as mentioned in 3.5. As shown in Fig. 3(b), the throughputs of all the three schemes are sharply degraded. The recovery process takes about 120 milliseconds for MRSA and B will decide which radio and which band to be selected according to Algorithm 1; now r_3 of E and r_1 of B are tuned to b_8. Note that the throughput of MRSA shows a degradation even after recovery. This is because the newly selected band b_8 contends with another link between B and D.

4.3 Random Topology

To evaluate the performance of MRSA, we carry out comprehensive tests with a random topology where 20 SUs and 5 PUs are uniformly placed in 100*100 m^2. The transmission range of each SU (or PU) is adjusted to 25 meters. Other settings are the same as the simple topology tests. Each simulation run is tested for 100 seconds, whose average is calculated from the results of ten runs.

In the first experiments, we evaluate how much throughput of MRSA is degraded as the number of PUs increases. At the beginning of each run, we start 1, 3, and 5 PUs, each of which selects its own band randomly. From the average end-to-end throughput of each flow shown in Fig. 4(a), we can see more PUs will degrade the performance of MRSA more. This is because the available radios and bands become scarce as more PUs appear.

The second experiments compare the performance of MRSA, SMR, and SPMR. We start 3 PUs at the beginning of each run, and we also vary the number of radios of each SU from 2 to 4. For instance, SPMR-3 means that each SU has three radios and run the SPMR scheme. From Fig. 4(b), MRSA outperforms SPMR, which exhibits that using multiple paths is better than using a single path in multi-radio networks. Even though SMR uses multiple paths, the limitation of using a single radio is critical. More radios will be beneficial since the chances of selecting non-overlapping bands are increased among the links of the same flow as well as of the difference flows.

The third test is carried out to quantify the effect of PU's onset on the connectivity of paths among SUs. At the beginning of each run, no PUs are active, and we start 5 arbitrary flows among SUs. While these flows are ongoing, we suddenly turn on a varying number of PUs at the same time. The y-axis in Fig. 4(c) is the average disconnectivity ratio, which means how many flows are disconnected due to the sudden onset of PUs and should be recovered. If at least one of the multiple paths of a particular flow is not broken, we deem that the flow is not disconnected. The results in Fig. 4(c) shows MRSA has the lowest disconnectivity ratio since multi-path routing guarantees the connectivity much better than single-path case in multi-radio environments.

5. CONCLUSIONS

In this paper, we proposed a new multipath routing and spectrum access (MRSA) framework for multi-radio mesh networks assuming cognitive radio (CR) environments. The proposed framework seeks to establish multiple paths that maximizes "spectrumwise" disjointedness to minimize contention and interference among links. We evaluated the proposed MRSA framework by simulation with a simple network topology for illustration and a random topology for general performance tests. MRSA achieves higher throughput than other reference routing approaches and also provides better resilience from the dynamic interruption of primary users (PUs). In future, we will focus on how to efficiently exchange signaling traffic over cognitive radio bands that are subject to PUs' interruption.

6. ACKNOWLEDGMENT

This research is partly supported by the Ministry of Knowledge Economy, Korea, under the Information Technology Research Center support program supervised by the Institute of Information Technology Advancement(grant number IITA-2009-C1090-0902-0006) and partly supported by NAP of Korea Research Council of Fundamental Science & Technology, and the Institute of Computer Technology (ICT) at Seoul National University provides research facilities for this study.

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