On Multipath Transmission Scheduling in Cognitive Radio Mesh Networks

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Abstract. Nodes in a cognitive radio mesh network comprised of secondary users may select from a set of available channels provided they do not interfere with primary users. This ability can improve overall network performance but introduces the question of how best to use these channels. Given a routing multipath M, we would like to choose which channels each link in M should use and a corresponding transmission schedule so as to maximize the end-to-end data flow rate (throughput) supported by the entire multipath. This problem is relevant to applications such as streaming video or data where a connection may be long lasting and require a high constant throughput as well as providing robust, high-speed communications in wireless mesh networks deployed in rural environments, where there are significant amounts of spectrum available for secondary use. Better transmission scheduling can lead to improved network efficiency and less network resource consumption, e.g. energy-use. The problem is hard to due the presence of both intra-flow and inter-flow interference. In this paper, we develop a new polynomial time constant-factor approximation algorithm for this problem. We also present an effective heuristic method for finding effective multipath routes. It has been shown by simulation results that the end-to-end throughput given by the proposed algorithms provide nearly twice the throughput of single path routes and that the schedules generated are close to optimal.

Keywords: Wireless mesh networks, cognitive radios, multipath scheduling, channel assignment, interference

1 Introduction

Wireless Mesh Networks (WMNs) are considered an economical method of providing robust, high-speed backbone infrastructure and broadband Internet access in large rural areas [1]. The mesh topology offers the advantages of alternative route selection to assure throughput and quality of service (QoS) requirements under dynamic load conditions. As aggregate traffic volume can be substantial on backbone links converging on gateways and servers, considerations of

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transmission scheduling, path selection and topology control are essential to assure that a WMN can meet the QoS and throughput requirements of end-users' real-time multimedia applications. Furthermore, range considerations and propagation characteristics demand careful attention to interference.

Spectrum is the most precious resource for wireless networks. Licensed spectrum is currently managed on a static and non-preemptive basis, where the license holder has exclusive use of the designated frequencies in a geographic area. Spectrum that is licensed but unused is not available to others on a demand basis. Unlicensed spectrum is used on a non-exclusive basis, meaning that is available to all users on an equal basis, and rules of etiquette are required to assure that users can coexist on selected frequencies in a particular area. Over the past few years, the world has experienced a very rapid proliferation of wireless devices operating in both licensed and unlicensed spectrum. Certain unlicensed parts of the spectrum, such as the 2.4GHz band and the 5GHz band, are heavily used by various wireless devices, resulting in serious interference and poor network performance. There is still a significant amount of spectrum that remains under-utilized or even not utilized at all in the licensed spectrum bands, which has been shown by recent studies and experiments [2]. Ideally, these fallow portions of spectrum could be used on a secondary, or pre-emptive basis to alleviate the congestion and meet the growing demands of wireless applications. Such blocks of spectrum, sometimes deemed as *white spaces*, often appear in the broadcast television bands, where the licensees are migrating their services to cable and satellite distribution, and in rural areas, where broadcast television is in very limited use. Therefore, the traditional static licensed spectrum allocation approach does not efficiently manage the spectrum access any longer. Emerging cognitive radios enable dynamic spectrum access. With cognitive radios, unlicensed wireless users (a.k.a secondary users) can sense and access the under-utilized licensed or unlicensed spectrum bands opportunistically as long as the licensed wireless users (a.k.a primary users) in these spectrum bands are not disrupted [2]. In this way, interference can be avoided and network capacity, QoS and robustness can be significantly improved.

Cognitive radios are desirable for a WMN in which a large volume of traffic is expected to be delivered since they are able to utilize available spectrum more efficiently than conventional, static channel assignment methods and therefore improve network capacity significantly [2]. However, they introduce additional complexities to bandwidth allocation. With cognitive radios, each node can access a set of available spectrum bands which may span a wide range of frequencies. Each spectrum band may be divided into channels, and the channel widths may vary from band to band. Different spectrum bands can support quite different transmission ranges and data rates, both of which have a significant impact on resource allocation and interference effects.

In this paper, we consider the problem of multipath scheduling: we are given a multipath M from a source to a destination and similarly must create a schedule for each link that maximizes the end-to-end throughput. This problem is relevant to applications such as real-time streaming video or data where a connection may be long lasting and require a high constant throughput. Better transmission scheduling can lead to improved network efficiency and less network resource consumption, e.g. energy-use. This work is different from most previous works on transmission scheduling which usually deal with the problem of scheduling a set of links for link-layer throughput maximization. Here, we focus on end-to-end performance, and consider the problem of allocating resources (timeslots, channels) along a multi-hop routing path or multipath, which is a very hard problem due to the constraints related to intra-flow interference (interference among links belonging to a common flow) and inter-flow interference (interference among links belonging to different flows) [21]. Previously, we presented a polynomial time constant-factor approximation algorithm for the path scheduling problem [12]. In this work, we generalize the approach to provide a constant factor approximation algorithm to create transmission schedules for multipaths that can further improve the achievable end-to-end transmission rate over single path routes. The approximation ratio is $\frac{1}{(\Delta_1+1)(\Delta_2+1)}$ where Δ_1 is the maximum degree of a vertex the multipath to be scheduled and Δ_2 is the maximum degree of vertex found in certain subgraphs of a flow conflict-graph. In addition, we also present an effective heuristic routing algorithm to find multipaths that can lead to high end-to-end throughput.

The rest of the paper is organized as follows. We discuss related work in Section 2. We formally define the system model in Section 3. In Section 4, we describe the formal problem and present our proposed multipath scheduling algorithm. In Section 5, we describe a routing heuristic for finding multipaths and then present numerical results in Section 6. Finally, the paper is concluded in Section 7.

2 Related Work

Cognitive radio wireless networks have recently received extensive attention. In [23], the authors derived optimal and suboptimal distributed strategies for the secondary users to decide which channels to sense and access with the objective of throughput maximization under a Partially Observable Markov Decision Process (POMDP) framework. In [24], Zheng *et al.* developed a graph-theoretic model to characterize the spectrum access problem and devised multiple heuristic algorithms to find high throughput and fair solutions. In [22], the concept of a time-spectrum block was introduced to model spectrum reservation, and a centralized and a distributed protocol were presented to allocate such blocks for cognitive radio users. Tang *et al.* introduced a graph model to characterize the impact of interference and proposed joint scheduling and spectrum allocation algorithms for fair spectrum sharing based on it in [16]. In [5], a distributed spectrum allocation scheme based on local bargaining was proposed for wireless ad-hoc networks with cognitive radios.

Cross-layer schemes have also been proposed for cognitive radio wireless networks. In [7], the authors proposed the Asynchronous Distributed Pricing (ADP) scheme to solve a joint spectrum allocation and power assignment problem.

In [18], Wang *et al.* presented a joint power and channel allocation scheme that uses a distributed pricing strategy to improve the network performance. In [20], a novel layered graph was proposed to model spectrum access opportunities, and was used to develop joint spectrum allocation and routing algorithms. In [19], the authors presented distributed algorithms for joint spectrum allocation, power control, routing and congestion control. A mixed integer non-linear programming based algorithm was presented to solve a joint spectrum allocation, scheduling and routing problem in [6]. A distributed algorithm was presented in [15] to solve a joint power control, scheduling and routing problem with the objective of maximizing data rates for a set of user communication sessions. In [17], a PTAS is presented for a more general maximum multiflow scheduling problem (maximize the total flow of a set of commodities with no specific routing path) and several constant-factor approximations are given for special cases. This paper also points out some errors in previous work on that problem. In [9], Karnik *et al.* proposed an optimal flow scheduling for multihop networks in the more general SINR model for interference. Their approach was based on solving a linear program (of potentially exponential size). More recently, in [10,11], the authors explore the use of column generation methods for improving the efficiency of finding optimal multiflow schedules in the SINR model.

The differences between this work and previous works are summarized as follows: 1) We consider a channel assignment and scheduling problem for a given routing multipath in cognitive radio networks with heterogeneous channels with the objective of maximizing end-to-end throughput, which is different from those works addressing link layer (single-hop) throughput such as [5,7,16,18,22,23,24]. 2) We propose a provably good algorithm to solve the formulated problem. However, many related works (such as [5,7,18,20]) only presented heuristic algorithms which cannot provide any performance guarantees. 3) While our link interference model is more idealized than SINR-based models, our multipath scheduling algorithm runs in low-degree polynomial time in contrast to the potentially exponential time methods proposed for SINR-based scheduling [9,10,11].

3 System Model

We consider a wireless mesh backbone network with static mesh routers and study the problem of scheduling transmissions along a path from a source node to a destination node so as to maximize the end-to-end throughput. We focus on a dynamic setting where source-destination connection requests arrive intermittently and once a routing path is established for a request, a schedule must be quickly constructed. Each establish source-destination flow exists for some time and reduces the availability of network resources for subsequent routing requests. In addition, similar to [4,16], a spectrum server is assumed to manage the spectrum allocation and scheduling in the network. It can collect channel availability information from the FCC's database and computes a spectrum allocation and scheduling solution using the proposed algorithm and broadcasts it to all the users at the beginning of each scheduling period. All the users can then access the spectrum according to the received solution.

We define our assumptions about the parameters of the cognitive radio network: Let m be the number of channels available in the network. In general, each link e_i will have only a subset of these channels available at any given time. This can be due to interference, the link distance being greater than the transmission range, or that channel being already in use on that link. We will also assume that each available channel j on link e_i has an associated bit rate $b_{e,j} \geq 0$. This bit rate can depend on the link distance and other factors.

We assume that communication in the network is done using synchronized transmission frames of a fixed length L. For simplicity we assume a slightly idealized case where the transmission frame is infinitely divisible, although a simple rounding scheme can be employed to produce an integer time slot schedule [12]. Let C_e be the set of channels available to link e during the current frame. We define a variable $f_{e,j} \geq 0$ to indicate the flow amount allocated on the link e on channel j, where $j \in C_e$. A link flow $f_{e,j}$ is active if it is positive. An active link flow f must be scheduled at some point during the frame. We assume that a scheduled link flow $f_{e,j}$ occupies a single continuous interval $[s_{e,j}, s_{e,j} + f_{e,j}) \subset [0, L)$, where $s_{e,j}$ indicates the starting time for the link flow.

We adopt the following simple interference model. We assume that there is an interference distance R_j for each channel j such that a link $e = (u, v)$ *interferes* with another link $e' = (u', v')$ on channel j if and only if $|u - v'| \leq R_j$ or $|u' - v| \leq R_j$. We will also consider that the nodes in question are half-duplex. This means that nodes cannot simultaneously transmit and receive. The duplexing and interference constraints impose conditions on which link flows can be active at the same time. We summarize these conditions in a well-known *conflict graph*, $G_c = (V_c, E_c)$, where the vertices V_c are the link flow variables $f_{e,j}$ and the edges (undirected) indicate which pairs of link flows that cannot be scheduled simultaneously due to interference or duplexing constraints. For a transmission schedule to be *valid*, it must not contain any pair of conflicting scheduled link flows at any time; i.e. for any two active link flows $f_{e,j}$ and $f_{e',k}$, $(f_{e,j}, f_{e',k}) \in E_c \Rightarrow [s_{e,j}, s_{e,j} + f_{e,j}) \cap [s_{e',k}, s_{e',k} + f_{e',k}) = \emptyset$.

4 Multipath Scheduling

In this section, we first formalize the problem considered and then present an algorithm to solve the problem.

A multipath $M = (V_M, E_M)$ from s to t is a subgraph of G such that $s, t \in V_M$ and for any $v \in V_M$, there exists a simple path in M from s to t that goes through v as an intermediate node.

Let $v_{in} \subset E_M$ be the set of incoming edges to $v \in V_M$ and let v_{out} be the set of outgoing edges from v. The scheduled bit flow entering any interior vertex on the path is equal to the bit flow leaving that vertex. This leads to the following constraint:

$$\sum_{e \in v_{in}} \sum_{j} b_{e,j} f_{e,j} = \sum_{e \in v_{out}} \sum_{j} b_{e,j} f_{e,j}; \ \forall v \in V_M \setminus \{s, t\} \tag{1}$$

We are interested in the following optimization problem:

Definition 1. MaxFlow-Multipath*: Find a valid transmission schedule for the links in E_M that maximizes the total bit flow $F = \sum_{e \in t_{in}} \sum_j b_{e,j} f_{e,j}$ from s to t using links belonging to M, subject to (1).*

We note that this formulation is very similar to other multicommodity network flow formulations [9,17] but we view the problem in a restricted sense where M is a relatively small subset of all possible links in the network and each link in M belongs to a path from s to t.

The general algorithm approach will be to use graph coloring to identify individual link flows that can be scheduled simultaneously and then use linear programming to determine optimal link flow values and build a transmission schedule for the active link flows that maximizes the end-to-end throughput. The pseudocode is given in Algorithm 1.

Algorithm 1. Multipath-Schedule

Step 1 For the input multipath $M = (V_M, E_M)$, first color the links E_M in duplex-only conflict graph (two links conflict if they share an endpoint). Suppose D *duplex colors* are used.

Step 2 For each channel j and duplex color d, color G_c^{dj} using a simple greedy algorithm. Suppose g^{dj} colors are used.

Step 3 Associate *color variables* $o_1^{dj}, \dots o_{g^{dj}}^{dj}$ to the colors used in coloring G_c^{dj}.

Step 4 Solve the following linear program (LP):

1. $x_d \geq 0, o_k^{dj} \geq 0;\ \forall d, j, k$
2. $\sum_{k=1}^{g^{dj}} o_k^{dj} \leq x_d;\ \forall j, d$
3. $\sum_d x_d = L$
4. Each link flow $f_{e,j}$ was given a color with associated variable o_k^{dj} in Step 1. Add the constraint $0 \leq f_{e,j} \leq o_k^{dj}$ to the LP.
5. Include the conservation-of-flow constraint given by (1).
6. Maximize $F = \sum_{e \in t_{in}} \sum_j b_{e,j} f_{e,j}$

Step 5 For each channel j and duplex color d, we define the starting times as follows: Let $s_1^{dj} = 0$ and $s_k^{dj} = s_{k-1}^{dj} + o_{k-1}^{dj}$ for $1 < k \leq g_{dj}$.

Step 6 Create a schedule S for the time frame with the following rule: A link flow $f_{e,j}$ associated with color variable o_k^{dj} will be active in the interval $[\sum_{i=0}^{d-1} x_i + s_k^{dj}, \sum_{i=0}^{d-1} x_i + s_k^{dj} + f_{e,j})$.

The main idea of the algorithm is to first use a graph coloring approach to on the conflict graph restricted to duplexing constraints only. We note that for a simple transmission path P, this requires two colors and decomposes that graph into odd and even links along the path. For a more general multipath M, we first color the vertices of M so that the endpoints of each link are given different colors. We refer to these colors as *duplex colors*. If $e = (u, v)$ is a link in M, then we consider e to have the same duplex color as u. In this way, the links (and their associate flows) also receive a duplex color. Suppose that D duplex colors are used; this paritions the links of M into D groups. In order to prevent duplexing conflicts, we will subdivide the frame into D separate intervals and only schedule links in the interval corresponding to their duplex color.

To ensure that for each channel, all conflicting link flows on that channel are scheduled at different times, will use some additional graph coloring. In particular, for each duplex color d and channel j, we consider the subgraph G_c^{dj} of the conflict graph G_c, consisted of only those flows $f_{e,j}$ on channel j for which e has duplex color d. We color each of the subgraphs G_c^{dj} separately and further divide the portion of the frame devoted to duplex color d into non-overlapping intervals for scheduling the link flows of each color (the intervals for different colors can overlap). In Step 3, the algorithm solves a linear program (LP) to find the optimal link flows subject to the color interval conditions. Steps 4 and 5 create the frame schedule from the LP solution.

While the algorithm as presented is centralized, in principle it is possible to create a distributed implementation for it. The algorithms requires performing distributed graph coloring of interference graphs and also a distributed approach to linear programming. There exist distributed algorithms to both of these problems that require only local sharing of information [3,14].

4.1 Analysis

It is clear by construction that this transmission schedule is valid, since no conflicting links are scheduled at the same time. Let F_S be the path bit flow obtained by the schedule created by Algorithm 1 and let F_{S^*} be the path bit flow obtained by an optimal schedule S^*.

Definition 2. *We say a transmission schedule is* duplex equal *if and only if link flows with duplex color $d \in \{1, \ldots, D\}$ are scheduled in the frame interval $[(d-1)\frac{L}{D}, d\frac{L}{D})$.*

Lemma 1. *Let S^{*de} be an optimal duplex-equal schedule for the path P with associated bit flow $F_{S^{*de}}$. Then $F_{S^{*de}} \geq \frac{1}{D}F_{S^*}$.*

Proof. A simple way to see this is to take the schedule S^* and scale it by $1/D$ to create a schedule for the half-frame $[0, L/D)$. Place a copy of the scaled S^* in each interval $[(d-1)\frac{L}{D}, d\frac{L}{D})$ and delete any link flows in this interval that do not have duplex color d. The resulting schedule is now duplex-equal with bit flow value $\frac{1}{D}F_{S^*}$, so the total flow for optimal duplex-equal schedule will be at least this value.

It is well-known that the greedy coloring algorithm used in Steps 1 and 2 provides a coloring that uses $\Delta(G)+1$ colors, where $\Delta(G)$ is the maximum degree of a vertex in the input graph G. Let $\Delta_1 = \Delta(M)$, the maximum degree of a vertex in the multipath M and let $\Delta_2 = \max_{d,j} \Delta(G_c^{dj})$. Then for all d, j, $g^{dj}, h_j \leq \Delta_2 + 1$.

Lemma 2. $F_S \geq \frac{1}{\Delta_2+1} F_{S^{*de}}$

Proof. Since S^{*de} is a duplex-equal schedule, each link flow $f_{e,j}$ will satisfy $f_{e,j} \leq L/D$. Scale each link flow in S^{*de} by $\frac{1}{\Delta_2+1}$. The resulting link flows now satisfy

$0 \leq f_{e,j} \leq \frac{L}{D(\Delta_2+1)}$. Letting $x_d = L/D$ for each d and $o_k^{dj} = \frac{L}{D(\Delta_2+1)}$ for all d, j yields a feasible solution to the LP in Algorithm 1 with total bit flow $\frac{1}{\Delta_2+1} F_{S^{*de}}$. Since F_S is an optimal solution for the same LP, it follows that F_S will be at least $\frac{1}{\Delta_2+1} F_{S^{*de}}$.

We next observe the running time of Algorithm 1 is polynomial: Step 1 and 2 invokes a standard greedy coloring algorithm that runs in linear time in the size of the graphs colored. Steps 3 and 4 solve a linear program with $O(|V_c|)$ variables and constraints (note: the number of color variables is bounded by $|V_c|$ since giving each link flow its own unique color is a trivially valid coloring). This can be solved in $O(|V_c|^{3.5}L)$ using Karmarker's algorithm (L is the number of bits used to represent the input). Steps 5 and 6 require $O(|V_c|)$ time to create a valid link flow schedule. This leads to the following theorem.

Theorem 1. *Algorithm 1 is a* $\frac{1}{(\Delta_1+1)(\Delta_2+1)}$*-approximation algorithm running in polynomial time.*

Proof. From Lemmas 1 and 2 and the fact that $D \leq \Delta_1 + 1$, Algorithm 1 produces a schedule S that satisfies

$$\begin{aligned} F_S &\geq \frac{1}{\Delta_2+1} F_{S^{*de}} \\ &\geq \frac{1}{D(\Delta_2+1)} F_{S^*} \\ &\geq \frac{1}{(\Delta_1+1)(\Delta_2+1)} F_{S^*}. \end{aligned}$$

5 Finding Multipath Routes

We present a simple multipath construction heuristic based on performing a depth first search (DFS) in G starting from the source node s. As subpaths to the destination node t are discovered, they are added to the multigraph M. A heuristic that we employ is to find a multipath that has chromatic index of 2; meaning that the nodes v in M can be assigned a parity (odd or even) and that all links in M have endpoints with opposite parities. This ensures that the number of duplex colors needed in Step 1 of Algorithm 1 is 2. The source vertex s is assigned odd parity. During DFS from a vertex u, if edge (u, v) is followed and v is already part of M, a check is made to see that u and v have opposite parities; if not that branch of the search fails and a different outgoing edge from u must be tried (if one exists). If u and v have opposite parities then the new subpath reaching v is added to M. This ensures the constructed multipath M has chromatic index 2. If the search path fails to reach t or a compatible existing path to t, the algorithm backtracks (clearing parity assignments as it goes back). A key decision to make while performing this search is the order in which outgoing edges are explored from any intermediate vertex u. This effects which subpaths get added to M. We use a simple heuristic rule to rank outgoing edges $e = (u, v)$ based on their capacity as well as their direction relative to the destination vertex v. We define the link capacity $c(e)$ as follows:

$$c(e) = \sum_{j \in C_e} b_{e,j}. \tag{2}$$

The link capacity provides an upper bound on the bit flow rate achievable by link e ignoring intra-path interference. Let θ_e be the angle between (u, v) (considering the link as vector) and the vector (u, t). Then the rank of an edge is defined by

$$r(e) = c(e) \cdot \cos(\theta_e). \tag{3}$$

We presort the adjacency lists of outgoing edges for each vertex u into decreasing order of $r()$-value and then conduct the depth-first search described above from the source vertex s. Once a DFS branch reaches t, that subpath is added to M. This continues until no new subpaths are discovered and DFS terminates. At this point, the multipath M is fully constructed.

6 Numerical Results

In the simulation, we used the DFS-based algorithm from Section 5 to compute multipath routes. As a benchmark, we also considered shortest path routes and another path routing approach that attempts to find a routing path whose links all have high estimated capacity as defined by (2). We define the *bottleneck capacity* of a path P to be $c(P) = \min_{e \in P} c(e)$. Our goal is to find a path P that maximizes $c(P)$. This is a well-known problem that can be efficiently solved by computing a minimum spanning tree T on the network graph using an edge weight function $w(e) = -c(e)$. The unique path in T from s to t will have maximum bottleneck capacity. For the path routes, we used our existing path routing solution proposed in [12]. In order to estimate how close to optimal the schedules are in practice, we also computed an upper bound on the optimal transmission schedule following the approach described in [12].

All of our numerical results were gathered using a random network created by placing 50 stationary nodes at random locations in a 50 km $\times$ 50 km grid. For our experiments, we assumed there was a maximum of 13 channels available per frequency band and that the link throughput for each channel was the maximum available given the link distance and frequency used. Three widely spaced frequency bands were chosen, typical of bands available for licensed and unlicensed operation in different regions of the world. The bands exhibit widely ranging propagation, transmission range and usage characteristics, highlighting the potential value of cognition in transmission scheduling. Tables 1 and 2 summarize our assumptions about the transmission rates and interference ranges of

Table 1. Maximum transmission distances by frequency and data rate

Transmission rate	700 Mhz	2400 Mhz	5800 Mhz
45 Mbps	15.4 km	4.5 km	1.8 km
40 Mbps	18.4 km	5.3 km	2.2 km
30 Mbps	30 km	8.6 km	3.6 km
20 Mbps	41 km	11.8 km	4.9 km
10 Mbps	68 km	20 km	8.2 km

Table 2. Interference ranges by frequency

Frequency	Interference range
700 Mhz	30.8 km
2400 Mhz	9 km
5800 Mhz	3.6 km

each frequency. These values are based on a scenario where each node transmits at 1W with a 2dBi antenna and the receiving mode antenna has a gain of 2dBi. The channel bandwidth is 10 MHz and the receiver noise figure is 5dB, and implementation losses of 3dB are assumed for each link. Path loss is calculated using line of sight and free space characteristics. Typical 802.16 adaptive modulation and coding parameters performance parameters are used to estimate the throughput achievable as a function of CNR (carrier to noise ratio), and are then translated into the allowable path loss threshold. The maximum channel transmission rate is a function of distance and frequency (at lower frequency, the maximum distance for a given transmission rate will be greater).

We also varied the number of primary users in the network (not shown). The number of primary users was set to be one third of the number of available channels used in the each particular scenario. Primary users were placed at random locations and assigned a random channel. This channel was then made unavailable to any link within the interference range of the primary user. The frame length L was set to 1 second and each frame was divided into 100 time slots.

6.1 Scenario 1: Performance on Random Connection Requests

In this scenario, 10 connection source-destination pairs were randomly created and routing paths and multipaths were found. The number of channels available in the network was set to 15 (5 from each frequency band). Each connection lasts 200 seconds. The transmission starting times for each path are staggered by 100 seconds, e.g. Connection 1 is active in the time interval $[0, 200]$, Connection 2 is active in the time interval $[100, 300]$, etc. The results are shown in Figure 1. We compared the performance of the schedules obtained to upper bounds on the optimal schedule performance. We found that, on average, the schedules obtained for shortest path routing, bottleneck path routing and multipath routing were, respectively, within 97%, 94%, and 86% of optimal.

6.2 Scenario 2: Varying the Number of Channels Available

In this scenario, the number of channels available to secondary users was varied from 9 to 39 in increments of 6 (chosen equally from each frequency band) and the same routing paths and multipaths in Scenario 1 were used. The average end-to-end transmission rate for all paths and multipaths is reported. The results, shown in Figure 2, indicate an almost linear improvement is gained by adding additional channels to the network in terms of additional throughput. The slopes of the lines (as found by a linear regression through each point set) were 8.0, 8.9 and

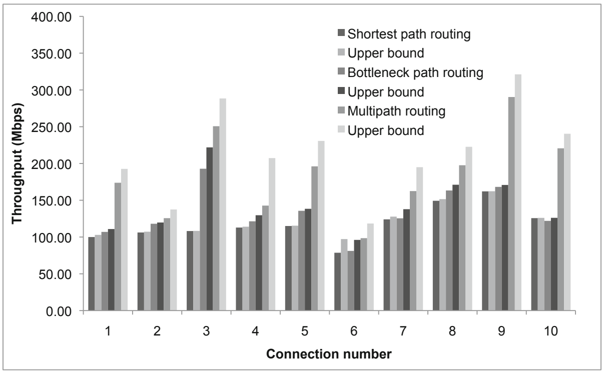

Fig. 1. Schedule performance results for each connection request

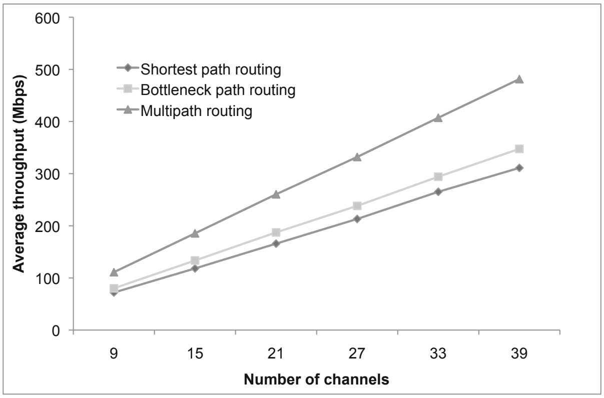

Fig. 2. Average path transmission rate versus the number of available channels

12.3 Mbps / channel respectively for shortest path routing, bottleneck path routing and multipath routing. A possible explanation for the higher slope of multipath routing is that the multipath can make more use of additional channels since the data flow through the multipath is physically more spread out.

6.3 Scenario 3: Network Saturation

In this scenario, we considered how quickly the network would saturate as additional traffic was added to it. We used the original 10 connection pairs from Scenario 1 and also created 10 new random source-destination pairs in the network. The number of channels available in the network was set to 15 (5 from each frequency band). We further assumed that once a connection was established that it would stay active for the remainder of the simulation. The results are shown in Figure 3. As would be expected, multipath routing appears to saturate the network the most quickly, although it is able to achieve the highest

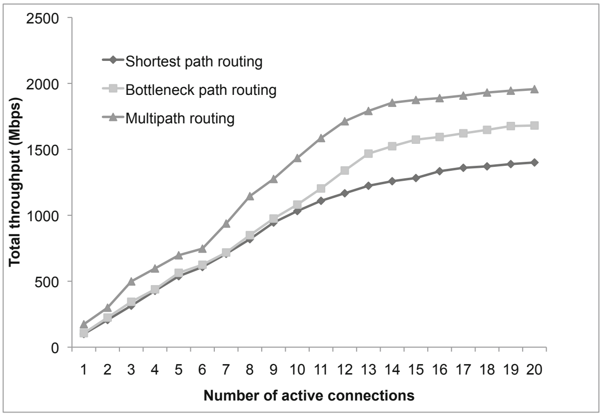

Fig. 3. Network saturation as the number of active connections increases

total throughput. The network saturates the most slowly if shortest path routing is used. Shortest paths in general will use fewer links than the other methods and so will tend to tie up fewer resources per connection.

7 Conclusions

In this paper, we presented a novel polynomial-time constant-factor approximation algorithm for the problem of scheduling transmissions along a multipath in a cognitive radio mesh network and a heuristic routing algorithm for finding multipaths. According to the simulation results, the end-to-end throughput provided by our scheduling algorithm is always close to a computed upper bound on the optimal solution. Our proposed bottleneck path routing approach has improved performance over shortest paths and the proposed multipath routing algorithm can achieve almost twice the performance of shortest path routing. The results demonstrate the potential of using cognitive radios to share spectrum on a non-interfering basis with primary users, while at the same time offering substantial throughput to secondary users.

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