

# Routing and Spectrum Allocation for Video On-Demand Streaming in Cognitive Wireless Mesh Networks

Yong Ding, Li Xiao

Department of Computer Science and Engineering

Michigan State University

East Lansing, MI 48824

Email: {dingyong, lxiao}@cse.msu.edu

**Abstract**—Cognitive radio, which enables dynamic access of under-utilized licensed spectrums, is a promising technology for more efficient spectrum utilization. Since cognitive radio enables the access of larger amount of spectrum, it can be used to build wireless mesh networks with higher network capacity, and thus provide better quality of services for high bit-rate applications. In this paper, we study the multi-source video on-demand application in multi-interface cognitive wireless mesh networks. Given a video request, we find a joint multi-path routing and spectrum allocation for the session to minimize its total bandwidth cost in the network, and therefore maximize the number of sessions the network can support. We propose both distributed and centralized routing and channel allocation algorithms to solve the problem. Our algorithms not only increase the maximum number of concurrent sessions that can be supported in the network, but also improve each session's adaptivity to spectrum mobility.

## I. INTRODUCTION

Cognitive Radio (*CR*) is envisioned to be the key enabling radio technology of the next generation wireless networks [1]. Today's wireless networks operate within a fixed spectrum, such as Wi-Fi, Bluetooth, TV, etc. However, a considerable portion of the licensed spectrum is under-utilized with the variation of time and geographic locations. A cognitive radio is able to sense the spectrum holes across the licensed bands over a wide range of spectrum and switch to any free frequency band. Therefore, a cognitive radio wireless mesh network has the potential to utilize more spectrum resource than traditional wireless mesh networks, and provide better quality of service for user applications.

The video on-demand application (*VoD*) has become a popular Internet service recently. There have already been several commercial products developed to support *VoD* applications, such as PPLive, YouTube, and PP-Stream. Most of them use peer-to-peer (*P2P*) technology to improve the *VoD* performance [2]. Under this

architecture, assume users can store the videos that they have recently watched in their local storage (e.g., PPLive buffers 1G bytes of the most recently watched videos, which is enough for over two 2-hour movies, in a peer's local storage). When a client wants to watch a new video, he or she first discovers which peer clients have buffered the video, and then streams the video from both the servers and peer clients through multiple paths. The multi-path multi-source video on-demand streaming has been applied in wired networks with great success. However, it remains a challenging task in wireless networks, because the network throughput is limited due to the wireless interference and the limited channel resources. Fortunately, the use of cognitive radio has the potential to alleviate this problem.

Cognitive radio is more powerful and flexible than the traditional radio used in multi-channel multi-radio wireless mesh networks. 1) *CR* can utilize both unlicensed bands and unused licensed bands, and therefore a *CR* network can enjoy more spectrum resource. 2) Traditional radio can only use fixed channels. For example, each channel of 802.11b/g has around 22M frequency bandwidth. In contrast, *CR* has the flexibility to adjust the center frequency as well as the width of frequency band. Moreover, by using Discontiguous Orthogonal Frequency Division Multiplexing (*DOFDM*), a *CR* is able to work on non-contiguous spectrum fragments, which makes it more flexible in channel allocation. 3) Traditional radio has non-negligible channel switching overhead. *CR* is targeted for switching of channels on packet level, and thus it is suitable for dynamic channel allocation. In this paper, we focus on deploying *VoD* applications in cognitive wireless mesh networks.

In a cognitive wireless mesh network, assume a user initiates a *VoD* request. If there are peers buffering the video in the local cognitive wireless mesh network, the

user can stream the video from these local peers. In addition, even if there are no such local peers, the user can still stream from peers in the Internet through the multiple gateways. As the wireless network is usually the bottleneck of *VoD* performance, we study the multipath routing and spectrum allocation within the cognitive wireless mesh network in this paper. For each *VoD* session, we find  $k$  paths from local peers or gateways (through which peers in the Internet can be accessed) to the user with appropriate spectrum allocation on the links of each path, which satisfies the following constraints: 1) The multiple paths are edge-disjoint with each other. As a result, the failure of one link will affect at most one path, which improves the robustness of the application. 2) Each path is allocated with the appropriate bandwidth of spectrum to satisfy the traffic rate. 3) It must guarantee the independency between the multiple paths with regard to spectrum mobility. In other words, when a primary user reclaims a certain channel, at most one path of the session is affected. In order to support more *VoD* sessions (each session corresponds to a new video request from a user) and thereby provide services for more *VoD* clients, we set our optimization goal to minimize the total bandwidth cost of each session in the network. We also propose both distributed and centralized algorithms to solve the formulated problem.

The rest of the paper is organized as follows. We summarize previous work in Section II. In Section III, we present the system model. In Sections IV and V, we propose both distributed and centralized algorithms to solve the problem. We evaluate our algorithms in Section VI and conclude our work in Section VII.

## II. RELATED WORK

Existing wireless network architectures are characterized by a fixed spectrum assignment policy. However, the spectrum assigned to licensed users is often under-utilized, which can be shown from the measurements in [3]. Cognitive radio, which enables dynamic spectrum access, can improve this inefficient use of spectrum [1]. For example, as the cognitive radio technology enables the access to larger amount of spectrum, it can be used to build wireless mesh networks with less contention and therefore provide higher network capacity.

With cognitive radio, a secondary user can opportunistically utilize unused licensed spectrum without interfering with primary users. There are several studies on the optimal spectrum assignment for single-hop flows in cognitive radio networks. In [4], the authors focused on maximizing both spectrum utilization and fairness. They reduced the problem to a graph multi-coloring problem, and proposed some heuristic algorithms. In

[5], the authors proposed a faster distributed algorithm, which computes a new spectrum assignment on topology change based on the prior spectrum assignment. In [6], a group-based coordination scheme has been proposed for spectrum allocation without relying on the existence of a preassigned common control channel. The spectrum allocation could be more efficient if the cognitive radio supports Discontiguous Orthogonal Frequency Division Multiplexing (DOFDM). In [7], the authors proposed a spectrum assignment algorithm that takes spectrum aggregation into consideration.

The optimal spectrum assignment for multi-hop flows in cognitive radio networks is more complex than the case of single-hop flows. In [8], the authors assumed a known traffic profile, and formulated the problem of finding the optimal routing and spectrum assignment that satisfies the given traffic demand. In [9], the authors presented a similar problem formulation to maximize the fairness of satisfying different flows. In [10], the authors further considered power control of cognitive radios in addition to routing and spectrum assignment. Unlike these studies that assume a priori known traffic profile and utilize global optimization, we consider dynamic traffic in this paper, because *VoD* requests may arrive randomly at different times. The authors of [11] studied the link-based spectrum allocation in a multi-hop cognitive radio network. They proposed a distributed heuristic algorithm for each link to determine a time-spectrum block with the goal of maintaining proportionally-fair throughput among all the link demands. In contrast to the link-based spectrum allocation, we study flow-based routing and spectrum allocation in this paper.

There are several studies on joint routing and spectrum allocation for dynamic arrival of flows. In [12], the authors proposed a delay-motivated on-demand routing protocol to find a minimum delay route and channel assignment for an arriving flow. In [13], a spectrum-aware routing protocol has been proposed to find a route and channel assignment for an arriving flow that maximizes the throughput. Unlike the previous work in single-interface cognitive radio network, the authors of [14] studied the problem in a multi-interface cognitive radio network. They proposed heuristic algorithms for finding the joint routing and channel assignment that maximizes the throughput for the flows. All these previous studies utilize the fixed channel approach, that is, they treat each primary user's frequency band as a channel, and each cognitive radio can be assigned only one channel in the channel assignment. In this paper, we assume *DOFDM*-based cognitive radios, which enable more flexible channel assignment. Each radio can be

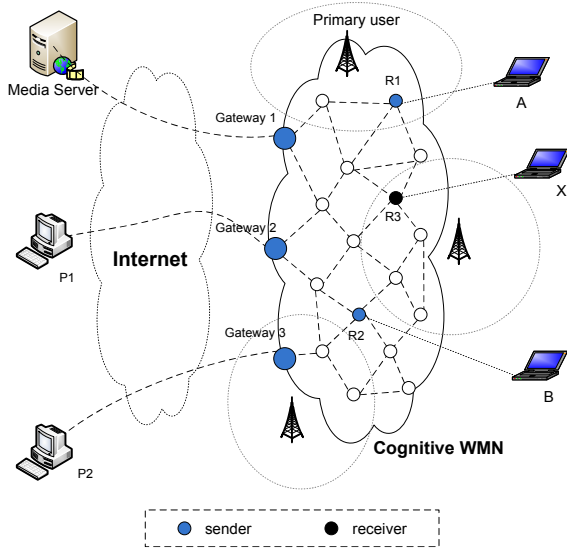


Fig. 1: Multi-Source VoD in Cognitive Wireless Mesh Networks

assigned a set of non-contiguous spectrum fragments, where each fragment consists of multiple subcarriers.

There are generally two ways to support the control protocol in a cognitive radio network. 1) Use a traditional radio in each node to be used as a control interface only, such as [12] [13]. 2) Use the cognitive radios for both control and application traffic. However, a common control channel may not always be available due to the heterogeneous set of available channels in each cognitive node. In [15], the authors coped with this problem by using a cluster-based framework, in which clusters are formed by neighboring nodes sharing local common channels. The authors of [16] theoretically studied the problem of finding the minimum number of connected clusters, where nodes within each cluster share a common channel. In this paper, we use the first approach for exchanging control messages.

### III. OVERVIEW

In this section, we first introduce some preliminaries, and then we present the problem formulation.

#### A. Preliminary

Consider a large community network constructed by wireless mesh networking technology. The network is formed by static mesh routers that establish mesh connectivity with neighboring routers, and they have multiple special routers as gateways to connect to the Internet. Each mesh router is equipped with multiple cognitive radio interfaces. The cognitive radios are able to sense

the spectrum holes in the neighborhood and dynamically switch to available channels. In addition, we assume each mesh router is equipped with a traditional radio that works on a common control channel such as in [12] [13]. All mesh routers exchange control messages via the control interface to establish routes and allocate channels dynamically. An example topology of a cognitive wireless mesh network is illustrated in Fig.1.

In the *VoD* applications, we assume users can buffer the video they have watched in their local storage (e.g., PPLive buffers 1G bytes of the most recently watched videos). Whenever a user has requested a video, he or she registers to the server so that the server keeps a list of the users that have buffered the video. When a new user visits, he or she queries the server for the list of peers from which they can stream the video. If there are such peers, the new user can stream the video not only from the media server, but also from the other peers. For the peers that are located in the community network, the user can stream the video over a multi-hop wireless path, while for the peers in the Internet, the user can stream the video over a path, which consists of a multi-hop wireless path from the user to the gateway and a path from the gateway to the peer in the Internet.

For a specific video, we call a mesh router as *sender* if it is directly connected with a peer or server that can provide the download of the video, or it is a gateway through which the new user can download the video from a peer or server in the Internet. The mesh router that the new user directly connects with is called *receiver*. In the example illustrated in Fig.1, we assume *P1*, *P2*, *A*, *B* are the peers that have buffered the video. If *X* wants to watch the video, there are five available senders in this case, which include *R1*, *R2*, and the three gateways. In this paper, we are interested in multipath routing and spectrum allocation between the receiver and senders in the cognitive wireless mesh network.

Multiple Description coding (*MDC*) has been proposed for multipath multimedia transport in [17]. With *MDC*, a video source is coded into  $k$  equivalent streams, such that any subset of these streams can be used to reconstruct the video. Due to its advantage of error-resilience, *MDC* is especially suitable to be used in wireless networks. As it is shown in [18] that the most significant performance gain is achieved when  $k$  increases from 1 to 2, we use double-description coding in this paper. In other words, we assume a receiver streams the two descriptions from two senders via two paths respectively for each *VoD* session.

For cognitive radio to achieve flexible spectrum assignment, Orthogonal Frequency Division Multiplexing

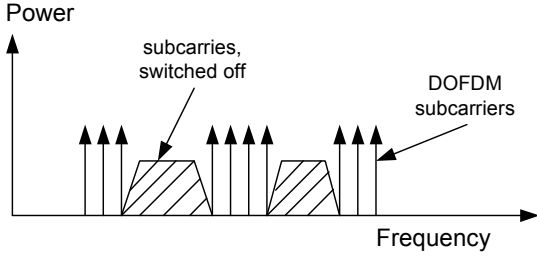


Fig. 2: cognitive radio transmits on three spectrum fragments simultaneously

(OFDM) [19] is one of the most widely used technologies to fulfill the requirement. By dividing the spectrum into sub-bands that are modulated with orthogonal subcarriers, the data can be divided into several parallel data streams, one for each subcarrier. Thus, a cognitive radio can dynamically adjust the width of frequency band by turning on different numbers of subcarriers. Furthermore, with the advancement of technology in Discontiguous Orthogonal Frequency Division Multiplexing (DOFDM) [19], a radio can access several non-contiguous spectrum fragments simultaneously, that is, a radio is able to transmit and receive data on multiple spectrum fragments at the same time. As illustrated in Fig.2, a cognitive radio can access three spectrum fragments simultaneously, where each fragment consists of one or multiple subcarriers. In this paper, we assume each cognitive radio is DOFDM based, and thus it has more flexibility in spectrum assignment.

### B. Problem Formulation

Consider a cognitive wireless mesh network with  $N$  nodes. Let  $M$  be the spectrum range that the cognitive radio can sense and work within. Let  $M_i \subseteq M$  be the set of available bands at node  $i \in N$ , called spectrum opportunities (SOPs). Due to the different usage of bands by primary users at different locations, it is likely that  $M_i \neq M_j$  for  $i \neq j$ .

Assume there are two interfaces in each node. We use one radio as incoming interface and the other radio as outgoing interface. Each wireless link  $l_{ij}$  is constructed between the outgoing interface in node  $i$  and the incoming interface in node  $j$  if the two nodes are within radio transmission range of each other and share some common available bands. Note that the direction of the link defined here corresponds to the direction of data flows in application level. This can be generalized to  $2K$  radios each node, where  $K$  radios are used as incoming interfaces and  $K$  radios are used as outgoing interfaces.

Let  $A_{ij}$  be the set of available bands of link  $l_{ij}$ . A band  $b_k \in A_{ij}$  if  $b_k \in M_i$ ,  $b_k \in M_j$ , and nodes  $i, j$  are within radio transmission range of each other on  $b_k$ . Given the receiver  $r$  and the set of senders  $S = \{s_1, s_2, \dots, s_m\}$ , we want to find two paths  $P_{s,r}$  and  $P_{s',r}$  ( $s_i \neq s_j$ ,  $s_i, s_j \in S$ ) together with the spectrum allocation on each path, while satisfying the following constraints.

**Edge-disjointness constraint:** In edge-disjoint paths, no two paths share a same link, and therefore any link failure will only affect one path. Especially in the multipath streaming of MDC, if one path fails, the video stream can still be reconstructed by the streams from other paths by sacrificing some video quality. Therefore, the guarantee of edge-disjointness can improve the robustness of the application. This constraint is formally described as:

$$l_i \neq l_j, \text{ for } l_i \in P_1, l_j \in P_2 \quad (1)$$

**Interference-free constraint:** In DOFDM-based cognitive radios, the spectrum is divided into subbands (or subcarriers). This enables more flexible channel assignment than traditional radios, because each cognitive radio can be assigned a different set of subbands such that they will not interfere with each other. Therefore, we desire interference-free spectrum allocation on the multiple paths. In other words, a feasible spectrum allocation must ensure that there is no intra-flow or inter-flow interference. Let  $b_i$  be the band assigned to link  $l_i$ ,  $d(l_i, l_j)$  denote the distance between the two links, and  $I$  be the interference range. The constraint is formally described as:

$$b_i \cap b_j = \emptyset, \text{ for } l_i, l_j \in (P_1 \cup P_2) \wedge d(l_i, l_j) \leq I \quad (2)$$

**Bandwidth constraint:** We use double-description coding for each VoD session. Assume the rate for each flow (each description) is  $r$ , and thus each link in each path must be allocated with enough frequency bandwidth (or enough number of subcarriers) to satisfy the data rate. Similar to [11], we assume spectrum utilization is linear in the bandwidth, that is,  $C(b_i) = \gamma \cdot W(b_i)$ , where  $C(b_i)$  is the capacity of  $b_i$ ,  $W(b_i)$  is the width of  $b_i$ , and  $\gamma$  is a constant. The allocated band must satisfy:

$$C(b_i) \geq r \text{ for } l_i \in (P_1 \cup P_2) \quad (3)$$

**Path-independency constraint:** In the case when a primary user reclaims a channel that the VoD session is using, the cognitive radios need to give up the corresponding band and seek a new available band. Let  $B(b_i)$  be the primary-user channel that band  $b_i$  belongs to. To guarantee that at most one path is affected in each time,

the following constraint needs to be satisfied:

$$B(b_i) \neq B(b_j), \text{ for } l_i \in P_1, l_j \in P_2 \quad (4)$$

**Interface constraint:** Each cognitive radio interface is limited by the max span of frequency range, denoted by  $Q$  (e.g., 40MHz). Let  $B^i$  be the spectrum that interface  $i$  is assigned.  $B^i$  consists of several discontinuous spectrum fragments. Let  $f_{top}(B^i)$  and  $f_{bot}(B^i)$  be the top and bottom boundary of frequency of  $B^i$ . we have

$$f_{top}(B^i) - f_{bot}(B^i) \leq Q \quad (5)$$

As the infrastructure-based cognitive wireless mesh network is intended to support many users, we set the maximum number of concurrent sessions that can be satisfied in the network as our optimization goal. Assume we assign  $b_i$  to link  $l_i$ . Let  $IE(l_i, b_i)$  be the set of links that have  $b_i$  as available channel and are within interference range of  $l_i$ . Note that  $IE(l_i, b_i)$  also includes  $l_i$ . The bandwidth cost of assigning  $b_i$  to  $l_i$  is  $bc(l_i, b_i) = |IE(l_i, b_i)| \cdot W(b_i)$ . In other words, by assigning  $b_i$  to  $l_i$ , we cannot assign  $b_i$  to the other interfering links afterwards. The cost includes the sum of bandwidth occupied in the network for the assignment. Therefore, the optimization goal is to minimize the total bandwidth cost of each session, and therefore enable the network to support more concurrent sessions.

$$\text{Minimize } \sum_{l_i \in P_1 \cup P_2} bc(l_i, b_i) \quad (6)$$

#### IV. DISTRIBUTED ROUTING AND CHANNEL ALLOCATION PROTOCOL

In this section, we propose a heuristic distributed protocol to find a joint routing and spectrum allocation for a single *VoD* session request that minimizes the total bandwidth cost in the network while satisfying the constraints. The basic idea is as follows. We use two rounds to find two paths together with spectrum allocation. In each round, the receiver broadcasts the path discovery message to its neighbors. Each intermediate node updates its currently best path and spectrum allocation to the receiver, and further broadcasts the update information. Once the sender has received the update messages, it selects a best path and spectrum allocation and replies to the receiver.

Assume each router keeps a list of its own links and the set of available channels for each link. Initially, each router broadcasts its own links and available channels to all neighbors within two hops away. As a result, each router knows the interfering links and their available channels for each of its own links.

##### A. Path Discovery

Initially, the receiver broadcasts a *RREQ* message to its neighbors. The *RREQ* message contains the currently best route and channel allocation found from the node itself to the receiver. The message is composed of  $\langle P, A, bc \rangle$ , where  $P = (l_1, l_2, \dots, l_m)$  denotes the route,  $A = (b_1, b_2, \dots, b_m)$  is the channel allocation for the route ( $b_i$  is the channel allocated for  $l_i$ ), and  $bc$  is the total bandwidth cost of the path. In the *RREQ* message broadcast by the receiver,  $P = \phi$ ,  $A = \phi$ ,  $bc = 0$ .

When a node  $q$  receives a *RREQ* message from  $p$ , node  $q$  knows the best path from  $p$  to the receiver, denoted by  $\langle P_{pr}, A_{pr}, bc_{pr} \rangle$ , which includes the best route, the channel allocation, and the total cost. The node  $q$  then needs to determine the optimal channel assigned to link  $l_{qp}$  with minimum bandwidth cost.

Assume the frequency bandwidth required by the flow is  $w$ , which equals one or multiple subcarriers, then we can discretize the available channels of  $l_{qp}$  into  $C = (c_1, c_2, \dots, c_k)$ , where each  $c_i$  has bandwidth of  $w$ . The optimal channel for  $l_{qp}$  can be calculated as follows:

- 1) For each  $l_i \in P_{pr}$ , if  $l_{qp}$  is within interference range of  $l_i$ , remove  $b_i$  from  $C$ . Let the new available channel list be  $C'$ . This guarantees the interference-free channel assignment.
- 2) For each  $c_i \in C'$ , calculate the bandwidth cost of assigning  $c_i$  to  $l_{qp}$ , denoted by  $bc(l_{qp}, c_i)$ . Let  $IE(l_{qp}, c_i)$  be the set of links that have  $c_i$  as available channel and are within interference range of  $l_{qp}$ , then  $bc(l_{qp}, c_i) = |IE(l_{qp}, c_i)| \cdot w$ .
- 3) Select the channel  $c^*$  with the minimum bandwidth cost and assign it to link  $l_{qp}$ .

As a result,  $q$  has discovered a new path, where  $P = (P_{pr}, l_{qp})$ ,  $A = (A_{pr}, c^*)$ , and  $bc = bc_{pr} + bc(l_{qp}, c^*)$ . If the new path has lower total cost than the currently best path recorded by node  $q$ ,  $q$  updates its recorded path and broadcasts a new *RREQ* message containing the updated path. If the new path does not exist, or is no better than its recorded path,  $q$  discards the message and does nothing. This significantly reduces the number of broadcast messages during path discovery. To further reduce the overhead, each node sets up a random timer  $t_a$ . If an intermediate node finds a better path, it will hold on for  $t_a$  time before broadcasting the *RREQ* message. If the node finds better paths within this period of time, the node restarts the timer. In this way, the number of *RREQ* broadcast messages can be further reduced.

##### B. Path Selection

When a sender receives a *RREQ* message, it needs to notify the receiver of this path if it is the best path

currently found. We set a timer  $t_s$  at each sender. If the sender has found a better path, it will hold on for  $t_s$  before notifying the receiver. If during this period, some better paths have been found, the sender will restart the timer. The sender uses source routing to send an *RREP* message to the receiver through the best path currently found. It includes the path information  $\langle P, A, bc \rangle$  in the *RREP* message. Note that the sender will not broadcast any *RREQ* message. The reason is that the receiver wants to find the minimum cost path among all the available senders. Assume the best path is from the receiver to sender  $s^*$ , then the path will not traverse any other senders. Therefore, it is not necessary for each sender to further broadcast the *RREQ* message.

When the receiver gets the *RREP* message, it knows the best path to a particular sender. We set a timer  $t_r$  for the receiver, so that it will hold on for  $t_r$  time before determining the best path among all the senders. If there is no *RREP* message from other senders before the timer expires, the receiver will choose the minimum cost path among all the paths replied from the senders.

After the first path has been selected, the receiver initiates a similar path discovery process to find a second path. The only difference is that the information of the first path will be inserted in the *RREQ* message. Thus, when each node receives and processes the *RREQ* message, it will be aware of the first selected path and guarantee the edge-disjointness, interference-free, and path-independency constraints during the discovery of the second path. For example, when  $q$  receives a *RREQ* from  $p$ , if  $l_{qp}$  is used in the first path, the message should be discarded to guarantee the edge-disjoint constraint. In addition, the channel assignment for  $l_{qp}$  should be aware of the channels assigned in the first path to guarantee the other constraints.

### C. Path Reservation

After both paths have been selected, the receiver sends a *RSV* message along each of the two path to reserve it for video streaming. The message includes  $\langle P, A \rangle$  information, so that the nodes along the path can reserve the frequency band on the corresponding interface. Each node along the path also broadcasts a *UPD* message within two hops so that the nodes within interference range know the update of its channel usage. Once each path has been reserved, the sender of the path sends a *CFM* message to the receiver for confirmation.

## V. JOINT ROUTING AND CHANNEL ALLOCATION

The distributed algorithm proposed in the previous section may not find near-optimal solutions due to the following reasons. 1) In the path discovery stage, we

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### Algorithm 1 Path Discovery - Heuristic 2

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- 1: Let  $cap(l_i)$  be the number of available channels for the link  $l_i$ .
  - 2: Find shortest pair of edge-disjoint paths from  $r$  to  $s_1, s_2$  with regard to hop count, denoted by  $H$ .
  - 3: Let  $T = \max\{cap(l_i)\}$ .
  - 4: **repeat**
  - 5:    $T = T / 2$
  - 6:   Generate a subgraph, which only contains links  $l_i$  such that  $cap(l_i) \geq T$ .
  - 7:   Find shortest pair of edge-disjoint paths from  $r$  to  $s_1, s_2$  with regard to hop count, denoted by  $H'$ .
  - 8: **until**  $length(H') < \gamma \cdot length(H)$
  - 9: return  $H'$
- 

assign channel to one link in each step, and the assigned channels do not change in the further discovery. 2) Some timers ( $t_s$  and  $t_r$ ) are used in the protocol for the purpose of fast path discovery. Although this improves the path discovery speed, it leads to incomplete enumeration of all possible good paths. In this section, we propose a centralized algorithm, which has the promise of finding more optimal solutions.

We solve the problem in two steps. 1) Find two edge-disjoint paths, which satisfies the edge-disjointness constraint. 2) Allocate channels on the the pair of paths to minimize the total bandwidth cost, while satisfying the other constraints. (We will later prove that even this second sub-problem is NP-hard.)

### A. Multipath Routing

Given a receiver  $r$  and two senders  $s_1, s_2$ , there are two heuristic strategies that can be used for path discovery:

- *Heuristic 1*: As our optimization goal is to minimize the total bandwidth cost, we prefer the link that has an available channel with lower cost. For each link  $l_i$ , assume the discretized list of available channels to be  $C(l_i) = (c_1, c_2, \dots, c_{k_i})$ , then we can calculate the bandwidth cost of each channel on the link  $bc(l_i, c_j), c_j \in C(l_i)$ . We define the weight of  $l_i$  as

$$weight(l_i) = \min_{c_j \in C(l_i)} \{bc(l_i, c_j)\}$$

Therefore, a weighted graph can be generated. We use the Suurballe's algorithm to find two edge-disjoint paths with minimum total cost.

- *Heuristic 2*: We prefer the link with a greater number of available channels, so that we have more flexibility in finding a channel assignment that minimizes the total cost of all links. On the other hand, we also prefer shorter paths because they may

also lead to smaller total cost. The path discovery algorithm using these heuristics is shown in Algorithm.1. In the algorithm, we iteratively lower the threshold for the number of available channels of each link until we find paths whose total length is less than  $\gamma$  times the length of shortest paths in the original topology. In the implementation, we set  $\gamma = 1.5$ .

### B. Channel Assignment

Given the two edge-disjoint paths, we next find a channel assignment scheme that minimizes the total bandwidth cost of the paths. Let  $L = (l_1, l_2, \dots, l_m)$  be the set of links in both paths, and  $C = (1, 2, \dots, n)$  be the discretized channels over the whole spectrum range. We can then calculate the bandwidth cost of each link  $l_i$  if it is working on channel  $j$ , denoted by  $t_{ij}$ . If a channel is not available for the link, then the cost is set to infinite.

Let  $A$  be a channel assignment scheme, where  $A_i \in \{1, 2, \dots, n\}$  is the channel that the link is assigned. A valid channel assignment scheme must satisfy both the interference disjointness constraint and the independence constraint. We define the *minimum-cost channel assignment problem* as finding a valid channel assignment, which minimizes the total bandwidth cost:

$$\text{Minimize } \sum t_{iA_i}$$

**Theorem 1:** *The minimum-cost channel assignment problem is NP-hard.*

*Proof:* The hardness of the problem can be proved by referring to the optimum cost chromatic partition problem (*OCCP*), which is NP-hard. Given a graph  $G = (V, E)$  with  $n$  vertices and sequence of coloring costs  $(k_1, k_2, \dots, k_m)$ , the *OCCP* problem finds a feasible coloring  $f(v)$  for each vertex  $v$  such that the sum of coloring costs  $\sum_{v \in V} k_{f(v)}$  is minimized. We consider a simplified version of our channel assignment problem. We build a conflict graph from the set of links  $L$ , where each link corresponds to a vertex. There is an edge between two vertices if the two corresponding links interfere with each other. For each vertex  $i$ , it has a coloring cost array  $t_i = (t_{i1}, t_{i2}, \dots, t_{in})$ . Assume each vertex has the same coloring cost array, that is,  $t_i = t_j$  for  $i \neq j$ . As a result, this simplified problem is *OCCP*. Therefore, the problem is NP-hard.

In this section, we propose a fast heuristic algorithm to find a good channel assignment. In each step, we select a link from the set of links that have not been assigned channels, and determine an optimal channel for the link.

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### Algorithm 2 Channel Assignment

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- 1: Let  $L$  be the set of links,  $C$  be the set of channels,  $t$  be the cost matrix, where  $t_{ij}$  is the bandwidth cost of assigning channel  $j$  to link  $l_i$
  - 2: **repeat**
  - 3:   Calculate  $cost_{ij}$  for each  $l_i$  on each channel  $j$
  - 4:   Find  $cost_{pq} = \min\{cost_{ij}\}$
  - 5:   Assign link  $l_p$  with channel  $q$
  - 6:   Update available channels for interfering links.
  - 7:    $L = L - l_p$
  - 8: **until**  $L$  is empty
- 

For each link  $l_i \in L$ , we define the minimum cost of the link  $mc(l_i)$  as

$$mc(l_i) = \min_{j \in C} \{t_{ij}\}$$

Intuitively, we prefer to select the link that has the minimum  $mc$  for channel assignment in each step. Denote the link by  $l_p$  and the channel that has the minimum cost on  $l_p$  as  $q$ . Thus, by assigning channel  $q$  to  $l_p$ , the algorithm is causing minimum increase in the total cost in each step. However, this strategy may not find near optimal results. Let  $N(l_p) \subseteq L$  be the set of interfering links of  $l_p$  in  $L$ , then the links in  $N(l_p)$  cannot use channel  $q$  subsequently. However, if  $q$  is the min-cost channel for some link  $l \in N(l_p)$ , then  $l$  must be assigned another channel with higher cost.

To find more optimal results, our algorithm takes the strategy of looking one step ahead. For each link  $l_i \in L$ , let  $mc_1(l_i)$  and  $mc_2(l_i)$  be the minimum and second minimum cost on all the channels. Note that they can be the same value. The cost of assigning channel  $q$  to link  $l_p$  is

$$cost_{pq} = t_{pq} + \sum_{l_i \in N(l_p) \wedge t_{iq} = mc_1(l_i)} [mc_2(l_i) - mc_1(l_i)]$$

In other words, the total cost not only includes  $t_{pq}$ , but also includes the cost of the case when the other interfering links cannot use this channel anymore, i.e., they can only use the second minimum cost channel in subsequent channel assignment. The algorithm is illustrated in Algorithm.2. In each step, we select a minimum cost  $cost_{pq}$  for all the remaining edges on all the channels, and assign link  $l_p$  with channel  $q$ .

### C. Joint Routing and Channel Assignment

The joint routing and channel assignment algorithm is illustrated in Algorithm.3. We scan all possible pairs of senders for the double-path streaming, and select a best solution from them. Through experiments, we find that Path-Discovery Heuristic 1 is more efficient for the case

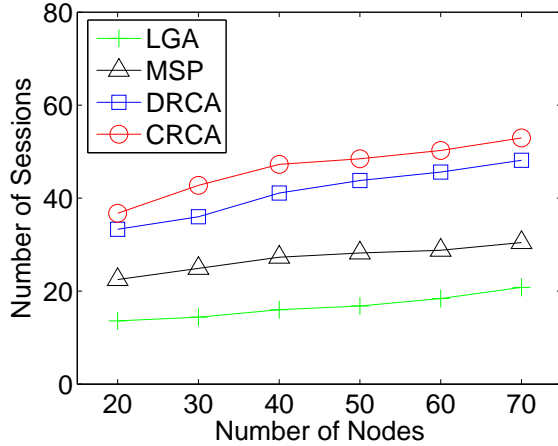


Fig. 3: Maximum Number of Sessions under Different Network Scales

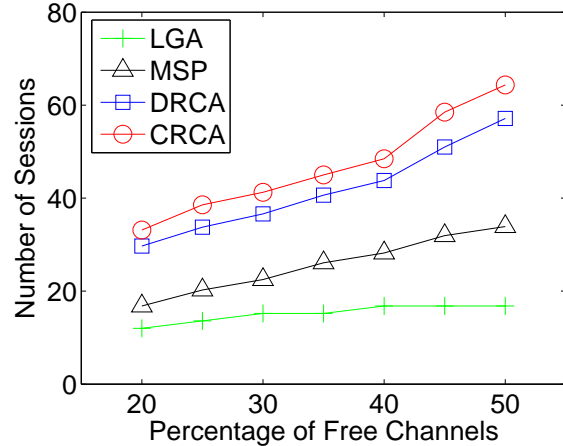


Fig. 4: Maximum Number of Sessions under Different Percentage of Available Spectrum

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### Algorithm 3 Routing and Channel Assignment

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- 1: Let  $S$  be the set of senders, and  $r$  be the receiver.
  - 2: **for** each pair  $(s_i, s_j)$ ,  $s_i, s_j \in S \wedge s_i \neq s_j$  **do**
  - 3: Find two paths by Path Discovery - Heuristic 1
  - 4: Assign channels on paths by Algorithm.2
  - 5: **if** no feasible solution is found **then**
  - 6: Find two paths by Path Discovery - Heuristic 2
  - 7: Assign channels on paths by Algorithm.2
  - 8: **end if**
  - 9: **end for**
  - 10: Select the routing and channel assignment with minimum total cost among all the choices.
- 

when the network is below saturation, i.e., the number of session requests is not large. When the network is near saturation, there might not be any feasible channel assignment for the paths discovered by Heuristic 1. In this case, we use Heuristic 2 to find paths that are more likely to have feasible channel assignment. Therefore, we use a combination of the two heuristic path discovery algorithms in Algorithm.3.

## VI. PERFORMANCE EVALUATION

We evaluate our algorithms in random mesh network topologies with different numbers of nodes. We assume each node has multiple cognitive radio interfaces and one traditional radio interface for control message transmission. The cognitive radios are able to use free spectrums in the TV broadcast band  $[470MHz, 698MHz]$ , where the width of each TV channel is  $6MHz$ . We assume that each cognitive radio has *DOFDM* capability, so that it can access several spectrum fragments simultaneously.

The max span of the spectrum that each cognitive radio can use is set to  $40MHz$ . The control interface works on  $802.11b$  channels and uses *CSMA/CA MAC* protocol.

We use the following method to simulate the *SOPs* of each mesh router in the cognitive wireless mesh network. As the radio transmission range at each channel is constrained by the spectrum usage of primary users and the *SOP* usage polices in the neighborhood, each radio cannot always use the maximum power to reach the maximum transmission range, but has to limit its transmission range within an acceptable value on the specific channel. Thus, we simulate the radio transmission range on each channel by uniform distribution at each node in our experiments. We assume a certain percentage of the 38 TV channels are available to use, while the transmission range of each channel is randomly generated at each node. Given node positions, we can then calculate the common *SOPs* between each pair of nodes. We set the maximum transmission range to  $250m$  in the simulations, and we generate networks with different numbers of nodes by keeping the node density at one node per  $150m \times 150m$ .

In each network topology, we randomly select 4 nodes from the network as gateways, which provide access to the Internet. We assume any *VoD* user within the network can access the media servers or peers in the Internet through all these gateways. As a result, we regard them as senders. Assume there are 10 popular movies, each of which is available to be downloaded from any of the 4 senders. We randomly generate a sequence of *VoD* requests for a random hot movie from users that are associated with any mesh router in the network. If a *VoD* request has been satisfied, then the corresponding user

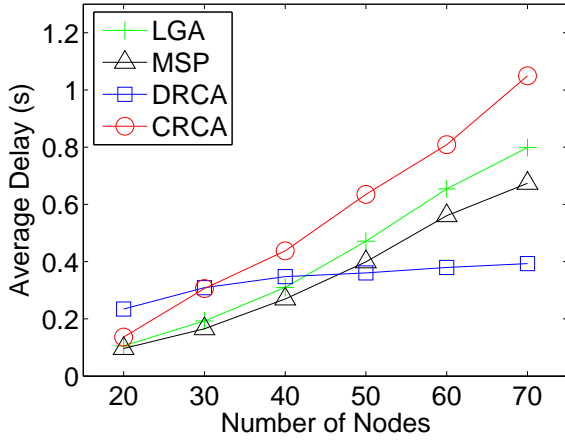


Fig. 5: Average Delay for Session Setup

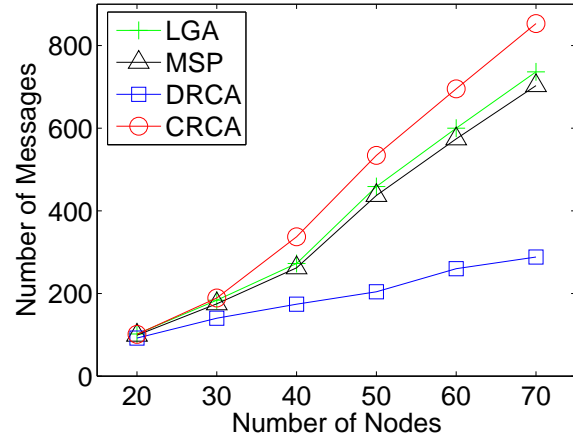


Fig. 6: Control Packets Overhead for Session Setup

becomes a sender for the video, because it can provide download of the video for subsequent users.

We compare our algorithms with the modified version of the shortest path routing algorithm (*MSP*). Given  $n$  senders, and a receiver  $r$ , it first finds the shortest and the second shortest paths from  $r$  to the senders, and then assign channels on the paths. We use the following heuristic channel assignment algorithm for *MSP*. In each step, we select an edge that has the minimum number of *SOPs*, and assign a channel that does not interfere with any other edges that have been assigned channels in the two paths. In the following simulations, we denote the distributed and centralized routing and channel allocation algorithm by *DRCA* and *CRCA* respectively. We assume each mesh router has two cognitive radios.

#### A. Maximum Number of Sessions

To evaluate the maximum number of concurrent *VoD* sessions that can be supported in the network under different algorithms, we assume there are 10 popular movies and set the 4 gateways as initial senders for all the movies. We generate a sequence of 60 *VoD* requests. Each request is from a random user in the network for a random movie. If the *VoD* request has been satisfied, the receiver becomes a sender and can provide the download of the movie for subsequent users. We assume the bit rate requirement of each *VoD* session is  $800Kbps$ , and every  $1MHz$  of spectrum delivers  $1.2Mbps$  [20]. As we use double description coding to stream the video from two paths, considering the overhead of packet header and control messages in video streaming, we assume the frequency bandwidth requirement for each flow is  $0.5MHz$ .

The simulation results are shown in Fig.3. We assume 40 percent of the 38 TV channels in  $[470MHz, 698MHz]$  are available. The figure shows the maximum number of concurrent *VoD* sessions that can be supported when the network size varies. We can observe that both *DRCA* and *CRCA* support a greater number of sessions than *MSP*. The reason is that they consider minimizing the bandwidth cost of each session, and therefore lead to more efficient allocation of network resources such as channels. *DRCA* is able to improve the capacity by around 50 percent, while *CRCA* leads to a further improvement of around 20 percent. In addition, with the increase of network size, the number of sessions increases for all the algorithms.

We set the network scale to 50 nodes and change the percentage of available spectrum in our experiments. The simulation results are shown in Fig.4. We can observe that the maximum number of concurrent sessions increases with the increase of available spectrum. Similar with the previous experiment, both *DRCA* and *CRCA* outperform *MSP* under different percentage of available spectrum.

#### B. Protocol Overhead

We implemented *DRCA*, *CRCA* and *MSP* in *NS2*. All the control message transmissions occur on the control interface (traditional radio) of each node. The *CSMA/CA MAC* protocol is used, and the bit rate is set to  $11M$ . For *DRCA*, we set  $t_a$  to be a random value in  $[0, 5ms]$ ,  $t_s = t_r = 25ms$ . We evaluate the overhead in two aspects: 1) The delay for setting up each *VoD* session, including the discovery and establishment of routes and channel allocation. 2) The total number of control messages transmitted for setting up each session.

The average session setup delay is illustrated in Fig.5. The algorithms are run on a Pentium 2.0GHz machine. We can observe that *DRCA* is scalable with the network size. With the increase of the number of nodes, the delay only increases slightly. On the other hand, the delay of *CRCA* and *MSP* increase dramatically with the network size. The delay of both algorithms includes the calculation of the routing and channel assignment together with the delay for reserving the routes and channels. When the network size is over 40 nodes, *CRCA* begins to experience larger delay than *DRCA*.

The number of control messages for each session setup is illustrated in Fig.6. For *DRCA*, the control overhead includes route/channel discovery and reservation. For *CRCA* and *MSP*, the control overhead includes route/channel reservation only. However, both algorithms need to notify all nodes in the network of the reservation, while *DRCA* only needs to inform nodes within interference range of the reservation. We can observe that *DRCA* is more scalable than *CRCA* and *MSP*.

## VII. CONCLUSION

We studied the multi-source video on-demand streaming in cognitive wireless mesh networks. The *DOFDM*-based cognitive radios are more powerful and flexible than traditional radios, which enables the access of larger amount of spectrum and more flexibility in channel assignment. We have formulated the joint multipath routing and channel allocation problem to minimize the total bandwidth cost for each *VoD* session. Therefore, more concurrent sessions can be supported in the network. We have proposed both heuristic distributed and centralized routing and channel allocation algorithms to solve the problem. Simulation results have shown that the network is able to serve more *VoD* users by using our proposed algorithms.

## VIII. ACKNOWLEDGEMENTS

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