A Novel Framework For Scalable Video Streaming Over Multi-Channel Multi-Radio Wireless Mesh Networks*

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ABSTRACT

In this paper, we study the problem of scalable videos multicast streaming over multi-channel multi-radio wireless mesh networks over a contention-based MAC, with the objective of maximizing the overall received videos quality. We propose a three-stage heuristic framework solution for the complex joint channel assignment, video quality selection and multicast routing problem. That framework is called Channel Assignment with Iterative Routing and Quality Selection (CAIRoQS), it is implemented using C and evaluated with NS2 using video traffic traces. Our performance evaluation shows noticeable improvement in both network and application level metrics in comparison to state of the art solutions, e.g., 23% improvement in the packet drop ratio mean.

CCS Concepts

•Networks → Wireless mesh networks; •Information systems → Multimedia streaming;

1. INTRODUCTION

Video currently has the largest traffic share in both wired and wireless networks. More importantly, it is getting more pervasive with the widespread of smart devices and new technologies. Wireless mesh networking (WMN) is evolving as a fast, robust and low cost communication infrastructure technology [10]. A WMN consists of stationary wireless mesh routers, which are connected to one another in a multi-hop manner to form a wireless backbone. End-user mobile devices can connect to the wireless backbone through some mesh routers within their transmission range. The intersection between video and WMN can create new opportunities for new video services, e.g. replacing the text labels describing an object exhibited in a museum with a video being streamed to the visitors' hand-held devices.

Interference is one of the main limitations in wireless networks and it significantly reduces the network capacity. Additionally, it increases packet delay which is critical for real-time applications such as video streaming. Previous studies, e.g. [11] [5], show that using multiple radios increases the network capacity by benefiting from simultaneous operation. Additionally, using scalable video coding (SVC) [13] in such lossy setting may improve the user quality of experience as the application maybe able to decode lower frame quality specifications in comparison to complete frame loss.

In this paper, we focus on developing a novel framework for streaming scalable video in multi-channel multi-radio WMNs that use a contention-based MAC protocol, e.g., IEEE 802.11. That framework is called Channel Assignment with Iterative Routing and Quality Selection (CAIRoQS). Our main objective is to maximize the quality of multicasted streams while taking channel assignment, video quality adaptation, and routing decisions. The main contributions of this paper are multi-fold:

- First, we mathematically formulate the problem of channel assignment and multicast routing with the objective of maximizing the received quality of scalable video in a multi-radio WMN settings.
- Second, we propose a three-stage novel framework to perform channel assignment, video quality adaptation, and multicast routing in the aforesaid WMN settings.
- The proposed framework is implemented in C and integrated with NS2[1] to evaluate its performance using scalable video traces.

The rest of the paper is organized as follows. In Section 2, we discuss related work. In Section 3, we present the system model. The problem formulation is presented in Section 4. In Section 5, we introduce our CAIRoQS framework and heuristic algorithms for solving the problem. Our simulation setup and performance evaluation are shown in Section 6. Finally, conclusions is presented in Section 7.

2. RELATED WORK

Video may be encoded to be scalable or non-scalable. Scalable video techniques, as SVC, encodes a video into a base layer and multiple enhancement layers. The base layer provides a basic video quality, while each enhancement layer improves video quality incrementally. In lossy networks, the application would only fail to decode the video if the base layer is lost while a lower quality video can be decoded if

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[1] ns Network Simulator. http://www.isi.edu/nsnam/ns/.

losses only affect enhancement layers. SVC feature is very useful for highly variable environment such as WMNs.

The problem of video streaming in WMNs is studied in different settings. Many of the published work in this area focus on systems with contention-free MAC. In [16], Farzinvash et al. addressed the bandwidth heterogeneity problem of multicast receivers for multi-channel multi-radio WMN and proposed an algorithm to maximize the sum of the achieved data rates by the receivers over TDMA networks. Chiu et al. [3] consider the problem of constructing a bandwidth-guaranteed multicast tree in multi-channel multi-radio WMN with the objective of maximizing the call acceptance rate assuming a schedule-based MAC protocol. In [18], the authors provide a video multicast framework over TDMA-based WMNs, using SVC with heterogeneous user demands. Avokh et al. [1] introduce a load-aware routing scheme based on dynamic costs for the WMN links. They also propose an algorithm for creating load-balanced multicast tree for reservation-based MAC. Chuah et al. [12] investigate resource allocation of scalable video multicast over resource constrained wireless networks. They formulate a multicast strategy that maximizes video quality under transmission energy and channel access time constraints based on contention-free MAC for a single-hop wireless network.

A few works, including our work, consider WMN using random-access MAC. In [9], Li et al. use SVC and propose a dependency-aware rate scheduling scheme that assigns each video layer a rate according to dependency between layers with objective of maximizing the visual quality of the multicast group. It uses IEEE 802.11 MAC protocol and It is modeled for a single-hop wireless network. Zhu et al. [14] address the problem of rate allocation for scalable video multicast over contention-based MAC WMNs. Their optimization objective is to minimize the total video distortion of all receivers without incurring excessive network utilization. In our work, we consider a different network settings including SVC multicast streaming over a multi-hop multi-channel multi-radio WMNs.

3. SYSTEM MODEL

In this paper, we consider a scalable video distribution system over a multi-channel multi-radio WMN. The WMN is modeled as a connected graph $\mathscr{G} = (\mathscr{V}\ , \mathscr{E}\ )$ with $\mathscr{V}$ representing the set of network nodes and $\mathscr{E}$ corresponds to the set of communication links between these nodes. The nodes communicate over K orthogonal channels that have the same capacity C. These channels constitutes a channel set $\mathscr{K}$. Each node is equipped with I radios with $I \leq K$. Each link $(i\ , j)\ \epsilon\, \mathscr{E}$ is allowed to operate on a single channel that is determined by a channel assignment algorithm. This link-channel association is maintained in the association set $\mathscr{A}\,(\mathscr{E}\ )$. Additionally, $\mathscr{K}_i$ denotes the set of channels assigned to node i.

We assume a contention-based MAC, e.g., 802.11 DCF. We also assume that the transmission and interference range of all nodes are identical. We define link utilization of channel k, denoted as u_{ij}^k, as the fraction of time during which each link is active. We also denote the set of links that interfere with link $(i\ , j)$ as ξ_{ij}^k [14]. We also consider a protocol interference model [3].

We consider a set of video streams, denoted as $\mathscr{S}$. Each video stream s is multicasted from the WMN gateway to a set of receivers, denoted as $\mathscr{R}_s$, where the multicast tree of each stream is denoted as T_s. Each stream s is encoded to a set of layers, denoted as $\mathscr{L}_s$. $l_{i,s}$ denotes the i^{th} layer of stream s, with $l_{0,s}$ denoting the base layer of stream s.

4. PROBLEM FORMULATION

Our main design goal is to maximize the perceived video quality for the multicasted streams while taking video quality adaptation, channel assignment and routing decisions.

Let $\mathcal{D}_{l_{i,s},x}$ denotes the probability that layer $l_{i,s}$ is decodable at node x. A video layer is considered *decodable* iff all the packets of this layer and its predecessors dependency layers are received. Hence $\mathcal{D}_{l_{i,s},x}$ can be expressed as

$$\mathcal{D}_{l_{i,s},x} = \prod_{l'_{i,s} \preccurlyeq l_{i,s}} \left(\Pi_x^{(l'_{i,s})}(0).I_{l'_{i,s}} \right) \tag{1}$$

where $\Pi_x^{(l'_{i,s})}(0)$ denotes the probability of zero packet loss of layer $l'_{i,s}$ at node x, that probability is derived in [7]. $I_{l'_{i,s}}$ denotes the decision of whether layer $l'_{i,s}$ is selected to be transmitted or not, $l'_{i,s} \preccurlyeq l_{i,s}$ means that $l_{i,s}$ depends on $l'_{i,s}$ and this product is on all the layers that $l_{i,s}$ depends on, including itself. The overall received videos quality can then be derived as

$$\sum_{s \epsilon \mathscr{S}} \sum_{l_{i,s} \epsilon \mathscr{L}_s} \left(I_{l_{i,s}} w_{s,l_{i,s}} \left(\sum_{r \epsilon \mathscr{R}_s} \mathcal{D}_{l_{i,s},r} \right) \right) \tag{2}$$

where the quality impact metric $w_{s,l_{i,s}}$ acts as a weighting factor for the importance of each layer and we sum the decodability at each receiver of the streams. In this expression, $w_{s,l_{i,s}}$ signifies the impact of layer $l_{i,s}$ in stream s on the perceived quality and is computed as the drop in PSNR from the PSNR of the highest quality when layer $l_{i,s}$ is lost [12]. Our objective is to maximize (2) by optimizing the channel assignment, stream routing, and controlled quality streaming, subject to channel assignment, routing, and traffic flow constraints. Hence, this program is expressed as

$$max \ \sum_{s \epsilon \mathscr{S}} \sum_{l_{i,s} \epsilon \mathscr{L}_s} \left(I_{l_{i,s}} w_{s,l_{i,s}} \left(\sum_{r \epsilon \mathscr{R}_s} \mathcal{D}_{l_{i,s},r} \right) \right) \tag{3}$$

$$s.t. \ : \ 0 \leq N_i^k \leq \sum_{j:(i,j) \epsilon \mathscr{E}} e_{ij}^k \ \ \forall i \epsilon \mathscr{V},\, k \epsilon \mathscr{K} \tag{4}$$

$$e_{ij}^k \leq N_i^k \leq 1 \ \ \forall j : (i,j) \epsilon \mathscr{E} \tag{5}$$

$$\sum_{k \epsilon \mathscr{K}} N_i^k \leq I \ \ \forall i \epsilon \mathscr{V} \tag{6}$$

$$\sum_{k \epsilon \mathscr{K}} e_{ij}^k = 1 \ \ \forall (i,j) \epsilon \mathscr{E} \tag{7}$$

$$e_{ij,k}^{T_s} \leq e_{ij}^k \ \ \forall (i,j) \epsilon \mathscr{E},\, k \epsilon \mathscr{K},\, s \epsilon \mathscr{S} \tag{8}$$

$$r_g^s = 1 \ \ \forall s \epsilon \mathscr{S} \tag{9}$$

$$\sum_{i \epsilon \mathscr{V}} r_i^s = 1 \ \ \forall s \epsilon \mathscr{S} \tag{10}$$

$$\sum_{i:(i,j) \epsilon \mathscr{E}} \sum_{k \epsilon \mathscr{K}} e_{ij,k}^{T_s} \leq 1 - r_j^s \ \ \forall j \epsilon \mathscr{V} / \mathscr{R}_s,\, s \epsilon \mathscr{S} \tag{11}$$

$$\sum_{i:(i,j) \epsilon \mathscr{E}} \sum_{k \epsilon \mathscr{K}} e_{ij,k}^{T_s} = 1 \ \ \forall j \epsilon \mathscr{R}_s,\, s \epsilon \mathscr{S} \tag{12}$$

$$\sum_{i:(i,j) \epsilon \mathscr{E}} \sum_{k \epsilon \mathscr{K}} e_{ij,k}^{T_s} \geq \sum_{k \epsilon \mathscr{K}} e_{jb,k}^{T_s} - r_j^s \ \ \forall (j,b) \epsilon \mathscr{E},\, j \epsilon \mathscr{V} / \mathscr{R}_s,\, s \epsilon \mathscr{S} \tag{13}$$

$$\sum_{b:(j,b)\epsilon\mathscr{E}} \sum_{k\epsilon\mathscr{K}} e^{T_s}_{jb,k} \geq \sum_{k\epsilon\mathscr{K}} e^{T_s}_{ij,k} \;\; \forall(i,j)\epsilon\mathscr{E},\, j\epsilon\mathscr{V}/\mathscr{R}_s,\, s\epsilon\mathscr{S} \quad (14)$$

$$e^{T_s}_{ij,k} + e^{T_s}_{ji,k} \leq 1 \;\; \forall(i,j)\epsilon\mathscr{E},\, s\epsilon\mathscr{S} \quad (15)$$

$$v^s_j - v^s_i \geq \sigma \sum_{k\epsilon\mathscr{K}} e^{T_s}_{ij,k} - (1 - \sum_{k\epsilon\mathscr{K}} e^{T_s}_{ij,k}) \;\; \forall(i,j)\epsilon\mathscr{E},\, s\epsilon\mathscr{S} \quad (16)$$

$$F^k_{ij} = \sum_{s\epsilon\mathscr{S}} \sum_{l_{i,s}\epsilon\mathscr{L}} e^k_{ij} e^{T_s}_{ij,k} I_{l_{i,s}} F_{l_{i,s}} \;\; \forall(i,j)\epsilon\mathscr{E},\, k\epsilon\mathscr{K} \quad (17)$$

$$F^k_{ij,s} = \sum_{l_{i,s}\epsilon\mathscr{L}} e^k_{ij} e^{T_s}_{ij,k} I_{l_{i,s}} F_{l_{i,s}} \;\; \forall(i,j)\epsilon\mathscr{E},\, k\epsilon\mathscr{K},\, s\epsilon\mathscr{S} \quad (18)$$

$$F'^k_{ij} = \rho C_{ij} \;\; \forall(i,j)\epsilon\mathscr{E},\, k\epsilon\mathscr{K} \quad (19)$$

$$F_T{}^k_{ij} = F'^k_{ij} + F^k_{ij} \;\; \forall(i,j)\epsilon\mathscr{E},\, k\epsilon\mathscr{K} \quad (20)$$

$$u^k_{ij} = \frac{F_T{}^k_{ij}}{C_{ij}} \;\; \forall(i,j)\epsilon\mathscr{E},\, k\epsilon\mathscr{K} \quad (21)$$

$$\tilde{u^k_{ij}} = \sum_{(i',j')\epsilon\xi^k_{ij}} u^k_{i'j'} \leq \gamma \;\; \forall(i,j)\epsilon\mathscr{E},\, k\epsilon\mathscr{K} \quad (22)$$

$$\sum_{s\epsilon\mathscr{S}} \left(\left[\sum_{k\epsilon\mathscr{K}} \sum_{i:(i,j)\epsilon\mathscr{E}} F^k_{ij,s} \right] [1 - j^s_r] \right) = \sum_{s\epsilon\mathscr{S}} \left(\frac{\sum_{k\epsilon\mathscr{K}} \sum_{i:(j,i)\epsilon\mathscr{E}} F^k_{ji,s}}{\sum_{i:(j,i)\epsilon\mathscr{E}} \sum_{k\epsilon\mathscr{K}} e^{T_s}_{ji,k}} \right) \;\; \forall j\epsilon\mathscr{V}/Gateway \quad (23)$$

$$\sum_{k\epsilon\mathscr{K}} \sum_{i:(i,j)\epsilon\mathscr{E}} F'^k_{ij} \geq \sum_{k\epsilon\mathscr{K}} \sum_{i:(j,i)\epsilon\mathscr{E}} F'^k_{ji} \;\; \forall j\epsilon\mathscr{V}/Gateway \quad (24)$$

$$\sum_{k\epsilon\mathscr{K}} \left[\sum_{i:(i,j)\epsilon\mathscr{E}} u^k_{ij} + \sum_{i:(j,i)\epsilon\mathscr{E}} u^k_{ji} \right] \leq I \;\; \forall j\epsilon\mathscr{V} \quad (25)$$

$$\frac{\sum_{s\epsilon\mathscr{S}} \left(\left[\sum_{k\epsilon\mathscr{K}} \sum_{i:(i,j)\epsilon\mathscr{E}} F^k_{ij,s} \right] j^s_r \right)}{C_{downlink}} \leq 1 - \rho \;\; \forall j\epsilon\mathscr{V} \quad (26)$$

$$I_{l_{0,s}} = 1 \;\; \forall s\epsilon\mathscr{S} \quad (27)$$

where e^k_{ij}, $e^{T_s}_{ij,k}$, and $I_{l_{i,s}}$ represent our binary decision variables. e^k_{ij} is set to 1 if link (i, j) is assigned to channel k, $e^{T_s}_{ij,k}$ is set to 1 if link (i, j) assigned to channel k is on the tree of stream s, and $I_{l_{i,s}}$is set to 1 if layer $l_{i,s}$ is sent. Also, N^k_i, r^s_i, and j^s_r are indicator functions. N^k_i is equal to 1 if node i is assigned to channel k. r^s_i is equal to 1 if node i is a root (source) of stream s. j^s_r is equal to 1 if node j is a receiver for stream s.

Equations (4-7) represent our *channel assignment constraints*. Equations (4) and (5) implies that node i is assigned to channel k, if and only if at least one of the outgoing links is assigned to channel k. Equation (6) limits the number of assigned channels to a node to the maximum number of radios a node can have. Equation (7) implies that each link (i, j) must be assigned only one channel.

Multicast Routing constraints are presented in equations (8-16), we refer to [3]. Equation (8) relates the two decision variables e^k_{ij} and $e^{T_s}_{ij,k}$. Equations (9),(10) mandates that there is only one source for each multicast tree; i.e.,the gateway. Equation (11) indicates that if node j is a source for the tree then it will have no incoming links that are on that tree, and if node j is not a source nor a receiver for the tree then it will have at most one incoming link that is on the tree. Equation (12) indicates that there must be only one incoming link to each receiver, while equation (13) states that if there is an outgoing link from any non-receiver node then there must be an incoming link to it. Equation (14) states that if there is an incoming link to any non-receiver node then there must be at least one outgoing link from it. Equation (15) states that tree links are unidirectional and equation (16) prevents loops inside the trees.

Equations (17-26) represents the *traffic flow constrains.* Equation (17) defines F^k_{ij} which is the total multicast flow on link (i, j) on channel k, while equation (18) defines $F^k_{ij,s}$ which is the multicast flow of stream s on link (i, j) on channel k, F'^k_{ij} is the unicast flow on link (i, j) on channel k which is represented by equation (19), ρ is a ratio of the total capacity of the link reserved for other traffic in the network, The sum of both unicast and multicast flows is presented by $F_T{}^k_{ij}$ in equation (20). In equations (21,22), u^k_{ij} is the utilization of link (i, j) on channel k, $\tilde{u^k_{ij}}$ is the total utilization within its interference set ξ^k_{ij}, $\gamma < 1$ is an over provisioning factor to absorb various effects not included in our model such as random back-off, inaccurate estimates of link capacities, etc. [14]. Equation (23) states the flow conservation constraint for multicast flows. Equation (24) represents the flow conservation constraint for unicast flows [11]. Equation (25) indicates that the sum of incoming and outgoing link utilization from a node cannot exceed its number of radios [11, 16] and finally equation (26) states that the multicast flow intended for the downlink cannot exceed the capacity of the downlink channel. Equation (27) denotes that the base layer of each video must be transmitted.

In [6], Raniwala et al. proved that the channel assignment problem with complete knowledge of network topology and traffic matrix is NP-hard. Therefore, our problem is also NP-hard since it is a generalized problem with multiple sub-problems jointly optimized and additional decision variables. That is, the link-channel assignment problem in [6] is merely a sub-problem of (3) to (27).

5. PROPOSED FRAMEWORK CAIRoQS

Since our problem is NP-hard, we propose a novel three-stage heuristic framework called CAIRoQS to solve the problem. *First,* orthogonal channel assignment is performed in a greedy fashion to minimize the overall interference between the network links. *Second,* the quality of streamed videos is then determined by solving a linear program (LP) assuming the gateway to be the network bottleneck. *Third*, the multicast trees of different streams are determined. The *second* and *third* stages are performed iteratively if the proposed routing algorithm identifies a new bottleneck in the network as detailed below.

5.1 First Stage : Channel Assignment

The objective of this stage is to assign orthogonal channels to the links of WMN such that the overall interference between the links is minimized and putting into consideration a restricted number of radios at each node. In order to realize this goal, we define a conflict graph $\mathscr{C}.\mathscr{G}. = (\mathscr{M}, \mathscr{N})$ derived from $\mathscr{G} = (\mathscr{V}, \mathscr{E})$ such that each vertex $m_{i,j}\,\epsilon\mathscr{M}$ corresponds to link $(i, j)\,\epsilon\mathscr{E}$ and there exists an edge $m_{i,j}m_{x,y}\,\epsilon\mathscr{N}$, if the distance between the two corresponding links (i, j), (x, y) $\epsilon\mathscr{E}$ is within the interference range of each other. Note that the distance between two links is defined as the minimum distance between any node of one link and any node of the other link [15]. Two links $(i,\, j)$ and $(x,\, y)\,\epsilon \mathscr{E}$ interfere with each other if there is a link between their corresponding vertices in the conflict graph, $m_{i,j} m_{x,y}\,\epsilon \mathscr{N}$, and they are assigned the same channels $\mathscr{A}\,(m_{i,j}) = \mathscr{A}\,(m_{x,y})$, where $\mathscr{A}\,(x)\,\epsilon K$ and it determines the channel assigned to link x.

Similar to [15], the channels are assigned to links in a sequential manner that involves two steps: *select* and *assign*. However, we consider a different metric for the selection step as we use orthogonal channels. In the *select* step, the link with the largest number of interfering links is selected. At the *assign* step, the selected link is assigned with channel k that has the least interference with neighboring links, which means that the selected link assigned to channel k will interfere with a number of links less than that if the selected link is assigned with channel other than k.

As an initialization step, we start with the gateway and assign each of its radios a distinct channel from a channel set $\mathscr{K}$ to ensure the maximum gateway capacity. The algorithm then proceed with its typical select and assign stages. It is worth noting that the set of channels, from which a channel is assigned to link $(i,\, j)$, differs depending on the selected link. If both end-nodes of the selected link have a radio with unassigned channels, then the channel assignment set is $\mathscr{K}$. If one of the end-nodes, say node i, do not have free radios, then the channel assignment set is limited to $\mathscr{K}_i$. If both end-nodes , i and j , do not have free radios, then the channel assignment set is $\mathscr{K}_i \cap \mathscr{K}_j$, which is the common channels on both nodes. If $\mathscr{K}_i \cap \mathscr{K}_j = \phi$, then link $(i,\, j)$ will be removed from $\mathscr{G} = (\mathscr{V}\,,\, \mathscr{E}\,)$.

5.2 Second stage: Bottleneck-Restricted Video Quality Selection (BReViQS)

The objective of this stage is to identify a subset of the layers from every stream to be transmitted such that the overall quality of the videos is maximized subject to bandwidth and layer dependency constraints. This problem can be expressed as a LP as follows

$$max \sum_{s\epsilon\mathscr{S}} \sum_{l_{i,s}\epsilon\mathscr{L}_s} I_{l_{i,s}}.F_{l_{i,s}} \tag{28}$$

$$s.t.\ :\ I_{l_{i,s}} - I_{l'_{i,s}} \leq 1 \ \forall l'_{i,s} \preceq l_{i,s} \tag{29}$$

$$\sum_{s\epsilon\mathscr{S}} \sum_{l_{i,s}\epsilon\mathscr{L}_s} I_{l_{i,s}}.F_{l_{i,s}} \leq C_{max} \tag{30}$$

$$I_{l_{0,s}} = 1 \ \forall s\epsilon\mathscr{S} \tag{31}$$

where $F_{l_{i,s}}$ is the transmission rate of layer $l_{i,s}$, equation (29) ensures that layer dependency is maintained, equation (30) mandates an upper bound on the total rate of the selected layers, equation (31) ensures a minimum base-layer quality for the transmitted videos. C_{max} is the maximum rate allocated for the multicast streams and is initially set to the gateway capacity as a typical bottleneck. If the routing part claims a different capacity bound, this program is resolved using the new value in an iterative fashion.

5.3 Third stage: Multicast Routing with Ranked Links Algorithm (MuRRaL)

The objective of this step is to identify a multicast tree for every stream from the WMN gateway to the corresponding stream receivers. Toward this goal, we develop a novel routing algorithm that aims to create a set of trees such that the load is balanced across the WMN nodes and any link excessive utilization is avoided.

The algorithm proceeds based on the knowledge of: network topology as defined by graph $\mathscr{G} = (\mathscr{V}\,,\, \mathscr{E}\,)$, the channel assignment identified in the first stage, the target set of receivers for every stream, and the stream rate determined in the second stage. The streams are processed sequentially to determine their corresponding multicast trees. The algorithm continuously update the current traffic load at each node and the channel utilization observed at every node. These parameters are used to determine the cost of using different network links for routing decisions. In this work, we estimate the link cost metric as [1]

$$f(x,y) = DF(x,y).CF(x,y)$$

where $DF(x,y)$ represents a discouragement factor and $CF(x,y)$ represents a congestion factor. $DF(x,y)$ has lower values for links that serve more receivers by taking advantage of the broadcasting nature of the wireless medium to minimize the number of transmissions. $CF(x,y)$ tends to have lower values for lightly loaded links and is employed to improve the load balancing across different nodes. For more details, the reader is referred to [1] due to space limitation.

Our algorithm creates the tree in a sequential manner and the link costs are updated after every step. On doing such update, a link cost would be set to zero if it is already added to current tree in a previous step. Additionally, the cost of link $(x,\, y)$ may be set to infinity if its addition would lead to a channel utilization larger than unity in its neighborhood.

On creating the tree of stream s, the tree is initialized by its source node; i.e., the WMN gateway. We then proceed by adding links until this source is connected to the stream receivers identified in $\mathscr{R}_s$ as follows

- We employ Dijkstra's algorithm [4] to identify the shortest path to each individual receiver in $\mathscr{R}_s$.
- These paths are then processed to identify a rank for every link in these paths.
- This rank is calculated as the number of individual paths that are using this link provided that the addition of the link would result in a connected tree graph. Otherwise, the link rank is set to zero.
- The link with the highest non-zero rank is added to the tree (the case of all zero rank is handled below).
- The channel utilization matrix and traffic load vector are updated. Note that this update would affect the link costs as presented above.
- If the added link adds an unconnected receiver, the tree is updated by trimming links that are not part of the path to a connected receiver and the channel utilization matrix and traffic load vector are updated.

The case of all zero rank means that the cost of the paths to the remaining receivers are all infinity and thus there is no paths to the remaining receivers. This situation implies that there exist a network bottleneck away from the gateway. In order to overcome this, the LP of the second stage is resolved with the capacity bound C_{max} set to the sum of the bandwidths of the video streams that has been routed before the new bottleneck is identified.

6. PERFORMANCE EVALUATION

In this section, we first present our evaluation setup and performance metrics, then we present the evaluation results.

We simulate an $n * n$ grid of multi-channel multi-radio WMN in NS2.35 with a default value of $n = 6$. The multi-channel multi-radio is supported by using the extension presented in [2]. In all the simulations, we set the radio transmission range to 250 m, which is slightly larger than the diagonal distance between neighbor nodes, and the interference range to 500 m. We use 802.11 MAC with a bit-rate of 30Mbps for each radio and a two ray propagation model. Each mesh router is equipped with 4 radios, including one to communicate with the end-clients and the remaining radios are used to communicate over the backbone mesh. The end-clients are randomly located in the simulation area.

Original 720p HD YUV video sequences are obtained from publicly available sequences[2][3] and encoded as H.264/SVC video using JSVM [20]. Each video is encoded into 3 resolutions including HD, 4CIF and CIF and two qualities per picture resolution with frame-rate of 30 fps and GOP size of length 16. The encoded videos are streamed from a server, collocated with the gateway, to the end-clients using NS2 tools from myEvalSVC [19] and AVIS [8] extensions.

The proposed routing algorithm MuRRaL is implemented by modifying MAODV NS2 extension [21] to support offline multicast tree formation. Additionally, the optimization problem of Section 5.2 is implemented in a C program using GUROBI optimization library [17]. We compare the performance of our proposed scheme CAIRoQS with other two variants, one includes the first and second stages of CAIRoQS but uses the routing algorithm proposed in [1], we call that variant “Avokh”. The other variant is same as “Avokh” but with random channel assignment, that variant is called “AvokhRandomCA”. In [1], a complete shortest path between the source and a receiver is added at every iteration of the tree creation. In our algorithm, a link is chosen in every decision iteration based on the rank as described in Section 5.3. We found that CAIRoQS ensures that the link utilization is better maintained below the target threshold and hence, a fewer collisions take place. Our performance metrics include:

- Packet drop ratio (PDR): A network-level performance metric that identifies the percentage of dropped packets to the total number of transmitted packets. A packet drop occurs when the packet is lost due to the collision in wireless transmission. It influence the quality of the decoded video.
- Average packet end-to-end delay: This metric determines the average time needed for a packet to be transmitted from the source to the receivers.
- Percentage of decodable frames: A received frame maybe undecodable if it is missing packets from any of its layers or missing any of its predecessor frames.
- Frame quality index: This metric represents the individual quality of received frames. Larger frame resolution indicates a higher quality index. Additionally, a higher picture quality for the same resolution would account for a higher quality index.
- Frame quality switches: This is an application-level metric that shows the change in quality that occurs between consecutive frames.

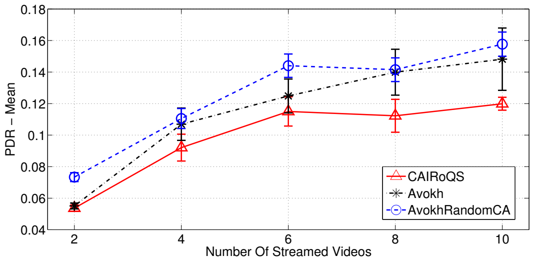

Figure 1: Mean of PDR

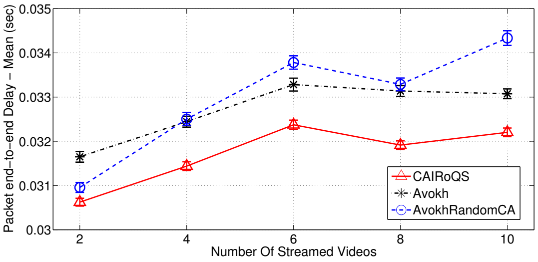

Figure 2: Average End-to-End Delay of packets

In the shown results, we vary the number of multicasted streams in a 36-node grid network. In each simulation, each video is multicasted to a randomly selected mesh routers, the multicast group is of size 4 and each mesh receiver is associated with an end-client. The number of available orthogonal channels in the network is 5. In the following figures, each point corresponds to the average of 30 simulation runs.

In Fig. 1, we plot the mean of packet drop ratio against the number of streamed videos in the network. The figure shows a noticeable reduction in the number of dropped packets that reaches 23% and 20% compared to AvokhRandomCA and Avokh schemes respectively. These performance gains are attributed to the channel assignment algorithm and the granularity of the proposed routing algorithm MuRRaL that results in a more balanced load and reduced interference across the network. Fig. 2 plots the average packet delay versus the number of streamed videos. The figure shows that the proposed scheme also attains a reduction of 6% and 3% in the average packet delay compared to AvokhRandomCA and Avokh schemes respectively.

Fig. 3 plots the percentage of received decodable frames against the number of streamed videos. It suggests that the better performance at the network level is reflected on the application performance by increasing the percentage of decodable frames. This gain reaches 11.6% and 10% compared to AvokhRandomCA and Avokh schemes respectively.

Fig. 4 plots a histogram for the quality indices of the received frames for both scenarios of 2 and 10 videos streamed. For our encoding there exist 6 different frame quality levels

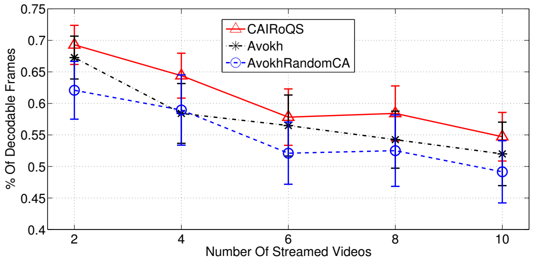

Figure 3: Percentage of Received decodable frames

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[2] http://ultravideo.cs.tut.fi

[3] https://cs-nsl-wiki.cs.surrey.sfu.ca

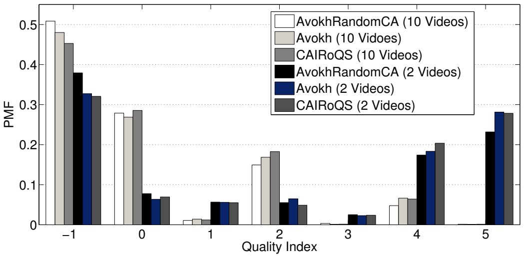

Figure 4: Histogram for The Quality Indices of The Received Frames

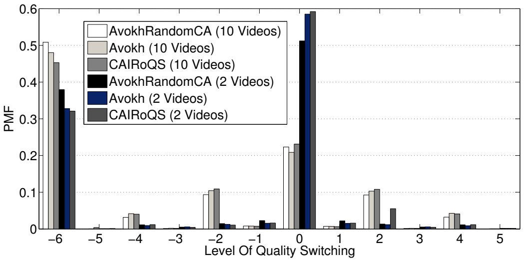

Figure 5: pmf of Levels of Quality Switching of The Received Frames

(3 resolutions x 2 qualities/resolution). A quality index of -1 means that the frame is undecodable. The figure shows that the quality index of the received frames drops as the number of the streamed videos increases. Note that as the number of videos increases, the video quality adaptation components starts to reduce the quality of streamed videos. Another factor that contributes to the quality drop is the increase of the packet drop ratio. However, our proposed solution CAIRoQS remains superior to the other schemes.

In Fig. 5, we plot the probability mass function (pmf) of the level of quality switching between consecutive frames, for both scenarios of streaming 2 and 10 videos. A level switch of -6 means a frame has been lost, due to collision or inability of decoding. A level switch of x means that the difference between the quality indices of two consecutive frames is equal to x. The figure shows that few switches are encountered for lightly loaded networks in comparison to the case of heavily loaded networks. Our proposed scheme CAIRoQS is still superior to the other schemes.

7. CONCLUSION

In this paper, the problem of the multicast transmission of multiple scalable videos over multi-channel multi-radio WMNs over a contention-based MAC is shown to be NP-hard. Hence, a three-stage heuristic framework solution CAIRoQS is proposed to perform channel assignment, traffic adaptation, and multicast routing. The performance is tested using NS2 simulations with real video traces. The proposed framework shows a noticeable improvement for both network and application layer performance metrics in comparison to state of the art solutions from the literature.

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