# Error Resilient Concurrent Video Streaming Over Wireless Mesh Networks

Danjue Li* Qian Zhang† Chen-Nee Chuah* S. J. Ben Yoo *

ECE Department, University of California, Davis*
CS Department, Hong Kong University of Science and Technology †
Email: djli, chuah, yoo@ece.ucdavis.edu* qianzh@cs.ust.hk†

***Abstract*— In this paper, we propose a multi-source multi-path video streaming system for supporting high quality concurrent Video-on-Demand (VoD) services over Wireless Mesh Networks (WMNs), and leverage forward error correction to enhance the error resilience of the system. By taking wireless interference into consideration, we present a more realistic networking model to capture the characteristics of WMNs. We then design a route selection scheme using a joint rate/interference-distortion optimization framework to help the system optimally select concurrent streaming paths. We mathematically formulate such a route selection problem, and solve it heuristically using the genetic algorithm. Simulation results demonstrate the effectiveness of our proposed scheme.**

## I. Introduction

Wireless mesh networks (WMNs) are ad-hoc networks with full or partial mesh topologies, where nodes can automatically establish and maintain mesh connectivity among themselves. Such a mesh topology provides each node multiple communication paths to reach its peers. In the presence of link failures caused by, for example, node failures or interference, information can be rerouted through alternative paths to the destination. Meanwhile, WMNs have no fixed infrastructure and are easily deployed. All these features make WMNs an appealing solution to enable new applications and provide untethered broadband connections in home, neighborhood, and community-wide networks. In this paper, we will mainly focus on WMNs deployed inside residential areas and target providing high-quality concurrent Video-on-Demand (VoD) service to various clients over WMNs.

In achieving this goal, there are a number of challenges. In a typical residential WMN, most nodes have little mobility and are not power limited. Hence, the focus of the proposed streaming system design is improving the streaming performance instead of coping with mobility or improving power-efficiency. One of the main problems here is the reduction in total capacity due to the interference between multiple simultaneous transmissions. This is exacerbated by the fact that video transport typically has stringent delay requirements and is bandwidth intensive. However, it is difficult to maintain an end-to-end route with stable bandwidth and bounded delay in WMNs due to MAC layer contention. Although video transport can tolerate certain degrees of packet loss, it is more probable that WMNs exceed this because of the multiple wireless hops each packet makes.

However, not all the news is bad. There are also some features of WMNs and streaming applications that can help us to deal with the above challenges. The first is the mesh connectivity of WMN nodes. Having multiple paths between any pair of WMN nodes makes it possible to support multi-path transport [1], which has been shown to be an efficient way to improve video streaming quality over ad-hoc networks [2]. Meanwhile, we also notice that, due to reduced computer memory and storage prices, there is an increasing tendency that clients will not delete previously viewed video contents right way. Instead, they will save it for a while for future review, which means that a video file might have multiple replicas on different clients across the WMN. Consequently, to get a video file, now the requesting client will have multiple sources from which to choose. In our previous work, thorough simulation showed that such multi-source diversity can help improve the quality of wireless VoD services [3]. In addition, forward error correction (FEC) has been widely used to improve video streaming quality over the error-prone channels. Based on those observations, we propose to combine multi-source, multi-path diversity and FEC to design an error resilient concurrent video streaming system.

There has been considerable research [2], [4], [5], [6] on multi-path video streaming, however, most of them consider a wired network at the physical layer. Although Mao et. al [6] consider ad-hoc scenarios, they oversimplify the wireless network model by not taking wireless interference into account and do not jointly consider multi-path diversity and multi-source diversity. In addition, few of these works use the rate-distortion optimization framework, which can successfully improve the streaming quality under constrained network resources [3]. Here, we integrate an interference model into our design and rely on the rate/interference-distortion optimization framework to design a route selection scheme for choosing the optimal source/path for each of our concurrent streaming sessions.

Toward this goal, we make the following contributions. First, we leverage both multi-path multi-source diversity and forward error correction (FEC) to design an error-resilient video streaming system for supporting high quality concurrent VoD service over WMNs. In the proposed system, multiple wireless clients can simultaneously stream from multiple senders using different paths. Second, we jointly take the media source characteristics, underlying WMN conditions (e.g. bandwidth, packet loss rate, delay, jitter, and interference), WMN connectivities, and applications requirements into consideration, and develop a more realistic analytical model for multi-source streaming over multiple paths. Third, based on the analytical model, we formulate an interference-aware route selection problem for the proposed streaming system using a joint rate/interference-distortion optimization framework and select the optimal sets of paths by solving this problem heuristically with a genetic algorithm(GA). The simulation results show that the proposed error resilient multi-source multi-path streaming schemes can provide better video quality than those without error resilience and/or multi-source multi-path diversity. Meanwhile, the simulation results using the interference-aware route selection scheme demonstrate the performance improvements over those using an interference-blind route selection scheme.

The rest of this paper is organized as follows: In Section II, we present some related works. In Section III, we will introduce the proposed video streaming system for providing concurrent VoD services over WMN, and in Section IV, we will define models, including source model, network model and request model, for analyzing such a streaming system. Based on those, we formulate the interference-aware route selection problem as a joint rate/interference-distortion minimization problem and present its solution in Section V. In Section VI, we show our simulation results to compare our proposed path selection and other existing schemes, and in Section VII we conclude and discuss future work.

## II. Related Work

There have been many previous works related to ours. Begen et al. [7] also considered multiple description video streaming but they focused on streaming different descriptions from a single sender using different paths, and considered the Internet as the underlying network support. Mao et al. [2] designed a video streaming scheme over ad-hoc networks by leveraging multi-stream coding and multi-path transport but they did not formulate the path selection scheme using the rate-distortion optimization framework. Such an approach made the scheme less adaptive to network status. Moreover, they only considered one single streaming session at a time. Xu et al. [4] proposed a peer-driven video streaming network, where peers could act both as clients and servers at the same time. They encoded each video into multiple sub-streams and placed each sub-stream on a different server. Each client could stream different sub-streams from different senders (server/peers) simultaneously. Taking a different approach, Setton et. al [5] adopted a cross-layer approach to design a congestion-optimized scheduling scheme for video streaming over wireless ad-hoc networks. However, this work did not consider path diversity. The most closely related work is by Mao et al. [6]. In the work, the authors studied the problem of supporting multiple concurrent video communication sessions in ad-hoc network. They formulated the problem as an application-centric network-wide optimal routing problem and aimed at minimizing the average distortion for all video sessions. However, they overlooked one important characteristics of wireless networks, interference, which results in a less practical network model. In contrast, we integrate interference into our network model and formulate a rate/interference-distortion optimization route selection problem by jointly considering rate constraint, route loop-free constraints and interference constraints. Meanwhile, we also use FEC to further enhance the streaming quality.

## III. Error Resilient Multi-source Multi-path Video Streaming System over WMN

Figure 1 illustrates a residential WMN scenario that we consider in our design. Unlike current IEEE802.11x WLANS, where clients are interconnected by a single wireless router, here they are interconnected to each other via multiple wireless routers, creating a mesh connectivity among them. The methodologies to support bandwidth-intensive video streaming applications over such a network vary depending on client requests. If multiple clients are interested in the same video file at nearly the same time, multicasting can be leveraged to save bandwidth while maintaining satisfying video quality [8]. However, if clients are interested in various video files or their requests do not come closely enough in the time, building up multiple multicasting trees will not be cost-efficient. In this case, we would like to leverage the existing multi-path characteristics of WMNs and a hybrid server/P2P video streaming service model to find the best video source location/path(s) to concurrently stream video content to various clients. To achieve this goal, we propose an error resilient multi-source multi-path video streaming system as shown in Figure 2. We have made the following assumptions about the WMNs. These assumptions are not necessary for the correct operation of the proposed system and the route selection algorithm we will propose later in this paper.

- All WMN nodes in the system are stationary.
- All WMN nodes wishing to use the streaming system are willing to fully participate in streaming as content providers, and forwarding packets for other nodes in the system.
- Each WMN node has storage space to save local copies of previously viewed/forwarded video files for further distribution to other WMN nodes. Once they choose to save a local copy, they always keep the complete description instead of some segments of a video file.
- Each WMN has the same wireless network interface card (WNIC), which can be an IEEE802.11, 11a, b, or g radio.
- The media server itself is a WMN node, whose IP address is known to all clients.
- Since we are mainly concerned with concurrent streaming requests that cannot be handled by multicasting, streaming requests in this paper refers to requests for different video files.

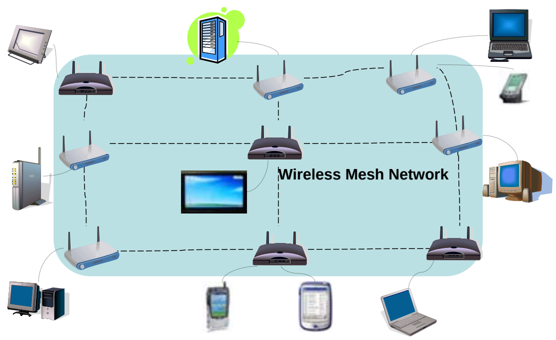


Fig. 1. A Wireless Mesh Community Network

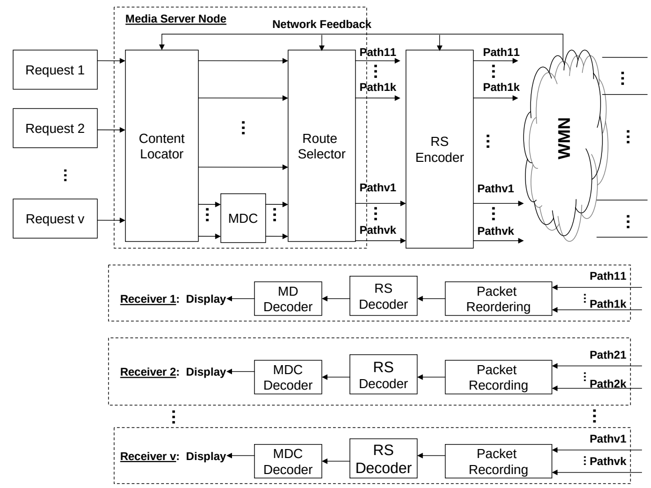


Fig. 2. System Architecture of the proposed error resilient concurrent video streaming over wireless mesh networks using multi-source multi-path transport

In the proposed architecture, the status of each WMN link will be periodically collected by the media server using link state quality announcements [9]. Meanwhile, the server will gather the location information for all video clips available on various clients and save them using a distributed hash table (DHT). To start video streaming, WMN nodes first send requests to the media server. Upon receiving new requests, the media server sets up a sliding window to group incoming requests. All streaming requests arriving within the same window will be treated as concurrent requests. To serve a set of concurrent streaming requests, denoted by $V$, the media server will then search to locate $k$ different descriptions for each of the requested video files among WMN nodes. For a request, if there do not exist all $k$ descriptions, the media server generates missing descriptions for it using multiple description coding (MDC). Based on the content locating results and collected path QoS parameters, the route selector will decide: i) from where each description of the requested video file can be fetched, and ii) what is the optimal path to stream it to the corresponding receiver. The group of senders can include the media server itself or other nodes in the WMN. If WMN nodes other than the media server are chosen to be senders, the media server will redirect corresponding requests to those nodes and piggyback the information of selected routes. Each sender then applies packet-wise Reed-Solomon (RS) codes across video packets and streams them to the receiver using source routing over the selected route. At a receiver, packets arriving from different paths are put into a reordering buffer where they are reassembled into different descriptions after a preset playout delay. A RS decoder will then be applied to each description and process it to remove the redundant information and recover lost packets. Finally, an MDC decoder will attempt to reconstruct a video sequence from the $k$ RS-decoded descriptions.

A key to the success of the proposed system is how to utilize gathered network status information at the application layer to help the media server locate the content and make decisions on where and how to stream requested video files to various receivers. In the rest of this section, we will discuss some related design issues in more details.

## A. *Multiple description coding*

Multiple description coding is a source coding technique that generates multiple, equally important bitstreams, called descriptions, for a single video file. Different levels of reconstructed video qualities can be achieved by successfully decoding different subsets of descriptions. The advantage of doing this is that descriptions can be streamed to a receiver using disjoint streaming paths, which can potentially increase the resilience to packet loss. Unlike scalable coding, there is no interdependency among MDC descriptions, and each description can be independently decoded. Successfully decoding more descriptions results in better video quality. These features make MDC appealing for use in the design of a concurrent video streaming system.

In this work, we only use 2 descriptions, i.e. $M = 2$, instead of larger number due to the fact that generating more than two descriptions increases the overhead of MDC and the performance gain is usually insufficient to justify this overhead [1]. There are different ways to generate multiple descriptions [10]. In this paper, we will use time-domain partitioning, i.e. use a standard video codec to generate one bitstream and then split it into two independent descriptions by sending all odd frames over one path and all even frames over the other path in an alternative fashion.

### B. Monitoring WMN status

The quality of WMN links vary over time due to channel fading, interference, and congestion. Monitoring and updating link quality information is critical for providing satisfying video quality. To accomplish this, we leverage some of the components proposed in link quality source routing (LQSR) [9] for discovering neighbors of a node, measuring the link quality between a node and its neighbors, and propagating this information to other nodes in the WMN. Meanwhile, we also make some modifications to LQSR to support multipath routing. In LQSR, as in its parent protocol DSR [11], each node only uses the first route although multiple routes might exist in its route cache. In our modified version, packets are routed according to their flow identifier, which is jointly decided by video file name and description identifier. We also require that any packet in the send queue on a WMN with an estimated delivery time later than the predefined playout deadline be dropped. Finally, all the link quality information will be collected by the media server. The media sever will then jointly consider link quality and its impact on application layer performance to select several paths simultaneously.

## IV. MODELING

In this section, we model the proposed video streaming system. We start by introducing the source model and then add details on modeling the wireless mesh networks including loss, delay and interference.

### A. Source model

We assume there exists a set of concurrent video streaming sessions, denoted as $\boldsymbol{V}$. For the video clip $v$ ($v \in V$) in each session, $M$ equally important descriptions will be generated using multiple description coding (MDC). Let $d_m$ ($m \in \{1,2\}$) be the perceived distortion when only the $m^{th}$ description is successfully received, $d_0$ be the distortion when both descriptions successfully arrive in the receiver, and $\sigma^2$ be the distortion when both descriptions do not successfully arrive in the receiver. Let $b_v^m$ ($m \in \{1,2\}$) be the rate of the $m^{th}$ description for video clip $v$, defined in terms of the number of bits per pixel (bpp) on the $m^{th}$ channel. Given that $R_v^m$ is the data rate of the $m^{th}$ description, which is encoded at a frame rate of $F_v$ (frames/second) and a resolution of $W \cdot H$ (pixels/frame), we have $b_v^m = \frac{R_v^m}{W \cdot H \cdot F \cdot C}$, where $C$ is a known constant decided by the chroma subsampling format. Therefore, the average distortion perceived by the receiver can be computed as [12]:

$$D_v = q_v^1 q_v^2 d_0 + q_v^1(1-q_v^2)d_1 + (1-q_v^1)q_v^2 d_2 + (1-q_v^1)(1-q_v^2)\sigma^2 \quad (1)$$

$$d_0 = \frac{2^{-\alpha(b_v^1+b_v^2)}}{2^{-\alpha b_v^1} + 2^{-\alpha b_v^2} - 2^{-\alpha(b_v^1+b_v^2)}} \cdot \sigma^2 \quad (2)$$

$$d_1 = 2^{-\alpha b_v^1} \cdot \sigma^2 \quad (3)$$

$$d_2 = 2^{-\alpha b_v^2} \cdot \sigma^2 \quad (4)$$

where, $\sigma^2$ is equal to the variance of the source and $\alpha$ is decided by the video codec. Here, $q_v^m$ is the probability of successfully receiving the $m^{th}$ description of video clip $v$, which will be jointly decided by the packet loss rate and delay distribution associated with the corresponding path.

### B. Network model

Consider a WMN with $N$ nodes arbitrarily distributed on a plane with $c_{ij}$ as the distance between two nodes $i$ and $j$. Each wireless mesh node is equipped with a radio having communication range $r_i$ and interference range $r'_i$ ($r'_i > r_i$). A communication link exists between two nodes if they are within the transmission range of each other, and as a result the number of links is $L$. We model such a WMN using a time-varying directed graph ***G = G (N, L)***, where ***N*** is the set of vertices, representing nodes in the WMN, and ***L*** is the set of directional edges (i.e. $\{ij\} \neq \{ji\}$), representing wireless links between nodes. A direct link $\{ij\}$ exists from node $i$ to node $j$ if $c_{ij} \le r_{ij}$ and $i \neq j$. We characterize link $\{ij\} \in \boldsymbol{L}$ using: i) $R_{ij}$: the capacity of link $\{ij\}$, ii) $t_{ij}$: the delay of link $\{ij\}$, and iii) $p_{ij}$: the packet loss of link $\{ij\}$. Here, we assume that there is only one wireless channel associated with each node. Let the path for delivering the $m^{th}$ description of video clip $v$ be $L_v^m$ , which includes a set of link $\{ij\}$. For each link $\{ij\}$ we define an index variable:

$$X_{ij}^{v,m} = \begin{cases} 1 & \{ij\} \in L_v^m \\ 0 & \{ij\} \notin L_v^m \end{cases}, \forall \{ij\} \in \boldsymbol{L}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (5)$$

*1) End-to-end packet loss rate and delay:* Let the bit error rate on link $\{ij\}$ be $e_{ij}$, and the maximum allowable packet size on each link is identically set to be $S$. The end-to-end packet loss rate associated with path $L_v^m$ can be defined as:

$$p_v^m = 1 - \prod_{\{ij\} \in \boldsymbol{L}} (1 - X_{ij}^{v,m} p_{ij}), \forall v \in \boldsymbol{V}, \forall m \in \{1,2\}. \quad (6)$$

where $p_{ij} = 1 - (1 - e_{ij})^S$ is the packet loss on link $\{ij\}$. To model the delay, we do not assume any particular density function. However, for the sake of simulation design, we model the delay $t_{ij}$ on link $\{ij\}$ using an exponential distribution with the probability density function (PDF) $f_{t_{ij}}(x) \sim \lambda_{ij} e^{-\lambda_{ij} x}, \forall \{ij\} \in \boldsymbol{L}$, where $\lambda_{ij}$ is jointly decided by the link capacity and the traffic load on $\{ij\}$. As a result, the end-to-end delay for path $L_v^m$ can be defined as:

$$T_v^m = \sum_{\{ij\} \in \boldsymbol{L}} X_{ij}^{v,m} t_{ij}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\}, \quad (7)$$

By assuming that the delay on each link is independent of each other, when the number of hops in a streaming path is large enough, the distribution of $T_v^m$ can be well approximated using Gaussian distribution, i.e. $T_v^m \sim N(E(T_v^m), Var(T_v^m))$. Therefore, the probability that the packet streamed over path $L_v^m$ has delivery delay longer than $\Delta_v^m$ can be expressed as:

$$P(T_v^m > \Delta_v^m) = \frac{1}{2}(1 - erf\frac{\Delta_v^m - E(T_v^m)}{\sqrt{2 \cdot Var(T_v^m)}}) \tag{8}$$

where $erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$. $E(T_v^m) = \sum_{\{ij\} \in \boldsymbol{L}} \frac{X_{ij}^{v,m}}{\lambda_{ij}}$ and $Var(T_v^m) = \Sigma_{\{ij\} \in \boldsymbol{L}} \frac{X_{ij}^{v,m}}{\lambda_{ij}^2}$.

When the number of hops along $L_v^m$ is not large enough, we will use the moment generating function (MGF) to find a solution. Based on (7) and the PDF of $t_{ij}$, we find the MGF of $T_v^m$ as:

$$g_{T_v^m}(s) = \prod_{\{ij\} \in \boldsymbol{L}} g_{t_{ij}}(X_{ij}^{v,m} s) = \prod_{\{ij\} \in \boldsymbol{L}} \frac{\lambda_{ij}}{\lambda_{ij} - X_{ij}^{v,m} s}. \tag{9}$$

If we assume that in the wireless mesh network there are no two identical wireless links, i.e. $\lambda_{ij} \neq \lambda_{mn}$ ($\{ij\} \neq \{mn\}, (\forall \{ij\}, \{mn\} \in \boldsymbol{L}$), then (9) can be expanded as:

$$g_{T_v^m}(s) = \sum_{\{ij\} \in L_v^m} \frac{\{(\lambda_{ij} - X_{ij}^{v,m} s) g_{T_v^m}(s)\} \big|_{s=\lambda_{ij}}}{\lambda_{ij} - X_{ij}^{v,m} s} \tag{10}$$

Therefore, the PDF of $T_v^m$ can be computed as:

$$f_{T_v^m}(x) = \sum_{\{ij\} \in L_v^m} \{(\lambda_{ij} - X_{ij}^{v,m} s) g_{T_v^m}(s)\} \big|_{s=\lambda_{ij}} \cdot X_{ij}^{v,m} \cdot e^{-\lambda_{ij} x} \tag{11}$$

Using (11), we can get $P(T_v^m > \Delta_v^m)$ when the number of hops on the path is small, as:

$$\begin{aligned} P(T_v^m > \Delta_v^m) &= \int_{\Delta_v^m}^{\infty} f_{T_v^m}(x) dx \\ &= \sum_{\{ij\} \in L_v^m} \{(\lambda_{ij} - X_{ij}^{v,m} s) g_{T_v^m}(s)\} \big|_{s=\lambda_{ij}} \frac{X_{ij}^{v,m}}{\lambda_{ij}} \cdot e^{-\lambda_{ij} \Delta_v^m} \end{aligned} \tag{12}$$

*2) Error Protection Using Forward Error Correction:* Each packet in the $m^{th}$ description of the video file $v$ is protected by packet-wise forward error correction based on Reed-Solomon (RS) codes, where the codewords are formed across $k_v^m$ information packets and $n_v^m - k_v^m$ redundancy packets. The receiver can successfully reconstruct the packet if $k_v^m$ or more of the $n_v^m$ packets have been received. If we choose $n_v^m$ to be a fixed number $n$, $k_v^m$ will determine the protection level of the $m^{th}$ description of video file $v$. The higher $k_v^m$ is, the less protection we add. Here, we choose $k_v^m$ based on the end-to-end packet loss rate $p_v^m$ on the delivery path $L_v^m$. If $p_v^m$ is high, we need heavy protection, and as a result we will choose smaller $k_v^m$, and vice versa. For a frame delivered over path $L_v^m$, when an $(n, k_v^m)$ RS code is implemented, the probability of successfully receiving this frame will be:

$$q(n, k_v^m, p_v^m) = \sum_{i=k_v^m}^{n} (1 - p_v^m)^i \cdot (p_v^m)^{(n-i)} \tag{13}$$

Given (8), (12) and (13), we can get the probability that the $m^{th}$ description of video clip $v$ can be successfully delivered to the client before its deadline $\Delta_v^m$:

$$q_v^m = q(n, k_v^m, p_v^m) \cdot (1 - P(T_v^m > \Delta_v^m)). \tag{14}$$

*3) Interference model:* Unlike wired networks, neighboring nodes in WMNs suffer from interference. There are different ways to model the interference in a multi-hop WMN, and in this work we use the protocol model proposed by Jain et. al [13]. This protocol model is mainly concerned with the interference requirement on the receiver side. For a single wireless channel, node $i$ can successfully finish a transmission to node $j$ only if it can satisfy both of the following requirements: i) $d_{ij} \leq r_i$; ii) any node $n_k$, which satisfies $d_{kj} \leq R'_k$, does not transmit when node $i$ is transmitting. In this paper, we assume that the interference range is equal to the communication rage. Based on this model, we define a conflict graph, ***C***, with vertices corresponding to the links in the connectivity graph ***G***, i.e. the vertex set is identical to ***L***. For two vertices, link $\{ij\}$ and link $\{mn\}$, if they cannot transmit simultaneously, there is an edge to connect them. Otherwise, there is no direct connection between them. Using the protocol model, we draw an edge between $\{ij\}$ and $\{mn\}$ when $d_{in} \leq r'_i$ or $d_{mj} \leq r'_m$. Given the conflict graph ***C*** and the vertex set ***L***, we define a conflict vector to characterize the interference between a give link $\{ij\}$ and other links in L. If, in the conflict graph ***C***, there is an edge existing between the given link $\{ij\}$ and a link $\{mn\}(\{mn\} \in \boldsymbol{L}, \{mn\} \neq \{ij\})$, then we will have $C_{\{ij\},\{mn\}} = 1$. Otherwise, it is set to be zero. For each link we can get a similar conflict vector. The final result is an $\|L\| \times \|L\|$ conflict matrix.

## V. INTERFERENCE AWARE ROUTE SELECTION

Following the discussion in Section III, we see that the key issues are how to choose the optimal source node and streaming path for each streaming request based on current network status. Here, we treat the source selection as the initial step of path selection and integrate it into the route path selection problem. Building upon the models defined in the previous section, we will mathematically formulate such a route selection problem and present its solution.

There are several issues we have to consider during the problem formulation. First, all the concurrent streaming sessions will co-exist in the system and compete for wireless bandwidth resources, and as a result, they will affect each others' performance. Here, streaming performance refers to the distortion perceived by a receiver. Instead of focusing on optimizing the performance of a single receiver, we evaluate the system-level performance and focus on optimizing the overall performance for all concurrent streaming sessions. In this way, we can take the interdependency of concurrent streaming traffics into consideration and fairly allocate the network resource among them. Second, each link has limited bandwidth available for supporting streaming service. Overloading the link will cause network congestion and degrade the system performance. Therefore, when selecting paths for each streaming session and allocating bandwidth among them, we have to guarantee the aggregated traffic on each selected link will not exceed its available bandwidth. Moreover, when selecting nodes to build up the path, there is a probability of creating routing loops in the path selection. As shown by Iannaconne et al. [14], routing loop can locally trap the traffic, introduce redundant traffic and increase the end-to-end delay, which is harmful for real-time applications such as video streaming. Thus it is critical to satisfy the loop free constraints in order to efficiently use network resources, and reduce the end-to-end delay. Third, as we have mentioned in previous discussions, the wireless interference can adversely affect the performance of multi-source multi-path diversity due to the fact that conflicting links cannot be used simultaneously. We can formulate the optimal route selection problem as: given a WMN ***G(N, L)*** and a set of MDC-encoded video clips (each with multiple replicas across the WMN), for ***V*** streaming requests, find a set of optimal paths so that the aggregate distortion of ***V*** concurrent video sessions is minimized while satisfying all the wireless constraints. Before presenting the mathematical formulation of the route selection problem, we would like to define some variables first. In the following discussion, we define $L_v^{m(i)}$ as the sub-path which includes all the links along the path $L_v^m$ up to the link $\{ij\}$, and $\overline{L_v^{m(i)}}$ as the complementary set, i.e. $\overline{L_v^{m(i)}} = L_v^m - L_v^{m(i)}$. Let node $\delta_v$ be the node which requests video clip $v$. Therefore, the total traffic on link $\{ij\}$, $\rho_{ij}$, will be:

$$\rho_{ij} = \sum_{v \in \boldsymbol{V}} \sum_{m \in \{1,2\}} \prod_{\{mn\} \in L_v^{m(i)}} \{(1 - p_{kn}) X_{kn}^{v,m}\} \cdot R_v^m, \forall \{ij\} \in \boldsymbol{L} \quad (15)$$

Using (1), (14) and (15), this route selection problem can be mathematically formulated as:

- Minimize:

$$\sum_{v \in \boldsymbol{V}} D_v \quad (16)$$

- Subject to:

$$\rho_{ij} \leq R_{ij}, \forall \{ij\} \in \boldsymbol{L} \quad (17)$$

$$\sum_{j:\{ij\} \in L_v^m} X_{ij}^{v,m} - \sum_{j:\{ij\} \in L_v^m} X_{ji}^{v,m} = \begin{cases} 1, & if\ i : L_v^{m(i)} = \Phi \\ -1, & if\ i = \delta_v, \\ 0, & if\ otherwise \end{cases},$$
$$\forall i \in \boldsymbol{N}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (18)$$

$$\sum_{j:\{ij\} \in L_v^m} X_{ij}^{v,m} \begin{cases} 0, & i : i \in L_v^m, L_v^{m(i)} = \Phi \\ \leq 1, & otherwise \end{cases},$$
$$\forall i \in \boldsymbol{N}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (19)$$

$$\sum_{j:\{ji\} \in L_v^m} X_{ij}^{v,m} \begin{cases} 0, & i = \delta_v \\ \leq 1, & otherwise \end{cases},$$
$$\forall i \in \boldsymbol{N}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (20)$$

$$X_{ij}^{v,m} \in \{0,1\}, \forall \{ij\} \in \boldsymbol{L}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (21)$$

$$\frac{\rho_{ij}}{R_{ij}} + \sum_{m,n:C_{\{ij\},\{mn\}}=1} \frac{\rho_{mn}}{R_{mn}} \leq 1, \forall \{ij\} \in \boldsymbol{L} \quad (22)$$

where $D_v$ is the average distortion of received video clip $v$ at the receiver node $\delta_v$. (17) shows the rate constraint to satisfy. (18), (19), and (20) guarantee that each path $L_v^m$ provides a loop-free end-to-end connection. (22) guarantees that links in selected concurrent paths will not interfere with each other and cause system performance degradation.

The distortion minimized route selection problem defined by (16)-(22) can be treated as a joint optimization of several single-streaming session route selection problems. Wang et al. [15] showed that each of these problems is already NP-complete. Therefore, we expect the joint optimization defined by (16)-(22) is also NP-complete. In this paper, we solve this joint optimization problem heuristically using a genetic algorithm (GA) [16]. GA is a method for solving both constrained and unconstrained optimization problems that is based on natural selection. It is a type of machine learning algorithms. It employs chromosomes (also called individuals) in a population to stand for the possible solutions to the problem. As time evolves, these chromosomes are given different chances to reproduce according to their fitness. During reproduction, one chromosome will probably mutate, or two chromosomes can crossover. After many generations, one expects the optimum chromosomes or solutions emerge from the population [17].

## VI. Performance Evaluation

To evaluate our proposed streaming system and the route selection scheme, we have conducted several sets of simulations. Through simulations, we demonstrate how interference awareness and multi-source multi-path streaming can help to improve system performance.

### *A. Simulation methodology*

We simulate an IEEE802.11-based WMN by randomly placing 12 wireless nodes in a $200m \times 200m$ square region as shown in Figure 3. To do that, we first divide the area into a 3x4 even grid, and then randomly choose a position in each block to place a node. For each WMN node, we set the transmission range $r_i$ to be $85m$, and its interference range $r_i'$ to $100m$. Two wireless links exist between a pair of nodes if they are within the transmission range of each other. At this point, we assume there is no node mobility. The media server node and concurrent receiver nodes are randomly chosen from 12 WMN nodes. In our simulations, we consider three concurrent streaming sessions. For each wireless link, its bit error rate $e_i$ is randomly selected from $[10^{-5}, 10^{-6}]$ with a uniform distribution, and the average RTP packet size is set to be 1000bytes. The data rate of each WNIC is chosen to be $11Mbps$.

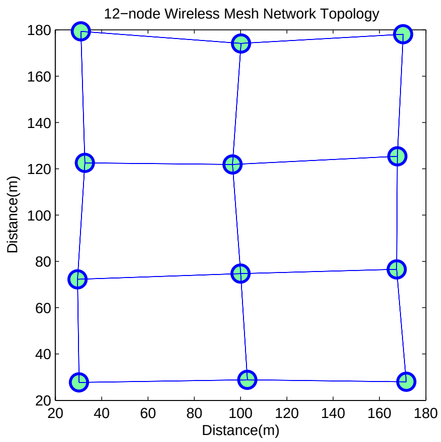


Fig. 3. A wireless mesh network consisting of 12 WMN nodes

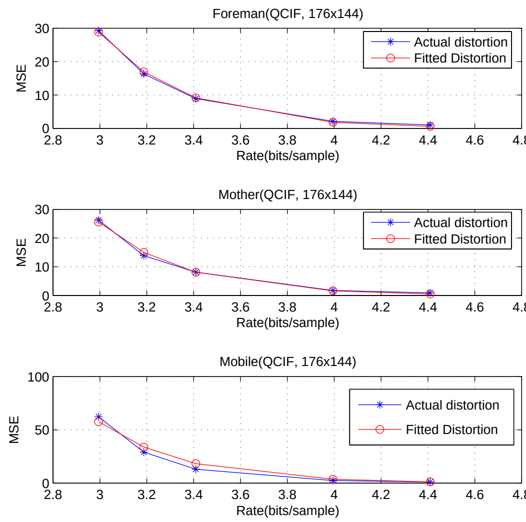


Fig. 4. Fitting rate-distortion model: (a) *Foreman*, $\sigma$=170.5; (b)*Mother*, $\sigma$=113.5; (b)*Mobile*, $\sigma$=113.5

We use three standard QCIF video sequences *Foreman*(176×144), *Mother*(176×144) and *Mobile*(176×144) in our simulations, and they are requested by three randomly selected WMN nodes simultaneously with a delivery delay tolerance of 150ms. Each sequence is composed of 300 frames, and we repeat each clip several times to generate a longer sequence. For each sequence, we will use $H.264$ codec (version JM8.4) [18] to generate single description(SD) encoded and multiple description (MD) encoded streams, respectively. We choose the quantization step-size to be 24 for *Foreman* sequence, 20 for *Mother* sequence, and 32 for *Mobile* sequence. First however, we would like to verify the efficacy of the source model introduced in Section IV first. To generate SD encoded streams using the $H.264$ codec, we encode each sequence into one 264-format RTP stream with a frame rate $30fps$ and a GOP structure consisting of one I-frame and four P-frames. For generating MD encoded streams, we first divide the sequence into two subsequences in an alternative fashion, i.e. all the even frames in one subsequence and all the odd ones in the other, and then for each subsequence we encode it into one description.Then we use equation (1) to estimate $d_0$, $d_1$ and $d_2$ using corresponding bit-per-sample rate. Due to space limitations, here we only show the fitting results for $d_0$. For $d_1$ and $d_2$, we have the similar findings. Figure 4 shows the rate-distortion curves produced by the H.264 encoder and the fitted values based on (1) ($\alpha = 2$). From this figure, we can see that the source model we have defined is a valid estimation of the MDC distortion.

The above encoding process can be done offline and encoded streams will be randomly distributed among WMN nodes during the simulation setup phrase. Since error concealment scheme design is not the focus of this work, we will adopt very simple error concealment method, that is, replacing the missing slices with corresponding ones in the previous successfully decoded frame. To enhance the error resilience, we choose different levels of FEC protection based on the estimated end-to-end packet loss ratio. Here, we consider two levels of FEC for each SD and MD encoded stream, one for heavy loss scenario and the other for light loss scenario. The parameters for SD and MD encoded streams with different FEC level are shown in Table I, where a entry with *NULL* description ID refers to a SD encoded stream.

| File(Desc. ID) | Data Rate* | RS code | Total Rate* |
|---|---|---|---|
| Foreman(1) | 237.38 | (15,11), (15,13) | 327.7, 273.9 |
| Foreman(2) | 237.92 | (15,11), (15,13) | 324.4, 274.5 |
| Foreman(NULL) | 403.7 | (15,11), (15,13) | 550.5, 465.8 |
| Mother(1) | 244.1 | (24,12), (24,20) | 478.4, 292.89 |
| Mother(2) | 243.9 | (24,12), (24,20) | 478.2, 292.8 |
| Mother(NULL) | 448.1 | (24,12), (24,20) | 896.20, 537.72 |
| Mobile(1) | 239.6 | (18,15), (18,17) | 331.7, 276.80 |
| Mobile(2) | 239.9 | (18,15), (18,17) | 332.2, 276.8 |
| Mobile(NULL) | 459.5 | (18,15), (18,17) | 551.40, 486.53 |

TABLE I

SD AND MD ENCODED VIDEO FILES WITH FEC(*: $kbps$)

In the GA, we encode each feasible solution, i.e. paths for all concurrent streams, as a set of chromosomes, with each chromosome corresponding to a path between a sender and receiver pair. We choose the fitness function as the inverse of the overall distortion, and use the spinning roulette wheel method to select next generation candidates. We set the population size to be 500, mutate rate to be 0.1 and the crossover rate to be 0.85. The GA program will terminate after evolving for 50 generations.

### *B. Simulation results and analysis*

The first set of simulations is used to demonstrate how multi-source, multi-path diversity improves the streaming performance. We compare our proposed scheme with a single source single path scheme, and plot the instantaneous PSNR

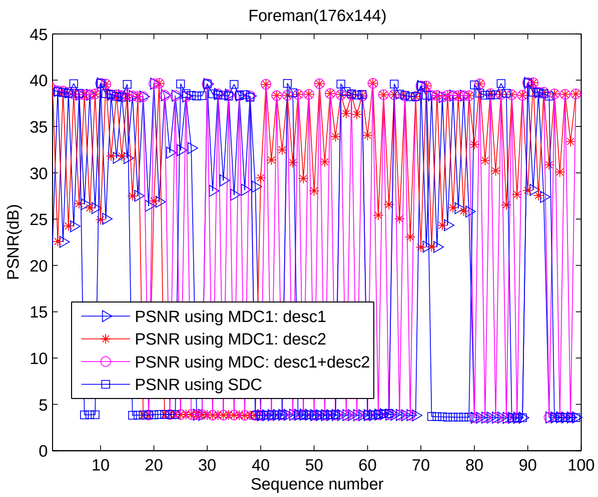


Fig. 5. Instantaneous PSNR (*Foreman(176x144)*)

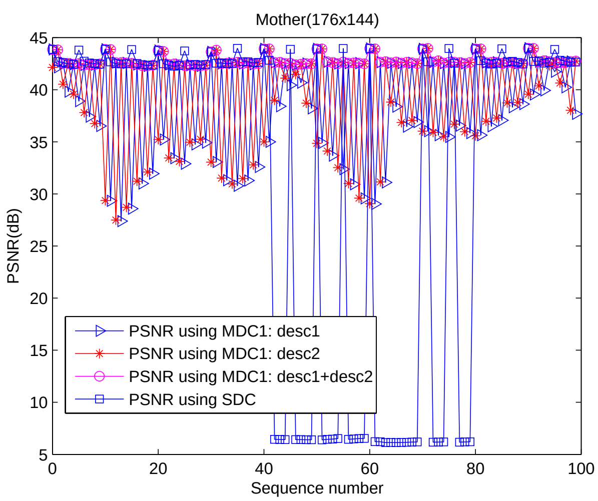


Fig. 6. Instantaneous PSNR (*Mother(176x144)*)

value over time for different streaming schemes. In both Figure 5 and Figure 6, the curve labeled as *SD* is the performance when only single source single path streaming is supported. Curves labeled *MDC: desc1/2* correspond to scenarios, where multi-source multi-path streaming is supported, but only one description is successfully used for decoding. The curve *MDC: desc1+ desc2* shows the performance when both descriptions from multi-source multi-path streaming are used to recover the video sequence. The same notations will be used in later discussions. From Figure 5 and Figure 6, we can see that by leveraging multi-source multi-path diversity, the streaming system can achieve more stable performance. To get statistically stable simulation results, we repeated the experiments to get the average PSNR by first averaging over one simulation run and then across multiple runs. The results of all three concurrent test sequences are shown in Table II, Table III, and

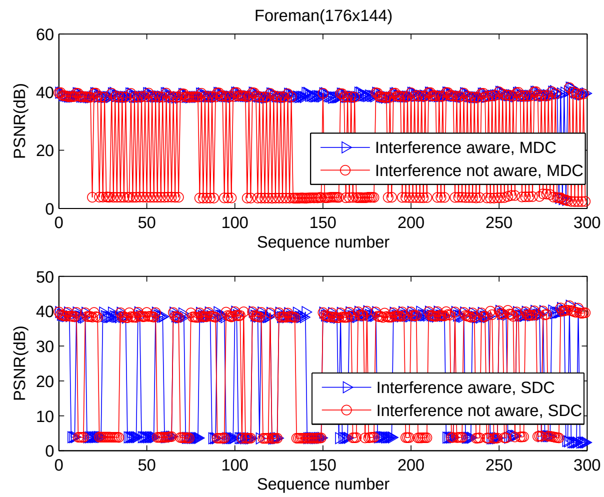


Fig. 7. Evaluation of interference awareness (*Foreman(176x144)*)

| | Int. aware | Int. not aware |
|---|---|---|
| Loss free PSNR(dB) | 38.85 | 38.85 |
| PSNR w/ SD(dB) | 25.92 | 25.15 |
| PSNR w/ MDC: desc1 (dB) | 32.54 | 24.30 |
| PSNR w/ MDC: desc2 (dB) | 33.09 | 15.04 |
| PSNR w/ MDC: desc1+desc2 (dB) | 38.45 | 22.80 |

TABLE II
AVERAGE PSNR(*Foreman(176x144)*)

Table IV, respectively. Again, we can see that multi-source multi-path streaming can provide better performance than single source single path streaming system. By distributing the stream load among WMN nodes, we can compensate for the quality degradation by leveraging source and path diversity to enhance the error resilience.

Another interesting result is how interference awareness affects the system performance. For both multi-source multi-path and single-source single path scenarios, we conduct two different sets of simulations, one with interference awareness and one without. Here, being aware of interference means that when the media server makes the route selection decision, it has to make sure that a set of selected paths will not interfere with each other and cause quality degradation. On the contrary, when the system does not consider interference when making path selections, some nodes on the selected paths may be

| | Int. aware | Int. not aware |
|---|---|---|
| Loss free PSNR(dB) | 42.84 | 42.84 |
| PSNR w/ SD(dB) | 41.91 | 30.633 |
| PSNR w/ MDC: desc1 (dB) | 40.41 | 39.94 |
| PSNR w/ MDC: desc2 (dB) | 40.09 | 39.37 |
| PSNR w/ MDC: desc1+desc2 (dB) | 42.60 | 42.00 |

TABLE III
AVERAGE PSNR(*Mother(176x144)*)

| | Int. aware | Int. not aware |
|---|---|---|
| Loss free PSNR(dB) | 30.01 | 30.01 |
| PSNR w/ SD(dB) | 24.37 | 20.66 |
| PSNR w/ MDC: desc1 (dB) | 22.80 | 19.48 |
| PSNR w/ MDC: desc2 (dB) | 24.80 | 21.01 |
| PSNR w/ MDC: desc1+desc2 (dB) | 26.01 | 22.00 |

TABLE IV
AVERAGE PSNR(*Mobile*)

close enough to interfere each other. When using those nodes to stream information simultaneously, the interference will increase the probability of MAC layer collisions and degrade performance. Whether two links interfere with each other or not can be determined using the conflict graph introduced in Section IV-B.3. Figure 7 compares the PSNR values of a set of 300 frames for the test sequence *foreman* when different streaming methods are used. From Figure 7 we can see that the quality of both single-source single-path and multi-source multi-path schemes will be affected by whether the system is interference aware or not but the latter is affected more. This is due to the fact that strong interference will make some source nodes unable to transmit at the same time and as a result, will decrease the effectiveness of multi-source multi-path diversity. Meanwhile, the performance gain also varies from sequence to sequence. As illustrated by Table II, Table III, and Table IV, video sequences with larger temporal variations, such as *Foreman* and *Mobile*, can benefit more by adding interference awareness to route selection than sequences with less temporal variation, such as *Mother*.

We repeat the above simulation multiple times and get the average PSNR values as shown in Table II, Table III and Table IV. From those tables, we can see that adding the interference awareness to the streaming system can help prevent potential interference-triggered packet loss, and provide better and more stable performance. As a final remark, we observed that FEC is an effective way to provide better error resilience. From the RS code length given out in Table I, we can see that three test sequences will get different FEC level, among which *Mother* sequence gets the highest. This high error protection is reflected by much higher average PSNR values shown in Table III as compared to the qualities of other two sequences.

## VII. CONCLUSION AND FUTURE WORK

In this paper, we leverage multi-source multi-path diversity and forward error correction to design an error resilient concurrent video streaming system for delivering high quality VoD services over wireless mesh networks. By integrating interference into system model, we formulate the route selection problem for the proposed system using a joint rate/interference-distortion optimization framework, and heuristically solve it using a genetic algorithm. Simulation results show that by leveraging multi-source multi-path diversity, the proposed system has better performance than using single-source single path delivery, while adding interference-awareness can also help improving the system performance.

## REFERENCES


[1] J. G. Apostolopoulos, W. Tan, S. J. Wee, and G. W. Wornell, "Modeling path diversity for multiple description video communication," in *IEEE ICASSP*, May 2002.

[2] S. Mao, S. Lin, S. S. Panwar, Y. Wang, and E. Celebi, "Video transport over ad hoc networks: Multistream coding with multipath transport," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 10, December 2003.

[3] D. Li, C-N. Chuah, G. Cheung, and S.J Ben Yoo, "MUVIS: Multi-Source Video Streaming server over wlans," *Journal of Communications and Networks-Special Issue on Toward the Next Generation Mobile Communications*, vol. 7, no. 2, pp. 144–156, June 2005.

[4] X. Xu, Y. Wang, S. P. Panwar, and K. W. Ross, "A peer-to-peer video-on-demand system using multiple description coding and server diversity," in *IEEE ICIP*, Singapore, October 2004.

[5] E. Setton, X. Zhu, and B. Girod, "Congestion-optimized scheduling of video over wireless ad hoc networks," in *IEEE ISCAS*, Kobe, Japan, May 2005.

[6] S. Mao, S. Kompella, Y. T. Hou, H. D. Sherali, and S. F. Midkiff, "Routing for multiple concurrent video sessions in wireless ad hoc networks," in *to appear in IEEE Trans. on Vehicular Technology*, 2005.

[7] A. C. Begen, Y. Altunbasak, O. Eregun, and M. H. Ammar, "Multi-path selection for multiple description video streaming over overlay networks," *EURASIP Signal Processing: Image Communication*, vol. 20(1), January 2005.

[8] P. Chou, A. E. Mohr, A. Wang, and S. Mehrotra, "FEC and pseudo-ARQ for receiver-driven layered multicast of audio and video," in *IEEE Proc. Data Compression Conference*, March 2000.

[9] R. Draves, J. Padhye, and B. Zill, "The architecture of the link quality source routing protocol," Technical Report MSR-TR-2004-57, Microsoft Research, 2004.

[10] Y.C.Lee, Y. Altunbasak, and R. M. Mersereau, "A two-state multiple description video coder with drift-preventing motion compensated prediction," in *IEEE ICIP*, 2002.

[11] D. B. Johnson, D. A. Maltz, Y. C. Hu, and J. G. Jetcheva, "The dynamic source routing protocol for mobile ad hoc networks," http://h-lug.org/ griswold/Drafts-RFCs/draft-ietf-manet-dsr-05.txt, March 2001.

[12] M. Alasti, K. Sayrafian Pour, A. Ephremides, and N. Farvardin, "Multiple description coding in networks with congestion problem," *IEEE Trans. on Information Theory*, vol. 47(3), March 2001.

[13] K. Jain, J. Padhey, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *Proc. of ACM MOBICOM*, San Diego, CA, September 2003.

[14] Gianluca Iannaccone, Chen-Nee Chuah, Richard Mortier, Supratik Bhattacharyya, and Christophe Diot, "Analysis of link failures in an IP backbone," in *Proc. ACM SIGCOMM Internet Measurement Workshop*, November 2002.

[15] Z. Wang and J. Crowcroft, "Quality-of-service routing for supporting multimedia applications," *IEEE Journal on Selected Areas in Communications*, vol. 17(8), pp. 1488–1505, August 1999.

[16] T. Back, D. Fogel, and Z. Michalewicz, *Handbook of Evolutionary Computation*, Oxford University Press, New York, NY, 1997.

[17] Z. Michalewicz, *Genetic algorithms + data structures = evolution programs (3rd revision)*, Springer-Verlag, 1996.

[18] Iain E G Richardson, *H.264 and MPEG-4 Video Compression*, John Wiley & Sons, 2003.