Multi-source Multi-path Video Streaming Over Wireless Mesh Networks

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***Abstract*— In this paper, we propose a multi-source multi-path video streaming system to support concurrent Video-on-Demand (VoD) services over Wireless Mesh Networks (WMNs), and approach the route selection problem for such a system using rate-distortion optimized framework. By taking wireless interference into consideration, we capture the characteristics of wireless networks with a more realistic networking model. Based on that, we mathematically formulate the route selection problem, and solve it heuristically using a genetic algorithm. Simulation results demonstrate the effectiveness of our proposed scheme.**

I. Introduction

Recently, wireless mesh networks (WMN) have emerged as a promising technology to provide ubiquitous and reliable broadband network services. Although current wireless mesh networks are still mainly used for data transmission, the increase in both wireless channel bandwidth and the computing power of mobile devices now makes video streaming service feasible.

To design a suitable scheme for video transport over WMNs, we will first examine some unique qualities of WMNs. In WMNs, the existence of multiple paths between any pair of source and destination nodes makes multi-path transport [1] suitable for VoD services over WMNs. If we also include caching at nodes in the WMN, a video file can have multiple replicas from previous requests. As a result, a newly requesting client now might have multiple sources from which to get this video file. In our previous work, we proved that such multi-source diversity can improve wireless video streaming quality [2]. Based on those observations, now we consider leveraging both multi-source and multi-path diversity in the streaming scheme design. Unlike in conventional wired networks, wireless interference makes simultaneous use of some adjacent links impossible. To decrease the quality degradation caused by interference and maximize the benefit of multi-source diversity, the system should be able to widely distribute the requests across the WMN. Another difficulty is maintaining an end-to-end route with stable bandwidth and bounded delay in multi-hop WMNs.

There have been considerable research in the past literature to deal with the above challenges [3], [4], [5], [6]. However, most of these works consider wired network at the physical layer. Although Mao et. al [6] consider ad-hoc scenarios, they do not consider multi-source diversity and also oversimplify the wireless network model by not considering wireless interference. In addition, few of these works use the rate-distortion optimization framework, which can improve the streaming quality under constrained network resources [2]. Here, we integrate an interference model into our design and combine multi-source multi-path diversity to improve video streaming quality. In this paper, we make the following contributions. First, we propose a multi-source multi-path video streaming system for supporting concurrent VoD service over a WMN, where each client can distribute its streaming load among several senders and simultaneously stream from them using multiple paths. Second, we consider more realistic wireless networking scenarios, where we model the loss, delay, and interference in WMNs. Third, we formulate the route selection problem for the proposed streaming system using the rate/interference-distortion optimization framework and implement a genetic algorithm to solve it heuristically.

II. System Overview

Figure 1 illustrates the scenario considered in this work: delivering concurrent high quality VoD services to multiple clients over WMNs. This set of clients might be interested in the same video file, which has been extensively explored by leveraging multicasting. However, when clients are interested in various video files or their requests do not come closely enough in the time, building up multiple multicast trees will not be cost-efficient. In this case, we would like to leverage the existing multi-path characteristics of wireless mesh networks to build up a hybrid server/P2P video streaming system and find the best video source location(s)/path(s) to stream content to various clients concurrently. To achieve this goal, we first assume that each WMN node will have some storage space to save local copies of video files for further distribution to other peering WMN nodes. In the following discussions, we will use the terms video file and video clip interchangeably. The status of each link in the WMN will be periodically collected by the media server using link state quality announcements [7]. Meanwhile, the server will gather the file location information for all concurrent streamed video clips and save them using a distributed hash table (DHT). The whole streaming process will proceed as following: the client node sends a request to the well-known media server when it wants to start streaming a video file. Upon receiving the request, the media server will decide i) from where each description of the requested video file can be fetched, and ii) what is the optimal path

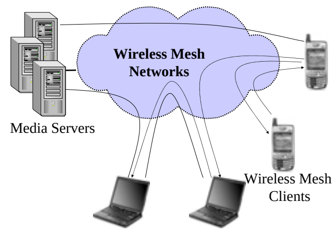

Fig. 1. Multi-Source Video Streaming over Wireless Mesh Networks

for streaming the video file to the client. If the video file is available in nodes other than the media server itself, the media server will redirect the request to selected WMN nodes and piggyback the determined path information. The video file will then be streamed to the client along the selected path from those WMN nodes. Meanwhile, nodes along the streaming path will decide whether they want to keep a local copy of the video file, depending on their available storage space and how much caching the video file can benefit the whole streaming system. The client will make a similar decision after it finishes viewing the video file. Due to space limitations, we will leave the discussion on the caching scheme to future work. In this paper, we mainly explore the route selection problem.

III. Route selection

In this section, we model the proposed video streaming system and formulate the route selection problem.

A. Source model

We assume there exist 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). In this work, we assume M to be 2 [1]. Let d_m ($m \in \{1,2\}$) be the perceived distortion when only m^{th} description is successfully received, and d_0 be the distortion when both descriptions successfully arrive in the receiver. Let b_v^m ($m \in \{1,2\}$) be the rate of m^{th} description for video clip v in terms of bits per pixel. Therefore, the average distortion perceived by the receiver can be computed as [8]:

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

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

$$d_1 = 2^{-2b_v^1} \cdot \sigma^2, \qquad d_2 = 2^{-2b_v^2} \cdot \sigma^2$$

where σ^2 is the variance of the source, and q_v^m is the probability of successfully receiving m^{th} description of video clip v.

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. The number of links is L. Each wireless mesh node is equipped with a radio having communication range r_i and interference range r_i' ($r_i' > r_i$). We model such a WMN using a time-varying directed graph ***G = G (N, L)***, where $\boldsymbol{N}$ is the set of vertices, representing nodes in the WMN, and $\boldsymbol{L}$ 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}: delay of link $\{ij\}$, and iii) p_{ij}: packet loss of link $\{ij\}$. Here, we assume that there is only one wireless channel associated with each node. Let the path for delivering 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:

$$X_{ij}^{v,m} = \begin{cases} 1 & \{ij\} \in L_v^m \\ 0 & \{ij\} \notin L_v^m \end{cases}, \forall \{ij\} \in \boldsymbol{L}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (3)$$

Then L_v^m can be expressed using a routing vector $X^{v,m} = \{X_{ij}^{v,m}\}_{\{ij\} \in L}$.

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:

$$p_v^m = 1 - \prod_{\{ij\} \in \boldsymbol{L}} (1 - X_{ij}^{v,m} p_{ij}), \forall v \in \boldsymbol{V}, \forall m \in \{1,2\}. \quad (4)$$

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 on link $\{ij\}$ using an exponential distribution with 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 λ_{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:

$$T_v^m = \sum_{\{ij\} \in \boldsymbol{L}} X_{ij}^{v,m} t_{ij}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\}, \quad (5)$$

From (5), we can see that T_v^m is the sum of multiple random variables $t_{ij} (\forall \{ij\} \in \boldsymbol{L})$. By assuming that t_{ij} are independent on each other, when the number of links along path L_v^m 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 T_v^m is larger than the acceptable delivery delay can be expressed as:

$$P(T_v^m > \Delta_v^m) = \frac{1}{2}(1 - erf\frac{\Delta_v^m - E(T_v^m)}{\sqrt{2 \cdot Var(T_v^m)}}) \quad (6)$$

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 links along L_v^m is not large enough, we will use the moment generating function (MGF) to find a solution. Based on (5) and PDF of t_{ij}, we get the MGF of T_v^m as:

$$g_{T_v^m}(s) = \prod_{\{ij\}\in \boldsymbol{L}} g_{t_{ij}}(X_{ij}^{v,m}s) = \prod_{\{ij\}\in \boldsymbol{L}} \frac{\lambda_{ij}}{\lambda_{ij} - X_{ij}^{v,m}s}. \quad (7)$$

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 (7) can be expanded as:

$$g_{T_v^m}(s) = \sum_{\{ij\}\in L_v^m} \frac{\{(\lambda_{ij} - X_{ij}^{v,m}s)g_{T_v^m}(s)\}\,|_{s=\lambda_{ij}}}{\lambda_{ij} - X_{ij}^{v,m}s} \quad (8)$$

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

$$f_{T_v^m}(x) = \sum_{\{ij\}\in L_v^m} \{(\lambda_{ij} - X_{ij}^{v,m}s)g_{T_v^m}(s)\}\,|_{s=\lambda_{ij}} \cdot X_{ij}^{v,m} \cdot e^{-\lambda_{ij}x} \quad (9)$$

Using (9), we can get $P(T_v^m > \Delta_v^m)$ when the number of hops on the path is not large enough as:

$$P(T_v^m > \Delta_v^m) = \int_{\Delta_v^m}^{\infty} f_{T_v^m}(x)dx$$
$$= \sum_{\{ij\}\in L_v^m} \{(\lambda_{ij} - X_{ij}^{v,m}s)g_{T_v^m}(s)\}\big|_{s=\lambda_{ij}} \frac{X_{ij}^{v,m}}{\lambda_{ij}} \cdot e^{-\lambda_{ij}\Delta_v^m} \quad (10)$$

Given (4), (6) and (10), we can get the probability that m^{th} description of video clip v can be successfully delivered to the client before its deadline Δ_v^m:

$$q_v^m = (1 - p_v^m)(1 - P(T_v^m > \Delta_v^m)). \quad (11)$$

2) Interference model and conflict graph: Unlike wired networks, neighboring nodes in WMNs suffer from the interference. There are different ways to model the interference in a multi-hop WMN, and in this work we will use the protocol model proposed by Jain et. al[9]. This 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. Based on this model, we define a conflict graph, $\boldsymbol{C}$, with vertex corresponding to the links in the connectivity graph $\boldsymbol{G}$, i.e. the vertex set is identical to $\boldsymbol{L}$. For two vertex, 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 $\boldsymbol{C}$ and the vertex set $\boldsymbol{L}$, we define a conflict vector to characterize the interference between a give link $\{ij\}$ and all other links in $\boldsymbol{L}$. If, in the conflict graph $\boldsymbol{C}$, an edge exists 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. Collecting our conflict vectors together, we can construct a $\|L\| \times \|L\|$ conflict matrix.

C. Rate-distortion optimized route selection problem

We can formulate the optimal route selection problem as: given a WMN ***G(N, L)*** and a set of video clips ***V*** with multiple descriptions across the WMN, for the incoming request on v, find a set of optimal paths for its descriptions so that the average distortion of 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 as well. In the following discussions, 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 δ_v be the node which requests video clip v, and R_v^m be the data rate of m^{th} description of video clip v. Therefore, the total traffic on link $\{ij\}$, ρ_{ij}, will be:

$$\rho_{ij} = \sum_{v\in \boldsymbol{V}} \sum_{m\in\{1,2\}} \prod_{\{mn\}\in L_v^{m(i)}} \{(1 - p_{kn})X_{kn}^{v,m}\} \cdot R_v^m, \forall\{ij\} \in \boldsymbol{L} \quad (12)$$

Using (2), (4) and (12), this route selection problem can be mathematically formulated as:

- Minimize:

$$\sum_{v\in \boldsymbol{V}} D_v \quad (13)$$

- Subject to:

$$\rho_{ij} \leq R_{ij}, \forall\{ij\} \in \boldsymbol{L} \quad (14)$$

$$\sum_{j:\{ij\}\in L_v^m} X_{ij}^{v,m} - \sum_{j:\{ij\}\in L_v^m} X_{ji}^{v,m} = \begin{cases} 1, & if\ i : L_v^{m(i)} = \Phi \\ -1, & if\ i = \delta_v, \\ 0, & if\ otherwise \end{cases},$$
$$\forall i \in \boldsymbol{N}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (15)$$

$$\sum_{j:\{ij\}\in L_v^m} X_{ij}^{v,m} \begin{cases} 0, & i : i \in L_v^m, L_v^{m(i)} = \Phi \\ \leq 1, & otherwise \end{cases}$$
$$\forall i \in \boldsymbol{N}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (16)$$

$$\sum_{j:\{ji\}\in L_v^m} X_{ij}^{v,m} \begin{cases} 0, & i = \delta_v \\ \leq 1, & otherwise \end{cases}$$
$$\forall i \in \boldsymbol{N}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (17)$$

$$X_{ij}^{v,m} \in \{0,1\}, \forall\{ij\} \in \boldsymbol{L}, \forall v \in \boldsymbol{V}, \forall m \in \{1,2\} \quad (18)$$

$$\frac{\rho_{ij}}{R_{ij}} + \sum_{m,n:C_{\{ij\},\{mn\}}=1} \frac{\rho_{mn}}{R_{mn}} \leq 1, \forall\{ij\} \in \boldsymbol{L} \quad (19)$$

where D_v is the average distortion of received video clip v at the receiver node δ_v. (14) shows the rate constraint to satisfy. (15), (16), and (17) guarantee that each path L_v^m provides a loop-free end-to-end connection. (19) guarantee that links in selected concurrent paths will not interfere with each other to cause system performance degradation.

The distortion minimized route selection problem defined by (13)-(19) can be treated as a joint optimization of several single-streaming session route selection problems. Wang et al. [10] showed that each single-streaming session route path selection problem without interference constraints is already NP-complete. Therefore, we expect the joint optimization defined by (13)-(19) is also NP-complete, which we will solve using a genetic algorithm (GA) [11]. GA is a method for solving both constrained and unconstrained optimization problems that is based on natural selection. It employs chromosomes in a population to represent the possible solutions to the problem, and generates a population of points at each iteration, which is different from single-solution based trajectory methods such as simulated annealing (SA) and tabu search (TS). Since the best point in the population approaches an optimal solution, GA has less tendency to be trapped in a local optimum. This makes GA intrinsically more feasible for solving concurrent route selection problems.

IV. Performance evaluation

To evaluate our proposed designs and test the GA method, we simulate an IEEE802.11-based WMN by randomly placing 10 wireless nodes in a $300m \times 300m$ square region. For each node, $r_i = 150m$, $r_i' = 160m$. At this point, we assume no node mobility. The media server node and concurrent receiver nodes are randomly chosen from the 10 nodes. In our simulations, we consider three concurrent streaming sessions. Two directional wireless links exist between a pair of nodes if they are within one hop distance of each other. For each wireless link, its e_i is randomly selected from $[10^{-4}, 10^{-5}]$ with a uniform distribution, and the transmitted packet size is set to be 1000bytes. The available bandwidth of each link is randomly selected from $[400kbps, 800kbps]$, evenly spaced at $100kbps$ according to the uniform distribution. Since σ^2 only affects the absolute values of distortions and does not affect on route selection decisions, we set it to 1. In the GA, we encode each feasible solution, i.e. paths for all concurrent streams, as a set of chromosome, with each chromosome corresponding to a path between a pair of selected sender and receiver. 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 100, and both the mutation rate and the crossover rate to be 0.5. The GA program will terminate after evolving for 20 generations.

We run two sets of simulations. In the first set of simulations, we compare two scenarios with and without considering interference, and examine the impact of the decoding deadline on the distortion of concurrent video sessions. We repeat the simulation with the same settings 10 times and average the performance on each data point over 10 runs. As shown in Figure 2(a), by integrating the interference model into the design, the system can achieve better performance than the one blind to underlying interference. This is due to that fact that being aware of interference helps to prevent overloading wireless links and reduces packet collisions. In the second set of simulations, we compare the proposed multi-source multi-path scheme with the scheme using single-source single path. Again, we get each point by averaging over 10 runs. Figure 2(b) shows that multi-source multi-path diversity can help defend against performance degradation. From both graphs in Figure 2, we can see that the overall distortion is a decreasing

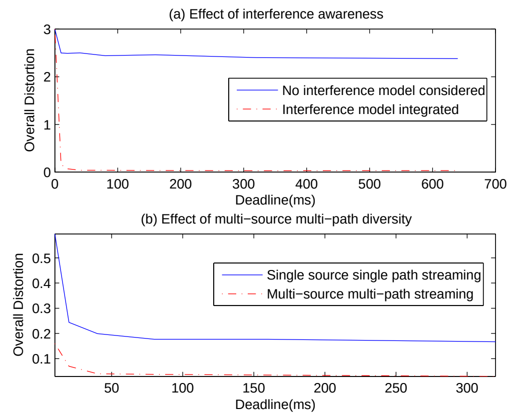

Fig. 2. Overall distortion vs. playout deadline (N = 10, V = 3)

function of decoding deadlines. As the decoding deadline increases over certain values, the overall distortion converges.

V. Conclusion

In this paper, we leverage multi-source multi-path diversity to design a concurrent video streaming system for wireless mesh networks. After integrating interference into system model, we formulate the route selection problem using rate/interference-distortion optimization framework and heuristically solve it using a genetic algorithm. Simulation results show that the proposed system has better performance than systems using single-source, single-path and systems that do not consider interference.

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