Joint Routing and Server Selection for Multiple Description Video Streaming in Ad Hoc Networks

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Abstract— **Multiple Description (MD) coding has a great potential for multimedia communications in wireless ad hoc networks. In this paper, we study the important problem of joint routing and server selection for MD video in ad hoc networks. We take a cross-layer approach to formulate the task as a combinatorial optimization problem and present tight lower and upper bounds for the achievable distortion. The upper bound also provides a feasible solution to the formulated problem. Our extensive numerical results show that the bounds are very close to each other for all the cases studied, indicating the near-global optimality of the derived upper bounding solution. Moreover, we observe significant gains in video quality achieved by the proposed approach over existing server selection schemes. This justifies the importance of jointly considering routing and server selection for optimal MD video streaming in wireless ad hoc networks. The proposed algorithms are computationally efficient and can be easily incorporated into existing ad hoc routing protocols, making them highly suitable for supporting MD video streaming in wireless ad hoc networks.**

I. Introduction

With the rapid advances in wireless ad hoc networking, there is a compelling need for content-rich multimedia communications (e.g., video streaming) in such networks. It is expected that techniques such as caching and server replication will have a great potential in providing scalable multimedia services in wireless ad hoc networks [1], due to their great success for content delivery in the Internet [2].

The recent advances in Multiple Description (MD) coding has made it highly suitable for providing multimedia communications in wireless ad hoc networks [3]–[7], especially for distributed media deliveries. MD coding is a technique that generates multiple equally important descriptions, each giving a low, but acceptable video quality [3]. The decoding independence among the descriptions permits a reconstruction of video from *any* subset of received descriptions, achieving a quality commensurate with the number of received descriptions. This feature makes MD video an excellent match for multimedia applications in ad hoc networks, where wireless links are unstable and reliable paths are hard to maintain.

MD for distributed storage has been suggested in [3], where a typical user would have fast access to the local video descriptions. For higher quality, one or more remote descriptions could be retrieved and combined with the local ones. An interesting and thorough study of MD streaming for content delivery networks (CDN) is presented in [4]. More specifically, three server selection algorithms, i.e., Shortest Path (SP), Heuristic, and Distortion are proposed for a client to select a pair of servers having complementary descriptions for improved video quality. Although these algorithms have been shown to be effective in content delivery networks, the first two simple algorithms only consider hop-counts of the paths when choosing servers. Such a network-centric approach does not necessarily guarantee good application layer performance, such as video quality [6], [7]. The third proposed server selection algorithm, Distortion, selects servers based on the expected video distortion, but it does not consider the more important optimal routing problem. In other words, the Distortion algorithm only chooses a pair of servers whose default routes to the client are optimal among the default routes from all the other servers to the client.

In wireless ad hoc networks, links are much more diverse in terms of quality (e.g., available bandwidth and loss) than links in wireline networks: any link in an ad hoc network could be highly fragile with dynamic state conditions. In such an environment, pure server selection-based algorithms, although effective in the Internet, may produce low video quality if the default route links happen to have low available bandwidth or high loss rates.

In this paper, we study the important problem of joint routing and server selection for MD video streaming in wireless ad hoc networks. In addition to selecting a pair of servers, we also explore optimal routing strategies to find good paths to the servers. Such a joint routing and server selection scheme opens a new dimension of freedom for further improving the MD video quality, since it explores a much larger solution space than existing server selection schemes.

Specifically, we first take an application-centric, cross-layer approach to formulate the joint routing and server selection task as a combinatorial optimization problem that minimizes the received video distortion. Due to the high complex nature of the formulated problem, exact solutions are hard to find. Rather, we present schemes to compute an upper bound and a lower bound on the best achievable video distortion based on the monotonicity properties of the objective function. In addition, the upper bound produces a near-optimal pair of servers and a pair of corresponding paths for the client. The proposed approach is computationally efficient and can be easily incorporated into existing routing protocols for ad hoc networks. Our extensive numerical results show that the upper and lower bounds are very close to each other for all the cases studied, indicating that they are very close to the global optimum. We also observe significant gains in video quality achieved by the proposed approach over existing server selection schemes, which justify the importance of jointly considering routing and server selection for optimal MD video streaming in wireless ad hoc networks.

The remainder of this paper is organized as follows. In Section II, we formulate the joint routing and server selection task

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as a combinatorial optimization problem. We then examine the properties of the objective function and present algorithms for computing an upper bound and a lower bound for the achievable optimal distortion in Section III. Our extensive experimental studies are presented in Section IV. We discuss practical issues in Section V and related work in Section VI. Section VII concludes the paper.

II. Problem Description

In this section, we formulate the problem of joint routing and server selection for MD video streaming in wireless ad hoc networks. The notation used in the following presentation is given in Table I.

TABLE I
NOTATION

$\mathcal{G}\{V,E\}$:	graph representation of the network.
V :	set of vertices.
E :	set of edges.
$\mathcal{S}_h$:	server set that hosts description h, $h=1,2$.
s_h :	a chosen server, $h=1,2$.
u :	a client node.
$\mathcal{P}_h$:	a path from s_h to u, $h=1,2$.
$\{i,j\}$:	a link from node i to node j.
b_{ij} :	available bandwidth of link $\{i,j\}$.
p_{ij} :	success probability of link $\{i,j\}$.
l_{ij} :	average loss burst length of link $\{i,j\}$.
R_h :	rate of description h in bits per sample,$h=1,2$.
d_0 :	distortion when both descriptions are received.
d_h :	distortion when only description h is received, $h=1,2$.
D :	average video distortion.
T_{on} :	average "up" period of the joint links.
P_{00} :	probability that both descriptions are received.
P_{01} :	probability of receiving description 1 only.
P_{10} :	probability of receiving description 2 only.
P_{11} :	probability that both descriptions are lost.
x_{ij}^h :	routing index variables, defined in (3).
α_{ij}:	"up" to "down" transition prob. of link $\{i,j\}$.
β_{ij} :	"down" to "up" transition prob. of link $\{i,j\}$.
p_{jnt} :	average success prob. of joint links.
p_{dj}^h :	average success prob. of disjoint links on $\mathcal{P}_h$.
x_u^* :	constructed upper bounding solution.
x_l^* :	constructed lower bounding solution.

A wireless mobile ad hoc network can be modeled as a probabilistic directed graph $\mathcal{G}\{V,E\}$, where V is the set of vertices and E the set of edges. We assume that nodes are reliable during the video session, but a link may fail with certain probabilities. Accurate and computationally efficient characterization of an end-to-end path in a wireless ad hoc network with consideration of mobility, interference, and time-varying wireless channels, is extremely difficult and remains an open problem. As an initial step, we focus on network layer characteristics in this paper, assuming that physical and MAC layer dynamics of wireless links are translated into network layer parameters. For example, we could characterize a link $\{i,j\}\in E$ by:

- b_{ij}: available bandwidth of link $\{i,j\}$.
- p_{ij}: "up" probability of link $\{i,j\}$.
- l_{ij}: average packet loss burst length on link $\{i,j\}$.

In practice, these parameters can be measured by nodes in the network, and distributed throughout the network using Link State Advertisements (LSAs) [8] or route replies (RREP) [9].

A. Rate Distortion Model of MD Coding

For video coding and communications, a rate distortion model describes the relationship between the bit rate and the achieved distortion. We use the double-description (DD) coding to illustrate the problem formulation, since it is most widely used in MD video streaming in practice [4]–[7], [10], [11]. For two descriptions, each generated for a sequence of video frames, let d_h denote the achieved distortion when only description h is received, $h=1,2$, and d_0 as the distortion when both descriptions are received. Also, let P_{00} be the probability of receiving both descriptions, P_{01} the probability of receiving Description 1 only, P_{10} the probability of receiving Description 2 only, and P_{11} the probability of losing both descriptions. Then, the average distortion of a received DD video can be expressed as [10]:

$$D = P_{00}d_0 + P_{01}d_1 + P_{10}d_2 + P_{11}\sigma^2, \tag{1}$$

where σ^2 is the variance of the source.

Let R_h be the rate in bits per sample of description h, $h=1,2$. The rate-distortion region for an *i.i.d.* memoryless Gaussian source with the square error distortion measure was first introduced in [12]. For computational efficiency, in [10], Alasti *et al.* employed the following rate-distortion region, which is also used in the present paper.[1]

$$\begin{cases} d_0 = \frac{2^{-2(R_1+R_2)}}{2^{-2R_1}+2^{-2R_2}-2^{-2(R_1+R_2)}}\cdot\sigma^2 \\ d_1 = 2^{-2R_1}\cdot\sigma^2 \\ d_2 = 2^{-2R_2}\cdot\sigma^2. \end{cases} \tag{2}$$

B. Computing Distortion for Two Given Paths

Within the network, let there be two sets of server nodes, denoted as $\mathcal{S}_h$, each hosting description h of a video in their cache or public directory, $h=1,2$. Note that these two sets do not have to be disjoint. If $\mathcal{S}_1\cap\mathcal{S}_2\neq\emptyset$, then nodes in $\mathcal{S}_1\cap\mathcal{S}_2$ can offer both descriptions of the video clip. For video streaming, usually the server nodes do not perform on-line coding. Therefore, we assume that the descriptions have fixed and balanced rates, i.e., $R_1=R_2=R$.[2]

Before we mathematically formulate the problem of joint routing and server selection, we need to compute the average distortion D as a function of link statistics for a *given* pair of servers and paths. We first define the following indices for describing the choice of a pair of paths:

$$x_{ij}^h = \begin{cases} 1, & \text{if } \{i,j\}\in\mathcal{P}_h,\ \forall\{i,j\}\in E, h=1,2 \\ 0, & \text{otherwise},\ \forall\{i,j\}\in E, h=1,2. \end{cases} \tag{3}$$

With these index variables, an arbitrary path $\mathcal{P}_h$ can be represented by a vector $\mathbf{x}^h$ of $|E|$ elements, each of which corresponds to a link and has a binary value. Then, the bandwidth constraints of the links can be expressed as:

$$x_{ij}^1\cdot R_1 + x_{ij}^2\cdot R_2 \le \rho\cdot b_{ij},\ \ \forall\{i,j\}\in E, \tag{4}$$

where $\rho=\gamma\cdot W\cdot H\cdot R_f$ for a video with frame rate R_f and frame size $W\times H$; γ is a constant determined by the chroma

[1] Note that other empirical rate-distortion models, e.g., [4], can be incorporated into this framework as well.

[2] Unbalanced descriptions and on-line coding can be easily handled in the proposed framework, which we have omitted for the sake of brevity.

subsampling format (e.g., $\gamma = 1.5$ for the quarter common intermediate format (QCIF) videos).

We now consider how to compute the end-to-end success probabilities. Since we do not mandate "disjointedness" in routing, $\mathcal{P}_1$ and $\mathcal{P}_2$ may share nodes and links. We classify the links along the two paths into three sets: set one consisting of joint links shared by both paths, denoted as $\mathcal{J}(\mathcal{P}_1, \mathcal{P}_2)$, and the other two sets consisting of disjoint links on the two paths, denoted respectively as $\bar{\mathcal{J}}(\mathcal{P}_i)$, $i = 1, 2$. For disjoint portions of the paths, it suffices to model the packet losses as Bernoulli events, since the losses of the two descriptions are independent. Therefore, the success probabilities on the disjoint portions are:

$$p_{dj}^h = \begin{cases} \prod_{\{i,j\} \in \bar{\mathcal{J}}(\mathcal{P}_h)} p_{ij}, & \text{if } \bar{\mathcal{J}}(\mathcal{P}_h) \neq \emptyset,\ h = 1, 2 \\ 1, & \text{otherwise},\ h = 1, 2. \end{cases} \quad (5)$$

On the joint portion of the paths, the losses of the two streams are correlated. In order to capture such correlation, we model each link $\{i, j\}$ as an on-off process modulated by a discrete-time Markov chain, as shown in Figure 1(a). There is no packet loss when the link is in the "up" state, and the packet loss rate is 1 when the link is in the "down" state. The transition probabilities, $\{\alpha_{ij}, \beta_{ij}\}$, can be computed from the measured link statistics, as $\beta_{ij} = 1/l_{ij}$ and $\alpha_{ij} = (1 - p_{ij})/(p_{ij} l_{ij})$. If there are K shared links, the aggregate failure process of these links is a Markov process with 2^K states. In order to simplify the computation, we follow a similar approach in [4] and [11] to model the aggregate process as an on-off process. Observe that a packet is successfully delivered on the joint portion if and only if all joint links are in the "up" state. Therefore, we can lump all the states having at least one link failure into a single "down" state, while using the remaining state where all the links are in the good condition as the "up" state. Letting T_{on} be the average length of the "up' period, we have,

$$T_{on} = \frac{1}{1 - \prod_{\{i,j\} \in \mathcal{J}(\mathcal{P}_1, \mathcal{P}_2)} (1 - \alpha_{ij})}.$$

Furthermore, the average success probability of the joint portion is:

$$p_{jnt} = \begin{cases} \prod_{\{i,j\} \in \mathcal{J}(\mathcal{P}_1, \mathcal{P}_2)} p_{ij}, & \text{if } \mathcal{J}(\mathcal{P}_1, \mathcal{P}_2) \neq \emptyset \\ 1, & \text{otherwise}. \end{cases} \quad (6)$$

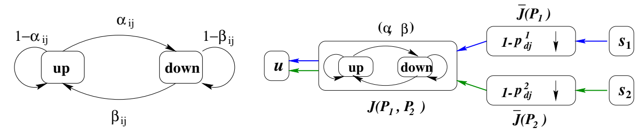
Finally, the transition probabilities of the aggregate on-off process are:

$$\begin{cases} \alpha = \frac{1}{T_{on}} \\ \beta = \frac{p_{jnt}}{T_{on}(1 - p_{jnt})}. \end{cases}$$

Note that $\alpha = 0$ and $\beta = 0$ if $\mathcal{J}(\mathcal{P}_1, \mathcal{P}_2) = \emptyset$. The consolidated path model is illustrated in Figure 1(b), where $\mathcal{J}(\mathcal{P}_1, \mathcal{P}_2)$ is modeled as a two-state Markov process with parameters $\{\alpha, \beta\}$, and $\bar{\mathcal{J}}(\mathcal{P}_h)$ is modeled as a Bernoulli process with parameter p_{dj}^h, $h = 1, 2$.

With the above path model, the joint probabilities of receiving the descriptions can be computed as:

$$\begin{cases} P_{00} = p_{jnt} \cdot (1 - \alpha) \cdot p_{dj}^1 \cdot p_{dj}^2 \\ P_{01} = p_{jnt} \cdot p_{dj}^1 \cdot [1 - (1 - \alpha) \cdot p_{dj}^2] \\ P_{10} = p_{jnt} \cdot p_{dj}^2 \cdot [1 - (1 - \alpha) \cdot p_{dj}^1] \\ P_{11} = 1 - p_{jnt} \cdot [p_{dj}^1 + p_{dj}^2 - (1 - \alpha) \cdot p_{dj}^1 \cdot p_{dj}^2]. \end{cases} \quad (7)$$



(a) The two-state Markov link model.

(b) A consolidated path model for double-description video.

Fig. 1. Link and path models.

Let $a = 2^{-2R_1}$ and $b = 2^{-2R_2}$. For balanced descriptions, we have that $a = b$. The average video distortion can be computed by substituting (2) and (7) into (1):

$$\frac{D}{\sigma^2} = 1 + p_{jnt} \cdot \Big[(a - 1) \cdot p_{dj}^1 + (b - 1) \cdot p_{dj}^2 + (1 - \alpha) \frac{(a + b)(a - 1)(b - 1)}{a + b(1 - a)} \cdot p_{dj}^1 \cdot p_{dj}^2\Big]. \quad (8)$$

C. The Optimal Routing Problem

With the above preliminaries, we can mathematically formulate the joint routing and server selection problem for MD video (OPT-JRSS) as follows:

OPT-JRSS For two given server sets $\{\mathcal{S}_1, \mathcal{S}_2\}$ and a given client u, find an optimal solution $x^* = \{s_1^*, s_2^*, \mathcal{P}_1^*, \mathcal{P}_2^*\}$ that minimizes the average distortion D defined in (1). That is,

Minimize: D (9)

subject to:

$$\sum_{j:\{i,j\} \in E} x_{ij}^h = \begin{cases} \leq 1, & \text{if } i \neq u \\ = 0, & \text{if } i = u \end{cases}, \forall i \in V, h = 1, 2 \quad (10)$$

$$\sum_{j:\{i,j\} \in E} x_{ij}^h - \sum_{j:\{j,i\} \in E} x_{ji}^h = \begin{cases} 1, & \text{if } i = s_h \\ -1, & \text{if } i = u \\ 0, & \text{otherwise} \end{cases}, \forall i \in V, h = 1, 2 \quad (11)$$

$$x_{ij}^1 \cdot R_1 + x_{ij}^2 \cdot R_2 \leq \rho \cdot b_{ij}, \ \forall \{i, j\} \in E \quad (12)$$

$$x_{ij}^h \in \{0, 1\}, \ \forall \{i, j\} \in E, h = 1, 2 \quad (13)$$

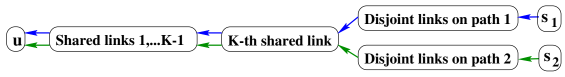
$$s_h \in \mathcal{S}_h, \ h = 1, 2. \quad (14)$$

In Problem OPT-JRSS, $\{x_{ij}^h\}_{\{i,j\} \in E, h=1,2}$ and $\{s_h\}_{h=1,2}$ are optimization variables, representing the choice of a pair of servers and the links on a pair of paths from the chosen servers to the client. Constraints (10) and (11) guarantee that the paths are loop-free,[3] while constraint (12) guarantees that the links are stable. For a given pair of paths, the average video distortion D is determined by the end-to-end statistics and the correlation of the paths, as given in (1), (2), and (7). If multiple solutions are found having the minimum distortion, we can break ties by choosing the solution that has the largest bandwidth along the two chosen paths (see (12)).

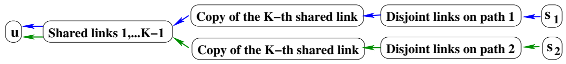
III. Lower and Upper Distortion Bounds

In the following, we first introduce several monotonicity properties of the objective function (9). Then, we construct

[3]Note that although the feasible region permits disconnected subtours for any $h = 1, 2$, the optimization problem model automatically precludes such a solution.



(a) Solution $\hat{x}$.



(b) Solution $\bar{x}$.

Fig. 2. The two solutions have the same set of links. The only difference between them is that a link is shared in $\hat{x}$ (the K-th shared link), but not shared in $\bar{x}$ (appended to each of the disjoint portions).

a lower bound and an upper bound on the achievable video distortion.

A. Properties of the Objective Function

The objective function of Problem OPT-JRSS, (9), has the following *monotonicity* properties.

Property 1: D is non-increasing with R_h, $h = 1, 2$.

Proof: Recall that $a = 2^{-2R_1} \leq 1$ and $b = 2^{-2R_2} \leq 1$. From (1) and (2), we have

$$\frac{1}{\sigma^2}\frac{\partial D}{\partial R_1} = -P_{00}\frac{2\ln 2 \cdot ab^2}{(a+b-ab)^2} - 2\ln 2 \cdot P_{01}a \leq 0$$

Similarly, we have $\frac{\partial D}{\partial R_2} \leq 0$ due to the symmetry in (8). ∎

Property 2: For two completely disjoint paths, D is non-increasing with p_{dj}^h, $h = 1, 2$.

Proof: For a disjoint path set $\{\mathcal{P}_1, \mathcal{P}_2\}$, we have that $p_{jnt} = 1$ and $\alpha = 0$. Then, we have

$$\begin{aligned}\frac{1}{\sigma^2}\frac{\partial D}{\partial p_{dj}^1} &= (a-1)\left[\frac{(1-p_{dj}^2)(a+b(1-a)) + b^2 p_{dj}^2}{a+b(1-a)}\right] \\ &\leq 0.\end{aligned}$$

Similarly, we have $\frac{\partial D}{\partial p_{dj}^2} \leq 0$ due to the symmetry in (8). ∎

Property 3: Consider the two solutions $\hat{x}$ and $\bar{x}$ shown in Figure 2. If the the on-off failure process of the K-th shared link is random or bursty, i.e., $\alpha_{ij} + \beta_{ij} \leq 1$, then $D(\hat{x}) \geq D(\bar{x})$.

Proof: For solution $\hat{x} = \{s_1, s_2, \mathcal{P}_1, \mathcal{P}_2\}$ in Figure 2(a), let there be K joint links with parameters $\{\alpha_k, \beta_k\}$, $k = 1, \cdots, K$. We have:

$$\begin{aligned}\frac{1}{\sigma^2}\left[D(\hat{x}) - D(\bar{x})\right] = p_{jnt} \cdot p_{dj}^1 \cdot p_{dj}^2 \cdot \prod_{k=1}^{K-1}(1-\alpha_k) \cdot \\ (1-\alpha_K-\beta_K)(1-p_K)\frac{(a+b)(1-a)(1-b)}{a+b(1-a)} \geq 0,\end{aligned}$$

according to the "bursty" assumption. ∎

The intuition behind Property 3 can be illustrated by examining the covariance of two consecutive failure events on link $\{i, j\}$:

$$\text{Cov}\{X_k, X_{k+1}\} = \frac{\alpha_{ij}\beta_{ij}}{(\alpha_{ij}+\beta_{ij})^2}(1-\alpha_{ij}-\beta_{ij}). \qquad (15)$$

If $\alpha_{ij} + \beta_{ij} < 1$, the two successive failures (or losing both descriptions sent back to back on this link) are *positively* correlated, i.e., the failure process is bursty, which, we argue, is not atypical in wireless ad hoc networks. When $\alpha_{ij} + \beta_{ij} = 1$, the two successive failures are un-correlated, corresponding to *random* packet losses. When $\alpha_{ij} + \beta_{ij} > 1$, the successive failures are *negatively* correlated (called *sub-bursty*), which, we believe, is rare in wireless ad hoc networks. In Figure 2, if the Kth shared link has bursty losses, then $\bar{x}$ yields a lower distortion than $\hat{x}$; if the Kth shared link has random losses, then the two solutions yield the same distortion.

1. Remove link(s) $\{i, j\}$ having $\rho \cdot b_{ij} < R$, $\forall\{i, j\} \in E$ to obtain a reduced graph $G(V, E')$;
2. Set the cost of link $\{i, j\}$ to $\log(1/p_{ij})$, $\forall\{i, j\} \in E'$;
3. Find the path $\mathcal{P}_h^l$ from a server $s_h^l \in \mathcal{S}_h$ to u in $G(V, E')$ that has the minimum cost among all paths to all $s_h \in \mathcal{S}_h$, $h = 1, 2$;
4. Assuming $\mathcal{P}_1^l \cap \mathcal{P}_2^l = \emptyset$, compute $D(x_l^*)$, where $x_l^* = \{s_1^l, s_2^l, \mathcal{P}_1^l, \mathcal{P}_2^l\}$.

Fig. 3. ALG-LB: Construct a lower bounding solution x_l^*.

B. A Distortion Lower Bound

We are now ready to construct a tight lower bound on the average video distortion. From the monotonicity properties of D, we need to find a path pair having the best loss characteristics.

Algorithm ALG-LB in Figure 3 can be used to construct a solution x_l^* that yields a lower bound for D. In ALG-LB, we set the cost of a link $\{i, j\}$ to $\log(1/p_{ij})$, $\forall\{i, j\} \in E$. Then, the total cost of a path $\mathcal{P}$ is:

$$\sum_{\{i,j\}\in\mathcal{P}} \log\left(\frac{1}{p_{ij}}\right) = \log\left(\frac{1}{\prod_{\{i,j\}\in\mathcal{P}} p_{ij}}\right).$$

Applying a shortest path routing algorithm, we can find a path having the minimum cost, so that then, $\prod_{\{i,j\}\in\mathcal{P}} p_{ij}$ is maximized. According to (8) and Property 2, if the paths $\{\mathcal{P}_1^l, \mathcal{P}_2^l\}$ found in ALG-LB are disjoint, then they are the optimal solution to Problem OPT-JRSS; otherwise, the computed distortion assuming that $\{\mathcal{P}_1^l, \mathcal{P}_2^l\}$ are disjoint will be a lower bound of the distortion achieved by the optimal solution (according to Property 3). For the constructed solution x_l^*, we have the following proposition holding true.

Proposition 1: The distortion, $D(x_l^*)$, of x_l^* constructed by ALG-LB is a lower bound for the average distortion D defined in (8).

Proof: The formation of the optimal solution $x^* = \{s_1^*, s_2^*, \mathcal{P}_1^*, \mathcal{P}_2^*\}$ could conform with one of the following two cases:

Case I: If x^* is comprised of a pair of disjoint paths, then from the construction procedure, we have that $p_{dj}^1(\mathcal{P}_1^l, \mathcal{P}_2^l) \geq p_{dj}^1(\mathcal{P}_1^*, \mathcal{P}_2^*)$ and $p_{dj}^2(\mathcal{P}_1^l, \mathcal{P}_2^l) \geq p_{dj}^2(\mathcal{P}_1^*, \mathcal{P}_2^*)$, where $p_{dj}^h(\mathcal{P}_1, \mathcal{P}_2) = \prod_{\{i,j\}\in\bar{\mathcal{J}}(\mathcal{P}_h)} p_{ij}$ for disjoint paths $\{\mathcal{P}_1, \mathcal{P}_2\}$, $h = 1, 2$ (see (5)). From Property 2, we have that $D(x_l^*) \leq D(x^*)$.

Case II: If $\mathcal{P}_1^*$ and $\mathcal{P}_2^*$ share K links, we can construct a virtual solution $\bar{x}^* = [\bar{\mathcal{P}}_1^*, \bar{\mathcal{P}}_2^*]$, by (i) appending a copy of the shared link k to the disjoint portions of the two paths; (ii) removing the shared link k from the shared portion, $k = 1, \cdots, K$ (see Figure 2). That is, we construct a solution $\bar{x}^*$ with disjoint paths and identical links to x^* by duplicating each shared link in x^*. Note that as a result, $\bar{x}^*$ may not be realizable. By applying Property 3 repeatedly for K times, we have that $D(\bar{x}^*) \leq D(x^*)$. Finally, from Case I, we have that $D(x_l^*) \leq D(\bar{x}^*) \leq D(x^*)$. ∎

1. Remove link(s) $\{i,j\}$ having $\rho \cdot b_{ij} < R$, $\forall\{i,j\} \in E$ to obtain a reduced graph $G(V,E')$;
2. Set the cost of link $\{i,j\}$ to $\log(1/p_{ij})$, $\forall\{i,j\} \in E'$;
3. Find the path $\mathcal{P}_1^u$ from a server $s_1^u \in \mathcal{S}_1$ to u in $G(V,E')$ that has the minimum cost among all paths to all $s_1 \in \mathcal{S}_1$;
4. From $G(V,E')$, remove link(s) $\{i,j\}$ having $\rho \cdot b_{ij} < 2R$, $\forall\{i,j\} \in \mathcal{P}_1^u$ to obtain a further reduced graph $G(V,E'')$;
5. Find the path $\mathcal{P}_2^u$ from a server $s_2^u \in \mathcal{S}_2$ to u in $G(V,E'')$ that has the minimum cost among all paths to all $s_2 \in \mathcal{S}_2$;
6. Compute $D(x_u^*)$, where $x_u^* = \{s_1^u, s_2^u, \mathcal{P}_1^u, \mathcal{P}_2^u\}$.

Fig. 4. ALG-UB: Construct an upper bounding solution x_u^*.

In ALG-LB, $\mathcal{P}_h^l$ can be found by applying Dijkstra's algorithm to first find the lowest cost paths to each server in $\mathcal{S}_h$, with a time complexity of $O(|\mathcal{S}_h| \cdot |E'| \cdot \log|V|)$, and then choose the server (and the corresponding path) having the minimum cost path among all servers in $\mathcal{S}_h$, with a time complexity of $O(|\mathcal{S}_h|)$, $h = 1,2$. Note that although the computed $\mathcal{P}_1^l$ and $\mathcal{P}_2^l$ may share links, we assume that they are completely disjoint in order to obtain a distortion lower bound. As a result, the solution x_l^* that achieves the lower bound may not be realizable.

C. A Distortion Upper Bound

Although the above lower bound is very useful in providing a close approximation for the lowest achievable distortion by jointly selecting the optimal servers and the corresponding optimal paths to them, Algorithm ALG-LB does not provide a usable set of servers and paths for client u. In this section, we present an algorithm to construct a feasible solution that yields an upper bound on D.

Algorithm ALG-UB in Figure 4 can be used to construct a solution x_u^* that achieves an upper bound for D. As in ALG-LB, we set the cost of a link $\{i,j\}$ to $\log(1/p_{ij})$, $\forall\{i,j\} \in E$. Thus the minimum cost path has the best end-to-end loss characteristics. In addition, we also take into consideration the link bandwidth constraints, by removing those links that do not have sufficient bandwidth to support both descriptions when computing the optimal path to the second server set, in order to make a feasible solution. As in ALG-LB, $\mathcal{P}_1^u$ can be found by applying Dijkstra's algorithm with a time complexity of $O(|\mathcal{S}_1| \cdot |E'| \cdot \log|V| + |S_1|)$ and $\mathcal{P}_2^u$ can be found with a time complexity of $O(|\mathcal{S}_2| \cdot |E''| \cdot \log|V| + |S_2|)$. For the constructed solution x_u^*, we have the following result holding true.

Proposition 2: The distortion of x_u^* constructed in ALG-UB, $D(x_u^*)$, is an upper bound for the average distortion D defined in (8).

Proof: Clearly, $x_u^* = \{s_1^u, s_2^u, \mathcal{P}_1^u, \mathcal{P}_2^u\}$ is a feasible solution to Problem OPT-JRSS, since it satisfies all the constraints (10)–(14). Therefore, $D(x_u^*)$ must be an upper bound for D, which is the distortion of the global optimal solution x^*. ■

The four-tuple $\{s_1^u, s_2^u, \mathcal{P}_1^u, \mathcal{P}_2^u\}$ provides a usable solution to Problem OPT-JRSS. We will show that the lower and upper bounds are very close to each other. In other words, the upper bound is near-optimal in all of the cases that we examined.

IV. Numerical Results

In this section, we examine the performance of the proposed distortion bounds via a set of experiments. In each experiment, we generated an ad hoc network topology by placing a number of nodes at random locations in a square region. Connectivity was determined by the distance coverage of each nodes transmitter (set to 250 m in all the following experiments). The client node and server nodes were randomly chosen.[4] For all of the experiments reported, the success probability p_{ij} was randomly chosen from $[0.9, 0.995]$, $\forall\{i,j\} \in E$. We set the variance σ^2 to 1, since it does not influence routing and server selection decisions. Other parameter settings will be introduced in the following when the results are being discussed. The computation time was in tens of milliseconds for all the experiments performed.

A. Optimality of the Distortion Bounds

One important performance concern is the optimality of the proposed lower and upper distortion bounds. Due to the complex nature of Problem OPT-JRSS, a closed-form optimal solution is not obtainable. But the global optimal solution may be numerically obtained via an exhaustive search for small-sized networks.

The distortion bounds for two 15-node networks found by ALG-UB and ALG-LB are presented in Tables II, as well as the global optimal distortion values found by an exhaustive search. We also varied the video description rate and mean burst length to examine their impact. In these experiments, the available bandwidth of each wireless link b_{ij} was randomly chosen from $[128Kbps, 448Kbps]$, in steps of $64Kbps$, $\forall\{i,j\} \in E$. We observe that for all the cases, the global optimal distortion (found by exhaustive search) always lies between the corresponding lower and upper bounds. In addition, the difference between the bounds is negligible. In Table II, the largest difference between the lower and upper bounds is 0.0061, giving a relative difference of 1.3%.

We also performed extensive simulations for larger sized networks (i.e., 50-, 80-, and 100-node networks) where exhaustive search is impractical, and for different MD description rates R. The results are shown in Table III. Again, the proposed bounds were very close to each other in all of the cases examined. In many cases, the lower and upper bounds yield the same distortion value, implying that they are actually the global optimal solutions. The maximum relative difference between the lower and upper bounds in Table III is 6.4% (the 80-node network with $R = 384Kbps$), indicating the near-global optimality of the derived upper bounding solutions.

Clearly, the proposed bounds can provide an excellent estimation for the global optimal solution. The servers and the corresponding paths found by ALG-UB yield a highly competitive solution to Problem OPT-JRSS. In addition, since ALG-UB is based on Dijkstra's algorithm, the computation time for each run was in tens of milliseconds using a Pentium-4 2.4 GHz computer (with 512 MB memory). The proposed algorithms are computationally efficient and are suitable for joint routing and server selection for large-sized ad hoc networks.

B. Comparison with Existing Algorithms

In order to compare with the existing server selection schemes, we implemented the following three server selection algorithms proposed in [4] for MD video streaming in CDN.

1) Shortest Path (SP): pick the closest server (in terms of hop count) from each server set.
2) Heuristic: compute a score, $r_{mn} = (L_m + L_n)/2 + L_{mn}^J$, for each pair of servers $\{s_m, s_n\}$ having complementary

[4] We avoided the trivial cases where the servers are within two hops from the client node.

TABLE II

COMPARISON OF THE PROPOSED BOUNDS FOR TWO 15-NODE NETWORKS

	$R = 128Kbps$		$R = 192Kbps$	
l_{ij}	[2,6]	[10,25]	[2,6]	[10,25]
Upper Bound	0.5928	0.5931	0.4752	0.4758
Exhaustive Search	0.5916	0.5917	0.4721	0.4722
Lower Bound	0.5897	0.5897	0.4697	0.4697
SP	0.7976	0.7104	0.7247	0.6136
Heuristic	0.7976	0.7104	0.7247	0.6136
Distortion	0.7883	0.6846	0.7247	0.5816

TABLE III

COMPARISON OF THE UPPER AND LOWER BOUNDS FOR DIFFERENT NETWORKS: $l_{ij} \in [2, 6], \forall \{i, j\} \in E$

R (Kbps)	64	128	192	256	320	384
UB(50n)	0.756	0.589	0.496	0.407	0.350	0.302
LB(50n)	0.756	0.589	0.485	0.396	0.341	0.289
UB(80n)	0.755	0.596	0.478	0.404	0.348	0.316
LB(80n)	0.755	0.587	0.467	0.402	0.342	0.297
UB(100n)	0.758	0.593	0.477	0.385	0.316	0.328
LB(100n)	0.758	0.592	0.473	0.385	0.316	0.309

descriptions, where L_m (L_n) is the path length in hop-count (i.e., for the default or shortest path) from server s_m (s_n) to u, and L^J_{mn} is the number of joint links. Then, choose the server pair having the lowest score.

3) Distortion: calculate the expected distortion for each server pair having complementary descriptions. Then, choose the pair that yields the lowest distortion.

Note that although the Distortion algorithm performs a server selection based on the average video distortion, it does not take advantage of using an optimal routing for MD video. In other words, the distortion is computed for a server pair using two *default* paths (e.g., the shortest paths) from the two servers to the client.

The distortion value obtained by the three algorithms are also presented in Table II. It can be observed that the Heuristic algorithm usually has a performance no worse than SP, while the Distortion algorithm has the best performance among the three. Another interesting observation is that sometimes a distortion values found by an algorithm are the same for different mean burst lengths. This is because the paths to the chosen servers in these cases were completely disjoint, where the average distortion D did not depend on mean burst lengths (see (5), (6), and (7)).

In Tables II, ALG-UB outperforms all the three existing algorithms with a significant margin, implying that the latter three algorithms may not be suitable for wireless ad hoc networks, although they have been shown to be quite effective in the Internet. We observed the similar trend in results for large-sized networks (50 to 100-node networks), which we have omitted for the sake of brevity. In wireless ad hoc networks, links have highly diverse qualities. Therefore, only considering hop-count in server selection would not produce good perceived MD video quality. For the Distortion algorithm, although it selects servers based on the computed distortion values, it does not necessarily provide good results since it only considers the default routes from the servers to the client. It may not be efficient in handling the cases when there are low quality links (e.g., low available bandwidth or high loss rates) in the default routes.

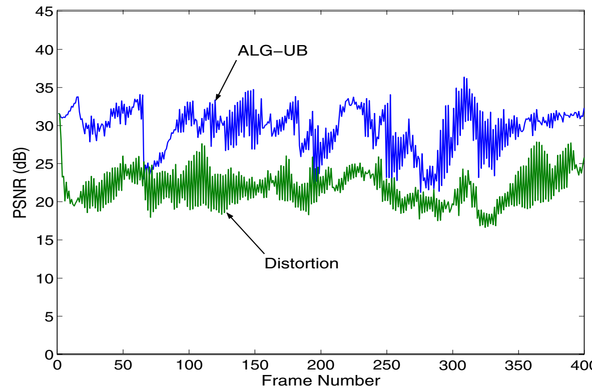


Fig. 5. PSNRs of reconstructed frames obtained by Algorithm ALG-UB and the Distortion scheme.

Since the Distortion algorithm has the best performance among the three existing algorithms, we further compared its performance with ALG-UB by transmitting MD video in a 50-node ad hoc network. There were 10 servers in each server set. We chose a time-domain partitioning coding scheme [4]–[7], [11], where two descriptions are generated by separating the even and odd-numbered frames and coding them separately (with a 10% macroblock level intra-refreshment). For the experiment, the 400-frame QCIF [176×144 Y pixels/frame, 88×72 Cb/Cr pixels/frame] sequence “Foreman” was encoded at 15 fps and $192Kbps$ for each description. The descriptions were then packetized (one GOB per packet) and transmitted over the paths found by the algorithms.

The PSNRs of the reconstructed video frames are plotted in Figure 5. It can be observed that during the period of Frame 65 to 92 and the period of Frame 270 to 290, the ALG-UB curve suffers big drops. By examining the packet loss trace, we found that these valleys were caused by bursty, concurrent loss of packets from both descriptions. Furthermore, the PSNR curve obtained by ALG-UB is well above that obtained by the Distortion algorithm for most of the frames. We also plot the decoded Frame 229 obtained by the two algorithms in Figure 6 to illustrate the visual quality. It can be seen that the image delivered by ALG-UB has a much better quality than that delivered by the Distortion algorithm. The average PSNRs obtained by ALG-UB and Distortion are $29dB$ and $21.9dB$, respectively. By jointly optimizing the routing and server selection decisions, an $8.1dB$ gain in average PSNR has been achieved, which demonstrates the efficacy of the joint routing and server selection approach for MD video in wireless ad hoc networks.

(a) Frame 229 (ALG-UB). (b) Frame 229 (Distortion).

Fig. 6. Reconstructed Frame 229 and Frame 322 at the client node.

V. Practical Implications

In practice, the joint routing and server selection scheme can be incorporated into existing distributed routing protocols for wireless ad hoc networks. Existing routing protocols can be roughly categorized as *proactive*, where a consistent and up-to-date view of the network is always maintained, and *reactive*, where route discovery is performed on-demand. For proactive routing protocols (e.g., OLSR [8]), we can define a new type of Link State Advertisement (LSA), in addition to the original types that report link states and statistics, to represent the availability of video descriptions at each node. Then, a client node can determine the two server sets from the received LSAs and use Algorithm ALG-UB to quickly find near-optimal servers and paths to them.

Under reactive routing protocols (e.g., DSR [9]), we can let the client node broadcast Video Request (VREQ) messages (rather than Route Request (RREQ) messages in the original DSR) to the network in order to discover nodes that host one or both of the video descriptions. Such a node, after receiving the VREQ message, will return a Video Reply (VREP) message (rather than Route Reply (RREP) in the original DSR) to the client, carrying information on which description(s) it has, link statistics, and path information. After receiving a number of such VREPs, the client can construct a partial view of the network and the server sets, and then run Algorithm ALG-UB to select the best servers along with associated routes to them.

VI. Related Work

Caching and server replication are common techniques for providing scalable distributed service over the Internet. The single server selection problem, i.e., how to select a server from a set of mirror sites for a client request so as to provide the "best" service for the client, has been studied over the years (e.g., see [2] and the references therein). In existing server selection schemes, either the client or the servers monitor the server loads and/or network performance (e.g., round trip times (RTT) from the servers to the client) and then select a "best" server that has the lowest load or the lowest delay based on these measurements [2]. These schemes are mainly designed for data applications (e.g., web service) and do not explicitly attempt to optimize video quality. Moreover, the important optimal routing problem has not been addressed.

As discussed, Apostolopoulos *et al.* presented an interesting study of server selection for MD video in the context of CDN networks in [4]. It has been shown that server selection for MD video streaming provides an effective means of exploiting the path diversity provided by CDN. As a result, significant reduction in video distortion has been observed [4]. However, similar to existing approaches for single server selection, the proposed MD server selection algorithms only consider default routes on selecting optimal servers. As a result, the achieved optimal solution by the algorithms in [4] are for a much smaller solution space. Optimal routing, which can further improve MD video quality, has not been considered.

An empirical path distortion model was presented in [4] that computes received SD or MD video distortion from link loss characteristics. Recently, a similar path distortion model was introduced in [11] for MD video in overlay networks, which takes into account more link statistics, such as delay, jitter, and bandwidth, in addition to loss. In this paper, we took a similar methodology as these papers, e.g., modeling the loss process on the joint portion of two paths as a Markov chain and modeling the losses on the disjoint portions as Bernoulli events. Note that the method used for computing the parameters for the consolidated path model is different.

VII. Concluding Remarks

In this paper, we studied the important problem of jointly selecting servers and determining optimal routes for MD video streaming in wireless ad hoc networks. We took an application-centric, cross-layer approach to formulate the joint routing and server selection task as a combinatorial optimization problem that minimizes the received video distortion. We derived a lower bound and an upper bound for the best achievable video distortion. The upper bound was demonstrated to produce a near-optimal pair of servers along with a pair of corresponding paths. The proposed approach can be easily incorporated into existing routing protocols for ad hoc networks. Our extensive numerical results show that the bounds are very close to each other for all the cases studied, indicating the near-global optimality of the derived upper bounding solution. We also observed significant gains in video quality achieved by the proposed approach over existing server selection schemes. This justifies the importance of jointly considering routing and server selection for optimal MD video streaming in wireless ad hoc networks.

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