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Joint routing and rate allocation for multiple video streams in ad-hoc wireless networks*

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Abstract: The support for multiple video streams in an ad-hoc wireless network requires appropriate routing and rate allocation measures ascertaining the set of links for transmitting each stream and the encoding rate of the video to be delivered over the chosen links. The routing and rate allocation procedures impact the sustained quality of each video stream measured as the mean squared error (MSE) distortion at the receiver, and the overall network congestion in terms of queuing delay per link. We study the trade-off between these two competing objectives in a convex optimization formulation, and discuss both centralized and distributed solutions for joint routing and rate allocation for multiple streams. For each stream, the optimal allocated rate strikes a balance between the selfish motive of minimizing video distortion and the global good of minimizing network congestions, while the routes are chosen over the least-congested links in the network. In addition to detailed analysis, network simulation results using ns-2 are presented for studying the optimal choice of parameters and to confirm the effectiveness of the proposed measures.

Key words: Ad-hoc wireless networks, Video streaming, Rate allocation, Multi-path routing
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INTRODUCTION

Ad-hoc networks are attractive owing to their self-organizing nature and absence of a fixed infrastructure. They are particularly suited for communication in disaster-affected areas, coordinating military operations, and sensing environmental conditions. With the growing availability of supporting hardware and decreasing equipment cost, ad-hoc networking based applications are proliferating. Meshes of wireless nodes are being deployed in cities and housing communities to support Internet access and peer-to-peer communication (Cass, 2005; Bicket *et al*., 2005). Streaming of multimedia content over such kind of networks is compelling for many application scenarios, including vehicular platoons, community meshes, and home entertainment networks.

The nodes in an ad-hoc network communicate in a peer-to-peer fashion and help in relaying data from a source to the destination. Routing is a challenging task owing to the dynamic network topology and variations in wireless channel conditions. Over the years several distributed protocols have been proposed and analyzed for ad-hoc routing. Many of them employ simple metrics such as hop count or end-to-end delay while selecting a route between a given source and a destination. Routing mechanisms using the existence of multiple paths between a source-destination pair have also been proposed, and are shown to result in enhanced performance over single-path routing methods (Lee and Gerla, 2000; Marina and Das, 2001).

Video streaming applications additionally impose high rate requirement and stringent latency constraints on resource-limited ad-hoc networks. It is observed that quality of the received video stream is affected not only by encoder quantization, but also by self-inflicted network congestion leading to packet

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drops due to late arrivals (Zhu *et al*., 2005). An attempt to enhance the system performance should therefore account for both metrics in a congestion-distortion optimized fashion. When multiple streams are present in an ad-hoc network, the chosen rate and routes for each stream would also affect the performance of others. Both rate allocation and routing need to be optimized for all streams in the network, preferably in a decentralized manner.

In this paper, we study a convex optimization formulation of the joint routing and rate allocation problem for multiple streams. A centralized solution based on optimal flow assignment is derived as an upper bound of performance. A distributed scheme is also proposed, where the allocated rate at each stream depends on both the distortion-rate (DR) characteristic of the video and the network congestion increment, which in turn is obtained from a distributed routing procedure (Zhu and Girod, 2005a). We show that the optimal global trade-off between total video distortion of all streams versus overall network congestion can be translated into the local balance between reducing encoded video distortion versus constraining network congestion at each stream.

The rest of the paper is organized as follows. In the next section, we present related work on ad-hoc routing protocols and rate allocation for multiple video streams. The network and video models are explained in Section 3, where we also introduce notations used throughout the paper, and provide a convex optimization formulation of the problem. Section 4 summarizes previous work on congestion-distortion optimized routing, which serves as the basis for the joint routing and rate allocation schemes described in Section 5. Network simulation results are discussed in Section 6.

RELATED WORK

Ad-hoc routing protocols

Several ad-hoc routing protocols that have been proposed over the years include proactive table-driven protocols like Destination-Sequenced Distance-Vector (DSDV) routing (Perkins and Bhagwat, 1994) and Optimized Link State Routing (OLSR) (Clausen and Jacquest, 2003), as well as on-demand protocols like Dynamic Source Routing (DSR) (Johnson and Maltz, 1996) and Ad-hoc On-demand Distance Vector (AODV) routing (Perkins *et al*., 2003). The former involve the evaluation and storage of the routing tables pertaining to the topology at each node. The routing tables are periodically updated to counter the topological changes associated with node mobility and wireless channel variations. This can result in significant protocol overhead, especially under high node mobility and dynamic channel conditions. The on-demand protocols on the other hand involve discovery of the route whenever data need to be transmitted between a source-destination pair. They typically incur less overhead traffic than the table-driven protocols, and can consequently better adapt to dynamically varying topologies. Comparative study of various routing protocols has been an active research area in the wireless ad-hoc networking community (Royer and Toh, 1999; Lee *et al*., 1999).

The aforementioned routing strategies evaluate the best sequence of nodes in accordance with criteria like minimum hop or delay, and forward data along a single path. de Couto *et al*.(2002; 2003) pointed out the inadequacy of minimum-hop routing in wireless ad-hoc networks, and proposed alternative link metrics for evaluating a path. Extensions to multi-path routing have also been proposed for multi-path AODV (Marina and Das, 2001) and for ExOR, an opportunistic multi-hop routing strategy that broadcasts data packets to explore multiple paths in the network (Biswas and Morris, 2005). For video streaming, benefits of multi-path routing over ad-hoc networks are demonstrated in terms of robust packet delivery via path diversity (Mao *et al*., 2003; Wei and Zakhor, 2004) and higher sustainable rate and quality due to bandwidth aggregation (Setton *et al*., 2004).

Unlike most previous works that consider routing for generic data traffic over ad-hoc networks, we take into account specific characteristics of video streaming in the evaluation of routes. Network congestion is incorporated explicitly into the route selection metric, to meet the stringent latency requirement for video packet delivery. The rate-distortion characteristic of each stream is also considered in the rate allocation procedure to accommodate multiple streams with various video contents and complexity.

Multi-stream rate allocation

The problem of rate allocation among multiple traffic streams over a common network has been well studied. Kelly provided a mathematical formulation of the problem (Kelly, 1997) and investigated two classes of distributed rate control algorithm corresponding to the primal and dual decomposition of the optimization (Kelly *et al*., 1998). The application of such rate allocation algorithms has been investigated for elastic traffic over the Internet (La and Anantharam, 2002) and for video streaming over ad-hoc networks with 802.11-like wireless nodes (Zhu and Girod, 2005b).

For a more practical setting, a rate allocation algorithm combined with a packet partitioning algorithm has been proposed to support video streaming from multiple senders to a single receiver over the Internet (Nguyen and Zakhor, 2004). The rates are chosen to match the available network bandwidth for each stream, and the packet partitioning is designed to minimize start up delay. For video streaming over a wireless hop, a rate control scheme has been shown to efficiently utilize the available wireless link capacity using multiple TFRC connections (Chen and Zakhor, 2004).

Our approach targets rate allocation in conjunction with route selection. The optimization objective function is comprised of both video distortion and network congestion. This differs from most existing works where routing and rate allocation are performed separately, without the notion of limiting overall network congestion.

PROBLEM FORMULATION

In this section we explain the wireless network model and a parametric video distortion-rate (DR) model used for formulating the joint routing and rate allocation problem. A convex optimization framework is also presented, together with the notations used throughout the rest of the paper.

Wireless network model

Consider an ad-hoc network comprised of N nodes. The collection of links between neighbouring node pairs in the network is designated as:

$$L=\{(i,j) \mid \text{Node } j \text{ can hear Node } i\}. \tag{1}$$

The link capacity from Node i to Node j is denoted as C_{ij}, and the set of link capacities can be represented as:

$$C=\{C_{ij} \mid (i,j)\in L\}. \tag{2}$$

Let F_{ij} represent the background traffic from Node i to Node j, already present before any new video stream is initiated. The set of background traffic over the network is denoted by:

$$F_{\text{cross}}=\{F_{ij} \mid (i,j)\in L\}. \tag{3}$$

When a node in the network initiates a video stream transfer, additional traffic flows are introduced over the links chosen by routing. The set of these flows is expressed as:

$$F=\{f_{ij} \mid (i,j)\in L\}. \tag{4}$$

We denote congestion on each link as the average queuing delay normalized by the average packet size, and congestion over the network as the sum of all link delays weighted by the traffic rate on each link. In general, the total congestion X is a function of link capacities C and existing flow rates F_{cross} and F. Following the M/M/1 queuing model, the congestion on each link can be expressed as $1/(C_{ij}-F_{ij}-f_{ij})$, and thus the total congestion becomes:

$$X=\sum_{(i,j)\in L}\frac{F_{ij}+f_{ij}}{C_{ij}-F_{ij}-f_{ij}}. \tag{5}$$

When the M/M/1 assumption does not hold, the above expression can be viewed as an approximation of the average link delay, capturing the non-linear dependency of delay on traffic flow (Kleinrock, 1976).

Video distortion-rate model

Denote the set of video streams presented in the network as S. Each stream $s\in S$ is associated with a mean squared error (MSE) decoding distortion of D_s when encoded and streamed at a rate R_s. The distortion-rate (DR) characteristic of each stream can be fitted to a parametric model (Stuhlmüller *et al*., 2000):

$$D^s(R^s)=D_0^s+\frac{\theta^s}{(R^s-R_0^s)}, \tag{6}$$

where the parameters D_0^s, θ^s and R_0^s depend on the coding scheme and the content of the video. They can be estimated from three or more trial encodings using non-linear regression techniques. The operational range of encoded video rate is $[R^s_{\min}, R^s_{\max}]$.

We will show later in Section 5.2 that, by representing the video DR characteristic using a parametric model, one can derive analytical expressions for distortion reduction per rate increment: this facilitates the rate allocation procedure. It should also be pointed out that the optimization framework discussed in this paper is general enough to accommodate any other video distortion-rate model as long as it is convex.

Optimization objective

We denote as $F_s=\{f^s_{ij} | (i,j)\in L\}$ the traffic flows introduced by the video rate R^s from Stream s, originating from source node $src(s)$ and terminating at destination $dst(s)$. Due to the latency constraint of video streaming, increasing the allocated rate R^s would introduce excessive network congestion, which in turn causes severe degradation of received video quality. On the other hand, decreasing the allocated rate leads to higher video distortion during encoding. We therefore seek to strike a balance between both objectives, and minimize the Lagrangian sum of total video distortion and overall network congestion:

$$\min \sum_{s\in S} D^s(R^s) + \lambda X(C, F_{\text{cross}}, F). \tag{7}$$

The optimization is over all R^s for rate allocation and F for route selection for all streams in S. The choice of λ adjusts the trade-off between distortion and congestion. Incorporating the M/M/1 model for calculating congestion Eq.(5) and the video distortion model Eq.(6), this is equivalent to:

$$\min_{\text{s.t.}} \sum_s \frac{\theta^s}{R^s - R^s_0} + \lambda \sum_{(i,j)} \frac{F_{ij}+f_{ij}}{C_{ij}-F_{ij}-f_{ij}}, \tag{8a}$$

$$f_{ij} = \sum_s f^s_{ij},\ \forall (i,j)\in L, \tag{8b}$$

$$0 \le f_{ij} < C_{ij} - F_{ij},\ \forall (i,j)\in L, \tag{8c}$$

$$\sum_{r:(n,r)\in L} f^s_{n,r} - \sum_{r:(r,n)\in L} f^s_{r,n} = \begin{cases} -R^s, & n = src(s), \\ R^s, & n = dst(s), \\ 0, & \text{otherwise.} \end{cases} \tag{8d}$$

$$R^s_{\min} \le R^s \le R^s_{\max},\ \forall s\in S. \tag{8e}$$

It can be easily verified that the objective is convex over the variables f^s_{ij}, f_{ij}, R^s, where $(i,j)\in L$, $s\in S$.

All constraints to this optimization problem are linear, as given in Eqs.(8b)~(8e). In particular, Eq.(8d) states that for any stream s, the net incoming flow for stream s equals $-R^s$ for $src(s)$ and R^s for $dst(s)$. The net incoming flow of all other nodes from stream s is zero, i.e., there is flow conservation.

CONGESTION-OPTIMIZED MULTI-PATH ROUTING

Consider a simpler special case of the problem formulated in Eq.(8), where only one video stream is involved, and its rate R^s is fixed. This then becomes the classical problem of minimizing network congestion via optimal flow assignment (Kleinrock, 1976; Bertsekas and Gallager, 1987). A centralized routing and traffic partitioning algorithm is proposed for video over ad-hoc networks, where multiple routes are extracted from the optimal flow assignment result, and the total traffic is dispersed over the multiple paths in a congestion-optimized manner (Setton *et al.*, 2004).

This centralized scheme, however, requires knowledge of global network information such as capacities and flows along all the links, which restricts the scalability of the network. The computational complexity of the optimization and route extraction from the flow assignment may also exceed the capabilities of any single node in the network. To counter the problem, a distributed algorithm for multi-path routing of the video stream is proposed (Zhu and Girod, 2005a). The total rate of the video stream R is split into K small increments such that $R=\sum_{k=1}^{K}\Delta R_k$. Then the optimal allocation of increment ΔR_k can be achieved by finding a path P^*_k that accomplishes the following:

$$\min_{P_k} \sum_{(i,j)\in P_k} \frac{C_{ij}}{(C_{ij}-F'_{ij})^2}\Delta R_k, \tag{9}$$

where $F'_{ij}=F_{ij}+\sum_{k'=1}^{k} f^{k'}_{ij}$ includes existing background traffic F_{ij} and $k-1$ rate increments from the present stream. Note that the minimization objective in Eq.(9) corresponds to end-to-end accumulated sum of $C_{ij}/(C_{ij}-F'_{ij})^2$, which can be interpreted as "congestion sensitivity" over that link (i.e., amount of increase in congestion per unit increase in rate). Consequently, the optimal path P_k^* in Eq.(9) can be found via the distributed Bellman-Ford algorithm (Ford and Fulkerson, 1962), by setting the link cost to congestion sensitivity. Every node maintains a minimum-cost path from itself to the source, exchanges this information with its neighbors, and updates to a lower cost path if it discovers one via a neighbor. When the destination node reports the chosen path for a given rate increment ΔR_k to the sender, it can easily append the corresponding accumulated congestion sensitivity value to the path information, for later use in the rate allocation process as explained in the next section. The reader is referred to the original paper for further details of the distributed routing protocol.

JOINT ROUTING AND RATE ALLOCATION

For the more generic scenario of multiple sources streaming video in the ad-hoc network, we show in this section how route selection and rate allocation for each stream can be jointly optimized to trade-off between overall network congestion and total video distortion of all streams.

Centralized solution

The optimal rate allocation and flow assignment for the streams in S can be obtained by solving the convex optimization problem in Eq.(8) using standard techniques, e.g., the interior point method (Nesterov and Nemirovsky, 1994). Multiple routing paths can then be extracted from the optimal flow assignment result (Setton *et al.*, 2004). The complexity of the process can be limited by restricting the number of extracted paths along which a stream is to be routed.

Although the centralized solution provides an upper bound of performance in terms of congestion-distortion trade-off, it relies on several impractical assumptions. The algorithm requires knowledge of global information pertaining to network topology L, capacity C, background traffic rate F over all links, and video distortion model parameters R_0^s, θ^s of all streams in S. In practice, the collection of link state information C and F would incur overhead traffic; the RD model parameters might simply not be available at nodes other than the source and destination due to security or privacy concerns. Moreover, the complexity of centralized optimization may exceed the computational capability of any wireless node in an ad-hoc network. It is hence desirable to investigate a distributed algorithm where rate allocation is performed for each stream separately and routes are discovered over the network in a decentralized manner.

Distributed scheme

We next discuss the framework for a distributed methodology to allocate rate to a video stream s. The Karush-Kuhn-Tucker (KKT) necessary and sufficient conditions for the optimal solution to Eq.(8) state that the allocated rate to Stream s should either meet the boundary condition exactly, or correspond to zero partial derivative (Boyd and Vandenberghe, 2004):

$$\frac{\mathrm{d}D^s}{\mathrm{d}R^s}+\lambda\frac{\mathrm{d}X}{\mathrm{d}R^s}=0. \tag{10}$$

In Eq.(10), $\mathrm{d}D^s/\mathrm{d}R^s$ is derived from the video distortion model Eq.(6) as

$$\frac{\mathrm{d}D^s}{\mathrm{d}R^s}=-\frac{\theta^s}{(R^s-R_0^s)^2}. \tag{11}$$

Hence the distortion reduction caused by increasing encoding rate by $\Delta R_{(k)}^s$ is

$$-\Delta D_{(k)}^s\approx\frac{\theta^s}{(R^s-R_0^s)^2}\Delta R_{ij,(k)}^s. \tag{12}$$

The slope of congestion increment $\mathrm{d}X/\mathrm{d}R^s$, on the other hand, can be expressed as:

$$\frac{\mathrm{d}X}{\mathrm{d}R^s}=\sum_{(i,j)\in L:f_{ij}^s>0}\frac{C_{ij}}{(C_{ij}-F_{ij}-f_{ij}^s)^2}. \tag{13}$$

If the rate-allocation is performed in sufficiently small increments $\Delta R_{(k)}^s$ at each step k, one can further confine the corresponding flow increment $\Delta f_{ij,(k)}^s$ to a single path $P_{(k)}^s$ (Zhu and Girod, 2005a). The resulting congestion increment $\Delta X_{(k)}^s$ can then be approximated as:

$$\Delta X_{(k)}^s \approx \sum_{(i,j)\in P_{(k)}^s} \frac{C_{ij}}{(C_{ij}-F'_{ij})^2}\Delta R_{(k)}^s, \tag{14}$$

where cross-traffic F'_{ij}'s include contributions from other video streams and previously assigned rate increments:

$$F'_{ij} = F_{ij} + \sum_{s'\in S:s'\neq s} f_{ij}^{s'} + \sum_{k'=1}^{k-1} f_{ij,(k')}^{s}. \tag{15}$$

Note that Eq.(14) is the same as the optimization criterion in Eq.(9) for routing, and can be accumulated over the chosen links of a path. This information is then collected at the destination node and fed back to the source.

Given the congestion increment $\Delta X_{(k)}^s$ in Eq.(14) and the video distortion reduction in Eq.(12), the source node can make the rate allocation decision by comparing the two quantities. The allocated rate will be increased by $\Delta R_{(k)}^s$ until $-\Delta D_{(k)}^s > \lambda \Delta X_{(k)}^s$, i.e., when the benefit of distortion reduction is no longer worthwhile the consequential network congestion. Due to the convex nature of both D^s and X, the initial distortion reduction is typically significant for small rate increments, whereas increase in network congestion starts out slowly. Therefore, the rate allocation algorithm can continue until it reaches the optimal rate that strikes a balance between the two trade-off slopes.

When multiple streams are present in the network, each of them performs joint routing and rate allocation as described above, treating the flows from other video streams as background traffic. This procedure needs to be carried out periodically at each stream, adapting to the dynamic nature of the underlying wireless channel conditions, accommodating newly initiated video streams, and reallocating overall network resources after the termination of a certain video stream.

The scheme can be naturally extended to also handle admission control. Given a minimum quality and rate requirement for a newly initiated video stream, the source node can invoke the joint rate allocation and routing procedure for that stream, and admit the new stream if the allocated rate is greater than the minimum request.

SIMULATION RESULTS

Experimental setup

Simulations are performed in a network with 15 stationary nodes randomly placed in a 500 m-by-500 m square, as illustrated in Fig.1. Nodes within 250 m of each other are considered neighbors, and can communicate directly. Link capacities from Node i to Node j are computed as:

$$C_{ij} = \frac{BW}{2}\log(1+\gamma SINR_{ij}), \tag{16}$$

where signal-to-interference-plus-noise-ratio $SINR_{ij}$ is calculated assuming simultaneous fixed power transmission at all nodes, BW is the double-sided bandwidth for transmission, and the coding gain γ<1 indicates the performance gap of a practical channel coder with respect to Shannon's information-theoretical limit (Rappaport, 1996).

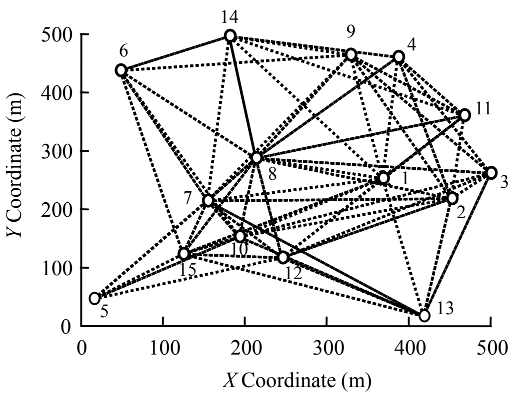

Fig.1 Example network with 15 nodes randomly positioned in a 500 m-by-500 m square area. Dashed lines indicate the link between two neighboring nodes. All three video streams are sent from Node 3 to Node 6

Here, the network model assumes that the underlying media access control follows a fixed CDMA procedure, where multiple nodes can simultaneously transmit and receive, and the effect of interference is captured in the calculation of the $SINR$ values. For other networks such as one operating under the IEEE 802.11b protocol, the link capacities also depend on the traffic rate and contention from adjacent flows. It will be a more challenging task to determine the link capacity values.

Three CIF video sequences, Foreman, Mother and Daughter, and Bus are encoded using the H.264/AVC reference codec (http://iphome.hhi.de/suehring/tml/) at 30 fps. As the contents of the video sequences differ, their respective distortion-rate characteristics are also different, as illustrated in Fig.2. A discrete set of available rates is obtained by encoding each video sequence at various quality levels. The number of paths used for routing is limited to be 3.

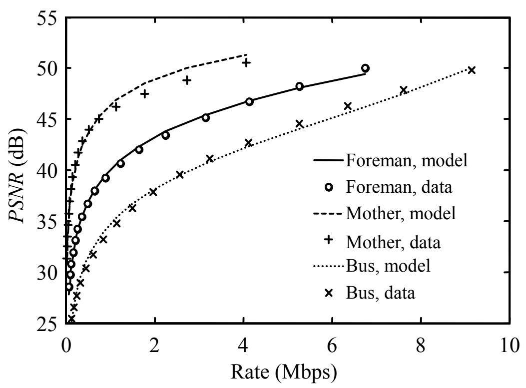

Fig.2 Rate-*PSNR* performance of Foreman, Mother and Daughter, and Bus CIF sequences, all encoded using H.264/AVC at 30 frames/s, with GOP length of 15. The experimental data points are fitted with the model curve

The solution to the centralized scheme in Section 5.1 is calculated as an upper bound of performance, whereas the distributed algorithm is executed using various rate increments: 20, 50, 100 and 200 kbps.

Network simulations using ns-2 (http://www.isi.edu/nsnam/ns/) are also performed to evaluate the distributed algorithm in terms of received video quality. The background traffic is simulated using packets with fixed size of 500 bytes and exponentially distributed arrival intervals on each link, with randomly assigned average bit rate of up to 50% of link capacity. For video traffic, the actual encoded packet traces are used. Packets are dropped if they do not arrive at the receiver by the playout deadline 350 ms. Previous-frame concealment is used in the decoder to recover from dropped video packets. For each experiment, the video sequence is looped for more than 500 s, corresponding to 50, 150, and 100 realizations for Foreman, Mother and Daughter, and Bus respectively. The calculated average values of all realizations are interpreted as the expected performance of the algorithm in a snapshot of time for the given network.

Single stream

In this section, we study the simple special case where only one video stream is present in the network. Fig.3 shows the allocated rate and corresponding video distortion and network congestion[1], for each of the streams by varying its trade-off choice λ. Smaller values of λ lead to higher allocated rate and encoded video quality, at the expense of greater network congestion. Due to the difference in RD characteristics of the sequences, their allocated rates also differ for the same given λ. The Mother and Daughter sequence with slow motion is allocated a lower rate, achieving higher encoded video quality. Whereas the Bus sequence is allocated a much higher rate corresponding to lower quality, due to its active content and hence the steeper rate-distortion trade-off curve. It is also interesting to note that for all three video streams, the resulting rate-congestion trade-off over the network is the same, as the routing algorithm is congestion-minimized and performs regardless of video content.

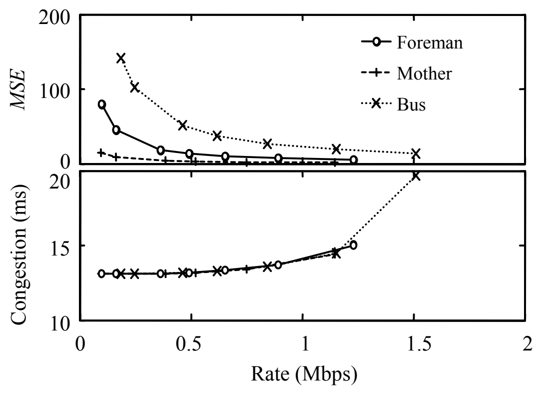

Fig.3 Trade-off between network congestion in terms of average link delay and video distortion in MSE resulting from the joint routing and rate allocation scheme, when streaming a single video sequence over the network

Results from network simulation are shown in Fig.4 for sequence Foreman. The decoded video qual-

[1] Network congestion is shown here in the sense of average link delay of all packets in the network, which is X (see Eq.(5)) normalized by the total traffic over all links in the network

ity is plotted against the allocated rate and network congestion respectively. The encoder quality is also shown in dashed lines for reference. Here it is observed that the reconstructed video quality degrades when the chosen λ is too small, which leads to high allocated rate of the video and consequently excessive network congestion. As the video streams are decoded with a latency constraint, the self-inflicted network congestion at too high a rate causes a greater percentage of the video packets to arrive too late at the decoder, thus suffering from severe quality drop. Similar phenomena are observed for the other two sequences.

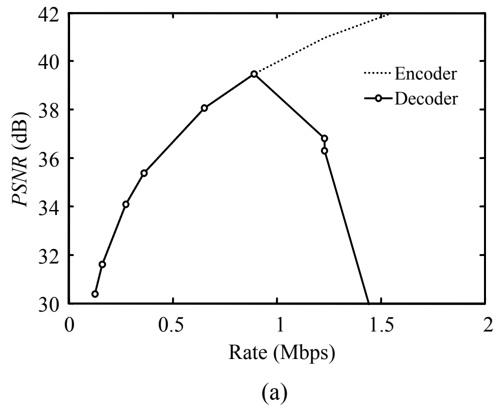

Fig.4 Encoded and received video quality in PSNR versus (a) allocated rate and (b) network congestion in terms of average link delay, when streaming the Foreman sequence over the network using joint routing and rate allocation

Multiple streams

We next evaluate the performance of the proposed optimization measures with multiple video streams. Note that if the chosen routes for each stream travel over non-overlapping links, then the network can be decomposed into independent subsets supporting each stream unaffected by others, which reduces to the scenario in the last subsection[2]. In order to investigate the interactions among multiple streams, we choose the same source and destination nodes for all streams so as to have shared links in the chosen routes.

Fig.5 illustrates the initial and final routes chosen for all three streams during the optimization of the joint routing and rate allocation process. The corresponding rate allocated to each stream is shown in Fig.6 over iteration steps. It can be observed that the selected routes for two of the streams (Mother and Daughter in dashed line and Bus in dotted line) have

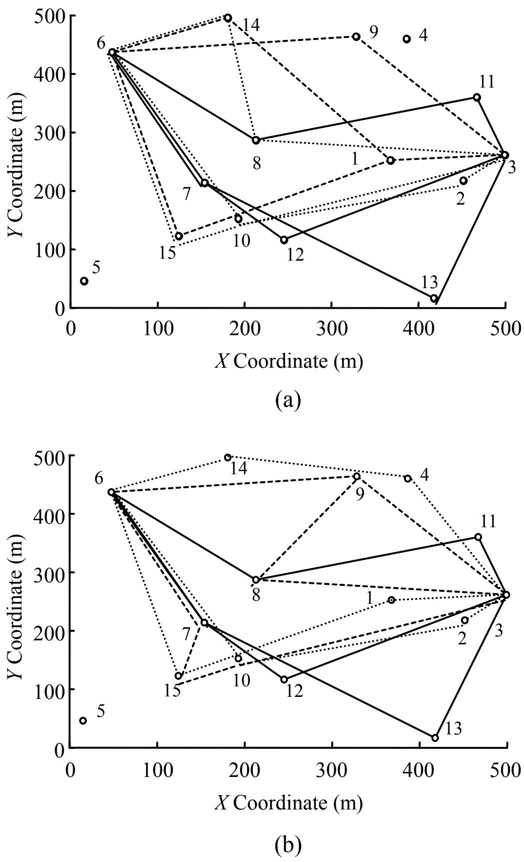

Fig.5 (a) Initial and (b) final route selections of all three streams: Foreman in solid line, Mother and Daughter in dashed line and Bus in dotted line. Two routes for Mother and Daughter and three routes for Bus have changed over the iterations. For this instance, the λ in Eq.(8a) is chosen to be 0.1, and the rate increment is 100 kbps

[2] This is a consequence of the assumption of fixed link capacities in our simple wireless network model. In practice, the existence of traffic over other wireless links may affect the capacity of the current link via increased interference or contention, the study of which is intended for future work

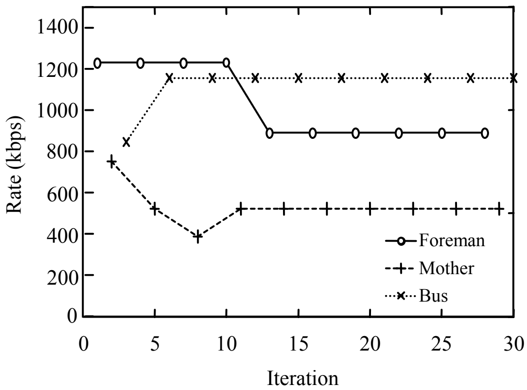

Fig.6 Allocated rate for each stream over the iterations, corresponding to the same settings in Fig.5

changed over the iterations, each re-dispensing its own traffic over the network to avoid already congested links. Changes in the routes also affect the congestion-increment information calculated during routing, which in turn leads to changes in the rate allocation decisions.

In Fig.7 the trade-off between overall network congestion and average video distortion of all streams is compared among various schemes. It can be noticed that finer rate increments in the distributed algorithm yields slightly better results. When λ is large, implying a heavy penalty for network congestion in the optimization objective, the performance of all the schemes are essentially the same. As λ decreases and more congestion is allowed in the network, with higher allocated rate, the performance gaps between the centralized and distributed schemes become more pronounced.

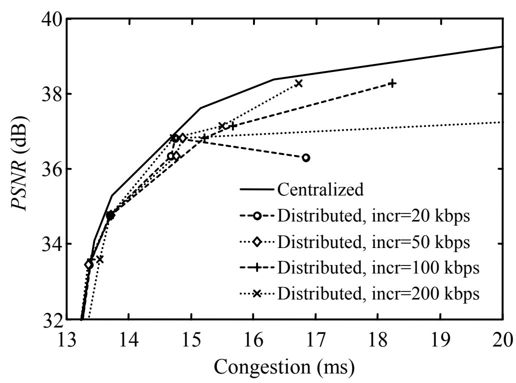

Fig.7 Trade-off between overall network congestion in terms of average link delay and average video quality of all three video streams in PSNR, using the proposed distributed joint routing and rate allocation algorithm. The performance of the centralized solution is also plotted in solid lines for reference

CONCLUSION

In this work, a congestion-distortion optimized framework is investigated for streaming multiple videos in a common wireless ad-hoc network. We propose a distributed scheme for joint routing and rate allocation. The allocated rate at each video stream is chosen to achieve a common trade-off slope between network congestion increment obtained during the routing procedure, and reduction in video distortion. When a minimum quality and rate requirement is imposed on each video stream, the scheme can be naturally extended to handle admission control. A centralized solution for joint flow assignment and rate allocation is also derived to serve as an upper bound of performance.

Simulation results confirm the effectiveness of the scheme in achieving the optimal congestion-distortion trade-off for the overall system. Compared to the performance bound provided by the centralized solution, various versions of the distributed algorithm are shown to incur small loss of optimality when the network is not congested.

As part of future work, we intend to investigate joint routing and rate allocation over a more realistic wireless network model, for instance one capturing the CSMA/CA MAC behaviors of the widely used 802.11 devices. Simulation comparison against conventional benchmark schemes such as min-hop routing or TCP-friendly rate control will also be conducted for a more comprehensive evaluation of the proposed congestion-distortion optimized algorithm.

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