

# CONGESTION-OPTIMIZED MULTIPATH STREAMING OF VIDEO OVER AD HOC WIRELESS NETWORKS

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## ABSTRACT

We analyze the benefits of optimal multipath routing on video streaming, in a band-limited ad hoc network. In such environments the actions of each node can potentially impact the overall network conditions. Thus optimal routing solutions which seek to minimize congestion are attractive as they make use of the resources efficiently. For low-latency video streaming, we propose to limit the number of routes to overcome the limitations of such solutions. To predict the performance in terms of rate and distortion, we develop a model which captures the impact of quantization and packet loss on the overall video quality. Simulations are performed to illustrate the advantages of the multipath congestion-based partitioning scheme and confirm the validity of the model.

## 1. INTRODUCTION

In ad hoc networks, nodes self-organize to create a mesh, in which each node can act as a source, a destination or a relay for traffic. The flexibility offered in such networks may be leveraged in a variety of contexts. For example, in disaster areas or in search-and-rescue operations, it is very appealing to be able to rapidly deploy a wireless ad hoc network without the need of a fixed infrastructure. However, because of adverse channel conditions and potential node mobility, traditional networking tasks such as routing can be challenging even when the number of nodes is limited.

Several distributed routing protocols exist and have been tailored to wireless ad hoc networks [1, 2]. Routes can either be stored in routing tables and periodically updated at each node [3], or discovered on demand by the sources [4]. In most wireless ad hoc networks, the action of a single user may affect the rest of the network, for instance by saturating a bottleneck link. Consequently, the network conditions may change frequently. This makes traditional table driven algorithms less efficient and motivates the use of on-demand

source routing protocols. Some of these schemes extend to multipath routing and provide several mostly independent paths [5]. The use of multiple routes reduces the frequency of path updates and increases robustness against changes in the network condition.

Routing algorithms generally share the goal of minimizing the number of hops between source and destination. An alternative approach is to minimize the overall network congestion. The classic problem of congestion-optimized routing has been analyzed for generic networks [6]. Path diversity is one important characteristic of the solutions to such problems. In this paper, we study the benefits of optimal multipath routing for low-latency streaming of video, and attempt to model its impact in a band-limited environment.

The rest of the paper is organized as follows. We give a simple model of an ad hoc wireless network in Section 2 and explain how to formulate the congestion-minimized routing problem in Section 3. To bypass the complexity of the optimal solution, an approximate solution based on a given set of paths is also presented. In Section 4, we describe a video distortion model which captures the influence of compression and that of network congestion. The rate distortion tradeoff predicted by this model will be analyzed and compared to experimental results in Section 5 for the proposed scheme and for a heuristic scheme.

## 2. WIRELESS AD HOC NETWORK MODEL

We consider an ad hoc wireless network with 15 nodes randomly placed within a 100m-by-100m square. In such a network, the *signal-to-interference-plus-noise-ratio* ( $SINR_{ij}$ ) and the link capacity ( $C_{ij}$ ) from node  $i$  to node  $j$  can be calculated from [7]:

$$SINR_{ij} = \frac{d_{ij}^{-\alpha}}{BN + \sum_{\substack{k \neq j \\ k \neq i}} d_{kj}^{-\alpha}} \quad (1)$$

$$C_{ij} = \frac{B}{2} \log(1 + \gamma SINR_{ij}) \quad (2)$$

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where  $d_{ij}$  is the distance between node  $i$  and node  $j$ ,  $\alpha$  denotes the path loss exponent,  $N$  represents the power spectral density of the noise,  $B$  is the bandwidth and  $\gamma$  is the coding gain. In this model the transmission power is equal at all nodes. In the following, we will assume the nodes are static and base our analysis on the capacity map derived from 2, with  $N = 0$ ,  $\alpha = 2$  and  $\gamma = 1$ . While this is a simplified model for the wireless ad hoc network, the analysis we present would be easily extended to more sophisticated link capacity calculation.

### 3. CONGESTION-MINIMIZED MULTIPATH ROUTING

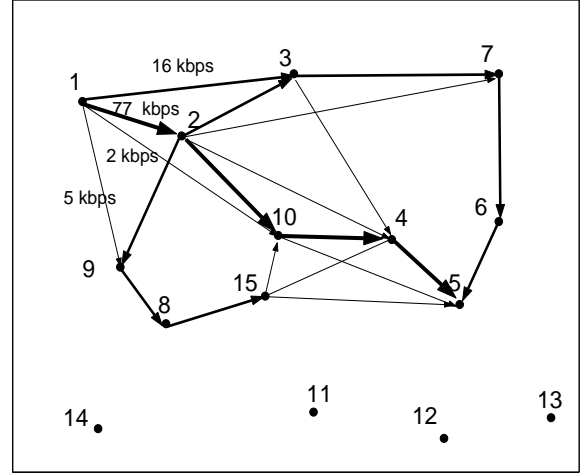
The problem of congestion-optimized flow assignment on a generic network has been studied extensively, see e.g. [6][8]. Based on [6] and assuming the M/M/1 queuing model, the average delay over the network has a closed form expression which only depends on the capacity of the links and on the network traffic flows. This average delay is a convex function of the flows and can be used as a measure of congestion. Minimizing the network congestion results in the following convex optimization problem :

$$\text{Min.} \quad \sum_{(i,j)} \frac{f_{ij} + F_{ij}}{C_{ij} - F_{ij} - f_{ij}} \quad (3)$$

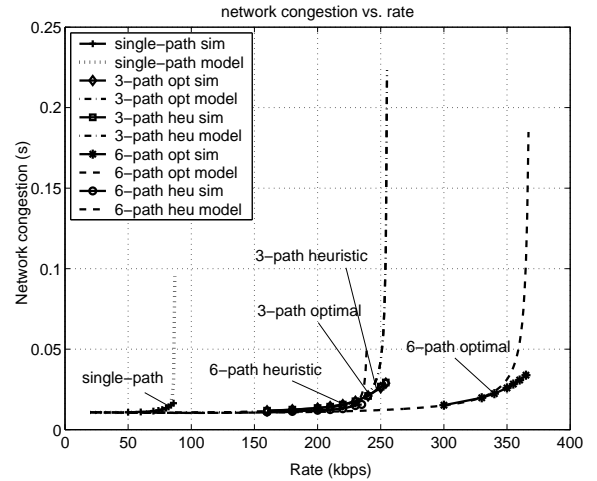
In (3), the sum is taken over all the links of the network.  $F$  is a constant matrix indicating background traffic and  $f$  is a variable matrix indicating new traffic to be routed over the network. In addition, the variables  $f_{ij}$ 's need to satisfy rate constraints at the source and at the destination, flow continuity and positivity, all of which are linear constraints.

As an example, a solution to this problem is shown for a 15-node network randomly distributed on a 100m-by-100m square. Figure 1 illustrates the optimal allocation of 100 kbps from node 1 to node 5. This optimal solution has two main limitations. First, its complexity renders the implementation of such a solution impractical. Second, in order to compute the optimal solution each source node needs to know the capacity map of the network and the prior traffic on each link, which is unrealistic.

As an alternative, traffic can be limited to a set of predetermined paths. In this case, the only information required to perform the optimization is the state of the links of this set. Even in this simplified case, performing the traffic partitioning optimally can lead to large gains in terms of bandwidth utilization. Figure 2 shows the difference in terms of congestion between the optimized routing scheme and a heuristic scheme. The latter performs load balancing with respect to the bottleneck of each path, but is oblivious to the existence of joint links. Experimental points are obtained



**Fig. 1.** Optimal flow assignment example. The width of the arrows reflects the data rate of the additional flows.



**Fig. 2.** Average network congestion for data transmission using routing over 1 path, 3 paths and 6 paths.

from network simulations (see Section 5) for traffic following Poisson processes and plotted on top of the curves for the M/M/1 model. Results are shown for a set of 1, 3 and 6 paths. The selected paths are the ones carrying the most traffic in the globally optimum solution. When only one path is used, both schemes are obviously equivalent. In the 3-path case, the links of the paths are largely independent, hence the optimal routing strategy reduces to the load-balancing heuristic scheme at high rates. Note that the amount of traffic supported by the network is almost tripled compared to the single-path routing case. In the 6-path case, however, as the network resources are increasingly stressed by higher bit rate, due to the presence of joint links in the paths, the optimal scheme yields significantly lower network congestion than the heuristic algorithm.

#### 4. VIDEO DISTORTION MODEL

For live video streaming applications, video packets are transmitted over the network and need to meet a playout deadline. Decoded video quality at the receiver is therefore affected by two factors: encoder compression performance and distortion due to packet loss or late arrivals. Assuming an additive relation of these two independent factors, a video distortion model can be derived based on [9].

With the *Mean Squared Error (MSE)* criterion, distortion of the decoded video is:

$$D_{dec} = D_{enc} + D_{loss}. \quad (4)$$

The encoder distortion may be modelled by :

$$D_{enc} = D_0 + \theta/(R - R_0), \quad (5)$$

where  $R$  is the rate of the video stream, and the parameters  $D_0$ ,  $\theta$  and  $R_0$  are estimated from empirical rate-distortion curves via regression techniques.

In addition, we suppose, as in [9], that  $D_{loss}$  is linearly related to the packet loss rate :

$$D_{loss} = \kappa P_{loss}, \quad (6)$$

where the scaling factor  $\kappa$  depends on the encoding structure, e.g., the ratio of intra-coded blocks. Based on the  $M/M/1$  queuing model, the delay distribution of packets is exponential:

$$\text{Prob}\{Delay > T\} = e^{-\lambda T}, \quad (7)$$

where  $\lambda$  is determined by the average delay:

$$\mathbf{E}\{Delay\} = 1/\lambda = L/(C - R) \quad (8)$$

for a single link of capacity  $C$  supporting the bit-rate  $R$  and average packet size  $L$ . Together with the random packet loss rate  $P_r$  due to transmission errors, the total packet loss rate is:

$$P_{loss} = P_r + (1 - P_r)e^{-(C-R)T/L}, \quad (9)$$

where  $T$  denotes the maximum delay allowed for each packet. Combining (4)-(9), the received video distortion can be expressed as:

$$D_{dec} = D_0 + \theta/(R - R_0) + \kappa(P_r + (1 - P_r)e^{-(C-R)T/L}). \quad (10)$$

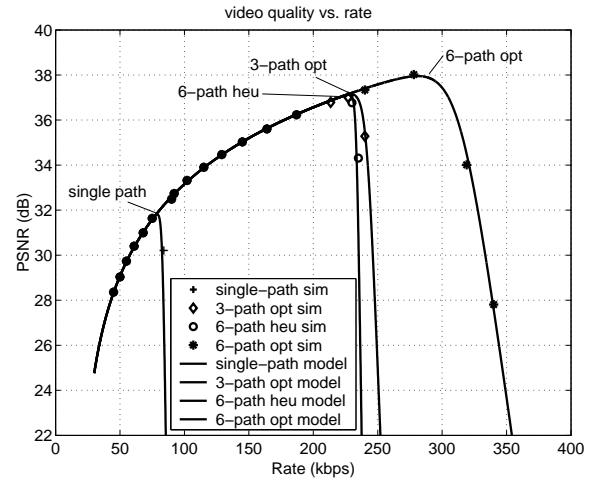
Although this formula is derived for the single  $M/M/1$  link, we propose to generalize it to the case of video transmission over a multi-hop, multipath network. In this case,  $C$  will denote the maximum rate supported by a given routing scheme, and  $R$  will be the sum of the rates over the considered paths. The value of  $T$  now needs to be determined empirically. It is interesting to note that changes in

the real playout deadline seem to be reflected linearly in the variation of the fitted parameter  $T$ .

The proposed formula models the impact of the rate on the video distortion. At lower rates, reconstructed video quality is limited by coarse quantization, whereas at high rates, the video traffic leads to higher network congestion, hence more packet drops due to delays and reduced reconstruction quality. For live video steaming in a bandwidth-limited environment, we therefore expect to achieve maximum decoded quality for some intermediate rate.

#### 5. SIMULATION RESULTS

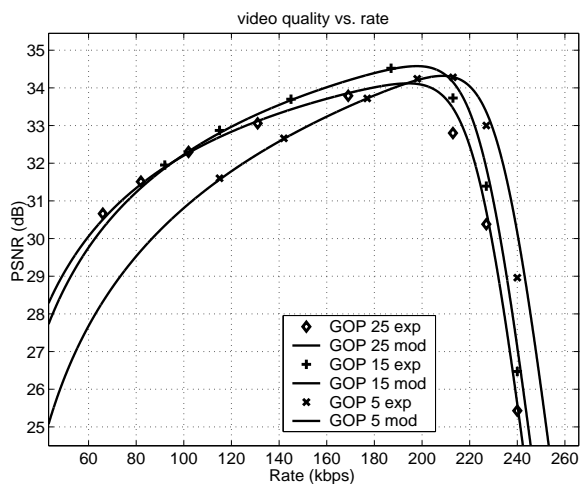
Simulations are performed over the 15-node network shown in Fig. 1 using the network simulator ns-2 [10]. Video traffic is streamed from node 1 to node 5 using the proposed and the heuristic schemes. We use the Constant Bit Rate (CBR) model in ns-2 for video traffic and enable source routing to compare the different schemes. Cross traffic is specified randomly, up to 50% of the capacity on each link, with exponentially distributed packet sizes. We generate and decode the *Foreman* QCIF video sequence using the H.26L codec, at 30 frames per second at various quantization levels and for different *Group of Pictures (GOP)* lengths. Packets are dropped if they do not arrive at the receiver by their playout deadline.



**Fig. 3.** Rate-PSNR performance for live video streaming using single-path, 3-path and 6-path routing with different traffic partitioning algorithms.

Figure 3 shows the tradeoff of decoded video quality versus transmission rate using the optimal and the heuristic traffic partitioning schemes with various numbers of paths. The playout deadline is set to 500 milliseconds (ms). Decoded video quality is measured in terms of *Peak-Signal-to-Noise-Ratio (PSNR)* of the luminance component. The

individual points obtained from experiments are fitted with the solid lines predicted from the proposed distortion model. While the low rate region of the curve follows closely the encoder rate-PSNR performance as few packets experience excessive delays, there is a sharp degradation when the rate exceeds a certain threshold, as predicted by the model. This is the region where some bottleneck link is overwhelmed by the video stream, and received video quality is predominantly affected by late packet arrivals. By using more paths for routing and partitioning the traffic in a congestion-optimized fashion, the video stream can be transmitted at higher rates without incurring excessive network congestion, hence decoded with better quality. Compared to the single link case, 6-path routing leads improves the performance by up to 6 dB in terms of PSNR. The proposed scheme also outperforms the heuristics by 1 dB in PSNR.



**Fig. 4.** Rate-PSNR performance for live video streaming using 3-path optimal routing and different coding structures, with 1% of random packet loss

In Fig. 4, we compare the influence of different video coding structures for 3-path optimal routing. The GOP length is chosen to be 5, 15 or 25. The playout deadline is set at 350 ms and a random loss rate of 1% is simulated on each path. At very low bit rates, there is no loss due to congestion and the best GOP length is 25 as this stream is encoded with highest efficiency. As the rate increases, however, the video stream with the longest GOP suffers most severely from packet drops due to late arrivals, whereas the intermediate GOP length of 15 achieves the best tradeoff between coding efficiency and robustness against losses as predicted by the distortion model.

## 6. CONCLUSION

We analyze the impact of path diversity on live video streaming in wireless ad hoc networks. A congestion-optimized traffic partitioning scheme is proposed and compared to a load balancing heuristic. For live video streaming, we derive a video distortion model to incorporate contributions from both encoder distortion and packet loss due to congestion. This model also predicts the rate-distortion tradeoff of different video coding structures in a bandwidth-limited network. Simulation results confirm the validity of the model and show that gains of 6 dB in PSNR of reconstructed video quality can be achieved if traffic partitioning is performed optimally among multiple routes.

## 7. ACKNOWLEDGMENTS

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