Optimized multi-path routing using dual decomposition for wireless video streaming

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Abstract—For video streaming over wireless ad hoc networks, source rate allocation and routing scheme are two important issues. In this paper, we propose a fully distributed algorithm to jointly optimize the source rate and routing scheme. We use dual decomposition to separate the optimization problem into multiple subproblems, which are then solved in parallel. The distributed nature of the proposed algorithm is extremely adequate for wireless ad hoc networks. Simulation results show that the proposed routing scheme outperforms some existing multi-path routing schemes.

I. INTRODUCTION

With the recent advance in the technologies of digital video and wireless communications, there is an increasing expectation on enabling real-time video streaming over wireless ad hoc networks, in addition to just data communications. For instance, a soccer fan in a stadium may like to use his PDA to receive the real-time video of the match that is playing. The service provider can deliver the video from a fixed access point to the subscriber via the relays of other mobile users in the same area.

This paper considers the problem of how to deliver a real-time video from a single source to a single receiver over a wireless ad hoc network. We would focus on two issues: routing and source rate allocation. Routing is quite challenging in wireless ad hoc networks due to the dynamic topology and variable channel conditions. In multi-path routing, how to optimally split the traffic into multiple paths is a problem requiring carefully investigation. Source rate allocation addresses the problem how to scale the source rate to meet the available bandwidth of the end-to-end path. Different routing scheme accommodates different optimal source rate.

In the literature, it has been demonstrated that multi-path transport of multiple video sub-streams can achieve a significant gain compared to single-path video transmission scheme [1, 2]. Optimization technique has also been used in the multi-path routing. In [3], the authors use genetic algorithm (GA) to compute two optimal paths by minimizing the expected distortion. The video is encoded into two descriptions, each transporting over one path. However, GA is computationally intensive and essentially centralized. Distributed algorithm is desired to compute the routing in wireless ad hoc networks. Recently, Zhu et al have proposed a congestion-minimized routing scheme using a distributed algorithm [4]. However, the link quality (e.g. failure probability) has not yet been considered in [4]. Source rate allocation is often be neglected. Some works [1, 2, and 3] just simply allocate the rate for each path in advance, which may not be optimal.

In this paper, we propose an algorithm to jointly optimize the source rate and the routing scheme for video streaming over wireless ad hoc networks. Our algorithm use dual decomposition to split the problem into multiple subproblems, and then solve each subproblem in parallel. The fully distributed nature of the proposed algorithm leads to two main advantages. First, it is very efficient, the optimal results converge quickly. This characteristic makes fast re-routing possible when the network topology changes due to mobility or channel failure. Secondly, it shares the computation among all the nodes, thus saving the power consumption of each node.

II. OPTIMIZED MULTIPATH ROUTING

A. Source coding

We use a scalable source coding called forward error correction (FEC) based multiple-description coding (MDC) proposed in [5]. We briefly review the FEC based multiple description (MD) coding scheme here. Each frame of a video sequence is first layered encoded into $H$ layers, labeled with $h=1,...,H$. Then, we split the $h$-th layer bit-stream into $h$ equal blocks, and then encode it using Reed-Solomon erasure-correction block code $(H, h)$, where $H$ is the number of the total blocks, and $h$ is the number of the source blocks, and $(H-h)$ is the number of the FEC blocks. Up to the $h$-th layer bit-streams can be recovered if any $h$ blocks of $H$ blocks are received at the receiver. FEC based MD coding scheme transforms a hierarchical layered bit-stream into an equal MD packet stream.
In multi-path transport, duplicated packets may be delivered to the same destination node. In this paper, we assume such delivery redundancy problem is solved by applied a certain coding scheme such as network coding [6]. Therefore, there is no need to reconcile the content difference during transport. Hence, the more packets the receiver receives, the more layers it can reconstruct. The obtained video quality is determined by the received video. The problem is mathematically formulated as

\[ d = D_0 + \frac{\theta_0}{r} \]

where \( d \) is the expected distortion of the reconstructed video; \( R \) is the expected received rate at the receiver; \( D_0, \theta_0 \) and \( \phi_0 \) are model parameters which can be found using data fitting techniques.

In the presence of packet loss, the expected distortion of the received video is given by

\[ d = D_0 + \frac{\theta_0}{r(1 - p^{E-E}) + \phi_0} = D_0 + \frac{\theta_0}{r - \sum f_l p_l + \phi_0}. \]

C. Video rate-distortion modelling

The distortion of the reconstructed video is determined by the expected received rate. We model the rate-distortion relationship with [11]

\[ d = D_0 + \frac{\theta_0}{R + \phi_0}, \]

subject to:

\[ \sum_n e_{nl} f_l = \eta_n, \quad n = 1, \ldots, N, \]

\[ 0 \leq f_l \leq b_l, \quad l = 1, \ldots, L, \]
\[ r \geq 0. \quad (10) \]

The optimization problem stated in (7)-(10) can be converted to an equivalent linear program below:

\[
\begin{align*}
\text{minimize:} & \quad - \left( r - \sum_i f_i p_i \right) \\
\text{subject to:} & \quad \text{constraint (8), (9), and (10).}
\end{align*}
\]

subject to: constraint (8), (9), and (10).

The above optimization problem can be solved by using centralized algorithms such as the simplex method. However, imposing the entire computational tasks on a central node is inefficient and unreliable in wireless ad hoc networks. Therefore, a distributed algorithm is desired. We revise the objective function by adding a corresponding quadratic regulation term for each optimization variable. The optimization problem becomes:

\[
\begin{align*}
\text{minimize:} & \quad - \left( r - \sum_i f_i p_i \right) + \delta r^2 + \sum_i \left( \delta_i^2 \right) \\
\text{subject to:} & \quad \text{constraint (8), (9), and (10).}
\end{align*}
\]

subject to: constraint (8), (9), and (10).

The objective function in (12) is strictly convex. When \( \delta \) is small enough, the solution of problem given in (12) is arbitrarily close to the solution of original optimization problem given in (7).

III. DISTRIBUTED ALGORITHM

Since the problem has a coupling constraint in (8), the dual decomposition technique [7] is appropriate to solve the optimization problem in (12). By Lagrangian relaxation, the optimization problem can be decoupled into several subproblems, which can be solved in parallel.

We introduce the dual variables \( \lambda_n \) \((n=1, \ldots, N)\) for each node, we have the Lagrangian of the primal problem (12) as follows.

\[
L(r, f, \lambda) = -r + \sum_i f_i p_i + \delta r^2 + \sum_i \left( \delta_i^2 \right) + \sum_n \left( \lambda_n \eta_n - \sum_i e_{ni} \lambda_n \right),
\]

where \( f \) is the vector of link flows, and \( \lambda \) is the vector of dual variables.

The Lagrange dual function \( G(\lambda) \) is the minimum value of the Lagrangian over primal variables \( r \) and \( f \).

\[
G(\lambda) = \inf \\left( L(r, f, \lambda) \right) = \inf \left( -r + \delta r^2 + \sum_n \lambda_n \eta_n + \sum_i f_i p_i + \sum_i \left( \delta_i^2 \right) - \sum_n \left( e_{ni} \lambda_n \right) \right)
\]

where \( \delta \) is a positive parameter.

The Lagrange dual problem is to maximize the Lagrange dual function, that is:

\[
\text{maximize } G(\lambda).
\]

In the primal problem, the objective function is strictly convex and the constraints are linear. Therefore, Slater’s condition for strong duality holds. The optimal duality gap is zero [8]. The primal variables \( r \) and \( f \) converge to the optimal solution of the primal problem (12) when Lagrange dual problem (15) converges. At the \( k \)-th iteration, the optimal primal variables \( r \) and \( f \) can be computed in parallel by solving the following problems.

\[
\begin{align*}
\lambda_n^{(k)} = \arg \inf_{\lambda_n} \left( \frac{r + \delta r^2 + \sum_n \lambda_n \eta_n}{\lambda_n} \right), \\
f_i^{(k)} = \arg \inf_{f_i} \left( f_i p_i + \delta_i^2 - f_i \sum_n e_{ni} \lambda_n \right),
\end{align*}
\]

We use subgradient method to solve the dual problem (15). Subgradient method is very efficient due to little requirements of memory usage and amenability for distributed implementation [9]. A subgradient of the negative dual function \( G(\lambda) \) at \( \lambda_n^{(k)} \) is given by

\[
\lambda_n^{(k)} = \sum_i \left( e_{ni} f_i^{(k)} \right) - \eta_n^{(k)}.
\]

The dual variable \( \lambda_n \) at the \((k+1)\)-th iteration is updated by

\[
\lambda_n^{(k+1)} = \lambda_n^{(k)} - \alpha^{(k)} \left( \sum_i \left( e_{ni} f_i^{(k)} \right) - \eta_n^{(k)} \right),
\]

where \( \alpha^{(k)} > 0 \) is the step-size at the \( k \)-th iteration. For a diminishing step-size: \( \alpha^{(k)} = \frac{1}{(k+1)(k+2)} \), where \( \rho > 0 \), the algorithm is guaranteed to converge to the optimal value [9].

The above algorithm performs in a fully distributed way. First, the source node computes the optimal source rate using only its local dual variable. Second, each node computes the optimal flow rate of its outgoing links, using the packet loss rates of its outgoing links, the dual variables of itself and its neighboring nodes. To handle topology changes due to mobility or channel failures, our algorithm can run in a discrete-time manner and quickly obtain the optimal source rate and routing scheme in each time slot.

IV. SIMULATIONS

We simulate a wireless ad hoc network by randomly place 10 nodes in a square region of 500 * 500m. We set the coverage threshold to be 250m. Two nodes can connect to each other if their distance is less than the coverage threshold. The available bandwidth of each link is randomly generated based on a Gaussian distribution with a mean of \( 800 \log_2(1 + (100/d_i)^2) \) Kbps where \( d_i \) is the distance in meters between the transmitter and receiver, and the variance \( \sigma^2 = 20 \). For each link, the transition probability from a UP state to the next UP state is uniformly distributed between [0.85,
0.95, and the transition probability from a DOWN state to the next DOWN state is uniformly distributed between [0.05, 0.15]. In the optimization, we set $\delta$ to 0.01, and $\rho$ to 0.3. We encode Foreman QCIF 300-frame sequence using FEC based MDC [5]. 8 descriptions are generated, each having a bit rate of 0.23 Mbps.

Fig. 1 shows the iteration of the optimal source rate. After 133 iterations, the optimal source rate converges to 1.13000 Mbps with a convergence threshold of $10^{-5}$. The average CPU time the proposed algorithm takes is 0.125 s on a Pentium-4 3.06GHz laptop (512 MB memory) with MATLAB 6.1. The computed routing flow at each link is shown in Fig. 2. The thickness of an edge is proportional to the amount of flow at the corresponding wireless link. The traffic is dispersed into multiple paths by fully utilizing the link bandwidth, and the good links with smaller packet-loss-rates are chosen with priorities.

We compare the proposed multi-path routing scheme to the other two multi-path routing schemes: 1) congestion-minimized routing [4], where the link flow is computed by minimizing $\sum_i (f_i/(b_i-f_i))$; and 2) Double-disjoint-path routing [10], where we find two disjoint paths by maximizing the end-to-end available bandwidth. In congestion-minimized routing, the maximal source rate that guarantees the convergence is 1.0 Mbps, the average PSNR of Foreman 300-frame QCIF video reconstructed at the receiver is 31.51 dB. Double-disjoint-path routing achieves a maximal sending rate of 0.59 Mbps, and an average PSNR of 26.38 dB. The proposed routing outperforms the other two routing schemes with an average PSNR of 36.28 dB. The reason is that the proposed scheme fully utilizes the link bandwidth in a loss-aware manner. The PSNR of the first 100 frames for these three routing schemes is plotted in Fig. 3.

V. CONCLUSIONS

In this paper, we propose an algorithm to jointly optimize the source rate and the routing scheme. We use dual decomposition to separate the optimization problem into multiple subproblems, which are then solved in parallel. The fully distributed nature of the proposed algorithm is extremely appropriate for the wireless ad hoc networks. The numerical results show that the proposed optimized routing outperforms the congestion-minimized routing and double-disjoint-path routing scheme.

REFERENCES