PATH SELECTION FOR MULTI-PATH STREAMING IN WIRELESS AD HOC NETWORKS[1]

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ABSTRACT

In this paper, we propose a novel multi-path selection framework for streaming over wireless ad hoc networks. Our approach is to approximately estimate the concurrent packet drop probability of two paths by taking into account the interference between different links, and to select the best path pair based on that estimation. We prove the optimal path selection problem to be NP-hard, and propose a heuristic solution, whose performance is shown to be close to that of the optimal solution, while significantly outperforming other heuristic protocols.

1. INTRODUCTION

There are many challenges for supporting video communication over wireless ad hoc networks. Mobility of nodes, time-varying nature of the wireless channel, and congestion all make video communication unreliable. Recent efforts on using Multiple Description Coded Video (MDC) together with multipath routing for multimedia transport [1-3] have successfully demonstrated that the combination of path diversity and MDC provides robustness in video communication applications; this is done by either assuming that the set of paths is given, or by simply selecting two node/link disjoint paths. Begen et al. [4] have studied how to select multiple path so as to maximize the *average* video quality at clients on Internet overlay networks. Mao et al. [5] further propose a meta-heuristic approach based on genetic algorithms to solve the above path selection problem in wireless ad hoc networks. However these approaches are too complex to be performed in real-time. Also the model in [4][5] considers neither the interference of flows on neighboring links, nor the influence of the incoming video flow on the characteristics of links.

In this paper, we propose an optimal scheme for selecting two node-disjoint paths, so as to minimize concurrent Packet Drop Probability (PDP) over all possible path pairs, i.e. maximizing the *worst* video quality. We propose a model to estimate the concurrent PDP of two node-disjoint paths. We show that the above optimization is an NP-hard problem. We then propose a heuristic protocol based on our path selection model, whose performance is shown to be close to that of the "optimal routing", while significantly outperforming other heuristic protocols.

The rest of this paper is organized as follows. In Section 2, we formulate the optimal multipath selection problem for video streaming over wireless ad hoc networks. Section 3 presents a heuristic multipath routing protocol based on our path selection model. Simulation results are included in Section 4.

[1]This work was supported by AFOSR contract F49620-00-1-0327.

2. OPTIMUM MULTIPATH SELECTION

Our approach is to minimize concurrent PDP of two node-disjoint paths in a wireless ad hoc network. This is equivalent to optimizing the worst case video quality at clients. The node-disjoint constraint is useful for mobile wireless ad hoc networks, because it reduces the correlation of packet drop in different paths significantly.

2.1. Envisioned Network Model

A wireless ad hoc network can be modelled as a directed graph $G(V, E)$, whose vertices V correspond to wireless stations and the edges E correspond to wireless links. Let $n_i \in V$, $1 \leq i \leq N$ denote the nodes, and d_{ij} denote the distance between nodes n_i and n_j. Each node is equipped with a radio with communication range r, and a potentially larger interference range ω. There is a link l_{ij} from vertex n_i to vertex n_j if and only if $d_{ij} < r$. If the transmission over link l_{ij} makes the transmission over link l_{kl} unsuccessful, link l_{ij} interferes with link l_{kl}. We use a model similar to the protocol interference model introduced in [6] to determine whether two links interfere with each other.

2.2. The Optimal Multipath Selection Problem

Let $P^1_{S,D}$ and $P^2_{S,D}$ be any two paths connecting nodes N_S and N_D, $L^1_{S,D}$ and $L^2_{S,D}$ denote the set of links on each path respectively, and $N^1_{S,D}$ and $N^2_{S,D}$ denote the set of the nodes on each path respectively. We define two indication vectors $\mathbf{x} = (\ldots, x_{ij}, \ldots)^T$ and $\mathbf{y} = (\ldots, y_{ij}, \ldots)^T$ to represent $P^1_{S,D}$ and $P^2_{S,D}$ respectively, where x_{ij} is set to be 1 if link $l_{ij} \in L^1_{S,D}$ and is set to be 0 otherwise, and y_{ij} is defined similarly for path 2.

For the optimal multipath selection, we select two node-disjoint paths with minimum concurrent PDP. This corresponds to the following optimization problem:

$$\text{Minimize } P_{\text{drop}}(P^1_{S,D}; P^2_{S,D})$$

$$\text{with respect to } x_{ij}, y_{mn} \in \{0,1\}, \ \forall (i,j), (m,n) \in E$$

subject to

$$\sum_{j:(i,j)\in E} x_{ij} - \sum_{j:(j,i)\in E} x_{ji} = \begin{cases} 1 & i = N_S \\ -1 & i = N_D \\ 0 & otherwise \end{cases} \quad (1)$$

and

$$\sum_{n:(m,n)\in E} y_{mn} - \sum_{n:(n,m)\in E} y_{nm} = \begin{cases} 1 & m = N_S \\ -1 & m = N_D \\ 0 & otherwise \end{cases} \quad (2)$$

$$N^1_{S,D} \cap N^2_{S,D} = \{N_S, N_D\} \quad (3)$$

Equation (1) is the flow constraint to guarantee the first path to connect the source N_s and the destination N_d. It represents that 1) for each node in the first path, except the source and the destination, the number of incoming links is equal to the number of outgoing links; 2) for the source node, the number of outgoing links is 1; 3) for the destination node, the number of incoming links is 1. Similarly, Equation (2) is the flow constraint for the second path. Equation (3) is the node-disjoint constraint to ensure that the two selected paths do not share nodes. We have shown that the optimal multipath selection problem for video streaming over wireless ad hoc networks is NP-hard.

One approach to solve the optimal multipath selection problem is to enumerate all possible pairs of node-disjoint paths from a source N_S to a destination N_D, estimate the concurrent PDP for each path pair using the scheme proposed in Section 2.3, and choose the best one. We refer to this solution as the Optimal Multipath Routing (OMR). Unfortunately the computation complexity of the OMR grows exponentially with the size of the network; thus it can not be run in real time. However, as will be seen shortly, OMR can be used in non-realtime simulations to provide an upper bound on the performance of other lower complexity heuristic schemes.

2.3. Concurrent PDP of two node-disjoint paths

In this section, we show how to compute the concurrent PDP of any given two node-disjoint paths connecting the same source and destination nodes, in order to solve the optimal multipath selection problem.

We now argue that PDP of two node-disjoint links have low correlation. In a wireless ad hoc network, congestion, contention, time-varying wireless channel, and mobility of nodes are four main reasons for packet loss. Packet drop due to mobility of two node-disjoint links is independent of each other. PDP due to contention or wireless channel error is generally small, because of the 802.11 MAC layer retransmission scheme. As for congestion, even though two node-disjoint links may interfere with each other, causing their PDP to be correlated, we expect that the random backoff scheme in the 802.11 MAC layer protocol reduces the correlation significantly. We have applied NS simulations to verify our conjecture. Specifically, our results show that packet drop over two node-disjoint interfering links have low correlation, as long as PDP of each link is small.

Since two node-disjoint paths only share the source and the destination nodes, packet drop over two node-disjoint paths also have low correlation. Thus we can approximate the concurrent PDP over two node-disjoint paths $P^1_{S,D}$ and $P^2_{S,D}$ as

$$\begin{aligned} P_{\text{drop}}(P^1_{S,D}; P^2_{S,D}) &\approx P_{\text{drop}}(P^1_{S,D}) \cdot P_{\text{drop}}(P^2_{S,D}) \\ &= [1 - \prod_{l_{ij}\in L^1_{S,D}} (1 - P_{\text{drop}}(l_{ij}))] \\ &\cdot [1 - \prod_{l_{mn}\in L^2_{S,D}} (1 - P_{\text{drop}}(l_{mn}))] \quad (4) \end{aligned}$$

2.4. Computation of PDP over a link

In order to complete the computation of the concurrent PDP of two node-disjoint paths, we now show how to estimate PDP over one link, assuming that we have already estimated the flow rates F_i over each link l_i. In a wireless ad hoc network, congestion, contention, time-varying wireless channel, and mobility of nodes are four main reasons for packets loss. Thus PDP over link l_{ij} can be represented as

$$\begin{aligned} P_{\text{drop}}(l_{ij}) &= P_{\text{drop-cong}}(l_{ij}) + P_{\text{drop-cont}}(l_{ij}) \\ &+ P_{\text{drop-chan}}(l_{ij}) + P_{\text{drop-mob}}(l_{ij}) \quad (5) \end{aligned}$$

where $P_{\text{drop-cong}}(l_{ij})$, $P_{\text{drop-cont}}(l_{ij})$, $P_{\text{drop-chan}}(l_{ij})$, and $P_{\text{drop-mob}}(l_{ij})$ are packet drop over link l_{ij} due to congestion, contention, wireless channel error, and mobility respectively. It is possible to apply the broadcast packet technique described by De Couto et al. [8] to estimate PDP due to contention and wireless channel error, and apply results on link availability [9] to estimate the PDP over a link due to mobility. In our simulations, we only focus on PDP due to congestion, since we assume (a) static scenarios, and (b) packet loss caused by channel error and contention is mostly recovered by 802.11 MAC layer retransmissions.

In the remainder of this section, we describe how to compute PDP over link l_{ij} due to congestion $P_{\text{drop-cong}}(l_{ij})$. An *interfering link set* of link l_{ij} is defined to be a set consisting of all links that interfere with it. We partition the interfering link set $I(l_{ij})$ into several disjoint subsets, such that each subset is an independent set. An *independent set* denoted by IS is defined to be a set of links, which can transmit successfully simultaneously without interfering with each other. The set of independent sets resulting from partitioning $I(l_{ij})$ is denoted by $PT(l_{ij})$. We define equivalent rate of flows over all links in the k^{th} independent set IS_k as follows:

$$CF_k = \max_{l_m\in IS_k} F_m \quad (6)$$

where F_m is the aggregate incoming flow rate over the m^{th} link l_m in the k^{th} independent set IS_k. Since links of the same independent set can transmit simultaneously, the equivalent rate of an independent set denotes link l_{ij}'s channel resource needed by all the links in that independent set per unit of time.

Given a partition of the set $I(l_{ij})$, we could estimate the PDP due to congestion of link l_{ij} as follows:

$$P_{\text{drop-cong}}(l_{ij}|PT(l_{ij})) \approx \max(1-\frac{C}{\sum_{IS_k \in PT(l_{ij})} CF_k}, 0) \quad (7)$$

where C is wireless channel capacity.

We name the partition $PT(l_{ij})^*$ that minimizes $P_{\text{drop-cong}}(l_{ij}|PT(l_{ij}))$ *the most efficient partition*. Since computing the actual PDP due to congestion is prohibitively compute intensive, we choose to use its lower bound instead, i.e. the PDP of the *most efficient partition*, as a metric in comparing PDP of two links, and subsequently two paths. We note that using the most efficient partition results in underestimating the PDP due to congestion, and the total PDP. However simulations show that it is sufficient to use the lower bound of PDP due to congestion to compare and select paths. Also with the development of more efficient MAC layer protocol in the future, our underestimation is likely to approach the actual results.

We propose a greedy algorithm to approximately find the most efficient partition. The basic idea behind the greedy partitioning algorithm is to combine as many links with large flow rates together as possible to reduce the sum of equivalent flow rates of independent sets, thus minimizing $P_{\text{drop-cong}}(l_{ij}|PT(l_{ij}))$.

Combining Equations (4), (5), and (7), we obtain an estimate of PDP of two node disjoint paths, thus completing the solution to the optimal multipath selection problem described in Section 2.2.

3. A HEURISTIC SOLUTION TO THE OPTIMUM MULTIPATH SELECTION

Since the optimal multipath selection problem is NP-hard, we propose a heuristic solution, called Interference aWare Multipath Routing (IWM), which can be implemented in real time. By assuming that the PDP of each link is small, we can approximate $P_{\text{drop}}(P^1_{S,D}; P^2_{S,D})$ in (4) as follows:

$$P_{\text{drop}}(P^1_{S,D}; P^2_{S,D}) = \sum_{l_{ij} \in L^1_{S,D}} P_{\text{drop}}(l_{ij}) \cdot \sum_{l_{mn} \in L^2_{S,D}} P_{\text{drop}}(l_{mn}) \quad (8)$$

Our approach is to first determine the first path so as to minimize PDP, and then to choose to minimize the second path's PDP among paths node-disjoint from the first one. The optimization problem of finding the first path can be formulated as follows.

$$\underset{\mathbf{x}}{\text{Minimize}} \sum_{l_{ij} \in E} x_{ij} P_{\text{drop}}(l_{ij})$$

such that the flow constraint in Equation (1) is satisfied. $P_{\text{drop}}(l_{ij})$ denotes the cost assigned to link l_{ij}.

After obtaining the first path, we first update flowrate over each link, by taking into account the allocated video flow into corresponding links. Given the first path, we compute the second path, by defining a link cost for each link as follows:

$$C_{mn} = P_{\text{drop}}(l_{mn}) + \text{nd\_cost}_{mn} \quad (9)$$

where

$$\text{nd\_cost}_{mn} = \begin{cases} b_1 \gg 1 & \text{destination node of link } l_{mn} \in P^1_{S,D} \\ 0 & \text{otherwise} \end{cases}$$

is a penalty factor to maintain the node-disjointness between the two paths. The optimization problem to find the second path minimizing PDP and node-disjoint from the first path can be formulated as follows:

$$\underset{\mathbf{y}}{\text{Minimize}} \sum_{l_{mn} \in E} y_{mn} C_{mn}$$

subject to the constraint, the indicator vector for the second path satisfies (2). We solve both optimization problems with the Dijkstra's algorithm, whose complexity is polynomial.

4. SIMULATION RESULTS

In this Section, we compare the optimal multipath routing (OMR) as described in Section 2, IWM as described in section 3, the node-disjoint multipath routing (NDM) [10], and the shortest widest path routing (SWP) [11]. We use a simulation model based on NS-2[12], and focus on the case of static wireless ad hoc networks. Each node's radio range is 250 meters, and its interference range is 550 meters. We consider a grid network consisting of 49 nodes, placed in a 7×7 grid with the distance between neighboring nodes being 200 meters.

We randomly choose one video sender and one video receiver. For MDC we encode one frame into two packets, and the Group Of Pictures (GOP) size is chosen to be 15. Standard MPEG QCIF sequence Foreman is coded with a matching pursuit multiple description codec[13] at 121.7 kbps. We insert 20 one-hop cross traffic flows, whose bit rates are uniformly distributed in the range [0,200.0] kbps. The bit rates of cross flows are changed every 30 seconds. We run 30 simulations for different network topologies, and select different sender and receiver in each scenario. Each simulation lasts 900 seconds.

We evaluate the performance using the following metrics:

a. **The ratio of bad frames:** The ratio of bad frames is the ratio of the number of non-decodable frames to the total number of video frames that should have been decoded in the receiver. A description of an I-frame is non-decodable, if the packet corresponding to the description is not received on time. A description of a P-frame is non-decodable, if at the playback deadline, either the packet corresponding to the description is not received or the same description of the previous frame is non-decodable. A frame of a MDC stream is non-decodable, if both of its two descriptions are non-decodable. This metric takes into account the dependency between consecutive frames in a predictive coding scheme, and also reflects the fact that MDC can, to some extent, conceal the undesirable effects caused by missing packets.

b. **The number of bad periods:** A bad period consists of contiguous bad frames. This metric reflects the number of times that received video is interrupted by the bad frames.

Figures 1(a) and 1(b) show the ratio of bad frames and the number of bad periods of the four schemes respectively. Simulation results show that the average performance of IWM is very close to that of OMR, and is significantly better than that of NDM and SWP, even though its computational complexity is similar to NDM and SWP. Specifically, shown in Table 1, IWM has the lowest ratio of bad frames among all protocols in 26 out of 30 runs. The results show that the relaxation of the optimal multipath selection problem used by IWM is very efficient.

Table 1. Summary: the ratio of bad frames

	OMR	IWM	NDM	SWP
Average	0.0655	0.0685	0.1864	0.1755
Num. of Best	29	26	7	8

5. CONCLUSIONS AND FUTURE WORK

In this paper, we formulate an optimal multi-path selection problem for streaming, and propose a computation efficient heuristic solution. The proposed protocol significantly outperforms other heuristic protocols. We are currently testing our proposed scheme in an actual experimental testbed with computers and laptops.

6. REFERENCES

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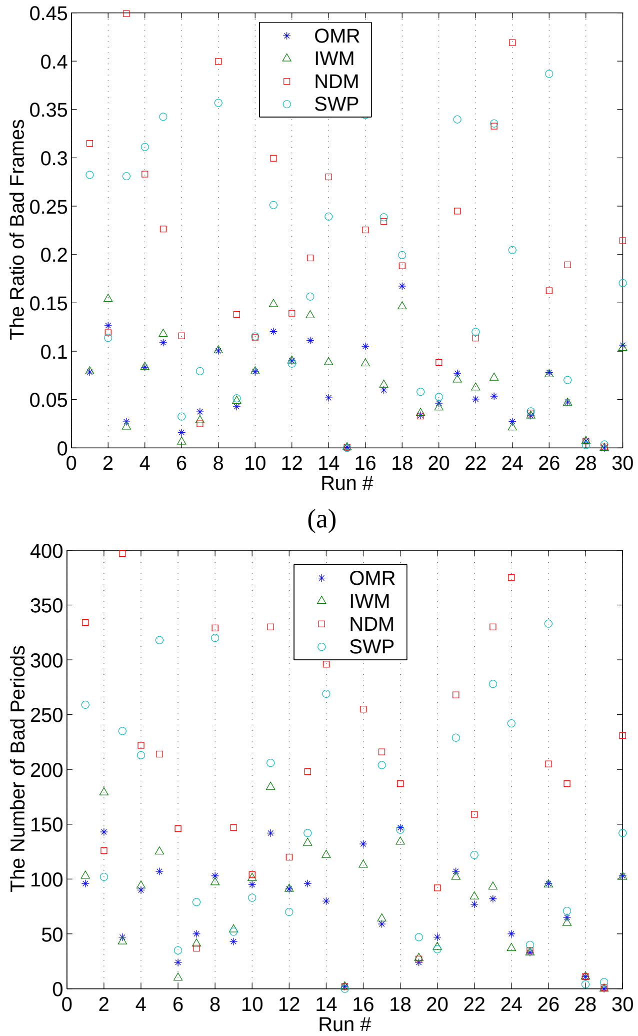

(a)

(b)

Fig. 1. Simulation Results: (a) The ratio of bad frames; (b)The number of bad periods.

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