Quality-aware Video Streaming over Wireless Mesh Networks with Optimal Dynamic Routing and Time Allocation

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***Abstract* - In this paper, a general quality model for scalable coded video streaming over wireless mesh networks is applied in the paper for determining the cross-layer transmission strategies over wireless multi-hop networks. Our proposed solution is enabled by the scalable coding of the video content (i. e. users can transmit and consume video at different quality layers). The adaptive cross-layer strategies – application layer packet scheduling, the policy for choosing a relay, the MAC retransmission strategies, the PHY modulation and coding schemes – are determined per packet, at each intermediate node of the network, in a distributed manner. Unlike the conventional end-to-end flow-based centralized approach, the main component of the proposed solution is a distributed dynamic routing algorithm, called self-learning policy which selects the routing relays and the corresponding time allocation for the various packets. We show that our proposed dynamic routing approach significantly outperforms the static optimization algorithm, since it provides the ability to alleviate the congestion in the changing network.**

I. INTRODUCTION

Multi-hop wireless networks are emerging due to the low-cost and flexible infrastructure that can be simultaneously deployed by multiple users for a variety of applications, including multimedia transmission. However, the wireless infrastructure is often unreliable and provides dynamically varying resources with only limited Quality of Service (QoS) support for multimedia applications. Different from the regular data traffic, multimedia video streaming is a quality-centric, delay-sensitive, and loss-tolerant application with content dependency. Efficient solutions for multimedia streaming must accommodate cross-layer design [1][3][4] with time-varying bandwidths and probabilities of error introduced by the shared nature of the wireless medium. Collaborations among users [2] are needed to ensure the multimedia applications are provided with necessary QoS, because of the shared nature of the wireless infrastructure, where the cross-layer transmission strategy deployed by one user impacts and is impacted by the other peers.

In this paper, we introduce a novel video streaming approach based on priority queuing that enables us to optimize the cross-layer transmission strategies per packet in order to maximize the overall video quality across all users. The proposed cross-layer adaptation differs from existing solutions for multimedia transmission over multi-hop networks, where the path (or limited multiple paths) is predetermined for the entire bitstream or layer [4]. Moreover, the MAC retransmission and PHY link adaptation are often not considered for these flow-based/layer-based solutions [1]. We deploy scalable video coding schemes that enable a fine-granular adaptation to changing network conditions and a higher granularity in assigning the packet priorities. Our approach is based on a multi-path routing algorithm that determines the next relay per packet.

Existing research [1][3] poses the problem of multi-user resource allocation and cross-layer adaptation over ad-hoc wireless networks as a static, centralized optimization that maximizes the total quality of the various users given pre-determined channel (capacity) constraints and video rate requirements. These solutions have several limitations. First, the video bitstreams are changing over time in terms of required rates, priorities and delays. Hence, it is difficult to timely allocate the necessary bandwidths across the wireless network infrastructure to match these time-varying application requirements. Second, the delay constraints of the various packets are not explicitly considered in centralized solutions, as this information cannot be relayed to a central resource manager in a timely manner. Third, the complexity of the centralized approach grows exponentially with the size of the network and number of video flows. Finally, the channel characteristics of the entire network (the capacity region of the network) need to be known for this centralized, oracle-based optimization. This is not practical as channel conditions are time-varying and having accurate information about the status of all the network links is not realistic. Alternatively, in our solution, we optimize the cross-layer at the various intermediate nodes in a distributed manner that allows us to efficiently adapt to changes in traffic and channel characteristics. This is in line with the informationally decentralized nature of the investigated multi-user video transmission problem. We also discuss the required information/parameters exchange among networks/layers for implementing such a distributed per-packet solution.

The paper is organized as follows. Section II introduces the multi-user video streaming specification and subsequently gives the cross-layer optimization problem formulation and highlights the need for a distributed per-packet solution. In Section III, we present our distributed per-packet solution. In Section IV, we give the simulation results. Finally, Section V concludes the paper.

II. MULTI-USER VIDEO STREAMING SPECIFICATION

A. *Video priority classes*

We assume that there are V video users (with distinct source-destination pairs) sharing the same multi-hop wireless infrastructure. Similarly, in this paper, we categorized the video units (video packets, video frames) of the video bitstream into several priority classes. We adopt an embedded 3D wavelet codec and construct video classes by truncating the embedded bitstream. We assume that the packets within each class have the same delay deadline, similar to [5]. For a video sequence v, its video classes are characterized by:

- $\boldsymbol{\lambda}_v$, a vector of the quality impact of the various video classes. The video classes are organized in an embedded bitstream in terms of their video quality impact.
- $\mathbf{R}_v$, a vector of the rate requirements of the video classes.
- $\mathbf{d}_v$, a vector of the delay deadlines of the various video classes. Due to the hierarchical temporal structure deployed in 3D wavelet video coders (see [5][10]), the lower priority packets also have a less stringent delay requirement. However, if the used video coder did not exhibit this property, we needed to deploy indeed more sophisticated prioritization techniques that considered jointly the distortion impact and delay constraints [6].
- $\mathbf{L}_v$, a vector of the average packet lengths of the various video classes.
- $\mathbf{P}_v^{succ}$, a vector containing the probabilities of successfully receiving the packets in the various video classes at the destination.

At the client side, the expected received video quality of video v can be modeled using a general video rate-distortion model:

$$Q_v^{rec} = F_v(\boldsymbol{\lambda}_v, \mathbf{R}_v, \mathbf{d}_v, \mathbf{L}_v, \mathbf{P}_v^{succ}), \quad (1)$$

represented by the function $F_v(\cdot)$ which can be computed in [5][10], and is an increasing function of the available rate (goodput). Importantly, our formulation is not restricted by the choice of rate-quality models. Any model could be deployed in our formulation to determine the prioritization for a specific class f_k (which can be characterized by the elements $\lambda_k, R_k, d_k, L_k, P_k^{succ}$ in the mentioned vectors.) For instance, with a quality-rate curve of the video stream v, the received video quality can be modeled as a piecewise linear approximation:

$$Q_v^{rec} = \sum_{f_k \in v} \lambda_k R_k P_k^{succ} \quad (2)$$

Regarding the P_k^{succ}, we assume that the client implements a simple error concealment strategy, where the lower priority packets are discarded whenever the higher priority packets are lost [5]. Hence,

$$P_k^{succ} = \begin{cases} 0 & \text{,if } P_{k'}^{succ} \neq 1 \text{ and } f_{k'} \prec f_k \\ (1 - P_k) = E[I(D_k \leq d_k)], & \text{otherwise} \end{cases}, \quad (3)$$

where we use the notation in [6] - $f_{k'} \prec f_k$ to indicate that the class f_k depends on $f_{k'}$. Specifically, if f_k and $f_{k'}$ are classes of the same video stream, $f_{k'} \prec f_k$ means $k' < k$ due to the descending ordering ($\lambda_{k'} > \lambda_k$). P_k represents the end-to-end packet loss probability for the packets of class f_k. $I(\cdot)$ is an indicator function. Note that the end-to-end probability P_k^{succ} depends on the network resource, competing users' priorities as well as the deployed cross-layer transmission strategies vector, which will be discussed in more details later in Section III.*C*.

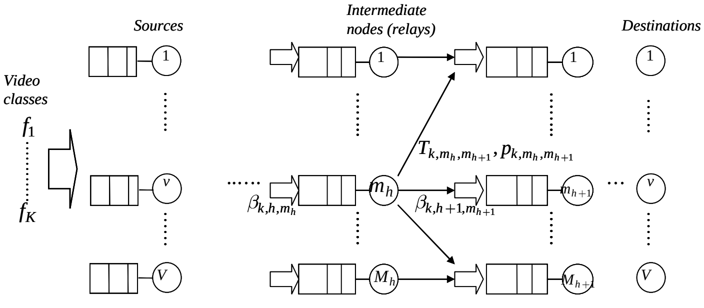


Fig. 1. The multi-hop network model with V video users and K classes.

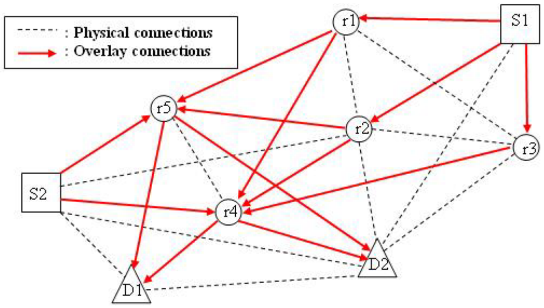
B. *Network specification*

Let Γ represent the available network resource, which the given network graph (including the source nodes, destination nodes and relays) and the available transmission links in the multi-hop wireless network. Besides the V source-destination pairs, we assume the network graph Γ consists of H hops with M_h intermediate nodes (relays) at each h-th hop ($0 \leq h \leq H - 1$). The number of source and destination nodes are the same, i.e. $M_0 = M_H = V$, and each node will be tagged with a distinct number m_h ($1 \leq m_h \leq M_h$) as shown in Fig.1. For the case that users may have different number of hop-count, we introduce a concept of "virtual node" as a node with 0 transmission time to pass through. Fig. 2 demonstrates an example of the multi-hop overlay network over a mesh network with 9 nodes.

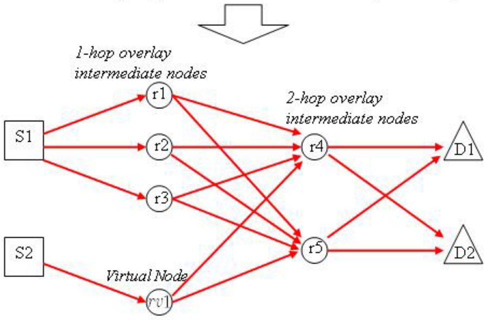
C. *Cross-layer joint transmission strategy vector*

Next, we discuss the transmission strategies of video units (video packets) at various layers. Let us define the cross-layer joint strategies vector $\mathbf{STR} = \{STR_{h,m_h}(\vartheta) \mid \vartheta = 1 \ldots N^{tot},$

$1 \le m_h \le M_h$, and $0 \le h \le H-1\}$ as a vector of transmission strategies that can be deployed for packets present in the queue at various nodes. N^{tot} represents the total number of packets. $STR_{h,m_h}(\vartheta \in f_k) = [\pi_{h,m_h},\ \beta_{k,h+1,m_{h+1}},\ \gamma^{MAX}_{k,m_h,m_{h+1}}(\vartheta),\ \theta_{k,m_h m_{h+1}}(\vartheta)]$ represents the cross-layer transmission strategies for a packet ϑ at the intermediate node m_h at the h-th hop.



Actual Network Topology that has 2 sources-destination pairs, 5 relay nodes



Overlay Network Topology that has 2 sources-destination pairs, 6 relay nodes (with one virtual node in hop-1 intermediate nodes)

Fig. 2. An overlay network example with a virtual node

- **Application layer**

The packet headers are extracted at the various relays, to determine the packet priority, delay deadlines and packet lengths required for our cross-layer solution. Based on this information, the packet scheduling π_{h,m_h} deployed at the node m_h of the h-th hop will be determined.

- **Network layer**

We define β_{k,h,m_h} as the percentage of packets in priority class f_k (fraction of time) to select the node m_h as its relay at the h-th hop. We refer to this term as the *relay selecting parameter*. By assigning relays according to the relay selecting parameter, multiple paths could be chosen for the packets in the class f_k i.e. $0 \le \beta_{k,h,m_h} \le 1$. The relay selecting parameters provide a routing description across the network with multi-path capability. Since the total number of intermediate nodes in the h-th hop is M_h, we have $\sum_{m_h=1}^{M_h} \beta_{k,h,m_h} = 1$. Note that since each class f_k has a pre-determined destination (i.e. $m_H = v$), the relay selecting parameter at the last hop (β_{k,H,m_H}) is equal to '1', if m_H is the destination of the class, and '0', otherwise. Instead of making decision for each class f_k, video packets select the intermediate nodes m_{h+1} as their next relay according to the corresponding $\beta_{k,h+1,m_{h+1}}$.

- **MAC layer**

At the MAC layer, we assume the network deploys a protocol similar to that of IEEE 802.11a/e, which enables packet-based retransmission and polling-based time allocation with a service interval *SI*. Let $\gamma^{MAX}_{k,m_h,m_{h+1}}(\vartheta)$ represent the maximum number of retransmissions for the packet ϑ of priority class f_k from node m_h to node m_{h+1} at the h+1-th hop. And the time allocated for the packet ϑ is $Time^{allocated}_{k,m_h,m_{h+1}}(\vartheta)$

- **PHY layer**

Let $\theta_{k,m_h,m_{h+1}}(\vartheta)$ denote the modulation and coding scheme used for the packet ϑ of class f_k for transmission from node m_h to node m_{h+1}, during the h+1-th hop. Let $T_{k,m_h,m_{h+1}}(\theta_{k,m_h,m_{h+1}})$ and $p_{k,m_h,m_{h+1}}(\theta_{k,m_h,m_{h+1}})$ represent the corresponding transmission rate and packet error rate supported by the $\theta_{k,m_h,m_{h+1}}$. Let us define the link goodput as $T^{goodput}_{k,m_h,m_{h+1}} = T_{k,m_h,m_{h+1}}(1 - p_{k,m_h,m_{h+1}})$.

D. *Problem formulation*

The conventional formulation of the multi-user wireless video transmission problem can be regarded as a cross-layer optimization that maximizes the overall average video quality:

$$\mathbf{STR}^{opt} = \arg\max_{\mathbf{STR}} \sum_{v=1}^{V} \sum_{f_k \in v} \lambda_k R_k P_k^{succ}(\mathbf{STR}, \Gamma)), \qquad (4)$$

with the constraint that all successfully received packets must have their end-to-end delay D_k smaller than their corresponding delay deadline ($D_k(\vartheta) \le d_k,\ \vartheta \in f_k$, for $\forall \vartheta$).

Due to the informationally decentralized nature of the multi-users video transmission over multi-hop networks, a centralized solution for this optimization problem is not practical. For instance, the optimal solution depends on the delay incurred by the various packets across the hops, which cannot be timely relayed to a central controller. Instead, we propose a distributed packet-based solution to optimize the quality of the various users sharing the same multi-hop wireless infrastructure.

Consider the error concealment policy described in (3). Once a higher priority packet is lost in the network, all the video packets that depend on it are useless. Therefore, the network nodes should keep transmitting the highest priority packet in the queue until the transmission success or deadline expired. The higher priority packets are transmitted to the level that the network can accommodate, while the lower priority packets will be dropped due to the delay constraint.

By exploiting the prioritized video classes and the mentioned error concealment scheme, the above centralized cross-layer optimization problem in (4) can be reduced to a distributed per-hop minimization of the end-to-end packet loss rate at the node m_h of the h-th hop:

$$\begin{aligned} STR^{opt}_{h,m_h}(\vartheta^* \in f_k) &= \arg\max_{STR} R_k \cdot P^{succ}_k(STR_{h,m_h}(\vartheta^*), \Gamma) \\ &= \arg\min_{STR} P_k(STR_{h,m_h}(\vartheta^*), \Gamma) \end{aligned}, \quad (5)$$

where we minimize P_k of the class f_k for the selected packet ϑ^* in the queue of the node m_h according to the scheduling π_{h,m_h}. Note that the decisions of the transmission strategies are made for the packet $\vartheta^* \in f_k$, although minimizing the end-to-end packet loss rate of the class f_k.

III. THE DISTRIBUTED PACKET-BASED SOLUTION

The packet priorities (determined by λ_k for class f_k) and their delay constraints (d_k) drive the selection of optimal transmission strategies at the different layers hop by hop. In order to realize the mentioned priority queuing framework for multimedia transmission, we define the following two kinds of information fed back to a node m_h for the distributed algorithm.

$E[Delay_{k,m_{h+1}}]$: The expected delay from all the node m_{h+1} to the destination of the packets in each of the class f_k.

$SINR$: The Signal-to-Interference-Noise-Ratio (SINR) from the nodes m_{h+1} in the next hop which are able to establish a link with node m_h according to the network graph Γ.

This distributed approach not only simplifies the proposed cross-layer solution but also makes it adaptive to the varying network characteristics, as it does not require feedback about the entire network status. We provide a block diagram in Fig. 3 that indicates the parameters/information that need to be exchanged across layers/various nodes in the proposed cross-layer transmission solution.

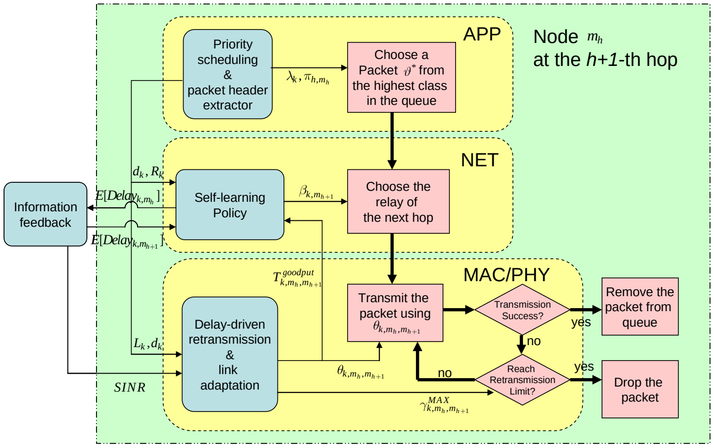


Fig. 3.Integrated block diagram of the distributed per-packet algorithm

A. *Dynamic routing policy*

To minimize the end-to-end packet loss probability P_k as stated in (5), by definition, $P_k = E[I(D_k > d_k)]$, it is equivalent to minimize the end-to-end delay $E[D_k]$, given a fixed delay deadline d_k for the most important class f_k of traffic in the queue. To minimize the end-to-end delay over the multi-stage overlay structure shown in Figure 1, we propose a dynamic routing policy for the relay selecting parameters in this section. Each node m_h maintains and feeds back the information of the expected delay from itself to the destination, $E[Delay_{k,m_h}]$, for each class of traffic (class f_k). Recall that each traffic class has exactly one destination node predetermined for the video stream v that the class belongs to. This $E[Delay_{k,m_h}]$ is the cost that will be minimized at each stage, and it will be constantly updated at each node using the information feedback from the next hop. Specifically, if the current node is node m_h at the h-th hop, the expectation of delay to the destination of each class can be formulated as:

$$\begin{aligned} E[Delay_{k,m_h}] = \min_{\beta_{k,h+1,m_{h+1}}} \{ & E[W_{k,m_h}(\beta_{k,h+1,m_{h+1}}, T^{goodput}_{k,m_h,m_{h+1}})] \\ & + \sum_{m_{h+1}=1}^{M_{h+1}} \beta_{k,h+1,m_{h+1}} E[Delay_{k,m_{h+1}}]\} \end{aligned}, \quad (6)$$

where $E[Delay_{k,m_{h+1}}]$ is provided from the information feedback of the nodes of the next hop, and the relay selecting parameter $\beta_{k,h+1,m_{h+1}}$ is chosen to minimize the expected delay to the destination. $E[W_{k,m_h}]$ is the average queuing delay at the current queue, which can be averaged over time with the measurement of the queue size. In a congested network, (6) is dominated by the second term (the accumulated queuing delay in the rest of the network). Thus, we simplify the equation as:

$$E[Delay_{k,m_h}] = E[W_{k,m_h}] + \min_{\beta_{k,h+1,m_{h+1}}} \left(\sum_{m_{h+1}=1}^{M_{h+1}} \beta_{k,h+1,m_{h+1}} E[Delay_{k,m_{h+1}}] \right) \quad (7)$$

We set $\beta_{k,h+1,m_{h+1}} = 0$ for the nodes whose information feedback is not received to avoid sending packets through this congested region. The routing policy will dynamically adapt the relay selection to minimize the delay through the network. This method is inspired by the Bellman-Ford shortest path (delay) routing algorithm that minimizes the end-to-end delay across the network. Our routing algorithm reduces to the well-known Bellman-Ford algorithm when $\beta_{k,h+1,m_{h+1}} = 1$ to the node m_{h+1} that feedbacks the smallest $E[Delay_{k,m_{h+1}}]$. Note that our algorithm is prioritized and the delay of class f_k will be influenced by the same or higher priority traffic.

B. *Packet-based delay-driven time allocation*

After a node m_{h+1} is selected as $\beta_{k,h+1,m_{h+1}}$ for the selected packet ϑ^* at each intermediate node m_h, we determine the corresponding goodput for each link by selecting $\theta_{k,m_h,m_{h+1}}$ based on the *link adaptation* scheme presented in [9]. The relay in the hop m_{h+1} is selected according to the relay selecting parameter $\beta_{k,h+1,m_{h+1}}$ discussed in the previous subsection. To describe the channel conditions, we assume as in [9] that each wireless link is a memoryless packet erasure channel. The link packet error rate for a fixed packet of length L_k bits is $p_{k,m_h,m_{h+1}}(\theta_{k,m_h,m_{h+1}}, L_k) = 1 - \left(1 - BER(\theta_{k,m_h,m_{h+1}})\right)^{L_k}$, where $BER(\theta_{k,m_h,m_{h+1}})$ is the bit error rate when the modulation scheme $\theta_{k,m_h,m_{h+1}}$ is selected. The packet error rate and the effective transmission rate (goodput) can be approximated using the sigmoid function as in [9]:

$$p_{k,m_h,m_{h+1}}(\theta_{k,m_h,m_{h+1}}, L_k) = \frac{1}{1 + e^{\zeta(SINR - \delta)}}, \tag{8}$$

$$T_{k,m_h,m_{h+1}}^{goodput} = \frac{T_{k,m_h,m_{h+1}}(\theta_{k,m_h,m_{h+1}})}{1 + \mathrm{e}^{-\zeta(SINR - \delta)}}, \tag{9}$$

where $SINR$ is the Signal-to-Interference-Noise-Ratio, and ζ and δ are constants corresponding to the modulation and coding schemes for a given packet length [9]. This method maximizes the goodput given the average packet length L_k of the specific class over a selected link (m_h, m_{h+1}) based on the SINR feedback. Then, time allocation for the packet ϑ^* is $Time_{k,m_h,m_{h+1}}^{allocated}(\vartheta^* \in f_k) = L_k \big/ T_{k,m_h,m_{h+1}}^{goodput}(\vartheta^*)$.

For a fixed $T_{k,m_h,m_{h+1}}^{goodput}$, we choose the appropriate retransmission limit $\gamma_{k,m_h,m_{h+1}}^{MAX}$ for the selected packet ϑ^* in priority class f_k such that the delay constraint is satisfied. Specifically, let $delay_{h,m_h}^{curr}(\vartheta^*)$ represent the current delay incurred by the selected packet from the source to a current node m_h. The maximum retransmission limit for the packet of class f_k over the link from m_h to m_{h+1} is determined based on the delay deadline d_k (where $\lfloor\cdot\rfloor$ is the floor operation):

$$\gamma_{k,m_h,m_{h+1}}^{MAX}(\vartheta^*) = \left\lfloor \frac{T_{k,m_h,m_{h+1}}^{goodput}\left(d_k - delay_{h,m_h}^{curr}(\vartheta^*)\right)}{L_k} \right\rfloor - 1. \tag{10}$$

IV. SIMULATION RESULTS

Two video sequences “Mobile”, and “Coastguard” are compressed using a scalable video codec. Each bitstream is separated into 4 classes ($N_v = 4, K = 8$). The PSNR-rate curves of the two video streams are modeled by (2). Based on this, λ_k and R_k are determined for each class. The delay deadline d_k is set to 0.533 seconds for all classes, which is the interval of one GOP (16 frames per GOP at a frame rate of 30 Hz). We simulate our self-learning policy over a 6-hop network shown in Fig. 4.

In Table 1, we compare the proposed self-learning policy with a state-of-the-art routing algorithm [7]– “Fixed optimal path” and a multi-path routing algorithm “Fixed multi-path” [8]. In “Fixed optimal path”, we statically select the links for transmission such that the goodput is maximized (determined a single path per class). In “Fixed multi-path”, besides the optimal path, several loop-free paths are selected per class. In all three cases, the proposed priority queuing framework was deployed. The simulation results show that the proposed dynamic routing approach significantly outperforms the static routing algorithm, since it provides the ability to alleviate congestion and interference.

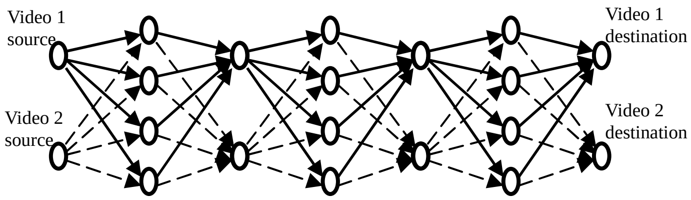


Fig. 4. The 6-hop network for simulation with 2 scalable video sequences

TABLE I COMPARISON OF THE ROUTING ALGORITHMS

Method	Low network efficiency		Medium network efficiency	
	“Mobile” Y-PSNR (dB)	“Coastguard” Y-PSNR (dB)	“Mobile” Y-PSNR (dB)	“Coastguard” Y-PSNR (dB)
Fixed optimal path	24.98	30.67	31.37	34.32
Fixed multi-path	28.39	31.86	32.85	35.58
Self-learning policy	30.42	33.27	33.10	35.61

V. CONCLUSIONS

In this paper, a novel distributed cross-layer streaming algorithm is proposed for the transmission of multiple videos over a multi-hop wireless network. Our per-packet cross-layer strategies include the selection of the appropriate relay nodes for multi-hop routing. We introduce the self-learning policy for dynamic routing that minimizes the end-to-end packet loss for the classes of the video streams. The proposed distributed cross-layer algorithm is fully adaptive to changes in the network, number of users, and the priorities of the users.

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