Cross-layer and Path Priority Scheduling based Real-time Video Communications over Wireless Sensor Networks

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***Abstract*—This paper addresses the problem of real-time video streaming over a bandwidth and energy constrained wireless sensor network (WSN). Considering the compressed video bit stream is extremely sensitive to transmission errors, and the constraints in bandwidth and energy in WSNs and delay in video delivery, we exploit the construction of an application-specific number of multiple disjoint paths to enlarge the aggregate bandwidth and facilitate load balancing and fast packet delivery. For efficient multi-path routing of real-time video frames, we propose a path priority scheduling algorithm to satisfy the delay constraint of video frames while balancing energy and bandwidth usage among all the available paths. In the case that the aggregate bandwidth is still not enough to satisfy the required coding rate, we further exploit a cross-layer technique for adaptive coding according to path status. The effectiveness of the proposed scheme is evaluated and demonstrated by simulations.**

I. INTRODUCTION

Recent advances in hardware miniaturazation have allowed the fabrication of sensor devices that support the use of specialized add-on modules for imagery applications. As an example, the Cyclops image capturing and inference module [1] is designed for extremely light-weight imaging, and can be interfaced with popular wireless sensor network (WSN) nodes, such as Crossbow's MICA2 and MICAz [2]. The availability of such inexpensive imaging hardware has fostered the development of visual sensor networks (VSNs) that allow collection and dissemination of video streams [3], [4]. As surveyed in [5], it is clear that VSN research is a field of growing activity, in which innovations in applied signal processing interact with emerging applications and technology.

In this paper, we investigate H.26L [6], [7] real-time video communications in VSNs, where video streams are transmitted under a number of resource and performance constraints, such as bandwidth, energy, and delay. Though a high compression ratio makes H.26L real-time video applications suitable for low bit-rate channels, the received video quality is susceptible to transmission errors. It remains a challenging problem to deliver H.26L video data with a high quality of service (QoS) in WSNs with bandwidth-limited error-prone wireless channels.

Since the compressed video bit stream is extremely sensitive to transmission errors due to dependencies between video frames, error control techniques such as forward error correction (FEC) and automatic repeat request (ARQ) are necessary to obtain the high reliability required by video services [8]. However, links in a WSN may not have adequate bandwidth to satisfy the higher bandwidth requirement of FEC coding. Thus, conventional single-path routing schemes based on shortest paths [9] are not very effective to support video transmissions in unreliable and bandwidth-limited WSNs, as they will cause either significant degradation in the perceived quality of the video at the sink nodes if FEC coding is not used, or large queuing delays when bandwidth becomes insufficient if FEC coding is used. Furthermore, transmitting a video stream using the shortest path will drain the energy of the nodes along this path and shorten the network lifetime.

In WSNs, multipath routing is used to establish multiple paths between each source-sink pair. Most applications of multipath routing in WSNs aim to increase the reliability for a single flow [11], [12]. By comparison, in our previously proposed directed geographical routing (DGR) [10] scheme, multipath routing is used to support the delivery of multiple flows in a VSN, while the responsibility of reliable data delivery at the routing layer is relieved by the use of FEC coding. This paper presents an extension of DGR for efficient multi-path routing of real-time video frames. Specifically, we propose a path priority scheduling algorithm to meet the delay constraint of video frames while balancing energy and bandwidth usage among all of the available paths. As in DGR, multiple end-to-end paths are computed and the aggregate bandwidth is used for the video session. In the case that the aggregate bandwidth is still not enough to satisfy the required coding rate, we further consider the estimated path information and real-time video encoder's ability to mitigate fluctuations of network dynamics by exploiting cross-layer techniques.

The rest of this paper is organized as follows. Section II presents the related work. Section III describes the proposed path priority scheduling scheme for DGR in WSNs, and the cross-layer protection strategies at the application layer based on path information. Simulation model and experiment results are presented in Section IV. Section V concludes this paper.

II. BACKGROUND

Our work is closely related to video transmissions over WSNs, wireless local area networks (WLANs), and multipath

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routing in WSNs. We briefly review the existing work in these areas in the following.

In [13], a transmission strategy is examined that provides adaptive QoS to layered video for streaming over IEEE 802.11 WLANs. In [14], [15], hybrid transmission techniques that combine ARQ and FEC are proposed to improve real-time video transport over WLANs. In [16], an adaptive cross-layer protection strategy is proposed to enhance the robustness and efficiency of scalable video transmission by performing tradeoffs between throughput, reliability, and delay depending on the channel condition and application requirements. The above work focuses on video streaming in infrastructure-based wireless networks (for a survey, see [17]). The network context is quite different from the multi-hop, infrastructureless WSNs considered in this paper.

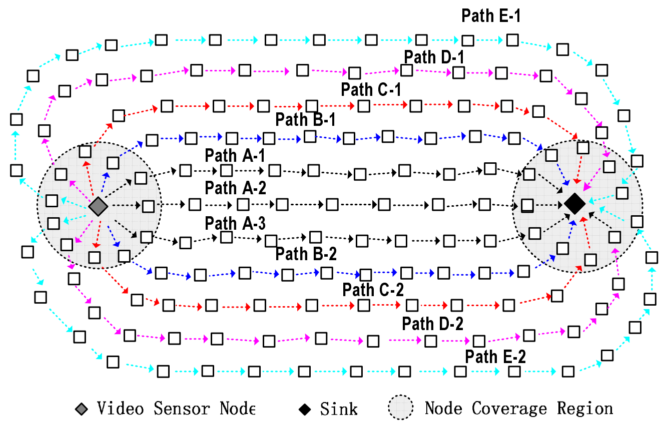
Mao et al. [18] combined multi-stream coding with multipath transport, and showed that, in addition to traditional error control techniques, path diversity provides an effective means to combat transmission errors in ad hoc networks. The typical application of multipath routing in WSN designs is to provide path redundancy for failure recovery. In [11], multiple disjoint paths are set up first, then multiple data copies are delivered using these paths. Instead of using disjoint paths, GRAB [12] uses a path interleaving technique to achieve high reliability. These multipath routing schemes for WSNs aim at increasing the reliability for a single flow [11], [12]. In contrast, this paper proposes to use multipath routing to support the delivery of multiple flows in a WSN, while the required level of reliability is achieved using FEC. Thus, in applying multipath routing, our goal is to maximize the load balancing effect by spreading traffic evenly over the WSN, and using all possible paths to maximize the end-to-end capacity.

In DGR [10], using a hop-by-hop deviation angle adjustment method, a path can be established successfully using any initial deviation angle specified at the source node. After the construction of multiple disjointed paths between the video source node and the sink the aggregate source-to-sink bandwidth is increased to tackle the natural unreliability of WSNs as well as their bandwidth constraints. We will briefly review DGR in the following section, and refer interested readers to [10] for a detailed description.

III. The Path Priority Scheduling Algorithm for DGR

A. Directed Geographical Routing

DGR aims to compute multiple paths to support a unicast video session. Figure 1(a) illustrates an example of the construction of multiple disjointed paths by DGR [10]. In order to set up an application-specific number of paths with different initial deviation angles, the source can transmit a series of control packets each specifying a different deviation angle. In Fig. 1(a) the source changes the absolute value of the deviation angle (i.e., α) from 0° to 90° in steps of 18°, and sends a different PROB message with each deviation angle. Thus, in total 11 paths are established with α equal to -90°, -72°, -54°, -36°, -18°, 0°, 18°, 36°, 54°, 72°, and 90°, respectively. To



(a) Multiple paths constructed by DGR [10]

Path Label	Availability	Bandwidth	Delay	Energy	PacketToSend
A-1	Y	40kbps	50ms	95Joulers	Seq(Data **1**)
A-2	Y	42kbps	48ms	95Joulers	Seq(Data **2**)
A-3	N	39kbps	50ms	90Joulers	N/A
B-1	Y	36kbps	56ms	80Joulers	Seq(FEC)
B-2	N	37kbps	58ms	85Joulers	N/A
C-1	Y	38kbps	65ms	70Joulers	Seq(FEC)
. . .	. . .	. . .	. . .	. . .	. . .

(b) An example of path Information for PPS

Fig. 1. Illustration of path priority scheduling (PPS) strategy.

establish a direction-aware path, a probe message is broadcast initially by the source for route discovery. A selected next hop will continue to broadcast probe message to find its next hop, and so forth. A node receiving a probe message will calculate its mapping coordinates based on α and the positions of the node itself, the upstream node and the sink. Then, DGR will select as the next hop node the neighbor whose mapping coordinates is closest to the *strategic mapping location*, instead of the neighbor closest to the sink as in traditional geographical routing protocols [10].

In the case that a delay guarantee is not required, the round-robin path scheduling algorithm can be adopted to achieve energy balancing among the paths across the network; e.g., the sequence of the used paths in round-robin path scheduling algorithm could be: A-1, A-2, A-3, B-1, B- 2, C-1, C-2,D-1,D-2, E-1, E-2, A-1, A-2, and so forth.

To support real-time video transmission over WSNs, delay should be considered in path scheduling; e.g., the paths with lower delays may be used more often in order to meet a tight delay constraint. However, if the low delay paths are excessively used, the nodes along these paths may deplete their energy quickly, and the WSN may not be able to support the video session as the remaining paths may not be able to meet the delay requirements.

B. The Path Priority Scheduling Algorithm

In the following, we propose a novel path priority scheduling (PPS) scheme, which intelligently specifies the number

TABLE I
PSEUDO-CODE FOR PPS BASED DGR

```
procedure PPS(V)
begin
  V is the set of paths;
  if aggregate bandwidth of multipath > required bandwidth
    if path satisfying delay constraint exists
      for each path satisfying delay constraint
        Calculate path weight; //refer to Fig. 2(b)
      endfor
      Perform weighted round robin path scheduling
              according to path weight and packet priority;
    else
      Drop packet;
    endif
  else
    Drop packet with lower importance;
    Perform procedure PPS(V);
  endif
end
```

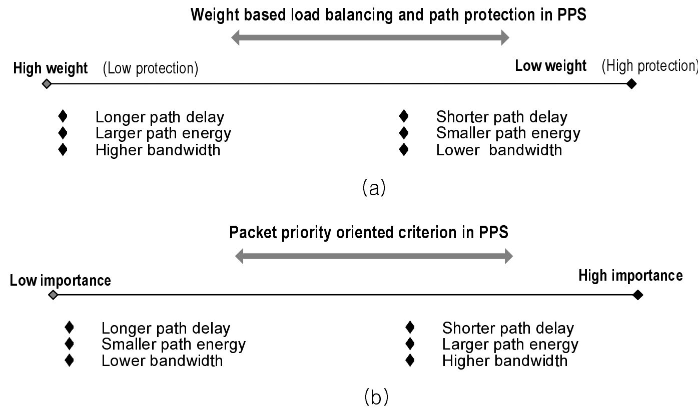


Fig. 2. Path weight and packet priority based criteria in PPS: (a) weight based load balancing and path protection; (b) packet priority oriented criterion.

of paths used and assign video sub-streams according to the status of the paths (e.g., the estimated bandwidth, path delay, path energy level) as recorded in the path information table, e.g., as in Fig. 1(b). In addition, if a path is under repair or some of its nodes have depleted their energy, the availability flag is set to "N" as shown in Fig. 1(b).

The pseudo-code of the PPS strategy is shown in Table I. The arrival of a video frame from the application layer of the video source node will invoke the PPS algorithm. Using the path information table, the path weight is calculated based on the criteria of protecting critical path and balancing traffic load among available paths, as illustrated in Fig. 2(a). Among the paths which meet the delay requirement, those with longer delay, higher energy, higher bandwidth will be scheduled more frequently due to their higher weights. Since the delays of multiple paths are likely lower than the required delay simultaneously, the relative "longer delay" paths will be used more often to protect the shorter delay paths. This is because, the path with shorter delay has stronger eligibility to support wide range of time-constrained applications. Such a strategy schedules video packets to satisfy the delay constraint of video frame while balancing energy and bandwidth usage among all of the available paths. In addition to path weight, the packet priority is also considered during the scheduling. The higher the importance of a packet, the path with stronger eligibility (i.e., shorter delay, higher bandwidth and larger energy) will be used to increase the reliability of packet delivery, since a path with less capacity and energy will more likely fail during the video session, as illustrated in Fig. 2(b).

If the required bandwidth is larger than the aggregate multipath bandwidth, PPS will selectively drop some packets with the least importance to minimize the perceived degradation of the decoded video quality.

C. Joint PPS and Cross-layer Protection Strategies

In the case where the aggregate bandwidth of multiple paths is still less than the required transmission bandwidth even after intelligent packet dropping using the PPS algorithm, the perceived video quality at the sink will degrade due to error propagations. In this section, we propose an adaptive cross-layer protection strategy to further exploit a real-time video encoder's ability to antagonize the fluctuations in available bandwidth.

The flowchart of the joint cross-layer and PPS strategies are shown in Fig. 3. Once a new frame arrives from the application layer, the video sensor node will check whether multiple paths exist. If multipaths have not been established, it starts DGR-based path construction a to set up multiple disjoint paths. Otherwise, it checks whether the estimated aggregate bandwidth meets the requirement. Frame skipping is performed to lower the required coding rate if aggregate bandwidth is not enough.

When an intermediate sensor node receives a frame, it estimates the packet delay to the sink. If the estimated delay is larger than the required delay by a certain threshold, it deems the packet highly likely to miss the frame deadline if its progress continues at the current estimated speed. To save bandwidth, it drops the packet, and transmits an ISLER (Inform Source to Lower Encoding Rate) message to the video source. Upon receiving an ISLER message, the video source updates the path information and marks the corrupted frames based on the feedback information piggybacked in ISLER. By using a multiple reference selecting strategy [6], the video source avoids taking the corrupted/lost frame as a reference frame. If at least one reference frame is intact, inter-coding still can be used. If all the reference frames are corrupted, intra coding is used by force. In this case, the next frame is skipped to achieve dynamic adjustment of bandwidth requirement since intra-frames are large but occurs infrequently. The use of multiple reference selecting and intra-frame refreshing strategies protects H.26L streaming from error propagation when frame errors occur [15].

When a node is close to exhausting its energy or fails to transmit a packet as indicated by a failure notification from the MAC layer, it initiates path maintenance [10] to find an alternate node with a higher energy level to replace it. If the path repairing fails, an ISLER message is sent to the video source node to mark the path as unavailable.

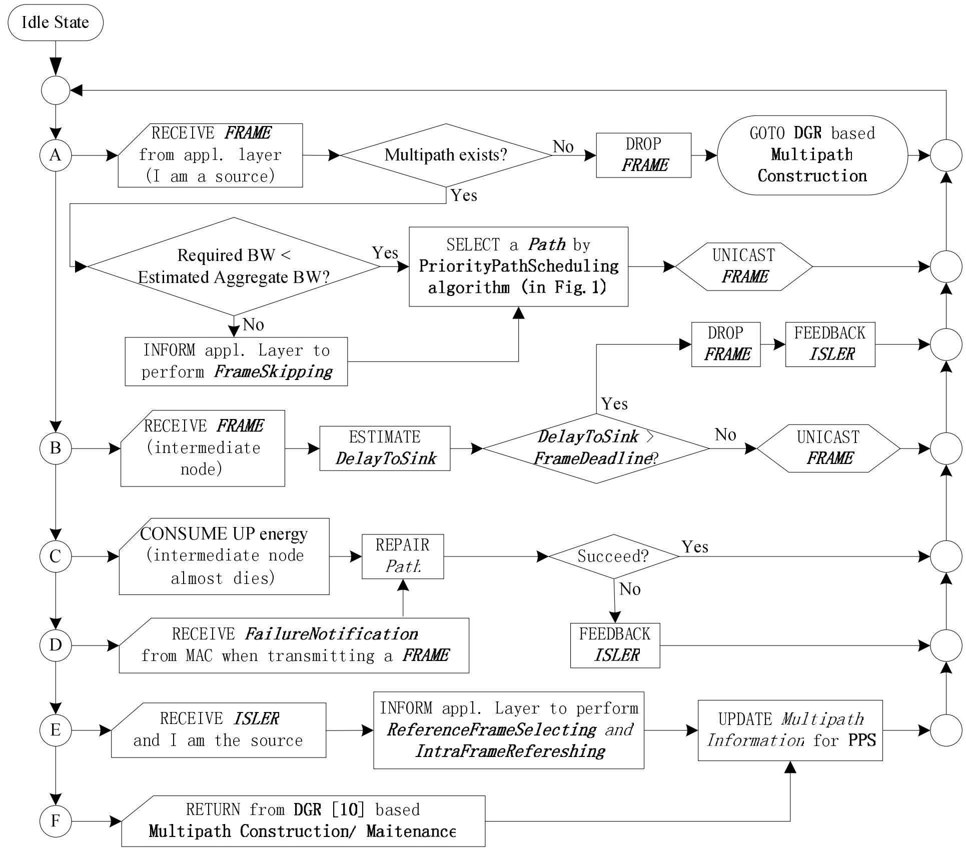


Fig. 3. Flowchart of joint PPS and cross-layer strategy.

IV. Performance Evaluations

A. Simulation Settings

We evaluate DGR enhanced by the joint PPS and cross-layer strategy for video transmission using OPNET Modeler [20]. For the results reported in this paper, a 500-node network is simulated. Nodes are uniformly deployed over a 300 m × 500 m field. As in [12], the sink is located at a corner of the field and one video source node is located at the diagonal corner.

Our video sensor node implementation is illustrated in Fig. 4(a), which has a four-layer protocol structure. The sensor application module consists of a H.26L video source, which encodes the test video sequence "Foreman" by the H.26L video coding standard [6], [7] in QCIF format (176 × 144 pixels/frame) at a temporal resolution of 20 frames/s, as shown in Fig. 4(b). The average bit rate of the video data is about 178kbps, and the average bit rate after packet encapsulation is about 200kbps. Each frame is packetized into 6 data packets. Three FEC packets are transmitted per video frame to protect the video data packets [10].

In order to be consistent with prior work [10], [12], we use the IEEE 802.11 MAC. The data rate of the wireless channel is 2 Mbps. The radio transmission range is set to 50 m. We also adopt the energy consumption model and link failure model used in [10]. We account for all types of energy consumptions in the simulations, including transmitting, receiving, idling, overhearing, collisions and other unsuccessful transmissions, MAC layer headers, retransmissions, and RTS/CTS/ACKs.

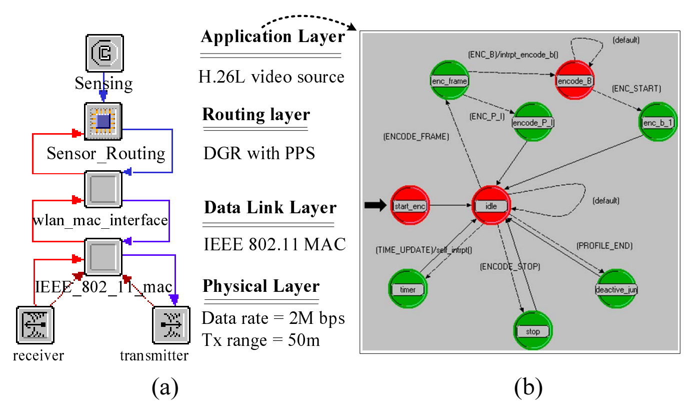


Fig. 4. H.26L Video Source Node Model.

B. Simulation Results

In order to demonstrate the performance of the proposed video transmission scheme, we compare it with the original DGR [10] and a representative shortest path based approach, i.e., GPSR [9]. In the simulations, the quality of the received video is evaluated by computing the peak signal-to-noise ratios (PSNR) of the reconstructed video frames.

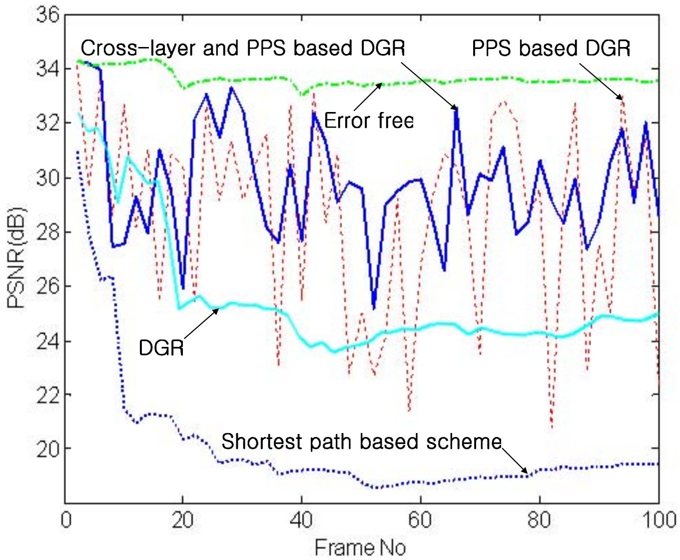


Fig. 5. Comparison of PSNR.

Figure 5 compares the PSNR of each frame resulting from the test sequence Foreman with packet loss rate = 0.2. Though FEC coding is used in the shortest path based scheme to prevent error propagations, it is still not very effective to support video transmissions in unreliable and bandwidth-limited WSNs, thus resulting in degraded received video quality. By comparison, the multiple disjoint paths constructed in DGR facilitate load balancing, bandwidth aggregation, and fast packet delivery. However, the PSNR curve of DGR still drops to lower than 26dB after twenty frames due to path failures and packet losses.

Figure 5 show that the proposed PPS based DGR achieves an improvement of about 3dB in PSNR compared with the original DGR. This is because, in PPS based DGR, paths are unequally protected by their weights, which provides a better QoS for packets with a higher priority. In the case that the aggregate bandwidth is still not enough, PPS drops the packets with low importance to adapt the video coding rate to the fluctuations in bandwidth. On top of PPS based DGR, the introduction of cross-layer techniques in the video coding layer improves PSNR further. This is because cross-layer and PPS based DGR adjusts the video coding parameters to further adapt the required bandwidth to the network dynamics and prevent error propagation.

V. Conclusion

Due to limited bandwidth, it is challenging to achieve delay guarantees and obtain a high perceived video quality for real-time video transmission over WSNs. To solve this problem, we have proposed a novel path priority scheduling scheme with frame skipping, reference frame selecting and intra-frame refreshing techniques for H.26L real-time video streaming over WSNs. Simulation results show that our DGR enhanced with PPS and cross-layer source rate adjustments is effective in exploiting multipath routing, path scheduling, and adaptive coding for dynamic WSNs. In future work, we will exploit multiple description/layer coding in combination with DGR to achieve scalable video transmissions over WSNs.

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