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Improving response time in time critical Visual Sensor Network applications

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ABSTRACT

Wireless sensor network (WSN) consisting of nodes equipped with cameras or advanced low-cost image sensors is known as a Visual Sensor Network (VSN). The main function of VSN is to capture images and send them to sink nodes for processing. Common applications of a VSN are surveillance, tracking, crowd management, scientific research, etc. Such applications require large amounts of data to be exchanged between camera nodes and sink. Image data is considerably larger than common sensor data such as temperature, humidity, and pressure. For data delivery in VSNs, the communication is constrained by many stringent QoS requirements like delay, jitter and data reliability. Moreover, due to the inherent constraints of WSN such as limited energy, low CPU power, and insufficient memory; the architect of VSN must choose appropriate topology, image compression algorithms, and communication protocols depending on application. In literature, different techniques have been proposed to resolve the bandwidth requirements for the VSN. The majority of these techniques are based on the compression of visual data. This paper focuses on one of these aspects, namely the communication protocol for VSN. In this paper, we present Priority Routing Framework for Image Transmission (PRoFIT), a new routing framework for VSN to deliver critical imagery information with system's time constraint. We demonstrate that PRoFIT improves response time in various VSN applications as compared to priority-less routing techniques. We have implemented PRoFIT along with an image processing application using Contiki and simulated it on Cooja simulator to support our claim.

1. Introduction

VSN consists of three types of nodes; visual sensing nodes, intermediate nodes and sink nodes. The visual sensing node is equipped with the sensor that captures images. Depending on the application this sensor can be of type that captures multi-colored images, grey-scale images, thermal, or infra-red images [1], etc. Nodes equipped with these sensors require more power to run additional hardware and software components such as frame-grabbers and image encoders. These nodes capture raw images, encode them, and send them towards the sink.

The main task of intermediate nodes is to send packets from visual sensing nodes to sink nodes. These nodes may also take part in sensing other scalar environmental variables such as temperature, humidity, pressure, and concentration level of certain chemicals depending on the

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nature of VSN application. Additionally, these nodes may also take part in encoding image data as a class of image encoding algorithms [2] offload some processing to intermediate nodes in order to conserve power of visual sensing nodes.

The sink nodes are responsible for processing the images captured by the camera nodes. For this purpose sink nodes are power-rich and have high computation ability. In order to take action depending on the VSN application, these nodes may additionally contain actuators or may be connected to a fourth type of nodes called actuator nodes.

The primary requirement of a WSN is to sense environmental factors using low-power, low-cost sensors and route meaningful data to power-rich sink nodes for processing. This requirement becomes challenging in a VSN as the amount of data to be transferred is much more than a conventional WSN due to the type of data being shared. Applications of surveillance require very large amounts of data to be exchanged between camera nodes and sink. In conventional WSN that sense light, humidity, pressure, etc. the traffic generated by a sensing node is limited to the scalar data [3]. In most cases the memory size required to store and send is 16-bits per reading [3]. On the other hand, a VSN node, equipped with a camera generates vector data. For instance, a raw RGB image of 128×128 pixels with 24-bits per pixel (8 bits per color) will be of $128 \times 128 \times 24 = 393{,}216$ bits (48 kilobytes). This is several orders of magnitude larger than conventional sensor data.

To minimize the size of the image data, image compression techniques such as Discrete Cosine Transforms [4] or Discrete Wavelet Transforms [5,6] can be used. Although these algorithms reduce the size of an image, yet the reduction is not comparable to conventional sensors data. Therefore, image data compression is not enough. The processing power of each node is also limited. Additionally, the topology of the network and routing protocols play a crucial role in transporting imagery information from visual sensing nodes to sink nodes. Hence, the tasks of capturing image data, compressing it, and sending it to sink are some of the most challenging tasks faced by VSN architects.

As mentioned before, using image compression algorithms the size of data can be reduced to some extent. Also, a category of image compression algorithms generates multiple layers of compressed image data. The first layer contains the most prominent features of the image, for example the edges of objects or coarse image data. The subsequent layers contain the details that when merged with the first layer, restore the original image. Some image processing algorithms consist of multiple passes requiring different levels of details of the encoded image for each pass. Using such algorithms in VSNs, system response time can be reduced. If the sink nodes receive image data required for first pass sooner than data required for subsequent passes, it can start processing the first pass and take action accordingly while data of subsequent layers arrive at the sink node. This paper helps alleviate the routing challenges of such image processing algorithms by proposing a routing framework based on the following features:

(1) The visual sensing nodes should be able to specify priority to outgoing packets. In this way, image data for first pass can be sent at higher priority than data for subsequent passes.
(2) The intermediate or routing nodes should be aware of packet priority so that higher priority packets are forwarded before lower priority packets.
(3) If packets from two nodes collide, high priority packets should be retransmitted before low priority packets.
(4) Finally, in event of congestion, lower priority packets should be dropped before any high priority packet is dropped.

The next section summarizes the various communication protocols being used in VSN architectures as of today. Section 3 discusses the VSN application scenario we address in this paper. Section 4 defines PRoFIT, our proposed priority-based routing framework. The implementation of PRoFIT is discussed in Section 5. Simulations were carried out to quantify the usefulness of PRoFIT. In Section 6, simulation environment and results are discussed. Section 7 discusses the transmission of image features for real-time VSN applications using PRoFIT to improve system's response time. Finally, the paper is concluded along in Section 8.

2. Existing routing techniques

Most of the research on routing techniques for image transmission has mostly been limited to wired networks [7–11]. Research on QoS supported routing protocols for mobile ad-hoc networks has been summarized by Chen and Heinzelman [12] and Hanzo-II and Tafazolli [13]. Liebeherr et al. [14], Wang et al. [15], Stoica and Zhang [16], Younis and Fahmy [17], and Soldatos et al. [18] discuss techniques to deliver image data on the Internet. None of these are applicable to VSNs.

Most of the work done in the field of routing techniques for VSNs has been conducted to achieve energy efficiency. The first routing protocol focused on QoS in VSNs by trying to minimize the average weighted QoS metric throughout the lifetime of the network. Sohrabi et al. [19] proposed Sequential Assignment Routing (SAR) that enforces maintenance of routing tables with status of all nodes.

RAP [20] is a priority based routing protocol that uses velocity monotonic scheduling and geographical forwarding to achieve QoS however its requirement of geographical awareness can only be fulfilled by having a pre-defined network topology or additional hardware to determine geographical location. SPEED [21], proposed by He et al., is a spatio-temporal, priority-based, QoS-aware routing protocol for sensor networks that provides soft real-time, end-to-end delay guarantees. SPEED does not provide differentiated packet prioritization. Moreover, a forwarding node can only forward the packet at a speed less than or equal to the maximum achievable speed even though the network can support it.

Real-time Power-Aware Routing (RPAR) [22] is another routing protocol that achieves application specific end-to-end delay guarantee at low power by dynamically adjusting transmission power and routing decisions based on the workload and packet deadlines. RPAR also calculates average link quality by taking link variability into consideration. Multi-path and Multi-SPEED (MMSPEED) routing protocol [23] supports probabilistic QoS guarantee by provisioning QoS in two domains, timeliness and reliability. MMSPEED adopts a differentiated priority packet delivery mechanism in which QoS differentiation in timeliness is achieved by providing multiple network-wide packet delivery speed guarantees.

3. VSN application scenario

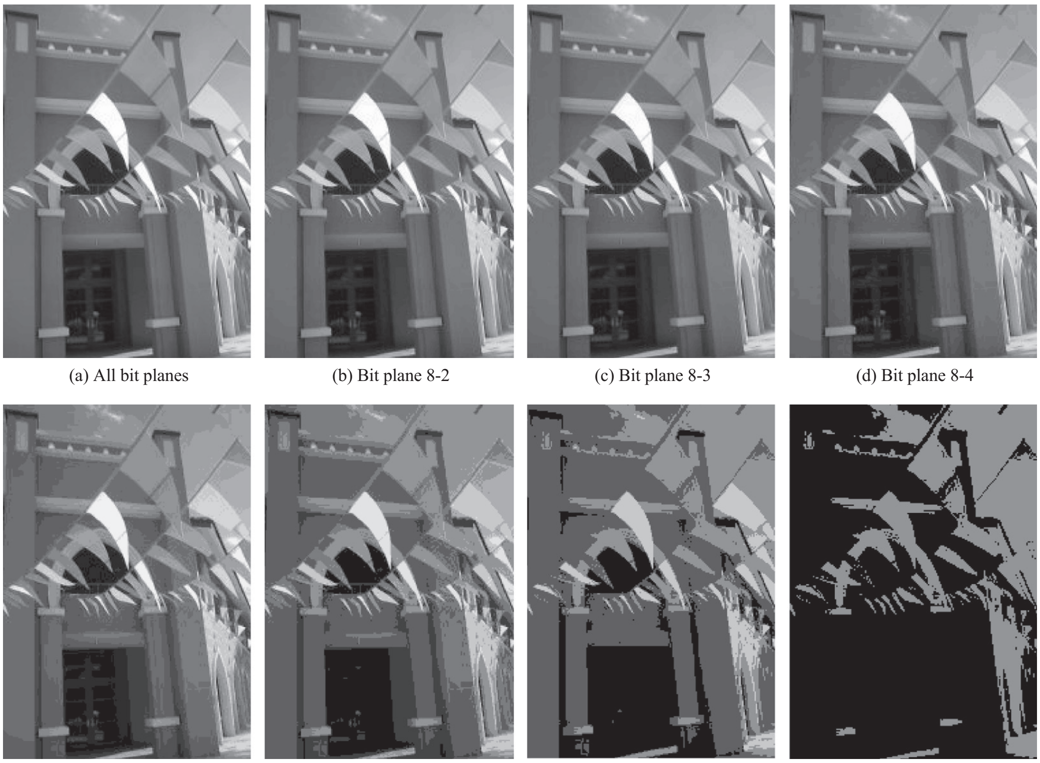
This section explains the VSN application scenario discussed in this paper. In our scenario, the visual sensing node captures an image and divides it into bit planes. A bit plane of a digital image is a set of bits corresponding to a given bit position in each pixel value of the digital image.

For example, if a grayscale image is represented using 8-bits (1 byte) for each pixel, then out of these 8-bits, bit-1 represents the least significant bit whereas bit-8 represents the most significant bit. Bit planes corresponding to higher significant bits contain major structural information or coarse information of the image while bit planes corresponding to lower significant bits contain detailed or fine information [24].

Fig. 1a–h shows sample images constructed using different numbers of bit planes. Fig. 1 visually shows the degradation of image quality based on number of bit planes used to reconstruct them. Fig. 1a shows the original image (bits 8-1). Fig. 1b shows the same image constructed by dropping the least significant bit (bits 8-2). Fig. 1c shows the image constructed by dropping the 2 least significant bits (bits 8-3) and so on. Finally, Fig. 1h shows the image comprising of only the most significant bit (bit-8 only). It is visually notable that higher order bits contain most of the significant visual information and lower order bits contain the fine information.

Based on visual analysis, we can conclude that image comprising of 3 most significant bit planes (bits 8-6), as shown in Fig. 1f, contain adequate visual information that can be used by VSN application for image processing. The 5 least significant bit planes do not contribute towards major structural information. These lower order planes have information for the refinement of the image. Therefore, at time of transmission, the visual sensing nodes use PRoFIT to assign high priority to packets containing 3 most significant bit planes (bits 8-6) where as low priority to packets containing 5 least significant bit planes (bits 5-1). Subsequently, when the sink node receives the high priority bit planes, it is able to construct an image of sufficient visible quality. In this way, PRoFIT enables the progressive image transmission for VSN applications, which is beneficial especially in case of low bandwidth environment [24].

Our network model does not restrict the number or position of any node type. One of the network topologies for a surveillance application is depicted in Fig. 2. In our scenario, the visual sensing nodes capture images and



(a) All bit planes (b) Bit plane 8-2 (c) Bit plane 8-3 (d) Bit plane 8-4

(e) Bit plane 8-5 (f) Bit plane 8-6 (g) Bit plane 8-7 (h) Bit plane 8

Fig. 1. Bit plane decomposition of an image.

divide them into two layers. The first layer (coarse image information) consists of 3 higher order bit planes (bits 8-6) and the second layer (fine image information) consists of 5 lower order bit planes (bits 5-1). The nodes use PRoFIT to send the first layer with high priority and the second layer with low priority. The sink uses the first layer (high order bit planes) to reconstruct the captured image with a certain level of detail that can be used to take immediate action, if necessary. The sink uses the second layer (lower order bit planes) to reconstruct a detailed image for further processing if image information from the first pass required additional image details to take action.

In our network, most of the nodes are the intermediate nodes. They are only responsible for routing packets from visual sensing nodes to sinks. They do not take part in sensing or sharing processing load of the sensing nodes or sink nodes. When the network is deployed, the intermediate nodes create routing tables that are necessary to take routing decisions when packets are received. To achieve their primary task of routing image data from visual sensing nodes to sink nodes, the routing tables in intermediate nodes are updated throughout the lifetime of the network as some nodes may die due to depleted power or other environmental factors, while other nodes may be added to the network when required. PRoFIT makes sure that intermediate nodes forward high priority packets faster than low priority packets. In this way, PRoFIT facilitates sink nodes to reconstruct an image using high order bit planes much sooner than when the entire image data is received at sink. As required, the sink node can add lower order bit planes to the first pass to construct a more detailed image.

4. PRoFIT – Priority Routing Framework for Image Transmission

This section provides detail of how PRoFIT works. PRoFIT can be distributed into two layers of any protocol stack along with a thin Application Interface Layer (AIL). These two layers are network layer and medium access layer. The AIL encapsulates the details of network layer and medium access layer. Fig. 3 depicts the layers of PRoFIT and their functional details are provided in the sub-sections below.

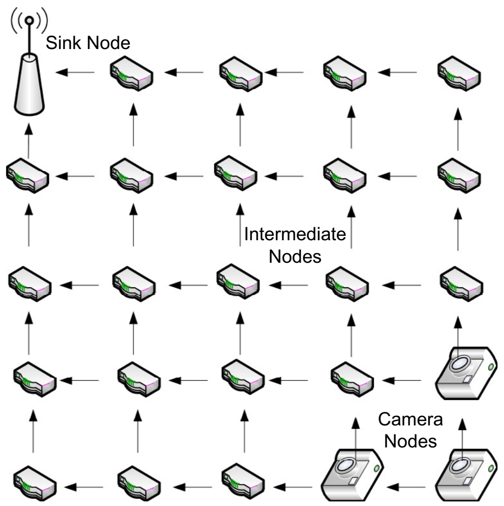


Fig. 2. A sample surveillance network using VSN.

4.1. Application layer interface

The Application Interface Layer (AIL) is the application layer component of PRoFIT. It is a very thin layer that provides VSN application with a set of primitives that can be used for fragmenting image data into packets, sending them, receiving them and assembling them to re-generate image data. The AIL hides the implementation details of the entire framework. The visual sensing node uses AIL's send primitive to send a captured image. The VSN application running on visual sensing node divides the image into two layers (coarse image information and fine image information), as discussed in Section 3. As input, the send primitive of AIL takes an image layer, address of sink node and priority of the layer. AIL of the visual sensing node fragments the image data into packets of size that network layer can send. This flow is depicted on the left side of Fig. 4. AIL also inserts image number and packet fragment number into the packet. This information is used by the AIL of sink node to join the fragments to reconstruct image data sent. The second block of Fig. 3 depicts AIL.

4.2. Network layer

The network layer component of PRoFIT works in two phases. The first phase builds the network and maintains it. The second phase assists in routing packets through the network with appropriate priority. Detail of each phase is given below. The third block of Fig. 3 depicts this layer.

4.2.1. Network configuration phase

When the VSN is deployed and brought up, the nodes send advertisements to their neighboring nodes declaring identities and their number of hops from the sink. These advertisements are sent periodically. Initially all nodes are configured as being infinitely away from sink node. When sink node advertises, it declares its number of hops from sink as 0. The nodes receiving this advertisement add the respective sink node to their routing tables and mark their number of hops from sink as one hop. Now when such a node sends out its own advertisement, it declares its number of hops from the sink instead of infinity. The nodes at multiple hops from sink update their routing table with sink address along with the addresses of their neighbor as next hop address from who they received the advertisement.

When a node receives advertisement of a sink from more than one neighbor, it keeps only the neighbor with lesser hops to the sink in its routing table. After a number of cycles of advertising, depending on the number of nodes, the network is established. Each node knows the number of hops to the sink as well as the next hop towards the sink. As the advertisements are sent out periodically, removal and addition of nodes to the network is possible dynamically. Moreover, for maintenance of routing tables, each

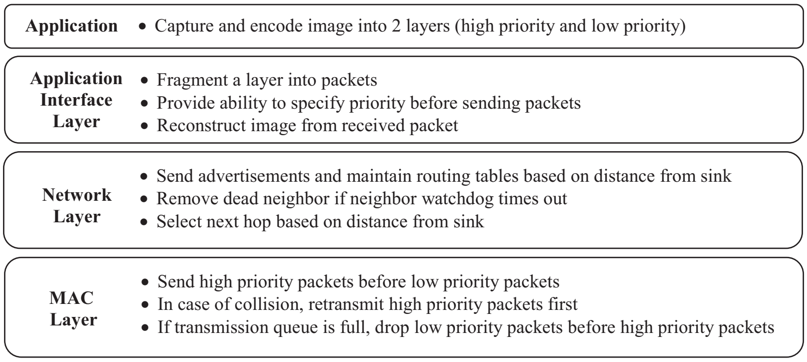


Fig. 3. VSN application and PRoFIT layers.

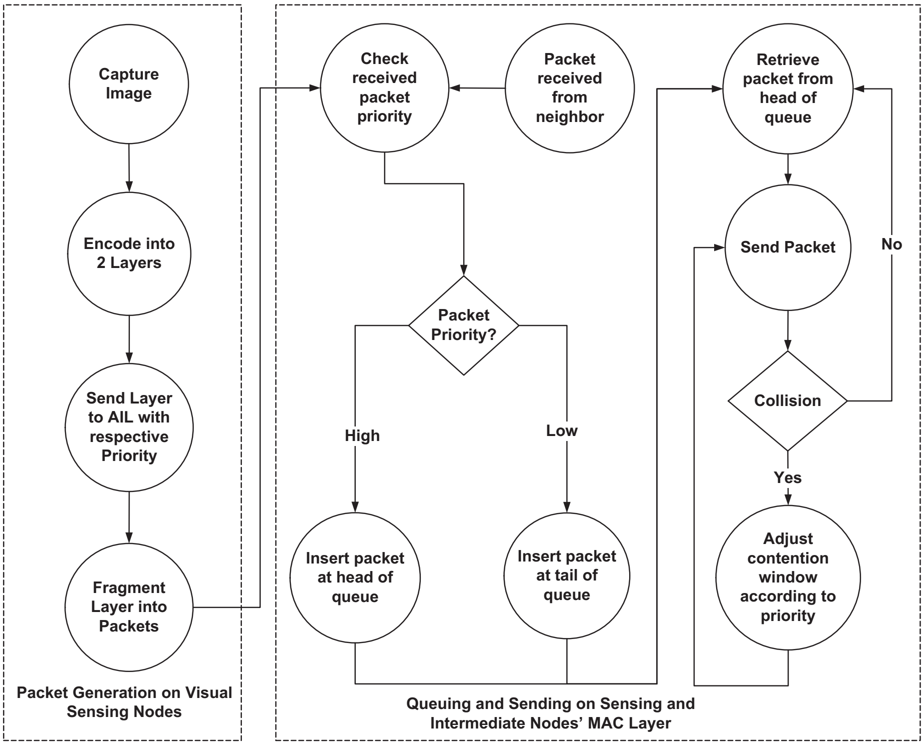


Fig. 4. PRoFIT flow chart.

node keeps track of live neighbors using a watchdog timer associated with each neighbor.

The energy cost overhead of network configuration phase is negligible because network configuration phase commences at the deployment of VSN and ends as soon as routing tables stabilize. By then visual sensing nodes have data to send, hence network operation phase commences.

4.2.2. Network operation phase

Once the network has been established, our routing framework is ready to transport image data from visual sensing nodes to sink nodes. The network layer receives packets from AIL of its own node or through MAC layer if the packet was forwarded from a neighbor. The network layer selects the next hop towards the sink that has been specified by the incoming packet. If the sink address as specified by the visual sensing node is not in the routing table, the packet is dropped. A neighbor's keep-alive watchdog is reset whenever a packet is received from that neighbor. If a packet is not received from a neighbor within a threshold, the neighbor is deleted from the routing table. In this way, routing tables are maintained during network operation phase.

4.3. Medium Access and Control Layer

At the Medium Access and Control Layer (MAC Layer), PRoFIT works at two levels. The first is the intra-node level, where PRoFIT makes sure that high priority packets are forwarded before low priority packets. The second level is the inter-node level, where PRoFIT makes sure that when two neighbors contest for transmission medium, the neighbor with high priority packet gets the chance to transmit its packet before the neighbor with low priority packet. The following sub-sections explain these two levels. The bottom block of Fig. 3 depicts MAC layer functions.

4.3.1. Queue insertion

When a packet arrives at MAC layer for transmission, it is sent instantaneously if the MAC layer is not already receiving or sending a packet. If the MAC layer is busy, the packet is placed in a queue where it has to wait for its turn. The packet transmission always retrieves a packet from the head of the queue for transmission. PRoFIT makes use of this queue. When a packet with high priority arrives, it is placed at the head of the queue so it is sent in the next go. If a packet of low priority arrives, it is placed at the tail of the queue. This is depicted in middle of Fig. 4. As the MAC layer always selects packets from head of the queue for transmission, it is made sure that at intra-node level a packet with higher priority is transmitted first.

4.3.2. Differential back-off window

When two nodes find the medium available and transmit at the same time, a collision occurs. In regular Carrier Sense and Multiple Access with Collision Detection (CSMA/CD), both nodes back off for a randomly selected time slot from a pseudo-fixed-size window. If they collide again, the window size is increased exponentially to a certain size. PRoFIT enforces CSMA/CD of MAC layer to maintain different windows for the different priorities. When a collision occurs, the MAC layer checks the priority of packet that collided and determines back-off times from particular windows. For high priority packet, the window is smaller than the window for a low priority packet. In this way, the node with high priority packet gets a chance to transmit its packet within a smaller timeframe than a node with a low priority packet. This is depicted in right side of Fig. 4. This mechanism makes sure that at the inter-node level, high priority packets transmit sooner than low priority packets. The optimal size of contention windows for both priorities is a topic that requires advance studies. The authors have left this topic for future research.

5. PRoFIT implementation using Contiki OS

To quantify the usefulness of PRoFIT, a VSN application was created and simulations were carried out. Though the framework can be implemented using any protocol stack, Contiki OS [25] was selected due to its acceptability as a real-time operation system for WSNs. The architecture is depicted in Fig. 5. Modifications have been made to network and MAC layer of RIME [26] protocol stack part of Contiki OS. RIME protocol stack provides a set of basic communication primitives ranging from best-effort single-hop broadcast and best-effort single-hop unicast, to best-effort network flooding and hop-by-hop reliable multi-hop unicast. The RIME protocol stack provides multiple options for each protocol layer. The configuration of RIME used for PRoFIT implementation consists of hop-by-hop reliable multi-hop unicast with a user-defined network layer, CSMA/CD as MAC layer and ContikiMAC [27] as Radio Duty Cycling layer. Modifications made to each layer of RIME protocol stack of Contiki OS are explained in the sub-sections below.

5.1. Modification in RIME network layer

The custom network layer contains a periodic timer that expires half a second. Whenever the timer expires, a node sends out an advertisement. These periodic advertisements from each node help build routing tables as explained in the previous section. A network packet in RIME protocol stack is 128 bytes long. 24 bytes of this packet are used by RIME for header and remaining 104 bytes are available as payload. When used as an advertisement, the payload contains addresses of sink nodes and their corresponding hops count from the node announcing the advertisement. The advertisement packet is depicted in Fig. 6a. When used to send image data, AIL inserts the image number and fragment number or packet sequence number into the data packet along with 96 bytes of image data. The image number and packet sequence number are used at the sink to reconstruct the image layer. A data packet is depicted in Fig. 6b.

When a packet is received at the network layer of an intermediate node from a neighbor, it is checked if the packet is for the node itself or it is an image data packet that needs to be routed to some sink. In case if the packet is to be routed to the sink, the next hop is determined from the routing table that maintains next hop addresses corresponding to the sinks address. The neighbor, whose number of hops from sink is least, is chosen as the next hop. The data packet is then sent to that neighbor so that it can forward the packet to the sink or next hop towards the sink.

5.2. Modification in RIME MAC layer

The RIME MAC layer chosen for implementation of routing framework is CSMA/CD. It contains a queue to store packets waiting for their turn for transmission. Modifications have been made to how a packet will be inserted into

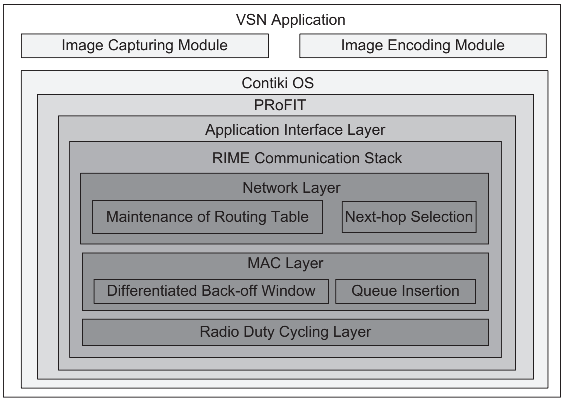


Fig. 5. VSN application architecture.

128 Bytes							
RIME Header	Sink 1 Address	Hops from Sink 1	Sink 2 Address	Hops from Sink 2	....	Sink 34 Address	Hops from Sink 34
24 Bytes	2 Bytes	1 Byte					

(a) Advertisement Packet

RIME Header	Image Number	Sequence Number	Priority	Sink Address	Unused	Image Data
24 Bytes	1 Byte	1 Byte	1 Byte	2 Bytes	3 Bytes	96 Bytes

(b) Image Data Packet

Fig. 6. Types of VSN packets.

the queue. When the packet is received by MAC layer from network layer, the priority of the packet is checked. If it is a high priority packet, it is placed at the head of the queue. If it is a low priority packet, it is placed at the tail of the queue. When sending a packet, the MAC layer always picks up a packet from the head of the queue. This way if there is any high priority packet in the queue, it will be transmitted before low priority packets giving precedence to first pass image information at intra-node level.

On sensing the medium to be free, if two nodes transmit at the same instance, a collision will occur. When this collision is detected by the MAC layer, it defers the transmission of that packet based on a random time slot out of a pseudo-fixed-sized contention window. The random time slot is selected using binary-exponential back-off algorithm. Without our modifications, the back-off algorithm maintains the same contention window for all types of packets that collide. The expected back-off time, $E(c)$, can be approximated using

$$E_c = \left(\frac{2^c - 1}{2}\right) \tag{1}$$

c is the number of times the packet collided.

With our modifications in place, the back-off time additionally depends on the priority of packet that collided. The modified expected back-off time, $E(c, p)$, can be approximated using Eq. (2). The factor pW causes contention window to shift for low priority packets, providing inter-node level precedence to high priority packets.

$$E_{c,p} = \left(\frac{2^{c(1+pW)} - 1}{2}\right) \tag{2}$$

$$p = \begin{cases} 0 & \text{if high priority packet collided} \\ 1 & \text{if low priority packet collided} \end{cases}$$

W is the contention window size.

6. Simulation results

The type of VSN applications targeted in this paper can be implemented using low-cost sensor network nodes such as TelosB [28]. Some motes can be equipped with CMUCam4 [29] giving them image capturing ability. The remaining TelosB nodes can be used to route image data from visual sensing nodes to sink nodes. These applications of such VSNs can capture images and use image encoding algorithms such Discrete Cosine Transform or Discrete Wavelet Transform to encode images into different level of details for progressive image transmission. In the future, we intend to integrate PRoFIT with real VSN application to measure its performance.

For simulations, we created an application that emulates a real VSN application by generating random image layers according to user-defined configurations. The simulation configurations set to quantify the usefulness of routing framework, consist of generating 90×90 pixels resolution image layers where each pixel is of 3 bytes, 1 byte per color. Therefore the entire image layer is $90 \times 90 \times 3 \approx 24$ kilobytes, approximately. One data packet can transport 96 bytes hence one image layer is transmitted in less than 256 packets. The ratio of high priority to low priority packets is kept as 50-50%. The size of MAC layer queue is set to 32 packets. The simulations consist of 25 VSN nodes arranged in a regular grid as depicted in Fig. 7. The channel check rate is set to 64 i.e. in one second the ContikiMAC radio duty-cycling layer checks the channel 64 times to see if a neighbor is transmitting. The dotted-line represents the transmission–reception ranges. The dot-filled circles represent sink nodes; the empty circles represent intermediate nodes, whereas the circles with stripes denote visual sensing nodes.

The nodes at the corner of the grid have only two neighbors in their transmission–reception range, e.g. Node-20 and Node-24 are in vicinity of Node-25. Remaining nodes on the sides have three nodes in their vicinity, e.g. Node-22, Node-18 and Node-24 are in transmission–reception range of Node-23. Finally, remaining nodes of the grid have 4 neighbors in their vicinity, e.g. Node-12, Node-8, Node-14 and Node 18 are in vicinity of Node-13.

The application can emulate different scenarios by modifying simulation configurations. The visual sensing nodes generate packets varying from 1 to 24 packets per second. Three network configurations, depending on the number of visual sensing nodes, have been tested with a large number of simulations for each configuration. Node-1 was selected as sink in all simulations. For each network configuration, packets were generated at rates

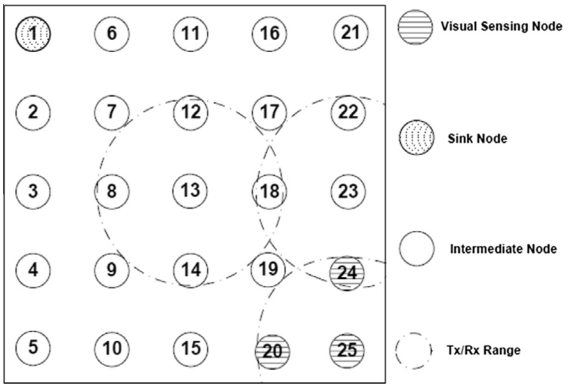


Fig. 7. Grid topology.

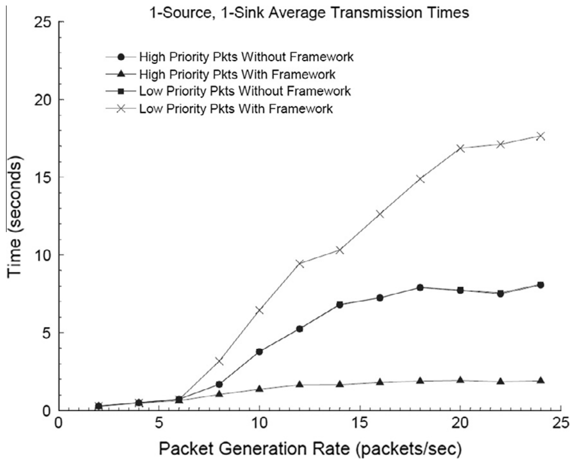


Fig. 8. Average transmission time for one source.

starting from 1 packet per second to 24 packets per second. Details along with results of each configuration are given in the sub-sections below. The parameters are summarized in Table 1.

6.1. Network performance simulations

The first network configuration contains one visual sensing node, Node-25, responsible for generating image layers. It is placed at 8 hops from the sink. Fig. 8 shows the average time taken by high priority packets and low priority packets to reach the sink node from visual sensing node. The lines represent average time taken with PRoFIT in place as compared to average time taken without PRoFIT. The lines with circle and square symbols denote average transmission times of high priority and low priority packets, respectively, with PRoFIT inactive. Simulations were carried out without PRoFIT in place to generate reference results. As PRoFIT did not manage MAC queues and retransmission times of packets, there is no difference in routing of high and low priority packets. Both types of packets are treated the same way by the network. As a result both high and low priority packets take almost same time to reach the sink node. This is why circle symbols are not clearly visible in Fig. 8.

With PRoFIT actively managing MAC queues and retransmission times, high priority packets (denoted by line with triangles) take much lesser time than low priority packets (denoted by line with crosses). The legend for all figures has been kept similar to Fig. 8 for easy comparison by the reader. At lower packet generation rates the difference in average transmission times is less visible because the MAC layer queues are almost empty. Moreover, as each node has lesser packets to transmit, collisions rarely occur. As the packet generation rate is increased, the effect of PRoFIT becomes visible. The average transmission time for high priority packets decreases significantly as compared to the reference simulations. On the same note, average transmission times for low priority packets have increased as compared to the reference simulations.

Fig. 9 represents packet delivery ratios at 30 s deadline. Packet delivery ratio denotes the ratio of packets generated from the visual sensing nodes to packets received at the sink. At low packet generation rates, the difference in packet delivery ratios is less visible because the MAC layer queues are almost empty and as each node has lesser packets to transmit, resulting in rare cases of collisions. As the packet generation rate increases delivery ratio of high priority packets improves as compared to low priority packets. Moreover, delivery ratio of high priority packets is better than reference graphs when PRoFIT was inactive.

Fig. 10 represents the packets received over percentage of simulation time with and without our PRoFIT in place. Without PRoFIT, the packets received over simulation time are same for both high and low priority packets. On the other hand, when our PRoFIT is active, the number of high priority packets received is higher than number of low priority packets received. Hence, at any time in the simulation, the sink node receives more high priority packets although the packet generation rate has been kept same for both types of packets in our simulations.

To reconstruct the image at the sink node within a certain time, the image decoding algorithms running on the sink node impose deadlines for each layer. As the image encoding and decoding algorithms are not part of this paper, we have selected a deadline of 10 s for high priority packets corresponding to coarse image information of first pass and a deadline of 30 s for fine image information of second pass. In a real VSN application, these deadlines will

Table 1
Simulation configuration parameters.

Parameter	Value
Network topology	Regular grid
Total VSN nodes	25 nodes
Number of sinks	1 node
Number of sources	1, 2 and 3 nodes
Image resolution	90 × 90 pixel
Bytes per pixel	3 bytes
Neighbor density	4 neighbors
Packet size	96 bytes
Packets/image	256 bytes
Packet generation rate	1–24 packets per second
High to low priority ratio	1.1
MAC queue size	32 packets
Contention window size (W)	2

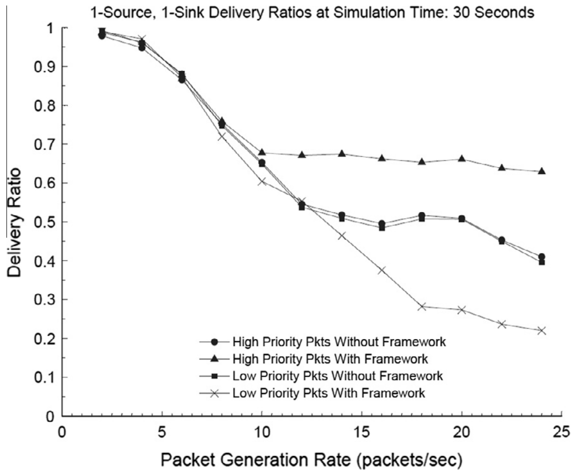


Fig. 9. Delivery ratios for one source at simulation time, 30 s.

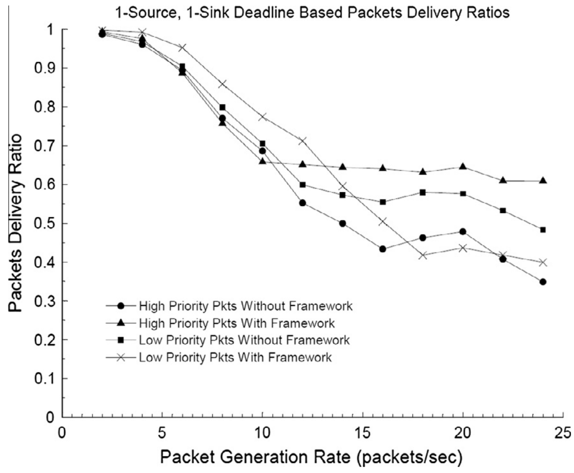


Fig. 11. Delivery ratios for one source within deadlines.

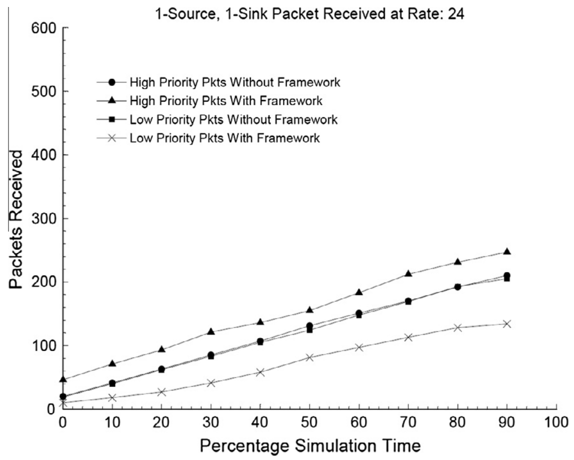


Fig. 10. Packets received for one source over percentage of simulation time.

be dependent on the image decoding algorithm. Fig. 11 represents the packet delivery ratio within these deadlines. With PRoFIT in place, the delivery ratio of high priority packets that reached the sink node within 10 s of transmission is significantly higher than without PRoFIT active. With PRoFIT active, the delivery ratio of low priority packets decrease as the packet generation rate increases. This decrease is due to the increase in delivery ratio of high priority packets. As the network resources remain same, the increase in packet delivery ratio of high priority packets is compensated with decrease in delivery ratio of low priority packets.

The second network configuration contains two visual sensing nodes, Node-20 and Node-24, both placed at 7 hops from the sink. Whereas the third network configuration contains three visual sensing nodes, Node-20, Node-24 and Node-25. Figs. 12, 13, 14, and 15 represent average transmission times, packet delivery ratios at 30 s simulation time, packets received over percentage simulation time, and deadline based packet delivery ratios for two visual sensing nodes simulations, respectively. Similarly, Figs. 16, 17, 18, and 19 represent average transmission times, packet delivery ratios at 30 s simulation time, packets received over percentage simulation time, and deadline based packet delivery ratios for three visual sensing nodes simulations, respectively. Simulations with two and three visual sensing nodes were carried out to see the effects of having more than one visual sensing node in the network.

As there is an overlap in the paths from the visual sensing nodes to the sink node for two and three visual sensing nodes simulations, difference in average transmission times can be seen as compared to simulation results of one visual sensing node. This overlap increases the average transmission times for all packet generation rates as compared to simulations with one visual sensing node. Similarly, there is a difference in packet delivery ratios and packets received within deadlines as compared to simulation results of one visual sensing node.

Increase in average transmission times and decrease in packet delivery ratios are because of two reasons. The first

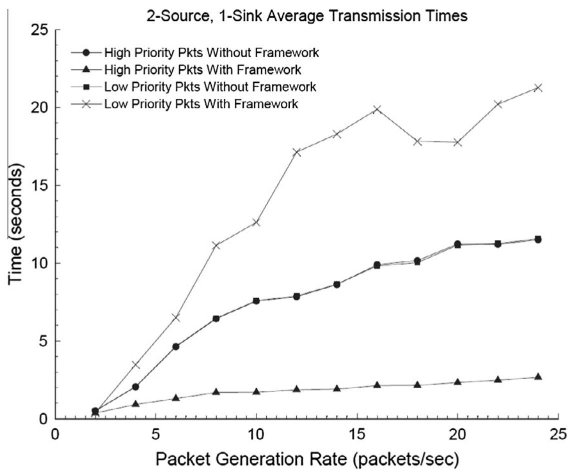


Fig. 12. Average transmission time for two sources.

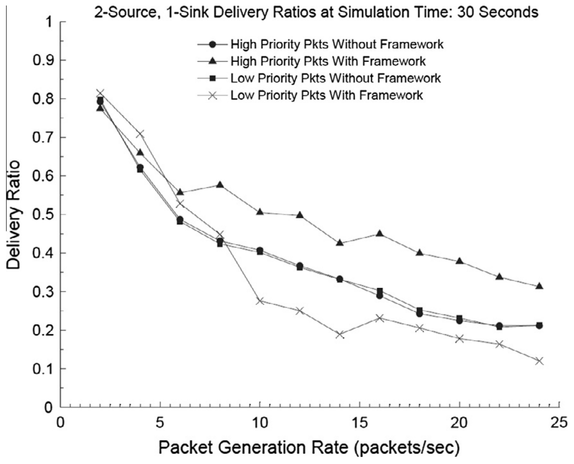


Fig. 13. Delivery ratios for two sources at simulation time, 30 s.

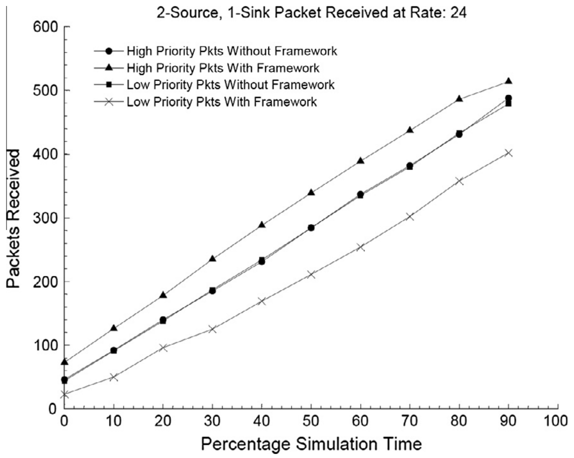


Fig. 14. Packets received for two source over percentage of simulation time.

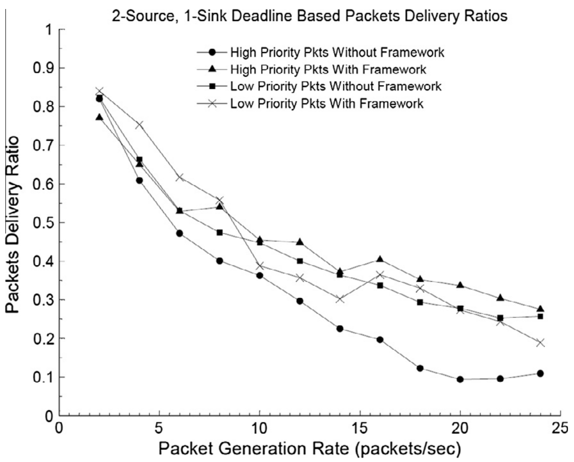


Fig. 15. Delivery ratios for two source within deadlines.

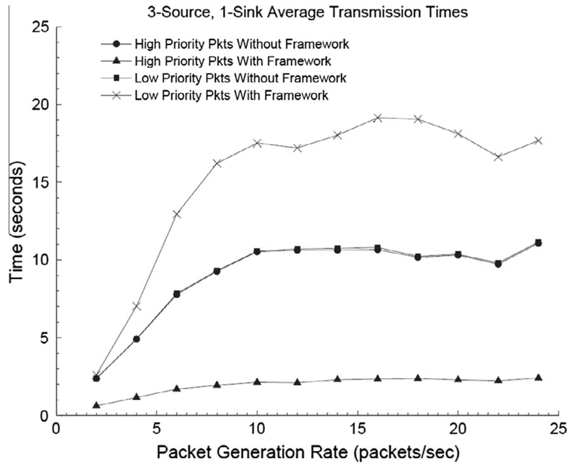


Fig. 16. Average transmission time for three sources.

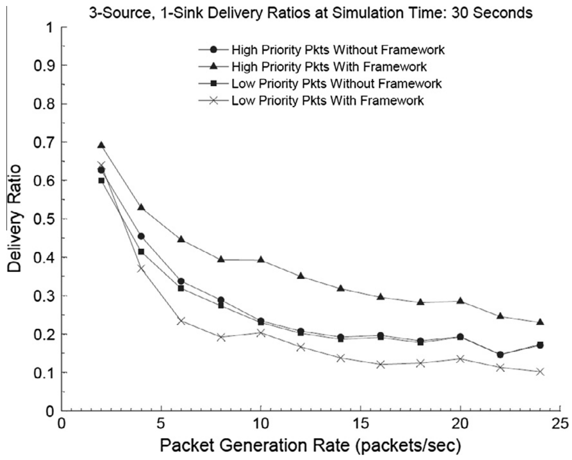


Fig. 17. Delivery ratios for three sources at simulation time, 30 s.

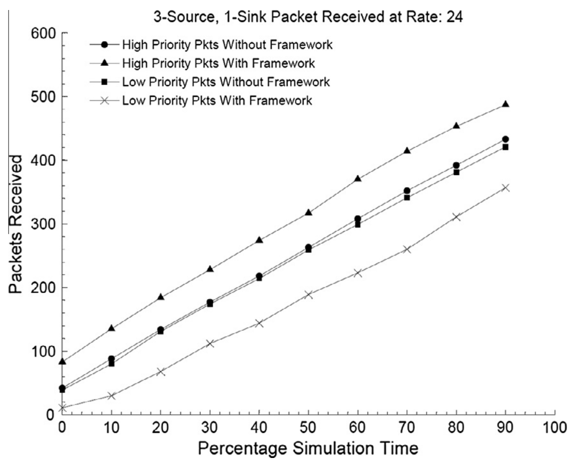


Fig. 18. Packets received for three source over percentage of simulation time.

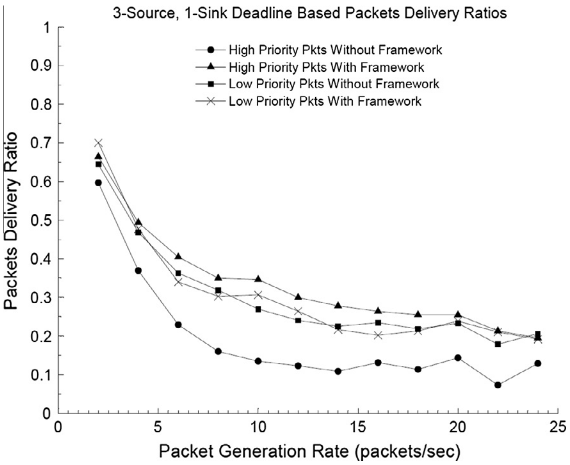


Fig. 19. Delivery ratios for three source within deadlines.

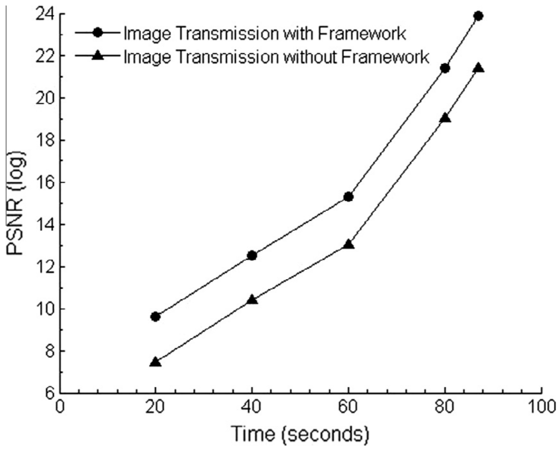


Fig. 21. PSNR at deadlines.

reason is that due to overlapping paths, packets collide. Collisions cause excessive retransmission. When the MAC layer's maximum retransmission threshold is achieved, the packet is discarded causing the packet delivery ratio to decrease. The packets that reach the sink take more time because of multiple retransmissions by the intermediate nodes causing the average transmission time to increase. The second reason is that as collisions increase, the lifetime of packet in the MAC layer queue also increases. This causes the queue to fill up sooner. As a result incoming packets do not find space in MAC layer queue and are dropped causing packet delivery ratio to decrease.

6.2. Image quality calculations based on peak signal-to-noise ratio

We used PRoFIT to send a test image from one source to the sink. We used peak signal-to-noise ratio (PSNR) to calculate the quality of received image. PSNR in terms of image processing is defined as the ratio between the maximum possible pixel value of an image and pixel value of noisy image. PSNR is used for the measurement of the quality of a reconstructed image (decompression of a lossy compressed image), where the reconstructed image is of degraded quality as compared to original image. PSNR is defined in

$$\mathrm{PSNR} = 20\log(x)(P_{\max}) - 10\log MSE \tag{3}$$

where $P_{\max}$ is the maximum pixel value and MSE is the Mean Squared Error (MSE) which is given as

$$MSE = \frac{1}{mn}\sum_{i=1}^{m-1}\sum_{j=1}^{n-1}(F_{(i,j)} - G_{(i,j)})^2 \tag{4}$$

Here m, n are dimensions of the image, F is the original image and G is the reconstructed image.Higher PSNR value

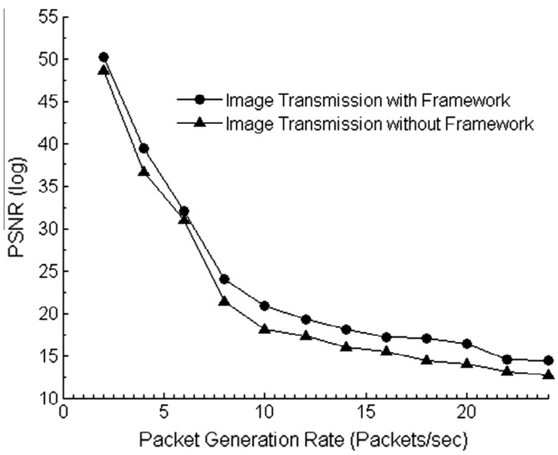


Fig. 20. Peak signal-to-noise ratio.

Fig. 22. Received image at 20 s.

Fig. 23. Received image at 40 s.

indicates better quality of the reconstructed image. In our experiment, as packets are dropped during transmission due to reasons discussed in the previous sections, the reconstructed images are not of the same quality as of the original image. Fig. 20 shows the PSNR values of the reconstructed image with varying the packet generation rate from the visual sensing node. PSNR values with PRoFIT are better than PSNR values without PRoFIT. PSNR value is increased by approximately 3 dB using PRoFIT. The maximum gain in PSNR is exhibited at packet generation rate of 8 packets per second.

6.3. Deadline based PSNR

We also tested our VSN application for deadline based reception. Fig. 21 shows the PSNR of images reconstructed at deadlines of 20 s, 40 s, 60 s, 80 s, and 87 s (when the complete image was received). Figs. 22–26 show the reconstructed images at these deadlines. This is a reasonable example of progressive image transmission. Fig. 26 shows the reconstructed image when all packets have been received. Some of the packets had been dropped in the network due to congestion and/or small MAC layer queue size. For visual comparison, the original image is shown again in Fig. 27.

7. Image features transmission using PRoFIT

Image features are information of an image that can be used in several image processing and computer vision applications. The foremost step of many image processing and computer vision applications is feature extraction. These image features are edges, corners, blobs, SIFT, etc. Where edges and corners are very basic features and these two basic features can be used in motion detection, image registration, object detection and recognition, image mosaicking, and 3D modeling [30–33].

The result of applying edge detection on our test image is an image containing black and white colors, only. Fig. 28 is the resultant image after apply edge detection technique. A pixel of a raw grayscale image is represented by 8-bits, whereas a pixel of RGB image is represented by

Fig. 24. Received image at 60 s.

Fig. 25. Received image at 80 s.

Fig. 26. Received image at 87 s (all packets received).

Fig. 28. Extracted edges.

24-bits. However, the result of edge detection produces an image represented by 1-bit (black or white color; 0 or 1) per pixel. The size of resultant image can be further reduced by applying various compression techniques. Similarly, in case of corner detection, the result can be represented either by using a two dimensional array; where each element corresponds to the position of the corner (*x*-coordinate and *y*-coordinate). Another technique to represent corners is a black and white image (binary image); where each corner is represented as white spot and the rest of the image is black. Fig. 29 is resultant of the original image after applying the corner detection.

In another set of simulations, PRoFIT has been used to transmit edges and corners. In these simulations, the visual sensing nodes extract the image features. These nodes use PRoFIT to transmit them using high priority, whereas the original image is transferred using low priority. This is another class of VSNs that can benefit from PRoFIT.

Fig. 27. Original image sent.

Fig. 29. Extracted corners.

8. Conclusion

Based on all simulation results we can conclude that PRoFIT, our proposed Priority Routing Framework for Image Transmission assists progressive image transmission in VSNs. Critical imagery information from visual sensing nodes can be received at sink nodes sooner than less critical imagery information. Progressive image transfer helps us in managing the low bandwidth issue of VSN environment. Priority based transmission of bit planes using PRoFIT has been discussed in this paper. Through simulations we have proved that PRoFIT produces better results as compared to the non-priority based routing. We also see that PSNR value of received images is increased by approximately 3 dB. We have also shown that VSN using image features extraction and transmission also benefits from PRoFIT. Hence, PRoFIT improves system response time in time-critical VSN applications as compared to non-priority based routing protocols.

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