Cross Layer Optimized Transmission for an Energy Efficient Wireless Image Sensor Network

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Abstract

Compared with traditional WSNs, image and multimedia data in wireless image sensor networks require sophisticated processing transmission techniques to meet the limited energy budget. Further image data require time efficiency and minimal jitter for maintaining the quality of data. Wavelet coding is used to separate an image into image-pixel-position and image-pixel-value information. This intra-image diversity is exploited to reduce the transmitted data by transmitting only the position information of the threshold . Simulation results demonstrates that there is no significant loss in visual quality of image, to the human eye, for the purpose of identifying an object. The resulting lower segment length ensures significantly higher bandwidth utilization, lower jitter and improved energy efficiency. A cross layer design provides adaptive modulation by exploiting intersegment dependencies across Physical, MAC and Application layers.

Keywords:*, cross layer, DWT, energy efficiency, image transmission, wireless sensor network*

1. Introduction

Wireless Image sensor networks [1], a new emerging type that contains nodes equipped with cameras, microphones, and other sensors capturing multimedia content. Each battery powered multimedia sensor node is equipped with a low power wireless transceiver which is capable of information processing, sending and receiving video and audio streams and still images that have the potential to enable a large class of applications including surveillance systems. Military applications, habitat and seismic monitoring, person locator service in fire detection, efficient industrial process control and biomedical applications are added advantages.

There are stringent constraints for deployment of sensor nodes : small sized , extremely power-conscious, operate in high density, autonomous, unattended and adaptive to the environment in addition to these sophisticated components. For most applications, the wireless sensor network (WSN) is inaccessible or it is not feasible to replace the batteries of the sensor nodes. Energy harnessing from the environment, like using solar cells are some options but the amount of energy that can be extracted is limited. As the battery powered sensors have limited energy supply, minimizing the energy consumption can extend the lifetime of the network. Wireless image sensor networks require larger bandwidth for transmitting image data. Minimizing average energy consumption and maintaining a good Quality of Service (QoS) are contradictory objectives. Mechanisms to efficiently deliver application level QoS and to map these requirements to network layer metrics such as latency and jitter need to be addressed.

The focus in this paper is on point-to-point image transmission over wireless image sensor networks that minimizes energy consumption given the expected distortion constraint with optimal delay using cross layer enabling the sensor networks to meet various QoS constraints of visual data transmission including communication within delay bounds.

The paper is organized as follows. Section 2 reviews related work in the area of image transmission in WSNs with emphasis on existing cross layer solutions, while Section 3 gives a brief background to this network. Problem definition is elaborated in section 4 with section 5 describing system model. Sections 6 and 7 give the performance analysis of the scheme and the concluding remarks respectively.

2. Related Work

Cross layer design has been seen several recent research works as a solution for optimizing network performance and energy optimization. Interfaces between protocol layers provide avenues for interaction and compatibility between these layers. While the traditional layered protocols do achieve very high performance in the context of individual layers, they can be intelligently interactive, without losing their layered character to maximize the overall network level performance. Given the scarce energy and processing resources of wireless networks deployed in remote areas, cross-layer design [2, 3] is a promising alternative to further improve the efficiency compared to the traditional the layered protocol approach.

The standard layered protocol architecture of networks can be altered to address many network level challenges that arise because of interactions between many layers, and because of the varying network conditions. . In this section, a few existing cross-layer solutions classified in terms of interactions among the physical (PHY), MAC, network and transport layers.

MAC and Network layers The cross-layer interactions between the MAC and network layers are mostly exploited in WSNs. In [4], a joint scheduling and routing mechanism is proposed to form on-off schedules for each flow of data in a network where the nodes are not active for the entire time. The usage of on-off scheduling in a cross layer scheme is also investigated in a TDMA based MAC scheme [2].The interdependencies of routing and scheduling using SMAC for multi-hop networks is exploited in [5].

MAC and Application layers The content of information carried by the sensor nodes has a direct impact on the network protocols. The information content of the sensor nodes is correlated, unlike in ad hoc networks. A cross layer design between the application layer and the MAC layer seeks to use the significance of information in the data to propose optimal solutions. An example of a cross layer design between MAC and application layers is the CC-MAC protocol [6] where spatial correlation between sensor observations is exploited to reduce the media access for redundant information. The design results in high performance in terms of energy, packet drop rate and latency.

Network and PHY layers Wireless channel dynamics affect the channel quality throughout the lifetime of the network. Although the distance between the nodes does not change, the unreliable wireless channel results in a fluctuating communication quality. The geographical routing protocol has been improved for lossy channels by considering channel quality information in the routing decisions [7].

Transport and PHY layers The transport layer regulates the transmission traffic to mitigate congestion in the network. The contention as well as the channel rate can be controlled by regulating the power at the PHY layer. The cross layer jointly optimal congestion control and power control (JOCP) algorithm [8] proposes an equilibrium solution among the nodes thorough an iterative update policy at every node.

Previous research on multimedia transmission has focused on image compression based on Unequal Error Protection (UEP) and cross layer optimization for multirate transmission to increase the energy efficiency. The Set-Partitioning in Hierarchical Trees (SPIHT) approach in [9] is a compact coding technique that improves the performance of embedded zero tree wavelet (EZW)[14]. However it is very vulnerable to bit corruption and requires precise bit synchronization.

Wei Wang et al., [10] proposed an unequal protection of P-V segments based on cross layer optimization to assure image transmission quality and achieve optimal energy efficiency. As demonstrated later in this paper unequal protection for transmission do not necessarily reduce distortion. Dongming Peng et al., [11] proposed Distributed Source Coding (DSC) and multirate transmission in wireless Sensor Network (WSN). Research related to multirate and power control has been extensively conducted in CDMA. The multirate and power control schemes in these works achieve high energy efficiency but are not suitable for WMSNs due to complexities in implementation and redundancies in transmission.

3. Background

A. Image transmission using wavelet coding

The information of a digital image is conveyed by shapes and objects. This information is depicted by the pixel values. The wavelet based image compression [9], [11] scheme extracts the shape and position information of the regions as well as the lighting magnitude information. Thus two groups of values called as small-magnitude wavelet coefficients and large-magnitude wavelet coefficients are formed.

The wavelet coefficients with small magnitude values are compressed by significance propagation, dominant encoding, and then run length based coding passes. These small-magnitude coefficients stand for the image-pixel-position information. Small-magnitude coefficients result in a large number of "0" bits in a bit-plane that can be efficiently compressed. The compressed small coefficients have error propagation effect as the errors in the number of consecutive "0" bits directly impact the positions of the large magnitude coefficients leading to irrecoverable misalignment and decoding difficulty.

stored in the *p* and *v* buffer are finally output in an embedded manner.

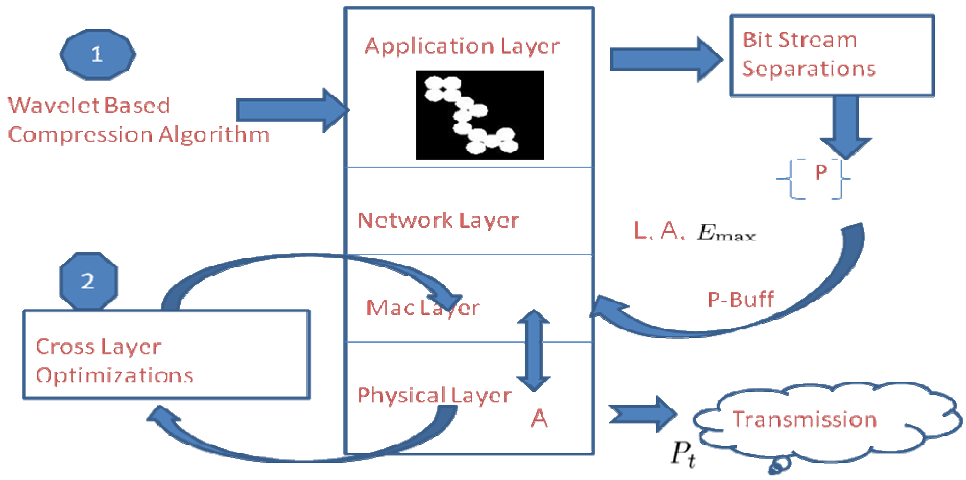


Fig 1: A block diagram showing the cross layer flow and interaction between different layers

The output of magnitude refinement is related to the large value wavelet coefficients and corresponds to the image-pixel-value (i.e., brightness) information. The large magnitude values are relatively unimportant but their locations are crucial for decoding and perception. The communication loss or errors in position information (*p*-data) will have significantly higher impact on the overall quality of the received image than the loss or errors in value information (*v*-data).

The image undergoes wavelet transform to form wavelet coefficients which are stored in a matrix. The number of bit planes of the image is identified and the initial quantization threshold for the bit planes is determined. Coding pass algorithm is applied on the wavelet coefficients by Morton scanning method. Based on the threshold wavelet coefficients can be grouped into small magnitude and large magnitude wavelet coefficients are obtained. Small magnitude coefficients are grouped as tree structure symbols. The large magnitude coefficients are classified either as positive or negative significant symbol. Both the small magnitude and the large magnitude wavelet coefficients are stored in the *p*-buffer and *v*-buffer. In the next step the threshold is reduced by half and the grouping of the coefficients into small and large magnitudes is continued for the remaining biplanes. The values that are

B. Cross Layer Optimization

A cross layer approach in network design seeks to enhance the performance of a network, by jointly designing multiple protocol layers. This helps upper layers in adapting better to varying link and network conditions. The resulting flexibility leads to an improvement in end-to-end performance and optimizes the use of scarce network resources. However, a cross layer can increase the design complexity. Given that the layered protocol helps designers to work on single protocol designs without the complexity and expertise required for considering the other layers, cross layer design cannot eliminate the conventional layering principle. Keeping some form of separation while allowing layers to interact is a good compromise for cross layer design. In such a structure, each layer is characterized by some key parameter that are passed on between layers to determine the operating modes that will best suit the current channel, network and application conditions.

The data delays at any of the layers of the protocol stack can happen due to several factors: channel contention, retransmissions of packets due to loss, long packet queues, nodes failure, and network congestion etc.

The concept of cross layer optimization [13,14] is adopted in this paper as the bit error rate information of the

MAC layer, the channel attenuation factor from the physical layer and the data encoding and decoding factors of the application layer are collaborated to find the optimal source coding rates. Fig. 1 gives the cross layer flow and the interaction between he various layers. The fig. 2 provides the block diagram depicting the interactions between the application, MAC and physical layers of the protocol stack.

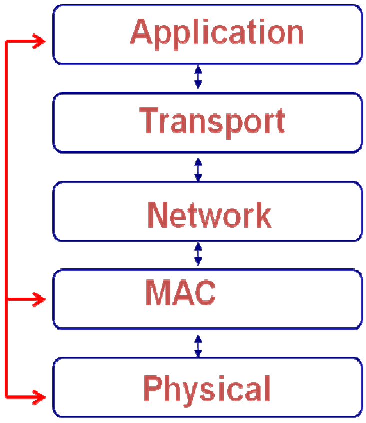


Fig. 2 block diagram sowing the cross layer interaction between the physical, MAC and Application Layers

Figure 4 shows three different 128x128 images where each pixel is 8 bit. *Im1* conveys very less information and most of the coefficient are zeros (more than half) and the highest coefficient value is 120. *Im2* has relatively more coefficients having values higher than 220 and less than half coefficient are zeros. Such images have moderate amount of information. In *Im3* most of the coefficients are greater than 220 and very few are zeros conveys very high information. From *Im1* to *Im3*, the size of *v*-segment increases drastically because the information content from images one to image three increases so the size of *v*- Segment also increases parallel because V-segment store the information of images that is the intensity of pixels. On increasing the length of *v*-segment will increase the over head transmission. Hence images which contain full information, that is, most of the coefficients are greater than 220 and very few are zeros then the size of *v*-segment increases at each bit plane. Increase in the size of *v*-segment will cause higher overheads and energy consumption.

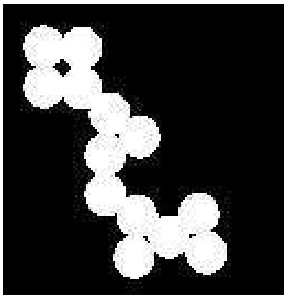
As The probability of loss of packet, *i.e.*, packet error rate will increase as the length of the *v*-segment increases. Bit error rate e_0 can be given as

$$e_0 = \left(\frac{1}{2}\right) erfc\left(\sqrt{\left(\frac{P_{max}A}{R_s b N_0}\right)}\right)$$

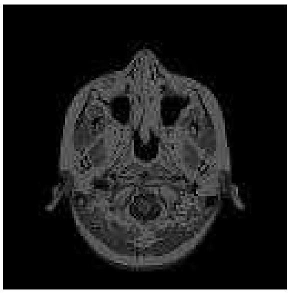
And packet error rate (PER) p_r can be given as:

$$p_r = 1 - (1 - e_0)^L$$

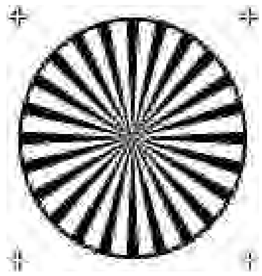
Hence as the length of the packet L increases, so will the probability of loss of packet.



Im1(1Lp,1Lv)



Im2(2Lp,2Lv)



Im3(3Lp,3Lv)

Fig.3: Three different images with three different level of information (Variation in image coefficient values)

4. Problem Definition

An innovative approach is explored in this paper to minimize the energy utilized for image transmission by reducing the data being transmitted per image. Wavelet

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coding extracts the position and value information of a region in an image to form two groups of coefficients. The small-magnitude coefficients stand for the image-pixel-position information (*p*-data) that result in a large number of '*0*' (zero) bits in a bit-plane that can be efficiently compressed.

The large magnitude values, the image-pixel-value information (*v*-data) are relatively unimportant, but their locations are crucial for decoding and perception. The data delays at different layers of the network protocol stack may be caused by various factors including the channel contention, packet retransmissions, the packet queue lengths, nodes' failure, and network congestion. The concept of cross layer optimization is used as the bit error rate information of the MAC layer, the channel attenuation factor from the physical layer and data encoding & decoding factors of the application layer are collaborated to find the optimal source coding rates.

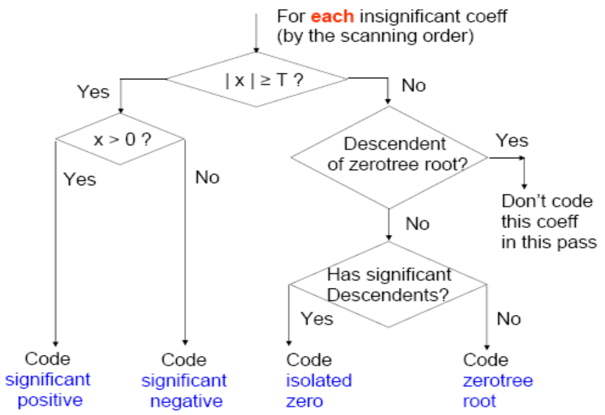

Fig 4: Flow chart of the steps in image compression in the EZW scheme

The objectives of the proposed scheme are to minimize energy utilization in a wireless multimedia sensor network while keeping the delay in transmission of multimedia data in a Wireless Multimedia Sensor Network minimal.

In order to simulate the network a few assumptions are made. It is assumed that the network is static containing homogeneous multimedia sensor nodes reporting to a single sink node. The data is snapshot-type of multimedia data i.e., monochrome 2D picture with 8 bits/pixel. The scheme is meant for security applications where it is more important to identify intrusion rather than get a very detailed image of the target and optimization of image quality is assumed sufficient to identify an event.

5. System Model

A. Network Architecture

This scheme for wireless multimedia sensor networks is based on a flat homogenous architecture in which every sensor has the same physical capabilities of capturing multimedia content and interact with neighboring sensors. The task of the sensors is to dynamically serve multimedia data from the target area to the sink in a multi-hop fashion.

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B. Mathematical Model

Energy required for transmission of a packet p can be given as:

$$E_p = \frac{LP_t}{mRP_p(\gamma)} \qquad (1)$$

Where L is the length of a packet, P_t the power required for transmission, m, information per bit, R, the data rate for a node, $P_p(\gamma)$, the probability of retransmission of packet. The energy expression in (1) shows that with the increase in the length of a packet or with lower probability of retransmission, the energy consumption is increased. Correct reception of data packet depends on channel condition and data rate on which data is transmitted on that channel.

N is the total number of bit-planes in the bit stream, $E_p(i)$ and $E_v(i)$the average energy for delivering the i^{th} segment of p-data segment and v-data respectively. The total energy required for transmission of whole image in the UEP approach is

$$\varepsilon_{pv} = \sum_{i=1}^{N-1} E_p(i) + \sum_{i=1}^{N-1} E_v(i) \qquad (2)$$

while the total energy required for the same under the scheme is

$$\varepsilon_p = \sum_{i=1}^{N-1} E_p(i) \qquad (3)$$

The per unit energy saving by the scheme in comparison to the UEP approach is

$$\varepsilon_{p.u.} = 1 - \left(\frac{\varepsilon_p}{\varepsilon_{pv}}\right) \qquad (4)$$

It is obvious that $0 \le \mathcal{E}_{p.u} \le 1$ as the second term ($\mathcal{E}p/\mathcal{E}pv$) is less than one in (3) which shows that this scheme is more energy efficient than the UEP approach. Similarly, the reduced segment length and transmission time in the scheme can be derived mathematically.

Table 1. CLOTEE Algorithm for the compression of image at the sender node based on EZW, Algorithm 2 for the reconstruction of image at the receiver node.

At sender node
Initialize p-buff to store p-data segments
Get wavelet coefficients of the image in an mXn matrix S
Get threshold by T=max(|S (i, j|)/2, where 0≤i≤m-1 and 0≤j<n-1
Count=1, WC=wavelet coefficients, CS=coefficient symbol
Get No. of bit planes-N according to compression ratio
While count < = N do
scan wavelet coefficients by Morton scanning order, compare WC with T
if (WC >T && CS== positive) then WC = p
elseif (WC >T && CS==negative) then WC = n
else if (WC < T && descendents of WC < T) then WC = zero_root symbol
elseif (WC < T && descendents of WC > T) then WC = isolated_zero symbol
6.3 Store isolated_zero , zero_root, p and n symbols in p-buff for each bit plane
T = T/2
End

At receiver node
Initialize all the elements of received matrices R = zero
Get threshold T
For each segment of p-buffer
3.1 get symbol according to Morton scan order
3.2 if (symbol==positive) then add positive T
else add negative T
3.4 T=T/2
3.5 Add T to all previous coefficient of matrices 'R' according to sign, and so reconstruct the matrices R for each p-buff.
4. Construct the image using received matrices R.
5. End

C. Algorithm

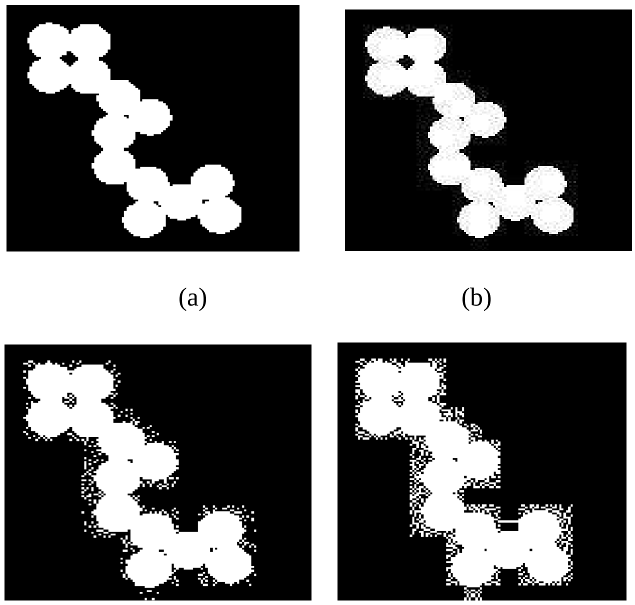
By applying wavelet based image compression scheme embedded Zero Tree Wavelet (*EZW*), the lighting magnitude information in a region of the image is extracted into position and value data coefficients matrices. Morton scanning is used to scan the coefficients of the image sub bands. The Figure. 4 show the flow chart for the steps in the *EZW* technique for image compression.

The steps followed in this paper to transmit the image from the sender to the receiver node are as follows: Construct *p*-data segments at the sender node for an image using standard wavelet coders and transmitting *p*-data segments. Reconstruct the image matrix for the p segment and reconstruct the image using these received matrix at receiver node.

The CLOTEE algorithm provides the pseudo code for compression and EZW at the source node and the reconstruction of the image at the receiver node, Table 1.

6. Simulations Results

In this section, the effectiveness in achieving energy efficiency while preserving image transmission quality is observed. MATLAB is used as the simulation tool with T-MAC as MAC protocol. MAC header is 11 bytes and payload is 36 bytes. For the control packet such as ACK, the length is 13 bytes; RTS and CTS packet are both 15 bytes. The receiver power is fixed to 0.01mW. The noise power density value is $4*10^{-21}$ J/z. Symbol rate is 1000 KHz. For adaptive modulation BPSK, QPSK and M-QAM modulation schemes with even constellation sizes are used in simulation.



(a) (b) (c) (d)

Fig. 5. Image used for processing between two nodes of size 128×128 pixel size where the size of each pixel is 8bit (a)Original Image (b) Reconstructed image for N=3 (c) N=5 (d) N=7

Moving from Layer 1 to Layer 8 more noise is added compared to image pixel value information as the threshold decreases and therefore more small value information (coefficient) is added which does not carry much information for reconstruction of a image, increasing distortion increases, Figure 8.

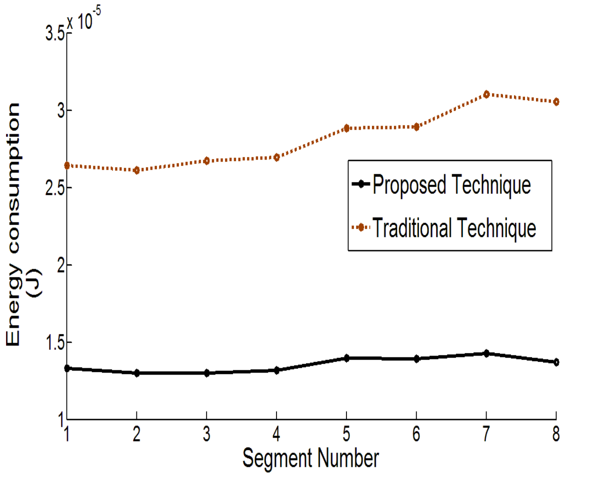


Fig. 6. A plot of the energy consumption in the proposed scheme in comparison with UEP

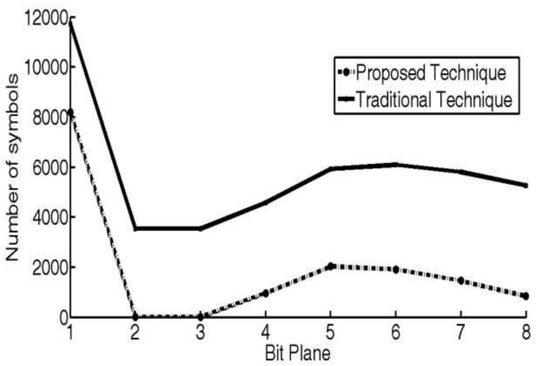


Fig. 7. Number of symbols generated during compression at each bit plane

The performance of proposed technique is compared with the traditional Unequal error protection (UEP) scheme. The simulation results and analysis show that the proposed image reconstruction technique required much less energy, bandwidth and time required to send data from one node to another while preserving the quality of multimedia data. The image shown in Figure 5 with 128×128 pixels and 8 bit per pixel is used as an example in the simulation.

Fig. 6 shows that the energy consumed during compression and transmission in case of the UEP scheme is much higher compared with the proposed scheme. This can be attributed to the reduced segment size in the proposed approach. In the resource starved wireless multimedia sensor network reduced energy consumption is of vital importance. Figure. 7 gives the graph of number of symbols generated in the bitplanes with a comparison between the proposed technique and the UEP scheme. It is clear that the quantum of symbols for the proposed scheme is lower at all bit

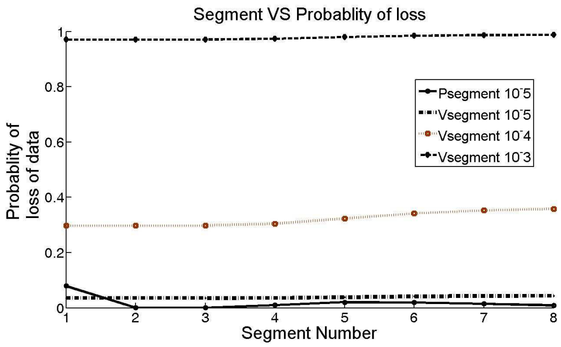


Fig 9. A plot of the probability of loss in comparison with the UEP scheme.

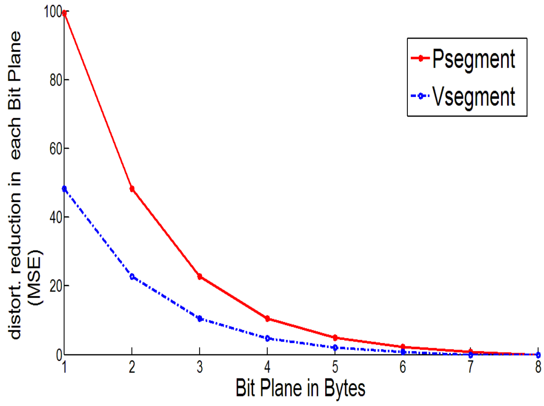


Fig. 8. Distortion reduction at each segment during reconstruction of image and importance level of each bit plane

planes, and the difference increases as we move to the higher bitplanes.

It is concluded that the number of symbol required for compression in the case of the traditional technique is much higher compared the proposed technique. In the case of traditional scheme as both *p* and *v* segments are constructed during compression, the size of segment is higher in comparison with the proposed technique. This increase in segment size causes a greater probability of loss of packet and therefore greater distortion, as sown from the plot in figure 9.

The graph in Figure 10 gives the distortion reduction of reconstructed image for each segment of each bit plane for UEP. On analyzing distortion reduction for each segment of *p*-data and *v*-data stream it is clear that distortion reduction decreases from Bit plane 1 to Bit plane 5 exponentially. This implies that these segments carry more important coefficient of image pixels location information as well as image pixels magnitude information. Thus these segments require preferential protection compared to the other segments. The processing time for each segment in the plot given in figure 11 shows that the proposed scheme demands lesser time for delivery, and thereby improves the latency. This is of great importance in applications where the sensor networks are employed for capturing real-time data.

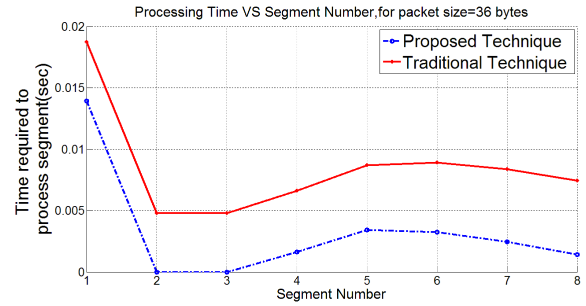


Fig. 11. A plot of the processing time for segments 1 to 8 for the proposed scheme in comparison with the UEP scheme

7. Conclusions

The scheme provides a significant improvement in performance with respect to energy efficiency and reducing the time required for processing between nodes without sacrificing the quality of image. Reduction in overall length of data packet will help to achieve higher throughput, reducing the delay in transmission of images as well as lesser amount of energy to process the data which will further prolong the life time of battery driven sensors. A cross layer approach with interaction between the application layer, MAC layer and the physical layer provides further efficient use of scarce network resources. Simulation results show that the proposed scheme is convergent and the energy consumption is efficient.

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