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Performance evaluation of error control schemes for distributed video coding over wireless multimedia sensor networks

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Abstract Distributed Video Coding (DVC) is a new approach in video coding which due to low computational complexity at the encoder side, has a great potential to be used in Wireless Multimedia Sensor Networks (WMSN). However, the different architecture of this codec affects the efficiency of transmission protocols and in order to efficient transmission of DVC over WMSN, it is necessary to evaluate the performance of the transmission protocols in the presence of DVC characteristics. In the view of these protocols, error control methods are important mechanisms that provide quality of service and robust multimedia communications. For this reason, we performed a comparative performance analysis for all error control schemes that consist of Automatic Repeat Request (ARQ), Forward Error Correction (FEC), Erasure Coding (EC), hybrid link layer ARQ/FEC and multi-layer hybrid error control schemes for DVC in WMSNs. These analyses are in the terms of the most importance metrics in multimedia communications over WSNs, such as objective and subjective video quality criteria, delay, energy consumption and some DVC-specific metrics. The results show the distinct behavior of DVC in the presence of channel error and can be used to propose an effective and efficient error control scheme for DVC over WMSN.

Keywords Distributed video coding · Error control · Wireless multimedia sensor networks

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1 Introduction

Distributed Video Coding (DVC) is a new paradigm in video coding that has a light encoding operation due to different architecture compared to the traditional video coding such as H.26× and MPEG [12]. Low encoding complexity makes DVC a suitable choice in Wireless Sensor Networks (WSN) however, the different architecture of this codec challenges all previous transmission protocols, as the most of these protocols are based on the structure and the predictive nature of standard video coding [17]. So, it is necessary to evaluate the transmission protocols in the face of unique characteristics of DVC. Then, the results of these evaluations can be applied to develop efficient protocols.

Among transmission protocols, error control mechanisms have considerable influence on video quality [33, 35, 36, 38, 48]. Popular error control mechanisms in multimedia communications over wireless networks include Automatic Repeat Request (ARQ), link layer Forward Error Correction (FEC), and Erasure Coding (EC). In addition, the literatures on WSN suggest using hybrid schemes in order to simultaneously achieve the best features of them [48]. For instance, link layer hybrid ARQ/FEC and multi-layer hybrid error control schemes are proposed in [13, 18, 29]. Furthermore, some of the literature propose cross layer schemes [9, 19, 42, 43] which are used in video communications (especially over WSN) with the aim of achieving greater efficiency and effectiveness. These schemes are based on the error resilience of the video codec and the efficiency of error control schemes. They consider the importance of frames to the perceived quality and apply more protection to those frames that are more important.

Therefore, when proposing efficient error control protocols for video data in WSNs, it is necessary to identify the error resiliency of the codec and to study the efficiency of the relevant common error control protocols. This has been done in many studies on a traditional video codec [4, 19, 42, 43], however as mentioned already, the specific characteristics of DVC means that these analyses and schemes are not usable for DVC.

We analyzed both the bit efficiency and the error resiliency of DVC in our previous work [30]. Here, we plan to study the robustness and efficiency of error control protocols for DVC over WMSNs by conducting a comparative performance analysis through the use of extensive simulations. The results of these analyses will establish the efficiency of error control schemes for DVC over WMSNs which can then be used to design an efficient error control scheme; specifically, cross layer scheme. We analyzed the performance of all error control schemes in notable parameters for multimedia transmission over WSNs such as energy consumption, delay, and both objective and subjective video quality criteria. These analyses are as a function of channel bit error rate, error correction capability, maximum number of retransmission, maximum allowable delay, and some DVC-specific metrics such as the number of bits from feedback channel and so on.

The rest of this paper is organized as follows. The next section is an overview of the DVC architecture and related works. Section 3 describes the system model which consists of error control schemes, the channel error model, and the energy consumption model. Section 4 is dedicated to the results of the simulation and the comparison between the performances of the error control schemes. Section 5 presents the conclusions and finally Section 6 provides an insight into future works.

2 Background

2.1 DVC architecture and characteristics

DVC is the best option for being used in WMSNs because of the low computational complexity at the encoder side [12]. In addition, independently frame coding in this codec provides attractive ability to multi view scenes without need for communication between nodes in dense network [22, 27].

This codec is based on Wolf-Slepian [44] and Wyner-Ziv [50] theories presented in information theory as "loss less" and "lossy" Distributed Source Coding (DSC) respectively. Currently, the two most common architectures for DVC are [12], interpolation-based distributed video codec [1, 2], and a backward prediction-based distributed codec known as PRISM [39, 40].

According to our analyses in [30] and other research such as [12, 46] the first architecture performs better in terms of bit efficiency than does PRISM; therefore, in this paper we will consider the first (interpolation-based) architecture. The block diagram of this architecture is shown in Fig 1.

The main idea in DVC is to exploit the temporal correlation of video signals in the decoding phase rather than in the encoding one. This causes frames encode completely independent and transfer computational complexity to decoder side.

In DVC, key frames are encoded in intra mode by one of the traditional video codec like H.264/AVC without any motion compensated prediction between the two frames. Inter frames (known as Wyner-Ziv (WZ) frames) are encoded based on distributed source coding principles. To this end, after a suitable discrete cosine transform (DCT) transformation and quantization operation, bits will be sent to a turbo encoder.

A turbo encoder is a channel coding that produces parity bits by encoding the bits and sending them to the decoder after discarding the main data. The turbo decoder then uses these bits in order to fully reconstruct the WZ frame that its rough estimation previously created by performing motion compensation interpolation in the decoder, between two previous key frames that is called Side Information (SI) [12].

A notable point in this architecture is the existence of a feedback channel. As is shown in Fig. 1, all the external bits from the turbo encoder do not get sent to the decoder. Based on the trade-off between the bit rate and the quality of the pictures, the size of the bits that must be sent to the decoder should be estimated. However, if we are not able to reconstruct corresponding WZ frames within the decoding time for any reason such as bad SI, we can request and receive more parity bits from the feedback channel. So, in this architecture, the number of requests from the feedback channel depends on the quality of the key frames and, since receiving from this channel causes more delay and energy consumption, the ability of error control schemes to reduce the number of requests from the feedback channel is very important [30].

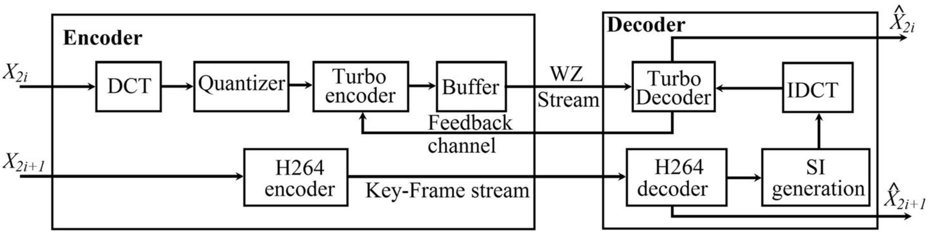


Fig. 1 Distributed video coding architecture

2.2 Related work

Performance analysis of error control schemes for WSNs and quality analysis of DVC have been discussed in many literatures [9, 13, 29, 30, 48, 49, 52]. In this section we will review theme as is summarized in Table 1.

In [48], the authors performed a comprehensive analysis of link layer error control schemes in WSNs in order to discover the impact of physical, medium access and network layer protocols on the performance of these schemes. Based on the results of their analyses, it is shown that FEC has more power in the protection of packets and less communications packet delay than ARQ. It should be noted that the mentioned method is not suitable for video communications because it is specified for scalar data. Also in [9], the relationship among the energy consumption, video quality and delay in wireless video-surveillance applications has been investigated. These investigations show that ARQ has less energy consumption than FEC and the strength of FEC must be adopted with the channel bit error rate for saving energy. This work does not consider other error control mechanisms such as the erasure coding and multi-layer schemes, which are common in video communications. Moreover, the most important performance metrics in video quality measurement such as the frame loss rate and PSNR, are not evaluated.

In [49] EC, FEC and ARQ compared with each other in terms of energy consumption and reliability within WSNs. These works did not consider the hybrid and multi-layer error control mechanisms. In addition, In addition, they consider scalar data only.

Similar results exist for WSNs in [52] which have also been obtained for scalar data. Only in [29], Naderi and et al. have conducted a detailed simulation analysis on error control schemes for WMSNs, considering the most important metrics in such networks. However, they used MPEG for video coding at the application layer of their simulation framework while MPEG is not a suitable choice for WMSNs due to the complexity and high energy consumption of the encoding operations [4, 27]. Therefore, their results are far from a realistic situation. In this paper, we use the DVC codec in the application layer of our simulation framework that is a suitable choice for video communication over WSNs. But the DVC codec has specific characteristics and thus, it needs to be analyzed specifically as noted in the previous section.

Finally, in our previous work [30] we studied the characteristics of DVC and performed comprehensive analyses on bit efficiency and error resiliency in DVC for both DVC architectures which show significant differences between DVC and traditional video coding in these two the most important criteria in video communications. Moreover, our results illustrated that channel error had a large impact on the number of requests from the feedback channel and the video quality. This and the reasons mentioned earlier means that it is necessary to design and use proper error control schemes, ones which consider DVC specifications and WMSN constraints. To design and develop such an error control scheme, it is necessary to analyze the efficiency of the layer and multi-layer error control schemes for DVC over WMSNs.

To this end, here we performed a comparative analysis of all layer and multi-layer error control schemes in DVC over WMSN in terms of perceived quality, delay, energy consumption and number of requests from the feedback channel, to achieve an accurate estimation for performance of each mechanism. The results of these analyses can be used to design efficient error control schemes for DVC over WMSN. Particularly, the results can be used for a cross layer error control scheme.

Table 1 Related works

Ref no	Scope of Ref	Scope of our work	Differences
[48, 52]	Performance analysis of error control in WMSNs for **Scalar Data**	Performance analysis of error control in WMSNs for **Video Data**	These works are done for scalar data and due to compression of video, high quality requirement and delay constraint they cannot be applied for video communication in WMSNs.
[49, 24]	Performance analysis of error control in WMSNs for **Scalar Data**	Performance analysis of error control in WMSNs for **Video Data**	These works did not consider the hybrid and multi-layer error control mechanisms. In addition, they only work for scalar data and cannot be applied for video communication in WMSNs.
[9]	Performance analysis of error control in WMSNs for Video Data **(coded by traditional video coding)**	Performance analysis of error control in WMSNs for Video Data **(coded by DVC)**	This work does not consider other error control mechanisms such as erasure coding and multi-layer schemes, which are common in video communications. Moreover, the most important performance metrics in video quality measurement such as frame loss rate and PSNR, are not evaluated in this study.
[29]	Performance analysis of error control in WMSNs for Video Data **(coded by MPEG)**	Performance analysis of error control in WMSNs for Video Data **(coded by DVC)**	They used MPEG for video coding while MPEG is not a suitable choice for WMSNs due to the complexity and high energy consumption [4, 27, 30, 37]. Therefore, their results are far from the realistic situation. In this paper, we used DVC codec that is the best choice for video communication over WSNs but it has specific characteristics and needs to specific analyses.
[30]	Analyzing the **bit efficiency and error resiliency** of DVC over WMSNs	Comparative analyzing **the efficiency of popular error control schemes** for DVC over WMSNs	We concluded from our previous work [30] that the DVC has unique behavior in presence of channel error and developing an efficient error control for this codec is essential specially in WSNs that have many resource constraints. To this end, in this work we compared the efficiency of error control schemes that can be used for proposing efficient cross layer error control for DVC over WMSNs.

3 System model

3.1 Error control mechanisms configuration

In this paper, all the error control mechanisms consist of ARQ, FEC, hybrid ARQ/FEC, EC and multi-layer schemes including EC/ARQ, EC/FEC and EC/ARQ/FEC will be compared and analyzed.

ARQ uses a retransmission mechanism when data packets have been lost. Retransmission of a packet will continue until either the packet has been successfully retrieved or a predetermined number of retransmission retries have been performed [10]. Here, this method will be denoted as ARQ(N), where N is the maximum number of retransmission retries.

In the link layer FEC, sender node added some redundancy to source packets then receiver node can detect and correct certain amount of bit errors in the packets. The amount of detectable error depends on the amount and structure of the redundancy [48]. There are many FEC schemes which here, we used the Reed-Solomon code. This is block-based and suitable for correcting the burst errors that usually occur in radio frequency (RF) band. In addition, among block-based FEC codes, the Reed-Solomon code has the lowest energy consumption [45]. In this study the Reed-Solomon method indicated by RS(u,w), where w is the number of data symbols in a block and u is the number of data and redundant symbols that are configured to 8-bit symbols which will be able to compensate uttermost $\frac{u-w}{2}$ corrupt symbols (Fig. 2).

Erasure coding is a packet-level FEC. In this method, N packets are first buffered and coded to N + K packets. The receiver node can then decode these packets if up to K packets have been lost [24]. Packet buffering using in this method imposes further delays to packets so making the use of this method impossible for WZ frames due to the constraints imposed by the feedback channel and strict delay requirement for sent packets from this channel. For this reason, we applied EC only to key frames and to each key frame separately using the rate $^{2}/_{3}$ and shown it by EC.

3.2 Channel model

In WSNs usually the RF band is used for data transmissions [3] that do not have uniform error characteristics over time. In addition, due to the erratic length of frames the length of video packets is variable; thus, using a packet-based error model will not provide valid results. For this reason and in order to achieve accurate and close-to-reality results, we used the Gilbert-Elliot two-state Markov model [28]; This is a bit level channel model which estimates the error characteristics of the wireless channel very well [16, 28]. For this reason it has been widely used in many literatures regarding WSN [29, 42].

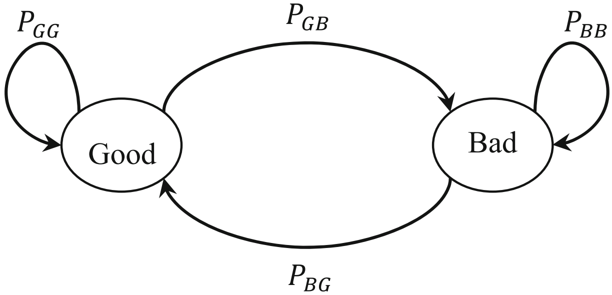


Fig. 2 Two states Markov Chain of Gillbert-Elliot erasure channel model

The Gilbert-Elliot channel model has two states named "Good" and "Bad", which are used to illustrate states with light and heavy bit error rate (BER) respectively. In the "Good" state the channel has bit error probability E_g with long intervals and in the "Bad" state, the channel has a bit error probability of E_b, with short intervals where, $E_b >> E_g$. The state diagram of this model has been shown in Fig. 2 that values of E_g and E_b and the $2x2$ stochastic transition matrix provides complete specification of this two-state Markov chain. To determine the state transition probability, the values P_{BB} and P_{GG} are required. These denote the probability of transmission to "Good" or "Bad" states, given that current state is the same mode. These values are based on actual experiences presented in several papers [7, 11, 32]. In this model, the mean sojourn time in each of these states (the duration of being in a state) will be equal to Eqs. (1) and (2):

$$T_G = \frac{1}{1-P_{GG}} \tag{1}$$

$$T_B = \frac{1}{1-P_{BB}} \tag{2}$$

The mean BER in this model can then be calculated by Eq. (3):

$$Average\ (BER) = T_G E_G + T_B E_B \tag{3}$$

This reflects the impact of the transition probabilities between states on the average BER.

This model preserves the independence of the frames packetizing method from the channel model and yields more realistic results.

3.3 Energy consumption model

In order to calculate the energy consumption of the error control schemes, we used the energy model that is presented in [29]. This models the energy consumption of nodes based on Micaz multimedia sensors [3]. In this model, nodes consume energy during the reception, transmission, encoding and decoding of the packets, as well as in the idle mode that if power consumption of nodes during the transmission mode, reception mode and idle mode are denoted by P_t, P_r and P_i respectively then energy consumption of nodes in T second of these modes can be calculated using $P_t\,T$, $P_r\,T$ and $P_i\,T$ and the sum of these values indicates energy consumption of radio transceiver.

Also, to calculate energy consumption of nodes for encoding and decoding the packets in RS, due to the negligible energy consumption for encoding [23], only consider decoding energy consumption that can be calculated as follows:

$$E_{dec} = VI_{proc}T_{dec} \tag{4}$$

Where V and I_{proc} denote the supply voltage and the current of the processor respectively, assuming that the execution of each instruction consumes the same amount of voltage and current. T_{dec} in this equation is the latency of decoding which according to [23, 24] for a RS(u,w), given by Eq. (5):

$$T_{dec} = \left(2mk + 2k^2\right)\left(T_{add} + T_{mult}\right) \tag{5}$$

Where, if we consider 8 bit symbol then, $m = 8u$ and $k = 4(u - w)$. In addition T_{add} and T_{mult} denote the energy consumption necessary for addition and multiplication of the field elements

$GF(2^n)$ with $n = \lfloor \log_2 m + 1 \rfloor$ [7]. An 8-bit microcontroller (MCU) which is used in MicaZ-based WMSN platform can perform addition and multiplication of 8 bits in one and two cycles, respectively. Therefore, because the one cycle duration of MicaZ processors is 250 ns [3],:$T_{add} + T_{Mult} = 3\left[\frac{n}{8}\right]\left(250^{*}10^{-9}\right)$ (6).

3.4 Simulation setup

We have performed extensive simulations to measure the performance of error control protocols for DVC in WMSN. To this end, Network Simulator (2) (NS2) [47] and video quality measurement tool-set called EvalVid [20] have been used. In the simulation scenario, a wireless sensor network within 200 × 200 meters with 50 wireless nodes capable of collecting, coding, and sending a live video to sink has been assumed. Table 2 summarizes the simulations key parameters.

In each simulation run, pair of sender and receiver nodes is selected randomly from the nodes. The sender then captures, encodes by DVC and sends video sequences by taking random hops to the destination through the AODV routing protocol [31]. Each node has a queue size of 100 and 40 (m) maximum transmission range. The length of packets is chosen to 200 bytes that has the best performance for video communications in WMSNs [41]. We have also used a CSMA/CA-based protocol to manage medium access control. Moreover we used the Foreman video sequence that have been coded by DISCOVER [6] with GOP Size = 2 and 15 fps. In DISCOVER codec, the key frames are generated by H.264/AVC. Then, they are broken into packets and transmitted to the receiver. In the receiver, if some packets related to a frame are lost, standard error concealment methods in H.264 are used to compensate for them [4, 51]. Additionally, the WZ frames are grouped and transmitted in a packet using the approach presented in [46]. Note that, due to the inefficiency of the feedback channel, in these analyses the feedback channel is only used to receive more parity bits and the lost WZ packets are not requested from feedback channel. The presented results are the resulting average of 10 repeats of the simulation run, using different random number seeds.

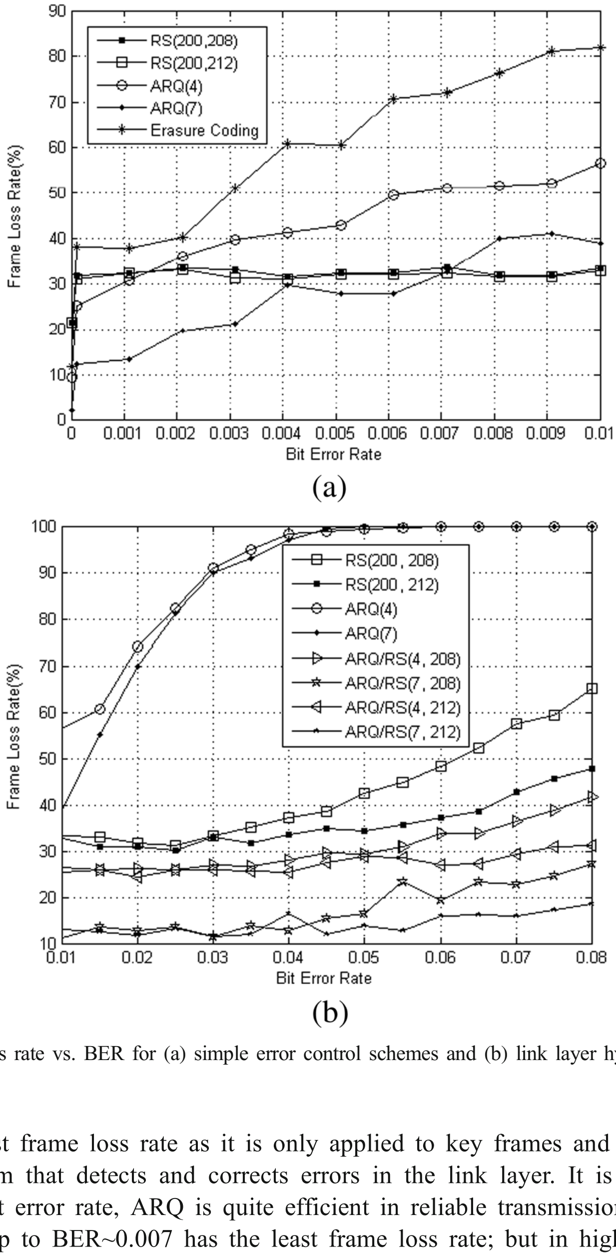
4 Performance evaluation

4.1 Frame loss rate analysis

In Figs. 3a, b, the frame loss rate is shown as a function of the channel bit error rate for ARQ, RS, EC and hybrid ARQ/RS, error control schemes. Based on Fig. 3a, EC

Table 2 Simulation parameters

parameters	Value
Channel Bandwidth	250 kbps
Packet Size	200 bytes
Transmission range	40 m
Transmit Power	52.2 mW
Receive Power	59.1 mW
Idle Power	0.06 mW
current	8 mA
Supply Voltage	3 V
One Cycle Duration	250 nS



(b)

Fig. 3 Frame loss rate vs. BER for (a) simple error control schemes and (b) link layer hybrid error control schemes

has the highest frame loss rate as it is only applied to key frames and does not have any mechanism that detects and corrects errors in the link layer. It is also observed that in low bit error rate, ARQ is quite efficient in reliable transmission of frames as the ARQ(7) up to BER~0.007 has the least frame loss rate; but in high BER, due to many retransmissions and occurrence of congestion in the nodes, the frame loss rate rapidly increased.

In this BER, the RS method shows a lower frame loss rate, so it is better to use ARQ where there is a low BER and to apply RS for high BER. Although, when using RS to protect video frames, it is necessary to adopt the strength of RS with the channel condition because the RS decoding energy consumption depends on the coded block length. For example, in Fig. 3a, RS(200, 212) has an identical frame loss rate to RS(200, 208) while will see in section 4.6 that consumes more energy.

In Fig. 3b the link layer schemes with different N and u are comparable. This fig confirms what was mentioned above. Furthermore, this figure shows that increasing the RS's strength and using the ARQ/RS(4212) rather than ARQ/RS(4, 208) results in a greater efficiency improvement than does increasing the maximum retransmission retries in ARQ/RS(7, 208). In other words, increasing the number of maximum retransmission retries in ARQ is more effective in reliable frame delivery than is increasing the strength of RS; but it should be noted that ARQ imposes more delays on data, which is unbearable in video communications, especially in DVC, where the feedback channel makes packets more sensitive to delay.

Finally, in Fig. 4 the ARQ, RS and ARQ/RS are compared with multi-layer schemes. Based on these curves, when ARQ combines with EC in a multi-layer approach, the redundancy of the EC method triggers the frame loss rate in ARQ and the poor performance of ARQ in high bit error rate intensifies.

Additionally, it has been shown that the frame delivery rate in ARQ/RS is better than in EC/RS and EC/ARQ/RS. This is because, in ARQ/RS or RS, successful reception of the first packet from one frame means that frame has been successfully received. However, in EC, if the number of lost packets from one frame becomes more than a threshold (which depends on the strength of EC), received packets cannot be decoded and so, that frame is considered as a lost frame. However, weaker performance in reliable frame transmission of EC/RS and EC/ARQ/RS does not prove inefficiency of them for DVC, because successful reception of a key frame in these methods, unlike other methods, means that all packets related to this frame have been successfully received which causes high quality in this key frame at the sink, consequently. In sections 3.1 and 3.2, we noted that in DVC, the quality of WZ frames and the number of requests from the feedback channel strictly depends on the quality of key frames. Thus the high quality of key frames in EC/RS and EC/ARQ/RS methods simultaneously improves video quality and saves network resources, as well as reducing delay by decreasing the number of requests from the feedback channel. In the following sections, we will show these results by analyzing and comparing the efficiency of error control schemes for DVC in terms of objective and subjective video quality, bitrate, energy consumption and delay.

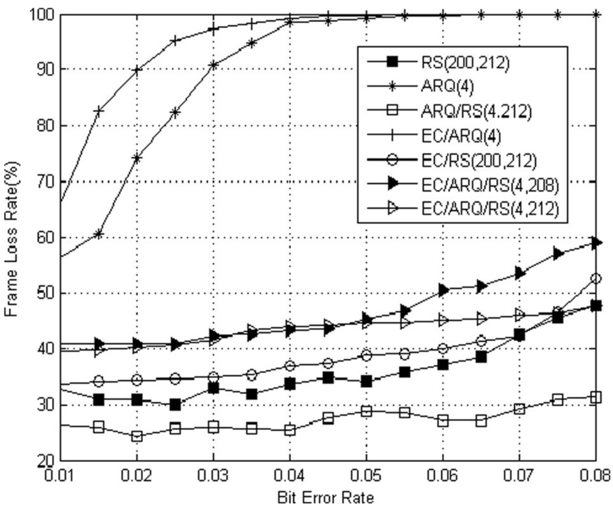


Fig. 4 Frame loss rate vs. BER for multi layers error control schemes

4.2 Video quality analysis

In this section we will analyze the perceived video quality of error control schemes in DVC. To this end, we have used both objective and subjective video quality criteria. We will begin with a PSNR analysis as an objective metric, afterward clearing and extending the results using subjective metrics such as snapshot of frames and Mean Opinion Score (MOS).

Fig. 5 shows the average PSNR of received pictures for layer and multi-layer error control mechanisms, as a function of BER. Based on this figure, protected video using ARQ and EC/ARQ has the lowest PSNR. This is due to plenty of frame loss in these two schemes. Also, in confirmation of what we said in the previous section, this figure shows that using EC in combination with strong and low redundancy link layer schemes such as RS and ARQ/RS achieves a higher PSNR than link layer schemes. For instance, EC/RS has more average PSNR than ARQ/RS while have already seen that has higher frame loss rate.

Indeed, packet-level FEC in multi-layer schemes provides either high quality key frames or nothing. In the first case high quality key frames result in high quality WZ frames. In the case of frame loss (nothing), previous successfully received key frame will be used instead of the lost frame and if, there were no significant different between them, using the last successfully received frame to construct the SI still gives better quality than a SI based on an incomplete key frame as would happen in link layer schemes.

To better understand, we show the snapshot of three consecutive frames of ARQ(4), RS(212,200), ARQ/RS(4212) and EC/RS(200,212) in Fig. 6a–d, respectively. In these figures, frame number 13 is a WZ frame, which its quality strongly depends on the quality of frame number 12 and 14 that are key frames. In the ARQ, RS and ARQ/RS methods, some packets from these two key frames have been lost, as they have been decoded incompletely and so have consequently formed a bad SI on the decoder side. So, even with a large amount of reception from the feedback channel, the quality of the WZ frame is poor. Conversely, in the EC/RS method where the key frames have either been received completely or where previously received key frame has been used, the WZ frame also has high quality, without the need to receive more parity bits from the feedback channel.

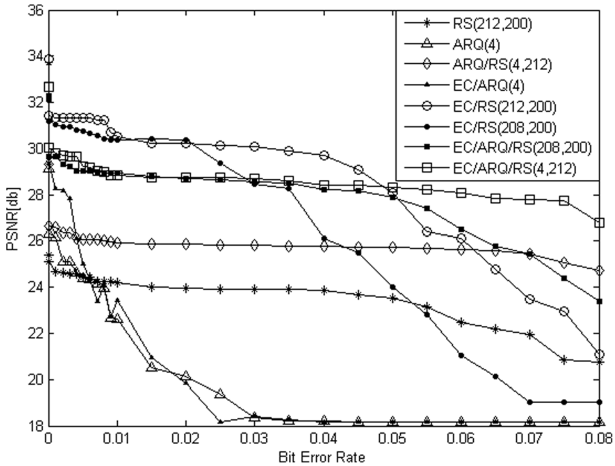


Fig. 5 PSNR vs. BER for error control schemes

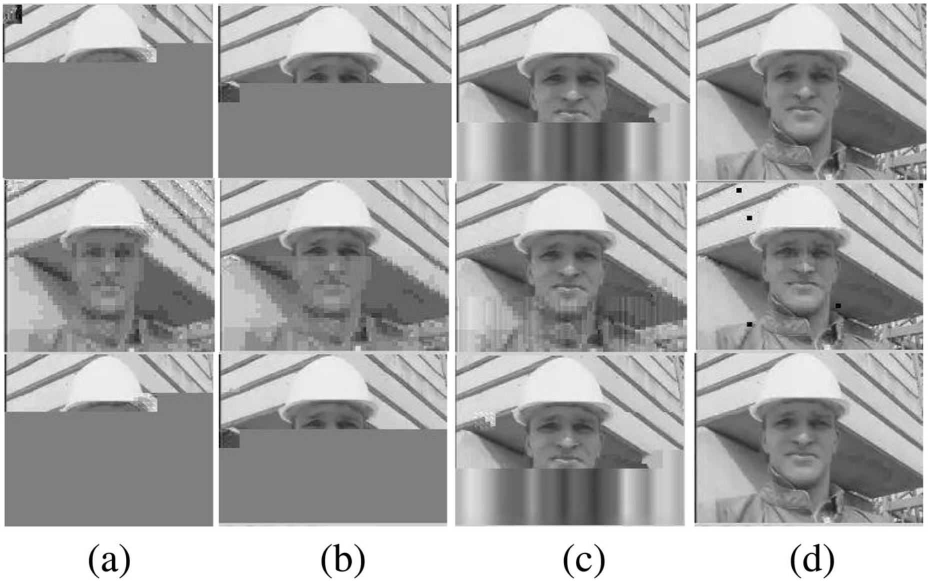


Fig. 6 snapshots of foreman frame number 13,14 and 15 for (a) ARQ(4), (b) RS(212,200), (c) ARQ/RS(4212) and (d) EC/ RS(212,200) in BER = 0.02

Although, it should be noted that based on Fig. 5 an increase in the frame loss rate in instances of high BER causes a severe drop in PSNR for both EC/RS and EC/ARQ/RS methods. This is because of many differences between lost and last received key frames and the formation of a bad SI for current WZ frame. The snapshot of frame number 69, 70 and 71 in Fig. 7 shows this condition as well. In this fig, the previous and next frame of frame number 70 which is a WZ frame, were missed. The last successfully received frame is also far from these frames thus the key frames will have low PSNR. As a result, the WZ frame decoded would be based on a bad SI and so would be of poor quality. Hence, in order to use EC/RS at a high BER should adopt EC and RS power with channel condition or combine it with ARQ in order to provide more protection for packets.

In Fig. 8, MOS has been used to show quality distribution of frames in error control mechanisms. MOS is a subjective parameter used to measure the Quality of Experience (QoE) of a video at the application-level; it indicates user experimental quality with a score ranging from 1 to 5 [24].

Here, PSNR values for each frame have been mapped to the MOS based on Table 3, and the percentage of frames in each area has been calculated. Based on this figure, EC/RS and EC/ARQ/RS have the highest number of frames with “Good” quality. Additionally, the quality distribution of the link layer error control methods shows that a combination of ARQ and RS only increases the number of frames with “Fair” quality, compared to the RS method. In fact,

Fig. 7 snapshots of foreman frame number 69,70 and 71 for Ec/RS(212,200) in BER = 0.06

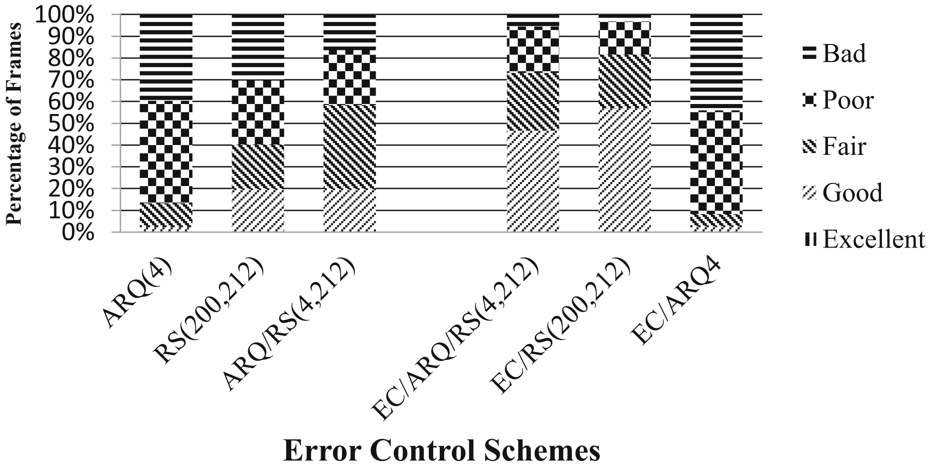


Fig. 8 comparison of freme quality for error control schemes with MOS

the lower packet loss in ARQ/RS result in a better decoding of key frames than does RS which improving their quality of them from "Poor" to "Fair"; however, this improvement is not enough to construct an appropriate SI and thereby achieving "Good" quality WZ frames.

In contrast, EC/RS and EC/ARQ/RS both have a high percentage of frames rated as "Good" due to high quality key frames as mentioned previously.

Finally, in Figs. 9a, b and 10, Frame-by-frame PSNR has been shown for ARQ(4), RS(212,200) and ARQ/RS(4212) at BER~0.02, respectively. Frame-by-frame PSNR is able to demonstrate the uniformity of quality in consecutive frames. Based on these figures, RS(212,200) and ARQ(4) have a high fluctuation between consecutive frames, which could be annoying for the user. This occurs due to the reception of more parity bits from the feedback channel. This problem can be partially resolved by combining ARQ and RS together, for increasing the protection of packets; however still occurs too many times.

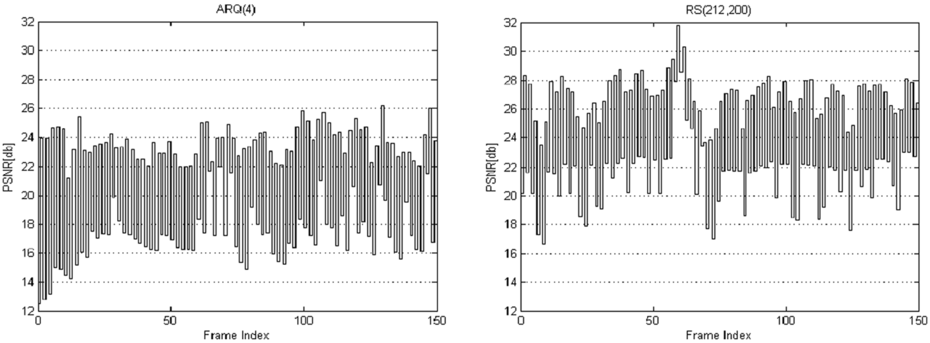
This problem can be fully resolved by the multi-layer error control methods. It is showed in Fig. 11, that illustrated a great reduction in the frequency of PSNR fluctuations for protected video by EC/RS(212,200) and EC/ARQ/RS(4212).

4.3 Bit rate analysis

Receiving from the feedback channel in the Stanford architecture of DVC takes more energy consumption and imposes greater delay on the frame decoding. Moreover, as we saw in the previous section, enhancing the quality of WZ frames through the feedback channel can cause none-uniform quality between WZ and key frames. Therefore, an error control method must be

Table 3 PSNR to MOS mapping

PSNR	MOS
≥ 37	1 (Excellent)
31–37	2 (Good)
25–31	3 (Fair)
20–25	4 (Poor)
≤20	5 (Bad)



(a) (b)

Fig. 9 frame-by-frame PSNR for (**a**) ARQ), (**b**) RS(212,200)

able to decrease the number of requests from the feedback channel. In this section, we will compare the efficiency of error control methods in terms of this factor. In Fig. 12 the bit rate of compressed video by DVC consists of key frames and required parity bits, is shown as a function of channel bit error rate for layer and multi-layer error control mechanisms. The curves in this figure are exactly the inverse of curves in the PSNR analyses, indicating an inverse relationship between the quality of video and the number of requests from the feedback channel. Thus, in order to achieve better video quality and resource management in DVC, it is essential to use an effective error control scheme for protecting the frames, especially key frames against channel error.

4.4 Delay analysis

There are many real time applications in WMSN that have strict delay constraints, as receiving the packets before the maximum allowable delay is crucial. In DVC, requested packets from the feedback channel have more delay constraints, resulting in a greater sensitivity to delay. In this section, we measure the effect of delay constraints on the performance of error control methods in DVC. To this end, we use the relationship between the packet loss rate and maximum allowable

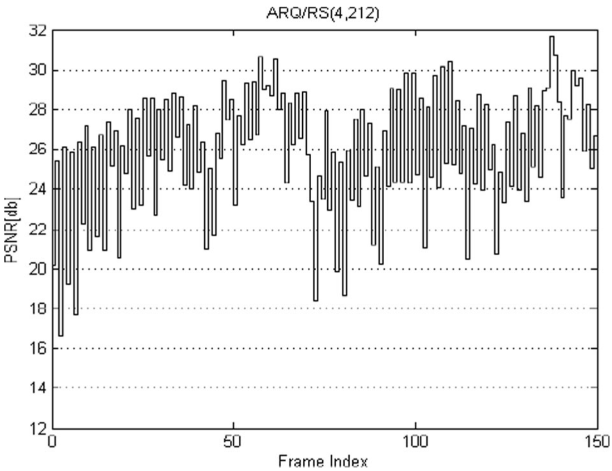


Fig. 10 frame-by-frame PSNR for ARQ/RS(4,212)

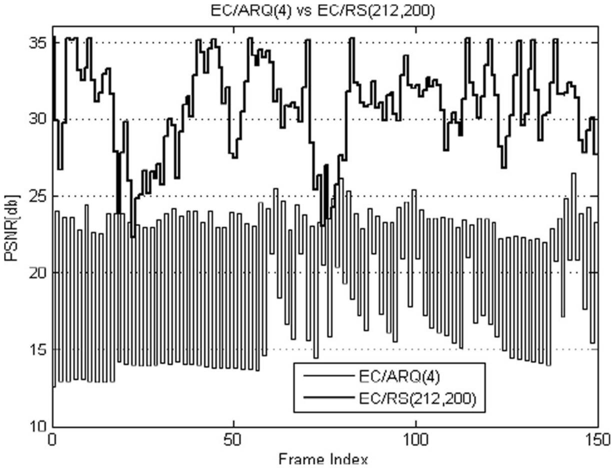


Fig. 11 frame-by-frame PSNR for EC/RS(212,200)

delay. These are inversely related to each other, as whenever an error control method imposes more delay to packets, this method would then lose more packets in predefined deadline that causes lower quality video frames.

In Fig. 13, this relationship is shown for simple error control methods in low BER. According to this fig, ARQ(7) receives the greatest impact from delay; as with increasing restrictions on the delay form 800 ms to 100 ms, the packet loss rate increases by nearly 40% that is unbearable in video communications. Figure also shows about a 20% increase in the packet loss rate when using the RS method, due to the increasing delay constraints. In addition, hybrid ARQ/RS is not able to significantly reduce this sensitivity to delay that is because of both retransmission retries and the high amount of receiving from the feedback channel in the link layer schemes.

Finally, EC takes the least impact from delay constraints. Generally, imposed delay by the EC method is more predictable than retransmission containing methods.

Fig. 14 shows the sensitivity of video that is protected by multi-layer error control methods to delay at high BER. Based on this figure, multi-layer methods are less sensitive to delay constraints. This is because there is a greater protection of frames and less request from the

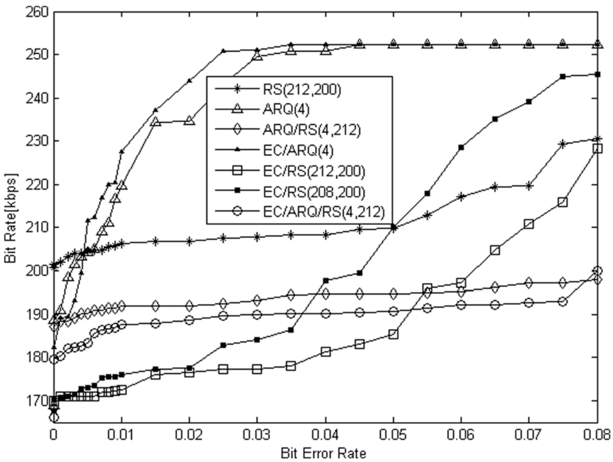


Fig. 12 Bitrate vs. BER for error control schemes in DVC

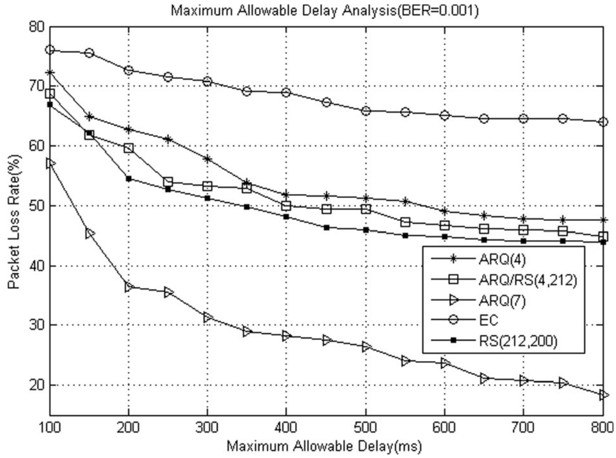


Fig. 13 Delay-bounded packet loss for simple error control schemes

feedback channel. Additionally, it is observed that combining ARQ with EC/RS achieves high quality however, makes the video more sensitive to delay.

4.5 Energy efficiency analysis

In this section, we analyzed the energy efficiency of error control methods in DVC for Micaz-based wireless multimedia sensor nodes. The average energy consumption in our analyses is calculated as the total energy consumption divided by transmission time [5, 14, 15, 25]. Total energy consumption is the summation of energy consumption by the sender, receiver and relying nodes [8]. Figs. 15 and 16 show energy consumption of nodes for transmission of protected video by error control schemes in BER~0.04. To illustrate the impact of RS and ARQ parameters on energy consumption, these figures are as a function of the number of correctable symbols and maximum number of retransmissions in RS and ARQ methods, respectively.

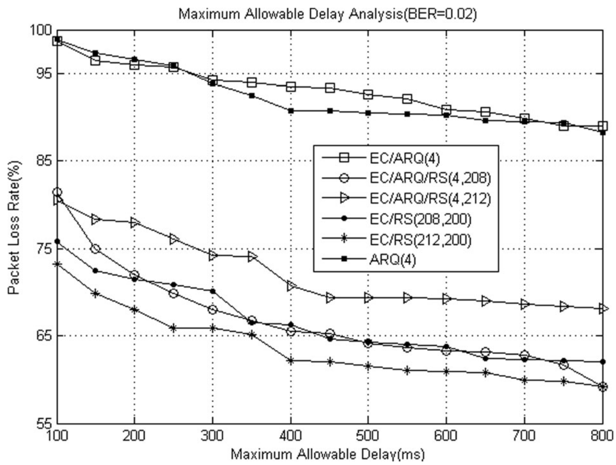


Fig. 14 Delay-bounded packet loss for multi layers error control schemes

Figure 15 indicates the high impact on the energy consumption of error control methods as a result of increasing the RS strength. It also, shows that multi-layer methods have almost with high video quality almost have the same amount of energy consumption as do the link layer methods. This is due to the large number of requests from the feedback channel in response to lower video quality when using link layer methods. Therefore, it is better to use an excellent error control method in DVC which by the same amount of energy consumption would be able achieves higher video quality. In addition, to more energy saving in multi-layer schemes, can adopt their parameters by the channel error rate.

Fig. 16 illustrates the energy consumption of error control schemes as a function of maximum number of retransmission retries. Based on this figure, there is not a linear relationship between energy consumption and the number of retransmission retries. Thus there is a need to find the optimal values for the protection of packets by the link layer error control schemes.

Moreover, due to great redundancy in the EC scheme, the combination of EC with ARQ/RS significantly increases the energy consumption of nodes. So, in order to optimize the energy consumption of nodes in this method, the parameters should be carefully determined.

5 Conclusion

In this study, we performed a comprehensive performance evaluation for all layer and multi-layer error control schemes for DVC over WMSN using extensive simulations. These analyses were used to identify the characteristics of DVC in presence of channel error. In addition, they were used to evaluate the efficiency of error control schemes for DVC that is an essential step to design an effective cross layer error control scheme for DVC over WMSN.

The results of these analyses are summarized in Table 4 for seven performance metrics including frame loss rate, objective and subjective video quality criteria, the number of requests from the feedback channel, delay and power consumption.

Based on this table, ARQ/RS is the most efficient method in terms of frame loss rate, and EC/ARQ has the worst performance in this metric. However, the PSNR and MOS results show that the high frame delivery rate in ARQ/RS did not result in high PSNR and user quality

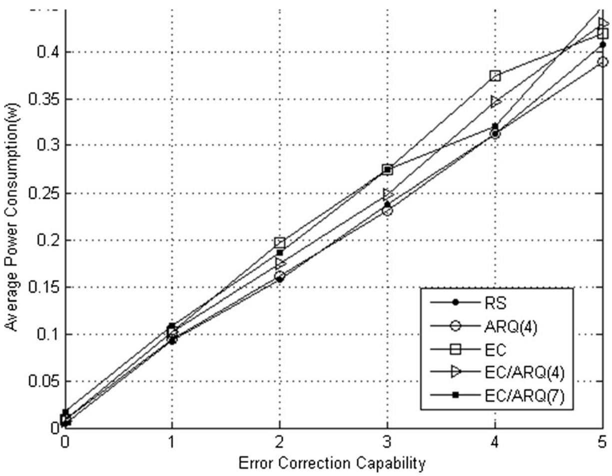


Fig. 15 Average energy consumption vs. Error correction capability

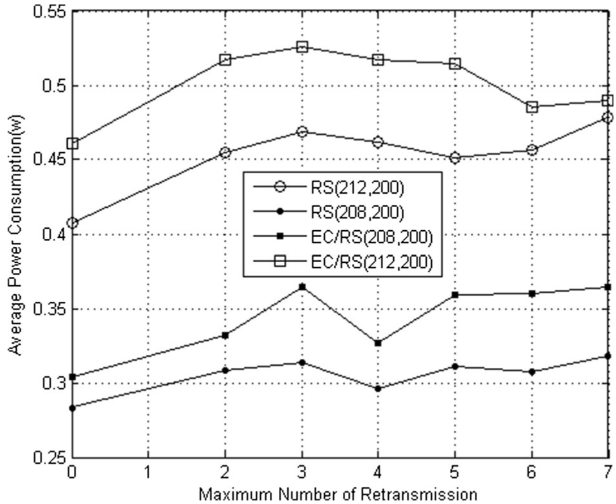


Fig. 16 Average energy consumption vs. Maximum number of retransmission retries

experience. In this parameter, up to BER~0.05, EC/RS provides the highest PSNR, afterward EC/ARQ/RS with higher protection of frames in high BER, obtained the highest quality. These two methods, due to "all or nothing" operation in the EC method and dependency of the WZ frames quality to the quality of key frames in DVC, have the best user experimental quality. The table shows that the EC and EC/ARQ give the lowest quality and most requests from the feedback channel. It also shows that retransmission of packets and many requests from the feedback channel makes the ARQ containing methods very sensitive to delay.

In terms of delay tolerance, EC and EC/RS have the highest performance due to the application level operation of EC and the low number of requests from the feedback channel. Finally, retransmission of packets consumes lower energy than does the RS method and the feedback channel has a significant impact on the energy efficiency of error control methods.

Although, in the recent years new video codecs such as HEVC [21, 26, 34] have obtained high bit efficiency compared to traditional video coding, DVC is the best choice for use in WMSN due to its light encoding operation. But, existence of a feedback channel and a separate frame encoding in DVC causes fundamental differences in the performance of transmission protocols compared to traditional video coding schemes. For this reason, analysis and evaluation of transmission protocols in dealing with DVC characteristics are required for proposing

Table 4 Overview of the simulation results

Performance metrics	The most efficient scheme	The worst scheme
Frame loss rate	ARQ/RS	EC/ARQ(4)
PSNR	BER < 0.05: EC/RS BER > 0.05: EC/ARQ/RS	EC
Perceived video quality	EC/RS	ARQ & EC/ARQ
Number of request from feedback channel	BER < 0.05: EC /RS BER > 0.05: EC/ARQ /RS	ARQ & EC/ARQ
Delay sensitivity	Low BER: EC High BER: EC/RS	ARQ
Cumulative Jitter	ARQ/RS & EC/RS	ARQ
Energy consumption	ARQ	RS

efficient transmission protocols. So, in this paper we performed a comparative analysis on the performance of all error control methods in terms of the most important video quality metrics for DVC. As mentioned earlier, the results of these analyses are very important to identify the DVC operation in the presence of channel error. These results can be used to discover appropriate strategies to deal with this situation over the wireless multimedia sensor networks.

6 Future work

The experimental analysis reported in this paper are obtained from accurate and extensive simulations resulting in attainment of reliable and convincing results. To take this study further, providing an analytical model to verify the results of this research is planned for future work. Also, proposing an effective cross layer error control scheme for DVC over WMSN based on the results of this paper can be performed by the interested readers. This paper provides a full comprehension of the DVC characteristics and proposes great ideas to design an efficient video communication method over WSN especially for multi-view scene scenarios.

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