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Error control for multimedia communications in wireless sensor networks: A comparative performance analysis

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ABSTRACT

The emerging multimedia applications of Wireless Sensor Network (WSNs) impose new challenges in design of algorithms and communication protocols for such networks. In the view of these challenges, error control is an important mechanism that enables us to provide robust multimedia communication and maintain Quality of Service (QoS). Despite the existence of some good research works on error control analysis in WSNs, none of them provides a thorough study of error control schemes for multimedia delivery. In this paper, a comprehensive performance evaluation of Automatic Repeat Request (ARQ), Forward Error Correction (FEC), Erasure Coding (EC), link-layer hybrid FEC/ARQ, and cross-layer hybrid error control schemes over Wireless Multimedia Sensor Network (WMSNs) is performed. Performance metrics such as energy efficiency, frame Peak Signal-to-Noise Ratio (PSNR), frame loss rate, cumulative jitter, and delay-constrained PSNR are investigated. The results of our analysis show how wireless channel errors can affect the performance of multimedia sensor networks and how different error control scenarios can be effective for those networks. The results also provide the required insights for efficient design of error control protocols in multimedia communications over WSNs.

1. Introduction

In recent years, there has been an increasing interest in applications of Wireless Sensor Networks (WSNs) to the areas such as real-time object tracking, multimedia surveillance and reconnaissance, traffic enforcement and control systems, advanced healthcare delivery, and industrial process control [1–4]. These applications require gathering of information in various multimedia formats. The multimedia content in sensor networks should be delivered with predefined levels of Quality of Service (QoS) under resource and performance constraints such as bandwidth, energy, and delay. These constraints limit the extent to which QoS requirements can be guaranteed. Although high compression ratios make multimedia applications suitable for low bit-rate wireless channels, the compressed multimedia streams become more vulnerable to transmission errors due to predictive nature of coding standards. In addition, low-power communication constraints of sensor nodes worsen the effects of wireless channel errors and require energy-efficient communication protocols in order to achieve application objectives, while delivery of multimedia streams may be an energy-consuming task. These challenges necessitate the energy-efficient and reliable error control schemes for QoS multimedia communication over multi-hop WSNs.

The well-investigated error control mechanisms to deal with wireless transmission errors in multimedia streaming applications include Automatic Repeat Request (ARQ), Forward Error Correction (FEC), Erasure Coding (EC), link-layer hybrid FEC/ARQ, and cross-layer hybrid error control schemes. The ARQ technique can be used either in the

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application or data link layers. The main disadvantages of ARQ are its variable network delay and the requirement of a reverse channel. Indeed, if a packet arrives late at the sink node, it misses the playback deadline and becomes a lost packet. To overcome this problem, link-layer FEC schemes, which provide a fixed network delay but consume more bandwidth and energy, are usually used [5,6]. Moreover, packet-level FEC (erasure coding) adds h redundant packets to k original source packets in the application layer to recover the lost packets. This scheme does not cause jitter problems because there is no feedback mechanism. Therefore, compared to FEC techniques, ARQ uses the bandwidth efficiently at the cost of additional latency.

To combine the best features of the ARQ and FEC schemes, several works in the wireless multimedia and sensor network literature have suggested link-layer hybrid FEC-ARQ approaches [7–9]. Furthermore, there has been some interest in using cross-layer information through the protocol stack in order to increase the efficiency of the overall system, enhance the video quality, maximize the usage of network resources [10], and save energy.

This paper has extended our pervious work in [11], which is, to the best of our knowledge, the first work that evaluated the performance of conventional error control schemes in WMSNs. The investigation of application-layer FEC (erasure coding) and cross-layer error control mechanisms is included to complete our performance analysis of error control schemes for real-time multimedia communication scenarios. Our analysis enables a comprehensive comparison of ARQ, wireless link-layer FEC, application-layer FEC, link-layer hybrid FEC/ARQ, as well as cross-layer hybrid error control schemes based on QoS and energy performance metrics in WMSNs. In addition, real-time performance metrics, such as delay-constrained PSNR and cumulative jitter, have been incorporated in our study.

More specifically, MicaZ video sensor nodes are considered when performing the analyses of frame loss rate, PSNR, delay-constrained PSNR, energy efficiency, and cumulative jitter. In our analysis, at the link-layer, similar to [12–15], the RS code has been used because it deals with bursty errors more effectively, has an acceptable performance, and consumes energy efficiently in compare to popular FEC schemes [13]. Also, regarding the different nature of error coding in each layer and similar to works such as [16–18], we have used erasure codes for the application-layer FEC and applied the packet-level RS across video packets (see Section 3.2.3). Moreover, for energy efficiency analysis, we take into consideration the power consumption of the radio part which includes the energy consumption during transmit, receive, and idle modes as well as energy consumption of FEC packet decoding (see Section 3.3).

The rest of this paper is organized as follows. In Section 2, an overview of the existing work on analysis of error control schemes in wireless multimedia and WSNs is provided. In Section 3, we describe the system model for WMSN channel, error control schemes, and energy consumption. Section 4 describes our simulation methodology and presents the results of our comprehensive performance evaluation. Finally, Section 5 presents the conclusions.

2. Related work

In recent years, there have been several research efforts on analysis of error control mechanisms in wireless multimedia and wireless sensor networks [12–15,19,17,20,21]. However, none of them is directly applicable to WMSNs; because in multimedia communications over sensor networks there are resource and performance constraints for WSNs, as well as QoS requirements for multimedia communications. This section provides a brief review of the related works that investigate and analyze the performance of error control techniques in wireless multimedia and wireless sensor networks.

In [12], a cross-layer analysis of error control schemes for WSNs is presented that considers the impacts of routing, medium access, and physical layers in sensor networks. It has been shown that FEC schemes at the link layer can improve the error resiliency when compared to ARQ. In a multi-hop network, this improvement can be exploited by reducing the transmission power or by constructing longer hops through channel-aware routing protocols. The analysis reveals that, for certain FEC codes, extension of hop-length decreases both the energy consumption and the end-to-end latency, subject to a target packet error rate when compared to ARQ. Thus, FEC codes can be preferred for delay-sensitive traffic in WSNs. Similarly, in [13], the cross-layer analysis methodology of [12] is extended, and Reed-Solomon (RS) codes have been included to exploit the benefits of FEC codes in WSNs. In addition, the effects of Medium Access Control (MAC) and hybrid ARQ schemes are investigated in the same reference.

In [14], the throughput and energy demand of 802.11-based WSNs have been analyzed as a function of the channel Bit Error Rate (BER) and RS symbol size. It has been shown that 802.11 with RS codes significantly outperforms the legacy 802.11 in terms of throughput and energy consumption. In addition, if the size of the FEC symbol adjusts dynamically to the underlying channel status, the performance of WSNs would increase markedly. A similar result is reported in [15] in which the impact of the size of the FEC symbol on the computation energy and transmission energy is analyzed. The results of the analysis show that the expenditure of total power varies widely, up to a maximum of 85%, depending on the FEC symbol size.

In [19], the tradeoffs between energy consumption, image quality, and delay for wireless video-surveillance networks have been studied for cases in which retransmission of corrupted packets and link level FEC are applied. It has been shown that the energy cost of ARQ retransmissions is negligible. Furthermore, effective error control schemes should adapt to the time-varying channel states. In particular, block-based FEC should be used under the most severe BER conditions, whereas stop-and-wait ARQ can be employed in all other cases. However, in [19], some important error control mechanisms such as erasure coding, hybrid FEC/ARQ, and cross-layer error control schemes, are not investigated. Moreover, the performance metrics that are used could not evaluate comprehensively the quality of the perceived video at the receiver, and other metrics, such as PSNR and frame loss rate, should be considered.

In [17], the authors have analyzed the impact of retransmission and wireless application-layer redundancy by using packet arrival probability and average energy consumption. They conclude that using the erasure code is more reliable and energy efficient than retransmission when the packet loss probability is low, but the performance of the erasure code deteriorates when high packet loss conditions occur. Similarly, in [20], the authors have been analyzed the roles of packet retransmission, block retransmission, erasure coding, and link layer FEC in reliable transport of WSNs. While the performance of erasure coding as an application-layer FEC are analyzed in this works, multimedia communication and its constraints have not been considered. In [21], ARQ is compared with FEC schemes in terms of energy efficiency and the cases where ARQ outperforms FEC and where FEC is more energy efficient are analyzed. However, it only considers the energy efficiency metric and two simple error control schemes without addressing any multimedia quality metrics. There are some other similar works in which the problem of energy consumption for some error control schemes in WSNs have been studied [22–25]. As one can see the existing works have not comprehensively analyzed conventional error control schemes for multimedia delivery in WSNs. In this paper, we perform extensive simulations to investigate the performance of error control schemes for WMSNs in terms of energy efficiency, frame Peak Signal-to-Noise Ratio (PSNR), frame loss rate, cumulative jitter, and delay-constrained frame PSNR.

3. System model

3.1. Channel model

To capture bit-level errors in WMSN, we model channels with a two-state discrete-time Markov chain called the Gilbert-Elliott channel model [26]. It has been demonstrated that Gilbert model is an accurate approximation of the error characteristics in a wireless channel [27,28] and can be used to abstract the WSN channel behavior [14,29,30]. Fig. 1 illustrates the state diagram for this channel model. This model has memory, takes into account the correlation between consecutive errors, and abstracts bursty error distribution with a bad state (B) that represents a heavy error rate with a short interval and a good state (G) representing light error rate with a longer interval. Each state has an associated BER probability, i.e., P_G for the good state and P_B for the bad state, and state transition probabilities could be derived from the experimental channel data. The stationary probabilities of being in the light and heavy error rate states are given by:

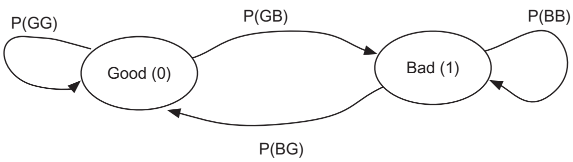

Fig. 1. Markov model for Gilbert–Elliot channel [26].

$$\pi_G = \frac{P_{BG}}{P_{BG} + P_{GB}} \qquad \pi_B = \frac{P_{GB}}{P_{BG} + P_{GB}} \tag{1}$$

where P_{GB} is the probability of the channel state's transiting from a good state to a bad state, and P_{BG} is the transition from a bad state to a good state. According to the described model, every bit is erased with probability π_G at the light error rate and erased with probability π_B at the heavy error rate, independently of other bits [31]. Furthermore, we can express the average bit error probability of the WMSN channel as follows:

$$P = P_G\pi_G + P_B\pi_B \tag{2}$$

which shows how the probability of average BER depends to the transition probabilities between the light and heavy error states. It is noteworthy that even though the higher order Markov chains can be used for characterizing the loss process in the wireless channel, the Gilbert model provides good accuracy with less complexity and has been extensively used in the literature to capture the erroneous nature of wireless channels from the bit-error process to the packet-loss process at different layers. Moreover, since the Gilbert-Elliot models the behavior of an erasure channel [31], it could also be called Gilbert-Elliot bit erasure channel.

3.2. Error control models

In our analysis, we study the performance of several error control scenarios in WMSNs, i.e., ARQ, link-layer FEC, erasure coding, link-layer hybrid FEC/ARQ, and cross-layer hybrid schemes.

3.2.1. ARQ

Automatic Repeat Request (ARQ) is an error control method that uses the retransmission mechanism when data packets have been lost. Although some ARQ protocols enable the receiver to request retransmission of lost packets if any error is detected, usually if timeout occurs before the transmitter receives acknowledgment from the receiver, the packet is retransmitted until it is correctly received or the predetermined maximum number of retransmissions (N) is reached. Moreover, when errors occur, the ARQ protocol introduces additional variable delay, overhead, and energy consumption costs, while it may outperform other schemes when channel conditions are suitable. Therefore, the efficiency of ARQ in WMSNs varies based on channel conditions, as well as the delay and energy constraints of the environment. In this work, the performance of link layer ARQ is compared with other error control schemes in terms of energy consumption, PSNR, and frame loss rate for the multimedia delivery scenarios over WSNs.

3.2.2. Link-layer FEC

In wireless link-layer FEC, the sender node adds some redundancy to the source packets and transmits them toward the sink node. The redundancy information is used by the receiver to detect and correct errors. Depending on the amount and structure of the redundancy, the receiver node can receive error-free packets even if some transmission bit errors occur. The two most widely-used schemes in

FEC are block codes (BCH and RS codes) and convolutional codes. Block codes are processed on a block-by-block basis and convolutional codes are processed on a bit-by-bit basis. In particular, a block-based FEC coder takes a block or a word of length k of p-ary source symbols and produces a block consisting of n of q-ary channel symbols [32]. In our analysis, we have used the popular RS code because it deals with bursty errors more effectively and consumes energy efficiently [13–15]. Moreover, we set $p = q = 2$ and $n \geqslant k$, and the symbols correspond to bytes (8-bit symbols). Note that RS (u,w) means w data bytes and $(u - w)$ correction RS bytes, where $(u - w)$ correction bytes can restore $(u - w)/2$ corrupt bytes.

3.2.3. Erasure coding (EC)

Erasure coding is an error control scheme for application-level FEC that is used to handle losses in real-time communication. In the coding theory, an error is defined as a corrupted symbol in an unknown position, while an erasure is a corrupted symbol in a known position [33]. Fig. 2 shows how erasure coding is applied to groups of media packets that are transmitted to the sink sensor node. Indeed, an (k,n) block RS erasure code encodes n input media packets into a group of k coded packets by generating $k - n$ additional packets and is denoted by $EC(k,n)$. At the sink node, we can reconstruct n original media packets by receiving any n out of k packets $(k > n)$ [16,17]. Clearly, the packet-level RS erasure coding is a complete different mechanism than link-layer RS coding, and has been employed in WSNs and wireless multimedia networks regarding to its suitability for video communications [18] and the nature of error coding at the application layer.

Moreover, erasure coding may cause an additional delay since k packets should be buffered before the encoding and decoding process in the application layer. To avoid additional delays in playback of the received multimedia streams at the sink node, we apply RS encoding to n source packets with the same playback deadline. Furthermore, if n is sufficiently large compared to the loss rate, we can achieve high reliability without retransmission at the expense of spending more bandwidth and energy. Hence, it is necessary to investigate the tradeoff between erasure coding strength, energy consumption, and perceived multimedia quality in WMSNs. In this work, we analyze the PSNR and energy consumption of erasure coding as a

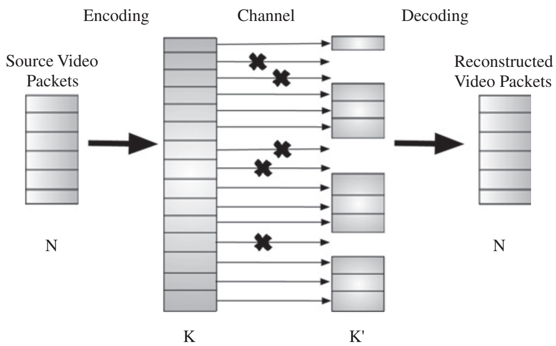

Fig. 2. Mechanism of erasure coding.

function of the channel bit error rate (BER) and error correcting capability.

3.2.4. Link-layer hybrid FEC/ARQ

Although the ARQ scheme uses bandwidth efficiently and provides predictable quality, it increases the latency and its throughput depends on the channel conditions. On the other hand, the FEC schemes behave in a complimentary fashion. They consume more bandwidth and energy but offer a fixed network delay with data quality depending on the channel conditions. These observations suggest the use of hybrid FEC/ARQ schemes. In particular, a hybrid FEC/ARQ mechanism at the data link layer can reduce the end-to-end latency, the required bandwidth for retransmissions, and the packet loss rate in wireless multimedia streaming [7]. Therefore, it is important to study the performance of this scheme compared to the other error control mechanisms in terms of energy efficiency and reliability. In the link-layer hybrid FEC/ARQ mechanism, a packet encoded with FEC is sent through the wireless channel. If this packet, after decoding, is received in error, the error recovery mechanism at the data-link layer will resort to ARQ for retransmission and the sender re-sends the packet coded with an FEC code. In our analysis, we denote the link-layer hybrid ARQ/RS error control scheme as ARQ/RS (N,M), which refers to an ARQ with a maximum of N retransmissions and a $RS(M,100)$ Reed-Solomon block coded FEC.

3.2.5. Cross-layer hybrid schemes

There are an increasing number of researches in wireless multimedia and wireless sensor networks that have focused on the cross-layer design and integration of protocols as an important paradigm to increase the efficiency of the overall system, enhance the video quality, and maximize the usage of network resources. Generally, there are two possible cross-layer design approaches: integrating functionalities of different layers in a single protocol and establishing tight cooperation between adjacent or non-adjacent layers [34]. The former cross-layer design approach results in reduction of the overhead and also provides the capability to implement advanced QoS mechanisms. The latter cross-layer case result in better reactivity to network fluctuations and other external factors by inter-layer interactions and cross-layer optimization [34].

In order to perform a generic evaluation of cross-layer performance of conventional existing error control mechanisms in WMSNs, in this paper, we have considered three different cross-layer hybrid schemes which follow the former cross-layer design approach. More specifically, they are erasure coding (application layer FEC) with link-layer ARQ, erasure coding with link-layer FEC, and erasure coding with a link-layer hybrid FEC/ARQ scheme. In each of these cross-layer hybrid schemes, the functionalities of different error control mechanisms at the application and link layer have been incorporated into a single error control protocol. The first cross-layer protocol is denoted by ARQ/Erasure coding (N,K), which integrates an ARQ with N retransmissions in the wireless link layer with an $EC(n + K,n)$ scheme in the application layer. Moreover, the second scheme RS/Erasure coding (M,K) is a cross-layer hybrid protocol that provides an $EC(n+K,n)$ error control at the application layer as well as an $RS(M,100)$ protection mechanism at the link layer. Finally, the third cross-layer hybrid protocol is denoted by ARQ/RS/Erasure coding (N,M,K), which combines the functionalities of an $ARQ(N)$ and $RS(M,100)$ in the wireless link layer with an $EC(n+K,n)$ error control in the application layer.

In the simulation results section, it is shown that how these cross-layer hybrid schemes improve the performance of error protection and the quality of perceived video by the end user in WMSNs. However, we also show the energy-reliability trade-off that multimedia sensors still need to leverage cross-layer hybrid error control schemes one step further to provide more energy efficient mechanisms. It is noteworthy that since the cross-layer hybrid scheme is a unified single protocol, it can be integrated with any current communication protocols for sensor networks.

3.3. Energy consumption model

We model the power consumption of both radio transceiver and computations for a wireless multimedia node. According to our model, a node may consume energy during the reception, transmission, decoding, and encoding of packets, as well as in the idle state. The power consumption during the transmit mode, receive mode, and idle mode, are denoted by P_t, P_r and P_i, respectively. If a sensor node spends T seconds transmitting or receiving a packet, the energy consumption can be computed as $E_{Tx}(T)=P_tT$ and $E_{Rx}(T)=P_rT$, respectively. The energy dissipated during an idle listening period of T seconds is also calculated as $E_I(T)=P_iT$. The sum of these values indicates the energy consumption of the radio transceiver.

Moreover, the major overhead of FEC codes is the energy consumption for decoding and encoding of packets. Since it is well known that the energy consumed at the FEC encoder is negligible [24,35], we only consider the decoding energy of FEC block codes in our simulations. In particular, the amount of power required by the multimedia sensor nodes to decode RS codes is computed based on the total length of the codeword and the length of the FEC code [24]. Hence, first the latency of decoding for an $RS(u,w)$ is calculated, and then the decoding energy consumption is computed using the supply voltage and current of the processor. According to [13,35], the decoding latency for an $RS(u,w)$ is given by:

$$T_{dec} = (2mk + 2k^2)(T_{add} + T_{mult}) \quad (3)$$

where $m=8u$ and $k=4(u-w)$ (since we consider 8-bit symbols in RS FEC codes). Moreover, T_{add} and T_{mult} are the energy consumptions for addition and multiplication of the field elements in $GF(2^n)$, with $n=\lfloor \log_2 m+1 \rfloor$ [24], respectively. A 8-bit microcontroller (MCU) [36], which is used in MicaZ-based WMSN platforms such as [37] and assumed in the simulation experiments, can perform addition and multiplication of 8 bits in one and two cycles, respectively. Therefore:

$$T_{add} + T_{mult} = 3\left\lceil \frac{n}{8} \right\rceil t_{cycle} \quad (4)$$

where t_{cycle} indicates the one cycle duration of processor and according to the data sheet of MicaZ processor, it is 250 ns [36,13]. Based on the decoding latency, the total energy consumption of RS decoding can be calculated as follows:

$$E_{dec} = VI_{proc}T_{dec} \quad (5)$$

where V is the supply voltage, and I_{proc} is the current of the processor. We have assumed that the execution of each instruction consumes approximately the same amount of voltage and current, regardless of the type of instruction.

4. Performance evaluation

We have conducted extensive simulations to study the robustness and efficiency of the popular error control protocols as a function of channel Bit Error Rate (BER), error correcting capability, maximum number of retransmissions, and maximum allowable delay in WMSNs. The results of these simulations are presented in this section. The simulations were performed with the ns-2 [38] network simulator, along with a video quality evaluation tool known as Evalvid [39]. We analyzed the performance of error control schemes in terms of energy consumption, average Peak Signal-to-Noise Ratio (PSNR), frame loss rate, cumulative jitter, and delay-constrained PSNR. In our simulations, 50 video sensor nodes were placed randomly in a 200×200-m area capable of capturing, encoding, and broadcasting live video sequences to a sink node. The sender/receiver pair was chosen randomly from a set within the area. Each node had a unique queue size of 100 and a maximum transmission range of 40 m. A CSMA-based medium access control was considered [40,41], and AODV was employed as the routing protocol [42,41]. Moreover, we used three video sequences akiyo, foreman, and coastguard, which have different characteristics in terms of motion, frame size, and quality, at QCIF resolution and frame rate of 30 fps. The frames were compressed with MPEG4 at a rate of 200 Kbps by using the FFmpeg video encoder software [43]. Also, the frames were packetized into 100-byte video packets in the interest of energy efficiency [24]. Furthermore, other energy related parameters were set based on the MicaZ mote hardware specifications [44,37]. Table 1 summarizes the key parameters of the simulations. All simulations were performed 20 times with different random number seeds and the results were averaged over all the outcomes. Note that based on the most well-known applications of WMSNs, such as multimedia surveillance, traffic avoidance and control systems, and industrial process control [1–4], the multimedia sensor nodes are assumed to be immobile. Moreover, due to space limitations, we present the results of foreman and coastguard video sequences only for the perceived (subjective) video quality analysis section while the results of akiyo video sequence are presented in the other sections. In Section 4.2, it is shown that, despite the different characteristics of three video sequences, the comparative performance of the studied error control mechanisms on such

Table 1
Simulation parameters.

Parameter	Default value
Channel bandwidth	250 Kbps
Packet size	100 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

videos has the similar behavior in terms of provided error protection and improvements.

4.1. Frame loss analysis

In Fig. 3a, the frame loss rate is shown as a function of channel bit error rate for simple error control schemes, i.e., ARQ, RS, and erasure coding. The erasure coding ($k = 4$) results in the highest frame loss rate, since no error detection or correction mechanism is used in the link layer. Moreover, RS (106,100) results in a frame loss rate that is lower than both ARQ and RS (104,100). The ARQ scheme with seven retransmissions results in a frame loss rate comparable to the ARQ with four retransmissions. In particular, Fig. 3a shows that, for ARQ ($N = 4$), even a channel bit error rate of 0.001 leads to more than 80% loss of the data. For a slightly higher bit error rate of 0.003, the end-to-end frame loss rate of ARQ ($N = 7$) is nearly 90%. The ARQ with seven retransmissions provides more frame delivery than ARQ ($N = 4$) for bit error rates up to ≈0.005. However, for error rates higher than these values, the ARQ ($N = 4$) provides a slightly better frame delivery rate. In general, when BER increases, the frame loss rate in all schemes also increases. Furthermore, it can be observed that RS codes always result in higher frame delivery rates than either ARQ or erasure coding.

The link-layer hybrid FEC/ARQ schemes exploit the best features of both ARQ and FEC techniques. Fig. 3b compares the frame loss rate of these schemes with the ARQ scheme and the RS (106,100) mechanism which is found to provide the best frame delivery rate among the simple schemes. An important result is that, in all cases, the frame delivery rate increased when the ARQ scheme was used along with FEC. However, the naive use of the ARQ cannot provide the best results, and carefully selected repeat schemes can decrease the frame loss rate more effectively. Fig. 3b shows that the use of the link-layer FEC reduces the frame loss rate markedly, especially at the low channel bit error rates. Moreover, ARQ/RS (7,104) is more reliable than the hybrid ARQ/RS (4,106) for channel bit error rates up to ≈0.018, while, for error rates higher than these values, the hybrid ARQ/RS (4,106) scheme results in a better frame delivery rate. Therefore, when link-layer hybrid schemes are considered, better reliability is provided by increasing the maximum number of retransmissions at lower error rates and increasing the strength of the RS scheme at higher error rates. There is no clear winner between the RS (106,100) and the hybrid ARQ/RS (4,104), since the first

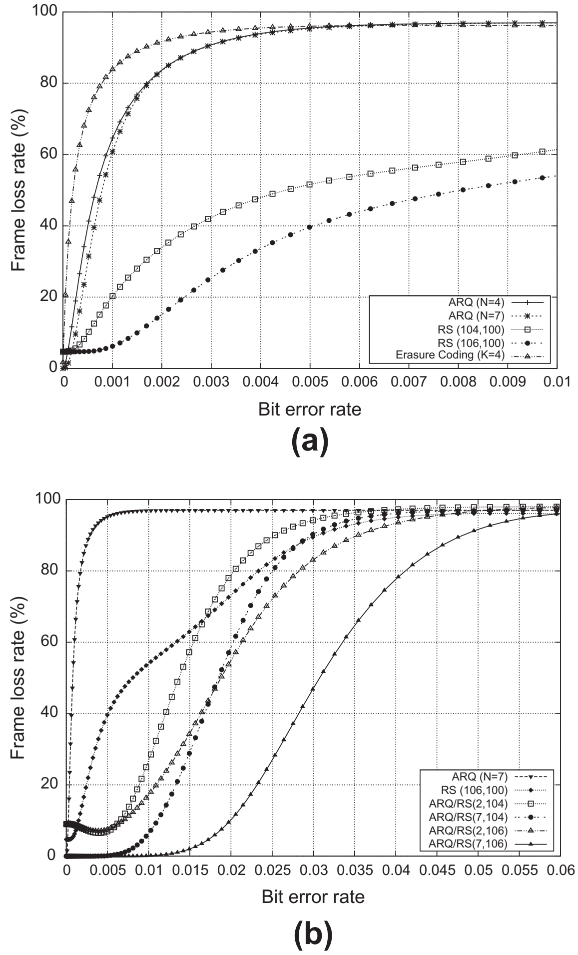

Fig. 3. Frame loss rate vs. channel bit error rates for (a) simple error control schemes, (b) link-layer hybrid schemes.

scheme works better for bit error rates up to ≈0.017, and the latter scheme provides slightly better results for error rates that are higher than these values.

The effect of cross-layer mechanisms on frame loss rate is shown in Fig. 4, where the ARQ, RS, and link-layer hybrid ARQ/RS mechanisms are compared with several cross-layer hybrid schemes. Fig. 4 suggests that the integration of erasure coding with RS codes is more powerful than integration with the ARQ protocol. In particular, the integration of erasure coding ($k = 4$) with ARQ leads to a slight reduction in frame loss rate, while the integration of erasure coding ($k = 4$) with RS (104,100) better improves the frame delivery rate. Also, Fig. 4 shows that the hybrid ARQ/RS (4,104) outperforms RS/Erasure coding (104,4), as well as ARQ/Erasure coding (4,4) schemes. This means that erasure coding can be employed with RS or ARQ to improve the frame delivery rate, but it will not provide better reliability than link-layer hybrid schemes. Furthermore, it is shown that the hybrid ARQ/RS (4,104) is more reliable than cross-layer hybrid RS/Erasure coding (106,4) for channel bit error rates up to ≈0.02. However, for higher error rates, the cross-layer hybrid RS/Erasure coding (106,4)

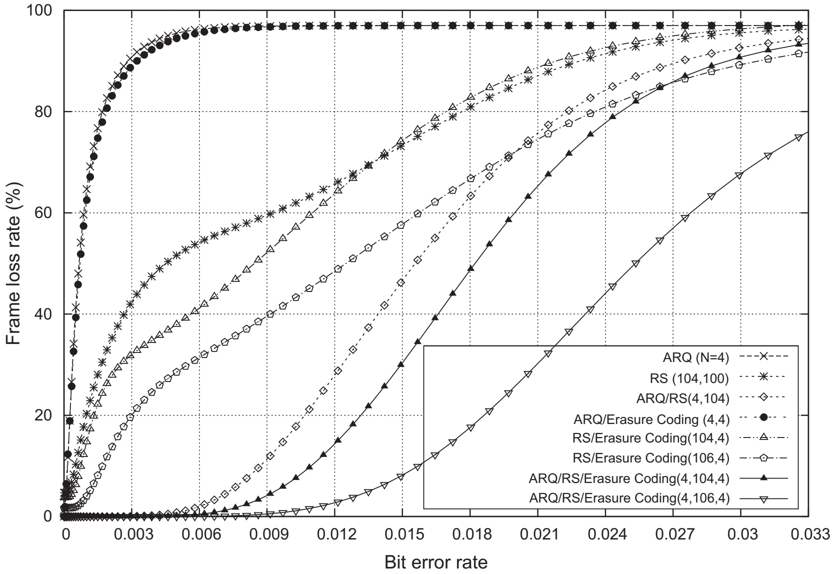

Fig. 4. Frame loss rate vs. channel bit error rates for cross-layer hybrid schemes.

scheme outperforms the link-layer hybrid ARQ/RS (4,104). Finally, as expected, it can be observed that the cross-layer hybrid ARQ/RS/Erasure coding (4,106,4) scheme has the best frame delivery performance among the competing schemes.

4.2. Perceived video quality analysis

In this section, we assess the subjective video quality of the akiyo, foreman, and coastguard video sequences, and in the next section provide our comprehensive PSNR analysis results. To compare the subjective quality of perceived video, frame numbers 150 and 82 for akiyo, 16, 160, and 305 for foreman, and frame numbers 70 and 250 for coastguard were chosen arbitrarily and the results are shown in Figs. 5–7. Fig. 5a–d are snapshots of ARQ ($N = 4$), ARQ/RS/Erasure coding (4,106,4), RS/Erasure coding (106,4), and RS (106,100) mechanisms, respectively, when the received frames are reconstructed at the decoder with a channel error rate of 0.007. In Fig. 5a, the degradation in video quality is visible and worse than other schemes. This means that the ARQ scheme at this error rate cannot provide good quality to the viewers. However, as shown in Fig. 5c and d, when the RS mechanism is used in video streaming, the visible errors are limited. To be more precise, the RS (106,4) scheme provides poor quality at the beginning of video streaming, as shown for frame 82 in Fig. 5d. Fig. 5b shows that the cross-layer hybrid ARQ/RS/Erasure coding scheme provided the best quality to the viewers.

Fig. 6 shows the snapshots of the reconstructed video frames for the same compared error control mechanisms as akiyo, when the foreman video sequence is transmitted over sensor channels with average BER 0.007. Accordingly, the ARQ scheme provides the worst quality while the cross-layer hybrid mechanism ARQ/RS/Erasure coding has the best quality compared to other schemes. In Fig. 6a and d, it is shown that both of ARQ and RS error control mechanisms could not provide an acceptable video quality at the beginning of their transmission. Moreover, Fig. 6 shows that the required packets to reconstruct frames 160 and 305 in the case of ARQ and RS schemes and frame 305 in the cross-layer hybrid schemes were not correctly received at the receiver and thus such frames have been reconstructed partially by using the pervious received frames as reference. Furthermore, it is shown that integration of the erasure coding mechanism with RS has improved the quality of the received foreman video. Fig. 7 shows the similar performance results of a coastguard video sequence in terms of provided quality, level of protection, and integration improvements, when it is transmitted over WMSNs. As shown in Fig. 7a and d, RS mechanism provided better error protection than ARQ at the both of beginning and end of transmission. Moreover, similar to the tested videos akiyo and foreman, although the RS mechanism resulted in a poor video quality at the beginning of video streaming, it performed better on protecting the later video frames. In addition, Fig. 7a shows that since ARQ mechanism could not protect even the video packets of late frame 250, this frame was reconstructed by using the pervious received frames. Fig. 7b and c present the improvements in the quality of perceived video due to the integration of erasure coding with the link-layer hybrid FEC/ARQ and the RS scheme, respectively. Finally, Table 2 shows a more detailed evaluation of the compared error control mechanisms on different video sequences akiyo, foreman, and coastguard. As shown in Table 2 and based on our obtained comprehensive results, even though these videos have different characteristics, such as motion, frame size, and quality, which result to different PSNR, frame loss rate, and jitter, the comparative performance of the studied error control mechanisms has similar behavior and pattern on different videos.

Fig. 5. Snapshots of akiyo frame numbers 150 and 82 while transmitted over WSNs in channel bit error rate 0.007 using (a) ARQ ($N = 4$), (b) ARQ/RS/Erasure coding (4, 106, 4), (c) RS/Erasure coding (106, 4), and (d) RS (106, 100).

Fig. 6. Snapshots of foreman frame numbers 16, 160, and 305 while transmitted over WSNs in channel bit error rate 0.007 using (a) ARQ ($N = 4$), (b) ARQ/RS/Erasure coding (4, 106, 4), (c) RS/Erasure coding (106, 4), and (d) RS (106, 100).

4.3. PSNR analysis

In this section, we investigate the performance of different error control schemes for video delivery over WSNs in terms of PSNR analysis. A reasonable quality is provided for the end-user if the typical PSNR of a frame exceeds 30 dB. Fig. 8 shows the average PSNR of simple, link-layer hybrid, and cross-layer hybrid error control schemes as channel bit error rate increases. It is shown that the average PSNRs of the link-layer hybrid ARQ/RS (4, 106), the cross-layer ARQ/RS/Erasure coding (4, 106, 4), and the ARQ/RS/Erasure coding (4, 106, 3) schemes do not drop until the channel BER reaches about 0.01, because these schemes are sufficient for error recovery under those BER conditions. However, the average PSNR begins to drop when the BER exceeds 0.01. Moreover, the drop in the average PSNR value is more severe for ARQ, erasure coding, and RS (106, 100) error control schemes. Clearly, these schemes cannot provide reasonable video quality when the error rate exceeds 0.0001 for EC, 0.0015 for ARQ, and 0.0003 for RS (106, 100). This indicates that simple error control schemes are not suitable candidates for multimedia communication over WSN. In the case of cross-layer hybrid RS/Erasure coding (106, 3) and RS/Erasure coding (106, 4) the average PSNR drops to 30 dB when the BERs are about 0.007 and 0.012, respectively. Furthermore, it can be seen that the link-layer hybrid ARQ/RS (4, 106) scheme produces higher video quality for channel bit error rates up to $\approx$.0037. However, the cross-layer hybrid RS/Erasure coding (106, 4) outperforms the link-layer hybrid ARQ/RS (4, 106) scheme for

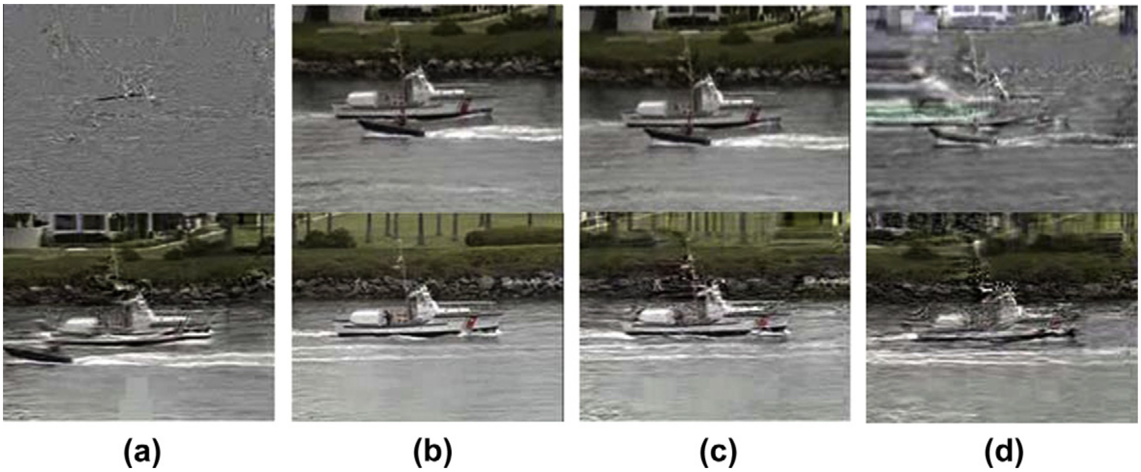

Fig. 7. Snapshots of coastguard frame numbers 70 and 250 while transmitted over WSNs in channel bit error rate 0.007 using (a) ARQ (N = 4), (b) ARQ/RS/Erasure coding (4,106,4), (c) RS/Erasure coding (106,4), and (d) RS (106,100).

Table 2
Comparative performance analysis of error controls on video sequences Foreman, Akiyo, Coastguard at BER = 0.007.

Video/EC	$\overline{PSNR}$	Frame loss rate	$\overline{Jitter}$	Video/EC	$\overline{PSNR}$	Frame loss rate	$\overline{Jitter}$
Foreman/a	16.69	0.77	0.282	Foreman/b	32.93	0.23	0.062
Foreman/c	23.65	0.48	0.69	Foreman/d	19.65	0.53	0.068
Akiyo/a	9.58	0.91	−0.208	Akiyo/b	44.45	10^{-3}	0.027
Akiyo/c	32.64	0.34	0.058	Akiyo/d	22.6	0.45	0.052
Coastguard/a	14.76	0.81	0.393	Coastguard/b	29.63	0.21	0.063
Coastguard/c	20.97	0.35	0.181	Coastguard/d	18.54	0.56	0.145

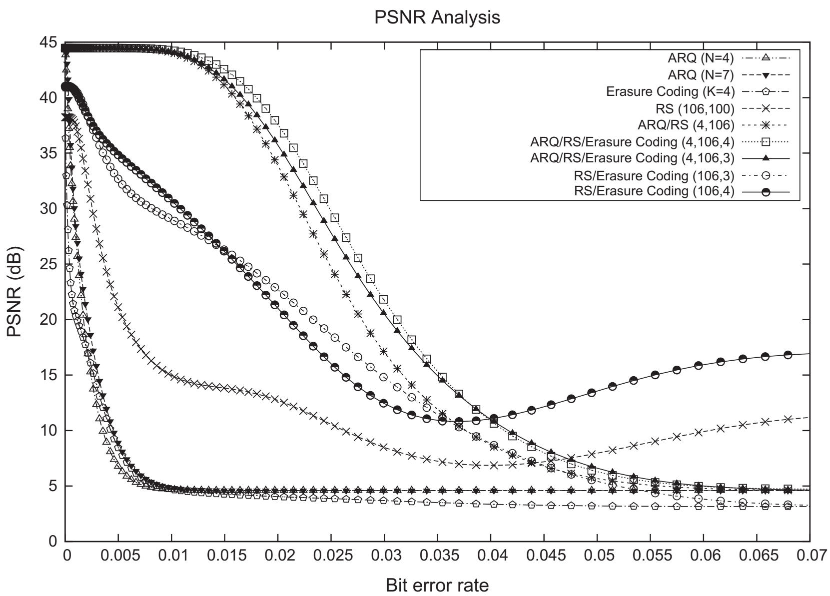

Fig. 8. Average PSNR under varying channel bit error rates.

error rates greater than these values. Finally, the cross-layer hybrid scheme is shown to always improve the quality of the received video. In particular, the RS/Erasure coding (106,3) and (106,4) schemes consistently outperform the RS (106,100) scheme, and the RS/Erasure coding (106,4) scheme provides better video quality than the RS (106,100) scheme.

To investigate video quality in more detail, the resulting PSNR values of the received frames for ARQ (N = 7), RS (106,100), and link-layer hybrid ARQ/RS (7,106) for a

BER of 0.0007, are shown in Fig. 9a, b, and c, respectively. Fig. 9 shows that the PSNR fluctuates more significantly for ARQ and RS error control schemes. Indeed, the quality variations due to packet errors in RS (106, 100) are smoother than those in ARQ. Moreover, the PSNR level changes are minimized in the case of the link-layer hybrid scheme. This is very important since smoothing improves the Mean Opinion Score (MOS) of the perceived video sequence.

Figs. 10 and 11 show the effect of delay bounds on the perceived quality of video at the receiver in terms of delay-constrained PSNR for real-time multimedia applications in WSN. Clearly, when the deadline time is decreased, the quality of the received video is affected adversely. The reason is that more video packets are considered as lost packets and are dropped because they violate the time constraint. The PSNR vs. maximum allowable delay of ARQ, RS, Erasure coding, link-layer hybrid ARQ/RS, cross-layer hybrid RS/Erasure coding, and cross-layer hybrid ARQ/RS/Erasure coding schemes in bad and good channel conditions are shown in Fig. 10a and b, respectively. As shown in Fig. 10b, the link-layer hybrid scheme, in all delay constraints, performs better than either ARQ or FEC schemes in terms of video quality. In addition, it is shown that ARQ ($N = 7$), below a specified delay constraint, performs worse than all the other schemes. The reason is that, in a strict delay constraint (i.e., $t \leqslant 100$ ms), the higher retry limits cause additional delays and useless retransmissions. However, when the maximum allowable delay is increased, the video quality for ARQ with seven retransmissions improved significantly, and it even performs better than other FEC and ARQ schemes for some values of the delay constraints. Furthermore, erasure coding provides the worse overall quality in most delay constraints. Fig. 10a shows that the cross-layer hybrid ARQ/RS/Erasure coding scheme outperforms the link-layer hybrid and simple schemes in terms of delay-constrained PSNR. In particular, in strict delay constraints, this cross-layer scheme provides significantly better video quality than other schemes, but, in high delay constraints, it results in a slightly better PSNR. Fig. 10a also suggests that the link-layer hybrid ARQ/RS scheme is more resilient to delay constraint than the cross-layer hybrid RS/Erasure coding scheme. The effect of delay bounds on different channel error rates for the ARQ scheme is presented in Fig. 11. As expected, in all cases, the delay-constrained PSNR is reduced by increasing channel bit error rates. Furthermore, it can be observed that, for low channel error rates, the PSNR is more tolerable to the strict delay constraints.

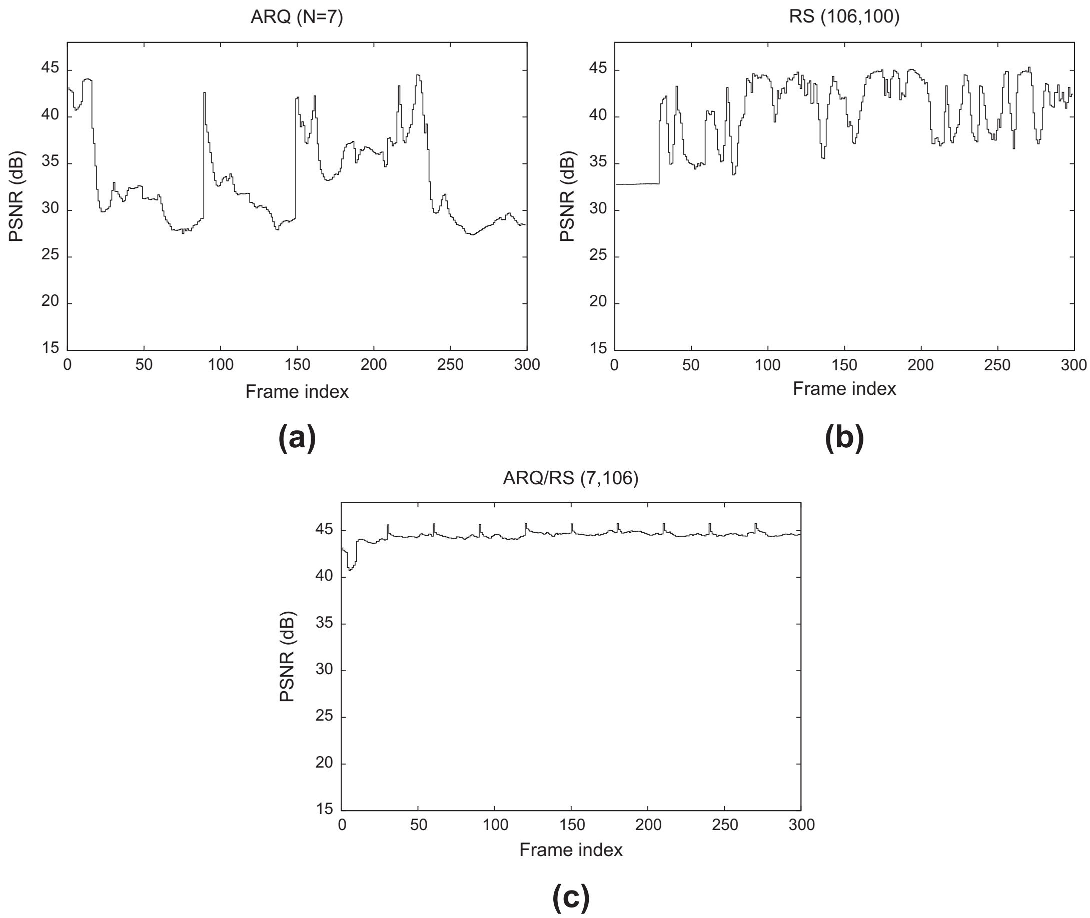

Fig. 9. PSNR over 300 frames of input video for (a) ARQ, (b) FEC, (c) link-layer hybrid ARQ/FEC.

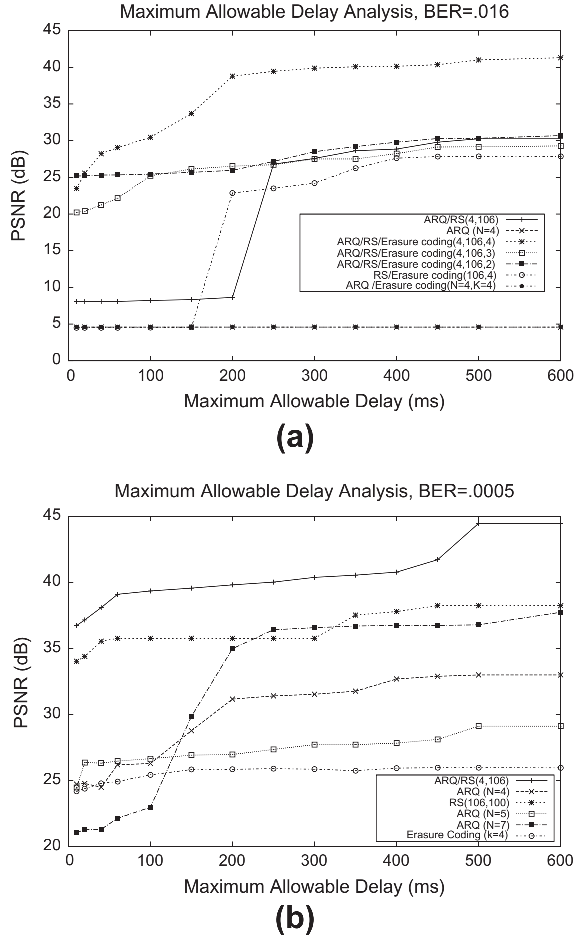

Fig. 10. Delay-bounded PSNR for (a) bad channel condition, (b) good channel condition.

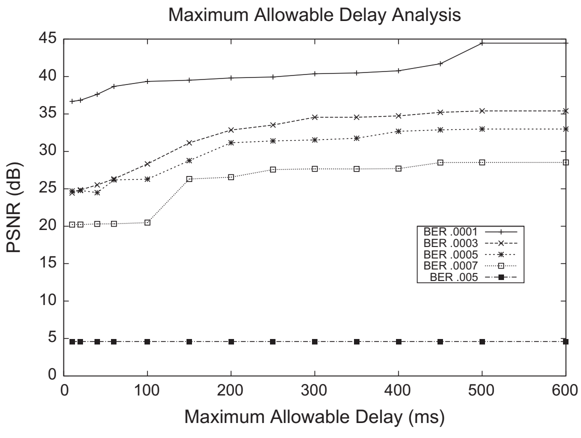

Fig. 11. Delay-bounded PSNR for different channel error rates for ARQ.

4.4. Energy efficiency analysis

The energy efficiencies of the error control schemes which have been discussed in this paper are shown in

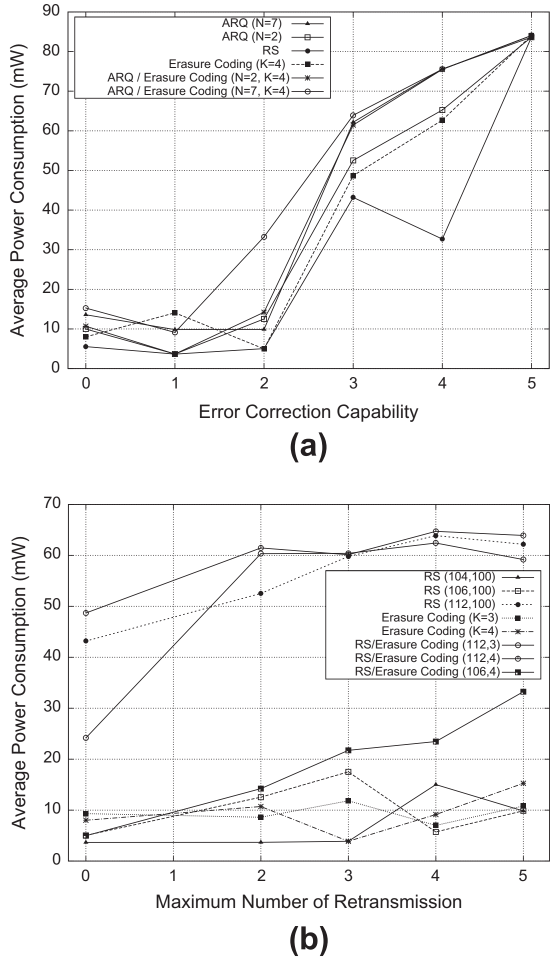

Fig. 12. (a) Average power consumption vs. error correction capability and (b) average power consumption vs. maximum number of retransmission.

Fig. 12 for MicaZ-based wireless multimedia sensor nodes. More specifically, the average power over all sensors for simple, link-layer hybrid, and cross-layer hybrid schemes subject to a channel bit error rate of 0.03 is shown as functions of error correction capability and maximum number of retransmissions. The average power consumption is calculated by dividing the total energy consumed in the sensors by the total simulated time. Note that the error correction capability indicates the strength of the RS scheme. For example, ARQ ($N = 7$) with error correction capability of 0 and 2 present simple ARQ ($N = 7$) and link-layer hybrid ARQ/RS (7,104) schemes, respectively. Fig. 12a shows that, as the error correction capability increases, the energy consumption of both link-layer hybrid and cross-layer hybrid schemes increases. It can be observed that the simple RS scheme consumes less power than the other schemes. Moreover, the cross-layer hybrid ARQ/RS/Erasure coding ($7,M,4$) scheme consumes more energy than the other schemes, regardless of error correction capability. This means that, although cross-layer schemes can provide acceptable video quality for delay-sensitive multimedia communications in sensor networks, they are not energy efficient. Furthermore, ARQ ($N = 7$) is less energy efficient than ARQ ($N = 2$) and Erasure coding ($k = 4$) schemes. The reason is that, in a bad channel condition (BER = 0.03), ARQ with a retry limit of seven, results in several retransmissions that are useless due to the high channel error rate. Also, the results indicate that ARQ schemes consume more energy than erasure coding. Finally, it can be observed that for different schemes and delay constraints, optimum configurations can be found to minimize the energy consumption while maximizing the PSNR.

Fig. 12b illustrates the energy efficiency of the discussed error control schemes as a function of the maximum number of allowable retries. It has been shown that error control mechanisms that use the RS (112,100) scheme result in significantly higher energy consumption than other error control schemes, regardless of their maximum number of retransmission attempts. In particular, the RS/Erasure coding (112,4) scheme, the RS/Erasure coding (112,3) scheme, and the RS (112,100) scheme have the greatest energy consumptions, since the energy of decoding is increased. Therefore, it can be concluded that energy efficiency is affected more by FEC strength than the number of retransmission attempts. Moreover, the optimum link-layer hybrid scheme for RS (104,100) and RS (106,100) can be found in maximums of three and four retransmissions, respectively. Finally, as shown in Fig. 12b, the energy efficiencies of reliable link-layer hybrid and cross-layer hybrid schemes, such as the cross-layer ARQ/RS/Erasure coding (N,106,4) and the link-layer hybrid ARQ/RS (N,112), are not optimized due to useless retransmissions and limited strength of the static FEC block-coding. These results indicate that there is a need for an adaptive QoS-based error control scheme that considers both reliability and energy efficiency in terms of delay-constrained PSNR and power consumption.

4.5. Cumulative jitter analysis

In WSN multimedia communications, delay and variations of delay both important for the perceived video quality. However, in many emerging applications of WMSNs such as multimedia surveillance, environmental monitoring, and industrial process control, the jitter analysis is more suitable [44]. In this section, we evaluate the performance of the frame cumulative jitter for several error control schemes. The variance of inter-frame time is considered as cumulative jitter [45]. More specifically, the cumulative jitter is an indicator for the variance of time difference between successfully delivered frames. Note that based on this definition, impact of the cumulative jitter is not dependent on the play-out delay. Fig. 13 shows the cumulative jitter of each delivered frame for ARQ, RS, link-layer hybrid, and cross-layer hybrid error control schemes at varying channel bit error rates. As shown in Fig. 13a, both ARQ ($N = 4$) and RS (106,100) error control schemes cause significant frame jitter on the receiver side, and the jitter increases linearly along the frame numbers in the RS (106,100) scheme and decreases linearly in the ARQ ($N = 4$) scheme. On the other hand, the link-layer hybrid ARQ/RS (4,106) scheme provides acceptable and smoother

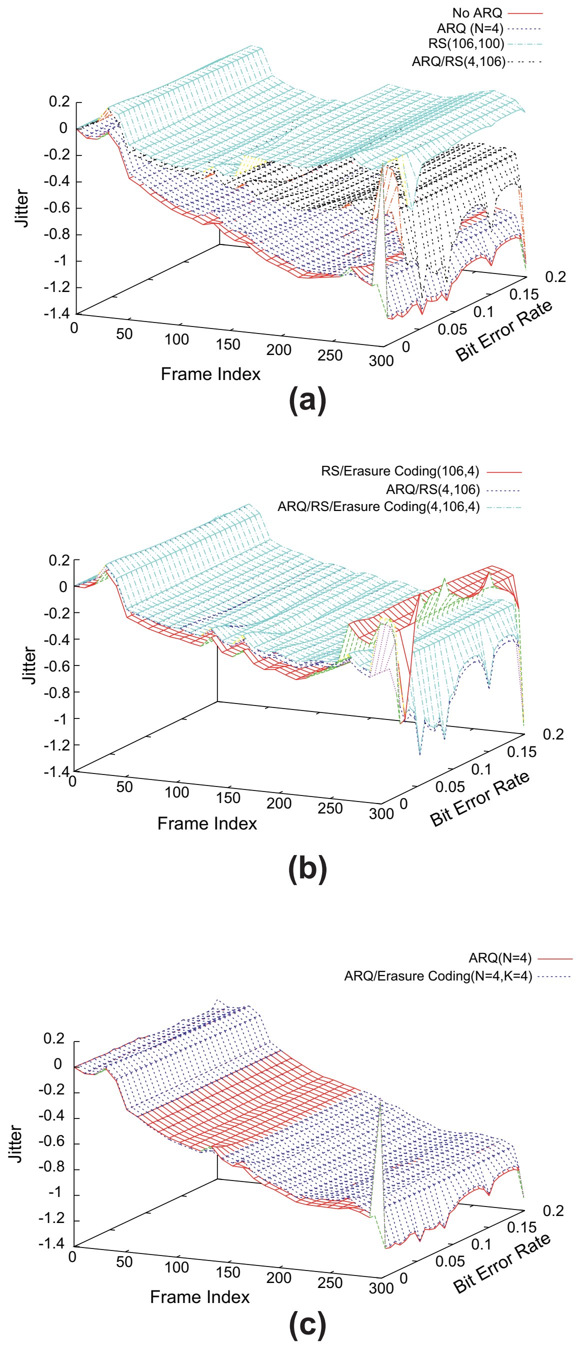

Fig. 13. Cumulative jitter vs. channel bit error rate and frame index.

cumulative jitter than simple mechanisms, which indicates that the time difference between frames that are successfully delivered can be reduced significantly by using link-layer hybrid schemes. This makes an link-layer hybrid scheme an important candidate for the delay-sensitive applications.

Moreover, as shown in Fig. 12a, the cross-layer hybrid RS/Erasure coding scheme is more energy efficient than the link-layer hybrid scheme, but the cumulative jitter

Table 3
Overview of the simulation results.

Performance metric	The most efficient scheme	The worst scheme
Frame loss rate	Cross-layer (4,106,4)	Erasure coding (k = 4)
PSNR	Cross-layer (4,106,k)	ARQ, Erasure coding
Delay-constrained PSNR (low delay constraint)	Cross-layer (4,106,4)	Erasure coding (k = 4)
Delay-constrained PSNR (high delay constraint)	Hybrid ARQ/RS (4,106), Cross-layer (4,106,2)	ARQ (N = 7)
Energy efficiency	RS	Cross-layer ARQ/RS/erasure
Cumulative jitter	Cross-layer (4,106,4)	ARQ, cross-layer ARQ/erasure

results (Fig. 13b) and the PSNR results (Fig. 8) show that there is no clear winner between the cross-layer hybrid RS/Erasure coding (106,4) scheme and the link-layer hybrid ARQ/RS (4,106) scheme in terms of jitter and PSNR. Also, it has been shown that cross-layer scheme (4,106,4) provides the smoothest jitter results along all frames. Furthermore, Fig. 13c shows that neither the ARQ (N = 4) scheme nor the cross-layer hybrid ARQ/Erasure coding (N = 4, K = 4) scheme can meet the expected cumulative jitter for real-time WSNs multimedia communications. As a result, the cumulative jitter of the cross-layer ARQ/RS/Erasure coding mechanism is more favorable than that of other schemes.

5. Conclusion

In this paper, we presented a comprehensive performance evaluation for different error control scenarios in WMSNs by conducting extensive simulations. It was shown that the existing error control protocols cannot provide a single overall best scheme for real-time multimedia delivery in WSNs. The results of the performance analyses are summarized in Table 3 where the most efficient and worst schemes for each metric are identified. The results reveal that link-layer hybrid and cross-layer hybrid schemes improve the quality of perceived video at the sink node compared to simple schemes. More specifically, this improvement can be utilized by using cross-layer scheme in low bit error rates and link-layer hybrid schemes in high bit error rates. Although in several cases the cross-layer hybrid scheme provided the best performance, it was inefficient in terms of energy consumption compared to the other error control schemes. In particular, it resulted in better perceived video quality at the cost of increasing energy. It has been shown that the cross-layer hybrid scheme outperformed the link-layer hybrid and simple schemes in high delay constraints and provided better video quality as delay bound decreased. The RS scheme energy consumption was more efficient than other schemes, but it could not provide acceptable video quality at the receiver when the error rates were high. The ARQ scheme had the worst performance in terms of PSNR and delay-constrained PSNR. Furthermore, it was observed from simulation results that the advantages of link-layer hybrid schemes were more considerable as the delay bound increased. Specifically, the link-layer hybrid ARQ/RS scheme outperformed other schemes based on high-delay constraint PSNR, but it did not provide the best energy-efficiency or the most reliable results. The error control protocols under observation do not consider delay, thus jitter is high and delay-constrained PSNR is very low. Energy-efficient and delay-constrained reliable multimedia deliveries are the most important changes that must be addressed together by new error control protocols for WMSNs. According to the results, cross-layer hybrid schemes seem to be promising for addressing multimedia challenges, and if their energy efficiency can be improved, they could be suitable candidates for delay-sensitive traffic in WSNs.

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