Error Resilient Video Streaming with BCH Code Protection in Wireless Sensor Networks

Matteo Petracca, Claudio Salvadori, Stefano Bocchino and Paolo Pagano

***Abstract*—Video streaming in Wireless Sensor Networks (WSNs) is a promising and challenging application for enabling high-value services. In such a context, the reduced amount of available bandwidth, as well as the low-computational power available for acquiring and processing video frames, imposes the transmission of low resolution images at a low frame rate. Considering the aforementioned limitations, the amount of information carried by each video frame must be considered of utmost importance and preserved, as much as possible, against network losses that could introduce possible artifacts in the reconstructed dynamics of the scene.**

In this paper we first evaluate the impact of the bit error rate on the quality of the received video stream in a real scenario, then we propose a forward error correction technique based on the use of BCH codes with the aim of preserving the video quality. The proposed technique, against already proposed techniques in the WSN research field, has been specially designed to maintain a full back-compatibility with the IEEE802.15.4 standard in order to create a suitable solution aiming at accomplishing the Internet of Things (IoT) vision. Performance results evaluated in terms of Peak Signal-to-Noise Ratio (PSNR) show that the proposed solution reaches a PSNR improvement of 4.16 dB with respect to an unprotected transmission, while requiring an additional overhead equal to 22.51% in number of transmitted bits, and minimal impact on frame rate reduction and energy consumption. When higher protection levels have been imposed, bigger PSNR values have been experienced at the cost of an increased additional overhead, lower frame rates, and bigger energy consumption values.

***Index Terms*—Video streaming, Wireless Sensor Networks, Internet of Things, Forward Error Correction, BCH codes.**

I. Introduction

Wireless Sensor Networks (WSNs) have experienced a rapid growth in the last several years due to the increasing efforts of both research community and private stakeholders in developing and standardizing this technology. WSNs have been recently adopted in a wide range of applications, where they replace old wired and wireless systems which are more expensive and hard to setup because of their necessity of power and connection cables. Moreover, they are nowadays considered the main building block in the so called Internet of Things (IoT) paradigm. A reduced set of WSN applications include climatic monitoring [1], structural monitoring of buildings [2], [3], human tracking [4], military surveillance [5], and, more recently, multimedia related applications [6], [7].

The development of the so-called Wireless Multimedia Sensor Networks (WMSNs) has been fostered by a new generation of low-power and very performant microcontrollers, able to speed-up the processing capabilities of a single wireless sensor node, as well as the development of new micro-cameras and microphones induced by the mobile phones industry. The WMSNs application fields are various and quickly growing during the last several years. As matter of example it is possible to cite the active surveillance of sensitive ambients [8] and the Intelligent Transport Systems (ITS) scenario, in which tiny devices equipped with a camera are used to collect traffic related data [9], [10]. In the aforementioned examples the acquired multimedia information, in particular the video data, is used in two completely different manners. While in ITS related applications the multimedia data can be processed on-board, thus transmitting aggregated information only (e.g., number of cars per unit of time passing through a checkpoint, as proposed in [11], [12], [13]), in case of video surveillance applications a full stream of images is usually sent through the network towards a final receiver node, in which they can be stored or analyzed [14], [15].

Multimedia streaming in a WMSNs scenario is a challenging application. Considering WSNs based on the IEEE802.15.4 standard [16], the main requirement for IoT systems, a very big issue is that of matching with a transmission bandwidth equal to 250 Kbps at physical layer, which is a value extremely limited with respect to other wireless technology (e.g., the IEEE802.11b standard provides 11 Mbps). This limitation implies the transmission of small size video frames (e.g., Q-VGA, QQ-VGA) at very low frame rates to avoid network congestion [17]. Furthermore, in case video compression techniques cannot be applied due to their computational complexity, expensive computation time [18], [19] and device memory limitations (a typical low-cost sensor node has an internal memory size of around 30 KBytes), raw video frames must be sent, then further reducing the frame rate, the frame resolution, or both of them.

Taking into account these limitations, it is important to stress that when reducing the frame rate and image size of a video stream, each video frame acquires a greater significance due to the lower redundancy in the information content it carries (i.e., any possible event must be discovered using a smaller sequence of images). As a consequence, a reliable video streaming transmission must be ensured to overcome the effects introduced by wireless channel variations, thus

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limiting unexpected errors in the transmitted bits with consequently losses of video frame portions. In the literature two main classes of data protection mechanisms are traditionally employed to mitigate the unreliability of the wireless channel, namely Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC). The former uses bandwidth efficiently, retransmitting data upon request, at the cost of additional latency, thus resulting unfeasible or strongly limiting for applications requiring real-time delivery of multimedia content. In FEC techniques, instead, the data to be sent through the network are protected a priori, thus requiring only additional bandwidth, without additional delays, to reconstruct an image at the receiver side. FEC based techniques for multimedia communications in a WSN scenario have been started to explore in the last years by several works. In [20] a cross-layer Unequal Error Protection (UEP) technique based on network resource allocation (e.g., transmission power) is presented for the transmission of compressed video frames in WSNs. Instead, the use of a cross-layer FEC approach based on Digital Fountain codes and targeted to WMSNs is presented in [21], where an increased network reliability is reached by jointly exploiting physical, transport, and application layer FEC approaches. Although in both aforementioned works the presented techniques have been proposed for video streaming purposes in WSNs, they are detailed without considering compatibility and constraints issues imposed by standard WSN communication protocols (i.e., IEEE802.15.4), or by analyzing their impact on the quality of the received video stream.

In this paper we propose, detail, and evaluate the performance of a FEC technique based on BCH codes for recovering bit errors in case of raw images based multimedia streaming applications over WSNs compliant with the IEEE802.15.4 standard. The presented work, against previous presented solutions, takes into account back-compatibility issues with the IEEE802.15.4 standard, thus proposing a novel suitable approach that represents a first step towards the definition of reliable video streaming applications in the IoT scenario. In the paper we first measure the Bit Error Rate (BER) for one-hop communications (WSN configured in a star topology) in a real outdoor scenario, thus showing its impact on the video streaming quality in terms of Peak Signal-to-Noise Ratio (PSNR). Then we detail the use of the BCH codes by proposing a solution fully back-compatible with the IEEE802.15.4 standard. In the last part of the paper we present, through simulations based on real collected loss traces, the performance of the proposed technique in recovering bit errors when BCH codes with different parameters are used. In the performance analysis the impact on the maximum allowable frame rate is analyzed by considering network bandwidth limitations, while energy consumption issues are discussed taking into account the introduced data transmission overhead.

The rest of the paper is organized as follows: in the next sections we first present the BER data collection results in a real scenario, as well as the impact of packet losses on video streaming quality. Then we discuss how BCH codes can be applied in IEEE802.15.4 data packets as a fully back-compatible extension of the standard. The performance evaluation of the proposed error recovery strategy is detailed in the last part of the paper before conclusions.

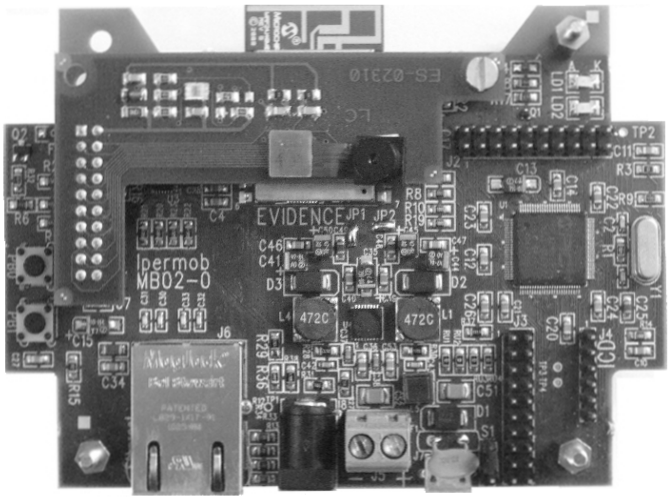


Fig. 1. The SeedEye board.

II. Experimental BER evaluation in IEEE802.15.4 networks and impact of bit error on video quality

To the end of evaluating the impact of bit errors on the quality of a video stream sent through a IEEE802.15.4 network, a set of real loss traces have been collected in an outdoor environment by using real devices.

A. Hardware and software

The BER in a real IEEE802.15.4 based transmission scenario has been experimentally evaluated by adopting the SeedEye board, developed within the IPERMOB project [22] and depicted in Fig. 1. The board is composed by:

- *Microcontroller unit.*
  The MCU is the PIC32MX795F512L, a 32 bits, 80 MIPS low cost integrated circuit produced by Microchip$^{\text{TM}}$.
- *Transceiver.*
  The transceiver is the Microchip$^{\text{TM}}$ MRF24J40MB which is fully compliant with the IEEE802.15.4 standard and characterized by an omnidirectional diagram pattern with a maximum transmission power of +20 dBm.
- *Camera.*
  The camera mounted on the device is the HV7131GP, a CMOS based which can be configured acquiring images at various resolutions (up to 640x480) and frame rates (up to 30 fps).
- *Ethernet interface.*
  A IEEE802.3 interface (LAN8720) for allowing possible connection towards Internet based systems.

The SeedEye has been specifically designed to support high demanding multimedia applications, both for on-board processing and video streaming, while requiring low power consumption during image acquisition. As matter of example, the SeedEye can acquire 160x120 gray scale raw images at 1 fps requiring only 75 mA, with the possibility to store up to 6 images in the internal MCU memory.

Regarding the data acquisition software for collecting real BER traces, two firmware (for sending and receiving data packets) have been developed as custom applications on top of the ERIKA RTOS [23], [24], an innovative real time operating system for small microcontrollers that provides an easy and effective way for managing operational tasks. Furthermore, the transceiver driver implemented in ERIKA allows to access to the MRF24J40MB functionality with a minimal time overhead, thus guaranteeing a jitter free periodic transmission of IEEE802.15.4 data packets. The firmware of the sender node has been developed for transmitting a priori defined IEEE802.15.4 data packets with a size equal to 127 bytes (highest packet dimension according to the standard). Thanks to the ERIKA functionality the data packets can be sent at the maximum frequency, thus reaching the nominal allowable bitrate of 250 Kbps. At the receiver side the firmware has been developed for gathering all the possible packets (with and without bit errors) from the wireless channel, for sending them to a laptop acting as storage unit.

B. *Data collection scenario and result analysis*

The scenario selected to collect real communication traces between sensor network devices is the testing area of the IPERMOB project, consisting of an outdoor parking lot and its accesses in the Pisa International Airport landside. The full data collection scenario with nodes positions and obstacles is depicted in Fig. 2, where the numbered dots represent the sender nodes, while the receiver, the WSN coordinator, is marked with the C letter. The network is organized in a star topology, thus the communication from each sender node to the receiver is only one-hop. The application scenario is that of a typical video surveillance system in which a set of nodes, six in this case, are installed to monitor the parking area. Each node of the system can in turn acquire and send an image to the network coordinator, the C node, which works as a point of service for the backhauling network. The data collection environment is heavily affected by reflections as well as permanent and temporary Non-Line-Of-Sight (NLOS) transmission conditions due to trees and moving cars.

Fig. 2. Data collection scenario deployed at the Pisa International Airport landside.

TABLE I. Data collection analysis results for all positions.

Pos.	Dist. [m]	BER	BL [bits]	BuIL [bits]	LQI	RSSI
1	64	$2.18 \cdot 10^{-4}$	1.66	122282.91	108.38	120.97
2	53	$1.69 \cdot 10^{-3}$	1.61	1347.91	99.86	122.09
3	43	$6.56 \cdot 10^{-7}$	2.23	1615032.00	116.38	147.88
4	68	$1.43 \cdot 10^{-4}$	1.69	14688.46	110.86	131.14
5	57	$1.24 \cdot 10^{-2}$	1.65	453.35	93.97	104.18
6	43	$9.12 \cdot 10^{-3}$	1.65	800.79	94.61	121.96

In all the performed experiments the hardware devices have been installed at a height of 2.5 m, collecting a dataset of three traces, each one consisting of nine thousands packets, for each position. The transmission power of the sender node has been set equal to +9 dBm to fulfill the ETSI requirements [25], selecting the transmission channel 11 (2.405 GHz) of the IEEE802.15.4 standard. The results of the experimental analysis are reported, for each position, in Tab. I in terms of: (i) BER; (ii) Burst Length (BL), the number of consecutive wrong bits; (iii) Burst Inter-arrival Length (BuIL), the number of consecutive correct bits between two bursts; (iv) Link Quality Indicator (LQI), which is provided by the transceiver and is a characterization of the whole link quality; and (v) Received Signal Strength Indicator (RSSI), which is provided again by the transceiver and only provides the strength of the signal. All results in the Tab. I have been averaged among the three collected traces in order to perform an overall comparison among data collected in different positions.

The complexity of the selected scenario is reflected by the high variability of the BER values, spanning in a range from 10^{-2} to 10^{-7}. Although higher BER values are expected for a larger distance between sender and receiver, when a Line-Of-Sight (LOS) transmission is performed (e.g., positions 1 and 3) the presence of moving obstacles causes unpredictable effects on such a parameter. Communications in NLOS conditions make impossible to correlate the BER with the transmission distance (e.g., positions 4 and 5). NLOS communications in the adopted scenario have been experienced to be permanent and temporary. While a permanent obstruction results in BER values dramatically high, as it happens for positions 5 and 6, which can be in any case mitigated with a careful sensor planning activity, temporary NLOS communications are totally unpredictable and associated to a sudden BER increment. As a matter of example, during the the collection, a trace in position 2, and afterwards discarded, has been acquired in condition of partial NLOS caused by a truck stopping for half of the time in the middle of the transmission path. The result was that the associated BER sharply increased showing a final value ten times bigger than the one experienced by previous traces collected in the same position. Regarding the BL, this is independent from the BER and close to 1.6 for each position. On the contrary, the averaged BuIL is strictly correlated to BER, showing as bigger bit error values reduce the inter-arrival time among bursts. The described behavior for both BL and BuIL is shown graphically in Fig. 3. Concerning the LQI and

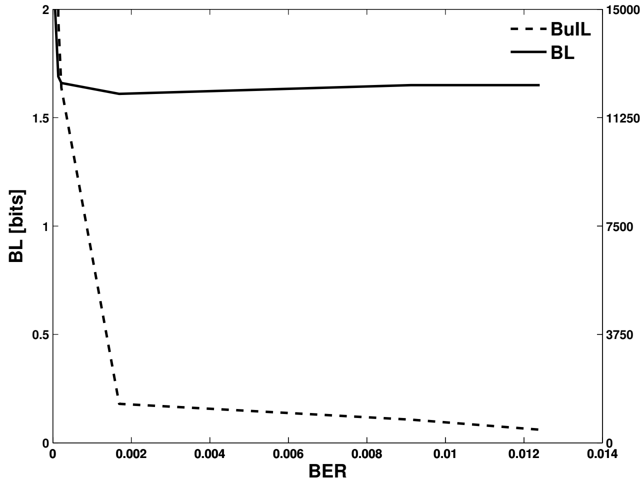


Fig. 3. BL and BuIL as a function of the BER.

the RSSI values, the BER is dependent on the LQI, when the LQI increases the BER decreases, while the RSSI is not simply related to the BER because its value is the sum of both effective signal and its reflections, higher values of RSSI do not coincide with lower values of BER (e.g., positions 1 and 2). The BER and RSSI behaviors as a function of the time are reported in Fig. 4 for a trace collected in position 1. In the picture it can be seen how peaks in the BER values can be experienced even if the RSSI remains close to its average value.

C. *Impact of bit errors on video quality*

The bit errors impact on the transmitted video streaming has been evaluated for each node position by simulating the transmission of uncompressed gray scale images (8 bits per pixel), at a resolution of 160x120 pixels. The images adopted in the performed simulations belong to the IPERDS [26] dataset created within the IPERMOB project. IPERDS is basically a collection of images related to traffic and parking

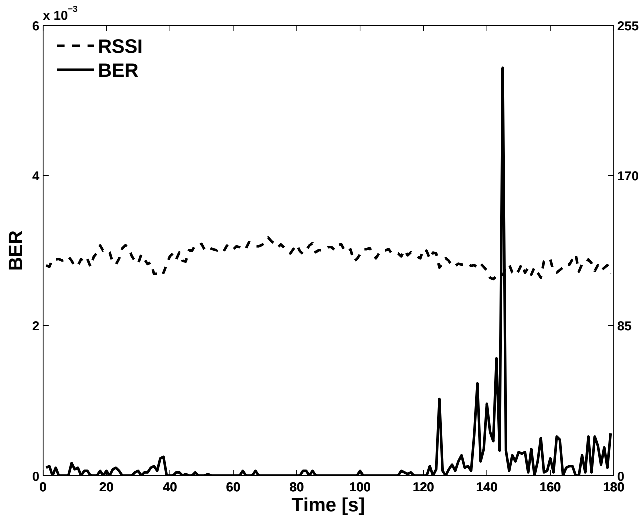


Fig. 4. BER and RSSI behavior for a trace in position 1.

lots conditions and hence characterized by slow and high motion. Each cataloged set of images is a video trace of more than 5 minutes with a frame rate equal to 1 fps. The dataset is composed of gray scale images with a size equal to 160x120 and 320x240 pixels. All the images composing the dataset have been collected by using real wireless sensor network devices equipped with a low-cost camera, the SeedEye board, hence they have all the necessary characteristics to prototype video streaming algorithms targeted to low-end devices.

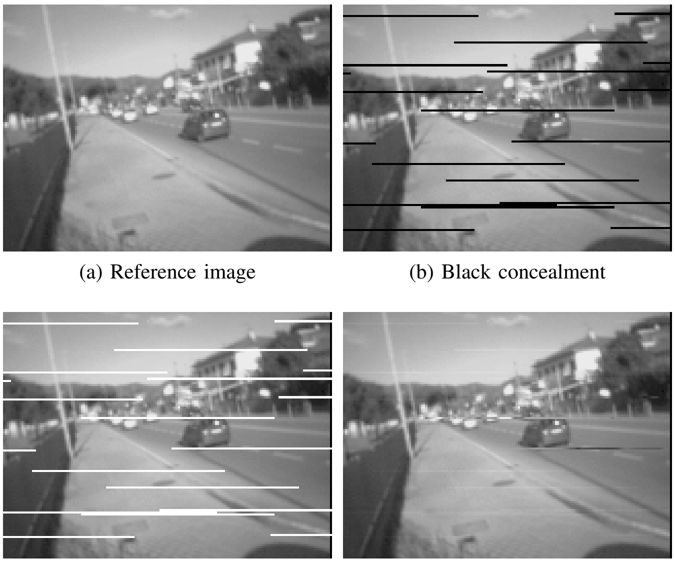
In the simulations each image is fragmented according to the maximum payload allowed by the IEEE802.15.4 standard, and an image fragment is considered lost if at least one bit error occurs in the received data packet, thus being fully compliant with the transmission standard in which packets with wrong Frame Check Sequence (FCS) values are discarded at the receiver side. According to the standard the FCS is evaluated on the whole packet (header plus payload). In the presented results an evaluation of the impact of three low-complexity concealment algorithms able to recover image data losses is shown. The considered concealment techniques will be identified as black insertion, white insertion and copy frame in the following of the paper. In case of black insertion concealment the lost fragment of a video frame is replaced with black pixels, while in case of white insertion concealment the color of the replaced pixels is white. The copy frame concealment is little more complicated with respect to the previous ones and it consists in replacing the lost fragments of a video frame with the ones of the last received frame. The BER impact on video quality has been evaluated in terms of PSNR for each one of the proposed concealment techniques, and results reported in Tab. II for a numeric comparison. In the table the PSNR in case of black concealment is labeled as PSNR-bc, the one for the white concealment as PSNR-wc, while PSNR-cc refers to the copy frame concealment.

TABLE II. PSNR for all the tested concealment techniques.

Pos.	BER	PSNR-bc [dB]	PSNR-wc [dB]	PSNR-cc [dB]
1	$2.18 \cdot 10^{-4}$	42.57	43.40	56.80
2	$1.69 \cdot 10^{-3}$	19.14	20.08	35.88
3	$6.56 \cdot 10^{-7}$	89.91	89.96	90.25
4	$1.43 \cdot 10^{-4}$	53.84	54.45	62.35
5	$1.24 \cdot 10^{-2}$	11.86	14.53	27.84
6	$9.12 \cdot 10^{-3}$	13.35	16.23	91.82

From results reported in Tab. II it is possible to see how the PSNR is directly correlated to the BER experienced in the transmission link. Higher values of BER produce low values of PSNR for each concealment technique considered in the simulation process. In case of BER values higher than 10^{-3} the video quality reduction is bigger than 60% with respect to the PSNR value experienced with a BER equal to $6.56 \cdot 10^{-7}$, while when the BER is slightly higher than 10^{-4} the video quality reduction is bigger than 35%. Although a BER equal to 10^{-4} cannot be considered as a critical value for wireless communications based on the IEEE802.15.4 standard [27], it produces a substantial quality reduction of the received video stream. The selection of an appropriate concealment technique mitigates the effects of the packet losses, guaranteeing a gain in the quality of the received video. More in particular, the copy frame concealment outperforms all the other concealment techniques under test, reaching a substantial gain in video quality for each position affected by BER larger than $6.56 \cdot 10^{-7}$. A graphical output of the applied concealment solutions is depicted in Fig. 5, where the frame with copy frame concealment is almost completely reconstructed.

In a WMSN scenario in which tiny devices send image frames with low resolution and low frame rate, error recovery techniques must be applied in order to avoid poor video quality and possible artifacts in the reconstructed dynamics of the scene at the receiver side, as it could happen in video surveillance systems.



(a) Reference image (b) Black concealment

(c) White concealment (d) Copy concealment

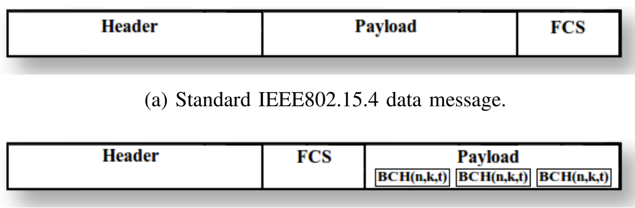
Fig. 5. Visual impact of the selected concealment algorithms.

III. BCH CODES BASED ERROR RECOVERY STRATEGY

In this paper the use of BCH codes is considered to define a FEC strategy for recovering bit errors in wireless multimedia sensor networks. According to the coding theory, the BCH codes [28] is a class of error-correcting block codes in which the coding and decoding procedures are characterized by low complexity and low power consumption [29], thus making these codes very suitable for a real implementation in low-end devices. In a very simplistic statement the aim of the block coding process is to add redundancy bits to the initial block of bits which constitute the information to be transmitted, thus providing the capability of correcting a certain number of errors caused by channel variability. Each BCH code is characterized by three main parameters: (i) the total number of bits after the coding procedure n, its value is given by the number of information bits plus the number of redundancy bits; (ii) k, the number of the information bits which must be protected ($k < n$); and (iii) t, the error correction capacity of the code. Each BCH code can correct up to t errors in each block on n bits, while adding $n-k$ bits of redundancy. In literature a BCH code is identified by the above introduced parameters with the labeling $BCH(n,k,t)$. The value $R_c = k/n$ is the code rate and is related to the redundancy level and overhead introduced by the code. Lower R_c values mean higher protection levels and higher additional overhead in terms of redundancy bits to transmit.

The use of a FEC strategy based on BCH codes in sensor networks compliant with the IEEE802.15.4 standard requires to define new policies in accepting corrupted packets at the receiver. According to the standard, a transmitted data packet is composed, at the Medium Access Control (MAC) layer, by three main fields: (i) MAC Header (MH), 23 bytes long with full addressing and no security; (ii) MAC Payload (MP), 102 bytes long with full addressing and no security; (iii) and FCS, which is evaluated on the two previous fields and has a fixed dimension of 2 bytes. The standard IEEE802.15.4 MAC data packet has been reported in Fig. 6a. Once a packet is received from a network node, a new FCS is evaluated and compared with the one encapsulated inside the packet by the sender. If the two FCS are identical the packet is accepted and transferred to the upper layers of the network stack, otherwise it is discarded and the carried information is lost. This approach cannot be pursued when FEC strategies based on error correction codes are applied, because it would result in neglecting the effects of the protection strategy itself. The approach proposed in this paper to effectively apply BCH codes based FEC strategies within IEEE802.15.4 networks is depicted in Fig. 6b. The FCS field is evaluated only on the packet header, thus avoiding to deliver packets to wrong nodes in case of errors in the addressing field, while in the payload no check on the correctness of the data is applied. In the payload, instead, the n bits of each BCH code word are considered and the k bits of the original information are extracted. The error correction capacity of the code guarantees the correction of up to t errors for each block of n bits. If a higher number of errors is experienced these cannot be revealed and corrected, as a consequence wrong bits are accepted for decoding purposes. The proposed protection strategy is especially indicated for the transmission of multimedia data in which the residual errors do not affect the validity of the full packet, but slightly affect the quality of the received media stream.

The proposed FEC strategy has been specially designed to avoid to change the MAC layer of the IEEE802.15.4 standard for a specific application. The new MAC data message depicted in Fig. 6b, in fact, can be defined using the bits



(a) Standard IEEE802.15.4 data message.

(b) Proposed MAC data message with FEC protection.

Fig. 6. Standard IEEE802.15.4 MAC data message and proposed solution for error recovery based on BCH codes.

reserved from the standard for specifying new possible MAC messages. In this case, a full back-compatibility with the standard is maintained, while extending it with error recovery capabilities due to the use of error-correction block codes. The basic messages of the IEEE802.15.4 standard, as well as the reserved bits combinations are reported in Tab. III. A selected reserved combination can be selected for extending the current standard with the proposed MAC data message. It must be emphasized that the use of the reserved bits to extend the type of the IEEE802.15.4 MAC data messages does not impose to change the network firmware of sensor devices already deployed for regular monitoring applications. In fact, although only the nodes with the extended MAC messages set will be able to use those messages, all the old nodes compliant with the standard will continue to operate properly discarding the unknown data packets.

TABLE III. Standard IEEE802.15.4 MAC messages.

Frame type value $b_2b_1b_0$	Description
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100-111	Reserved

IV. Performance evaluation

The performance of the error recovery strategy proposed in the previous section of the paper has been evaluated with a simulative study as a function of the error correction capacity of the code (t) and its code rate (R_c), by analyzing the effect on the allowable frame rate, the required additional data transmission overhead, and additional energy consumption due to the bigger number of bits to be sent. In the performed simulations the loss traces collected in the Pisa International Airport landside scenario, and analyzed in previous sections of this paper, have been used. In particular we adopted the ones collected in position 1, see Fig. 2, and characterized by a BER equal to $2.18 \cdot 10^{-4}$ and a video quality reduction of about 35% with respect to the highest value of Tab. II experienced in position 3. In all the simulations the same video traces of the IPERDS dataset adopted to study the impact of the BER on the video quality have been used, while only considering the copy frame concealment due to its better performance in terms of PSNR with respect to black and white insertion concealments. All results of the performed analysis are reported in Tab. IV, where for each code, together with the error correction capacity and code rate, are reported the maximum allowable frame rate, the additional overhead requested by the protection technique, the percentage of packets discarded due to wrong headers, the percentage of recovered errors and the obtained PSNR value. In all simulations the bandwidth constraints imposed by the IEEE802.15.4 standard have been taken into account by considering a payload size equal to 92 bytes and a header of 33 bytes (additional 10 bytes for security purposes), thus considering the case of a real application scenario. In the table, the impact of each code on the maximum allowable frame rate is reported in the fourth column. Such a value has been evaluated considering the sending time of each packet proportional to its dimension. The overhead introduced by each code, and reported in the fifth column of the table, has been evaluated as the additional number of bits required to send the video frames, including the headers of additional necessary packets. In fact, this parameter is affected not only by the additional redundancy bits imposed by the adopted code but also by the IEEE802.15.4 packet dimension limitation that imposes to fragment each video frame in a bigger number of packets with respect to the case in which no protection is applied. For evaluating the PSNR the proposed FEC strategy has been used to recover bit errors, moreover must be stressed that packets with corrupted headers because of wrong FCSs are entirely discarded, thus applying data concealment. For comparison purposes the first row entry of the table, labeled as No protection, reports frame rate and video quality performance when the standard IEEE802.15.4 transmission mechanism (Fig. 6a) is applied, in this case the reported PSNR is the same value for the position 1 in Tab. II.

In Tab. IV, four main classes of BCH codes have been considered, with n equal to 255, 127, 63 and 31 bits respectively, and for each one of them several correction capacities have been tested. The maximum considered error correction capacity is equal to 5, and has been chosen by considering the complexity and energy consumption values reported in [29]. In such a work, in fact, the authors have been experimentally proved that BCH codes with error correction capacities up to 5 have extremely low complexity and low power consumption in both encoding and decoding phases, thus resulting the best suitable solution for wireless sensor networks.

A. PSNR as a function of the error correction capacity

A first main effect of the proposed error recovery mechanism is the reduction of the number of discarded packets, from 4.06% to values lower than 1.26%, at the cost of accepting

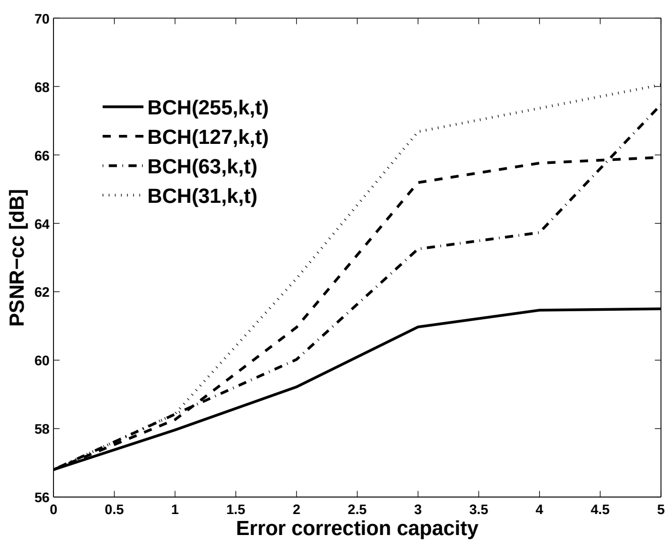
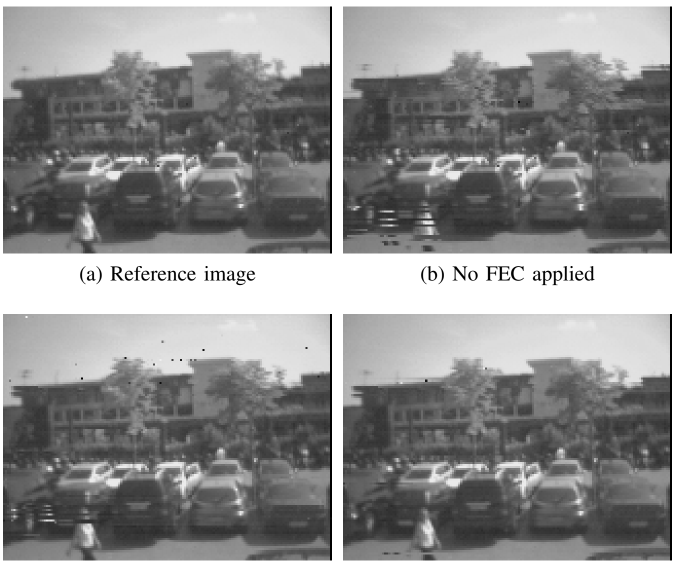


Fig. 7. PSNR as a function of the error correction capacity.

TABLE IV. Performance results for the four classes of selected BCH codes.

Protection	t	R_c	Frame rate [fps]	Overhead [%]	Packet discarded [%]	Error recovered in the payload [%]	PSNR-cc [dB]
No protection	0	1	1.20	0	4.06	0	56.80
$BCH(255, 247, 1)$	1	0.97	1.01	19.31	1.21	2.04	57.96
$BCH(255, 239, 2)$	2	0.94	0.97	23.14	1.21	15.66	59.22
$BCH(255, 231, 3)$	3	0.91	0.94	27.36	1.21	27.95	60.97
$BCH(255, 223, 4)$	4	0.87	0.91	32.09	1.21	31.27	61.46
$BCH(255, 215, 5)$	5	0.84	0.87	37.08	1.21	35.54	61.50
$BCH(127, 120, 1)$	1	0.94	1.04	15.30	1.22	2.06	58.26
$BCH(127, 113, 2)$	2	0.89	0.98	22.51	1.22	16.69	60.96
$BCH(127, 106, 3)$	3	0.83	0.92	30.61	1.22	33.96	65.19
$BCH(127, 99, 4)$	4	0.78	0.86	39.74	1.22	38.92	65.76
$BCH(127, 92, 5)$	5	0.72	0.80	50.08	1.22	41.59	65.93
$BCH(63, 57, 1)$	1	0.90	1.02	17.94	1.26	2.76	58.42
$BCH(63, 51, 2)$	2	0.81	0.91	31.90	1.26	19.62	60.02
$BCH(63, 45, 3)$	3	0.71	0.85	40.74	1.26	40.44	63.25
$BCH(63, 39, 4)$	4	0.62	0.70	71.10	1.26	45.63	63.73
$BCH(63, 36, 5)$	5	0.57	0.65	85.44	1.26	47.83	67.47
$BCH(31, 26, 1)$	1	0.84	0.97	24.10	1.15	3.65	58.43
$BCH(31, 21, 2)$	2	0.68	0.78	53.25	1.15	20.34	62.39
$BCH(31, 16, 3)$	3	0.52	0.60	100.98	1.15	39.26	66.68
$BCH(31, 11, 5)$	5	0.35	0.41	192.42	1.15	46.99	68.05

possible bit errors which cannot be corrected with the selected BCH code. Analyzing the video quality for a single class of codes it is possible to see how it mainly depends on the error correction capacity. In fact, increasing the error correction capacity a higher percentage of errors is recovered with a consequent increase of PSNR values. This behavior is depicted by means of graphs in Fig. 7 and graphically in Fig. 8, and it is common to all the four classes of codes analyzed. In Fig. 8c it is possible to notice the effect of errors in the packet header, a line in the image due to the applied concealment, as well as the effect of unrecovered bit errors in the payload, black dots in the upper part of the image. For all the four classes of codes a low percentage of errors is recovered with $t = 1$, despite the high value of the additional overhead, this is because the code cannot recover the whole burst error, which is equal to 1.66 on average. With $t \geq 2$ the improvement in percentage of recovered errors, and in PSNR, becomes more significant.



(a) Reference image (b) No FEC applied

(c) FEC applied with $t = 1$ (d) FEC applied with $t = 3$

Fig. 8. Impact of the FEC technique on received video frames.

B. PSNR as a function of the code rate

Considering the PSNR as a function of the code rate it is possible to notice an inverse dependency. For each class of codes lower values of the code rate parameter correspond to higher PSNR values, as depicted in Fig. 9. A PSNR analysis as a function of the code rate can also be used to analyze the benefit of a class of codes with respect to the other ones. In fact, considering a fixed value of error correction capacity the general trend in the PSNR values is that of reaching higher quality as much as the code rate decreases. This behavior is evident for t equal to 1 and 5, while in case of t equal to 2, 3 and 4 it is not directly observable. This effect is due by the lower PSNR values reached by the class of $BCH(63, k, t)$ codes in which a higher percentage of discarded packets respect to the other class of codes has been experienced. As a general rule, by considering BCH codes with the same error correction capacity, codes with lower code rate parameters

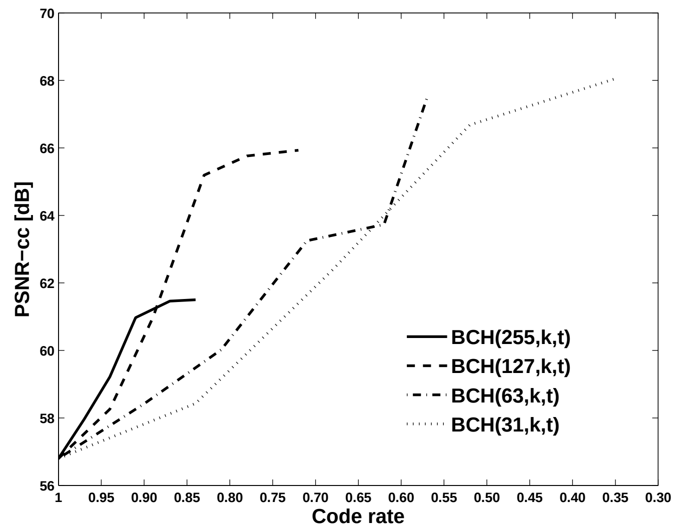


Fig. 9. PSNR as a function of the code rate.

guarantee better performance in terms of video quality at the receiver side.

C. Frame rate and energy consumption considerations

The proposed FEC technique requires an additional overhead in number of bits to perform error recovery. Such overhead produces two main effects: (i) the decrease of the maximum allowable frame rate of the video stream; and (ii) the increase of the energy consumed by the sensor node.

The maximum allowable frame rate proportionally decreases when increasing the protection strength (bigger overhead values), thus passing from a value equal to 1.20 fps when no protection is applied to 0.41 fps when using the strongest considered protection. The maximum allowable frame rate as a function of the code rate is depicted in Fig. 10 for the four classes of codes. It must be emphasized that lower frame rate values do not affect the PSNR, because it is an objective video

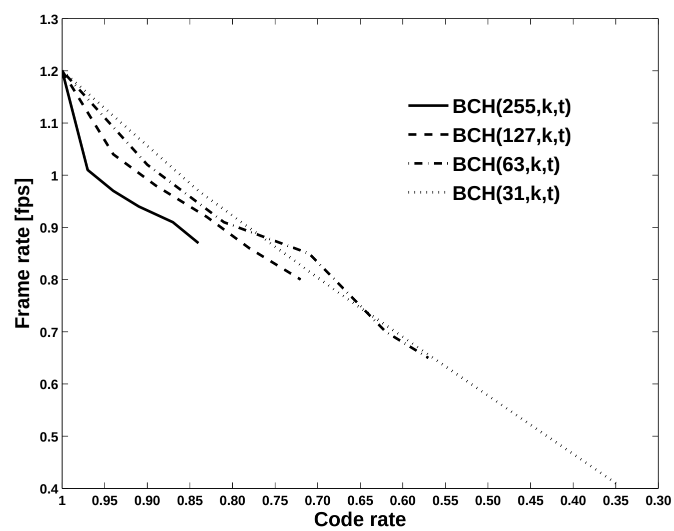


Fig. 10. Maximum frame rate as a function of the code rate.

quality measure based on the difference between original and reconstructed frames, thus without considering the effect of a frame rate reduction.

Concerning the additional energy required by the protection technique, this is only due by the additional number of bits to be sent through the wireless channel. In fact, as discussed in [29], in WSNs the power consumed by the transceiver dominates the total power consumption if BCH codes are used. As a consequence, the additional energy required by the sensor node can be easily evaluated by using an energy model of the transceiver, such that proposed in [30], and by considering the number of additional bits.

D. BCH code selection

The use of the proposed protection technique for video streaming over IEEE802.15.4 network guarantees significant performance improvements in terms of PSNR at the cost of an increased overhead. In case high transmission bandwidth overhead can be tolerated, the best choice is to select codes characterized by the highest error correction capacity and the lowest code rate. In the performed simulations the code $BCH(31, 11, 5)$ reach a gain in PSNR equal to 11.25 dB with an exaggerated additional overhead of 192.42% in number of transmitted bits. When a trade-off between video quality and additional overhead is required BCH codes with error correction capacity larger than the average burst length and minimum overhead must be chosen. Moreover, these codes guarantee to have both lower frame rate reduction and additional energy consumption values with respect to codes with the same error correction capacity. In the presented results the best trade-off is reached by $BCH(127, 113, 2)$ which is characterized by an error correction capacity equal to 2 (the average burst length is 1.66), and reaches a performance improvement in terms of PSNR is equal to 4.16 dB at the cost of an increased overhead of 22.51%.

V. Conclusions

In this paper the problem of improving perceptual video quality in multimedia streaming over wireless sensor networks is analyzed. Using real video traces collected using the SeedEye board, and exploiting experimental loss traces gathered in a complex real-world scenario situated in the Pisa International Airport landside, the impact of IEEE802.15.4 packet losses on the received video quality has been evaluated. Presented results show as BER values higher than 10^{-4} lead to a quality reduction in terms of PSNR close to 35% with respect to the highest quality value experienced. To overcome data losses a forward error correction strategy based on BCH codes and fully back-compatible with the IEEE802.15.4 standard is proposed, and its performance evaluated by means of a simulative study. The proposed data error recovery strategy has been developed by defining a new MAC data frame which makes use of the bits kept reserved by the standard for future purposes. Performance results as a function of the error correction capacity of the code and its code rate show how the proposed technique guarantees to improve the final PSNR. When the error correction capacity of the code is greater than the experienced burst length the performance improvement in terms of PSNR, with respect to a plain transmission in which no protection is applied, is equal to 4.16 dB. This performance improvement is reached with a minimum additional overhead of 22.51% in number of transmitted bits, while experiencing a minimum impact on the maximum allowable frame rate reduction and additional required energy consumption. Furthermore, when higher protection levels can be applied, bigger video quality improvements can be reached at the cost of additional transmission bandwidth overhead, lower frame rates and bigger energy consumptions.

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