Redundancy-Based Semi-Reliable Packet Transmission in Wireless Visual Sensor Networks Exploiting the Sensing Relevancies of Source Nodes

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Abstract: - Visual data monitoring in wireless sensor networks can significantly enrich a large set of surveillance and general purpose monitoring applications. However, transmission of image snapshots or video streams can rapidly deplete the energy resources of the deployed nodes, turning energy efficiency into a major optimization issue. During wireless transmissions, packets can be corrupted directly affecting the monitoring quality of the applications. One reasonable way to reduce quality loss is the transmission of redundant packets for higher error resilience, but additional packet transmissions may incur in undesirable energy consumption. Frequently, some monitoring quality loss may be tolerated since visual information retrieved from source nodes may have different relevance for the applications, according to the monitoring requirements and the current sensors' poses and fields of view. In such way, we propose that only high-relevant source nodes will transmit redundant packets, assuring error resilience only for the most relevant visual data for the monitoring application. Doing so, energy is saved over the network when fewer packets are transmitted in average, potentially enlarging the network lifetime with reduced impact to the overall monitoring quality.

Key-Words: - packet-level redundancy; wireless visual sensor networks; semi-reliable transmission; sensing relevance of source nodes.

1 Introduction

Wireless sensor networks (WSNs) have emerged in last decade as a multihop communication infrastructure for a series of innovative monitoring functions [1]. These networks are composed of low-cost battery-operated sensor nodes that communicate among themselves through low-rate ad hoc wireless links, imposing many challenges in deployment, operation and management [1, 2]. When sensor nodes are endowed with a low-power and low-resolution camera, visual information can also be retrieved from the monitored field, significantly enriching the monitored information and fostering the development of a new set of applications [3, 4].

Image transmissions and video streaming over wireless sensor networks bring many challenging issues, when compared with transmissions of scalar data [4, 5, 6]. While scalar data can be represented with few bytes, even small image snapshots may require thousands of bytes, besides requirements for low transmission latency and jitter in some cases. In fact, energy is a crucial issue since sensor nodes are usually expected to operate using a non-rechargeable battery and the network lifetime is a direct function of the energy consumption rate. In such way, visual data transmission is expected to consume more energy than transmission of scalar data as humidity, pressure and luminosity, turning energy efficiency into a major optimization issue.

When transmitting visual data packets over error-prone wireless links, packets can be corrupted. Generally, packet corruption can be recovered employing retransmission mechanisms or redundancy [6, 7]. Retransmission of corrupted packets assures that a new copy of the lost packet will be retransmitted in an end-to-end or hop-by-hop fashion, resulting in more information transmission over the network when corruption occurs. On the other hand, redundancy will add information in advance, either into data packets (as an additional header) or creating replicated packets. When redundancy is implemented adding information into data packets, correction codes are employed in different levels of complexity, where corrupted packets may be recovered processing the codes [8]. In a different way, we are most concerned herein with packet-level redundancy, implemented by the transmission of redundancy packets [7, 9].

A graphical representation of hop-by-hop retransmission, correction codes and packet-level redundancy for error recovery in wireless sensor networks is presented in Fig 1. In that figure, a packet error occurs during transmission from node 3 to node 4.

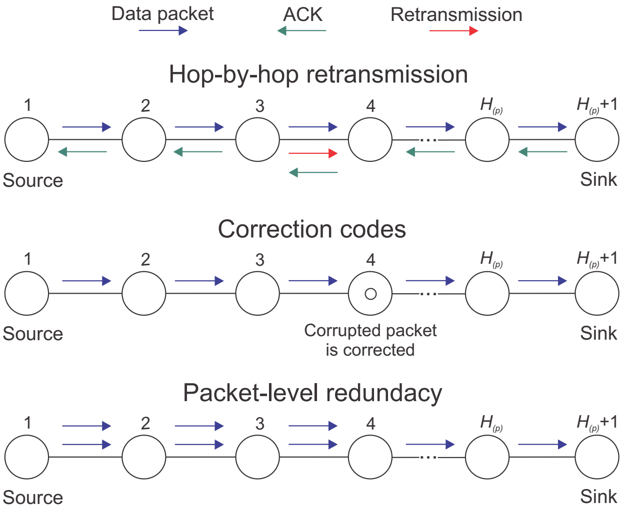

Figure 1. Different strategies for error recovery in WSNs.

Wireless links in visual sensor networks are expected to be error-prone. Packet retransmission is a reasonable option for error recovery, but it may incur in additional undesired end-to-end delay. On the other hand, error recovery by correction codes may add complexity to source and intermediate nodes with no success guaranties. In this work, we exploit spatial redundancy to replicate data packets as an effective strategy for error resilience with reduced impact to the average end-to-end delay. However, as higher energy consumption is expected when more packets are transmitted, transmission of redundancy packets may also negatively impact the expected network lifetime.

For many applications, the quality of a deployed wireless visual sensor network will be a function of how well an area of interest is viewed by the source nodes [10]. We can then establish a relation between monitoring quality and the actual application requirements, since quality will depend on what static or moving targets or even areas of interest need to be monitored by the source sensors. In other words, the significance of each source node is a direct function of the expected targets to be monitored, instead of only the deployed network characteristics, turning the network coverage-aware. We formulated this concept in [11].

As source nodes may have different relevancies for the monitoring functions of the applications, visual data packets will be transmitted under different levels of reliability according to the packets' origins. We propose that redundant copies of higher priority packets could be transmitted to increase the probability of successful reception, while low-relevant source nodes would transmit only a single copy of each data packet, reducing energy consumption over the network. As redundancy will still be assured for higher relevant packets, low harm is expected to the overall monitoring quality when the packet error rate rises. We investigate packet replication and erasure coding when implementing redundancy for error recovery.

The remainder of this paper is organized as follows. Section II presents some related works. The fundamental concepts and basic definitions for this work are discussed in Section III. The proposed approach is presented in Section IV. Section V brings some numerical results, followed by conclusion and references.

2 Related works

In general words, wireless links have a high bit-error rate when compared with wired links, which can result in packet corruption along the time. In fact, wireless visual sensor networks may be negatively impacted in different ways by bit-errors, depending on the application monitoring requirements and source nodes configurations. Many works have been concerned with error recovery in wireless sensor networks, proposing different recovery strategies that influence our investigation [6, 7].

To cope with errors due to congestion, MAC-layer collisions, interferences and node failure, many works have proposed optimizations to recover lost packets in wireless sensor networks, where retransmission is the most usual approach. In fact, we are most concerned with bit-errors during transmission, which are resulted from the nature of wireless transmissions whatever are the employed MAC protocols.

The work in [12] proposes an end-to-end retransmission mechanism, where an explicit message is sent to the source node requesting retransmission of a lost packet, if some gap is found in the sequence numbers of received packets. In [13], authors propose a transport protocol that performs in-network caching of transmitted packets for hop-by-hop retransmission. Packets losses are identified by proper timers enabled in intermediate nodes and notifications are performed by explicit NACK messages. The work in [14] employs multiple redundant paths and hop-by-hop retransmission for error recovery, where the transmission paths are dynamically chosen to mitigate congestion in intermediate nodes. A semi-reliable retransmission mechanism is proposed in [15], where the relevancies of DWT subbands are considered when corrupted packets need to be retransmitted. In that work, only high-relevant packets must be retransmitted if corrupted, saving energy while still assures playable images when the packet error rate rises.

Besides retransmission, error-resilience can also be provided by transmission of redundancy packets. In [16] it is discussed the impact of redundancy and retransmission for error recovery in wireless sensor networks, addressing reliability and energy efficiency issues. In that work, erasure coding is presented as an effective redundancy mechanism for wireless sensor networks. A similar discussion is taken in [17]. In [9], intermediate nodes perform error recovery based on redundancy and correction codes, providing an in-network recovery strategy. However, in-network processing may impact the average transmission delay of the application. The work in [18] also proposes packet redundancy for higher error recovery, employing an erasure coding scheme. The redundancy is implemented considering the relevance of video frames for the reconstruction of the original data.

Although very promising, packets from different source nodes have the same reliability level for the network, which may lead to energy wasting. Payload-based prioritization approaches as proposed in [15, 18] are indeed relevant but all visual source nodes are treated equally, whatever are the retrieved data. In a different way, we propose the exploiting of the sensing relevancies of source nodes when deciding the expected level of reliability for the transmitted packets, potentially reducing energy consumption when avoiding transmission of redundancy packets from low-relevant source nodes. Moreover, we expect to bring significant contributions to visual monitoring applications with time constraints. The concept of sensing relevance is very promising, potentially bringing many valuable results for wireless visual sensor networks [11]. Recently, we exploited this concept to propose different optimizations in visual data transmission [19], error control [20] and packet routing [21].

3 Fundamental concepts

We propose herein an innovative semi-reliable transmission mechanism based on packet redundancy and on the sensing relevancies of source nodes. The proposed approach is defined as a cross-layer optimization mechanism [6, 22], which disrupts the conventional information flow of the protocol layers for higher efficiency.

In this section we formulate the fundamental concepts related with the proposed transmission approach. Initially, we present an energy consumption model to be used when assessing the expected performance of the proposed redundancy schemes. After that, we state a packet error model for wireless communications. Finally, the sensing relevance concept is presented, supporting the development of this work.

3.1 Energy consumption in WSNs

We consider a wireless sensor network composed of P hop-by-hop wireless paths. Each path p, $p = 1, \ldots, P$, comprises $H_{(p)}$ intermediate nodes, where data packets flow from the source node ($h = 0$) to the sink of the network ($h = H_{(p)} + 1$). Each path p is supposed to be steady during the transmission of visual data packets.

Camera-enabled source nodes transmit visual data in small packets (reducing the error probability [23]) and typically many packets will be necessary to transmit a single image or video streams. The size of the transmitted data packets may vary according to the link layer technology and the application requirements, but we expect small data packets with the same size [23, 24]. For example, if we consider that most wireless sensor motes communicate through IEEE 802.15.4 wireless link-layer technology [25], the maximum frame size is 127 bytes including all packet's overhead. We define the maximum packet size as k, and x as the size in bits of all protocol headers in each packet. In fact, it is natural to expect transmission of full-size packets to achieve a minimal transmission overhead.

For simplicity, the communication scenario is assumed to be contention-free, considering packet transmission using protocols as TDMA or the CPF (Contention-Free Period) in IEEE 802.15.4, which is suitable for visual data transmission over wireless sensor networks [6, 9].

The actual energy consumption in each node depends on many factors, notably the sensor's hardware and the employed protocols. Nevertheless, we expect energy consumption as a direct function of the amount of information to be transmitted and the transmission and reception powers [9][25]. We define $D_{(p,h)}$ as the total amount of bits to be transmitted from hop h to the hop $(h + 1)$ in path p. If we assume the total amount of packets to be transmitted in path p as $W_{(p)}$, then $D_{(p,h)} = W_{(p)}.k$.

The consumed energy to send and receive bits depends on the transmission power of node h,

$Pwt_{(p,h)}$, and the power for bits reception, $Pwr_{(p,h)}$. We define $Et_{(p,h)}$ as the energy consumption in Joules for packet transmission from hop h to hop (h + 1) in path p and $Er_{(p,h)}$ as the energy consumption for packet reception in hop h in the same path. We also define $tx_{(p,h)}$ as the time for transmitting 1 bit from hop h. The total energy consumption in path p is defined as $E_{(p)}$, considering transmissions and receptions in all nodes, as presented in (1).

$$
\begin{aligned}
Et_{(p,h)} &= \begin{cases} D_{(p,h)}.Pwt_{(p,h)}.tx_{(p,h)} \\ 0 \qquad ,h=(H_{(p)}+1) \end{cases} \\
Er_{(p,h)} &= \begin{cases} D_{(p,h-1)}.Pwr_{(p,h)}.tx_{(p,h)} \\ 0 \qquad ,h=0 \end{cases} \\
E_{(p)} &= \sum_{h=0}^{H_{(p)}+1} \left(Et_{(p,h)} + Er_{(p,h)} \right)
\end{aligned}
\tag{1}
$$

The values for $Pwt_{(p,h)}$ can be easily computed in conventional sensor motes since most of them are powered by two AA batteries (3.3 V) and the energy consumed to transmit each bit is a known characteristic depending on the desired transmission range. The value for $tx_{(p,h)}$ is also known according to the packet transmission rate and the employed MAC protocol. For IEEE 802.15.4 sensors equipped with the CC24200 chipset, $tx_{(p,h)}$ = 0.000004 seconds (4μs) for the transmission of a single bit.

The radio of the sensor nodes will have to switch between at least the transmission and reception modes, considering that for each packet transmission or reception a mode switch operation is required, in average. In duty-cycle protocols, the radio may also be in the sleep mode, but we simplified considering only transmission and reception states, since node sleeping is hard to model. The resulting energy consumption model is presented in (2), assuming $Pws_{(p,h)}$ as the power for mode switching and $ts_{(p,h)}$ as the time for each switching operation.

$$
\begin{aligned}
Et_{(p,h)} &= \begin{cases} D_{(p,h)}.Pwt_{(p,h)}.tx_{(p,h)} + \\ +W_{(p)}.Pws_{(p,h)}.ts_{(p,h)} \\ 0 \qquad ,h=(H_{(p)}+1) \end{cases} \\
Er_{(p,h)} &= \begin{cases} D_{(p,h-1)}.Pwr_{(p,h)}.tx_{(p,h)} + \\ +W_{(p)}.Pws_{(p,h)}.ts_{(p,h)} \\ 0 \qquad ,h=0 \end{cases} \\
E_{(p)} &= \sum_{h=0}^{H_{(p)}+1} \left(Et_{(p,h)} + Er_{(p,h)} \right)
\end{aligned}
\tag{2}
$$

We model an average estimative of the number of mode switching, which depends on many unpredictable factors. Typically, $Pws_{(p,h)}$ is lower than 0.1ms.

3.2 Packet error rate

Wireless sensor networks are composed of resource-constrained nodes interconnected by ad hoc wireless links that are expected to be deployed in regions with diverse characteristics, where signal interference may be a constant. Due to the nature of packet transmission over wireless links, communications also face channel fading. Such characteristics incur in bit-errors that may happen in any part of the communications.

Bit-errors resulted from transmission over wireless links is an inner characteristic of radio communications that directly result in packet losses, potentially harming the quality of the monitoring application. Received corrupted packets are generally discarded and the deployed wireless sensor network may employ different recovery mechanisms according to the desired level of error resilience of the network and the considered application.

Errors in wireless links will happen as bursts, where the error rate depends on the size of the packets [23][24]. We consider the Gilbert/Elliot error model that defines a Markov chain with two states: “good” and “bad”. For simplicity, all the bits are corrected in the good state, while in the bad state the bits are corrupted [24]. Fig 2 presents the Gilbert/Elliot Markov chain, where g is the probability to stay in good state and b is the probability to stay in the bad state. This error model refers to the transmission of bits in a wireless link connecting two nodes, and the values for g and b depend on physical characteristics of the considered link.

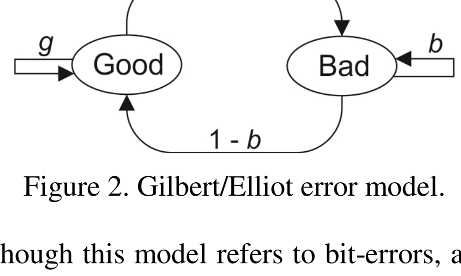

Figure 2. Gilbert/Elliot error model.

Although this model refers to bit-errors, an error in a single bit will corrupt a whole packet. In fact, we are concerned with the average Packet Error Rate (PER) for transmitted packets from hop h to hop $(h + 1)$ in path p, $Pn_{(p,h)}$, considering the transmission of n bits. For that, we compute the steady-state probability to good ($G_{(p,h)}$) and bad ($B_{(p,h)}$) states [24], as presented in (3).

$$G_{(p,,h)} = \frac{1-b_{(p,h)}}{2-\left(g_{(p,h)}+b_{(p,h)}\right)} \qquad B_{(p,h)} = \frac{1-g_{(p,h)}}{2-\left(g_{(p,h)}+b_{(p,h)}\right)} \tag{3}$$

Based on these probabilities, we can compute the average PER for a packet with n bits ($Pn_{(p,h)}$), as expressed in (4). Such formulation is obtained considering the two cases where no bit-error occurs during the transmission of a packet: the channel is in good state and remains there for the entire transmission or the channel is initially in bad state but the channel changes to good state before transmission and remains in good state for the transmission of all bits [24].

$$Pn_{(p,h)} = 1-\left(G_{(p,h)}.g_{(p,h)}^{(n)}+B_{(p,h)}\left(1-b_{(p,h)}\right)g_{(p,h)}^{(n-1)}\right) \tag{4}$$

The variable $Pn_{(p,h)}$ indicates the PER for a packet sizing n bits, ranging from 0 to 1. Assuming a generic data packet d, d=0,…, $d=W_{(p)}$, we define $Pd_{(p,h,d)}$ as the PER for a data packet d sizing k bits, in hop h of path p. In such way, the average probability of successful reception for a data packet d, $S_{(d)}$, can be estimated using the formulation in (5).

$$S_{(d)} = \prod_{i=0}^{H_{(p)}+1}\left(1-Pd_{(p,h,d)}\right) \tag{5}$$

3.3 Sensing relevance of source nodes

In many cases, source nodes may have different relevancies for the application, and such notion of relevance is more evident when source nodes follow a directional sensing model like in visual sensor networks. In a different way, neighbor nodes in scalar wireless sensor networks tend to collect the same information, but that is not necessarily true for neighbor camera-enabled source nodes. Visual sensors have a Field of View (FoV), indicating the area of the monitored field that can be viewed by them [10]. Fig 3 presents a graphical representation of the FoV in wireless visual sensor networks, where visual sensors may have different FoV depending on the characteristics of the embedded camera (as resolution, viewing angle, depth of view and zooming capability).

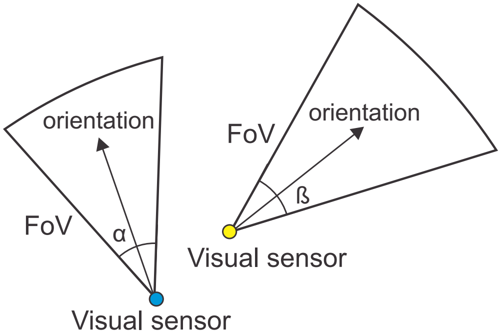

Figure 3. FoV in wireless visual sensor networks.

As visual sensors view differently, they may have different relevancies for the monitoring functions of the applications, whatever are the sensors' positions. For example, in wildlife observation, it is recommended high-quality monitoring of specific regions where it is more likely to find a desired group of an animal, although some of them may be found in other areas. In an intrusion detection system, some source nodes may be monitoring highly critical areas, demanding prioritized transmissions to the sink. For traffic control, nodes that collect top-view information of the traffic may be more relevant than cameras that can view cars' plates, or the opposite.

The differentiation of the monitoring relevancies of the camera-enabled source nodes may be exploited to optimize the network operation in different ways, achieving coverage-aware networks. In [11] we conducted a wide discussion of computing and assignment of the sensing relevancies of source nodes. In that work we defined that the sensing relevance of each source node is represented by a numeric value referred as the Sensing Relevance (SR) index. The SR is a 4-bit numeric value ranging from 0 to 15, representing a potential of the source nodes to provide relevant data for the monitoring functions of the application. In such way, the sensing relevance of each source depends on the application monitoring requirements and the network configuration after deployment.

The sensing relevance is computed according to the monitoring resources of the nodes (as camera resolution, processing resources and coding algorithms) and the group of relevance that source nodes belong to. As each source node is associated to only one group of relevance, a global perception of the network is required, which can be achieved employing some central unit at the sink side. That central unit associates each source node to a single group of relevance, as expressed in Table 1.

Table 1. Values for SR and Groups of Relevance.

SR	Associated Group of Relevance
0	**Irrelevant**. No visual information should be transmitted.
1-4	**Low relevance**. Applications may need only low-quality versions of the retrieved visual data.
5-10	**Medium relevance**. Applications can tolerate some monitoring quality loss.
11-14	**High relevance**. Assigned to source nodes that retrieve crucial visual information of the monitored field.
15	**Maximum relevance**. The retrieved visual information is highly critical.

The groups of relevance can be associated to source nodes in different ways, employing deterministic or automatic approaches. The retrieved visual information will be considered when defining the monitoring relevance, taking in account the application requirements. In such way, images or videos may be processed in order to find visual patterns or viewed area may be compared with predefined regions of interest. In a more direct way, a human operator may analyze the retrieved information, rating the source nodes according to his/her perception of the expected relevance of the visual data. We presented some useful approaches for such computing in [11], with different levels of complexity.

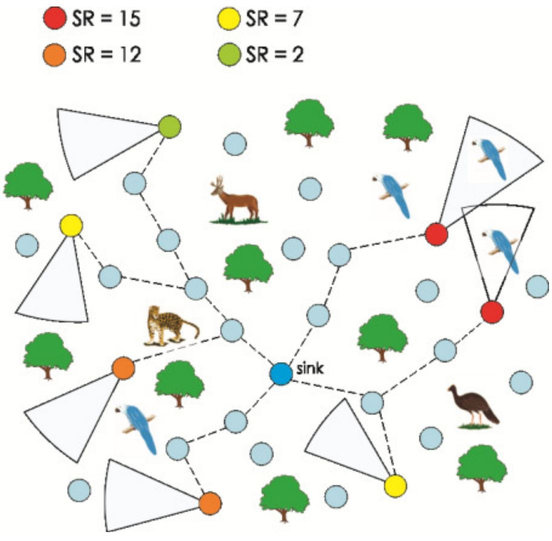

Figure 4. A wireless visual sensor network deployed for wildlife observation.

Fig 4 presents an example of a wireless visual sensor network deployed for wildlife observation. That network was deployed for monitoring of blue macaws, and thus visual sensors that can view regions where they are more likely to appear will have higher sensing relevance.

4 Proposed transmission mechanism

When visual data are transmitted over error-prone wireless links, packets may be corrupted. In general, corrupted packets are useless and the transmitted information will not reach the sink, potentially harming the monitoring quality. Besides mechanisms to reconstruct corrupted data using strategies as Forward Error Correction [16] applied over single packets, with different levels of complexity, corrupted packets may be recovered by retransmission or packet-level redundancy-based mechanisms.

Packet retransmission is a reasonable approach to recover lost data, but more energy is expected to be consumed when packets are retransmitted. In fact, the number of retransmitted packets will rise for higher packet error rates, incurring in additional energy consumption. Moreover, packet retransmission increases the average end-to-end delay of the communication, what may be too severe for real-time monitoring applications. In a different way, packet-level redundancy assures an acceptable level of reliability with very low impact to the overall communication delay.

We propose two different redundancy-based transmission approaches for wireless visual sensor networks, especially addressing monitoring applications with time constraints. For that, the sensing relevancies of source nodes are exploited to assure transmission with high reliability only for the most relevant sources for the applications. Packets from low-relevant source nodes are transmitted without redundancy. Doing so, energy is saved over the network with potential low impact to the overall monitoring quality, since corruptions of low-relevant packets will potentially incur in low quality losses.

In general words, the transmission delay may be originated from different aspects of the communication, where we can highlight the radio operation, the medium access mechanism, the congestion control, the error recovery and the transmission rate. Each transmission path is composed of one or more intermediate nodes, and all aforementioned aspects of wireless communications can be presented in a 1-hop wireless link. Depending on the adopted error recovery mechanism, the transmission delay may increase, potentially prejudicing real-time monitoring applications. We believe that packet-level redundancy will lower the communication delay by avoiding packet retransmission [21, 26].

4.1 Replication-based packet transmission

Packets can be replicated to increase the probability of successful reception of the original data at the destination. We define the number of replication of original data packets as R. For example, if R=1, every original data packet will be transmitted along with an additional copy, that will carry exactly the same payload. Each copy carries a clone of the original packet's payload and the sink must consider only one copy of the received packets.

The proposed mechanism is indeed very simple, but assures higher probability of successful reception. We define $Sr_{(d,R)}$ as the probability of successful reception of an original data packet d when the proposed replication-based transmission mechanism is employed, as presented in (6). Note that when R=0, packets are transmitted without replication.

$$Sr_{(d,R)} = \prod_{i=0}^{H_{(p)}+1} \left(1 - \prod_{0}^{R} Pd_{(p,h,d)} \right) \tag{6}$$

For higher R, we achieve higher values for $Sr_{(d,R)}$, However, defining $W_{(p,R)} = (R + 1).W_{(p)}$, we will expect that more energy will be consumed for higher values of R, as can be deducted from (2).

The sensing relevancies will be associated to a value of R for higher energy efficiency, as depicted in Table 2. Packets from low and medium relevance groups will be transmitted without redundancy, while the remaining packets will be transmitted considering some level of redundancy (R=1 for high-relevant packets and R=2 for maximum-relevant packets).

Table 2. Association between SR and R.

SR	R
1 - 10	0
11 - 14	1
15	2

4.2 Redundancy based on erasure coding

Transmission of redundancy packets based on replication is a reasonable option to assure some level of error-resilience, but it can considerably increase the energy consumption over the network. An alternative for replication is packet-level erasure coding, which provides additional packets to compensate packet losses [27]. In this scheme, M original packets are encoded in $M + N$ packets for higher resistance to corruption during transmission.

This mechanism assures that we can reconstruct the original packets if the sink receives at least any M packets out of the $M + N$ encoded data packets. If $M + N < M.R$, for $R > 1$, we achieve a better approach for redundancy-based packet transmission.

In visual sensor networks, the value for M may represent the number of packets for an entire image or a period of time of a video stream. There are some algorithms for erasure coding [16, 17, 27], where Reed-Solomon algorithm is most commonly employed, but their characteristics and performance are out of the scope of this work.

For simplicity, we define $F = M + N$. The probability of successful reception can be computed initially considering the case where F packets reach the sink, $F \geq M$, and then summing up all other probabilities. We formulate the success probability, $Sf_{(d,F)}$, as defined in (7).

$$Sf_{(d,F)} = \prod_{y=0}^{H_{(p)}+1} \left(\sum_{i=M}^{F} \binom{F}{i} . \prod_{j=0}^{i} \left(1 - Pd_{(p,h,d)}\right) . \prod_{j=i}^{F} Pd_{(p,h,d)} \right) \tag{7}$$

The probability of successful packet reception increases for higher values of F, but as higher F is achieved increasing the values of N, more energy will be expected to be consumed over the network, since $W_{(p,F)} = W_{(p)} + N$.

Table 3 associates the sensing relevancies of source nodes to values of N. We are not concerned with the algorithm required to implement the erasure code, but only with the level of redundancy.

Table 3. Association between SR and N.

SR	N
1 - 10	0
11 - 14	$M / 2$
15	$3 * M / 2$

5 Numerical results

The two proposed redundancy-based transmission approaches can bring valuable contributions for time-critical applications in wireless visual sensor networks. Although additional processing may be required in source nodes to implement the desired level of redundancy, energy may be saved over the network while an acceptable level or reliability is assured. For modern multi-tier wireless visual sensor networks [18, 28], camera-enabled source nodes are expected to satisfactorily handle such additional processing and as the transmission energy costs are in average much higher than the processing costs [25, 29], the overall solution is expected to present a good performance.

We estimated the average theoretical energy consumption and the probability of successful packet selection when the proposed redundancy-based transmission approaches were employed. For our verifications, we defined $(k - x) = 103$ bytes, $Pwt_{(p,h)} = 57.42$ mW (0dBm), $Pwr_{(p,h)} = 62$ mW and $tx_{(p,h)} = 4$ μs for all intermediate nodes. We also assumed $Pws_{(p,h)} = 62$ mW and $ts_{(p,h)} = 10$ μs. For the considered experiments, every source node transmits a very small 32 x 32 8-bit grayscale uncompressed image every second, resulting in 10 original data packets transmitted for every single image.

Initially we wanted to estimate the energy consumption for the replication-based packet transmission approach according to the value of SR, for 60 minutes of data transmission, as presented in Fig 5. In that figure, a single source node is transmitting an image snapshot every second through a single transmission path, and the energy consumption over the entire path was estimated.

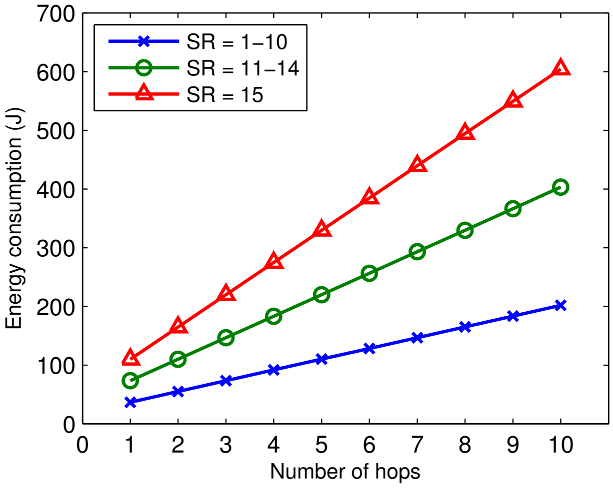

Figure 5. Energy consumption for the replication-based transmission mechanism.

When more copies of data packets are transmitted, more energy is expected to be consumed over the network, in theory. For higher relevance of the transmitting source node, more copies will be transmitted, according to the definitions in Table 2. Note that it does matter the PER of the considered links for that energy consumption estimation.

Although more energy is expected to be consumed for transmissions from more relevant source nodes, higher values of R also increase the probability of successful reception of transmitted packets, as presented in Fig 6 for a transmission path composed of 5 multihop intermediate nodes. In that experiment a PER from 0 to 20% is considered for all links between intermediate nodes, but different PER for each link could also be considered without compromising the achieved results.

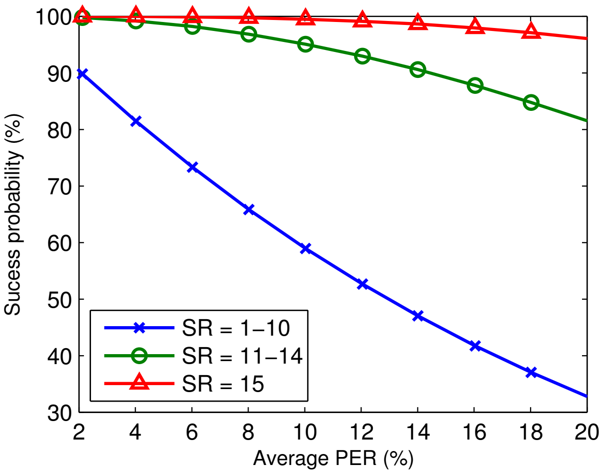

Figure 6. Successful packet reception according to SR, for replication-based transmission.

Fig 7 presents the theoretical energy consumption for the replication-based approach when compared with a traditional transmission mechanism where every single packet receives the same reliability level, for R=0, R=1 and R=2. We consider the transmission paths of the wireless visual sensor network described in Fig 4, which has 7 active camera-enabled sensors transmitting visual data to sink though single multihop paths. The exactly same sensing relevancies of the source nodes in Fig 4 are considered. Every source node will transmit a single image snapshot every second and the total energy consumption after 60 minutes of data transmission is presented.

When R=0 for all packets, fewer energy is consumed over the network, but the probability of successful reception is considerably reduced, as depicted in Fig 6. On the other hand, the proposed approach achieves optimized energy consumption while assures high average quality for higher relevant source nodes.

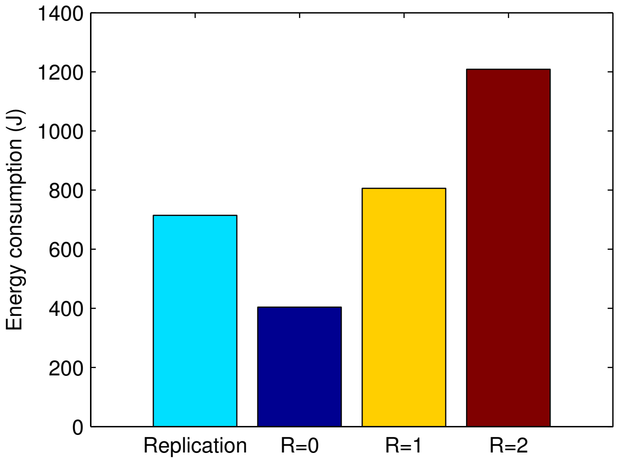

Figure 7. Replication-based transmission in a particular WVSN scenario.

The replication-based approach may save energy over the network while assures an acceptable level of reliability for higher relevant source nodes. However, packet-level redundancy based on erasure coding may bring more significant results. Fig 8 presents the energy consumption according to the value of SR.

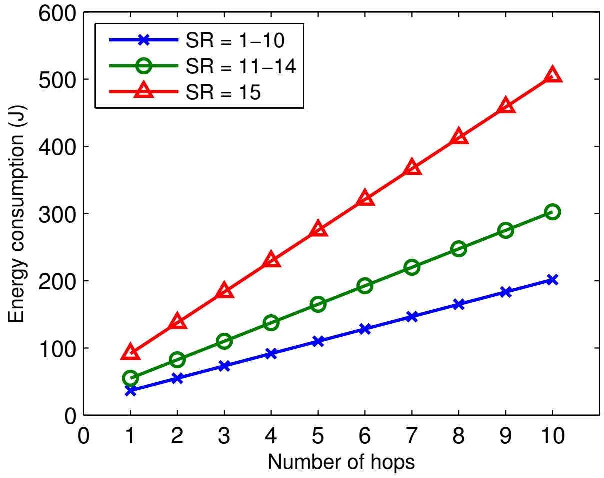

Figure 8. Energy consumption for packet-level redundancy based on erasure coding.

As expected, more relevant sources will consume more energy over the transmission path, according to the definitions in Table 3. Note, however, that less energy is consumed in average when compared with the replication-based approach, as can be seen analysing the results in Fig 5.

The probability of successful packet reception at the sink can also be estimated for packet-level erasure coding, as presented in Fig 9. We consider transmission over 5 intermediate nodes.

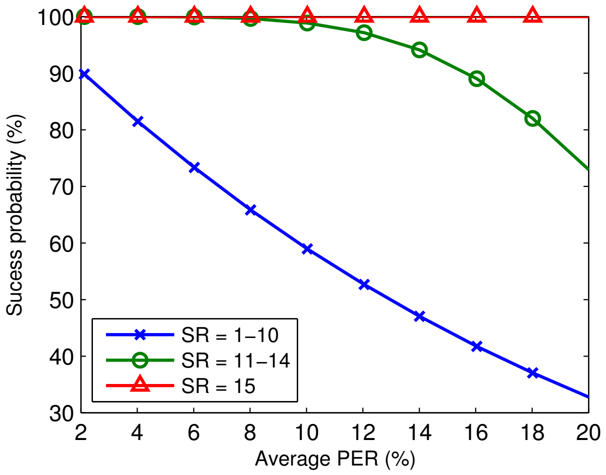

Figure 9. Successful packet reception according to SR, for packet-level erasure coding.

In the proposed approach based on packet-level erasure coding, packets originated from the most relevant sources (SR=15) will be transmitted with strong reliability guarantees, performing better than the transmission mechanism based on replication (with *R*=2). Nevertheless, the probability of successful reception for high-relevant sources (SR=11-14) was lower in Fig 9, when compared with Fig 6, but more energy was saved in average.

The expected energy consumption of the proposed approach based on packet-level erasure coding was assessed when compared with a traditional transmission mechanism where all source nodes have the same reliability level, for *N*=0, *N*=*M*/2 and *N*=3**M*/2. The communication scenario described in Fig 4 was considered for this experiment. The energy consumption results are presented in Fig 10.

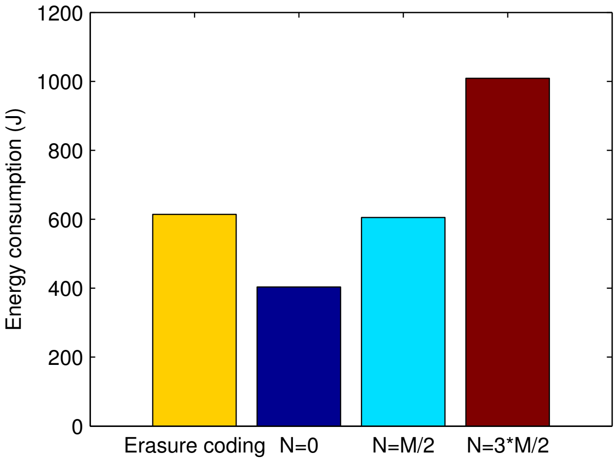

Figure 10. Redundancy based on erasure coding in a particular WVSN scenario.

In order to facilitate the analysis of the efficiency of the two proposed approaches, Fig 11 presents the energy consumption for both approaches over the communication scenario in Fig 4. Moreover, we also compared the proposed approaches with an unreliable transmission (without any error recovery mechanism) and an ARQ hop-by-hop retransmission mechanism where all corrupted packets are retransmitted if corrupted. For this last option, we considered two different PER for each link: 10% and 20%.

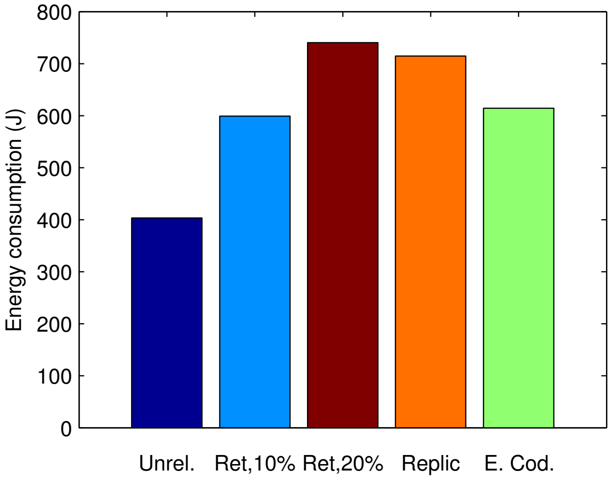

Figure 11. Results for different error recovery mechanisms.

The proposed approaches present equivalent performance when compared with hop-by-hop packet retransmission, but with lower complexity. When a corruption occurs, the packet is retransmitted by the previous hop, which may add undesired delay for the communication. Moreover, intermediate nodes must acknowledge each transmitted packet. In such way, the average end-to-end delay of the communication is expected to be lower when employing packet-level redundancy [21, 26].

Although retransmission will assure that all transmitted packets will reach the sink, transmissions from low-relevant sources may tolerate some quality loss since the overall transmission delay does not increase, especially for time-critical applications. We then believe that the proposed packet-level semi-reliable redundancy approaches can benefit wireless visual sensor networks.

As a final comment, packet-level redundancy can be implemented employing different algorithms, since respecting the relation between SR and *R* and *N-M* presented in Table 2 and Table 3, respectively. Whatever the case, we are mainly concerned in this work in how redundancy can be implemented according to the sensing relevancies of source nodes, potentially reducing energy consumption while assures high level of monitoring quality.

6 Conclusions

We have proposed two different semi-reliable transmission approaches based on packet-level redundancy for error-resilience in wireless visual sensor networks, where the sensing relevancies of source nodes are exploited to achieve energy-efficient reliability. The initial numerical verifications showed promising results that can benefit time-critical applications, assuring timeliness communications with low impact to the overall monitoring quality.

As future works, new associations between the expected level of reliability and the sensing relevance will be proposed. Moreover, new validations of the proposed approaches will be performed, considering discrete-event simulations and real-world experiments.

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