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Energy-Efficient Image Transmission in Sensor Networks

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Abstract: In this paper, we propose two image transmission schemes driven by energy efficiency considerations in order to be suitable for wireless sensor networks. The first one is an open-loop image transmission scheme while the second one is closed-loop. Both schemes are based on wavelet image transform and semi-reliable transmission to achieve energy conservation. Wavelet image transform provides data decomposition in multiple levels of resolution, so the image can be divided into packets with different priorities. Semi-reliable transmission enables priority-based packet discarding by intermediate nodes according to their battery's state-of-charge. Such an image transmission approach provides a graceful trade-off between the image quality played out and the sensor nodes' lifetime.

An analytical study in terms of dissipated energy is performed to compare our two schemes to a fully reliable image transmission scheme. Since image processing is computationally intensive and operates on a large data set, the cost of the wavelet image transform is considered in the energy consumption analysis. Results show up to 70% and 90% reductions in energy consumption with the open-loop and closed-loop schemes respectively compared to a non energy-aware one, with a guarantee for the image quality to be lower-bounded.

Keywords: Wireless sensor network; image communication; energy conservation.

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1 INTRODUCTION

Thanks to recent advances in microelectronics and wireless communications, it is predicted that wireless sensor networks (WSN) will become ubiquitous in our daily life and they have already been a hot research area for the past couple of years. A wide range of emerging WSN applications, like object detection, surveillance, recognition, localization, and tracking, require vision capabilities. Nowadays, such applications are possible since low-power sensors equipped with a vision component like “Cyclops” (Rahimi et al. (2005)) and “ALOHAIM” (Culurciello and Andreou (2006)) already exist. Although the hardware prerequisites are met, application-aware and energy-efficient algorithms for both the processing and communication of image have to be developed to make vision sensor applications feasible. Most of the work in literature is devoted to image processing (data extraction, compression and analysis) (Tang and Raghavendra (2004); Magli et al. (2003); Song et al. (2006); Wagner et al. (2003)) while the case of image transmission over WSN is still in an earlier stage of investigation.

In this paper, we propose two image transmission schemes driven by energy efficiency considerations suitable for WSN. They provide a graceful trade-off between the energy consumption to transmit the image data and the quality of the played-out image at receiver side. Both are based on discrete wavelet transform (DWT) and semi-reliable transmission to achieve energy conservation. DWT allows image decomposition into separable subbands for multi-resolution representation purposes. As a result, image data can be divided into priority levels that correspond to those of the resolution. In this way, full-reliable data transmission is only required for the lowest level of resolution. Others can be handled with a semi-reliable transmission policy in order to save energy. So, intermediate nodes between the source and the sink can decide to drop packets if they lack energy to forward, in accordance with packet priority. Our first scheme is qualified as open-loop since a node decides whether or not to drop packets of a given priority with respect to the state-of-charge of its battery independently of the other nodes. The second scheme is qualified as closed-loop since the discarding decision also depends on the available energy in the next intermediate nodes to the sink.

We have developed an energy consumption model in order to evaluate our proposals in terms of the amount of saved energy. Since image processing is computationally intensive and operates on a large data set, the cost of the wavelet image transform and the entropy coding is also considered in our model. Compared to a fully reliable image transmission scheme where no special care is given to the energy consumption, numerical results show an energy savings of about 70% and 90% in the open-loop and closed-loop schemes, respectively.

The remainder of this paper is organized as follows. In section 2, we describe the technical principles of the two

semi-reliable image transmission schemes. Their analytical models of energy consumption are presented in section 3 and obtained numerical results are given in section 4. Then, related works are overviewed in section 5. Finally, section 6 concludes and provides some future directions.

2 Image transmission principles

The proposed image transmission schemes are both based on wavelet image transform and semi-reliable transmission to achieve energy conservation. The first one is an open-loop scheme while the second one is closed-loop. This section describes their technical principles.

2.1 2D Discrete Wavelet Transform

Discrete wavelet transform (Mallat (1999)) is a process which decomposes a signal, *i.e.*, a series of digital samples, by passing them through two filters, a low-pass filter L and a high-pass filter H . The low-pass subband represents a down-sampled low-resolution version of the original signal. The high-pass subband represents residual information of the original signal, needed for the perfect reconstruction of the original set from the low-resolution version.

Since image is typically a two-dimensional signal, a 2-D equivalent of the DWT is performed (Antonini et al. (1992)). This is achieved by first applying the L and H filters to the lines of samples, row-by-row, then re-filtering the output to the columns by the same filters. As a result, the image is divided into 4 subbands, LL , LH , HL , and HH , as depicted in figure 1(a). The LL subband contains the low-pass information and the others contain high-pass information of horizontal, vertical and diagonal orientation. The LL subband provides a half-sized version of the input image which can be transformed again to have more levels of resolution. Figure 1(b) shows an image decomposed into three resolution levels.

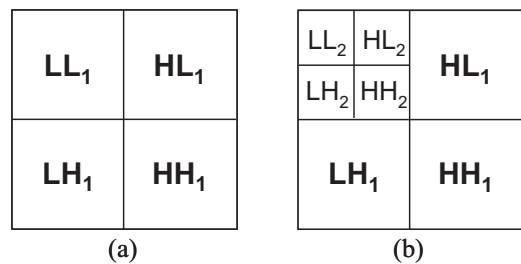


Figure 1: 2-D DWT applied once (a) or twice (b)

Generally speaking, an image is partitioned into p resolution levels by applying the 2-D DWT ($p - 1$) times. In this way, data packet prioritization can be performed. Packets carrying the image header and the lowest image resolution (represented by the LL_{p-1} subband) are the most important, assigned to priority level 0. They have to be reliably received by the sink in order to be able to rebuild a version of the captured image. Subsequent image resolution

levels have decreasing importance from the resolution 1 to $p-1$. So, packets carrying the ℓ^{th} resolution (corresponding to $HL_{p-\ell}$, $LH_{p-\ell}$, and $HH_{p-\ell}$ subbands) are assigned to priority level ℓ .

We adopted the Le Gall 5-tap/3-tap wavelet, which was designed explicitly for integer-to-integer transforms by Calderbank et al. (1998). This wavelet is amenable to energy efficient implementation because it consists of binary shifter and integer adder units rather than multiplier and divisor units. The coefficients of the low-pass filter and of the high-pass filter are rational, given by $f_L(z) = -\frac{1}{8} \cdot (z^2 + z^{-2}) + \frac{1}{4} \cdot (z + z^{-1}) + \frac{3}{4}$ and $f_H(z) = -\frac{1}{2} \cdot (z + z^{-1}) + 1$. Then, the output samples are rounded to the nearest integer so that the global amount of data remains the same.

Afterwards, each subband can be compressed to reduce the global amount of data to send. We adopted the Lempel-Ziv-Welch (LZW) technique, an entropy coding which is well known for lossless compression. LZW replaces symbols representation from equal-length to variable-length codes according to their probabilities of occurrence, the most common symbols being linked to the shortest codes. Note that lossy compression techniques could be also used. They achieve a high compression ratio although they are typically more complex and require more computations than the lossless ones. However, more investigations about them is out of the scope of this paper.

2.2 Semi-reliable image transmission

Once raw data of the captured image is encoded (applying 2D-DWT, then possibly LZW) and packetized into different priorities, the packets are ready to be sent. The source sensor transmits the packets starting by those with the highest priority, then continues with those of the next lower priority, and so on. Since it is not mandatory to receive all the priority levels at the sink, except the basic level 0, in order to play out a version of the image, packets of subsequent priorities are only forwarded by intermediate nodes if their battery state-of-charge is above a given threshold. This choice is motivated by the scarce energy in the context of sensor networks. Such image transmission thus is semi-reliable.

In fact, the hop-by-hop transmission is handled as reliable, i.e., the data packet is always acknowledged and retransmitted if lost, whereas the end-to-end transmission is handled as semi-reliable, i.e., the intermediate node decides to forward or discard a packet according to the battery's state-of-charge and the packet's priority. This is carried out using a threshold-based drop scheme where each of the p priorities is associated to an energy level $\alpha_0, \alpha_1, \dots, \alpha_\ell, \dots, \alpha_{p-1}$, subject to $\forall \ell \in \{0, 1, \dots, (p-1)\}, \alpha_\ell \in [0, 1[$ and $\alpha_\ell < \alpha_{\ell+1}$ (see figure 2). There remains the question: which values and which distribution for these parameters? In practice, this will depend on user application requirements, and it has to be answered prior to the implementation of the protocol. Of course, the choice of the α_ℓ distribution will influence the results. For instance,

if α_ℓ coefficients near 0 are applied, a node adopts a drop scheme which will increase the probability of forwarding packets. Such a policy will promote image quality instead of energy savings. On the contrary, α_ℓ coefficients near 1 will promote energy savings instead of a higher resolution of the final image. This choice will depend on the application in which WSN is involved.

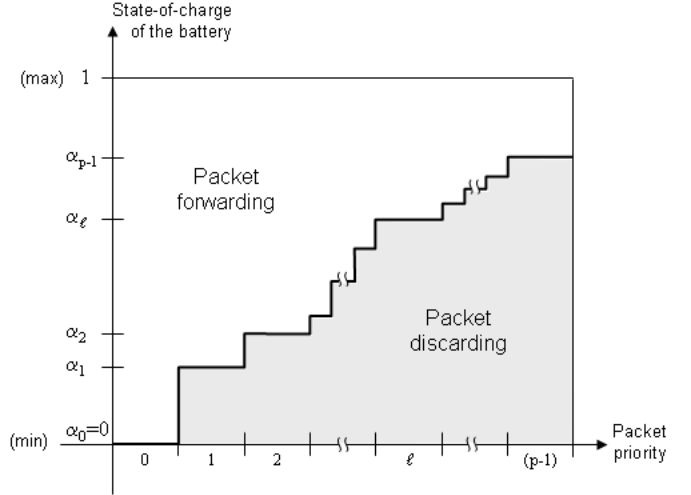


Figure 2: Priority-based packet forwarding at the intermediate nodes

From our approach, we developed two image transmission schemes, open-loop and closed-loop, that are described in the following.

2.2.1 Open-loop based scheme

In the first scheme, the decision performed by an intermediate node is done independently of the available energy in the other nodes. No feedback is used, such a scheme is qualified as an open-loop scheme (Lecuire et al. (2006)). We assume that the law of distribution of coefficients α_ℓ is given for each node. When a packet arrives at a node, two pieces of information are needed for the operation to proceed correctly: the priority level assigned to the packet and the total amount of priority levels. This information is provided in the source node by filling in the corresponding fields in the packet header. We have used a 4-byte-long packet header as depicted in figure 3(a). It contains the image identification number, the data offset in the whole image, the total amount of priority levels (p), and the packet priority level (ℓ). The intermediate node refers to the third and fourth fields of the packet header in addition to its energy thresholds so a decision can be made whether to discard or forward a received packet. The first and the second fields of the packet header are used by the destination node to store the data in sequence before decoding and playing out the image. The destination node substitutes zero for missing data due to lost packets. As said before, a data packet which is sent to an 1-hop neighbor is immediately acknowledged for transmission error control purposes, even if the receiver decides to discard it. The

format of the acknowledgment packet is shown in figure 3(b).

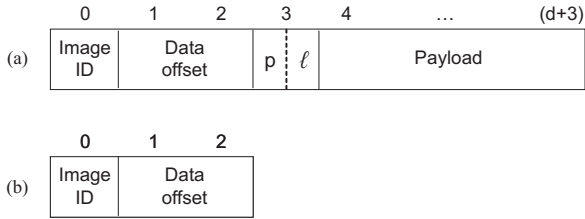


Figure 3: Packet format for data (a) and ack (b) used by the open-loop scheme

The open-loop scheme is very easy to implement. Furthermore, it can be used with any routing protocol. For example, simple routing protocols such as Flooding and Gossiping (Hedetniemi et al. (1988)) may be used. The open-loop scheme is generally suitable for an event-driven data delivery model. Some data-centric routing protocols can also be well adapted, such as Directed Diffusion (Intanagonwiwat et al. (2000)).

2.2.2 Closed-loop based scheme

In the second scheme, the decision performed by an intermediate node is based upon the knowledge of the available energy at the nodes which are located further on in the network path. In other words, the node is going to be able to anticipate the decisions of the next nodes: a node can discard packets even if it has sufficient energy to forward them, if it knows that a node further down the path has an insufficient amount of energy. Of course, the node does not initially know the state-of-charge of the other nodes. This knowledge is gradually obtained from received acknowledgment packets. Thus feedback is used to report the lowest energy level currently available in others nodes, and such a scheme is qualified as a closed-loop scheme. The delay induced by the feedback is proportional to the distance between the concerned nodes.

With the closed-loop scheme, the format of the data packets remains the same as that for the open-loop scheme. Only the acknowledgment changes; it includes a supplementary field to indicate the lowest energy level which is known at that time.

The closed-loop scheme is not much more complex than the open-loop one, but it supposes that the path from the source to the sink is maintained in a regular way over the duration of a complete image transmission. Thus, hierarchical routing protocols are generally adapted, such as LEACH (Heinzelman et al. (2000)), for example. Some query-driven protocols can also be quoted, such as Rumor routing (Braginsky and Estrin (2002)) or ACQUIRE (Sadagopan et al. (2003)).

3 Energy consumption analysis

In order to evaluate the benefits of the semi-reliable image transmission approach, we developed the energy consumption models for both open-loop and closed-loop schemes. These models are based on three elementary components: the radio transceiver model, the 2-D DWT processing model, and the entropy coding model. In order to make the formulas more readable, we made, without loss of generality, the following assumptions:

- All sensors have the same characteristics.
- The available energy in a node does not change significantly during the transmission of a complete image.
- The network path between the image source and the sink is established by n intermediate nodes numbered from 1 to n in this order (figure 4). This path is supposed to be steady during the transmission of an image. The 1-hop transmission is assumed to be lossless.
- The image is decomposed into p levels of resolution.

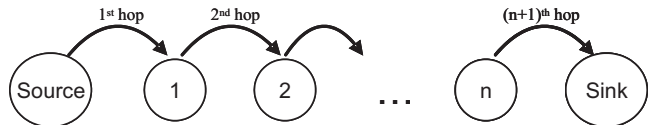


Figure 4: Network path representation

We wished to evaluate the average amount of dissipated energy to transmit an image throughout the network path from the source to the sink. We determined the number of hops performed by the packets, in relation to their priority level and the amount of available energy into the different intermediate nodes.

Let $R(\ell, n)$ be the probability that packets with priority ℓ are transmitted to the sink, so $(n + 1)$ hops are performed. It means that all the intermediate nodes have enough energy to forward level ℓ packets:

$$R(\ell, n) = (1 - \alpha_\ell)^n \quad (1)$$

with $0 \leq \ell \leq p - 1$. Let $B(\ell, i)$ be the probability that packets with priority ℓ are dropped before reaching the sink because of the i^{th} node. This corresponds to the probability that node i is the first on the path that does not have enough energy to forward them:

$$B(\ell, i) = \alpha_\ell \cdot (1 - \alpha_\ell)^{i-1} \quad (2)$$

with $1 \leq i \leq n$ and $1 \leq \ell \leq p - 1$. Equations 1 and 2 are used to define the energy image transmission model, for the open-loop scheme as well as the closed-loop one.

3.1 Energy model of open-loop scheme

Image data is generally transmitted in more than one packet. So, we introduce m_ℓ as the number of packets required to entirely transmit all data of priority level ℓ , and t_ℓ as their average size. Let $E(k)$ be the required energy to transmit and acknowledge a k -byte packet between two adjacent nodes (the energy cost per hop). Packets of priority 0 are necessarily transmitted to the sink, then the consumed energy is given by:

$$E_{T_0}(m_0, t_0) = (n+1) \cdot m_0 \cdot E(t_0) \quad (3)$$

For other priority levels, associated packets cross at least the first hop. Subsequent hops depend on the amount of energy in the following nodes. The number of hops crossed by packets of priority level ℓ is i if they are dropped at node i ; otherwise it is $(n+1)$. From equations 1 and 2, the mean consumed energy by the packets of priority level ℓ can be given by:

$$E_{T_\ell}(m_\ell, t_\ell) = \underbrace{\sum_{i=1}^n B(\ell, i) \cdot i \cdot m_\ell \cdot E(t_\ell)}_{\text{case where the node } i \text{ is blocking}} + \underbrace{R(\ell, n) \cdot (n+1) \cdot m_\ell \cdot E(t_\ell)}_{\text{case where all hops are performed}} \quad (4)$$

From 3 and 4, the total energy E_T required to transmit the entire image is:

$$E_T = (n+1) \cdot m_0 \cdot E(t_0) + \sum_{\ell=1}^{p-1} [m_\ell \cdot E(t_\ell) \cdot (R(\ell, n) \cdot (n+1) + \sum_{i=1}^n B(\ell, i) \cdot i)] \quad (5)$$

3.2 Energy model of closed-loop scheme

The closed-loop image transmission scheme benefits from 1-hop acknowledgment packets to report the lowest energy level currently available in other nodes.

Let us study this system in chronological order as defined by the transmitted packets from the source. First the source node transmits the m_0 packets in order to entirely send all the priority 0 data. These packets have to reach the sink, independently of the batteries' state-of-charge in the intermediate nodes. After the transmission of these packets, the source node knows (with the feedback) the lowest state-of-charge among the range of nodes from 1 to m_0 . Similarly, node 1 was informed of the lowest state-of-charge from nodes 2 to (m_0+1) , and so on.

If $m_0 \geq n$, then the source node knows the lowest state-of-charge among all the nodes in the network path. Thus it can determine for each priority from 1 to $p-1$, if the packets will reach the sink or not. If $m_0 < n$, then the source node only knows the lowest state-of-charge up to node m_0 . If the priority 1 packets can be conveyed up to node m_0 , then it transmits the first priority 1 packet, otherwise it does not send anything any more. Node 1, which

knows the batteries' state-of-charge up to node (m_0+1) , takes into account the state of this node (m_0+1) to determine whether or not it starts the following hop for this packet, and so on. Thus the number of hops which will be performed by the first priority 1 packet is equal to 0 if priority 1 is blocked by one of the nodes in the range from 1 to m_0 , equal to 1 if priority 1 is blocked by the node (m_0+1) , equal to 2 if priority 1 is blocked by the node (m_0+2) , ... equal to i if priority 1 is blocked by the node (m_0+i) ... equal to $(n-m_0)$ if priority 1 is blocked by node n , or equal to $n+1$ if priority 1 packets are not blocked by any nodes. After this packet is sent and acknowledged, the source node knows the state-of-charge up to the node (m_0+1) , node 1 knows the state-of-charge up to the node (m_0+2) , and so on. Now let us study the second priority 1 packet. In the same manner, the number of hops which are effected by this packet is equal to 0 if priority 1 is blocked by one of the nodes in the range from 1 to (m_0+1) , equal to 1 if priority 1 is blocked by the node (m_0+2) ... equal to i if priority 1 is blocked by the node (m_0+i+1) ... equal to $n-(m_0+1)$ if priority 1 is blocked by node n , or equal to $n+1$ if priority 1 packets are not blocked by any nodes.

On the one hand, if $m_0 + m_1 < n$, then the source node knows the state-of-charge up to the node $(m_0 + m_1)$ after the m_1 priority 1 packets have been processed. The batteries' state-of-charge on the remainder of the path, *i.e.*, the part between the nodes $(m_0 + m_1 + 1)$ and n , is still unknown by the source node. On the other hand, if $m_0 + m_1 \geq n$, then the state-of-charge on the entire path is known by the source after it processes $(n - m_0)$ priority 1 packets. To summarize, if $m_0 + m_1 \geq n$, and all the priority 1 packets have been processed, then the source node inevitably knows the state-of-charge along the entire path. If $m_0 + m_1 < n$, the same reasoning can be carried out with priority 2 packets, and so on.

The calculation of the total energy consumption for transmitting a whole image is generalized by three distinct cases. Assuming M_k^* denotes the sum $m_0 + m_1 + \dots + m_k$, the first case occurs when $M_0^* \geq n$, formulated by equation 6:

$$E'_T = (n+1) \cdot m_0 \cdot E(t_0) + \sum_{\ell=1}^{p-1} R(\ell, n) \cdot (n+1) \cdot m_\ell \cdot E(t_\ell) \quad (6)$$

The second case occurs when $\exists! \ell \in \{0, 1, \dots, (p-2)\}$ such that $M_\ell^* < n$ and $M_{\ell+1}^* \geq n$, formulated by equation 7:

$$E'_T = (n+1) m_0 \cdot E(t_0) + \sum_{k=1}^{p-1} R(k, n) (n+1) m_k \cdot E(t_k) + \sum_{k=1}^{\ell} \sum_{j=1}^{m_k} \sum_{i=0}^{n-M_k^*-j} B(k, M_k^* + j + i) (i+1) E(t_k) + \sum_{j=1}^{n-M_\ell^*} \sum_{i=0}^{n-M_\ell^*-j} [B(\ell+1, M_\ell^* + j + i) (i+1) E(t_{\ell+1})] \quad (7)$$

Otherwise, $M_{p-1}^* < n$, then, can be formulated by equation 8:

$$E'_T = (n+1)m_0.E(t_0) + \sum_{k=1}^{p-1} R(k, n)(n+1)m_k.E(t_k) + \sum_{k=1}^{p-1} \sum_{j=1}^{m_k} \sum_{i=0}^{n-M_k^*-j} B(k, M_k^* + j + i)(i+1)E(t_k) \quad (8)$$

3.3 Energy model of radio transceiver

The transmission of a message between two neighboring nodes requires a set of procedures, each of which consumes a certain amount of energy. Considering that all nodes have the same characteristics, a simple radio transceiver model considers E_{SW} , the consumed energy for mode switching, $E_{TX}(k, P_{out})$, for a k -byte message transmission with a power P_{out} , and $E_{RX}(k)$, for the message reception, as depicted in figure 5.

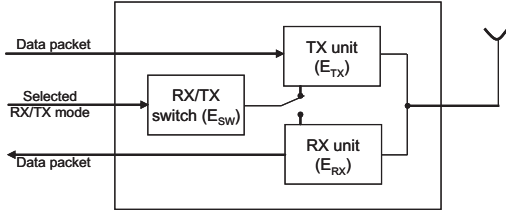


Figure 5: Energy model of radio transceiver

With this model, the energy consumed to transmit a k -byte from node i to node j is given by:

$$E_{i,j}(k) = 2.E_{SW} + E_{TX}(k, P_{out}) + E_{RX}(k) \quad (9)$$

Considering that the energy is defined in millijoules (mJ), then the energy component can be expressed as the product of voltage, current drawn, and time. So the formula 9 becomes:

$$E_{i,j}(k) = k.C_{TX}(P_{out}).V_B.T_{TX} + 2.C_{SW}.V_B.T_{SW} + k.C_{RX}.V_B.T_{RX} \quad (10)$$

where $C_{TX}(P_{out})$, C_{SW} and C_{RX} are the current drawn (in mA) by the radio respectively to transmit, to switch mode and to receive, T_{TX} , T_{SW} and T_{RX} are the corresponding operation time (in seconds), and V_B is the typical voltage provided by batteries. As we said in section 3.1, $E(k)$ is the energy consumed to send a k -byte packet and return the corresponding ACK. If L_{ACK} is the length of the ACK packet, then:

$$E(k) = E_{i,j}(k) + E_{j,i}(L_{ACK}) \quad (11)$$

3.4 Energy model of 2-D DWT processing

An energy consumption model is given by Lee and Dey (2002) for 2-D discrete wavelet transform based on the integer 5-tap/3-tap wavelet filter. They initially determined

the number of times that basic operations are performed in the wavelet image transform as the following: for each sample pixel, low-pass decomposition requires 8 shift and 8 add instructions, whereas high-pass decomposition requires 2 shift and 4 adds. Concerning memory accesses, each pixel is read and written twice. Assuming that the input image size is of $M \times N$ pixels and the 2-D DWT is iteratively applied T times, then the energy consumption for this process is approximately given by:

$$E_{DWT}(M, N, T) = MN.(10\varepsilon_{shift} + 12\varepsilon_{add} + 2\varepsilon_{rmem} + 2\varepsilon_{wmem}). \sum_{i=1}^T \frac{1}{4^{i-1}} \quad (12)$$

where ε_{shift} , ε_{add} , ε_{rmem} , and ε_{wmem} represent the energy consumption respectively for shift, add, read, and write basic 1-byte instructions.

3.5 Energy model of entropy coding

The energy spent in entropy coding is proportional to the amount of processed data. For k symbols to be coded, the energy consumption model is given by Wu and Abouzeid (2004) as:

$$E_{ENT}(k) = \varepsilon_{ent}.k \quad (13)$$

From this model, we note that the dissipated energy is the same when entropy coding is applied to the single-resolution image (no wavelet image transform is performed) or to its multi-resolution representation. In fact, there is a slight difference because the multi-resolution representation is not coded in just once, but per subband. However, this difference is negligible.

4 Numerical application and results

In this section, we apply the energy consumption models to evaluate and compare energy performance of image transmission schemes in various scenarios. A monochrome image of 128×128 pixels, presented in figure 6, is used as a test image. This one is 8 bits per pixel originally encoded. That means a data length of 16394 bytes, including the image header of 10 bytes. Numerical values adopted for the input parameters of energy models are described below. Then, we present the results of numerical application.



Figure 6: Original test image (128x128 pixels)

4.1 Input parameters

4.1.1 Hardware characteristics of sensor nodes

The adopted input parameters refer to the characteristics of MICA2 motes (Crossbow Technology Inc. (2007)). These devices are based on a low-power 7.37 MHz ATmega128L microcontroller, 4K bytes EEPROM, a Chipcon CC1000 radio transceiver with FSK modulated radio and an Atmel AT45DB041 serial Flash memory with 512K bytes for data storage. Typically MICA2 motes work with two AA batteries, able to provide 3 Volts. From technical documentations (Atmel Corporation (2006)) and some experients (Polastre et al. (2004); Shnayder et al. (2004); Mathur et al. (2006)), we adopted the parameters summarized in table 1.

Variables	Description	Value
V_B	Voltage provided by the power source of the i^{th} node	3V
$C_{TX}(0)$	Current consumed for the radio of the i^{th} node for sending 1 byte (with 0dBm)	20mA
C_{RX}	Current consumed for the radio of the i^{th} node for receiving 1 byte	15mA
C_{SW}	Current consumed for the radio of the i^{th} node for switching modes (rx/tx)	15mA
T_{TX}	Time spent for the radio of the i^{th} node for sending 1 byte	416E-6s
T_{RX}	Time spent for the radio of the i^{th} node for receiving 1 byte	416E-6s
T_{SW}	Time spent for the radio of the i^{th} node for switching modes (rx/tx)	250E-6s
ϵ_{shift}	Energy consumed for a microcontroller to execute a shift operation over 1 byte	3.3nJ
ϵ_{add}	Energy consumed for a microcontroller to execute an addition over 1 byte	3.3nJ
ϵ_{rmem}	Energy consumed to read 1 byte from the flash memory	0.26 μ J
ϵ_{wmem}	Energy consumed to write 1 byte in the flash memory	4.3 μ J

Table 1: Parameters for Mica2 motes

From table 1, we can compute the dissipated energy for transmission, reception and DWT processing per byte. The energy used to transmit and receive (with 0dBm) is $E_{TX} = 24.96\mu\text{J}$ per byte and $E_{RX} = 18.72\mu\text{J}$ per byte, respectively. Now, from equation 12, the energy consumed to perform the 2-D discrete wavelet transform once is $E_{DWT} = 9.19\mu\text{J}$ per byte. The energy consumption increases by 25% (11.49 μJ per byte) if image wavelet transform is performed twice.

4.1.2 Transmission characteristics of sensor nodes

MICA2 motes run with TinyOS/nesc from UC Berkeley (UC Berkeley (2007)). We used the basic format of Multihop message from TinyOS, that reserves 17 bytes for the header and synchronization. The maximum size of a TinyOS data packet is 255 bytes. As mentioned in section 2.2.1, image data packets have a header of 4 bytes. Since each image data packet will be encapsulated into a Multihop message, the maximum payload length for image data is 234 bytes. Similarly, ACK packet is 20 bytes (L_{ACK}) when the open-loop scheme is used, and 21 bytes for that of the closed-loop.

As we said in section 2.2, the choice of the α_ℓ distribution will depend of the application in which the WSN is used. In the following, we arbitrarily use an uniform distribution for coefficients α_ℓ (i.e., $\alpha_\ell = \frac{\ell}{p}, \forall \ell \in \{0, 1, \dots, (p-1)\}$) to study the impact of the DWT and data compression for both, open-loop and closed-loop, in the average energy consumption.

4.2 Impact of DWT

To get a reference, we evaluated the consumed energy by transmitting the whole image (16394 bytes) reliably without applying DWT or compression algorithms. In the following, we call that the "the original scenario". The amount of energy dissipated to transmit the original image is 846.39mJ per hop. Afterwards, we applied DWT once and then twice without compression. When DWT is applied once, we obtained a resolution 0 of 4106 bytes and a resolution 1 of 12288 bytes. Similarly, when DWT was applied twice, we obtained 1034, 3072 and 12288 bytes for resolutions 1, 2 and 3 respectively. From equations 5 and 12, we computed the average energy consumption to transmit the image for each scenario (open and closed-loop schemes with 1-level and 2-level DWT). Figures 7 and 8 show the average consumed energy per node as a function of the number of intermediate nodes for both schemes. We see that the consumed energy when DWT is applied is clearly lower compared to the case without DWT. Considering 30 intermediate nodes for instance, the average energy dissipated when the open-loop scheme is used is about 258.38mJ (1-level DWT) and 107.06mJ (2-level DWT), as shown in figure 7. That corresponds to a decrease of 69% and 87% of the consumed energy respectively, compared to the original scenario. For the closed-loop approach, the observed results are even better (see figure 8); the consumed average energy to send the image from the source to the sink is 218.26mJ (1-level DWT) and 61.56mJ (2-level DWT), decreasing the energy consumed by 74% and 92%.

These results demonstrate that our semi-reliable transmission approach allows for considerably reducing the average energy consumption thanks to DWT and the priority-based packet discarding policy. Moreover, in the closed-loop strategy, the knowledge of the available energy in nodes allows for saving more energy.

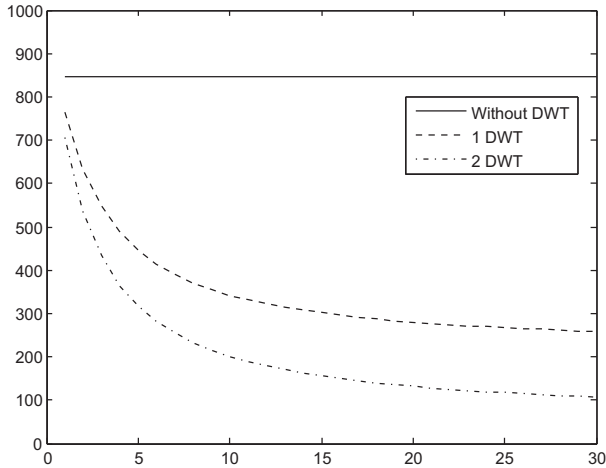


Figure 7: Energy consumption for transmitting uncompressed image with open-loop scheme

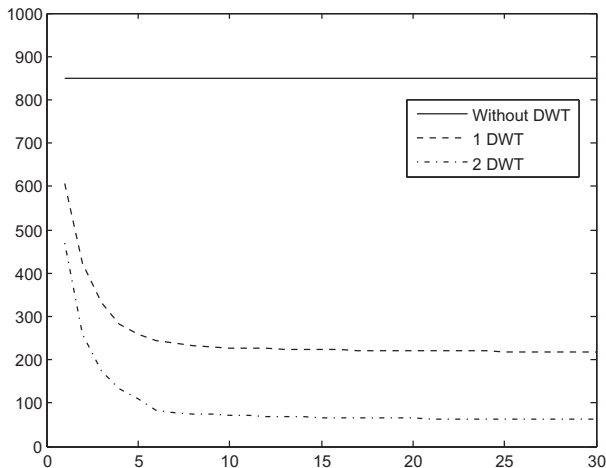


Figure 8: Energy consumption for transmitting uncompressed image with closed-loop scheme

With the semi-reliable approach, packets dropped during transmission necessarily lead to a decrease in the image quality. However, the image quality at the receiver side is lower-bounded by quality from the lower resolution. Figure 9 illustrates resulting images when only the lower resolution is received, in the case of 1-level DWT (a) and 2-level DWT (b). These represent the worst case scenario where nodes, applying a power saving policy, discard the remaining resolutions. In practice, the number of DWT iterations to be applied will depend on the image (initial resolution, details), and final user requirements.

4.3 Impact of compression

We will now consider the transmission of compressed images. Let us start with the compression of the original image without DWT processing. For that, we use a LZW lossless compression algorithm, assuming an entropy coding energy of $\varepsilon_{ent} = 160\text{nJ}/\text{byte}$. The initial 16394 bytes become 7890 bytes, and the energy dissipated, given by equa-

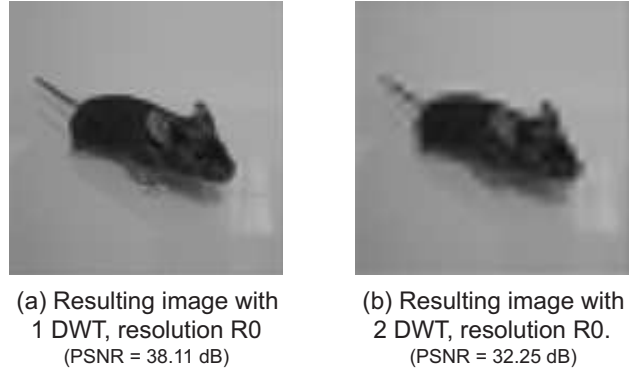


Figure 9: Image played out in the worse case scenario for 1-level DWT (a) and 2-level DWT (b)

tion 13, is 2.62mJ. The transmission of the compressed image implies a consumption of 407.27mJ and the energy dissipated decreases by 57% compared to the uncompressed transmission. Consequently, the energy consumed by the entropy coding is not relevant and highlights the benefit of compression to improve energy savings.

Now, let us study the average energy consumption for the open-loop approach. When DWT was applied once and each subband was independently compressed, we obtained a resolution 0 of 2425 bytes and a resolution 1 of 3356 bytes. Similarly, when DWT is applied twice, we obtained 789, 1181 and 3356 bytes for resolutions 0, 1 and 2, respectively. The consumed energy is about 139.15mJ (1-level DWT) and 58.35mJ (2-level DWT), corresponding to a decrease of 66% and 86% respectively (see figure 10). In the same way, the closed-loop strategy (figure 11) allows for reducing these rates by 74% (1-level DWT) and 92% (2-level DWT). In both open-loop and closed-loop approaches, we observe that the percentage differences between strategies (with and without compression) are similar. Hence, the behavior of each transmission strategy is not altered by the use of the compression algorithm.

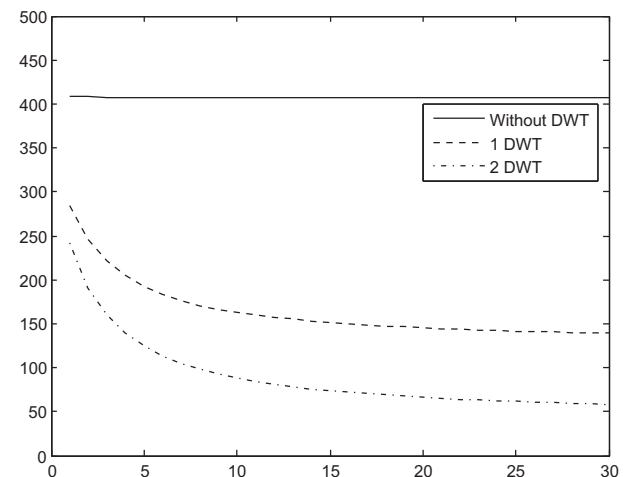


Figure 10: Energy consumption for transmitting compressed image with open-loop scheme

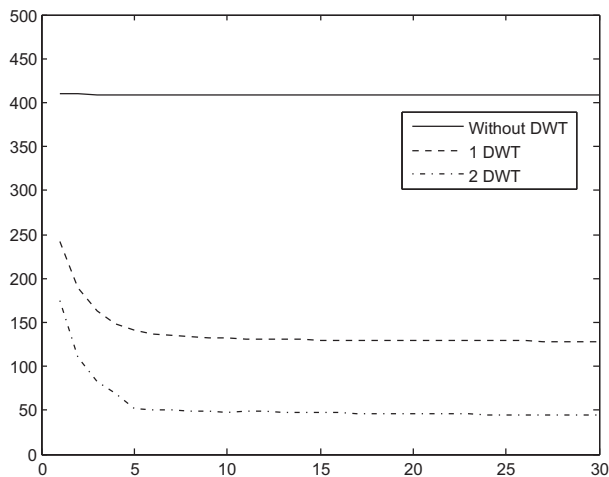


Figure 11: Energy consumption for transmitting compressed image with closed-loop scheme

4.4 Synthesis of the results

The results above show that the proposed image transmission schemes may involve significant energy savings; they are thus very effective for utilization in wireless sensor networks. We notice that the results are dependent on the device characteristics because hardware parameters are introduced into the energy consumption models. We adopted the parameters relating to Crossbow's Mica2 devices which are largely referenced in literature. The consumed energy could noticeably be different with other devices, especially those which have a different radio transceiver since it is the major consumer of energy in a sensor node. However, we notice that the results are very similar when the energy savings obtained with a semi-reliable scheme are shown in the form of percentage compared to the fully-reliable scheme. Presenting percentage tends to neutralize the influence of device characteristics on the simulation results.

5 Related works

Recently, WSN (Akyildiz et al. (2002)) has been an active area of research and a wide range of applications have been developed. Sensor nodes are mainly characterized by their scarce resources and limited energy. As a result, a considerable effort has been given to energy-efficient data transmission schemes ranging from the hop-by-hop medium access control level (Ye and Heidemann (2003); Langendoen and Halkes (2005)) to that of sensor-to-sink data delivery (Heinzelman et al. (2000); Tian and Georganas (2003); Kim et al. (2004); Liu et al. (2004)).

WSN applications for object detection, localization, and tracking can be strengthened by introducing visioning capability. Some small low-power camera sensors already exist, like "Cyclops" (Rahimi et al. (2005)) and "ALOHaim" (Culurciello and Andreou (2006)). The availability of different heterogeneous camera sensor nodes is exploited by Kulkarni et al. (2005) where a multi-tier camera sensor

network has been built.

Out of concern for energy efficiency, both image data processing and transmission must be considered. A lot of work has been done in data processing research area. Recent results on data compression and issues in their deployment in wireless sensor networks have been exposed by Tang and Raghavendra (2004) and Mishra et al. (2007). Chiasserini and Magli (2002); Gerla and Xu (2003); Magli et al. (2003) adopted JPEG with change/difference compression. This latter has the advantage of low processing power needs, however, it does not support error control.

In order to save energy, mainly in a densely deployed WSN, many proposals (Song et al. (2006); Wagner et al. (2003); Gerla and Xu (2003); Wu and Abouzeid (2004)) adopt a distributed coding approach where neighboring sensor nodes cooperate in performing image coding. However, a significant exchange of data, which would waste energy, may be necessary. Maniezzo et al. (2002) addressed the trade-off between computing and communication and show that there are an optimal number of nodes involved in a distributed coding process which minimizes the total energy consumption. Wu and Abouzeid (2004) adopted a multi-layer coding using JPEG2000 based on wavelet compression. Two methods of parallelizing the compression process are proposed and compared in terms of consumed energy and image quality. Yu et al. (2004) used DWT in order to obtain different layers with different quality. There is a focus on point-to-point image transmission with energy saving considerations. The optimal number of layers to be transmitted and the optimal strategies for each layer are determined thanks to an algorithm that minimizes the overall processing and transmission energy consumption given the expected end-to-end distortion constraint. This algorithm has the following inputs: the estimated channel condition, the characteristics of image content, and the set of available coding and transmission strategies.

Other approaches to save energy use buffering techniques (Magli et al. (2003); Wanghong and Nahrstedt (2003)). Wanghong and Nahrstedt (2003) proposes a scenario in which a source node buffers encoded frames and transmits them in bursts in order to better exploit idle intervals of the processor and network card.

6 Conclusion

This paper has presented two image transmission schemes driven by energy efficiency considerations. Both of them are based on wavelet image transform and semi-reliable transmission to achieve energy conservation. The results obtained by our analytical model of the energy consumption are promising since the energy savings are significant and communication protocols are of low complexity. In comparison to a fully-reliable image transmission, the energy savings is about 70% and 90% in open-loop and closed-loop schemes respectively, with a guarantee for the image quality to be lower-bounded. Consequently, we argue that our proposals are suitable for WSN. The choice

between the open-loop scheme and the closed-loop depends on the routing protocol adopted for the wireless sensor network. In fact, if the end-to-end network path is persistent over the transmission time of a complete image, then the closed-loop based approach is better, otherwise the open-loop approach is more suitable.

Our future work includes refining the analytical model by integrating packet loss and routing models which are characteristics of WSN. We also expect to carry out simulations in order to have more insight into our proposed schemes. Moreover, experimentations on an image sensor network testbed are planned.

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