Energy consumption analysis of a simple image transmission protocol in wireless sensor networks

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Abstract

This paper proposes and evaluates a simple energy-aware image transmission protocol suitable for wireless sensor networks. Energy savings is achieved through the use of a wavelet image transform and a semi-reliable transmission. On the one hand, wavelet image transform provides data decomposition in multiple levels of resolution, so the image can be divided into packets with different priorities. On the other hand, semi-reliable transmission enables priority-based packet discarding by intermediate nodes according to their battery's state-of-charge. Such approach provides a graceful trade-off between the image quality played out and the sensor nodes lifetime. An analytical performance evaluation in terms of mean dissipated energy is performed. Results show up to 90% reduction in the energy consumption achieved by our proposal compared to a non energy-aware transmission.

1. Introduction

Many potential applications of wireless sensor networks (WSN) like object detection, recognition, localization, and tracking, require vision capabilities. Nowadays, such applications are possible since sensors equipped with a visioning component [1] already exist. However, application-aware and energy-efficient algorithms for image compression and communication have to be developed. Many energy-efficient data transmission schemes exist in the literature ranging from the hop-by-hop medium access control level [2] to the sensor-to-sink data delivery level [3, 4]. Nevertheless, the case of image transmission over WSN is still in the earlier stage of investigation. In this paper, we present a simple energy-efficient image transmission scheme that benefits from data properties enabled by the discrete wavelet transform (DWT). This latter decomposes the image into separable subbands for multi-resolution representation purposes. As a result, image data can be divided into priority levels that correspond to the different resolutions. In this way, fully 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 : an intermediate node (located between the source and the sink) is able to perform a priority-based data packet discarding with respect to its battery's state-of-charge. In order to evaluate our image transmission scheme in terms of saved energy, we developed an energy consumption model. Since image processing is computationally intensive and operates on a large data set, the cost of the wavelet image transform is considered in our model. Numerical results show up to 90% reduction in the energy consumption achieved by our semi-reliable image transmission scheme compared to a fully reliable scheme where no special care is given to the energy consumption aspects.

The remainder of this paper is organized as follows. In section 2, our semi-reliable image transmission scheme is described. The analytical model of energy consumption is introduced in section 3. Related numerical results are presented in section 4. Finally, section 5 concludes and provides some future directions.

2. Simple image transmission overview

2.1. 2D Discrete Wavelet Transform

Discrete wavelet transform is a process which decomposes a signal (a series of digital samples), by passing it through two filters, a low-pass one L and a high-pass one 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.

In the case of an image which is a two-dimensional signal, a 2-D DWT is performed [5]. It consists in applying the L and H filters on the lines of the samples, afterwards, the same filters are applied on the output columns. As a result, the image is divided into 4 subbands, LL, LH, HL, and HH. 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 halfsized version of the input image. More levels of resolution can be obtained by recursively transform-

ing the LL subband. In our simple image transmission scheme, the source image sensor performs wavelet image transform on the raw data before transmitting them. We use the Le Gall 5-tap/3-tap wavelet with rational coefficients. This wavelet was designed explicitly for integer-to-integer transforms in [6].

2.2. Semi-reliable image transmission

In our semi-reliable image transmission scheme, we make use of a key property of the wavelet image transform which allows for data split into classes of packets with different priorities. The image captured by a sensor is partitioned into p priority levels (corresponding to the resolutions R_0, R_1, ... R_{p-1}, where R_i is the i^{th} resolution that corresponds to HL_{p-i}, LH_{p-i}, and HH_{p-i} subbands) by applying the 2-D DWT $(p-1)$ times. Afterwards, the source sensor starts transmiting highest priority packets that correspond to the lowest resolution level R_0. This latter has to be reliably received by the sink in order to be able to rebuild the captured image. Additional information have to be transmitted prior to the transmission of the R_0 data packets. These information include horizontal and vertical image size, image format (monochrome or color), number of bits per pixel and per plane, and the number of resolution levels.

Subsequent resolution levels are sent with a decreased priority from R_1 to R_{p-1}. Our scheme is semi-reliable in the sense that it is not necessary to reliably receive all the resolutions (except the basic one R_0) by the sink. This choice is motivated by the scarse energy in the context of sensor networks. Subsequent resolutions are only forwarded if node's battery level is above a given threshold.

An intermediate node located between the source sensor and the sink, is able to perform a priority-based data packet discarding with respect to its battery's state-of-charge. In a hop-by-hop perspective, a given resolution is reliably transmitted, *i.e.* corresponding data packets are acknowledged and retransmitted if lost. However, in an end-to-end perspective, an intermediate node is able to take the decision of transmitting or discarding a given resolution packets based on its battery state-of-charge. This is done independently of the available energy at the other nodes. This is why our scheme is qualified as an open-loop scheme in contrast to a closed-loop one which is also under evaluation and is beyond the scope of this paper.

In order to take a decision : drop or forward a given resolution packets, an intermediate node adopts a threshold-based drop scheme where each of the p resolutions is associated to an energy level α_i, $i = 0...p-1$, subject to $\sum_{i=0}^{p-1} \alpha_i = 1$ (see figure 1). Which values and which distribution for these parameters, is not a simple question and has to be answered prior to the protocol implementation. At this stage, it is worth mentioning that we do not assume that all the nodes adopt the same values.

We adopt a packet header of 4 bytes that contains the image number (ID), the total number of priority levels (p), the packet resolution priority level (ℓ) and the data offset

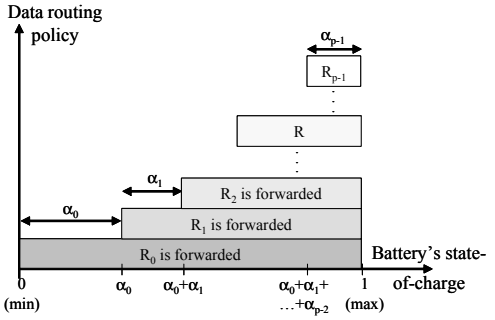

Figure 1. Priority-based packet forwarding at the intermediate nodes

in the whole image. A node refers to the information provided by the second and third fields of the packet header in addition to its threshold values to decide whether to discard or not a received packet.

3. Energy consumption analysis

In order to evaluate the benefit of our semi-reliable protocol, we developed an energy consumption model that takes into consideration the overall required energy to transmit one image split into p resolutions, a radio transceiver model and a 2-D DWT model. The assumptions adopted are as follows : (1) All sensors have the same characteristics. (2) Since we aim to compute the mean consumed energy, without loss of generality, we assume that a node energy does not change significantly during the image transmission. (3) There is n intermediate nodes numbered 1 to n in this order (figure 2) between the image source and the sink. These nodes are supposed to be stable during the transmission duration. (4) The image is decomposed into p levels of resolutions. (5) Finally, we assume that the 1-hop transmission is lossless.

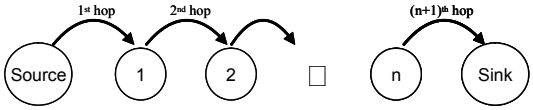

Figure 2. Network path representation

3.1. Energy image transmission model

In order to compute the overall consumed energy by all the nodes involved in the image transfer from the source to the sink, we need to determine the number of crossed nodes by a packet of a given resolution. This number depends on the packet's priority level and the amount of energy available at the different intermediate nodes.

Let $R(\ell, n)$ be the probability that packets with priority ℓ are transmitted until the sink, i.e., $(n+1)$ hops are accomplished. This means that all the intermediate nodes

have enough energy to forward level ℓ packets :

$$R(\ell, n) = (\alpha_\ell + \alpha_{\ell+1} + ... + \alpha_{p-1})^n \quad (1)$$

with $0 \leq \ell \leq p-1$. Let $B(\ell, i)$ be the probability that a packet with priority ℓ is only transmitted until the i^{th} node. This corresponds to the probability that node i drops ℓ level packets because it is the first on the path that does not have enough energy to forward them. That is :

$$\begin{aligned} B(\ell, i) &= (\alpha_0 + \alpha_1 + ... + \alpha_{\ell-1}) . \\ &\quad (\alpha_\ell + \alpha_{\ell+1} + ... + \alpha_{p-1})^{i-1} \end{aligned} \quad (2)$$

with $1 \leq i \leq n$ and $1 \leq \ell \leq p-1$. A priority level is likely to be transmitted within more than one packet. To take into consideration this case, we introduce m_ℓ the number of packets of size t_ℓ required to entirely transmit all packets of priority level ℓ. Let $E(k)$ be the required energy to transmit and acknowledge a packet of size k bytes between two adjacent nodes (the energy cost per hop). Packets of priority 0 are necessarily transmitted until the sink, then the corresponding consumed energy is given by :

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

For the other priority levels, associated packets cross at least the first hop. Subsequent hops depend on the amount of energy available at the different nodes. The number of hops crossed by packets of priority level ℓ is i if this priority level packets 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:

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

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

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

3.2. Energy radio transceiver model

The transmission of a message between two neighbor 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, $E_{TX}(k, P_{out})$, the one for a k-byte message transmission with a power P_{out}, and $E_{RX}(k)$, the one for the message reception, as depicted in figure 3.

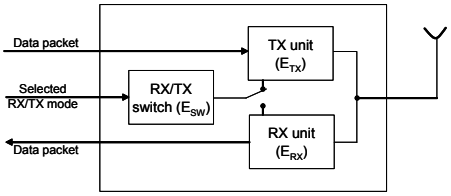

Figure 3. Radio transceiver model

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

$$E_{i,j}(k) = 2.E_{SW} + E_{TX}(k, P_{out}) + E_{RX}(k) \quad (6)$$

Considering that the energy is defined in milijoule (mJ), then energy component can be expressed as the product of voltage, current drawn and time. So the formula 6 becomes :

$$\begin{aligned} E_{i,j}(k) &= k.C_{TX}(P_{out}).V_B.T_{TX} + \\ &\quad 2.C_{SW}.V_B.T_{SW} + k.C_{RX}.V_B.T_{RX} \end{aligned} \quad (7)$$

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_{RW} are the corresponding operation time (in second), 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:

$$E(k) = E_{i,j}(k) + E_{j,i}(L_{ACK}) \quad (8)$$

3.3. Energy 2-D DWT model

An energy consumption model is given by Lee and Dey in [7] for 2-D discrete wavelet transform based on the integer 5-tap/3-tap wavelet filter. They initially determined the number of times basic operations are performed in the wavelet image transform as following : For each sample pixel, low-pass decomposition requires 8 shift and 8 add operations and high-pass decomposition requires 2 shifts 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 p times, then the energy consumption for this process is approximately given by :

$$\begin{aligned} E_{DWT}(M, N, p) &= (10\varepsilon_{shift} + 12\varepsilon_{add} + 2\varepsilon_{rmem} + \\ &\quad 2\varepsilon_{wmem}).MN.\sum_{i=1}^{p} \frac{1}{4^{i-1}} \end{aligned} \quad (9)$$

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

4. Numerical results

In this section, we evaluate the proposed protocol using parameters derived from the Mica2 Crossbow motes characteristics. From technical documentation [8] and some

experiences [9, 10, 11], we adopted the parameters summarized in table 1. We considered a transmission power of 0dBm and a power supply provided by two AA batteries (3 volts). The ATmega128L microcontroller used by Mica2 operates at 7.37 MHz (with a processing speed of 1 MIPS per MHz) and its current drawn is 8 mA in activity. Instructions to implement the DWT (add and shift) need a single clock cycle. The considered image in the scenario is an 8-*bpp* monochrome image of 128×128 pixels.

C_{SW}	15 mA	V_B	3 V
$C_{TX}(0)$	20 mA	ε_{shift}	0.0033 μJ
C_{RX}	15 mA	ε_{add}	0.0033 μJ
T_{SW}	$250E$-6 s	ε_{rmem}	0.26 μJ
T_{TX}	$416E$-6 s	ε_{wmem}	4.3 μJ
T_{RX}	$416E$-6 s	L_{ACK}	30 bytes

Table 1. Parameters for Mica2 motes

Three scenarios have been considered. First, we evaluated the consumed energy by transmitting reliably the whole image, that is 16390 bytes, without DWT. Afterwards, we considered the case of DWT applied once and then twice. When applied once, we obtain resolutions R_0 and R_1 of 4106 and 12288 bytes respectively. Similarly, when applied twice, we obtain 1036, 3072 and 12288 bytes for R_0, R_1 and R_2 respectively. From equations 5 and 9, we computed the average energy consumption to transmit the image for each scenario. Figure 4 shows the average consumed energy per node as a function of the number of intermediate nodes. We see that the consumed energy when applying DWT is clearly lower compared to the case without DWT thanks to the priority-based packet discarding policy. For instance, with one and two DWT and 50 intermediate nodes, the consumed energy is of about 247 and 87 mJ corresponding to a decrease of 72 and 90% respectively of the consumed energy when no DWT is applied (877 mJ). Obviously, discarded packets during transmission lead to the decrease of image quality. In the worst case, given by the lowest resolution of image, the PSNR is equal to 38.11 dB when DWT is applied once, and to 32.25 dB when DWT is applied twice.

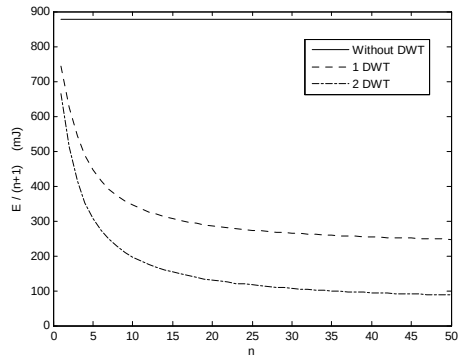

Figure 4. Average energy consumption

5. Conclusion and future work

This paper have presented a work-in-progress about an energy-aware image transmission protocol. This protocol is an open-loop scheme based on wavelet image transform and semi-reliable transmission to achieve energy conservation. The preliminay results obtained by our analytical model of the energy consumption are promising. Currently, we investigate the impact of compression algorithms on the energy savings. A closed-loop approach for image transmission is also studied.

References

[1] M. Rahimi, R. Baer, O. I. Iroezi, J. C. Garcia, J. Warrior, D. Estrin, and M. Srivastava, "Cyclops: In Situ Image Sensing and Interpretation in Wireless Sensor Networks", in *ACM 3rd International Conference on Embedded Networked Sensor Systems*, Nov. 2005, pp. 192–204.

[2] K. Langendoen and G. Halkes, *Embedded Systems Handbook*, chapter Energy-Efficient Medium Access Control, CRC Press, August 2005.

[3] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks", in *Hawaii International Conference on System Sciences HICSS*, volume 2, 2000.

[4] D. Tian and N. Georganas, "Energy Efficient Routing with Guaranteed Delivery in Wireless Sensor Networks", in *IEEE Wireless Communications and Networking Conference WCNC2003*, March 2003.

[5] M. Antonini, M. Barlaud, P. Mathieu, and I. Daubechies, "Image Coding Using Wavelet Transform", *IEEE Transactions on Image Processing*, vol. 1, no. 2, pp. 205–220, April 1992.

[6] A. R. Calderbank, I. Daubechies, W. Sweldens, and B.-L. Yeo, "Wavelet Transforms That Map Integers to Integers", *Applied and Computational Harmonic Analysis*, vol. 5, no. 3, pp. 332–369, 1998.

[7] D.-G. Lee and S. Dey, "Adaptive and Energy Efficient Wavelet Image Compression for Multimedia Data Services", in *IEEE International Conference on Communications ICC'02*, 2002.

[8] Atmel, "Atmega128L Microcontroller Datasheet", http://www.atmel.com.

[9] J. Polastre, J. Hill, and D. Culler, "Versatile Low Power Media Access for Wireless Sensor Networks", in *2nd ACM Conference on Embedded Network Sensor Systems*, Nov 2004, pp. 95–107.

[10] V. Shnayder, M. Hempstead, B. Chen, G. W. Allen, and M. Welsh, "Simulating the Power Consumption of LargeScale Sensor Network Applications", in *2nd ACM Conference on Embedded Network Sensor Systems*, Nov 2004, pp. 188–200.

[11] G. Mathur, P. Desnoyers, D. Ganesan, and P. Shenoy, "Ultra-Low Power Data Storage for Sensor Networks", in *5th International Conference on Information Processing in Sensor Networks*, 2006.