Trade-off between Reliability and Energy Cost for Content-Rich Data Transmission in Wireless Sensor Networks

Youssef Charfi, Naoki Wakamiya and Masayuki Murata
Graduate School of Information Science and Technology
Osaka University
Suita, Osaka 565-0871, Japan
{charfi, wakamiya, murata}@ist.osaka-u.ac.jp

Abstract— *In wireless sensor networks, the power of energy-constrained sensor nodes is largely drained by data communication tasks. Designing energy-efficient data communication mechanisms is, therefore, a major key to maximizing the life-time of wireless sensor networks. This challenge is magnified for visual sensor networks, where the collected and transmitted data is often very large and composed of multiple signals (Infrared signals, audio, video, ...) which have different and varying quality of service requirements (QoS). Motivated by this challenge, we investigate a forward error correction recovery mechanism for multi-path data transmission in wireless sensor networks. Based on this mechanism, we propose a fast algorithm for the trade-off between the end-to-end energy cost and reliability requirement of multi-path data transmission. Under the practical considerations of a fixed transmission power and a realistic modulation scheme, we derive the reliability and expected energy cost metrics of transmission paths. We then demonstrate the efficiency of our algorithm through simulations and discuss future work.*

I. Introduction

Recently, wireless sensor networks (WSN) have been attracting increasing importance [1]. This is due to the recent advances in wireless communications and micro-electronics, which made the development of tiny, low-cost and low-power wireless sensor nodes possible, and industrial-scale production of such sensor nodes conceivable in the near future. A lot of enthusiasm for this research area also stems from its many potential applications, such as habitat monitoring, remote video/audio surveillance, and health patient monitoring assistance, to name a few.

Data transmission over WSN is unreliable due to the unreliability of wireless links and the limited power sensor nodes can use for transmission, since they are battery-operated. This unreliability has, largely, been attacked using link-layer error control mechanisms, which include transmission power control, automatic repeat request (ARQ), and forward error correction (FEC). In the following, we briefly review these mechanisms and give representative examples of their use in WSN.

In power control mechanisms, higher transmission power reduces the packet error rate, but also increases energy consumption and interference with other nodes. In [2], Son et al. showed that the instability of link qualities in real-world WSN affects the efficiency of power control mechanisms. They then proposed a power control mechanism to reduce packet error rate while minimizing interference. For energy-efficient and reliable communication in multi-hop networks, Banerjee and Misra proposed a link cost that is a function of both the energy required for transmission and the link error rate [3]. Based on this link cost, they proposed a scheme for power control that estimates the optimal transmission power using the link distance and the channel characteristics [4]. A major drawback of all power control mechanisms is that they require a multi-power-level radio, which is a luxury that can not be afforded by regular sensor nodes.

ARQ mechanisms, which are used for error control in many conventional networks [5], are based on retransmitting lost packets. They, however, incur significant retransmission cost and additional delay, which make them unsuitable for energy and delay constrained networks. Although some attempts have been made to devise energy efficient ARQ mechanisms for WSN [6], [7], ARQ is largely unpopular for such networks, which have stringent energy constraints and, therefore, can not tolerate high retransmission costs that are often associated with ARQ [8].

On the other hand, FEC adds redundancy bits to an information packet that helps it recover from transmission errors using a corresponding decoder at the receiver [5]. FEC reduces the error rate for any given transmission power. It, however, requires additional processing power for the FEC codec [9]. Thus, energy-efficient FEC can be achieved by optimizing the trade-off between the additional processing power and the error rate reduction [10]. However, the gain from link-layer FEC can be limited when sufficiently low error rates can be tolerated at the receiver [11]. Recently, Howard et al. investigated in [12] error control coding schemes in WSN to determine the energy efficiency of these schemes. They mainly studied the decoder power consumption to determine at which conditions error control coding can be efficient and showed that analog decoders are the most energy-efficient.

A major issue of hop-by-hop link-layer error control is that sensor nodes may fail or switch to a sleeping state and, thus, break any link-layer recovery mechanism. Also, link-layer recovery mechanisms are typically implemented using a given number of retransmissions, or a fixed-rate FEC code and, thus, can not be adapted to the reliability requirement of the transmitted bitstream. Data generated by sensor nodes (especially visual sensors) can be very large and with varying importance [13], [14]. For such data, end-to-end recovery mechanisms, which can be scalable to the reliability requirement of the transmitted data, are better suited to protect from packet loss than link-layer recovery mechanisms. They also can be jointly implemented with them.

An approach that can be used for end-to-end error recovery is path diversification, where multiple paths are used for transmissions. This requires that multiple paths are available from the source to the destination. The process of searching for multiple paths is generally referred to as multi-path routing. Multi-path routing is largely investigated in the literature and a number of multi-path discovery techniques have been proposed [15]. For a review of multi-path routing techniques that are specifically designed for WSN, see [16]. In this paper, we assume that a number of disjoint paths from a source to a destination are available and address the issue of reliable and energy-efficient transmission using path diversification.

The first proposed schemes of path diversification for reliable transmission considered the transmission of a copy of each packet on all available paths [17], [18]. The major deficiency of such schemes is that the obtained reliability is limited by the number of available paths and, thus, cannot provide QoS guarantees. They also increase the amount of traffic in the network, regardless of the QoS requirements.

To overcome these deficiencies, Tsirigos et al. [19] proposed a routing scheme that adds redundancy (e.g., using FEC) to the information bitstream, fragments the obtained data into packets and transmits them over a number of paths. Given the failure probability of the paths, the number of packets transmitted over each path is determined in a way that maximizes the reliability. The authors showed that this scheme is suitable in the presence of frequent topology changes that characterize ad-hoc networks. The scheme, however, assumes that the efficiency, i.e., the ratio of the size of the information bitstream to that of the transmitted data, is fixed.

In [20], Dulman et al. proposed a mechanism to trade-off between the efficiency and the reliability. Assuming that the number of data packets N is equal to the number of available paths, their proposed mechanism estimates the number of successfully delivering paths E_N. It then adds redundancy to the packets to make sure that successfully transmitting E_N packets is enough to reconstruct the information bitstream. However, because of the assumption that the number of data packets should be equal to the number of available paths, this mechanism does not scale with the size of data bitstreams, due to the limited number of paths in typical networks.

Based on [19], Djukic and Valaee proposed in [21] two algorithms. One of them distributes the fragmented packets to the paths for maximum reliability, while the other maximizes the efficiency for a given bound on reliability. In [22], the authors extended their work to minimize the consumed energy for a given bound on reliability and efficiency. However, the energy consumed by the FEC encoder, which vary with the amount of added redundancy and, thus, with the efficiency, was not taken into consideration. Also, the energy consumed by each path was taken as the sum of the energy consumed by each node of the path. This is not always true since the actual energy consumption of a path depends on the packet error rates of the links that constitute the path; thus, the expected energy consumption is a more adequate measure of a path's energy cost (see Section II-B).

Path diversity has also been used in conjunction with multiple description coding of image and video data, which is based on encoding the information bitstream using a number of complementary and independent descriptions (packets) [23]. Different descriptions can be transmitted through different paths. Receiving only a certain number of these descriptions allows the reconstruction of the information bitstream. Multiple description coding was largely investigated for networks that do not have energy constraints and was shown to be beneficial for such networks [23], [24].

Following a different approach, Wu and Chen [25] considered for image transmission over WSN a scheme that combines quality scalable image coding, unequal error protection, and burst transmission of small packets. They show that this scheme provides graceful degradation of reconstructed image quality at the receiver in the presence of channel noise and saves energy consumed on control overhead and device switching from sleep to active states. However, no end-to-end energy cost investigation was carried out in their work.

In this work, we are interested in data communication over WSN. Especially, we investigate multi-path transmission of visual information (image, video) that have various quality of service requirements. We consider an end-to-end recovery mechanism that combines path diversity and FEC. This mechanism provides end-to-end reliability while incurs additional energy consumption due to both the redundancy introduced by FEC and the processing power it requires. To derive a trade-off between the reliability and the energy cost, we propose an algorithm that minimizes the end-to-end energy consumption of multi-path data transmission for a given reliability. By end-to-end energy consumption, we mean the energy spent for the transmission of an information bitstream by the source node for source encoding, error correction encoding, and transmission, by the intermediate nodes of the paths, and by the destination node.

In this paper, we consider the case when the destination is a sink, which has unlimited supply of energy and, therefore, its energy consumption does not need to be considered in the optimization problem. This simplifies the problem without loss of generality. In addition, we consider a fixed transmission power; thus, making our mechanism applicable to low-cost sensors that have fixed-power-level radios. Note, however, that the used mechanism is adaptable to sensor nodes with multi-power-level radios. Also, in contrast to previous work that choose arbitrary path transmission reliability and energy cost for simulations [19], [21], [22], we derive them using a realistic modulation scheme that relates a link bit error rate to the link distance.

The rest of the paper is organized as follows. In Section II, we present the end-to-end recovery mechanism and derive metrics for the transmission reliability and energy cost. In Section III, we discuss the trade-off between end-to-end energy consumption and reliability and propose an algorithm that finds the transmission scheme with the smallest energy consumption possible for a given bound on reliability. In Section IV, we present simulation results that show the performance of our algorithm. In Section V, we give our conclusions and directions of future work.

II. Problem statement and formulation

We consider the transmission of an information bitstream of size LM from a source node to a destination over K available paths in a wireless sensor network. Information bitstreams can be of any type. For example, in the case of image sensors, an image would be first compressed using a source encoder, whose output would constitute the information bitstream. In the case of video sensors, a compressed version of every group of pictures (GOP), would be considered as an information bitstream.

Every path k, $k = 1, ..., K$, is characterized by its probability of successful packet delivery $P^{(k)}$, expected energy consumption per transmitted packet $E_p^{(k)}$, and the maximal number of packets that can be transmitted over the path $a^{(k)}$. $a^{(k)}$ can be computed using the residual energy of the sensor nodes that constitute path k. We assume that $\sum_{k=1}^{K} a^{(k)} \geq L$.

As is the case with many multi-path transmission systems, the transmission paths should be disjoint. However, in realistic networks, paths may be braided (i.e., partially overlapped). Braided paths that have common nodes can be reduced to a single path. This can be done either by computing an end-to-end failure probability and energy cost for each set of braided paths [20] or by considering a single path in each set of braided paths and ignoring the others. Aside from the need that the paths be disjoint, no other constraint is placed on them. Although there exist routing techniques that find paths that satisfy energy efficiency or reliability constraints, this is handled by our end-to-end energy-cost/reliability trade-off algorithm.

To provide error recovery, the source node splits the information bitstream into L packets of size M each, appends to them $N-L$ redundancy packets of size M each using Reed-Solomon (RS) codes [5] (see Figure 1). Other erasure codes can also be used. The generated data bitstream, composed of the N packets, is then sent through the K paths. This

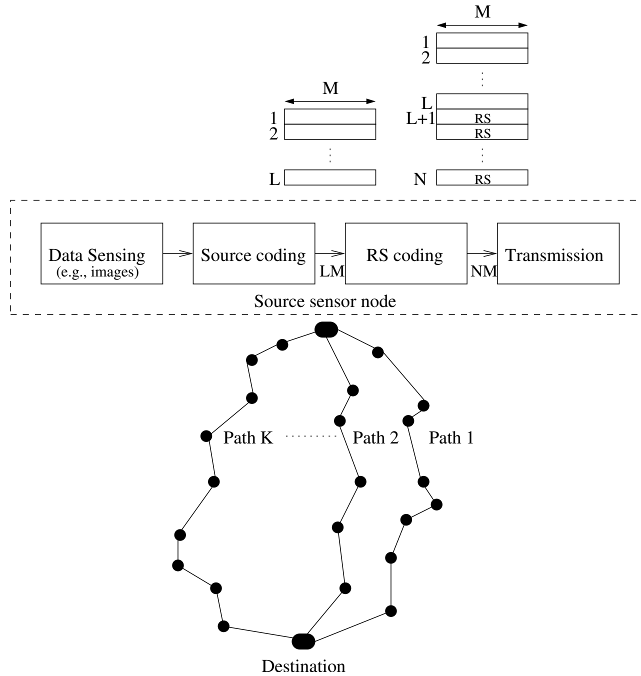

Fig. 1. Block diagram of the reliable multi-path transmission mechanism. A Reed-Solomon (RS) coder appends a number of redundancy packets to the L information packets. The resulting N data packets are then transmitted over the K paths to the destination.

recovery scheme ensures that the information bitstream can be successfully reconstructed at the destination if any L out of N sent packets are correctly received. Using this mechanism, it is not necessary to use link-layer recovery. In fact, we consider that no ARQ or FEC is used at the link layer. Error protection is provided solely by the end-to-end error recovery mechanism.

We also assume that the maximal value that N can take is $N_{max} \geq L$ and that $P^{(k)}$, $1 \leq k \leq K$, does not change during the transmission of N_{max} packets.

Let α be the required reliability, i.e., probability of successful reconstruction of the information bitstream at the destination. For a given α, find the transmission scheme, i.e., number of channel packets N and the path each packet should take, that results in a minimal use of energy. Before discussing this optimization problem, we first give the formulation we used for the energy cost and the reliability of the transmission.

A. Reliability

Regular sensor nodes use fixed transmission power for all transmissions. In a network of such nodes, the bit error rate is a function of the link distance. Let $\bar{p}_{j,j+1}$ and $D_{j,j+1}$ denote the bit error rate and the distance of a link between nodes j and $j+1$, respectively. Using the typical channel modulation scheme, Binary Phase Shift Keying BPSK, $\bar{p}_{j,j+1}$ can be written as

$$\bar{p}_{j,j+1} = 0.5\ erfc\ (\sqrt{\frac{P_t}{D^2_{j,j+1}\eta f}}), \quad (1)$$

where P_t denotes the transmission power per bit, and η and f denote the spectral noise density and the data transmission rate, respectively.

The packet error rate can be computed as

$$p_{j,j+1} = 1 - (1 - \bar{p}_{j,j+1})^M, \quad (2)$$

where M is the packet length. The probability of successful packet transmission over a path k, $k = 1, ..., K$, of n_k intermediate nodes is given by

$$P^{(k)} = \prod_{j=0}^{n_k} (1 - p^{(k)}_{j,j+1}), \quad (3)$$

where the indices 0 and $n_k + 1$ correspond to the source and the sink, respectively.

Consider now the event of sending N packets over K paths. Let X_N be a random variable whose value is the number of successfully transmitted packets out of N sent packets. Let k_i, $1 \leq k_i \leq K$, denote the index of the path over which a packet i, $1 \leq i \leq N$, is delivered. For a given transmission strategy $S = (N, k_1, ..., k_N)$, the expected number of successfully transmitted packets is given by

$$\mathbf{E}(X_N) = \sum_{i=1}^{N} P^{(k_i)}.$$

As noted earlier, the reliability of the successful reconstruction of the information bitstream, is equal to the probability that at least L packets are successfully transmitted out of N sent packets. Thus, for a given transmission strategy S, this reliability can be written as

$$R(S) = Prob[\mathbf{E}(X_N) \geq L].$$

$R(S)$ can be approximated by the Poisson cumulative distribution $\tilde{R}$ [26],

$$\tilde{R}(S) = \sum_{l=0}^{N-L} \frac{e^{-\gamma(S)}\gamma(S)^l}{l!},$$

where the mean parameter γ is given by

$$\gamma(S) = -\sum_{i=1}^{N} ln(P^{(k_i)}). \quad (4)$$

This approximation is accurate in the case of high probabilities of successful packet transmission [26], which is true in our application. And $\tilde{R}(S)$ is a close lower bound on reliability $R(S)$; thus, a lower bound on $\tilde{R}(S)$ is also a lower bound on $R(S)$. Note also that for a given N, $\tilde{R}(S)$ is monotonically decreasing with $\gamma(S)$. Therefore, for every lower bound on $\tilde{R}(S)$, there exists an upper bound on $\gamma(S)$. This remark will be used later in Section III to devise a fast algorithm for energy-reliability trade-off.

The validity of the analysis above is not limited to the BPSK bit error rate model. This model is used for the sake of simplicity. It can, however, be modified to take into account the multi-path effects of wireless channels. The log-normal shadowing path loss model can be used, for example [27].

B. Energy Cost

To evaluate the energy cost of the paths, we use the expected amount of the total energy consumption of the intermediate nodes of a path during packet transmission. It can be computed as

$$E^{(k)}_p = \sum_{l=0}^{n_k-2} [\prod_{j=0}^{l} (1 - p^{(k)}_{j,j+1}) p^{(k)}_{l+1,l+2} \sum_{j=0}^{l} e^{(k)}_{j+1}] + \prod_{j=0}^{n_k-1} (1 - p^{(k)}_{j,j+1}) \sum_{j=0}^{n_k-1} e^{(k)}_{j+1}, \quad (5)$$

where $e^{(k)}_j$ is the energy spent by the intermediate node j of path k, $1 \leq k \leq K$, in forwarding a packet of size M to the next node in the path. It can be written as

$$e^{(k)}_j = C_r M + P_t M, \quad (6)$$

where C_r is the energy consumption of receiver circuitry per received bit. As we have already indicated, P_t is the transmission power per transmitted bit. Note that since we have assumed that the transmission power per bit, P_t, is independent of the link distance, the intermediate nodes consume the same amount of energy for packet forwarding.

For a given transmission strategy $S = (N, k_1, ..., k_N)$, the total energy consumption due to the transmission of the data bitstream is given by

$$E(S) = E_s(N) + \sum_{i=1}^{N} E^{(k_i)}_p,$$

where $E_s(N)$ denotes the energy spent by the source node for RS coding, $E_c(N)$, and for the transmission of the data bitstream, $E_t(N)$, i.e.,

$$E_s(N) = E_c(N) + E_t(N).$$

We did not consider the amounts of energy spent for sensing, A/D conversion and source coding in computing $E_s(N)$ since their parameters are fixed and independent of the transmission strategy. Note that the size of the information bitstream is fixed at LM.

An (N,L) RS encoder over Galois field $GF(2^s)$ [5] requires the computation of $N-L$ redundancy symbols of length s. Its energy consumption per bit is modeled by [28]

$$E_b(N) = C_c \frac{N-L}{s},$$

where C_c is a constant that depends on the actual implementation. Thus, $E_c(N)$ can be computed as

$$E_c(N) = C_c \frac{ML(N-L)}{s}.$$

Given the transmission power per bit P_t, the transmission energy spent by the source node is given by

$$E_t(N) = NMP_t.$$

III. Energy-reliability trade-off

Let us first restate our optimization problem. We consider the transmission of L information packets over K paths, where each path k, $1 \leq k \leq K$ is characterized by $P^{(k)}$, $E_p^{(k)}$, and $a^{(k)}$. We set $N_{max} - L$ as the maximal number of redundancy packets to be generated using RS coding for the recovery mechanism. We recall that no more than $a^{(k)}$ packets can be transmitted over a path k, $1 \leq k \leq K$. For a given $N \geq L$, the set of possible transmission strategies, denoted by Ω_N, is given in the following definition.

Definition 1: Consider the transmission of N packets i, $i = 1, ..., N$, over K paths k, $k = 1, ..., K$. Let $\delta_i^{(k)}$ be a binary function that returns 1 if the index of the transmission path of packet i is k and 0 otherwise, i.e.,

$$\delta_i^{(k)} = \begin{cases} 1 & \text{for } k_i = k \\ 0 & \text{otherwise} \end{cases}.$$

The set Ω_N of transmission strategies is given by

$$\Omega_N = \{(N, k_1, ..., k_N) \mid k_i \in [1, K] \text{ for } i = 1, ..., N, \\ \text{and } \sum_{i=1}^{N} \delta_i^{(k)} \leq a^{(k)} \text{ for } k = 1, ..., K\}.$$

If we let N vary between L and the maximal number of packets N_{max}, the set of possible transmission strategies, denoted by Ω will be

$$\Omega = \bigcup_{N=L,...,Nmax} \Omega_N. \quad (7)$$

An optimal transmission strategy $S^* \in \Omega$ is the one that solves the constrained minimization problem

$$\min_{S \in \Omega} E(S) \quad \text{subject to} \quad R(S) \geq \alpha. \quad (8)$$

This constrained minimization problem can be simplified by converting it into the unconstrained problem

$$\min_{S \in \Omega} L(S, \lambda), \quad (9)$$

where

$$L(S, \lambda) = E(S) - \lambda R(S), \quad (10)$$

and $\lambda \geq 0$ is a Lagrange multiplier [29]. To meet the constraint on reliability, the bisection method can be applied requiring that the optimization be done for several values of λ.

Finding an optimal strategy by exhaustive search would diminish the gains we are seeking from minimizing the energy consumption. It can even be impractical due to the energy constraints of sensor nodes. In the following, we present our proposal to speed up the optimization.

Let us first assume that the number of data packets N is given. As we noted in Section II-A, maximizing $R(S)$ is equivalent to minimizing $\gamma(S)$ for a given N. Thus, the optimization problem (9) can be reduced to

$$\min_{S \in \Omega_N} L_N(S, \lambda), \quad (11)$$

where

$$L_N(S, \lambda) = \sum_{i=1}^{N} E_p^{(k_i)} + \lambda \gamma(S). \quad (12)$$

By replacing the form of $\gamma(S)$ in Equation (12) using Equation (4), we get

$$L_N(S, \lambda) = \sum_{i=1}^{N} E_p^{(k_i)} - \lambda \sum_{i=1}^{N} ln(P^{(k_i)}). \quad (13)$$

The Lagrangian cost $L_N(S, \lambda)$ can be written as

$$L_N(S, \lambda) = \sum_{i=1}^{N} L^{(i)}(k_i, \lambda),$$

where

$$L^{(i)}(k_i, \lambda) = E_p^{(k_i)} - \lambda ln(P^{(k_i)}). \quad (14)$$

It follows that the choice of the transmission path can be made independently for each packet. Minimizing $L_N(S, \lambda)$ is equivalent to minimizing $L^{(i)}(k_i, \lambda)$ for $i = 1, ..., N$. Based on this result, we propose a path allocation algorithm. A pseudo code of this algorithm, that we call *Alg-1*, is presented in Table I. The computational complexity of path allocation is linear with the number of packets N. Although the path allocation is preceded by a sorting operation that can have a complexity of $O(Kln(K))$, the number of paths K is generally limited to a single-digit number while the number of packets N can be very large.

Algorithm Alg-1 is designed to minimize $L_N(S, \lambda)$ for a given λ and N. Consider now the problem of the general optimization in Equation (9) where N can take different values, $L \leq N \leq N_{max}$. Using Equation (7) and algorithm

1. for $k := 1, ..., K$
   $L(k, \lambda) = E_p^{(k)} - \lambda ln(P^{(k)})$
2. *Arrange* $L(k, \lambda)$ *in increasing order, i.e.,*
   $L(j_1, \lambda) \leq L(j_2, \lambda) \leq \cdots \leq L(j_K, \lambda)$
   where $j_l \in [1, K]$ *for* $l = 1, ..., K$
3. $l := 1$; $t := 0$ // *initialization*
4. for $i := 1, ..., N$
   $k_i^* := j_l$ // *path allocation*
   $t := t + 1$
   if $t = a^{(j_l)}$ // *if the capacity of path* j_l *is reached*
      $l := l + 1$ // *go to the next best path*
      $t := 0$

TABLE I

PSEUDO CODE OF THE PATH ALLOCATION ALGORITHM ALG-1 FOR N PACKETS AND K PATHS. THE ALGORITHM COMPUTES AN OPTIMAL TRANSMISSION STRATEGY FOR A GIVEN LAGRANGE PARAMETER $\lambda \geq 0$.

Alg-1, we can speed up the Lagrangian minimization in Equation (9) by writing it as

$$\min_{N \in [L, N_{max}]} [E_s(N) + \min_{S \in \Omega_N} L_N(S, \lambda)].$$

Let us call this optimization *algorithm Alg-2*. Note that the nested minimization over Ω_N can be carried out using Alg-1.

IV. SIMULATION RESULTS

We consider a wireless sensor network, where sensor nodes use a fixed transmission power for all transmissions. This implies that the energy spent by a node for a packet transmission is the same, regardless of the link distance, while the error rate of a link increases with the link distance. We modeled the link error rate using Equation (1). In our simulations, the link distances are chosen randomly between 5 and 30 m, the transmission power per bit is P_t = 0.9 nJ/bit, the energy consumption of receiver circuitry per received bit is C_r = 0.5 nJ/bit, and the packet length is M = 48 bytes. Packet lengths are typically chosen to be short in WSN, which are low-bandwidth and prone to collisions.

Let P_m be the packet error rate that correspond to the link distance 30 m; we call it the *maximum link error rate*. To test the performance of our algorithms for different network reliability conditions, simulations are carried out for different values of P_m. For each value of P_m, the packet error rates for other link distances are calculated using Equations (1) and (2).

We have assumed that K disjoint paths from a source to a destination are available. The length of each path is chosen between 5 and 20 intermediate nodes where the length of each path is kept between 150 m and 250 m. For a path k, $k = 1, ..., K$, the probability of successful packet transmission over the path, $P^{(k)}$, and its related energy cost, $E_p^{(k)}$, are computed using Equations (3) and (5), respectively. Figure 2 shows the probability of successful packet transmission over

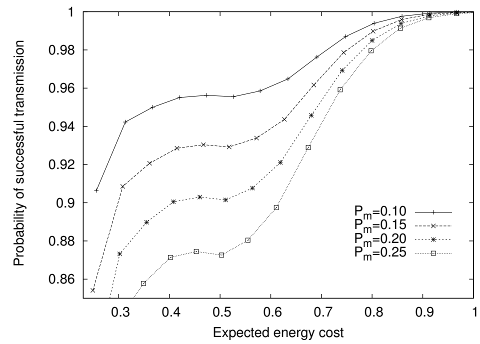

Fig. 2. Probability of successful packet transmission over a path versus its energy cost. Curves are displayed for various maximum link error rates P_m.

a path versus its energy cost. Results are given for various maximum link error rates P_m = 0.10, 0.15, 0.20 and 0.25. The curves in Figure 2 show the average obtained over 10000 simulations, i.e., 10000 packet transmissions. The figure shows that for a given maximum link error rate P_m, the probability of successful packet transmission over a path generally increases with its expected energy cost. It also shows that the expected energy cost of a path required to achieve a certain probability of successful packet transmission over the path increases with the maximum link error rate.

Consider now that a sensor node have sensed its environment (e.g., with a digital camera), encoded the collected data (e.g., an image) using a standard source coder, which generates L information packets of length M. The L packets should be received at a destination with a reliability greater than or equal to α. The information packets have to be encoder using an (N,L) RS encoder. The N data packets have then to be sent to a destination over K paths. We assume that each path can transmit at most a packets, i.e., $a^{(1)} = a^{(2)} = ... = a^{(K)} = a$.

The first simulations were carried out with $L = 10$, $K = 8$, $a = 4$ and $p_m = 0.20$. We consider the case when the number of data packets is fixed at $N = 14$ and compare the performance of the path allocation algorithm Alg-1 with that of exhaustive search. Figure 3 shows the energy consumption $E(S)$ versus reliability bound α for the transmission schemes generated by algorithm Alg-1 and exhaustive search. The figure shows that there is no apparent penalty in using the algorithm Alg-1 instead of the computationally expensive exhaustive search. It is, however, fair to note that the Lagrange multiplier optimization technique used in Alg-1 is not in general guaranteed to produce solutions for all constraint levels, i.e., lower bounds of reliability, which may add some loss of performance if these constraint levels are of interest to the application.

Let us now consider the case when N can take values between 10 and 20. Figure 4 shows the energy consumption for the transmission schemes generated by the energy-reliability trade-off algorithm Alg-2. It also displays curves for the transmission schemes generated by algorithm Alg-1 with fixed

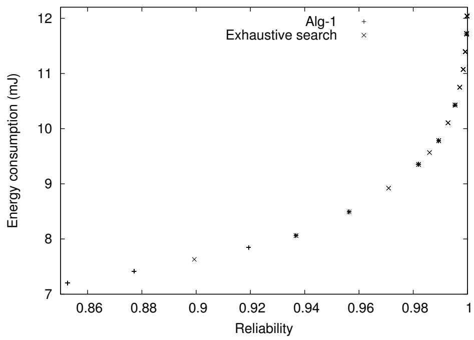

Fig. 3. Comparison between the performance of the path allocation algorithm Alg-1 with that of exhaustive search for a fixed number of data packets $N = 20$.

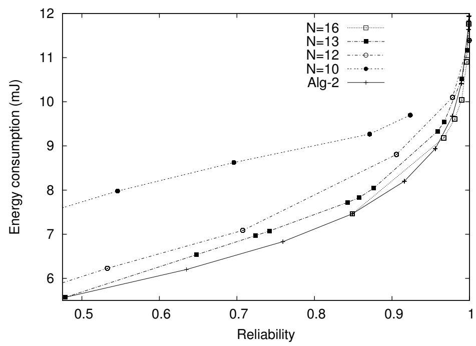

Fig. 4. Comparison between the performance of the energy-reliability trade-off algorithm Alg-2 (the bottom curve) with that of algorithm Alg-1, for which the number of data packets N is fixed. Curves of algorithm Alg-1 are displayed for various values of N.

number of data packets N. These curves are above the curve of algorithm Alg-2, which shows the efficiency of Alg-2 in selecting the transmission scheme with minimal energy consumption for different reliability requirements. Furthermore, comparison of Alg-2 with exhaustive search in Figure 5 reveals that Alg-2 does not exhibit any significant loss of performance compared to exhaustive search.

To show the performance of the energy-reliability trade-off algorithm Alg-2 for different network reliability conditions, we plot in Figure 6 the energy consumption versus the reliability bound for the transmission schemes generated by Alg-2 for various maximum link error rates P_m from 0.10 to 0.25. As expected, the figure shows that for each reliability bound, the energy consumption increases with the maximum link error rate.

Finally, we repeat the simulations whose results are shown in Figure 4, but this time for a different number of paths, $K = 4$, where each path can transmit up to $a = 8$ packets. The results are displayed in Figure 7. These results confirm those in Figure 4 and show the efficiency of the proposed energy-reliability trade-off algorithm Alg-2.

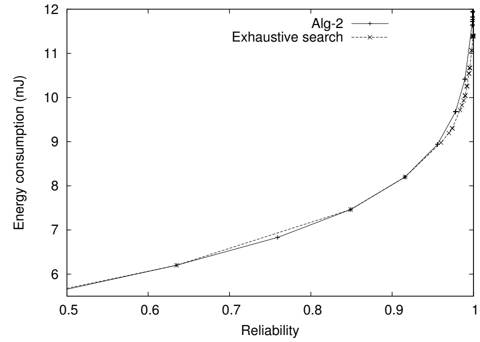

Fig. 5. Comparison between the performance of the energy-reliability trade-off algorithm Alg-2 with that of exhaustive search.

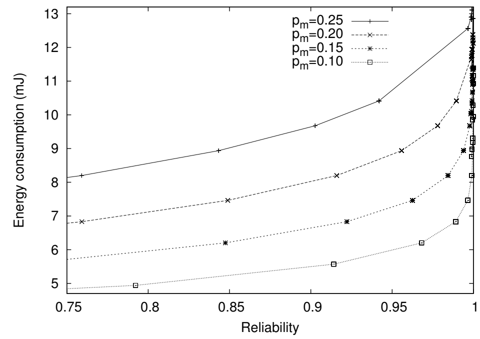

Fig. 6. Performance of the transmission schemes generated by the energy-reliability trade-off algorithm Alg-2 for various maximum link error rates.

V. Conclusions

This work is part of our research project on adaptive data communication in visual WSN. The major challenge is how to design mechanisms for the transmission of data, that may include image and video information with stringent and varying QoS requirements in WSN that are composed of unreliable low-power camera sensor nodes and have a very low bandwidth.

In this paper, we have studied the trade-off between the end-to-end energy cost and reliability of data transmission in WSN. We have used a flexible reliability mechanism that splits the information bitstream into small packets and adds a number of redundancy packets using a RS coder. We have proposed a fast algorithm that selects a multi-path transmission scheme with a minimal end-to-end energy consumption for a given lower bound on reliability. Through simulations, we demonstrated the efficiency of the proposed algorithm.

Although previous work has dealt with the energy efficiency and the reliability of data communication in WSN, this is, to our knowledge, the first work that tackles the issue of the trade-off between the end-to-end energy cost (i.e., that includes both transmission and processing energy costs) and the reliability of data communication in WSN.

In this study, we assumed that the length of the information

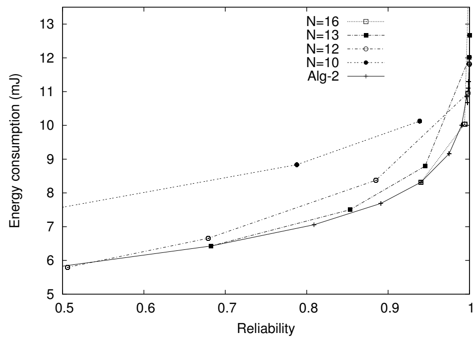

Fig. 7. Comparison between the performance of the energy-reliability trade-off algorithm Alg-2 (the bottom curve) with that of algorithm Alg-1, for which the number of data packets N is fixed. Curves of algorithm Alg-1 are displayed for various values of N. These results are generated with K=4 and a=8.

bitstream generated by the source coder of the source sensor node is fixed. However, using a quality-scalable source codec, where the source can be reconstructed with a certain quality even if only a prefix of the information bitstream reaches the destination, can be beneficial [25]. The reason is that the size of the information bitstream to be transmitted can be optimally determined, in a way that minimizes the total energy consumption for a given lower bound on reliability. This is part of our future work.

To improve the FEC-based reliability mechanism, we are, currently, considering a feedback scheme that lets the source node stop packet transmission when the base station acknowledges that the information bitstream is correctly reconstructed; thus, limiting the transmission of unnecessary data.

ACKNOWLEDGMENT

This work was partly supported by a Grant-in-Aid for JSPS Fellows relating to JSPS Postdoctoral Fellowships for Foreign Researchers of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Communications Magazine*, vol. 40, pp. 102–114, August 2002.

[2] Do. Son, B. Krishnamachari, and J. Heidemann, "Experimental study of the effects of transmission power control and blacklisting in wireless sensor networks," in *IEEE SECON 2004*, October 2004.

[3] S. Banerjee and A. Misra, "Energy efficient reliable communication for multi-hop wireless networks," *ACM/Kluwer Journal of Wireless Networks (WINET)*, Accepted for publication, 2005.

[4] S. Banerjee and A. Misra, "Power adaptation based optimization for energy efficient reliable wireless paths," in *IFIP Networking 2004 Conference (IFIP-TC6)*, May 2004.

[5] S. B. Wicker, *Error control systems for digital communication and storage*, Prentice Hall, 1995.

[6] A. Dunkels, T. Voigt, H. Ritter, and J. Alonso, "Distributed TCP caching for wireless sensor network," in *MedHocNet 2004*, June 2004.

[7] M. Tacca, P. Monti, and A. Fumagali, "Cooperative and noncooperative ARQ protocols for microwave recharged sensor nodes," in *Proceeedings of the Second European Workshop on Wireless Sensor Networks 2005*, 2005, pp. 45–56.

[8] O. B. Akan and M. C. Vuran, "Reliable transmission and congestion control," in *Wireless Sensor Networks, A Systems Perspective*, N. Bulusu and S. Jha, Eds. Springer-Verlag, 2005.

[9] R. Min and al., "Low-power wireless sensor networks," in *Proceedings of the 14. International conference on VLSI Design*, January 2001, pp. 205–201.

[10] R. Min and A. Chandrakasan, "A framework for energy-scalable communication in high-density wireless networks," in *Proceedings of the 2002 international symposium on Low power electronics and design*, August 2002, pp. 36–41.

[11] E. Shih and al., "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks," in *ACM Mobilecom'01*, July 2001, pp. 272–286.

[12] S. L. Howard, C. Schlegel, and K. Iniewski, "Error control coding in low-power wireless sensor networks: When is ECC energy-efficient?," *EURASIP Journal on Wireless Communications and Networking*, pp. 1–14, Accepted for publication, April 2006.

[13] W. Chi Feng, J. Walpole, W. Chang Feng, and C. Pu, "Moving towards massively scalable video-based sensor networks," in *Proceedings of the Workshop on New Visions for Large-Scale Networks: Research and Applications*, March 2001.

[14] W. Chi Feng, E. Kaiser, W. Chang Feng, and M. Le Baillif, "Panoptes: scalable low-power video sensor networking technologies," *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMCCAP)*, vol. 1, pp. 151–167, May 2005.

[15] P. Papadimitratos, Z. J. Haas, and E. G. Sirer, "Path selection in mobile ad hoc networks," in *Proceedings of Mobihoc, ACM*, 2002.

[16] J. N. Al-Karaki. and A. E. Kamal, "Routing techniques in wireless wensor networks: a survey," *IEEE Wireless Communications*, vol. 11, pp. 6–28, December 2004.

[17] N. F. Maxemchuk, "Dispersity routing," in *IEEE ICC '75*, June 1975, pp. 10–13.

[18] Ayanoglu Ender, I. Chih-Lin, Gitlin R. D., and Mazo J. E., "Diversity coding for transparent self-healing and fault-tolerant communication networks," *IEEE Transactions on Communications*, vol. 41, pp. 1677–1686, 1993.

[19] Aristotelis Tsirigos and Zygmunt J. Haas, "Multipath routing in the presence of frequent topological changes," *IEEE Communications Magazine*, vol. 39, pp. 132–138, November 2001.

[20] Dulman S., Nieberg T., J. Wu, and Havinga P., "Trade-off between traffic overhead and reliability in multipath routing for wireless sensor networks," in *WCNC Conference, New Orleans, Louisiana, USA*, 2003.

[21] P. Djukic and S. Valaee, "Reliable packet transmission in multipath routed wireless networks," *IEEE Trans. on Mobile Computing*, 2005.

[22] P. Djukic and S. Valaee, "Minimum energy reliable multipath ad hoc networks," in *22nd Biennial Symposium in Communications*, June 2004.

[23] V. K Goyal, "Multiple description coding: Compression meets the network," *IEEE Signal Processing Magazine*, pp. 74–93, September 2001.

[24] G. Barrenechea and 2003 al. Proc 13th Int. Packet Video Workshop, April, "Multiple description source coding and diversity routing: a joint source channel coding approach to real-time services over dense networks," in *Proceedings of the 13th Int. Packet Video Workshop*, April 2003.

[25] M. Wu and C. W. Chen, "Multiple bitstream image transmission over wireless sensor networks," in *Sensor Network Operations*, S. Phoha, T. F. La Porta, and C. Griffin, Eds. Wiley-IEEE Press, 2006.

[26] R. J. Serfling, "Some elementrary results on poisson approximation in a sequence of bernoulli trials," *SIAM Review*, vol. 20, pp. 567–579, July 1978.

[27] T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall, 2001.

[28] E. Erkip, Y. Wang, D. Goodman, Y. Wu, and X. Lu, "Energy efficient coding and transmission," in *Spring 2001 Vehicular Technology Conference*, Rhodes, Greece, May 2001.

[29] H. Everett, "Generalized Lagrange multiplier method for solving problems of optimum allocation of resources," *Operations Research*, vol. 11, pp. 399–417, 1963.