COST: Coding over Spatial-Temporal Diversity for Low-Duty-Cycle WSNs

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Abstract: In low-duty-cycle wireless sensor networks, designers have to cope with unreliable links and limited communication capacity. In this work, we propose COST, a coding scheme that leverages spatial-temporal diversity to achieve higher energy efficiency and lower delay of packet transmissions. We particularly address long sleeping intervals in low-duty-cycle networks by exploiting multi-path diversity. Specifically, we propose to employ an erasure-coding scheme to improve reliability. With respect to energy efficiency and delivery timeliness, we formulate the problem in optimal allocation of coded blocks over multiple paths, which is then proved to be NP-hard. We further propose a near-optimal algorithm to solve the allocation problem. Through extensive simulations, we evaluate the impact of network parameters and demonstrate the effectiveness of our proposal.

Key words: low-duty-cycle; multi-path; coding; wireless sensor network

I. INTRODUCTION

Many typical applications in Wireless Sensor Networks (WSNs), such as military surveillance [1], environment monitoring [2], and infrastructure protection [3], need to work for a very long time, usually for at least several months, even several years. Unfortunately, the energy supply for WSNs, which is constrained by 2 AA batteries is very limited compared with the working time. Low-duty-cycle WSNs, working at a very low frequency, usually of 1% or less, and sleeping most of the time, is a promising candidate for energy intensive WSNs. It has to be noted that, during the sleep period, a low-duty-cycle node in WSNs would shut-off the wireless transceiver, but could still sense the environment, and make computations if needed. Such a scheme could save energy significantly due to the constraints on the working window, and the sensor nodes in the network will not to be "bothered" by

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undesirable messages.

However, the energy efficiency in the low-duty-cycle WSNs will be challenged by two important issues. One is time delay. As in low-duty-cycle WSNs, a sender node has to wait until its potential receiver coming back to active state, which will lead to larger delay than ever. Also, packets arriving after the deadline would be useless and energy consuming. Another is the lossy link. Unreliable links would lead to retransmissions and extra energy consumption. Moreover, it is another main cause of packet delivery delay.

Due to the long sleep latency and unreliable links, timely feedback may be impossible and costly. A simple approach is to use pure replication-based strategy, which sends multiple copies of a message simultaneously over multiple paths to achieve relatively less delivery delay. However, simple replication would result in too much communication overhead which is energy consuming. Another approach is to use erasure coding packages over multiple paths, which could improve reliability and reduce delay as well. Compared with sending a full copy of the message over each path, only a fraction of coded blocks are sent over multiple paths. However, in low-duty-cycle WSNs, the packet transmission in active slot is constrained. The node has to experience relatively longer sleep latency waiting for the receiver to recover the active state again in the next cycle. Such strategies will probably result in longer delivery delay.

In summary, the spatial-temporal diversity in low-duty-cycle WSNs is underestimated due to the lack of efficient and effective use of it. The root reason is that, if there is no coding and allocation scheme, the lossy links will reduce the throughputs achieved via diversity. On the other hand, redundancies should be reduced and effectively organized in data paths with the time delay constraints. We believe that the coding scheme with appropriate allocation over multiple paths will exploit the spatial and temporal diversity to an optimal or near-optimal extent.

The contributions of this work are summarized as follows: 1) We propose COST, a coding scheme for spatial and temporal diversity, which effectively utilizes the potential opportunities in low-duty-cycle WSNs; 2)To the best of our knowledge, we are the first to formulate the problem in allocating erasure coded blocks over multiple paths in WSNs. The proposed scheme, which transmits erasure coded blocks over multiple paths, eliminates the need of sending acknowledgements while preserving relatively high reliability. It is also helpful to deal with asymmetric links in WSN deployments. 3) A near-optimal algorithm is proposed to solve it. Our simulations demonstrate that our proposal indeed achieves close-to-optimal performance and significantly reduces complexity.

The rest of the paper is organized as follows: In Section II, we present the spatial-temporal diversity in low-duty-cycle WSNs; in Section III, we present the problem formulation; we propose our solution in Section IV, followed by its evaluation in Section V; in Section VI, we conclude this paper and discuss about the future work.

II. UNDERSTANDING THE SPATIAL-TEMPORAL DIVERSITY IN LOW-DUTY-CYCLE WSN

In this section, we examine the spatial-temporal diversity in low-duty-cycle WSNs. As we know, different path has different delivery delay. However, in low-duty-cycle WSNs, using the path with minimum delivery delay will depend on the working schedule and the packet arriving time.

Obviously, the spatial-temporal diversity exists among different packets and different nodes in the network. Such spatial-temporal diversity is unique in low-duty-cycle WSNs. The route delay of each working flow is different. And the packet arriving

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time will also affect the delivery delay. As each packet must endure a period of waiting time before the receiver wakes up, selecting a fast forwarder would be important. Moreover, in multi-hop WSN, with an increasing number of nodes and decreased duty-cycle, temporal diversity will widely exist among different nodes.

In the following simulations, we are to show the spatial-temporal diversity on different paths. We investigate the usage of the minimum delay path, and the network duty-cycle. Consider a simple topology as shown in Figure 1. We assume the delivery ratio of every path is 1. In every experiment, all nodes randomly choose their active slots. 1000 packets were generated randomly in one experiment. For every packet, source node uses the path with minimum total delivery delay to deliver it. Total delivery delay is derived by adding sleep latency to path delivery delay. We record the path used by every packet, and calculate the used ratio of the path with minimum delivery delay. The duty cycles varies from 0.01 to 1. For every duty cycle the ratio was obtained by averaging 100 experiments.

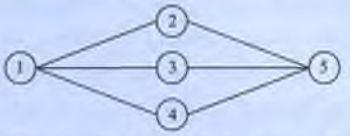

Fig.1 A simple topology to illustrate spatial-temporal diversity

The simulation result is shown in Figure 2. According to Figure 2, it can be seen that the used ratio of the path with minimum delivery delay is no more than 80% when duty cycle is less than 40%. Furthermore, nearly 30% paths should be explored even in a randomly deployed network. The simulation result indicates that spatial-temporal diversity could be exploited to decrease average delivery delay, which also indicates that exploring the diversity in low-duty-cycle WSNs is meaningful.

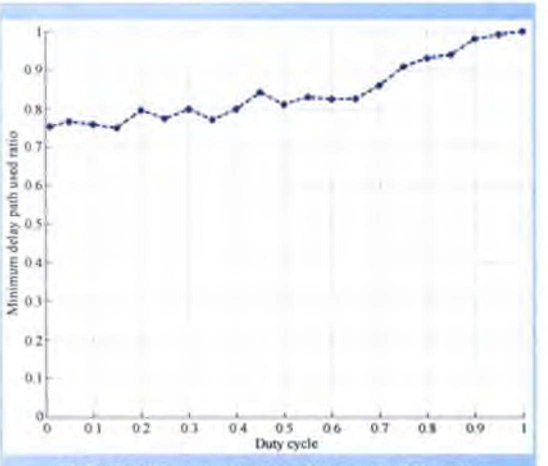

Fig.2 Simulation result of spatial-temporal diversity

III. PROBLEM FORMULATION

3.1 Network model

Without loss of generality, we suppose the working period of all the nodes in a network is T time slots. All the nodes randomly choose one of the T time slots as its active slot. The ith node's active slot is represented as $activeslot_i$. We denote the length of one slot as τ and the packet of size is denoted as l accordingly.

Besides the property of low-duty-cycle in our network model, a transmission from sender to receiver is success with a probability of q due to the unreliable nature of wireless communications links. In our network model, it does not need assumption for symmetric communications links. Also, there is no need to send acknowledgements. This significantly improves the efficiency of packet delivery, as it is usually time consuming and energy costly. However, the reliability is guaranteed by the replication factor and the success probability of routing path.

Based on the network model, we assume the network is synchronized so that a node knows when to send a packet. Each node randomly chooses its working schedule and shares it with all its neighbors. Synchronization can be achieved as described in Ref. [4] and the random distribution of working schedule

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can be achieved as in Ref. [5].

3.2 Formal problem definition

Assume a source node sending a message of size m to destination node d, and let there be n paths from s to d. For path i, let P_i be the success probability of transmiting a code block from s to d; and let D_i be total sleep latency along path i from s to d.

We assume that it takes one slot to send a code block from sender to receiver. If there are more than one coded blocks that need to be sent over one path, the sender has to wait T slots before it can send the next code bock when the receiver wakes up again. For example, a source node s sent b coded blocks through path i at time slot 1, with success probability and delivery delay of P_i and D_i respectively. Thus, the expected arrival time of the jth code block at destination d is $a_j = D_i + (j-1)T$.

Assume that an erasure coding algorithm can be used (with a replication factor r) to generate $b = mr/l$ coded blocks of size l, so that any $k = m/l$ coded blocks can be used to decode the original message.

The allocation problem is to determine the number of blocks sent over path i, subject to the condition that the Expected Delivery Ratio (EDR) is no less than $1-\varepsilon$.

IV. ALLOCATING CODED BLOCKS THROUGH SPATIAL-TEMPORAL DIVERSITY

Our solution is built upon such a model. And in the work by Jain and his co-writers [6], an optimal allocation scheme is used to maximize delivery ratio, given that the volume of a single path is limited. In addition, little consideration is given to delivery latency in Jain's work [6]. However, in this paper, using the path with highest link quality would achieve the maximum delivery ratio, but would possibly incur longer latency, which may not be tolerable for real-time applications. So our idea is to minimize the delivery delay under the condition that the expected delivery ratio is no less than $1-\varepsilon$.

4.1 Optimal solution

The destination node d is expected to receive b code blocks from source node s through n available paths. Given an allocation strategy $(x_1, x_2 \dots x_n)$, we could sort the expected arrival times of these b code blocks and let a_i be the ith expected code block and p_i is the corresponding probability. $p_i = P_j$ if the ith code block is received through the jth path.

Given those b code blocks, there are 2^b possible outcomes corresponding to the different combinations of successfully received code blocks. Let the possible outcomes be numbered $0,1,\dots,2^b-1$. The binary representation of a b-bit integer j can be used to encode the success of the jth outcome in the following manner. Define c_{ji} to be 1 if the binary representation of j has a 1 at the ith position and 0 otherwise. Let c_{ji} encode whether the ith expected code block was successful received in the jth outcome:

$$c_{ji} = j/2^{i-1} \bmod 2 \quad i=1,2,\dots,b \tag{1}$$

Let w_j denote the probability that the jth outcome occurs. Note that w_j is an input to the formulation as it is a function of the success probability of the expected code blocks. For the case when the success probability of the ith expected code block are independent:

$$w_j = \prod_{i=1}^{b} \left[p_i c_{ji} + (1-p_i)(1-c_{ji}) \right] \tag{2}$$

To capture the probability corresponding to the jth outcome, we define a binary variable y_j as 1 only if $(x_1, x_2, \dots, x_n)$ are chosen so that the sum of x_i corresponding to the successfully received code blocks in the jth outcome is greater than or equal to b/r.

$$\text{minimize EDD} = \sum_{i=k}^{b} a_i P'_{\text{decode}} \tag{3}$$

$$P'_{\text{decode}} = \sum_{u} w_u \text{ when } c_{ui} = 1 \text{ and } \sum_{t=1}^{i-1} c_{ut} = k-1$$

$$\text{EDD} = \sum_{j=0}^{2^b-1} y_j w_j > 1-\varepsilon$$

$$y_j = \{0,1\},\ \sum_{i=1}^{b} c_{ji} \geqslant y_j b/r \quad j=0,1,\dots,2^b-1$$

$$0 \leqslant x_i \leqslant b \quad i=1,2,\dots,n$$

$$\sum_{i=1}^{n} x_i = b \tag{4}$$

The formulation has an exponential number of constraints 2^b and uses integer variables. Given the

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allocation strategy $(x_1,x_2,\ldots,x_n)$, even computing EDR is NP-hard. Despite these difficulties, this formulation can be solved using matlab when b and n are small.

4.2 Approximation of optimal solution

Since solving the optimal allocation problem is NP-hard, we use some institute methods to decrease the complexity and derive a sub-optimal solution.

The main conceptions of this algorithm are as follows: Firstly, we allocate all these b code blocks to every path. So the receiver will get the delivery delay and corresponding delivery ratio and path for all these $n\times b$ code blocks. Sorting all these $n\times b$ code blocks by delivery delay, and let {SEA} denote it. Let SEA (i).Delay, SEA (i).Prob, and SEA (i). Path denote the delivery delay, delivery ratio and delivery path of the ith code block in {SEA} respectively. Then, select the first b code blocks from {SEA}, and the EDR of these b code blocks. If EDR $> 1-\varepsilon$, then the allocation strategy could be derived according to the paths which these b code blocks are delivered over. Otherwise, select the code block with minimal delivery ratio (noted as p_{min}) from the bth to the first code block. Then, delete the code block and all the following blocks delivered over the same path from {SEA}. Then calculate the EDR of the first b code block. And repeat this process until EDR $> 1-\varepsilon$ or $|\mathrm{SEA}| = b$.

To decrease impact of the deleted code blocks on EDD, we define a variable δ. If the delivery ratio of a code block p satisfies $p < p_{min} + \delta$, then delete the code block and all the following blocks.

V. SIMULATION AND EVALUATION

5.1 Simulation setup

In the simulation, we deployed 30 sensor nodes randomly in a 200 m × 200 m square field. All the nodes work in low-duty-cycle mode, except the sink node which always keeps awake. We set radio parameters strictly according to the CC2420 radio hardware specifications [7]. In our simulation, we just implanted simple CSMA mechanism. Once a node sensed a busy channel, it will try to send in the next cycle.

In all experiments, we set slot time τ to 10 ms. The working period T is determined by duty cycle, i.e. $T = \tau/\text{dutycycle}$. In each experiment, at most three best edge-disjoint paths were selected using minimum-cost algorithm. Edge cost was defined based on the expected transmission times. Node deployments and node working schedules is generated with different random seeds in each experiment. The message size and replication factor is 5 and 2 respectively. The size of code block is 1 and a node can only transmit 1 code block in one slot.

5.2 Performance evaluation

We now evaluate the performance of our near-optimal allocation strategy to minimize delivery delay. Our near-optimal allocation strategy is labeled as 'MDD'. Besides MDD, another two strategies were also implemented. The one used to maximize delivery ratio (labeled as 'MDR') only uses the path with the highest delivery ratio. The rest one is simply used to allocate blocks over multiple paths evenly (labeled as "EVEN"). Their delivery ratio, delivery delay and energy consumption are compared in this experiment.

We first evaluate the performance with different duty cycles. In this simulation, 30 nodes are generated randomly in a 200 m × 200 m field.

Figure 3 plots the average delivery ratio, average delivery delay and average number of sent blocks per received message when duty cycle varies from 1% to 10%. As duty cycle increases, more nodes will transmit packets at the same time, leading to delivery ratio decrease for the hidden terminal problem. This is validated in Figure 3(a). As Figure 3(b) shows, the delivery delay of all the three strategies will decrease. Since the node stays awake most of the time, thus delivery delay is decreased significantly. According to Figure 3(c), it can be seen that the average number of sent blocks per received message increases as duty cycle varies from 1% to 10%. The reason is the same as that for Figure 3(a).

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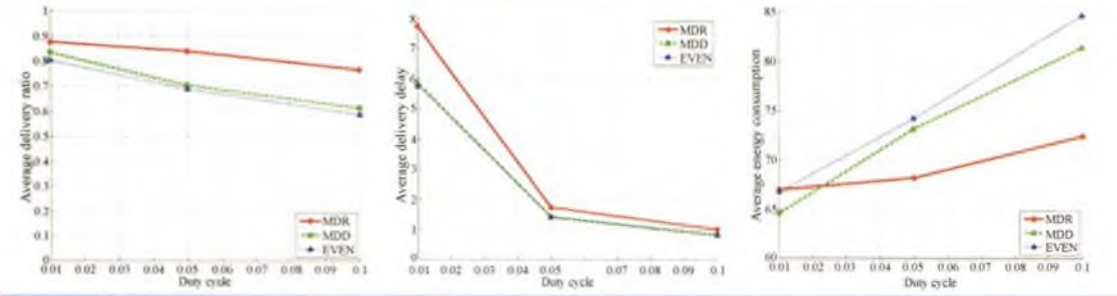
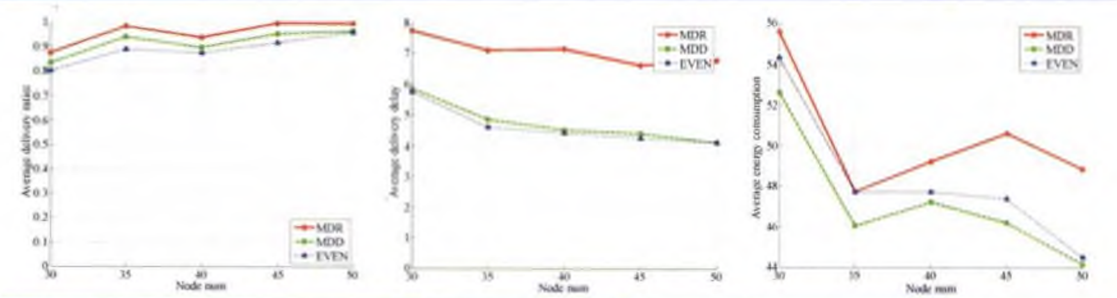


(a) Delivery ratio vs. duty cycle (b) Delivery delay vs. duty cycle (c) Energy consumption vs. duty cycle

Fig.3 Varying duty cycle

Then, we evaluate the performance of the three strategies with different network density. The side length of the area is fixed at 200 m, while the network size changes from 30 to 50. The duty cycle of all nodes is fixed at 1%.

Figure 4 plots the average delivery ratio, average delivery delay and average number of sent blocks per received message. The links between nodes become reliable as the number of nodes increases in a fixed area networks. However, collision will not become severe thanks to the low-duty-cycle nature of our networks. So delivery ratio will increase as node number increases as Figure 4(a) shows. When delivery ratio increases, it is earlier that sink node receives *k* code blocks. Thus delivery delay decreases as Figure 4(b) indicates.



(a) Delivery ratio vs. node number (b) Delivery delay vs. node number (c) Energy consumption vs. node number

Fig.4 Varying Node Number

As Figures 3 and 4 show, MDD reduces delivery delay while achieving comparable delivery ratio and using less energy. EVEN could reduce the delivery delay, but at the cost of decreased delivery ratio.

VI. RELATED WORKS

Though low-duty-cycle WSNs could save energy significantly, the performance especially timely delivery is not satisfactory to network designers. Energy consumption and performance tradeoff still exist in low-duty-cycle WSNs. Many works have been presented for efficient scheduling in dealing with this difficulty [8-10]. S-MAC [11] is a low-duty-cycle medium access protocol, which needs periodical sleeping and working. On improving the network efficiency, Ref. [12] proposes a pipe-line based working schedule, where all nodes can cooperatively work for lowering the delay. Unfortunately, it cannot support clustering and tired network. Thus, a more complicated scheduling based on "even-odd" switching is proposed, which would also

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easily lead to failures. Compared with to these works, ours does not need very complicated scheduling or very strict time synchronization. More importantly, the proposed coding scheme can be to network failures.

As an essential operation in WSNs, data routing has been extensively studied in literature. However, little work has been done on low-duty-cycle WSNs with unreliable communications links. In Ref. [13], end-to-end data forwarding has been studied, and the concept of dynamic switch-based forwarding (DSF) was proposed which optimizes either expected data delivery ratio, expected communication delay, or expected energy consumption. However, Ref. [13] could be energy costly due to the unlimited transmissions for better throughput. Also, Ref. [14] proposes an efficient latency control method for low-duty-cycle wireless network, where time delay in the network can be reduced. Compared with these works, ours is an energy conservative method in speeding up the data transmission. The energy conservative method is twofold: one is we use efficient coding for pre-processing; the other is we limit the multi-path routing and allocate coded messages effectively over them.

In delay-tolerant networks, erasure coding [6,15] and multiple paths are used to improve data delivery ratio. Ref. [6] proposes an algorithm to optimize the probability of successful message delivery by erasure coding messages and allocating them over multiple delivery paths. Although in low-duty-cycle WSNs where node working schedules are predetermined, and the inter-contact time is known, it has to be noted that, the uncertainty in lossy links also increases the complexity. Moreover, retransmission will cost too much energy. Ours makes it possible for decreasing message delivery delay and achieving comparable message delivery ratio at the same time.

To the best of our knowledge, ours is the first to utilize both the advantage of erasure coding and the spatial-temporal diversity, which could speed up data delivery over unreliable links for low-duty-cycle WSNs in an energy-efficient way.

VII. CONCLUSIONS AND FUTURE WORK

In this work, we propose COST, a coding over spatial and temporal diversity scheme, which effectively utilizes the potential opportunities in low-duty-cycle WSNs. A series of preliminary tests have shown the potential opportunities in the WSNs, both in the coding dimension and in the spatial-temporal dimension. We formulate optimal allocation of erasure coded blocks over multiple paths for WSNs. It has been shown that sending erasure coded blocks over multiple paths will be important to energy efficiency. Also, it is proved to be suitable for asymmetric links. As the coded message allocation problem is NP-hard, a near-optimal algorithm is proposed for solving this problem. Extensive simulations verify the effectiveness of our proposed scheme.

In the future, we shall extend our model to the scenario where working schedule is determined by a certain well defined pattern to provide better message delivery performance. 中国通信

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