Energy-Efficient Cooperative Communication for Data Transmission in Wireless Sensor Networks

Weiwei Fang, Feng Liu, Fangnan Yang, Lei Shu, and Shojiro Nishio

Abstract — *It is a practical challenge to provide reliable and efficient communication for data transmission in wireless sensor networks. To recover from packet losses, conventional approaches tried to use retransmission or FEC mechanisms. However, these mechanisms may introduce excessive energy overhead for reliability guarantee. By exploiting the wireless broadcast nature and the node overhearing capability, we propose a novel cooperative communication scheme EECC to improve data transmission performance for wireless sensor networks. In this scheme, cooperative reply is performed at each hop by the best-suited node elected from those that have successfully overheard the transmitted packet. EECC is not a routing protocol but rather works as an augment to minimize the impact of packet losses on network performance. Extensive analytical and experimental results confirm that our scheme is very effective in improving both energy efficiency and end-to-end delay for data transmission in lossy networks*[1].

Index Terms — Wireless Sensor Networks, energy efficiency, cooperative communication, QoS.

I. INTRODUCTION

One of the fundamental issues in wireless sensor networks is to provide efficient and reliable network communication mechanisms for data transmission. Experimental studies have revealed that wireless communication links, especially for the low-power sensor nodes, are extremely unreliable and have a significant impact on packet delivery [1], [2]. If left without handling, the packet losses caused by poor link quality would result in reduced information fidelity and increased energy wastage. Previous works [3] for reliable communication have tried to adopt two mechanisms for packet recovery, namely, packet retransmission and forwarding error correction (FEC) [4]. While both of these approaches are very useful, they will simultaneously bring about additional energy overhead for the network to perform control operations. To prolong the network lifetime, it is imperative to design new approaches in wireless sensor networks that can minimize energy consumption while achieving robustness against link transmission failures.

This work takes inspiration from a promising technique known as cooperative communication [5], which exploits the broadcast nature of wireless communication [6] to enhance network performance, especially to improve energy efficiency. Without additional transmissions, nodes in the neighborhood of a sender can obtain a copy of the forwarded packet through overhearing. Cooperative communication enables these nodes with a copy to cooperate with the sender for the relaying task. Although many previous cooperative schemes have exhibited satisfactory effectiveness in improving network performance, most of them cannot be directly applied to the wireless sensor network due to their requirements on more powerful or special designed radio hardware [5], [7].

In this paper, we propose EECC, a novel energy-efficient cooperative communication scheme for the sensor network to provide reliable and efficient transmission against unreliable wireless links. In EECC, cooperative relay is performed at each intermediate hop between source and sink. When a node fails to receive a data packet from its upstream sender node, nearby nodes which have successfully overheard the packet will start the cooperation proactively and select the "best" relay out of them to participate in the transmission. The node cooperation is implemented by a cross-layer design between the network and Medium Access Control (MAC) layers: the cooperative relay node is elected through the MAC layer acknowledgement contention from relevant candidate node sets, which are formed through partial routing information broadcasts. The theoretical analysis shows that EECC outperforms the non-cooperative mechanisms in terms of energy consumption in presence of transmission failures. Extensive simulation results confirm that EECC significantly improves data transmission performance.

As a summary, we have made the following contributions in this paper: 1) our paper introduces cooperative communication into wireless sensor networks to achieve reliable and efficient data transmission on lossy links, and presents the design and implementation of the EECC scheme in detail. 2) A theoretical analysis is performed to prove that EECC is much more energy efficient than traditional non-cooperative approaches. 3) The simulation results confirm that EECC can significantly reduce the total number of transmissions and thus saving energy and shortening delay, especially in networks with densely deployed sensor nodes and extremely unreliable wireless links.

The rest of the paper is organized as follows. We discuss previous work on related topics in Section II and give models and assumptions in Section III. Section IV describes EECC in detail. Section V provides analytical comparisons

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on energy efficient between EECC and the non-cooperative approaches. Section VI demonstrates and discusses the experiment results. Finally, Section VII concludes the paper.

II. Related Work

As in traditional networks, link-level retransmission based on Automatic Repeat reQuest (ARQ) [8] has also been widely applied for the sensor network [3]. Reference [4] points out drawbacks in this mechanism, and proposes to use one class of the FEC techniques called erasure coding, which attempts to encode error recovery information into packets to compensate for the effect of lossy links. The receiver node can reconstruct z original data packets by receiving any z out of y encoded packets. However, it requires a pre-knowledge of the channel conditions for a proper data redundancy setting, i.e., y/z.

While the above two approaches are quite useful, the energy efficiency of them could be considerably affected by unreliable links [9]. To solve this problem, there have been attempts to explore the cooperative communication technique to improve energy-efficiency for data transmission. We refer to REPF[10], ExOR[7], MRD[11], and CoopMAC[12] as the typical earlier works on this topic. However, they are designed for traditional wireless networks (e.g., MANET), and cannot be directly used due to the unique challenges of sensor networks [9].

Some recent studies on cooperative communication have considered the specific properties of wireless sensor networks. Reference [13] studied and compared the energy efficiency of cooperative communication and direct transmission schemes in sensor networks, without giving practical implement details for node cooperation. SPaC[14] allows nodes to buffer overheard corrupted packets and recover the original packet by combining multiple corrupt copies. SPaC inevitably increases the demand for storage space and computation overhead of sensor nodes. In [15], a "best" relay is selected based on RTS-CTS signaling from nodes that are neighbors of both the sender and the receiver. Then the relay node will forward the overheard data packet to the receiver separately. The receiver combines the received signal from the sender and the relay for joint decoding. It is obvious that this approach is not efficient for packet recovery, because cooperation is only needed when the receiver fails to decode signal from the sender. A similar idea on cooperative MAC (COMAC) has also been proposed in [16], which requires nodes with 802.11g radios. In CBF [9], each intermediate sensor node is able to organize qualified neighboring nodes into a cluster, and a suitable helper node out of potential candidates in the cluster can take the relay responsibility if the original receiver fails. Although not been discussed in [9], the overhead incurred by cluster management cannot be simply neglected in CBF. Apart from higher layer protocols discussed above, there are also some works focusing on node cooperation at physical layer for constructing "virtual" multiple-input multiple-output (MIMO) systems [17] [18].

III. Models And Assumptions

Before presenting EECC in detail, we introduce the models and assumptions used in this work.

A. Models

Previous studies [2] [9] have pointed out that the simple radio models (e.g., the ideal binary model assumes that there are perfect links within a given communication range, beyond which there is no link) is unlikely to be valid in any realistic environment. Actually, the reliability of a link is influenced by a lot of factors, such as the transmitter-receiver distance, the emitting power and the interference noise. To model the reliability, we choose to use the one derived in [2] and [19], which is based on the log-normal path loss model. The packet reception rate (PRR) p for a transmitter-receiver distance d is given by

$$p(d) = \{1 - \exp[-\gamma(d) B_N / 2R]/2\}^{8\rho f} \tag{1}$$

where B_N is the noise bandwidth, R is data rate in bits, ρ is the encoding ratio, and f is the frame length in byte. The signal to noise ratio (SNR) γ at the receiver can be given as

$$\gamma(d) = P_t - PL(d_0) - 10\eta \log_{10}(d/d_0) + N(0,\sigma) - P_n \tag{2}$$

where P_t is the output power, $PL(d_0)$ is the power decay for the reference distance d_0, η is the path loss exponent (rate at which signal decays with respect to distance), $N(0, \sigma)$ is a Gaussian random variable with mean 0 and variance σ^2 (due to multi-path effects), and P_n is the noise floor.

In this model, low-power wireless links are classified based on transmitter-receiver distance in distinct reception regions: connected ($p \to 1$), transitional ($0 < p < 1$), and disconnected ($p \to 0$). Then, the communication range R_c can be defined as

$$R_c = \max\{d \mid p(d) > p_{thres} \wedge p_{thres} > 0 \wedge p_{thres} \to 0\} \tag{3}$$

We model a sensor network by an undirected graph $G = (V, E)$, where V is the set of sensor nodes and the set of wireless communication links, E, is defined as

$$E = \{(u,v) \in V^2 \mid u \neq v \wedge d_{u,v} \leq R_c\} \tag{4}$$

The neighborhood set H(u) of a node u is defined as

$$H(u) = \{v \in V \mid v \neq u \wedge (u,v) \in E\} \tag{5}$$

B. Assumptions

A wireless sensor network composed of a large number of resource-constrained sensor nodes and several more powerful sinks in an area is considered in this paper. Sensor nodes are randomly distributed in the area and remain stationary after deployment, and all of them have similar capabilities and equal significance. Each sensor node sends its data packets to sink nodes through multi-hop wireless links. All nodes in the network are supposed to implement a CSMA-like MAC (with ARQ) to share the physical medium. Due to link unreliability, the network is assumed to employ a more optimal metric [19] [20] instead of the conventional shortest-path-first policy for setting up an optimum routing path (referred to as "intended path") between source and sink. Each node knows and keeps record of the PRR between itself and any neighboring node.

IV. EECC: Energy-Efficient Cooperative Communication Scheme

A. Motivating Observations

Consider a typical network scenario as shown in Fig. 1, where three gray nodes (A, B and E) are belong to the intended path while two other nodes (C and D) are located within the communication range of A. Node B is more superior to C and D as the next hop of A, because it can provide a well balance between hop count and link quality [20]. However, when node A forwards data to B, nodes C and D may correctly overhear the packet as well. We have the following two observations concerning their roles as the "cooperator" to improve data transmission on the intended path.

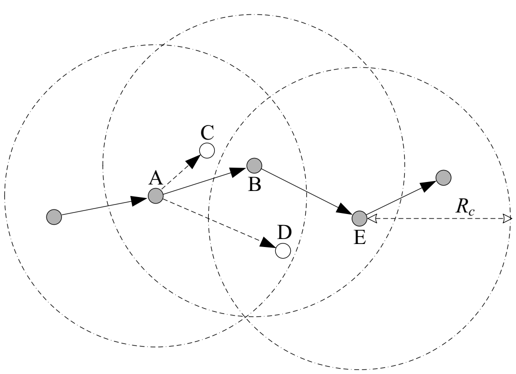

Fig. 1. A multi-hop data transmission scenario in wireless sensor network.

First, if the link (C, B) is better than the link (A, B), and if node B failed to receive the data packet from A while C has obtained a copy successfully through overhearing, it is better to shift the relay task from (A, B) to (C, B). Intuitively, such a shift can reduce the expected number of transmission times since retransmission from C is more likely to succeed than that from A. In such a scenario, node C acts as a cooperator of the intended sender A for relaying the packet to its next hop B.

Second, if the link (D, E) is better than the link (B, E), and if node D has overheard the packet from A, we can use D to substitute for B as the relay to the next hop E, and skip B. In such a scenario, node D acts as a cooperator of the intended receiver B for relaying the packet to its next hop E.

It is obvious that the probability that multiple independent links from node A fail simultaneously is much smaller than the probability of a failed intended link, e.g., (A, B). Therefore, qualified neighbors of the sender node A can help to relay the packet proactively to the downstream nodes over strong links (e.g., (C, B) or (D, E)) if possible. Such node cooperation can reduce the expected number of transmission times, and further improve network performance. However, cooperation behaviors above are not supported by the current unicast mechanism for data transmission, i.e., the overheard packet will be dropped silently by the non-receiver nodes like B and C. This limitation motivates us to design a novel technique to implement cooperative communication in wireless sensor networks, which will be introduced in the rest of this paper.

B. Cooperation Rules

Based on the analysis above, we can now set the rules for coordinating cooperation among nodes. It must be noted that in EECC only the sender nodes on the intended path can invoke transmission cooperation for the transmitted data packet (An additional binary bit in the MAC frame header can be set by the transmitting node to denote if this frame is sent out by an intended sender or a cooperator). Let s and r denote the sender and its intended receiver respectively, and u denotes the next hop intended receiver of r.

Definition 1. Let Q denotes the set of candidate nodes that can act as the role of a cooperator of s.

$$Q = \{q \in H(s) \mid d_{q,r} \le R_c \wedge d_{q,s} \le R_c \wedge p_{q,r} > p_{s,r}\} \tag{6}$$

Definition 2. Let T denotes the set of candidate nodes that can act as the role of a cooperator of r. If r is not the sink, then

$$T = \{t \in H(s) \mid d_{t,s} \le R_c \wedge d_{t,u} \le R_c \wedge p_{t,u} \ge p_{r,u}\} \tag{7}$$

Otherwise, $T = \varnothing$, since r is the last hop on the intended path.

As pointed out in [20] and [21], it is better to select $t \in T$ rather than $q \in Q$ when $Q \ne \varnothing$ and $T \ne \varnothing$, since t directly send data to the next hop intended node u rather than retransmit it to r. To sum up, the rules for node cooperation can be given as in Fig. 2:

s sends a data packet to r;
while (s has not received any acknowledgement for the data packet)
  if (r receives the data packet) **then**
    r returns the acknowledgement to s;
  elseif ($T \ne \varnothing$) **then**
    a packet holder t is selected from T as the cooperative node;
    t returns the acknowledgement to s;
    t forwards the data packet to u;
  elseif ($T = \varnothing$ and $Q \ne \varnothing$) **then**
    a packet holder q is selected from Q as the cooperative node;
    q returns the acknowledgement to s;
    q forwards the data packet to r;
  elseif ($T = \varnothing$ and $Q = \varnothing$) **then**
    s retransmits the data packet to r;
  endif
endwhile

Fig. 2. Cooperation rules for data transmission.

C. Implementation Details

After an intended path is set up between a source-sink pair, each node on the path must broadcast partial path information locally. This information contains the value of PRR between the current node and its next hop, source node ID, sink node ID, node IDs of the current node, its upstream and downstream nodes. The IDs of source and sink nodes are used to identify an intended path. Relevant nodes judge its role and operation in the cooperation according to the other ID information. For the partial path in Fig. 1, node C only knows of the link (A, B), while D knows of both (A, B) and (B, E). When the intended path is updated due to some reason, the newly added node should also perform broadcasting as in the path formation phase to renew sets of cooperator candidates accordingly.

Our EECC scheme is based on a cross-layer design with MAC layer as the anchor, operated under the CSMA MAC mechanism. After finishing data transmission, the sender waits for an acknowledgement (ACK). If the intended receiver has successfully receives the packet, it relies with an ACK after the Short Inter-Frame Space (*SIFS*). Otherwise, the channel keeps silence during this interval. A cooperative node learns that the intended link fails and replies an ACK to the sender to become the next replay. This is the difference between our scheme and standard CSMA. Instead of only the intended receiver replying an ACK to the sender after a successful reception, the qualified nodes that are eligible to cooperate can reply the ACK back to the sender, in which the first one will be the relay node. In case there is no cooperative node, the sender will try to retransmit the lost data packet after ACK time-out.

To reduce potential collisions among several qualified nodes, each of them is required to set a backoff timer, which defines the amount of time that the node must wait before responding ACK to the sender. It is obvious that the node with the shortest backoff time will be the first one replying with an ACK. Since the carrier sensing range is normally larger than twice of the communication range [22], this ACK will be heard or sensed by all the other qualified nodes. They will cancel their timers and stop competing for relay. Thereafter, the node competition for the relay task finishes.

Having determined that it can act as a cooperator, a node can adopt different policies in setting its backoff timer according to any combination of available metrics such as link quality, remaining energy and traffic load. While many metrics can be used to decide the backoff delay based on application specifics, without loss of generality, we adopt following formulas in the current EECC implementation according to the cooperation rules in Fig. 2.

The backoff delay for a receiver's cooperator $t \in T$ is

$$T_t = SIFS + \alpha W_t (DIFS - SIFS) \tag{8}$$

where

$$W_t = (w_e e_t / E + w_p p_{t,u} + w_v v) / (w_e + w_p + w_v)$$

and $0 < \alpha < 1$, *DIFS* is the standard Distributed Inter-Frame Spacing, e_t and E denotes the residual and initial energy of node t respectively, v is a random value between 0 and 1, w_e, w_p and w_v are weighting coefficients used to weight among the application requirements on the metrics.

Cooperator candidates of the sender always have relatively lower priority for relay than those of the receiver. The second competition stage begins if no nodes transmits in [*SIFS*, *SIFS* + α(*DIFS* - *SIFS*)]. Similar to the case above, the backoff delay for a sender's cooperator $q \in Q$ is

$$T_q = SIFS + [\alpha + (1-\alpha) W_q](DIFS - SIFS) \tag{9}$$

where

$$W_q = (w_e e_q / E + w_p p_{q,r} + w_v v) / (w_e + w_p + w_v)$$

It is noted that (8) and (9) are designed to be compatible with the timing rule of standard CSMA MAC by guaranteeing: (1) The minimum value of backoff delay is larger than the *SIFS* delay; (2) The maximum value of backoff delay is smaller than the *DIFS* delay to prevent other nodes from initiating a new transmission.

If a relay node hears or senses another transmission before sending out the ACK, the handshake of DATA and ACK may be interrupted. To avoid this situation, the new NAV (Network Allocation Vector) NAV_{new} is modified as the sum of NAV in CSMA MAC, $NAV_{original}$ and (*DIFS* – *SIFS*), written as

$$NAV_{new} = NAV_{original} + (DIFS - SIFS) \tag{10}$$

The ACK will be sent out before any NAV reaches zero if a relay node (i.e., r, q or t) exists. Though additional delay is incurred by this new NAV setting, we argue that it is much smaller than the time cost by retransmission.

After the elected cooperative node replies ACK to the sender, it will continue to forward data back to the original intended path in non-cooperative mode (since it is not an intended node). That is, data packet will be forwarded from q to r or from t to u.

V. Performance Evaluation: Analytical Results

Based on reasonable assumptions, we compare the energy efficiency of our EECC and the traditional methods, i.e., pure retransmission-based and FEC-based. According to previous researches [23], wireless communication is responsible for the greatest weight in the energy budget when compared to sensing and data processing. Assume M sensor nodes are randomly deployed in an area of size S. Let E_t and E_r be the energy consumed by a single transmission and reception respectively.

Theorem 1. Let the per hop energy consumption for FEC, pure retransmission and node cooperation are denoted by E_{FEC}, $E_{retrans}$, and E_{EECC} respectively, we have $E_{FEC} \geq E_{retrans} > E_{EECC}$.

Proof: The energy consumed for each transmission attempted by a sensor node is

$$E_{single} = E_t + (M\pi R_c^2 / S - 1)E_r \tag{11}$$

Ideally, we assume that a node retransmits for infinite times. Thus, in the retransmission-based mechanism, the expected energy consumption for a successful delivery from s to r is

$$\begin{aligned} E_{retrans} &= p_{s,r}E_{single} + \ldots + np_{s,r}(1-p_{s,r})^{n-1}E_{single} \\ &= \sum_{k=1}^{n} k p_{s,r}(1-p_{s,r})^{k-1}E_{single} \end{aligned} \tag{12}$$

When $n\to\infty$ and $0 < x < 1$, we have $\sum_{k=1}^{n} kx^{k-1} \approx 1/(1-x)^2$, then (12) can be rewritten as

$$E_{retrans} = E_{single} / p_{s,r} \tag{13}$$

In the FEC mechanism [4], it is required that

$$E_{FEC} = E_{single} y / z \geq E_{single} / p_{s,r} \tag{14}$$

Now we analyze the energy consumption of EECC in three different cases of cooperation scenario. From (13), it is more energy efficient to relay packet on link (t, u) than (r, u). Thus, to simplify the analysis, we only consider the energy consumed for data packet transmission in one hop range, i.e., from s to its next hop relay. Let the cardinality of T and Q is denoted by $|T|$ and $|Q|$ respectively.

Case 1: $|T| > 0$ and $|Q| = 0$

$$\begin{aligned} E_{EECC1} &= P_T E_{single} + \ldots + nP_T(1-P_T)^{n-1}E_{single} \\ &= \sum_{k=1}^{n} kP_T(1-P_T)^{k-1}E_{single} = E_{single} / P_T \end{aligned} \tag{15}$$

where $P_T = 1-(1-p_{s,r})\prod_{t\in T}(1-p_{s,t}) > p_{s,r}$. Therefore, we have

$$E_{EECC1} < E_{single} / p_{s,r} \tag{16}$$

Case 2: $|Q| > 0$ and $|T| = 0$

$$\begin{aligned} E_{EECC2} &= p_{s,r}E_{single} + (1-p_{s,r})P_Q\sum_{k=1}^{n} kp_{l,r}(1-p_{l,r})^{k-1}E_{single} \\ &\quad + (1-p_{s,r})(1-P_Q)\sum_{k=1}^{n} kp_{s,r}(1-p_{s,r})^{k-1}E_{single} \\ &= \{p_{s,r} + (1-p_{s,r})[P_Q / p_{l,r} + (1-P_Q)/ p_{s,r}]\}E_{single} \end{aligned} \tag{17}$$

where $P_Q = 1-\prod_{q\in Q}(1-p_{s,q})$ and $l\in Q$ is the node that relays the packet as the cooperator. Because $p_{l,r} > p_{s,r}$, we have

$$E_{EECC2} < (1-p_{s,r} + p_{s,r}^2)E_{single} / p_{s,r} < E_{single} / p_{s,r} \tag{18}$$

Case 3: $|T| > 0$ and $|Q| > 0$

$$\begin{aligned} E_{EECC3} &= P_T E_{single} + (1-P_T)P_Q\sum_{k=1}^{n} kp_{l,r}(1-p_{l,r})^{k-1}E_{single} \\ &\quad + (1-P_T)(1-P_Q)\sum_{k=1}^{n} kp_{s,r}(1-p_{s,r})^{k-1}E_{single} \\ &= \{P_T + (1-P_T)[P_Q / p_{l,r} + (1-P_Q)/ p_{s,r}]\}E_{single} \\ &< [1-(1-p_{s,r})P_T]E_{single} / p_{s,r} < E_{single} / p_{s,r} \end{aligned} \tag{19}$$

Summarizing the above analytical results in (11) ~ (19), the following inequality holds: $E_{FEC} \geq E_{retrans} > E_{EECC}$.

Now we give the performance bound of EECC.

Lemma 1. In idealistic cases with perfect links ($p_{s,r} = 1$), the data forwarding in one hop range succeeds at the first time. Thus, the lower bound of per hop energy consumption is E_{single}.

Lemma 2. In realistic cases with imperfect links, the packet can be received by the receiver and overheard by the cooperator candidates. The overall reception rate provided by these nodes is $[1-(1-p_{s,r})\prod_{t\in T}(1-p_{s,t})\prod_{q\in Q}(1-p_{s,q})]$. Hence, transmission cooperation is more likely to be realized when the node density is relatively high. In sparsely deployed scenarios, we can know that the per hop energy consumption is upper bounded by $E_{retrans}$ when there are few cooperation opportunities.

VI. Performance Evaluation: Simulation Results

The performance of EECC was evaluated by conducting simulations via the ns-2 simulator. Here, we adopted a model which is widely used in previous researches to calculate energy consumption for transmission. To receive l bits at the receiver with a distance of d from the transmitter, energy consumption for a single transmission and reception is given by

$$E_T(l,d) = \begin{cases} l(E_{elec} + \varepsilon_{fs}d^2), & d < d_0 \\ l(E_{elec} + \varepsilon_{mp}d^4), & d \geq d_0 \end{cases} \tag{20}$$

$$E_r(l) = lE_{elec} \tag{21}$$

where E_{elec} is the electronics energy, $\varepsilon_{fs}d^2$ and $\varepsilon_{mp}d^4$ are the amplifier energy in the free space and in the multi-path fading environment respectively, and d_0 is a distance threshold that depends on the environment. In our simulation experiments, the wireless link model is the same with that in [2], and other parameters are set as shown in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
R_c	32 m	Bandwidth	250 kbps
E_{elec}	50 nJ/bit	Frame	500 bytes
ε_{fs}	10 pJ/bit/m^2	Source Rate	1 packet/s
ε_{mp}	0.0013 pJ/bit/m^4	*SIFS*	10μs
d_0	75 m	*DIFS*	50μs
w_e:w_p:w_r	0.4 : 0.5 : 0.1	α	0.4

The first set of simulation experiments is performed to verify our analysis above in Section V. Thus, we manually deployed two sensor nodes and a single sink to create a simple 2-hop data transmission topology as that has been introduced in Section V. Different amount of sensor nodes are randomly deployed as the neighbors of the intended data source node to create different cooperation scenarios, i.e., ($|T| > 0$, $|Q| = 0$), ($|Q| > 0$, $|T| = 0$), and ($|T| > 0$, $|Q| > 0$). To make the results more pronounced, for each specific transmission scenario the experiment is carried out independently for multiple times by network redeployment. The performance metric selected is called transmission cost, which is defined as the ratio of the total number of data transmissions by the total number of non-redundant packets sent out by the data source. This metric reflects both communication overhead and energy efficiency. To fully investigate on the performance effect by EECC, experiments are performed under different routing reliability conditions (That is, the PRR metric for becoming an intended receiver, $p_{routing}$, is set as low (25%), middle (50%), and high (75%) respectively). The simulation results for this experiment set are shown in Fig. 3 to Fig. 5.

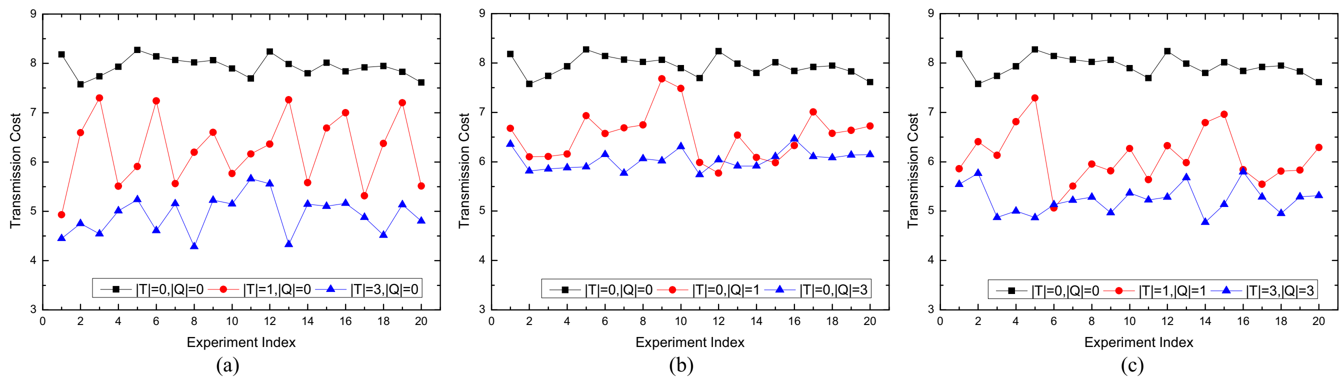

Fig. 3. Comparison on transmission cost when $p_{routing}$ = 25%.

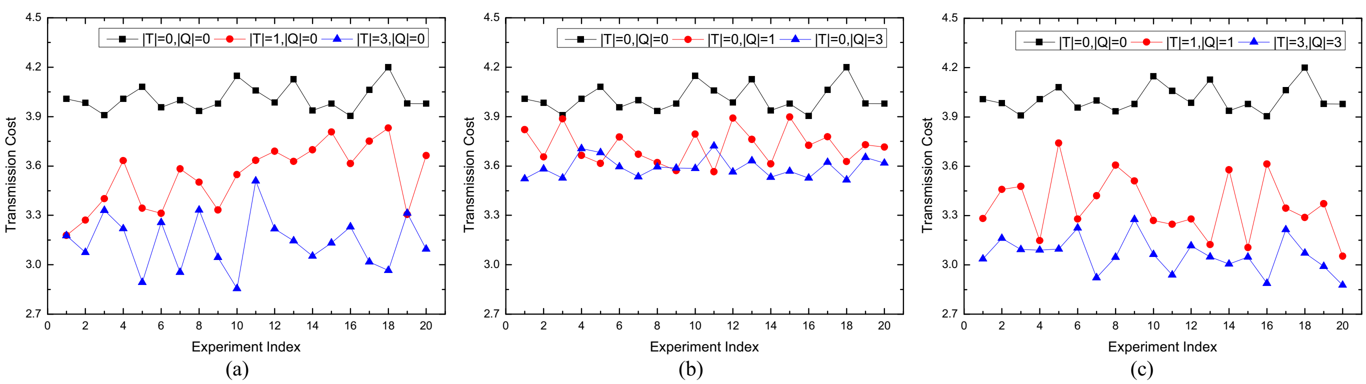

Fig. 4. Comparison on transmission cost when $p_{routing}$ = 50%.

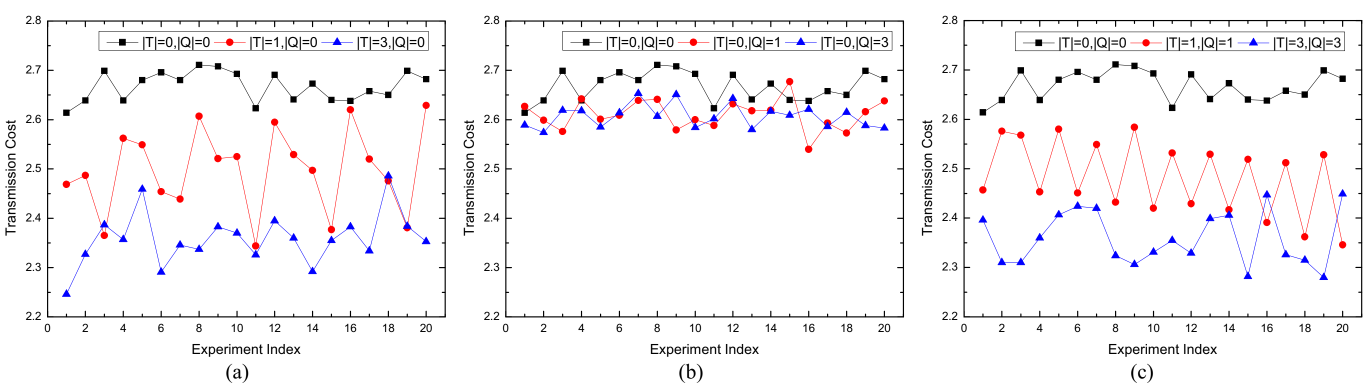

Fig. 5. Comparison on transmission cost when $p_{routing}$ = 75%.

We have several observations concerning these results. First, EECC can actually help to reduce transmission cost to some extent, as compared to the pure retransmission mechanism (i.e., ($|T|$ = 0, $|Q|$ = 0)). Such cost reduction is even more obvious and stable when $p_{routing}$ of the intended receiver is relatively low (e.g., $p_{routing}$ = 25%) and when the total amount of cooperator candidates is relatively high (e.g., $|T|$ = 3 or $|Q|$ = 3). On the other hand, node cooperation contributes little to the cost reduction when $|T|$ = 1 and $p_{s,t}$ is extremely low (e.g., Experiment Index = 12, 16, 20 in Fig. 5(a)) or when $|Q|$ = 1 and $p_{q,r}$ is slightly greater than $p_{s,r}$ (e.g., Experiment Index = 9, 10 in Fig. 3(b)). This observation helps to validate our analysis on EECC performance in Section V.

Second, relaying by the receiver's cooperator ($t \in T$) is more efficient than by the sender's cooperator ($q \in Q$) in general. The reason is that the receiver's cooperator is able to reach the next hop of the receiver directly, while the sender's cooperator just substitutes for the original sender to retransmit the packet to the receiver with a relatively better link. We could even notice that it becomes less effective to invoke the cooperation by the sender's cooperator when $p_{routing}$ becomes relatively higher, as shown in Fig. 3(b), Fig. 4(b) and Fig. 5(b). Therefore, EECC can be an optional choice if the sender has a good transmission link to the receiver while there are no receiver's cooperators.

The above two observations imply that a proper network density can provide EECC with more and better cooperation opportunities to minimize excessive transmission costs caused by unreliable links and packet losses. We argue that it is not so difficult to satisfy this condition since many applications have already required high density deployment of sensor nodes.

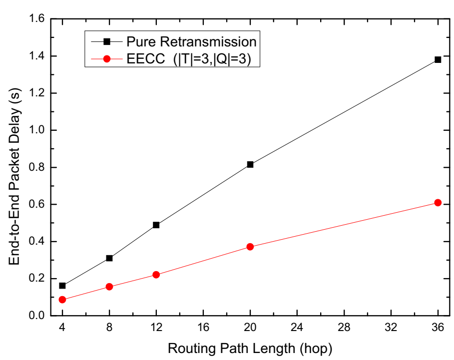

Fig. 6. Comparison on end-to-end packet delay.

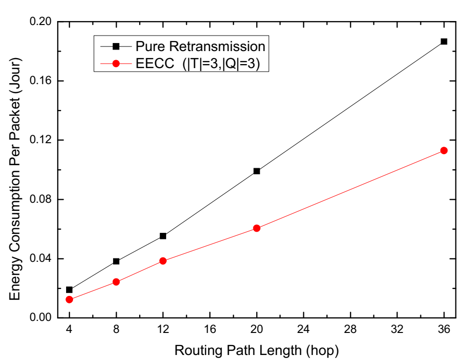

Fig. 7. Comparison on energy consumption per packet.

In the second set of experiments, EECC is evaluated in the multi-hop transmission scenarios, by measuring end-to-end packet delay and energy consumption per packet. The network is densely deployed so that for each intended node, $|T| \geq 3$ and $|Q| \geq 3$. The routing metric is the same as that introduced in [19]. The results are averaged from multiple simulation runs. As shown in Fig. 6, EECC significantly reduces end-to-end packet delay as compared to the pure retransmission method. An examination of ns-2 simulation traces reveals that this is attributed to a considerable decrease in the number of packet retransmissions: without EECC, the intended sender will time-out and resend the lost packet. The delay caused by such time-outs is far longer than that introduced by the new NAV setting in EECC. On the other hand, EECC is able to decrease such time-outs by node cooperation on data transmission, and thus effectively reducing the end-to-end delay. Meanwhile, the decrease in retransmissions also results in the energy saving for packet transmission, as shown in Fig. 7. These results justify the application of EECC in large-scale sensor networks with energy constrained sensor nodes and unreliable wireless links.

I. Conclusion

In this paper, we proposed an energy-efficient cooperative communication scheme (EECC) for unreliable sensor networks. This new scheme takes advantage of cooperative transmission to enhance the routing robustness against link unreliability. A best cooperator is elected from qualified neighbors of the relay node on the routing path to participate in the data transmission. In this way, EECC can reduce the total number of transmission times in the network. Through analysis and experiments, we validate that EECC is capable to improve data transmission efficiency in the sensor network with unreliable wireless links.

As future work, we would study how to extend EECC to operate in the presence of node mobility [24] or network congestion [25]. The scheme may need to be modified so that cooperative node sets could be updated in time to compensate for frequent changes of the link quality.

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