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QoS-aware distributed adaptive cooperative routing in wireless sensor networks

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ABSTRACT

In this paper, we investigate a cooperative routing problem in time-varying Wireless Sensor Networks (WSNs) targeting the achievement of quality-of-service guarantees in delay and reliability domains. We develop a distributed adaptive cooperative routing protocol, called DACR, that exploits cooperative communication on top of delay- and energy-aware end-to-end routes and optimizes the trade-off between the reliability and delay through Lexicographic Optimization at each hop. We employ a lightweight reinforcement learning method to update the routing nodes with knowledge of expected performances that could be provided by the candidate relay nodes, helping to determine the optimal relay with the least overhead. The decision of selecting a transmission mode (i.e., direct or relayed transmission) at each hop is taken adaptively so that the reliability is maximized. The performances of our DACR have been evaluated through ns-2 simulations for a wide range of link failure rates and data traffic generation rates and the results show that the DACR outperforms a number of state-of-the-art protocols.

1. Introduction

In a number of mission-critical applications of Wireless Sensor Networks (WSNs), such as battlefield surveillance, disaster response, wildlife monitoring, radioactive radiation monitoring, and so on, the sensed data packets have to meet certain quality-of-service (QoS) levels in multiple domains (e.g., end-to-end delay, reliability, i.e., packet delivery ratio, network resources, and so on) [1,2]. For example, in radioactive radiation monitoring application, the sensed data packets carrying radioactive leakage detection information need to be delivered to the control center within a predefined limited time while maintaining a certain level of packet delivery ratio for reliable event perception. However, due to time-varying wireless channel, dynamic network topology, and severe constraints on energy and computation power of tiny sensor nodes, achieving these QoS requirements in WSNs is a challenging problem.

In this paper, we exploit cooperative communications [3] to investigate QoS provisioning for mission-critical applications of WSNs, in the delay and reliability domains. The applicability of cooperative communication in resource-constrained WSNs is advantageous for the following reasons: (i) it exploits the spatial diversity gain in multiuser wireless systems to combat the effects of channel fading, (ii) it does not necessitate multiple antennas at each node; and (iii) it reduces energy consumption while improving network performance [4–6]. Cooperative routing, a routing method that uses cooperative communication, is effective for multihop WSNs because it involves more nodes in carrying data packets toward the

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destination sink, thus increasing the energy-distribution among the nodes [7,8]. The cooperation mechanism is the key to the performance of cooperative routing systems; however, it is challenging to find the optimal cooperative policies, e.g., when to cooperate, how to cooperate and with whom to cooperate, in a dynamic wireless network environment.

Although there has been significant effort to study cooperative routing systems, little work has been done on QoS provisioning in wireless networks exploiting such systems, especially in the context of achieving multiobjective QoS services, e.g., end-to-end (e2e) delay, reliability, network lifetime, and so on. REER [9] investigated the problem of reliable data delivery from many sensors to the destination sink by exploiting advantages of geographic and cooperative routing. A trade-off analysis between reliability and energy-efficiency was also carried out in that study. Backpressure-based control algorithms in dynamic cooperative policies have been developed in [10] for delay-limited mobile ad hoc networks to achieve the time average reliability and energy-efficiency. However, computing the optimal stationary, randomized policy explicitly can be challenging and often impractical in WSNs, since it requires advance knowledge of arrival and channel probabilities. A multi-agent reinforcement learning based cooperative communication mechanism (MRL-CC) has been proposed for QoS provisioning in delay and reliability domains for WSNs in [11]. Each MRL-CC candidate relay node maintains its *Q*-values and those of its cooperative partners. When a packet is received by a group of cooperative nodes, each node compares its own *Q*-value with that of others; and the node that determines it has the highest *Q*-value is elected to forwarding the data packet to the adjacent cooperative nodes toward the sink. Thus, the *reactive* relay selection mechanism of MRL-CC not only increases the overhead, but also fails to utilize the appropriate network channel conditions, since the *Q*-value alone does not reflect the exact qualities (e.g., delay, packet delivery ratio, energy-level) of the available relays. An extended version of this work is also presented in [12] by the same authors with similar contributions.

In this paper, we present a distributed adaptive cooperative routing (DACR) protocol to achieve the QoS requirements in the reliability and delay domains under the node energy level constraint. In DACR, an AODV [13]-based delay- and energy-aware e2e route from a source to the destination sink is created first, on which the data packets are transmitted using either direct transmission or relayed transmission mode. At each hop, the source of the link adaptively chooses the transmission mode that maximizes the per-hop reliability, given that the delay and energy constraints are maintained. The optimal relay selection criteria of DACR are locally available at each routing node. These criteria are the expected delay and reliability values that can be offered by a candidate relay node, if it is selected, and its residual energy level. Each routing node periodically learns the aforementioned criteria for all the candidate relays using a lightweight reinforcement learning (RL) method [14]. It then executes a lexicographic optimization (LO) [17] algorithm (with two functions) to determine the best relay *proactively* among the feasible candidates. What follows, we summarize the contributions of this work.

- We propose an adaptive cooperative routing protocol, which can be executed in a distributed manner without requiring *global* channel state information (CSI) at each relay or at a central controller in the network, thereby reducing the required cooperation overhead.
- We show that our hop-by-hop dynamic decisions about cooperation effectively optimize the QoS performances in the delay and reliability domains.
- We show that *proactive* relay selection is more efficient than *reactive* one in terms of trading-off the QoS performance improvements and operation overhead.
- We also show that our energy-aware route discovery and relay selection yield excellent energy-distribution among the network nodes, thereby increasing the network lifetime.

The rest of this paper is organized as follows. In Section 2, we describe the limitations of existing cooperative routing algorithms in meeting QoS requirements of WSN applications. In Section 3, we present the system model and the assumptions made in this work. The DACR architecture in described in detail in Section 4, and performance evaluations using Network Simulator-2 [18] are explained in Section 5. Finally, we conclude the paper in Section 6 and offer insights for further works.

2. Related works

A large number of prior studies on cooperative communication have investigated the problems of minimizing sum power [6,8,19], minimizing outage probability [20,21], meeting target throughput or SNR constraint [22–24] and references therein. It has been well demonstrated that the cooperative communication is effective in combating the multiple fading effects in wireless networks, and improving the network performance in terms of energy-efficiency, adaptivity, outage probability and network throughput. For example, in minimum power cooperative routing (MPCR) system [6], the cooperative routes are constructed based on the Bellman–Ford shortest path algorithm in terms of power usage and it has been proved, through analysis, that MPCR algorithm can have up to 37.64% power saving in random networks compared to traditional routing systems.

Recently, many researchers have focused on the advantages of cooperative routing systems. [25] proposes two interference-aware routing schemes for CDMA ad hoc networks, which enforce cooperation among nodes to determine the interference-minimized high throughput routes. Improvement in throughput of up to 60% has been observed compared to the classic minimum energy routing approach. Also, an interference-aware performance metric based on the effective data rate is formulated and evaluated in [26]. In [7], a throughput optimal distributed cooperative routing scheme is developed by constructing a contention graph based on virtual nodes and virtual links. An enhanced relay selection metric for cooperative communication is formulated in [27] by exploiting channel state information (CSI) and the residual energy of sensor nodes. However, QoS provisioning issues in the delay or reliability domains have not been explored previously.

Refs. [9–12] presents several proposals for QoS-aware cooperative routing systems. In [9,10], cooperative routing algorithms are developed to enhance the reliability in energy-constrained networks. The cooperative relay selection is based on the offered reliability of the candidate nodes. The performances have been analyzed to examine the trade-off between the reliability and energy-efficiency. However, they have not consider the e2e delay minimization problem. In [11,12], the QoS-aware cooperative routing algorithms are developed in both the delay and reliability domains, wherein it is assumed that the *Q*-value of a node represents the quality of its packet forwarding in terms of delay and packet loss ratio. Each candidate cooperative node maintains its *Q*-values and those of its cooperative partners, and when a packet is received by a group of cooperative nodes, each node compares its own *Q*-value with those of other nodes. The node that determines it has the highest *Q*-value is elected as the best relay and forward the packet to the adjacent node toward the sink. Thus, the *reactive* relay selection mechanism of [11,12] not only increases the overhead but also fails to utilize the appropriate network channel conditions, since the *Q*-value does not reflect the exact qualities (e.g., delay, packet delivery ratio, energy-level) of the available relays.

Out of the existing systems, MRL-CC [11] is the most similar to our approach. However, there are a few fundamental differences between the two. *First*, MRL-CC operates on a multihop mesh cooperative structure for data dissemination in WSNs, whereas in DACR, an e2e delay- and energy-aware path between the source node and the destination sink is created first on which the cooperative routing works. *Second*, MRL-CC uses the node with the highest *Q*-value as the relay node, but in our DACR, the problem of the best relay selection is converted into a Lexicographic Optimization (LO) problem that selects the node offering higher link reliability and lower delay under the minimum residual node-energy constraint. *Third*, MRL-CC's relay selection is *reactive*, i.e., after the source's transmission of a data packet, the node having the highest *Q*-value is elected as the best relay node; whereas DACR employs a *proactive* approach, the source node finds the best relay by executing LO functions before transmitting the data packet, reducing the overhead. *Finally*, at each hop of a path, MRL-CC routers exploit cooperative transmissions, whereas, DACR routers decide adaptively whether to use direct or cooperative transmissions based on the link conditions.

3. System model and assumptions

Consider a wireless sensor network consisting of a randomly distributed large set of sensor nodes where each node has a single omnidirectional antenna. The delay- and reliability-constrained sensing data packets flow from many sensors to a destination sink node (placed anywhere in the network) in multihop fashion. For each data packet, the application layer restricts a predefined e2e reliability requirement (K_{rel}^{e2e}) and delay-deadline (K_{del}^{e2e}), where, K_{rel}^{e2e} is the ratio of the total number of received packets by the sink to the number of sent packets by the sensor nodes, i.e., it defines the required minimum percentage of packets that should be delivered to the sink for reliable event perception; and, K_{del}^{e2e} is the time limit within which the packet must be reached at the destination sink, otherwise the content information of the packet will not be useful for the control center.

Furthermore, the wireless channel of the network is modeled as follows. The links between any two sensor nodes in the network is subject to narrowband Rayleigh fading, propagation path-loss, and additive white Gaussian noise (AWGN). The channel fading for different links is assumed to be statistically mutually independent; this assumption is reasonable since the nodes are usually spatially separated. In such an environment, the system requires an adaptive communication protocol that can meet up the above QoS requirements through cooperative spatial diversity.

We assume that, at each routing node of a multihop path from the source to the destination, neighbor nodes cooperating in sending the information to its next-hop node can precisely time their transmitted signal to achieve perfect phase synchronization at the receiver.[1] Rather selecting multiple relays at each routing hop, we use single-relay cooperative transmission, which has been evaluated as the most effective strategy considering the achievable network performance and the corresponding protocol operation overhead [8,11,12]. Under this setting, the information is routed to the next-hop node in a sequence of transmission slots, where each transmission slot corresponds to one use of the wireless channel. In each transmission slot, either a node is selected to broadcast the information to a group of nodes, or a selected relay node that have already received the information cooperate to transmit that information to the destination node, which is known as *cooperative or relayed-transmission* (*RTx*) [28]. Once a node is selected as relay, it gives higher priority to relay packets from other nodes than transmitting its own packet. Cooperation results in additional spatial diversity by introducing this artificial multipath through the relay link, which can, in turn, enhance the transmission reliability against wireless channel impairments such as deep-fading. At any hop of the path, a router may also opt for *direct transmission* (*DTx*) to its next-hop node if cooperation is not necessary.

The nodes are assumed to transmit over a single communication channel using any CSMA/CA-based medium access control protocol. The receiver uses Maximal Ratio Combining (MRC) [3] technique to decode the signals received from the source and the relay nodes. We also assume that the nodes use fixed transmission power and they work in half-duplex mode, i.e., any node cannot transmit and receive simultaneously.

We also emphasize that since the sensor nodes have limited computation power and are battery-operated, the solution methodologies should be light-weighted,

[1] This is a reasonable assumption for cooperative communications [8].

requiring less complex computations, exchanging minimum number of messages and thus consuming less energy.

4. The DACR architecture

The QoS-aware cooperative routing problem can be viewed as a multistage decision making problem, where the decision at each stage is to pick the transmission mode $m \in \{DTx, RTx\}$ as well as the best relay node, if necessary. The objective is to send the information to the destination satisfying the QoS requirements. In this paper, we convert QoS-aware routing decision into an optimization problem under our model and solve it by linear optimization. Fig. 1 shows the architectural components of our distributed adaptive cooperative routing protocol (DACR) and in the following subsections, we describe their design issues in detail. We first present an AODV [13]-based ad hoc routing algorithm DEAR that creates an e2e path from source to destination avoiding energy-critical nodes and minimizing the e2e delay. The DEAR also helps to identify sets of relay nodes $\mathbb{R}$s for the source and all intermediate nodes Is on the path, as shown in Fig. 2. We then present algorithms for optimal relay selection and adaptive transmission mode selection.

4.1. Delay- and energy-aware routing

Since energy is the most important constraint in a wireless sensor network, each sensor node has to manage its energy intelligently in addition to follow the rules regarding QoS provisioning of the underlying applications. A routing layer protocol along with cooperative communication option might be much effective to enhance this energy management. In our protocol, whether a node would work as a *router* of a multihop route from source to destination or as a *relay* for any source will be decided by it dynamically based on its current residual energy level. If the node has very low energy (i.e., less than certain threshold), it will defer any responsibility (either as a router or as a relay) even the performance that it can provide is better than other neighbor nodes.

In this section, we develop a delay- and energy-aware routing protocol (DEAR) that creates an e2e path from source to destination sink. The design principle of DEAR

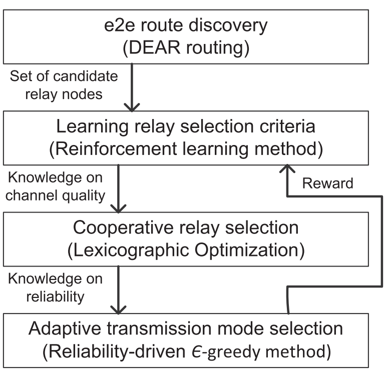

Fig. 1. The components of our DACR protocol.

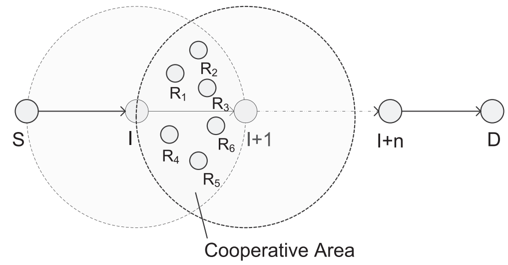

Fig. 2. Multi-hop cooperative routing path in WSNs.

is based on AODV with some modifications. Like in AODV, when a route is required, a DEAR source node broadcasts a route request (RREQ) packet. However, unlike in AODV, a DEAR source node tags a RREQ packet with a timestamp value T and a minimum node energy threshold value E_{th}. We replace the AODV RREQ fields 'hopcount' and 'reserved' with T and E_{th}, respectively; and thus incur no extra overhead or modifications to the basic RREQ packet structure. A neighbor node rebroadcasts this RREQ packet upon reception, only if the residual energy of the node is higher than the specified threshold value E_{th}. Also, the neighbor node deducts the sojourn period of the RREQ packet from the timestamp T before rebroadcasting the packet. Thus, like in AODV, multiple copies of the RREQ packet eventually reach the destination sink. The sink then returns a route reply (RREP) packet toward the source node for the RREQ packet with highest T value. Thus, a delay-minimized e2e path $\mathcal{P}$ is established consisting of non energy-critical nodes.

Note that T has a large initial value inserted by source nodes in the RREQ packets and is predefined by the sink node. All source nodes use the same T value when broadcasting RREQ packets. The update policy of T value at the intermediate nodes does not require any clock synchronization and works as follows. As a RREQ packet travels toward the sink, intermediate nodes update $T = T - T_{sojourn}$, where $T_{sojourn}$ is the sojourn period of the RREQ packet at an intermediate node. We measure the *sojourn period* at each node I and tag the packet with the updated T value and rebroadcast it. For this, when a node I receives the last bit of a RREQ packet, its MAC layer keeps record $T_{arrival}$ for the packet. The node I might need some time to process the packet and capture the channel before rebroadcasting it. The MAC layer calculates $T_{sojourn}$ just before it actually transmits the packet to the physical link as follows, $T_{sojourn} = T_{departure} + T_{transDelay} - T_{arrival}$, where $T_{departure}$ is the time at which node I transmits the first bit of packet to physical link and $T_{transDelay}$ is the transmission delay of the packet which can be computed using the transmission rate and packet length. Thus, any node $I+1$ receiving this RREQ gets the correct measurement of the updated T value without requiring any clock synchronization among the nodes. Finally, the sink node can easily determine the minimum delay path $\mathcal{P}$ by observing T values of the received RREQ packets.

Furthermore, unlike in AODV, DEAR route error (RERR) packets are generated by any node I on the path when any one of the following two conditions holds true: (a) the forwarding link from I to $I+1$ fails or (b) the residual energy of I falls below the threshold value. The second condition guarantees that an intermediate node will not die out of energy for carrying others data traffic. Note here that the amount of energy consumption by the intermediate node I for transmitting one or two RERR messages is trivial and thus the mechanism does not cause battery of the node die fast. In what follows, we describe how the DEAR routing packets are exploited by nodes on the routing path for developing a set of candidate relay nodes for each of them.

4.2. Cooperative relay-selection

For each hop on the cooperative routing path, determining the set of candidate relay-nodes ($\mathbb{R}$) between two adjacent routers and selecting the optimal one from among them is challenging. We address the first part of the problem by exploiting the routing packets of our DEAR protocol as follows. Once the route from the source to the destination is discovered, for two adjacent routers along the route, e.g., I and $I+1$, as shown in Fig. 2, any node can determine that it is a relaying candidate for them if it has received the RREQ packet broadcasted by I, and the RREP packet replied by $I+1$, and has not been selected by I as the next hop router in the route discovery procedure. Then, each $R \in \mathbb{R}$ relays the RREP packet (received from $I+1$) to node I and thus I comes to learn the set of candidate relay-nodes $\mathbb{R}$. In what follows, we present solution to the second part of the problem, i.e., selecting the most optimal relay from $\mathbb{R}$.

4.2.1. Optimal relay-selection criterion

The variation in channel quality affects the reliability and delay performances associated with the direct and cooperative transmission options. Also, the advantages of relay cooperation often depend on sufficiently reliable interuser channels. For example, in the decode-and-forward (DF) scheme, a node relays the message from the source only if it decodes the message reliably. Similarly, in the amplify-and-forward (AF) scheme, the quality of the relayed signal is limited by the quality of the source-relay link since both the signal and noise are amplified at relays. Therefore, relays should be adopted only if the source-relay channel is sufficiently reliable. Our second concern is the minimization of delay incurred by cooperative transmission since the packets transmitted via relay nodes might experience additional delays. This observation leads to the selective relaying (SR) cooperation scheme where relays are selected adaptively to retransmit the source message only if the quality of the transmission over the interuser channel meets a certain criterion. In this work, we define the reliability $r_{I,I+1}$ of a link between two nodes I and $I+1$ as the ratio of the number of packets received by $I+1$ to the number of packets sent by I over a period of time t. Since reliability is a multiplicative metric, the link reliability can be expressed as follows

$$r_{I,I+1} = \begin{cases} r^{DTx}_{I,I+1} & \text{Direct Tx.} \\ \\ r^{RTx}_{I,R,I+1} = r_{I,R} \times r_{R,I+1} & \text{Relayed Tx.} \end{cases} \quad (1)$$

Note here that transmission on the link (I,R) has no acknowledgment and thus it would be expensive for I to learn the link reliability $r_{I,R}$. When the next hop node $I+1$ receives the retransmitted signal from the relay node R, it tries to extract the packet information from received signals (from I and R) using Maximal Ratio Combining (MRC) method [3]. If node $I+1$ can correctly extract the information, it sends back an acknowledgment to I. Thus, the sender node I learns that the data packet has been correctly received by its next hop destination $I+1$ and can calculate the link reliability for relayed transmission, $r^{RTx}_{I,I+1}$, based on the number of acknowledgment packets received and the number of data packets sent by it during any measurement interval t. For example, assume that the sender node I sends 100 packets, out of which 80 packets are correctly decoded by the relay node R and only 60 packets are successfully extracted by the next hop node $I+1$. Now, if the sender node I receives 60 acknowledgments from $I+1$ during a measurement interval t, then the link reliability measured by I will be $r^{RTx}_{I,I+1} = 60/100 = 0.6$. Therefore, Eq. (1) can be rewritten as follows

$$r_{I,I+1} = \begin{cases} r^{DTx}_{I,I+1} & \text{Direct Tx.} \\ \\ r^{RTx}_{I,R,I+1} = r^{RTx}_{I,I+1} & \text{Relayed Tx.} \end{cases} \quad (2)$$

Our second criterion aims to select a relay node that provides with faster communication between its source and destination, i.e., the problem of finding the relay having lower relay-over delay. The relay-over delay $t_{I,R,I+1}$ for a packet is measured by the time it requires to successfully transfer a packet from I to $I+1$ through R. This delay quantifies the quality of the link $(R, I+1)$ as well as the congestion level of the selected relay R. Let t_{TX} and t_{ACK}, during an update interval t, are the time points at which the first data packet has been transmitted and the acknowledgment for the last data packet has been received, respectively, then the average relay-over delay per packet can be calculated as

$$t^m_{I,I+1} = \frac{t_{ACK} - t_{TX}}{N_{suc}}, \quad m \in \{DTx, RTx\}, \quad (3)$$

where N_{suc} is the number of packets successfully transmitted. Separate measurements are carried out for direct- and relayed-transmissions, $m \in \{DTx, RTx\}$.

We exploit reinforcement learning (RL) method [14], which provides a framework in which an agent can learn control policies in dynamic environment based on *experiences* and *rewards*, as shown in Fig. 3, to enable a sender node to acquire knowledge on the above parameters. Here, the wireless channel characteristics and data traffic flows are corresponding to the dynamic environment and sensor nodes are the agents of the RL system. Our RL system is a model-free learning technique, which can address parametric optimization to maximize the long-term award [15].

We define the set of states S, the set of actions A and the set of rewards Rwd of our RL system as follows:

(*a*) *State* : $S = \{s\}, \ s \in \{I, \ \mathbb{R}, \ I+1\}$,

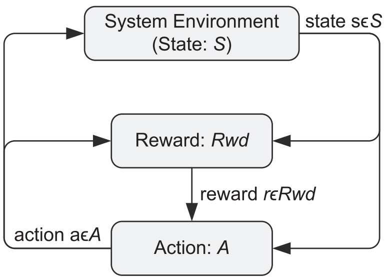

Fig. 3. The reinforcement learning system.

(*b*) *Action* : $A = \{a\}, \ a \in \{a_{DTx}, a_{RTx}, none\}$, where, the execution of a_{DTx} or a_{RTx} means that either direct-transmission or relayed-transmission, respectively, is selected by the agent. The selection policy will be detailed in Algorithm 1 in Section 4.3. The third option *none* will be chosen by the agent only when no node in the neighborhood environment is able to meet up the delay and/or reliability requirement of a given packet, as described at the end of Section 4.2.2.

(*c*) *Reward Function*: The *reward* is obtained when the agent executes an *action*. For each pair of consecutive routers, once a relay node or direct transmission is selected for delivering data packets (i.e., the *action* is executed), the performance of the transmissions is measured (during *t* periods of time) in terms of reliability and delay according to Eqs. (2) and (3), respectively, and the system gives reward to the sender of the communication as follows

$$Rwd = \begin{cases} K^m_{rel}(t) = (1-\alpha)K^m_{rel}(t-1) + \alpha r^m_{I,I+1}(t) \\ K^m_{del}(t) = (1-\alpha)K^m_{del}(t-1) + \alpha t^m_{I,I+1}(t), \end{cases} \tag{4}$$

where, $K^m_{rel}(t)$ and $K^m_{del}(t)$ are the updated knowledge on the reliability and delay, respectively, for direct- and relayed-transmission modes, $m \in \{DTx, RTx\}$. Rewards are given corresponding to the actions taken, i.e., if relayed transmission is chosen, the knowledge is updated for the selected relay node R, denoted as $K^{RTx}_{rel}(t,R)$ and $K^{RTx}_{del}(t,R)$. Note here that the exponential weighted moving average (EWMA) formula, with weight factor α, has been used to update the knowledge, in which the weighting for older data values decreases exponentially, giving much more importance to recent observations. The rationale of using EWMA in updating knowledge of a node regarding performance of its transmission environment is that expected behavior of the wireless links heavily depends on the historical behaviors and that behavior is well captured by the EWMA.

Furthermore, note that the above RL system provides with the most updated knowledge on expected performances of neighborhood nodes without using any complicated prediction techniques, or explicitly frequent updating and maintaining of precise network state information. In what follows, we discuss on the method of selecting the most optimal relay based on the knowledge acquired from the RL system.

4.2.2. Optimal relay-selection algorithm

Once the sender node learns the knowledge of its transmission environment, i.e., the performances of the relayed transmissions for different candidate relay nodes $R \in \mathbb{R}$, the problem of determining the optimal relay node boils down to formulating an equation that optimizes the trade-off between the reliability and delay. More elaborately, our goal is to select a relay node that provides with comparatively higher reliability and reduced delay toward the destination. Note that while the second criterion looks for a lightly-loaded relay, the first one attempts to choose a relay that can ensure a high quality linkage between the source and the destination. A weighted linear combination of the objective parameters may suffice to solve the problem [2]. However, the key problem of this technique is to set the optimal weight values associated with the parameters and wrong values might lead to produce a combined metric that fails to guarantee the QoS requirements [16].

Our proposed relay-selection algorithm uses a multiobjective Lexicographic Optimization (LO) approach [17] to manage this trade-off. In LO, the objective functions are arranged according to their absolute importance and the most important objective function is minimized first subject to the original constraints. If this problem has a unique solution, it will solve the whole multiobjective optimization problem. Otherwise, the second most important objective function is maximized (or minimized). Now, in addition to the original constraints, a new constraint is added. This new constraint is imparted to guarantee that the most important objective function preserves its optimal value. If this problem has a unique solution, it solves the original problem; otherwise, the process goes on as above.

In solution to our problem, there are only two objective functions of which the first one, the maximization of the reliability, is the most important. Let the objective functions be arranged according to the lexicographic order, with the most important function being, $f_1(R) = K^{RTx}_{rel}(t,R), \ \forall R \in \mathbb{R}$ and the least important one being $f_2(R) = \frac{1}{K^{RTx}_{del}(t,R)}, \ \forall R \in \mathbb{R}$. Thus, we write the lexicographic problem for any node $I \in \mathcal{P}$ on the path $\mathcal{P}$ as follows:

$$\text{lex maximize } f_1(R), \ f_2(R) \tag{5}$$

$$\text{subject to} \quad R \in \mathbb{R}. \tag{6}$$

The above LO problem can be divided into two separate problems with different constraint sets. The first problem is formulated as

$$\text{maximize} \quad f_1(R) \tag{7}$$

$$\text{subject to} \quad R \in \mathbb{R} \tag{8}$$

$$K^{RTx}_{rel}(t,R) \geqslant K^{min}_{rel}, \quad \forall R \in \mathbb{R} \tag{9}$$

$$E^R_{res} \geqslant E_{th}, \quad \forall R \in \mathbb{R}, \tag{10}$$

and its solution R^*_1 and $f^*_1 = (R^*_1)$ is obtained; here, E^R_{res} is the residual energy level of node R and K^{min}_{rel} is the minimum threshold link-reliability level that must be provided by the selected relay node. The measurement for K^{min}_{rel} has been carried out in Appendix section. The constraint in Eq. (10) restricts the system to select a relay node having residual energy below the threshold level even if it satisfies the other criteria well. This restriction allows relay nodes not to exhaust their minimum energy levels for carrying others data traffic; and thus, it avoids creating routing holes, ensures better sensing coverage and balanced energy consumption among the relay nodes at each hop, which in turn helps to improve the network lifetime.

Our second problem can be formulated as follows

$$\text{maximize } f_2(R) \tag{11}$$
$$\text{subject to } R \in \mathbb{R} \tag{12}$$
$$K_{rel}^{RTx}(t,R) \geqslant K_{rel}^{min}, \quad \forall R \in \mathbb{R} \tag{13}$$
$$E_{res}^{R} \geqslant E_{th}, \quad \forall R \in \mathbb{R} \tag{14}$$
$$K_{del}^{RTx}(t,R) \leqslant K_{del}^{max}, \quad \forall R \in \mathbb{R} \tag{15}$$
$$f_1(R) = f_1^*, \tag{16}$$

and the solution of this problem is R_2^* and $f_2^* = (R_2^*)$; here, K_{del}^{max} is the maximum allowable link-delay if packets are retransmitted through R and its value is analyzed in Appendix section. If R_2^* does not produce a unique solution, we break the tie by selecting the one that provides with higher reliability. With the proposed scheme, actually the link with the best quality in terms of reliability and delay, is used. Such a strategy makes our system robust to link dynamics.

In solution to the above optimization problems (7) and (11), in worst case, there may arise a situation that neither a routing node can find a single relay in its vicinity, which can meet up the minimum threshold link-reliability level K_{rel}^{min} and/or the maximum threshold link-delay level K_{del}^{max} for a certain packet nor the direct link could meet up the requirement. In such cases, we intentionally drop the packet assuming that its on-time delivery probability to the sink gets highly reduced due to poor neighborhood environments. A similar packet dropping policy was also adopted in MMSPEED [1] and DARA [2]; it has the following advantages: (a) it decreases the network traffic load thereby allowing other viable packets to reach the destination in time and (b) it decreases the energy wastage for carrying useless packets.

Note that the nice property of LO is its simplicity. The added computational expense of solving multiple optimization problems at each instant is not significant since simple linear equations are solved out. Therefore, such a lightweight but effective method is suitable for resource-constrained wireless sensor networks. Even though LO has the drawback of neglecting less important objective functions when the most important one produces the unique solution, in our case, such situations should occur less frequently due to the high density of the network nodes. Moreover, LO exploits only local information to make relay-selection decisions. The absence of a global information exchange scheme reduces the networks setup and updating costs and alleviates the possibility of incorrect information at the nodes as changes in system topology occur.

4.3. Adaptive transmission mode-selection algorithm

Our decision on whether to use direct or cooperative transmission from any source or intermediate node to its next-hop destination is adaptive to the conditions of the links I-to-$I+1$, I-to-R and R-to-$I+1$. The adaptation is made on the basis that there is no need for any relay to forward the source's information if the direct link between the source and the destination is of high quality. A source or an intermediate node makes its decision for direct and relay-based transmission mode $m \in \{DTx, RTx\}$ which yields the higher reliability.

Algorithm 1. Transmission mode selection algorithm for any node on a routing path

Initialization: Initialize K_{rel}^{m} which is the knowledge about the reliability
repeat
  if $K_{rel}^{DTx} > K_{rel}^{RTx}$ **then**
    if $RANDOM() \leqslant \epsilon$ **then**
      The node irrationally chooses relay-based transmission (i.e., $m = RTx$)
    else
      The node rationally chooses direct transmission (i.e., $m = DTx$)
  end if
  else
    if $RANDOM() > \epsilon$ **then**
      The node irrationally chooses direct transmission (i.e., $m = DTx$)
    else
      The node rationally chooses relay-based transmission (i.e., $m = RTx$)
    end if
  end if

  During the measurement interval t, the node computes instantaneous reliability r^{dir} and r^{rel} using Eq. (2)
  The node updates knowledge K_{rel}^{m} using reinforcement learning method as of Section 4.2.1
until the path is broken or the connection is terminated

In the transmission mode selection algorithm (as shown in Algorithm 1), each node on the routing path maintains knowledge about the reliability, given decision on mode m made before. The knowledge K_{rel}^{m} is defined as the exponentially weighted moving average of the perceived reliability of a sensor node, which is used by the node to make the current decision. Once the current decision on mode selection is made, the resulting reliability is used to update the knowledge K_{rel}^{m}, as discussed in Section 4.2.1. To avoid local optimal decisions (e.g., due to the lack of complete network information), the routing node may make an irrational decision with very small probability bounded by ϵ, known as ϵ-greedy method [29], to explore reliability resulting from alternative decisions. In Algorithm 1, the *RANDOM*() function generates a fraction in between 0 and 1, *i.e.*, $0 < RANDOM() < 1$. Therefore, with the probability $1 - \epsilon$, the relay candidate which is expected to be able to make the most contributions will be selected as the optimal relay; and with the probability of ϵ, direct transmission will be executed.

4.4. Discussion

Thanks to the hop-by-hop reliability- and delay-driven data delivery options with adaptive cooperative routing, we can claim that once a packet reaches its destination, it is likely that the packet meets its e2e deadline. However, not all packets are guaranteed to reach their destination since we are compromising the e2e reachability (i.e., probability of reaching) by intentionally dropping packets to guarantee the on-time packet delivery. Similarly, to assure a certain level of reachability, we compensate for choosing a transmission that could provide with minimum delay; rather, we maximize the link reliability at each hop so that the total reachability is increased.

Setting an appropriate value of E_{th} for nodes in the network is an important performance tuning parameter, especially for achieving uniform energy-distribution. According to the LO functions, the higher the value is, the smaller is the set of viable candidate relay nodes at each hop, which in turn reduces the probability of choosing relay node with the best performance. Conversely, if the value of E_{th} is very low, the energy dissipation rates of nodes might vary greatly and shorten the network lifetime. In order to trade-off the above facts, we allow the sink to control E_{th} value of sensor nodes as follows, it starts with the 80% of the initial energy level and steps down further by 20% after a certain period of interval and so on.

The nice performances of our DACR protocol do not come out of cost. The operation overhead of DACR includes the RREQ and RREP messages exchanged during the e2e route discovery and computation for acquiring knowledge on expected delay and reliability performances of the neighbor nodes. However, since our reinforcement learning-based knowledge update method does not require any additional messages to exchange, its overhead does not scale much. As the dominant source of energy consumption is the sensor radio module, our DACR incurs less overhead than that of MRL-CC, where a large number of messages need to be exchanged for constructing mesh cooperative structure.

The main limitation of this paper is related to a lack of sufficient understanding about the dynamics of several estimation tuning parameters. For example, the measurement interval t, EWMA weight factor α and the value of ϵ were determined through numerous simulation experiments. If we could build an analytical model for them, we would be able to dynamically select the optimal values to adapt to different situations. We left it for future work.

5. Performance evaluation

We have evaluated the performance of DACR using simulation experiments conducted on NS-2 [18], which supports the simulation of multihop wireless networks complete with physical, data link, and MAC layer models. We have compared the results with those of the minimum power cooperative routing – MPCR [6], REER [9], and MRL-CC [11] systems. The setting of the simulation environment parameters is listed in Table 1. Considering the applicability of DACR in practical mission-critical applications such as radioactive radiation monitoring, battlefield surveillance, forest monitoring, etc., we have taken a large network area of 2000×2000 sqm, where 2000 homogeneous sensor nodes are deployed randomly, producing node density $\rho = 0.0005$. Such a deployment is practical in the sense that it ensures the sensing coverage with sufficient redundancy. More specifically, it gives the number of source nodes $= \rho \times PI \times R_s^2 \approx 15$ [30] within an event radius $R_s = 52$ m. Furthermore, the link layer data transmission rate, transmission range, sensing radius, buffer size and initial node energy that we have considered in our simulation are quite reasonable for available sensor motes [31].

We have used event-driven data collection approach since it is more suitable for mission-critical applications. Two separate bursts of data traffic from four randomly chosen events, listed in Table 2, are considered in the performance studies. In each burst, the event durations are set to 30 s (e.g., $10 \sim 40$ s) with triggering intervals of 10 s. Thus the events of a burst are time-overlapped, i.e., the network has to carry data traffics generated from 2 or 3 events simultaneously. This traffic pattern helps us to study the performance behavior of the protocols in dynamically varying traffic load environment. Furthermore, for each data point in the graphs, we take the average of results from 20 simulation runs, executed with different

Table 1
Simulation setting.

Basic specification	
Network area size	2000 m $\times$ 2000 m
Deployment type	Random
Network architecture	Homogeneous and flat
Number of nodes	2000
Sink location	(1000, 1000)
Initial node energy	10 J
Buffer size	50
Radio range	100 m
Sensing radius	52 m
Link layer trans. rate	512 Kbps
Transmit power	$7.214e^{-3}$ W
Rcv. signal threshold	$3.65209e^{-10}$ W
Link failure rate, f	0.3
MAC	IEEE 802.11 DCF
Simulation time	200 s
Sensed traffic specification	
Application type	Event-driven
Sources in one event	≈15 Nodes
Packet size	64 Byte
Traffic type	CBR (3 pps)
DACR specification	
K_{rel}^{e2e}	0.8
K_{del}^{e2e}	500 ms
Measurement interval, t	2 s
EWMA weight factor, α	.2
E_{th}	5 J (initial value)
ϵ	0.1

Table 2
Events and bursts description.

	Event 1	Event 2	Event 3	Event 4
Burst 1	10–40	20–50	30–60	40–70
Burst 2	100–130	110–140	120–150	130–160

random seeds. Thus, the variations in the obtained results mainly occur due to the randomness of the event locations and network topology.

5.1. Performance metrics

We define the following metrics for performance comparisons:

- *Average end-to-end delay* – of a single packet is measured as the time difference between when the packet is received at the sink and its generation at the source node. Delays experienced by individual data packets are averaged over the total number of packets received by the sink. Lower value is correspond to the better performance.
- *On-time packet delivery ratio (i.e., reliability)* – is the ratio of the total number of packets received by the sink within the delay-deadline to the total number of packets generated by all the source nodes in the network. Higher value is correspond to better transmission efficiency.
- *Energy expenditure per successful packet delivery* – is measured as the ratio of total amount of energy dissipated by all source and forwarder nodes of the network for transmission, reception and overhearing to the total number of packets received by the sink. Therefore, if the same amount of total energy is dissipated by any two protocols then the one that has higher reliability performs better.
- *Protocol operation overhead* – is expressed as the number of control messages per successful data delivery, i.e., it can be measured as the ratio of the number of control messages transmitted to the number of data packets delivered to the sink before the expiratio of the network lifetime.
- *Integrated performance* – We plot graphs for integrated performances of the protocols in terms of reliability, delay and energy using the following relationship: Integrated performance = Reliability/(Energy $*$ Delay). Higher value is correspond to the better performance.
- *Network lifetime* – Since a node participates in transmissions from other nodes in addition to its own transmissions in a cooperative scenario, its lifetime depends on the energy consumed in both cases. Hence, we define the lifetime of a node in terms of the energy consumption per unit time. Thus, the lifetime of a node I with initial energy E_0 can be expressed as $LifeTime(I) = \frac{E_0}{e_I}$, where, e_I denotes the energy consumption per unit time for node I. We assume that all nodes have the same initial battery life. We can, therefore, define the network lifetime as the minimum lifetime of all nodes as follows: $LifeTime(network) = \min_{I \in N} LifeTime(I)$, where, N stands for all nodes in the network.

5.2. Results

5.2.1. Impacts of the link failure rate

In this section, we discuss the impacts of different channel conditions on the performances of the protocols. In this paper, we express the channel condition in terms of the link failure rate f and we vary the value of f from 0.05 to 0.5 by the step size of 0.05 keeping all other parameters in Tables 1 and 2 fixed.

The simulation results, as shown in Fig. 4, indicate that the performances of the protocols decrease as the link failure rate f increases in terms of all the performance metrics, as expected theoretically. However, the rate of performance degradation varies greatly between protocols. For example, in Fig. 4(a), even at lower values of $f(< .20)$ the average e2e packet delays of our DACR and MRL-CC protocols are similar; the gap between them increases sharply as f increases; and, we observe an improvement in the performance of DACR over MRL-CC as high as 37.6%. Our in-depth look into the simulation trace file reveals that when f increases, the quality of network environment measurement through node's Q-value in MRL-CC is insufficient to antagonize the high link failure rates. In DACR, relay-over delays of packets are observed during t period of time and knowledge on expected delay of a packet for different potential relays (as well as direct transmission) are updated through RL method exploiting EWMA formula. Therefore, more accurate measurement on network environment is captured by our DACR, thus helping to select the optimal mode of transmission and relay node (if required) and contributing to achieve faster e2e packet delivery. Moreover, the data delivery over the delay- and energy-aware routing (DEAR) path in DACR gives it added advantage in reducing delay compared to multihop mesh cooperative structure in MRL-CC. Also, the average e2e packet delays experienced by REER and MPCR protocols are incomparable to our DACR since they optimize mainly reliability and power, respectively.

Comparing graphs of Fig. 4(a) and (b) we can state that the cooperative routing systems are more robust to handling link failures in terms of reliability performance opposing to delay performance. More than 80% packets reach at the destination in time for all the protocols when $f \leqslant 0.3$, as shown in Fig. 4(b). The reliability performance of REER protocol is similar to that of our DACR until f reaches to 0.30. Beyond that, the performance of REER reduces at higher rate and as much as only 10.4% degradation compared to DACR is observed. This nice performance of REER comes from the fact that it is based on geographic routing (i.e., uses location information through GPS) and it can handle the dead-end routing problem efficiently. However, it experiences a significant amount of packet drops due to collisions since it does not consider the traffic load of neighborhood nodes while selecting relays and next-hop nodes. Thus, its performance is affected, especially, at higher values of f. On the other hand, DACR's adaptive decisions on transmission mode and relay selections at each hop maximizes the per-hop reliability and makes it more robust to link failures, achieving more than 80% on-time packet delivery even at 50% link failures.

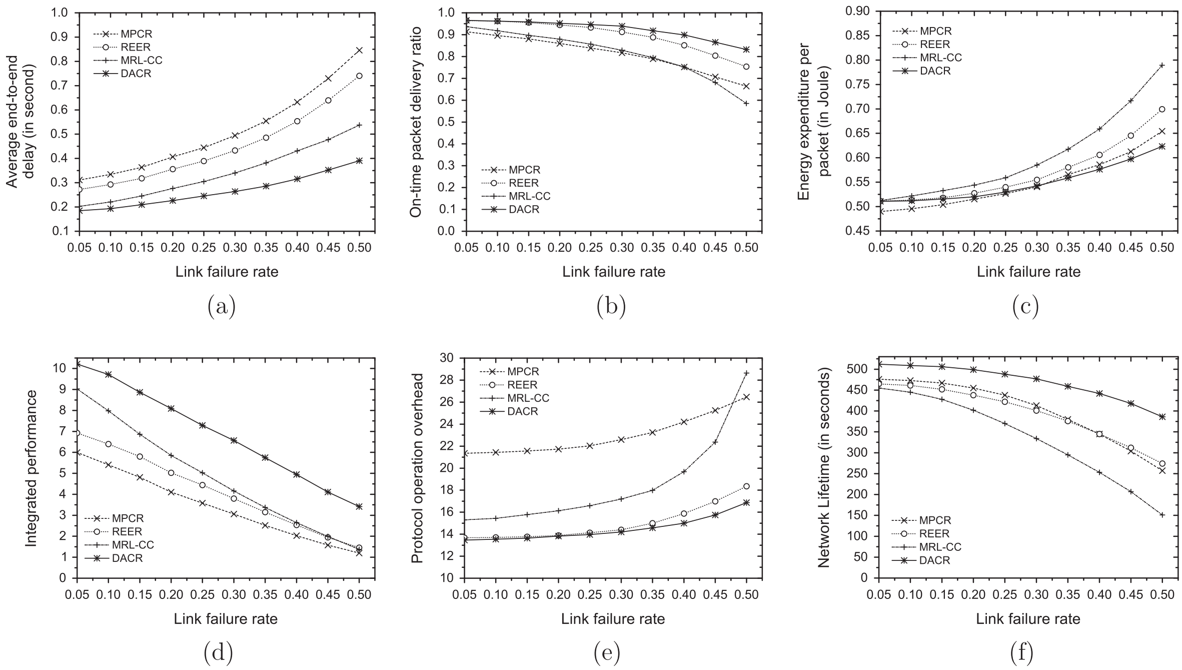

Fig. 4. Performance comparisons for varying link failure rates with data traffic load = 3 pps. (a) Average end-to-end delay. (b) Reliability. (c) Energy expenditure. (d) Integrated performance. (e) Protocol overhead. (f) Network lifetime.

The energy expenditure per successful packet delivery in MPCR is the lowest among the studied protocols till *f* reaches to 0.30, as shown in Fig. 4(c). This is due to MPCR's policy of minimum power routing and relay selection procedures. However, it experiences a large number of packet drops due to collisions and buffer overflow at intermediary hops when *f* is larger, thus increasing the per packet energy expenditure. Nevertheless, as expected theoretically, the simulation trace file content reveals that our DACR protocol can't save total energy consumption of the network nodes compared to REER and MRL-CC. But, since it achieves higher delivery ratio, its per packet energy expenditure does not increase much.

Fig. 4(d) shows the integrated performances of the studied protocols in terms of delay, reliability and energy expenditure. We see that the overall performance of our DACR protocol is much higher than the others, as high as 70.56% performance improvement over MRL-CC is observed. This is because DACR uses energy-aware route discovery and relay selection and optimizes the delay and reliability at each hop through adaptive decisions on selecting transmission mode and most optimal relay node. The results also prove that *proactive* approach of relay selection is more effective than *reactive* one, which is employed by MRL-CC.

Every QoS provisioning scheme has to exchange additional control packets (in addition to those for the basic routing mechanism) in order to update the nodes with the current neighborhood information necessary to provide better QoS services, incurring extra overhead. As shown in Fig. 4(e), the operation overhead of MPCR protocol is the highest and does not increase much with *f*. This result is caused by periodic HELLO packet broadcasting of MPCR nodes and executing Bellman-Ford shortest path algorithm for finding the relay that could provide with minimum power e2e path. An interesting result is found for MRL-CC; its overhead increases exponentially when the value of *f* crosses 0.30 and we reveal the fact that the number of control messages in MRL-CC suddenly increases to very high value for constructing the multihop mesh cooperative structure. The e2e route discovery procedures in REER and DACR have the similarity and both of them rely only on single hop neighborhood information for relay selection, thus showing almost same operation overhead.

Finally, network lifetime is an important performance metric for resource-constrained wireless sensor networks. As shown in Fig. 4(f), the network lifetime of our DACR protocol is much longer than the other protocols and starting from 12.5% to as much as 155.6% improvement over MRL-CC is observed for increasing values of *f*. The rationale behind achieving this result is that DACR takes the residual energy levels of nodes into consideration while creating e2e route and selecting the relays at each hop and thus distributes the energy-load more uniformly over the nodes of the network. Whereas in MRL-CC, neither the mesh cooperative structure formation nor the relay selection method is energy-aware; rather, the mere *Q*-value based relay selection might put extra loads on a certain node that performs better, thereby causing earlier death of the node and reducing the network lifetime drastically.

5.2.2. Impacts of data traffic load in unreliable environment

In this section, we evaluate the performances of the studied protocols for various data packet generation rates from sensors, when link failure is set to 0.30. Our DACR's policy of choosing a relay node that provides with lowest link-delay from the set of nodes guaranteeing the required reliability level, implemented through LO functions, enables it to achieve minimum delay e2e communication among all the protocols, as shown in Fig. 5(a). We also observe from Fig. 5(b) that, in meeting the reliability requirement of 0.8, our DACR protocol can tolerate the data traffic load of up to 7 packets per second (pps) compared to 5 pps for REER, 4 pps for MRL-CC and 3 pps for MPCR. Again, this is due to its judicious selection of transmission mode and relay nodes optimizing the reliability and delay hop-by-hop basis. Comparing the graphs of Fig. 4(a) and (b) and 5(a) and (b), we can also state that the cooperative routing systems are more robust to dealing with worse network conditions than with increasing traffic loads, i.e., performance degradation rate is much lower for the latter case than the former one.

As shown in Fig. 5(c), the energy expenditure per packet in DACR increases at higher rate for increasing traffic loads compared to that observed in Fig. 4(c). Since the number of collisions as well as the packet drops increase with higher traffic loads, the packet delivery ratio also decreases sharply and thus increasing the per packet energy expenditure. The integrated performance of our DACR protocol is still much higher than the other protocols, as shown in Fig. 5(d), which proves its superiority in handling various network conditions as well as data traffic loads.

The operation overhead of the protocols, except for MRL-CC, does not increase significantly with an increase in data traffic loads in the network, as shown in Fig. 5(e). Because the frequency of route creation (and thereby the number of control messages) is greatly increased when network link conditions decline; it is not dependent on the network traffic loads. However, the rate of fall of the network lifetime with the increasing traffic loads is very high, as shown in Fig. 5(f), compared to that in Fig. 4(f). This is because the transmission and reception of data packets consume a lot of energy of the nodes and its irrespective of the employed cooperative routing system. Therefore, distributing the total traffic load over the network nodes in such a way that their energy dissipation rate does not vary much from one to another is the most effective way to increase the network lifetime. Since our DACR protocol employs this policy through LO functions by regulating the threshold energy level (E_{th}) dynamically, its energy-distribution is capable of maintaining a high level of uniformity among the nodes and thereby prolonging the network lifetime compared to other protocols.

5.3. Impacts of ϵ

We have also carried out performance evaluations of our proposed DACR algorithm for various values of ϵ, a small probability with which a routing node selects an irrational cooperative node (discussed in Section 4.3). We observe in Fig. 6 that the introduction of ϵ in our algorithm gives slightly better performance (in terms of on-time packet delivery ratio, i.e., the reliability) both for varying link failure rates and data traffic loads. We also notice that a smaller value of ϵ (e.g., $\epsilon = 0.1$) is better than larger one (e.g., $\epsilon = 0.2$).

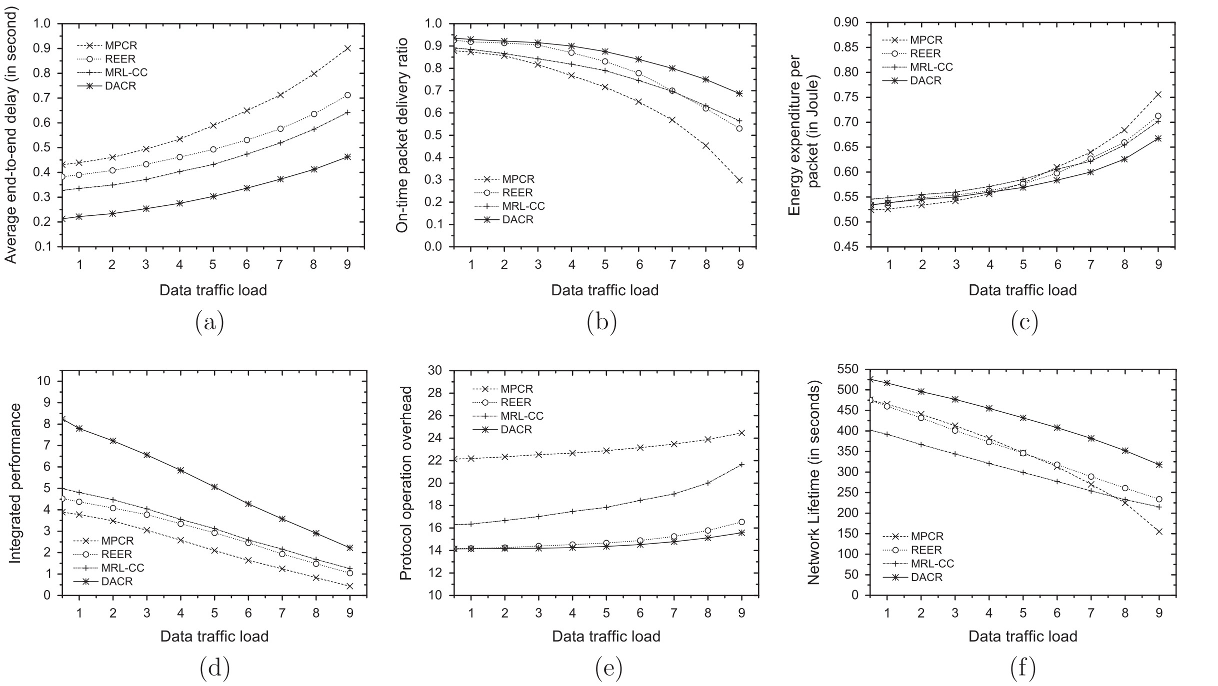

Fig. 5. Performance comparisons for varying data traffic loads with link failure rate = 30%. (a) Average end-to-end delay. (b) Reliability. (c) Energy expenditure. (d) Integrated performance. (e) Protocol overhead. (f) Network lifetime.

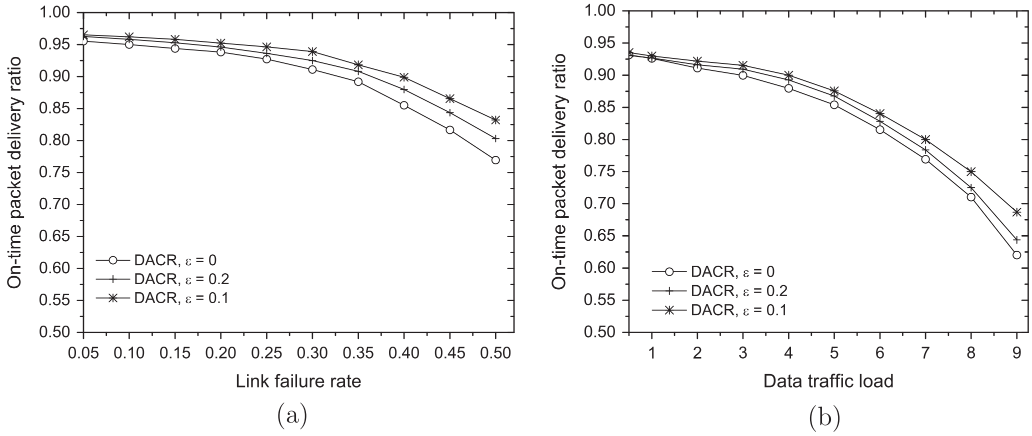

Fig. 6. Impacts of selecting irrational cooperative routing node with a small probability ϵ. (a) Impacts of link failure rates (traffic load = 3 pps). (b) Impacts of data traffic load (link failure rate = 30%).

5.4. Computation cost

Finally, we carry out computation energy cost performance comparisons in between our proposed DACR and the AODV routing algorithms for varying link failure rates and data traffic loads. Even though the computation cost is very much lower compared to the communication costs, this study helps us to understand the protocol operation overheads more in detail.

For computation energy cost measurement, we assume that the average computation cost per instruction is 1 μJ [32]. The *Y*-axis in Fig. 7 shows the total amount of computation energy consumed during the whole simulation period. The Fig. 7(a) shows that the proposed DACR routing system is more robust to the increasing link failures in terms of computation cost overhead compared to the classic AODV system. On the other hand, our DACR system consumes much computation energy for relay selection procedure and the amount sharply increases with the higher data traffic loads, as shown in Fig. 7(b). Our in-depth look into the simulation trace files reveals that the AODV experiences huge control packet processing due to increased route reconstructions required as well as the number of retransmissions is also increased at higher link failure rates. However, the cooperative relay nodes in DACR help to reduce the number of route reconstructions and packet retransmissions, saving a significant amount of computation energy. On the contrary, the computation cost for cooperative relay selections through solving LO equations in our proposed DACR system is exponentially increased at higher traffic loads. Finally, in measurement scale, the computation cost is negligible compared to the data transmission and reception costs and thus the overall energy cost performance of our proposed DACR system is much better compared to the state-of-the-art protocols, as depicted in the graphs of Figs. 4 and 5.

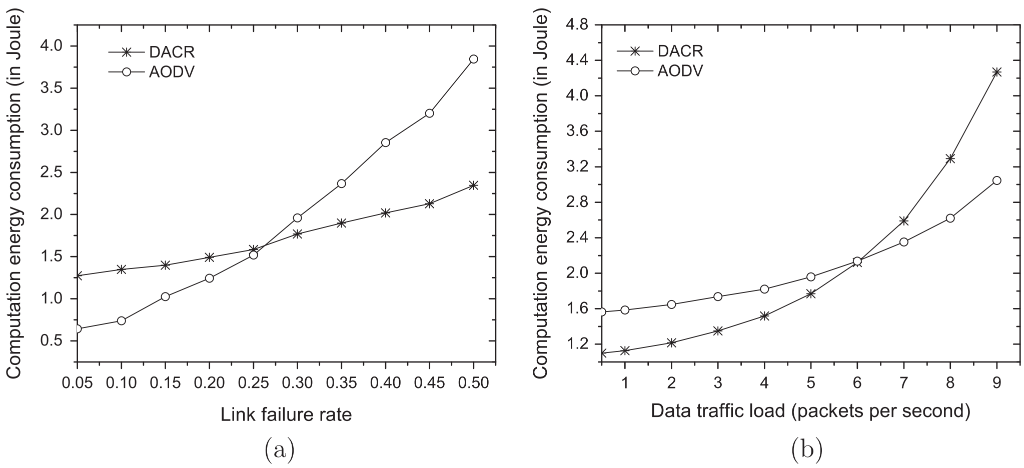

Fig. 7. Computation energy cost comparision for varying link failure rates and data traffic loads. (a) Impacts of link failure rates (traffic load = 3 pps). (b) Impacts of data traffic load (link failure rate = 30%).

5.5. Discussion

The simulation results show that our DACR can efficiently cater for the application requirements with various network conditions, i.e., different combinations of traffic loads and link failure rates. As a result, DACR can significantly improve the effective capacity of a sensor network in terms of traffic flows meeting the reliability, delay and network lifetime requirements with reduced overhead, under versatile network environments. The developed framework is expected to work with good performance in a large number of emerging WSN applications, particularly in which both delay- and reliability-sensitive traffic flows co-exist. For example, medical applications, forest monitoring, radioactive monitoring and object tracking applications, industrial process control and so on. However, it may not be suitable for applications that emphasize only on non-critical traffic flows, for instance, agricultural applications.

The rather pessimistic model of using the fixed value of ϵ for probabilistically selecting an irrational cooperative routing node, the measurement interval t and the EWMA weight factor α in our current work provides with the first step research. Some dynamic selection techniques might improve the DACR performance. The analytical modeling to dynamically select the optimal values of the parameters has been left for future work.

Furthermore, the introduction of random exploration factor ϵ in solving the transmission mode selection problem, in Algorithm 1, has added a random element in the feasible region. Thus, it has become a simulation optimization problem [36], where the objective function cannot be evaluated exactly, which in turn makes it difficult to predict the convergence speed of the algorithm. Adaptive random search methods for simulation optimization problem, that can maintain balance among exploration, exploitation and estimation, are more effective [36,37]. However, the development of an adaptive and almost surely convergent search method for our problem leads to a new research and we keep it as a future work.

Note that, in wireless sensor networks, the nodes are commonly set to operate at low-duty cycle for conserving energy and thereby increasing the network lifetime, which is typically implemented by employing duty cycle MAC protocols. In recent years, a number of cooperative MAC protocols have been developed for duty cycle enabled wireless sensor networks [33–35]. Our proposed distributed adaptive cooperative routing (DACR) system nodes may also employ duty cycling and thus could possess robustness against the underlying sensor network pattern through using a suitable MAC protocol. The study on the performance improvement due to joint effort of our DACR and a suitable duty cycled cooperative MAC protocol in WSNs has been left for future works.

6. Conclusions

This paper proposes a QoS-aware distributed adaptive cooperative routing system (DACR) to achieve both reliability and delay guaranteed data delivery in wireless sensor networks while distributing the energy consumption load among many nodes and thereby increasing the network lifetime. The DACR's adaptive decision on transmission mode selection and judicious choice of relay nodes based on their offered link-reliability and link-delay values at intermediate hops allow it to efficiently handle various network environments. The performances of our DACR have been evaluated through extensive simulations for a wide range of network link failure rates and data traffic loads; the results show that it improves the network performance significantly compared to state-of-the-art protocols.

A comparative study on the performances of cooperative and multipath routing systems in guaranteeing QoS services will be an important advance in the research, which we leave as a future work.

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Appendix A. Threshold values

A.1. Minimum link-reliability threshold K_{rel}^{min}

In a multihop wireless sensor network, the knowledge of per hop required minimum reliability K_{rel}^{min} is a function of the e2e required reliability K_{rel}^{e2e}, which is defined by the application, and the number of hops h between any source or intermediate node and the destination sink. Since the reliability is a multiplicative metric, the value of required per hop reliability K_{rel}^{min} increases with the number of hops h in order to meet the application defined reliability at the sink K_{rel}^{e2e}. Therefore, the value of K_{rel}^{min} can be found from the following equation

$$K_{rel}^{e2e} = (K_{rel}^{min})^h$$
$$K_{rel}^{min} = (K_{rel}^{e2e})^{1/h} \tag{A.1}$$

Consider QoS reliability requirement of 95%, if reliability of all outgoing links (using direct or cooperative transmission) is below 95% at an intermediate node, there is no feasible solution to satisfy the requirement. Even a degradation of 5% on each link will cause a total decrease of 27% on a path $\mathcal{P}$ with six hops. Also, as the number of hops on the path increases, the e2e reliability decreases. Usually the number of hops in large scale sensor networks is much larger than those in ad hoc networks. So, it imposes a severe problem on reliability. For the same $\mathcal{P}$ to achieve an e2e reliability of 90%, the geometric mean of reliability of all six links on a six-link path $\mathcal{P}$ has to be 98%, which is very restrictive in wireless communications. If the e2e reliability degrades so much that no route can meet the QoS requirement, cooperative routing seems to be an effective way to enhance the e2e reliability. Note here that K_{rel}^{e2e} is fixed for a particular packet; and thus, at each hop, we have to choose a transmission (either direct or relayed) in such a way that the per hop reliability is maximized, ensuring high e2e reachability of the packet.

A.2. Maximum link-delay threshold K_{del}^{max}

The value of K_{del}^{max} is also determined by the e2e application defined delay-deadline K_{del}^{e2e} of a packet and the number of hops h between any node on the path and the destination sink. Any node on the routing path can calculate this value as follows, $K_{del}^{max} = \frac{K_{del}^{e2e}}{h}$ for any packet, assuming that the sojourn period of the packet at the next intermediate hops will also be bounded by K_{del}^{max}. Using the same procedure for updating lifetime of RREQ packets, discussed in Section 4.1, the remaining lifetime of a data packet is updated by each node on the routing path, i.e., the sojourn period of the data packet ($T_{sojourn}$) at the current node is subtracted from the lifetime value of the packet received from its previous hop, $K_{del}^{e2e}(current) = K_{del}^{e2e}(previous) - T_{sojourn}$.

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