QoS Aware Geographic Opportunistic Routing in Wireless Sensor Networks

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Abstract—QoS routing is an important research issue in *wireless sensor networks* (WSNs), especially for mission-critical monitoring and surveillance systems which requires timely and reliable data delivery. Existing work exploits multipath routing to guarantee both reliability and delay QoS constraints in WSNs. However, the multipath routing approach suffers from a significant energy cost. In this work, we exploit the *geographic opportunistic routing* (GOR) for QoS provisioning with both end-to-end reliability and delay constraints in WSNs. Existing GOR protocols are not efficient for QoS provisioning in WSNs, in terms of the energy efficiency and computation delay at each hop. To improve the efficiency of QoS routing in WSNs, we define the problem of efficient GOR for multiconstrained QoS provisioning in WSNs, which can be formulated as a multiobjective multiconstraint optimization problem. Based on the analysis and observations of different routing metrics in GOR, we then propose an *Efficient QoS-aware GOR* (EQGOR) protocol for QoS provisioning in WSNs. EQGOR selects and prioritizes the forwarding candidate set in an efficient manner, which is suitable for WSNs in respect of energy efficiency, latency, and time complexity. We comprehensively evaluate EQGOR by comparing it with the multipath routing approach and other baseline protocols through ns-2 simulation and evaluate its time complexity through measurement on the MicaZ node. Evaluation results demonstrate the effectiveness of the GOR approach for QoS provisioning in WSNs. EQGOR significantly improves both the end-to-end energy efficiency and latency, and it is characterized by the low time complexity.

Index Terms—Wireless sensor networks, multiconstrained QoS, geographic opportunistic routing

1 Introduction

Wireless sensor networks (WSNs) have been designed and developed for a wide variety of applications, such as environment or habitat monitoring, smart battlefield, home automation, and traffic control etc. [1]. A sensor network consists of spatially distributed autonomous sensor nodes, to cooperatively monitor physical or environmental conditions. These sensor nodes usually operate on limited non-rechargeable battery power, and are expected to last over several months or years. Therefore, a major concern is to maximize the network lifetime, i.e., to improve the energy efficiency for WSNs. Since the sensor node normally has limited processing speed and memory space, it is also required that the algorithm running on sensor devices has a low computational cost.

Providing reliable and timely communication in WSNs is a challenging problem. This is because, the varying wireless channel conditions and sensor node failures may cause network topology and connectivity changing over time [2]. Under such conditions, to forward a packet reliably at each hop, it may need multiple retransmissions, resulting in undesirable long delay as well as waste of energy. Therefore, many existing works [3], [4], [5], [6], [7], [8], [9] have been proposed to improve the routing reliability and latency in WSNs with unreliable links.

QoS (*Quality of Service*) provisioning in network level refers to its ability to deliver a guaranteed level of service to applications [10]. The QoS requirements can be specified in the form of routing performance metrics, such as delay, throughput or jitter. For periodic environment reporting applications, delivery delay is not critically significant as long as the sensory data arrives at the sink node. While for other mission-critical applications, e.g., target tracking and emergency alarm, reliable and timely delivery of sensory data is crucial in the success of the mission. In this case, QoS routing for both the end-to-end reliability and delay guarantees becomes one of the important research issues in WSNs. However, due to the seemingly contradictory multiple constraints (e.g., reliability, latency and energy efficiency) and dynamics in WSNs, only soft QoS provisioning is attainable [11]. The soft QoS refers to meeting the QoS requirements with probability, it is also considered to be "good enough" regardless of the fact that it is not possible to guarantee a particular level of service. Qos provisioning in this work means the soft QoS provisioning unless otherwise specified.

Several existing works, MMSPEED [5], MCMP [6], EQSR [7], ECM [8], and DARA [9] propose to utilize multiple paths between the source and sink for multiconstrained QoS provisioning in WSNs. Data transmission along multiple paths can achieve certain desired reliability, and the delay QoS requirement is met as long as any one packet copy arrives at the destination before the deadline.

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Compared with the single path routing with retransmission to guarantee delivery reliability, the multipath approach may probably provide shorter end-to-end delay by removing the retransmissions. However, it has following two major disadvantages: 1) Sending a packet over multiple paths inevitably induces significant energy cost, which is one of the primary design concerns in WSNs; 2) Exploiting multiple paths also introduces more channel contentions and interference which may increase the delivery delay as well as cause transmission failures [12].

This work addresses two issues of the multiconstrained QoS routing in WSNs: 1) Is the multipath routing really suitable for multiconstrained QoS provisioning in WSNs? If it is not the case, what technique can help? We propose to exploit the *geographic opportunistic routing* (GOR) for QoS provisioning in WSNs. 2) Can existing GOR protocols be directly applied to guarantee both reliability and delay QoS constraints in an efficient manner? Considering the reliability and delay constraints as well as the intrinsic energy constraint in WSNs, how to design a GOR protocol which can achieve good balance among energy efficiency, end-to-end delay and reliability?

Our major contributions are listed as follows:

- We argue that multipath routing approach may not be suitable to guarantee both reliability and delay QoS constraints in WSNs. Correspondingly, we propose to exploit the opportunistic routing approach for multiconstrained QoS provisioning in WSNs.
- We find that existing GOR protocol cannot be directly applied for QoS provisioning in WSNs. Therefore, we investigate the problem of *efficient GOR for multiconstrained QoS provisioning* (EGQP) in WSNs, which is formulated as a multiobjective multiconstraint optimization problem. We provide insight into the properties of multiple routing metrics in GOR. Based on the theoretical analysis and observations, we propose an *Efficient QoS-aware GOR* (EQGOR) algorithm for QoS provisioning in WSNs.
- Through comprehensive performance comparisons, we demonstrate the low time complexity and effectiveness of EQGOR for multiconstrained QoS provisioning in WSNs.

The rest of the paper is structured as follows. Section 2 reviews related work. Sections 3 and 4 introduce the system model and problem formulation, respectively. The analysis of GOR routing metrics is presented in Section 5. In Section 6, EQGOR algorithm is proposed. Simulation results are shown in Section 7. We conclude the paper in Section 8. A conference paper [13] containing some preliminary results of this paper has appeared in IEEE MASS 2010.

2 Related Work

2.1 Geographic Opportunistic Routing

Opportunistic routing aims to improve wireless performance by exploiting spatial diversity in dense wireless networks [14]. A number of opportunistic routing protocols have been proposed [15], [16], [17], [18] in the literature. Geographic opportunistic routing (GOR) [19] is a branch of the opportunistic routing, where location information is available at each node. In opportunistic routing, at the network layer a set of forwarding candidates are selected while at the MAC layer only one node is chosen as the actual relay based on the reception results in an *a posteriori* manner. The candidate selection and relay priority assignment at each hop are the two important issues [20]. In GeRaF [19], the relay priority among forwarding candidates is simply assigned according to the single-hop packet progress provided by each potential forwarder. More recently, several opportunistic routing algorithms [21] are designed for duty-cycled WSNs. The authors in [22] analyze the opportunistic routing gain under the presence of link correlation and introduce a link-correlation-aware opportunistic routing scheme. Nevertheless, none of existing works address exploiting GOR for the multiconstrained QoS provisioning in WSNs such as the one presented in this paper.

2.2 QoS Provisioning in WSNs

Unique characteristics of WSNs, such as energy supply and computing power limitations of sensor devices, unreliable wireless links, and data-centric communication paradigm, pose challenges in the area of QoS provisioning in WSNs. Early studies on QoS aware routing in WSNs mainly focus on one QoS requirement, either delay or reliability. The authors in [23] present an energy-aware QoS routing protocol for wireless video sensor networks. The proposed protocol finds a set of QoS paths for real-time data transmission with certain end-to-end delay requirements. In SPEED [24] and RAP [25], the notion of packet speed is introduced for QoS-aware geographic routing in WSNs. The packet speed reflects the local urgency of a packet by considering both the end-to-end delay and communication distance constraints in WSNs.

For mission-critical applications, not only the end-to-end delay constraint should be met, but also certain packet delivery reliability is expected to be guaranteed. The authors in [5], [6], [7], [8], [9] propose to exploit the multipath diversity for QoS provisioning with both reliability and delay constraints in WSNs. Typically, the end-to-end QoS requirements are partitioned into the hop QoS requirements and each hop adaptively seeks multipath forwarding based on local estimation. If the hop requirement can be achieved at each hop, the end-to-end QoS requirement can also be met with a higher probability. By controlling the number of forwarding paths for each hop, the soft QoS requirement in reliability is guaranteed.

3 System Model

We consider a multi-hop WSN in a two-dimensional planar region. We assume the network is densely deployed, i.e., each node has plenty of neighbors. Nodes know the geographical location information of their direct neighbors and where the destination is [26]. We assume that the MAC layer provides the link quality estimation service, e.g., the *packet reception ratio* (PRR) information on each link can be obtained by counting of the lost probe messages or data packets [27]. Each node is aware of the PRR values to its one-hop neighbors.

To keep consistency, we follow the variable definitions about GOR in [20]. Assuming node i is sending a data packet to the sink node (denoted as $Dest$), and j is one of i's

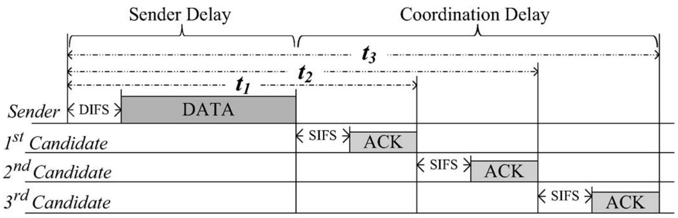

Fig. 1. Example illustrating the single-hop medium delay with three prioritized forwarding candidates.

neighbors which is closer to the sink than i. Define a_{ij} in Eq. (1) as the single-hop packet progress (SPP) to the $Dest$ when a packet is forwarded by neighbor j. C_i is defined as the available next-hop forwarder set of node i, where all nodes in C_i have positive SPPs.

$$a_{ij} = Dist(i, Dest) - Dist(j, Dest), \tag{1}$$

where $Dist(i, Dest)$ is the Euclidian distance between node i and the $Dest$. Let p_{ij} denote the PRR between node i and j. For any neighbor j, node i maintains the pair information (a_{ij}, p_{ij}) in its neighbor table. Let F_i ($F_i \subseteq C_i$) denote the selected forwarding candidate set of node i, in which all nodes are cooperatively involved in the local forwarding task when node i sends a data packet to the sink node.

The GOR procedure is described as following: when node i has a data packet to send to the sink node via multi-hop communication, it selects the forwarding candidate set F_i based on its local knowledge of available next-hop forwarder set C_i. Then node i broadcasts the data packet where the list of candidates and their priorities are included in packet header. These candidates follow the assigned priorities to relay the packet opportunistically. For each candidate, if having received the packet correctly, it will start a timer whose value depends on its priority. The higher the priority is, the shorter the timer will be. The forwarding candidate whose timer expires will reply an ACK, to notify the sender as well as all other candidates to cancel their timers. Subsequently, this forwarding candidate becomes the actual next-hop sender in an opportunistic manner. The forwarding process repeats until the packet reaches the sink node. If no forwarding candidate has successfully received the packet, the sender will retransmit the packet if the retransmission is enabled.

Denote t_k as the single-hop medium delay of the kth candidate, which is the time from the sender broadcasts a packet to the kth candidate claims it has received the packet. In GOR, the medium delay can be divided into two parts. One part is the sender delay, which includes the backoff delay and the transmission delay of the data packet (there is no RTS/CTS exchange for the broadcast transmission). The second part is the candidate coordination delay, which is the time needed for the kth candidate to acknowledge the sender and suppress other potential forwarders. The single-hop medium delay is defined as Eq. (2), where the signal propagation delay is ignored

$$t_k = T_{Backoff} + T_{DATA} + k \cdot (T_{SIFS} + T_{ACK}), \tag{2}$$

where $T_{Backoff}$ includes the *Distributed Interframe Space* (DIFS) and a random backoff time for the sender to acquire the channel, T_{SIFS} is the value of *Short Interframe Space* (SIFS). T_{DATA} and T_{ACK} are the transmission delays for sending a data packet and an ACK, respectively.

Fig. 1 shows an example illustrating the single-hop medium delay with three prioritized forwarding candidates. We know t_k is an increasing function of k, i.e., the forwarding candidate with higher priority has shorter coordination delay than the lower priority candidate. This is because the lower priority forwarding candidates always wait higher priority candidates to relay the packet first.

4 Problem Formulation

Let D and R denote the end-to-end delay and reliability QoS constraints, respectively. Due to the unreliable wireless link conditions, the complexity of obtaining the exact end-to-end link state information is beyond the computation and energy tolerance of sensor nodes [6]. However, per hop information is convenient to acquire and maintain at a low overhead cost. Therefore, we partition the end-to-end QoS requirements into the hop requirements to achieve the soft QoS provisioning.

Let d_i and r_i represent the hop QoS requirements for delay and reliability at node i, respectively. Denote rh_i as the estimated remaining hop count from node i to the sink. e_i denotes the elapsed delay experienced by a packet from the source node to the current forwarding node i, which can be obtained by piggybacking the elapsed time at each hop to the packet so that the following node can know the remaining time without globally synchronized clock [5]. We have the partitioned hop QoS requirements at node i

$$d_i = \frac{D - e_i}{rh_i} \tag{3}$$

$$r_i = \sqrt[rh_i]{R}. \tag{4}$$

The remaining hop count rh_i is estimated as Eq. (5)

$$rh_i = \left\lceil \frac{Dist(i, Dest)}{\widehat{adv(h_i)}} \right\rceil, \tag{5}$$

where $\widehat{adv(h_i)}$ is the estimated average single-hop packet progress since the packet has been forwarded from the source node, defined as Eq. (6). h_i is the current hop count of the forwarded packet at node i

$$\widehat{adv(h_i)} = \frac{(h_i - 1) \cdot \widehat{adv(h_i - 1)} + adv(h_i)}{h_i}, \quad (h_i \geq 1), \tag{6}$$

where $adv(h_i)$ is the single-hop packet progress of the h_i^{th} hop forwarding. $\widehat{adv(0)}$ is the estimated single-hop packet progress at the source node, which can be set as the expected packet progress given the available next-hop forwarder set.

Let $\pi_j(F_i) = \{j_1, j_2, \ldots, j_n\}$ be one permutation of nodes in F_i, and the order indicates that nodes will attempt to forward the packet with priority $(j_1 > j_2 > \cdots > j_n)$. The expected single-hop reliability $er_i(\pi_j(F_i))$, single-hop media delay $ed_i(\pi_j(F_i))$, and single-hop packet progress $ea_i(\pi_j(F_i))$ achieved by GOR for node i given the ordered forwarding candidate set $\pi_j(F_i)$ are shown in Eqs. (7), (8), and (9), respectively

$$er_i\big(\pi_j(F_i)\big) = 1 - \prod_{m=1}^{n} \overline{p}_{ij_m}, \tag{7}$$

$$ed_i\big(\pi_j(F_i)\big) = \sum_{k=1}^{n}\left(t_{j_k} p_{ij_k} \prod_{m=0}^{k-1} \overline{p}_{ij_m}\right) + t_{j_n} \prod_{m=1}^{n} \overline{p}_{ij_m}, \tag{8}$$

$$ea_i\big(\pi_j(F_i)\big) = \sum_{k=1}^{n}\left(a_{ij_k} p_{ij_k} \prod_{m=0}^{k-1} \overline{p}_{ij_m}\right), \tag{9}$$

where $\overline{p}_{ij_m} = 1 - p_{ij_m}$ and $\overline{p}_{ij_0} = 1$. n is the number of forwarding candidates in F_i. p_{ij_k} and a_{ij_k} are the PRR and single-hop packet progress between nodes i and j_k, respectively. In Eqs. (8) and (9), $p_{ij_k}\prod_{m=0}^{k-1}\overline{p}_{ij_m}$ is the probability of the kth forwarding candidate in $\pi_j(F_i)$ taking the forwarding task. t_{j_k} is the single-hop medium delay of the kth forwarder in $\pi_j(F_i)$.

We define $espeed_i(\pi_j(F_i))$ as the expected single-hop packet speed for node i given the ordered forwarding candidate set $\pi_j(F_i)$, which is calculated by dividing the single-hop packet progress to the single-hop media delay, as in Eq. (10)

$$espeed_i\big(\pi_j(F_i)\big) = \frac{\sum\limits_{k=1}^{n}\left(a_{ij_k} p_{ij_k} \prod_{m=0}^{k-1} \overline{p}_{ij_m}\right)}{\sum_{k=1}^{n}\left(t_k p_{ij_k} \prod_{m=0}^{k-1} \overline{p}_{ij_m}\right) + t_n \prod_{m=1}^{n} \overline{p}_{ij_m}}. \tag{10}$$

The hop QoS requirements d_i and r_i will be adaptively adjusted according to the actual accumulated delay and packet progress over preceding links. Intuitively, we know that: 1) Increasing the single-hop packet speed can relax both the hop QoS requirements, thus the end-to-end delay and reliability QoS requirements are more likely guaranteed as the packet is progressed toward the destination; 2) Although increasing the number of forwarding candidates would result in higher reliability, considering the energy constraint of sensor devices, it is expected to involve less forwarding candidates to save energy cost in WSNs (e.g., those neighbors that are not involved into local forwarding in GOR may turn off their radios for energy saving). From the discussion above, we formulate EGQP problem as a multiobjective multiconstraint optimization problem

$$\begin{aligned} \textbf{Problem formulation}: \quad & F_i \subseteq C_i \\ & \max\ espeed_i\big(\pi_j(F_i)\big) \\ & \min |F_i| \end{aligned}$$

Subject to

$$\begin{aligned} & ed_i\big(\pi_j(F_i)\big) \le d_i \\ & er_i\big(\pi_j(F_i)\big) \ge r_i \\ & Dist(j_m, j_k) \le Range \quad \forall j_m \in F_i,\ \forall j_k \in F_i, \end{aligned}$$

where $Range$ is the neighbor detection range between neighboring nodes. For opportunistic routing, the nodes in forwarding candidate set should be able to overhear from each other. Otherwise, the packet duplication problem would occur and there will be multiple data copies being transmitted [28]. Therefore, we have the constraint $Dist(j_m, j_k) \le Range$. Note that if the delay constraint is too restrictive to be achievable, we can only reduce the end-to-end delay in a *best effort* approach.

5 Properties of Different Metrics

In this section, we will analyze and have a better understanding of different routing metrics in GOR, where the proof can be found in the supplemental material which is available in the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2013.240.

5.1 Minimum Single-Hop Media Delay

Definition 1. *For sending node i, define $\min\{ed_i(C_i, n)\}$ be the minimum expected single-hop media delay achieved by selecting n forwarding candidates from C_i.*

Property 1.1 (Relay priority rule). *$\min\{ed_i(C_i, n)\}$ can only be achieved by assigning the relay priority to each neighbor based on their PRRs to the sending node i, the larger the PRR is, the higher its relay priority will be.*

Property 1.2 (Containing property). *Given the available next-hop node set C_i, the ordered candidate set that achieves $\min\{ed_i(C_i, n-1)\}$ is a subset of the ordered candidate set that achieves $\min\{ed_i(C_i, n)\}$. It indicates that the minimum expected single-hop media delay can be obtained through a greedy algorithm.*

Property 1.3 (Strictly increasing property). *$\min\{ed_i(C_i, n)\}$ is a strictly increasing function of n, which means involving more neighbors will increase the expected single-hop media delay. If there is no constraints on the expected delivery speed and reliability at each hop, the minimum single-hop media delay can be trivially achieved by including only a single neighbor which has the best PRR to the sender. However, this may lead to extremely low packet delivery ratio and low single-hop packet progress.*

Property 1.4 (Concavity property). *The minimum single-hop media delay increases when more nodes are included, while the successive increases become smaller.*

5.2 Maximum Single-Hop Packet Progress

Definition 2. *Define $\max\{ea_i(C_i, n)\}$ be the maximum expected single-hop packet progress achieved by sender i selecting n forwarding candidates from C_i.*

In [29], it has been proven that $\max\{ea_i(C_i, n)\}$ has following properties:

1. *Relay priority rule*: the maximum $ea_i(\pi_j(F_i))$ can only be achieved by assigning the relay priority to each candidate based on their closeness to the destination, that is, the larger the packet progress, the higher its relay priority.
2. *Containing property*: the ordered candidate set that achieves $\max\{ea_i(C_i, n-1)\}$ is a subset of the ordered candidate set that achieves $\max\{ea_i(C_i, n)\}$.
3. *Strictly increasing property*: it indicates that the more nodes get involved in the forwarding candidate set, the larger the $\max\{ea_i(C_i, n)\}$ will be.
4. *Concavity property*: it means that $\max\{ea_i(C_i, n)\}$ is a concave function of n, although the maximum

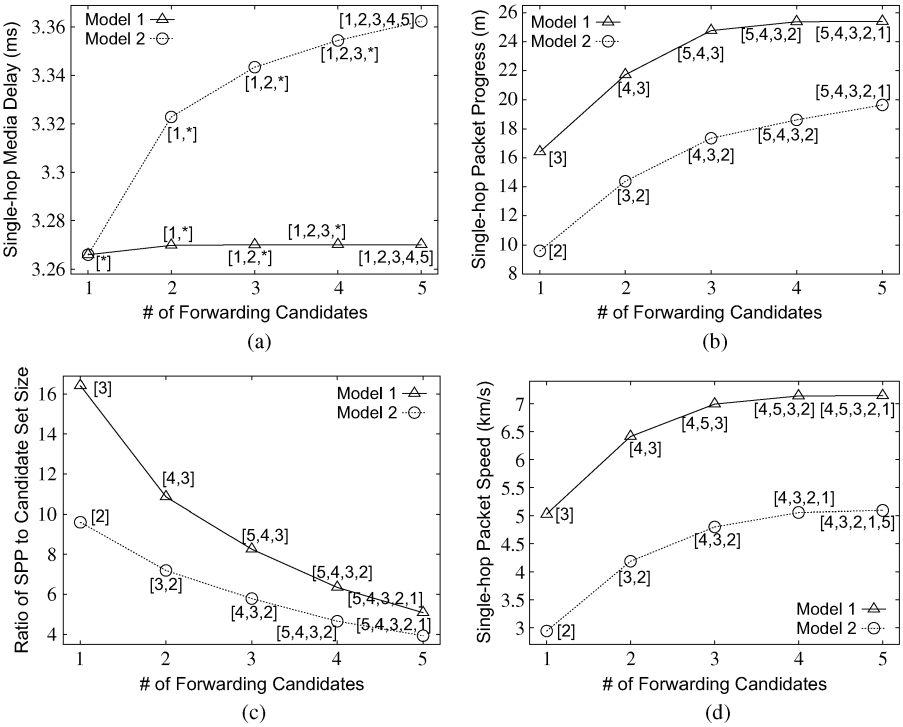

Fig. 2. Example illustrating the properties of EGQP's multiple objectives. (a) $\min\{ed_i(C_i, n)\}$ vs. n. (b) $\max\{ea_i(C_i, n)\}$ vs. n. (c) $\max\{ea_i(C_i, n)/n\}$ vs. n. (d) $\max\{espeed_i(C_i, n)\}$ vs. n.

$ea_i(\pi_j(F_i))$ keeps increasing when more nodes get involved, the gained extra progress becomes marginal.

5.3 Maximum Single-Hop Packet Progress per Candidate

Definition 3. *For sending node i, define $\max\{ea_i(C_i, n)/n\}$ be the maximum expected single-hop packet progress per candidate achieved by selecting n forwarding candidates from C_i. Given the size of the forwarding candidate set n, apparently, $\max\{ea_i(C_i, n)/n\}$ has the same relay priority rule and containing property as the $\max\{ea_i(C_i, n)\}$.*

Property 3.1 (Strictly decreasing property). *$\max\{ea_i(C_i, n)/n\}$ is a strictly decreasing function of n, which means the average contribution of each node in the local opportunistic forwarding decreases as more nodes getting involved.*

5.4 Maximum Single-Hop Packet Speed

Definition 4. *Define $\max\{espeed_i(C_i, n)\}$ be the maximum expected single-hop packet speed achieved by sender i selecting n forwarding candidates from C_i.*

From the properties of $\max\{ea_i(C_i, n)\}$ and $\min\{ed_i(C_i, n)\}$, we know that both $\max\{ea_i(C_i, n)\}$ and $\min\{ed_i(C_i, n)\}$ are increasing functions of n and have the concavity properties. In geographic routing, a neighboring node with larger single-hop packet progress is also likely to be farther away from the sending node and subsequently the PRR would be lower [30]. Thus, $\max\{ea_i(C_i, n)\}$ and $\min\{ed_i(C_i, n)\}$ have nearly opposite relay priority rules, which means they are of the conflicting metrics. The intuition is that the relay priority rule for $\max\{espeed_i(C_i, n)\}$ may balance both $\max\{ea_i(C_i, n)\}$ and $\min\{ed_i(C_i, n)\}$'s relay priority rules. That is, the heuristic relay priority assignment is based on the "$SPP \times PRR$" metric [31].

An example validating our analysis is illustrated in Fig. 2, in which node i is sending a data packet to the sink. Assume it has 5 available next-hop nodes. We set $t_k \approx (2.95 + 0.316 \cdot k)$ ms based on the measurement values in the ns-2 simulator, which will be introduced in detail in Section 7. The SPP-PRR settings for two different lossy link models are listed in Table 1. The figures in square brackets represent the selected optimal forwarding candidates and their relay properties. From Fig. 2, the numerical results clearly justify the proved properties of different metrics in GOR. It also shows that the changes of $\min\{ed_i(C_i, n)\}$, $\max\{ea_i(C_i, n)\}$ and $\max\{ea_i(C_i, n)/n\}$ are related with the SPP-PRR models.

5.5 Discussion

The above analysis leads to the following conclusion. It is not appropriate to transform the EGQP problem into a single objective optimization problem directly. This is because, if we choose $\max\{espeed_i(C_i, n)/n\}$ as a single objective, only those nodes with higher PRR but likely smaller single-hop packet

TABLE 1
Single-Hop Packet Progress (SPP) and PRR Setting

Index	SPP	Model 1		Model 2	
		PRR	$SPP \cdot PRR$	PRR	$SPP \cdot PRR$
1	10	0.98773	9.8773	0.82	8.2
2	15	0.939413	14.091195	0.64	9.6
3	20	0.820755	16.4151	0.46	9.2
4	25	0.617391	15.43477	0.28	7.0
5	30	0.367879	11.03637	0.1	3.0

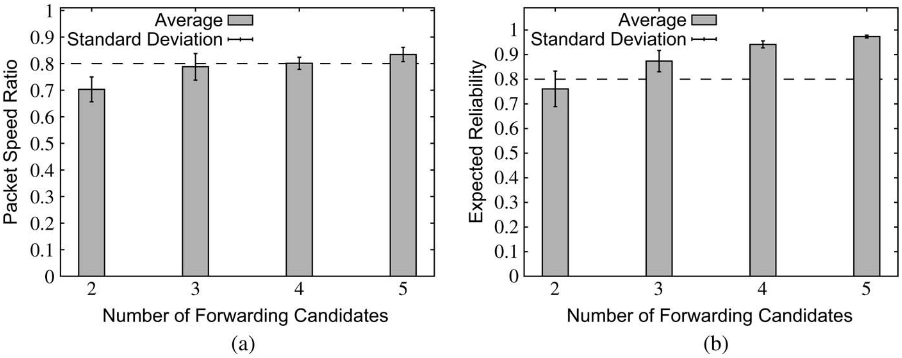

Fig. 3. Numerical example illustrating the similar pareto principle in GOR. (a) Ratio of the expected one hop packet speed to the optimal value. (b) Expected one hop reliability.

progress will be selected into F_i to meet the reliability constraint with the least number of forwarding candidates. In such case, usually, there exist multiple Pareto optimal solutions [32], rather than an optimal solution. In the literature, different approaches have been suggested to solve this complex problem, e.g., multiobjective evolutionary algorithms [33]. However, considering the limitation of sensor devices on processing power and memory space, it is not appropriate to execute such algorithms on sensor nodes. Thus, an efficient candidate selection and prioritization algorithm with low computational cost is desirable.

6 EQGOR Design

6.1 Motivation

The *pareto principle* (also known as the 80-20 rule in the field of economics) states that, for many events, roughly 80 percent of the effects come from 20 percent of the causes [34]. We observe that there also exists similar *pareto principle* in GOR. That is, most forwarding tasks for each hop are taken by the first two or three candidates in the ordered forwarding candidate set. This indicates that it may only need to order a very small number of candidates to obtain a close optimal solution in our design, by which the algorithm's time complexity can be effectively reduced.

Here, we give a numerical example illustrating the similar *pareto principle* in GOR, as shown in Fig. 3. We vary the number of available next-hop nodes $|C|$ from 10 to 25, where C is the available next-hop forwarder set of a sending node. For each potential relay node, the single-hop packet progress is randomly generated. We use $Nakagami$ distribution to model the attenuation of wireless signals, and derive the PRR with certain distance between the sender and receiver. The results have been averaged over 100 rounds. Table 2 illustrates the number of forwarding candidates involved in the proposed candidate selection and prioritization algorithm in [20]. We can see that it involves too many forwarding candidates, e.g., when $|C| = 10$, the algorithm will choose 8.87 forwarding candidates out of 10 on average. Then, we choose only the first 20 percent of the available next-hop nodes to calculate the single-hop packet speed, where candidates are descendingly sorted according to $''SPP \times PRR''$. From Fig. 3, it is seen that the first 20 percent of available next-hop nodes can achieve more than 80 percent of the optimal values on average.

6.2 EQGOR Description

The above theoretical analysis and observations motivate us to propose a tailored candidate selection and prioritization algorithm in EQGOR for QoS provisioning in WSNs. When node i is sending a data packet to the sink node, it selects and prioritizes forwarding candidates based on the scheme as proposed in Algorithm 1. Then it forwards the data packet following the GOR procedure as introduced in Section 3.

The design of Algorithm 1 is described as follows. We introduce two adjustable parameters α and β, which represent the minimum and maximum number of candidates to be prioritized, respectively. EQGOR will only prioritize the first k available next-hop nodes based on the observation of the similar *pareto principle* in GOR, where $k = \max\{\alpha, \min\{\beta, 0.2|C_i|\}\}$.

For sending node i, candidates in C_i are descendingly sorted according to the $''SPP \times PRR''$ metric. Initially, we include the first node of C_i into F_i and remove it from C_i (Line 1). Then, we check nodes in C_i in sequence, where c_1 always denotes the first node in C_i. When intending to add c_1 into F_i, it should be within the transmission range of any node in F_i (Line 5). Otherwise, it will be eliminated from C_i (Line 7). If there is no packet duplication (i.e., c_1 can overhear any node in F_i), we search the best place to insert c_1 into F_i, where the $espeed_i(\pi_j(F_i))$ is maximized (Lines 9-15). The searching procedure is to try every possible inserting position in F_i, and calculate the expected single-hop packet speed values. For the remaining nodes in C, candidates will be selected to meet the hop Qos requirements at a minimum cost, i.e., simply appending to F_i (Lines 17-18). When the number of available

TABLE 2
Number of Forwarding Candidates Involved in the Proposed Algorithm in [20]

# of available next-hop nodes	Avg. # of forwarding candidates	Standard Deviation
10	8.87	0.902
15	12.56	1.227
20	18.09	1.511
25	22.15	1.621

Input: available next-hop node set C_i ($|C_i| \geq 2$); hop QoS requirements: d_i, r_i; α and β, $k = \max\{\alpha, \min\{\beta, 0.2|C_i|\}\}$.
Output: the forwarding candidate set F_i.

1 $F_i \leftarrow \{c_1\}$, $C_i \leftarrow C_i - \{c_1\}$;
2 **while** $C_i \neq \emptyset$ **do**
3   **if** *meet QoS requirements* **then**
4   **return** F;
5   **else if** `CheckRange(`F_i, c_1`)==`*false* **then**
6   //c_1 denotes the first node in C_i; it should be within the transmission range of any node in F_i;
7     $C_i \leftarrow C_i - \{c_1\}$;
8   **continue;**
9   **else if** $|F_i| \leq k$ **then**
10   **for** *i=0* **to**$|F_i|$ **do**
11   temporarily insert c_1 as the i_{th} item in F_i; get the optimal insert position i^* in term of maximizing $espeed_i(\pi_j(F_i))$;
12   **end**
13   `Insert(`c_1, i^*, F_i`);`
14   //finally insert c_1 as the i^*_{th} item in F_i;
15   $C_i \leftarrow C_i - \{c_1\}$;
16   **else**
17     $C_i \leftarrow C_i - \{c_1\}$;
18   `Append(`c_1, F_i`);` //Append c_1 as the last item in F_i;
19   **end**
20 **end**

next-hop nodes increases in dense networks, the time complexity of EQGOR is approximate $O(|C_i|)$. In Algorithm 1, although the first node in C_i is included into F_i directly (Line 1), it is not necessary the first candidate of F_i finally. This is because the newly added nodes may still have higher priorities and thus being inserted ahead.

7 Evaluation

In this section, we first present simulation results to show that EQGOR achieves a good balance among energy cost, end-to-end delay and reliability. Then we show the effectiveness of EQGOR for multiconstrained QoS provisioning in WSNs using ns-2 simulator [35], by comparing it with the multipath routing approach and with two other baseline protocols. Lastly, we show the low time complexity of EQGOR through measurements on the MicaZ (with low-power 8-bit microcontroller) node. All the results have been averaged over 100 runs.

7.1 Simulation Settings

In the implementation of our simulation, sensor nodes are placed in a 200 m $\times$ 200 m square area. We define the node density as the number of nodes deployed in the field. A sink node is positioned at (0 m, 0 m), and the source node is located at (200 m, 200 m). A data packet generated by the source node is forwarded toward the sink over multiple hops. The sensor node transmission range is taken 50 m. Two parameters in EQGOR, α and β are set to 2 and 5, respectively. The MAC layer protocol is a modified version of the CSMA/CA MAC in ns-2, $T_{SIFS} = 10$ us, $T_{DIFS} =$ 50 us. Wireless links qualities are derived from the Nakagami fading model, where PRR is related with the distance between two nodes [13].

7.2 Evaluation Metrics

We choose six main evaluation metrics to evaluate the effectiveness of EQGOR for QoS provisioning in WSNs.

- *End-to-end Delay*: the time taken for a packet to be transmitted from the source node to the sink node. Given the end-to-end delay QoS requirement, this metric measures the on-time packet delivery ratio.
- *Packet Delivery Ratio*: the ratio of the amount of packets received by the destination to the total amount of packets sent by the source.
- *Data Transmission Cost*: measured as the total number of data transmissions for a successful end-to-end data delivery.
- *Control Message Cost*: defined as the total number of control message transmissions for sending a single packet to the destination, such as RTS, CTS and ACK.
- *Single-hop Packet Progress*: the ratio of the sum of single-hop packet progress in each hop to the number of hops in a simulation run.
- *Link Quality Per Hop*: the average link quality for successful data transmission at each hop.

7.3 The Balance Achieved by EQGOR

We compare EQGOR with two extreme solutions under the grid topology with different node densities: 1) maximizing the packet speed as the single objective (refer to as Max-Speed); 2) minimizing the number of forwarding candidates as the single objective (refer to as Min-F). The reliability requirement is set 0.99. For the extreme solutions (exhaustive searching method), the computation delay would be very high as the node density increases. To ensure the effectiveness, we set 9 as the maximum number of the available next-hop node set, that is, at most the first 9 nodes from the neighbor list will be selected and ordered.

Fig. 4a plots the average packet speed achieved by EQGOR and the two extreme solutions under different node densities. We can see that EQGOR provides very close packet speed to the Max-Speed scheme. Fig. 4b shows that EQGOR involves a little more forwarding candidates than the Min-F scheme, which serves as the lower bound of the size of forwarding candidate set. From the results in Fig. 4, we can see that EQGOR provides a good balance between the packet speed and the energy cost for GOR.

7.4 The Effectiveness of EQGOR for QoS Provisioning in WSNs

In term of the effectiveness for multiconstrained QoS provisioning in WSNs, we compare the performance of EQGOR against the multipath routing approach, named MPQP. We also report the evaluation results of two other baseline protocols, the single path geographic routing (GPSR) [36] with up to 3 MAC layer retransmissions, and the conventional GOR [19], where all the available next-hop nodes are involved in the local forwarding and the relay priority is assigned according to the single-hop packet progress provided by each candidate. Since our

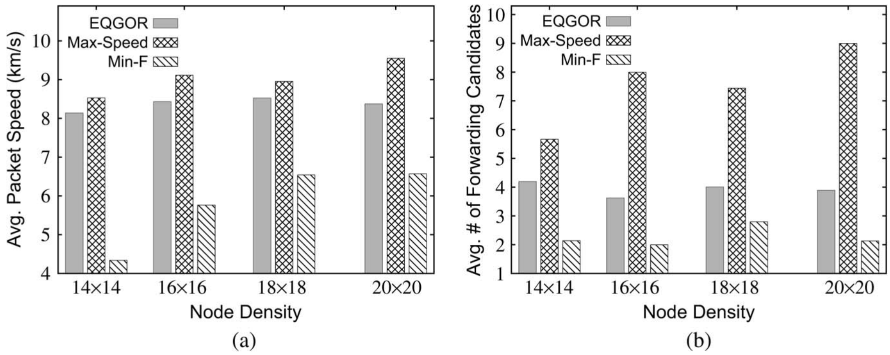

Fig. 4. Comparison with two extreme solutions in terms of the packet speed and number of forwarding candidates under different node densities. (a) Avg. packet speed. (b) Avg. # of forwarding candidates.

aim is to compare the multipath routing approach with the opportunistic routing approach for multiconstrained QoS provisioning in WSNs, we implement the common function of the multipath approach [5], [6], [7], [8]. To save the energy cost, at each hop, the sender selects the next-hop nodes with the minimum number of splitted paths to meet the reliability QoS requirement. In this section, different randomly connected topologies for each node density setting are generated using the *setdest* tool in ns-2, where the node density ranges from 120 to 200.

7.4.1 *Impact of the Node Density*

In this test, we evaluate the performance of EQGOR under different node densities by varying the number of nodes from 120 to 200. The reliability QoS requirement is set 0.95.

Fig. 5a reports the end-to-end delay under different node densities. EQGOR achieves shorter end-to-end delivery delay than that of GOR. This is because, GOR follows the maximum single-hop packet progress relay priority rule. While the minimum single-hop media delay has the nearly opposite rule, as discussed in Section 5. It is shown that MPQP is influenced by different node densities, and its end-to-end delay is much higher than others. The reason is that using multiple paths introduces more channel contentions which significantly degrades end-to-end delay performance. Note that only the successful end-to-end transmissions are counted in the results. GPSR will yield worse result if the retransmission limit is increased to achieve the comparable reliability to other protocols. We also observe that the end-to-end delay of EQGOR and GOR does not change much as the node density increases. This is partly because the node density setting is high, and there are enough forwarding candidates at each hop.

Fig. 5b illustrates the end-to-end packet delivery ratio. Compared with the single path routing scheme GPSR, the multipath approach MPQP improves the delivery ratio by 30 percent. However, MPQP is more sensitive to different random topologies than the GOR approach. For example, when the node density is 140, its delivery ratio is only 80 percent. This is because the problem of collisions among multiple paths arises and the retransmission is disabled in

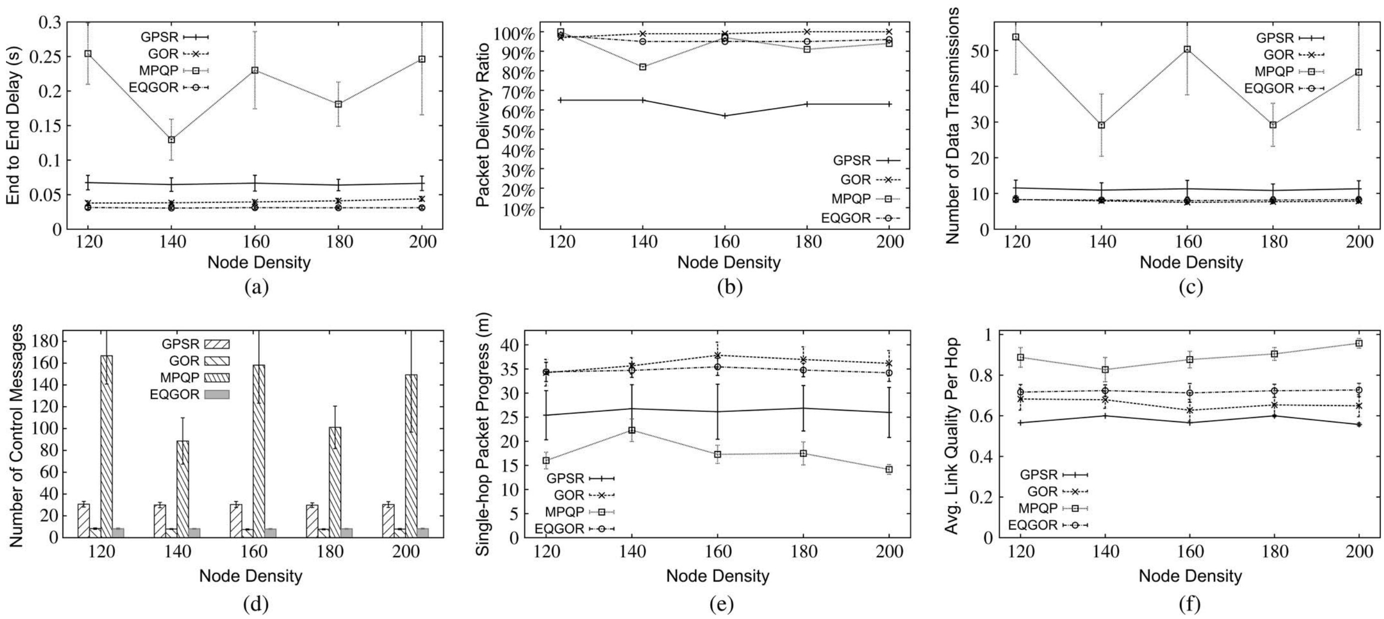

Fig. 5. Impact of the node density, the end-to-end reliability is set 0.95, and only the successful end-to-end transmissions are counted. (a) End-to-end delay. (b) Packet delivery ratio. (c) Number of data transmissions. (d) Number of control messages. (e) Single-hop packet progress. (f) Average link quality per hop.

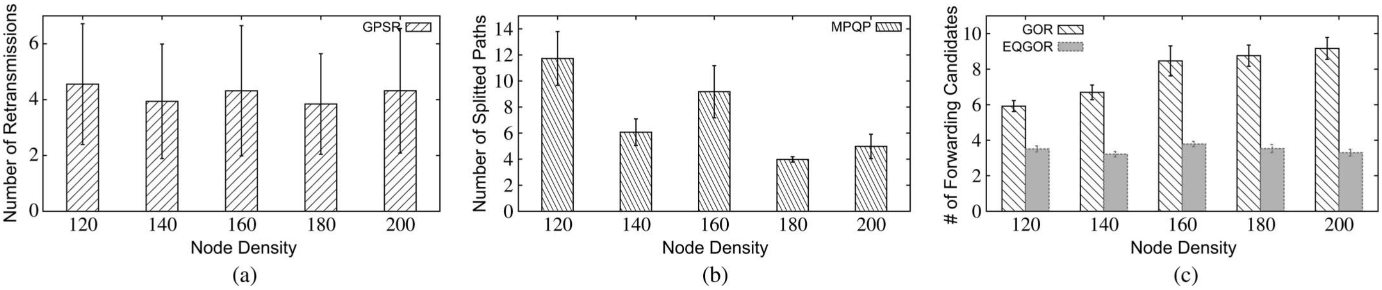

Fig. 6. Insights of the different routing protocols. (a) Number of retransmissions. (b) Number of splitted paths. (c) Number of forwarding candidates.

MPQP. Since the reliability constraint is set 0.95, only EQGOR and GOR meet the QoS requirement.

Figs. 5c and 5d depict the changes of the data transmission cost and control message cost under different node densities, respectively. Normally, the control message cost is directly proportional to the number of data transmissions. From Figs. 5c and 5d, it clearly shows that MPQP incurs more than four times higher than other approaches regarding the transmission cost. The significant energy cost makes MPQP unsuitable for multiconstrained QoS provisioning in WSNs. The data transmission cost metric also reflects the hopcount of a routing path. In our implementation of MPQP, since the minimum number of paths are chosen to meet the reliability constraints at each hop, it is more likely that neighbors with higher PRRs but smaller single-hop packet progresses are selected as the nexthop forwarding nodes. This increases the hopcount of the end-to-end routing paths. GPSR always chooses the neighbor with the maximum single-hop packet progress without considering the link quality. Considering the retransmissions incurred in GPSR, the transmission cost is still higher than EQGOR and GOR, although only the successful transmissions are counted.

Fig. 5e illustrates the single-hop packet progress among the four compared protocols. GOR has the highest packet progress at each hop due to its relay priority rule. It serves as the maximum bound of this metric. It is clearly seen that EQGOR achieves very close performance to GOR, which shows the very high efficiency of EQGOR.

Fig. 5f plots the average data transmission link qualities of different schemes. The results reveal that GPSR tends to choose poor link quality node as relay, and MPQP always selects good quality links. GOR and EQGOR opportunistically exploit the long distance but unreliable links, thus, their average data transmission link qualities are lower than the result of MPQP and higher than that of GPSR.

Fig. 6 demonstrates the system insight of each protocol and reveal the reasons behind the corresponding statistics in Fig. 5. Fig. 6a shows the number of retransmissions occurred in GPSR. There are around 4 retransmissions in each successful end-to-end data delivery. Fig. 6b reveals the number of splitted paths of MPQP in the evaluation. In the 120-node random network, the data packet is replicated more than 10 times to meet the reliability requirement. The number of splitted paths is reduced as the node density increases. However, the single-hop packet progress

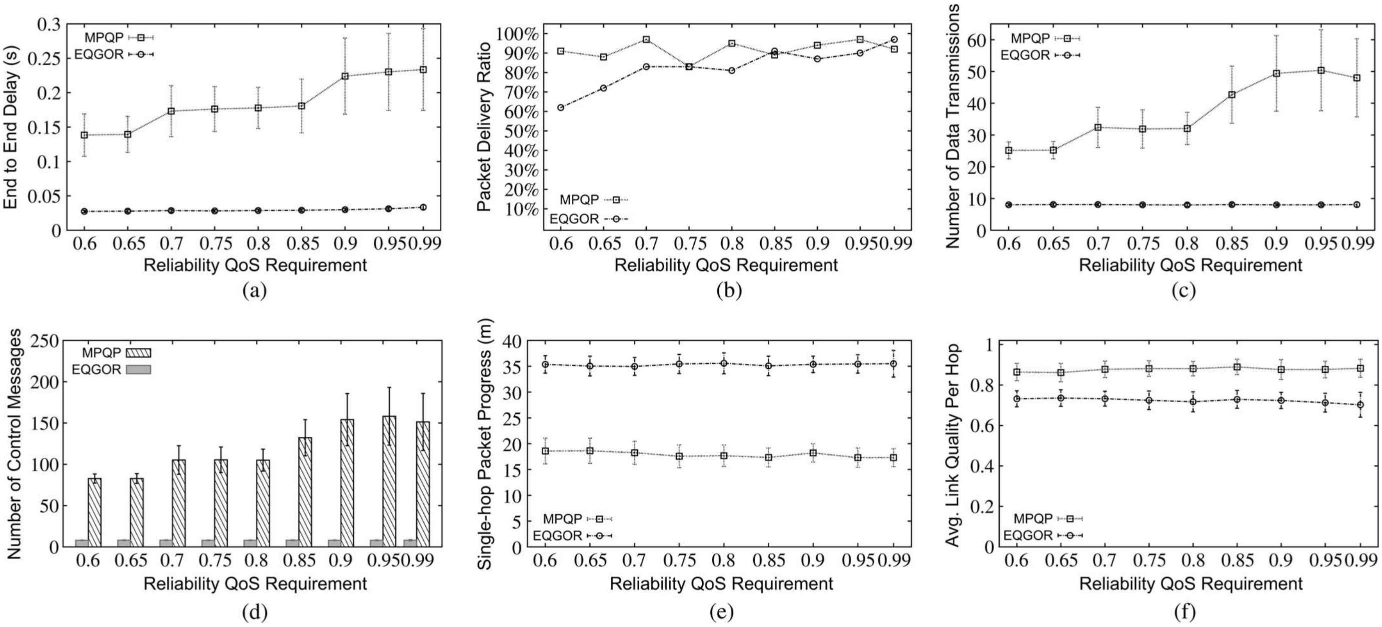

Fig. 7. Impact of the reliability QoS requirement in 160-node random network, and only the successful end-to-end transmissions are counted. (a) End-to-end delay. (b) Packet delivery ratio. (c) Number of data transmissions. (d) Number of control messages. (e) Single-hop packet progress. (f) Average link quality per hop.

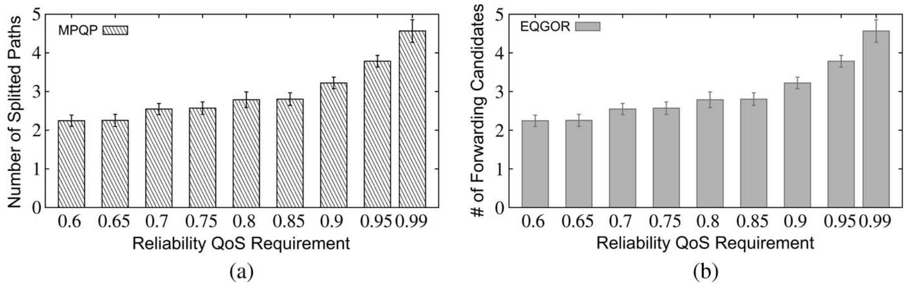

Fig. 8. Insights of MPQP and EQGOR. (a) Number of splitted paths. (b) Number of forwarding candidates.

decreases with the increase of node density, as shown in Fig. 5e. Fig. 6c plots the number of forwarding candidates involved in the local forwarding at each hop. The result highlights that the size of the forwarding candidate set in MPQP is stable and small at increasing the node density compared with GOR.

7.4.2 Impact of the Reliability QoS Requirement

In this comparison, we examine the performance differences of EQGOR and MPQP under different reliability QoS requirements in 160-node random network.

Fig. 7a illustrates the changes of the end-to-end delay at increasing the reliability constraint from 0.6 to 0.99. As the reliability QoS requirement increases, the end-to-end delay of MPQP also increases from 0.14 s to 0.23 s, and its variance is much higher than that of EQGOR. This indicates that the multipath approach is difficult to guarantee the on-time packet delivery ratio under strict delay requirement. While EQGOR is robust to the reliability constraint change, its end-to-end delay maintains below 0.05 s.

Fig. 7b shows the actual packet delivery ratio against the reliability QoS requirement. As seen in the figure, MPQP may suffer from the problem of overcounting to guarantee lower reliability constraints. EQGOR adaptively improves the packet delivery ratio as the reliability requirement increases. When the end-to-end reliability QoS constraint is 0.6, suppose the estimated hopcount is 15 from the source node to the sink, the partitioned hop reliability requirement is around 0.967. However, the actual single-hop reachability is higher than 0.967 when multiple paths are selected to route a packet.

Figs. 7c and 7d depict the tradeoff between the communication cost and the reliability QoS requirement. It clearly shows that EQGOR significantly improves the energy efficiency for the QoS provisioning in WSNs. With increasing the reliability requirement, MPQP incurs higher data transmission cost and control message cost. As shown in Figs. 7e and 7f, the single-hop packet progress and the average data transmission link quality are relatively stable at increasing the reliability requirement. EQGOR shows obvious advantage over MPQP.

Fig. 8 plots the system insights for MPQP and EQGOR. From Fig. 8a, as the reliability QoS requirement increases, more paths are required to guarantee the requirement in MPQP. For EQGOR, as shown in Fig. 8b, the average number of forwarding candidates increases from 2 to 4.5 when increasing the reliability requirement from 0.6 to 0.99.

From the above results, we can see that EQGOR is less influenced by the changes of the reliability requirement and node density. Together with its shorter end-to-end delay, lower communication cost and higher delivery ratio, we conclude that compared with the multipath routing approach, all the performances are greatly improved by exploiting the GOR for QoS provisioning in WSNs. However, the GOR approach requires the cross-layer interaction between the MAC and network layers, and incurs certain coordination overhead (such as forwarding candidate coordination delay). As other opportunistic routing protocols, the overhead of EQGOR is expected to be eventually compensated by the improved routing performance over a long-term of network operation.

7.5 The Time Complexity of EQGOR

We evaluate the computation delay of candidate selection and prioritization at each hop in EQGOR on MicaZ [37] node since such computation delay cannot be captured in simulation. The measured performance is shown in Fig. 9. In the experiment, we vary the number of available next-hop nodes from 3 to 10. From Fig. 9, when the hop reliability $r_i = 1.0$, the average computation delay of EQGOR grows linearly and slowly as the number of available next-hop nodes increases. When $|C_i| = 10$, the delay is around 10 ms, however, the candidate selection and prioritization algorithm proposed in [20] introduces 80.89 ms computation delay on average. When the required reliability goes to 0.99, the EQGOR's computation delay under different number of available next-hop nodes has very little change, from 2.29 ms to 2.74 ms. Thus, we conclude that EQGOR is characterized by its very low time complexity. Meanwhile, it also achieves the competing packet speed close to the optimal value as shown in Fig. 3 and Fig. 4, respectively.

8 Conclusion

In this paper, we proposed to exploit the *geographic opportunistic routing* (GOR) for multiconstrained QoS

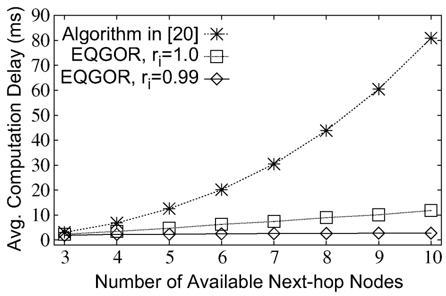

Fig. 9. Average computation delay measurement on the MicaZ node.

provisioning in WSNs, which is more suitable than the multipath routing approach. We found that existing GOR protocol cannot be directly applied to the QoS provisioning in WSNs. Because the computation delay of a GOR protocol should be also considered in WSNs. We studied the problem of *efficient GOR for multiconstrained QoS provisioning* (EGQP) in WSNs. We formulated the EGQP problem as a multiobjective multiconstraint optimization problem and analyzed the properties of EGQP's multiple objectives. Based on our analysis and observations, we then proposed an *Efficient QoS-aware GOR* (EQGOR) algorithm for QoS provisioning in WSNs. EQGOR achieves a good balance between these multiple objectives, and has a very low time complexity, which is specifically tailored for WSNs considering the resource limitation of sensor devices. We conducted extensive evaluations to study the performance of the proposed EQGOR. Evaluation results demonstrate its efficacy for QoS provisioning in WSNs.

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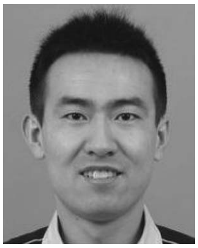

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