Exploiting Geographic Opportunistic Routing for Soft QoS Provisioning in Wireless Sensor Networks

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Abstract—In this paper, we exploit the geographic opportunistic routing (GOR) for QoS provisioning with both end-to-end reliability and delay constraints in wireless sensor networks (WSNs). Recent 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. We also find that existing GOR protocol may not be suitable for QoS provisioning in WSNs due to the large computation delay at each hop. To improve the efficiency of QoS routing in WSNs, we study the problem of efficient GOR for multiconstrained QoS provisioning in WSNs, which can be formulated as a multiobjective optimization problem. We look in depth at the properties of the multiple objectives. Based on the analysis and observations, we then propose a heuristic efficient GOR (EGOR) algorithm for QoS provisioning in WSNs. We evaluate EGOR by comparing it with the multipath routing approach through ns-2 simulation and evaluate its time complexity through measurement on the MicaZ node. Evaluation results demonstrate that EGOR can significantly improve both the end-to-end energy efficiency and latency for multiconstrained QoS provisioning in WSNs, and that EGOR is characterized by its low time complexity.

I. 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. A sensor network always consists of spatially distributed autonomous sensor nodes, to cooperatively monitor physical or environmental conditions. These sensors 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., improve the energy efficiency for WSNs. Since the sensor node currently has limited processing speed and memory space, it is also required that the algorithm that runs on sensor devices has a low computational cost.

Providing reliable and timely communication in WSNs is a challenging problem. This is because, in reality, the link conditions in wireless networks can be highly unreliable due to many factors such as interference, attenuation, and channel fading [1] [2]. Usually, to forward a packet reliably, it may need retransmissions at each hop, which results in undesirable delay as well as waste of energy. Different applications may have different QoS1 (Quality of Service) requirements. For the periodic environment reporting application, delivery delay is not critically significant as long as the sensory data arrives at the sink. While for some 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. Therefore, QoS routing for both the end-to-end reliability and delay guarantees becomes one of the important research issues in WSNs.

QoS support in wireless ad hoc networks [3] [4] can generally be obtained via end-to-end path discovery, resource reservation along the discovered path, and path recovery in case of topology changes. However, due to the long path discovery latency and high energy cost, such approaches are not suitable in resource constrained WSNs. Previous QoS provisioning studies in WSNs focus on only one QoS domain, either reliability [5] [6] or delay [7]. However, combined reliability and delay constraints always need to be satisfied at the same time, e.g., for mission-critical pervasive computing applications. Due to the seemingly contradictory multiple constraints and the dynamics in WSNs, only soft QoS2 provisioning is attainable [8].

Two recent work, MMSPEED [9] and MCMP [10] propose to utilize multiple paths between the source and sink pairs for multiconstrained QoS provisioning in WSNs. In [9] and [10], the multipath diversity is exploited to enhance the packet delivery reliability. Intuitively, the more paths to deliver a packet, the higher the probability that the packet reaches its final destination will be. The delay QoS requirement is met as long as any one packet copy arrives at the destination before the deadline.

Compared with single path routing with retransmission recovery mechanism for QoS provisioning, the multipath approach may provide shorter end-to-end delay. This is because the retransmission approach trades the end-to-end delay for the reliability. Although the multipath routing approach may ensure the end-to-end delay and reliability requirements, it has

1In this work, QoS specifically refers to the end-to-end reliability or delay that a routing protocol can provide in WSNs.

2Soft QoS refers to meeting the QoS requirements with probability. If not specified, the QoS provisioning in this work means the soft QoS provisioning.
following two disadvantages: 1) sending a packet on multiple paths induces significant energy cost, which is one of the primary design concerns in WSNs; 2) using multiple paths introduces more contentions which may increase the delivery delay as well as degrade the energy efficiency [11].

In order to improve the energy efficiency, in this work, we exploit the geographic opportunistic routing (GOR) for QoS provisioning with both end-to-end reliability and delay constraints in WSNs. The GOR is proposed to combat fading channels, thus improving the robustness, end-to-end latency and energy efficiency in wireless networks. The idea behind GOR is to take advantage of the broadcast nature of the wireless medium by involving multiple neighbors of the sender into the local forwarding, thus improve the transmission reliability. At the network layer a set of forwarding candidates are selected while at the MAC layer one node is chosen as the actual relay. For each hop, the candidate selection and relay priority assignment are the two important issues in GOR. Although involving more candidates can increase the expected transmission reliability and packet advancement per hop, it may also incur larger delay and more energy consumption.

This work addresses two issues: 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 GOR for QoS provisioning in WSNs. 2) Can the existing GOR protocol be applied to guarantee both reliability and delay QoS constraints in an efficient manner? We study the problem of efficient GOR for multiconstrained QoS provisioning (EGQP) in WSNs. With the reliability and delay constraints as well as the intrinsic energy constraint in WSNs, it should achieve a good balance between energy cost, end-to-end delay and reliability. Moreover, due to the limitation of sensor devices on processing power, it is necessary to have a tailored low time complexity candidate selection and prioritization algorithm for GOR such as the one presented in this work, otherwise the computation delay may deteriorate the QoS routing performance. We formulate the EGQP problem as a multiobjective multiconstraint optimization problem and provide more insight into the properties of the multiple objectives. Based on the theoretical analysis and observations, we then propose an efficient GOR (EGOR) algorithm for QoS provisioning in WSNs. Through extensive evaluations, we demonstrate the very low time complexity and effectiveness of EGOR for multiconstrained QoS provisioning in WSNs.

The rest of this paper is organized as follows: Section II briefly surveys related work. Section III and Section IV present the system model and problem formulation, respectively. The detailed analysis of the properties of EGQP’s multiple objectives is presented in Section V. In Section VI, the EGOR algorithm is proposed. Simulation results are presented in Section VII. Finally, Section VIII concludes this paper.

II. RELATED WORK

A. QoS provisioning in WSNs

Unique characteristics of WSNs, such as resource (energy supply, computing power and memory) limitations of sensor devices, unreliable wireless links, and data-centric communication paradigm, pose challenges in the area of QoS provisioning in WSNs. Previous studies on QoS provisioning in WSNs focus on only one QoS requirement, either delay or reliability. The authors in [12] 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 with certain end-to-end delay requirements. In SPEED [7] and RAP [13], 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 key constraints in sensor networks, namely, the end-to-end delay and the communication distance. Thus, it is suitable to represent the end-to-end delay requirement for geographic routing. By leveraging path redundancy, the multipath routing is always exploited to achieve reliability QoS support in WSNs, e.g., [5] and [14]. However, the multipath routing approach trades energy cost for reliability in an expensive way.
bility requirement. Assume the first hop reliability requirement is 0.95, a packet is splitted into two duplicate packets at the first hop. The new hop reliability requirement for A and B are 0.83 and 0.7, respectively. In this example, the packet will be progressed toward the destination along at least three paths. However, the price using multiple paths for achieving desired reliability is the significant energy consumption, which may be not suitable for the resource constrained WSNs. Alternatively, Fig. 1(b) shows the GOR approach, only one actual path is required to complete the data delivery.

### B. Geographic opportunistic routing

Geographic opportunistic routing (GOR) is a branch of the opportunistic routing [15], which takes advantage of the broadcast nature of wireless communication to improve the transmission reliability, end-to-end energy efficiency and latency. Generally, GOR assumes each node maintains the one-hop neighbor table, a set of forwarding candidates are selected and prioritized at the network layer while only one node is chosen as the actual next-hop at the MAC layer.

The local candidate selection and relay priority assignment are the two important issues in GOR. In GeRaF [16], the relay priority is assigned according to the packet advancement provided by each neighboring node. The authors in [17] [18] [19] provide an insightful understanding about the effect of candidate selection and prioritization on routing efficiency. The work in [17] addresses the tradeoff between packet advancement and coordination delay. In [18], the proposed algorithm considers the tradeoff between packet advancement and energy consumption. However, none of these work address exploiting GOR for the multi-constrained QoS provisioning in WSNs.

### III. System model

We consider a multi-hop wireless sensor network with $N \times N$ nodes deployed in a two-dimensional planar region; the network is densely deployed, each node has plenty of neighbors. The routing recovery mechanism facing "holes" is not considered in this work. We assume each sensor knows its own geographical location by using GPS or distributed location services [20], and the location information is exchanged with the immediate neighbors. Assume each node is aware of the packet reception ratio (PRR) to its immediate neighbors within radio range. The PRR information on each link can be obtained by using probe messages [21] [22] or estimated by the link quality indicator (LQI) or received signal strength indicator (RSSI) reported by the physical layer.

To keep consistency, we follow the variable definitions about GOR in [17] [18] [19]. Assuming node $i$ is sending a packet to a sink, and $j$ is one of $i$’s neighbors which is closer to the $Dest$ (sink) than $i$. Let $C$ denote the set of $j$, which is called the available next-hop node set of node $i$. Define $a_{ij}$ in Eq. 1 as the packet advancement (decreased geographical distance) to the $Dest$ when a packet is forwarded by neighbor $j$:

$$a_{ij} = Dist(i, Dest) - Dist(j, Dest)$$  \hspace{1cm} (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 $j$. Then, each neighbor $j$ is associated with a pair, $(a_{ij}, p_{ij})$. Let $F (F \subseteq C)$ denote the forwarding candidate set, in which all nodes are cooperatively involved to finish the forwarding task.

The GOR procedure is described as following: node $i$ selects $F$ based on its local knowledge of $C$, then broadcasts the data packet including the list of candidates and their priorities. Those candidates follow the assigned priorities to relay the packet. For each candidate, if having received the data correctly, it will start a timer whose value depends on its priority. The higher the priority is, the shorter the timer will be. The candidate whose timer expires will reply an ACK as the actual forwarder, to notify the sender as well as all other candidates to cancel their timers. 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 one-hop medium delay [17] of the $k^{th}$ candidate, which is the time from the sender broadcasts a packet to the $k^{th}$ candidate claims it has received the packet. For a contention-based (CSMA/CA) MAC protocol (like IEEE 802.11 or IEEE 802.15.4), the medium delay can be divided into two parts. One part is the sender delay, which may include the backoff delay and the transmission delay of the data packet (It is supposed that 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 $k^{th}$ candidate to acknowledge the sender and suppress other potential forwarders.

![Fig. 2. An example illustrating the one-hop medium delay with three prioritized forwarding candidates](image)

The one-hop medium delay is defined as Eq. 2, where the signal propagation delay is ignored. Fig. 2 is an example illustrating the one-hop medium delay with three prioritized forwarding candidates.

$$t_k = T_{Backoff} + T_{DATA} + (T_{SIFS} + T_{ACK}) \cdot k$$  \hspace{1cm} (2)

where $T_{Backoff}$ may include the Distributed Interframe Space (DIFS) and a random backoff time for the sender to acquire the channel. We can see $t_k$ is an increasing function of $k$, 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.
IV. 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 sensors [10]. 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 in WSNs. In geographic routing, the end-to-end delay constraint can be represented by the required packet speed [7] [9] defined as Eq. 3, which is calculated by dividing the distance between the source and destination to the end-to-end delay constraint.

$$\text{Speed} = \frac{\text{Dist(Source,Dest)}}{D_{\text{Elapsed}}}$$ (3)

Let $\text{speed}_i$ and $r_i$ denote the hop requirements for speed and reliability at node $i$, respectively; $\hat{h}_i$ denote the estimated remain hop count from node $i$ to the sink; $T_{\text{elapsed}}$ denote the accumulated delay experienced by a packet at current forwarding node. $T_{\text{elapsed}}$ 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. Thus, we have the partitioned hop QoS requirements at node $i$.

$$\text{speed}_i = \frac{\text{Dist}(i,\text{Dest})}{D_{\text{Elapsed}}}$$ (4)

$$r_i = \frac{\hat{h}_i}{\sqrt{R}}$$ (5)

The estimated remain hop count $\hat{h}_i$ is estimated as Eq. 6.

$$\hat{h}_i = \lceil \frac{\text{Dist}(i,\text{Dest})}{\text{adv}(hc)} \rceil$$ (6)

where $hc$ ($hc \geq 1$) is the current hop count, $\text{adv}(hc)$ is the packet advancement of the $hc^{th}$ hop, $\text{adv}(hc)$ is the estimated average packet advancement defined as Eq. 7,

$$\text{adv}(hc) = \frac{(hc-1)\cdot \text{adv}(hc-1) + \text{adv}(hc)}{hc}$$ (7)

$$\text{adv}(0) = \sum_{k=1}^{\lceil c \rceil} (a_{ijk} \cdot p_{ijk})$$ (8)

Let $\pi_j(F) = \{j_1, j_2, ..., j_n\}$ be one permutation of nodes in $F$, and the order indicates that nodes attempt to forward the packet with priority $(j_1 > j_2 > ... > j_n)$; $n$ is the number of nodes in $F$ ($n = |F|$). The expected one hop packet advancement $e_{\text{adv}}(\pi_j(F))$ and media delay $e_{\text{delay}}(\pi_j(F))$ achieved by GOR for node $i$ using the ordered forwarding candidate set $\pi_j(F)$ are shown in Eq. 9 and Eq. 10.

$$e_{\text{adv}}(\pi_j(F)) = \sum_{k=1}^{n} (a_{ijk} \cdot \hat{p}_{ijk} \cdot \prod_{m=0}^{k-1} \overline{p}_{ijm})$$ (9)

$$e_{\text{delay}}(\pi_j(F)) = \sum_{k=1}^{n} (t_k \cdot \hat{p}_{ijk} \cdot \prod_{m=0}^{k-1} \overline{p}_{ijm}) + t_n \cdot \prod_{m=1}^{n} \overline{p}_{ijm}$$ (10)

where $\overline{p}_{ijm} = 1 - p_{ijm}$ and $\overline{p}_{ij0} = 1$.

Then, we have the expected one hop packet speed $e_{\text{speed}}(\pi_j(F))$ and reliability $e_{\text{reli}}(\pi_j(F))$.

$$e_{\text{speed}}(\pi_j(F)) = \frac{\sum_{k=1}^{n} (a_{ijk} \cdot \hat{p}_{ijk} \cdot \prod_{m=0}^{k-1} \overline{p}_{ijm})}{\sum_{k=1}^{n} (t_k \cdot \hat{p}_{ijk} \cdot \prod_{m=0}^{k-1} \overline{p}_{ijm}) + t_n \cdot \prod_{m=1}^{n} \overline{p}_{ijm}}$$ (11)

$$e_{\text{reli}}(\pi_j(F)) = 1 - \prod_{m=1}^{n} \overline{p}_{ijm}$$ (12)

For opportunistic routing, there exists an implicit constraint. That is, the nodes in forwarding candidate set should be able to hear from each other. Otherwise, the packet duplication problem would occur. Fig. 3 depicts an example of this situation in GOR, in which, available next-hop nodes $j_1$ and $j_3$ cannot hear the ACKs from each other. Thus, it is possible that after $j_1$ sends an ACK to node $i$, $j_3$ then sends another redundant ACK. In this case, there will be multiple data copies being delivered, which we call the packet duplication problem.

Fig. 3. An example illustrating the packet duplication problem in GOR

The hop QoS requirements $\text{speed}_i$ and $r_i$ will be adaptively adjusted according to the actual accumulated delay and packet advancement over preceding links. Intuitively, we know that: 1) increasing the packet advancement per hop and reducing the one hop media delay 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 should involve less forwarding candidates to save the energy cost in WSNs (e.g., those neighbors not involved into GOR may turn off their radios for energy saving). From the discussion above, we formulate EGQP as a multiobjective multiconstraint optimization problem.

**Problem formulation:** \( \forall F \subseteq C \)

- \( \max e_{\text{adv}}(\pi_j(F)) \)
- \( \min e_{\text{delay}}(\pi_j(F)) \)
- \( \min |F| \)

**Subject to**

- \( e_{\text{speed}}(\pi_j(F)) \geq \text{speed}_i \)
- \( e_{\text{reli}}(\pi_j(F)) \geq r_i \) \( 0 < r_i \leq 1 \)
- \( \text{Dist}(j_m, j_k) \leq \text{Range} \) \( \forall j_m \in F, \forall j_k \in F \)

where \( \text{Range} \) is the transmission range of sensor nodes.
V. PROPERTIES OF THE MULTIPLE OBJECTIVES

In this section, we will get a deeper understanding of the properties of EGQP’s multiple objectives.

A. Minimum one hop media delay

Definition 1. Define \( ed_i^{min}(C, n) \) be the minimum expected one hop media delay achieved by selecting \( n \) forwarding candidates from \( C \).

Let \( F_n^* \) be the ordered candidate set that achieves the \( ed_i^{min}(C, n) \). From the definition of \( ed_i(\pi_j(F)) \), we know \( ed_i^{min}(C, n) \) is independent of the last candidate. Thus, we do not consider the last candidate in \( F_n^* \) when proving following properties.

Property 1. 1. (Relay priority rule) \( ed_i^{min}(C, n) \) can only be achieved by assigning the relay priority to each neighbor based on their PRRs to the sending node, the larger the PRR is, the higher its relay priority will be. That is, candidates in \( C \) are descendingly sorted according to PRR, i.e., \( p_k \geq p_m, 1 \leq k < m < n \).

Proof: We prove property 2.1 by mathematical induction on the size of the forwarding candidate set \( F \).

Basis: when \( |F| = 2 \), we have

\[
\begin{align*}
ed_i(p_n, p_k) - ed_i(p_k, p_m) &= t_1 p_m + t_2 (1 - p_m) - t_1 p_k + t_2 (1 - p_k) \quad (14) \\
&= (t_1 - t_2) (p_m - p_k) \leq 0
\end{align*}
\]

Thus, Eq. (13) holds.

Inductive step: Assume the statement is true when \( |F| = N(N > 2) \), that is

\[
ed_i^{min}(C, N) = \sum_{k=1}^{N-1} (t_k p_k \prod_{m=0}^{k-1} p_m) + t_N \prod_{m=1}^{N-1} p_m
\]

\( ed_i^{min}(C, N) \) is composed of two parts. For the second part, given the forwarding candidate set \( F \), the relay priority assignment has no effect on its value. We observe that the first part is the sum of subitem multiplication of following two inequalities.

\[
\{ t_1 < t_2 < \cdots < t_{N-2} < t_{N-1} \} \quad (16)
\]

\[
\{ p_1 \geq p_2 \geq \cdots \geq p_{N-2} \geq p_{N-1} \geq p_{N-2} \geq p_1 \}
\]

(17)

When \( |F| = N + 1 \), \( P_{N-1} > P_N \), we will prove the first \( N - 1 \) candidates in \( ed_i^{min}(C, N + 1) \) cannot include the node whose PRR is \( P_N \). We prove this by contradiction. Assume the \( P_N \) node is the \( l_{th} \) item in \( F_n^* \) achieving \( ed_i^{min}(C, N + 1) \), we have

\[
ed_i(F_{N+1}^*) = \sum_{k=1}^{l-1} (t_k p_k \prod_{m=0}^{k-1} p_m) + t_l p_N \prod_{m=1}^{l-1} p_m + \sum_{k=l+1}^{N} (t_k p_k - 1) p_N \prod_{m=1}^{k-2} p_m + t_{N+1} \prod_{m=1}^{N} p_m
\]

Then, exchange the \( l_{th} \) and the \( (l + 1)_{th} \) item, and denote the new permutation \( F_n^* \).

\[
ed_i(F_{N+1}^*) - ed_i(F_{N+1}^*) = t_l p_N \prod_{m=1}^{l-1} p_m + t_{l+1} p_{N+1} \prod_{m=1}^{l-1} p_m - t_l p_{N+1} \prod_{m=1}^{l-1} p_m - t_{l+1} p_N \prod_{m=1}^{l-1} p_m = (p_l - p_{N+1}) (t_l - l_{l+1}) \prod_{m=1}^{l-1} p_m < 0
\]

The inequality (19) contradicts with the assumption that \( ed_i(F_{N+1}^*) \) is the minimum. The node with \( P_N \) must be the \( N_{th} \) item in the permutation achieving \( ed_i^{min}(C, N + 1) \). Thus, when \( |F| = N + 1 \), Eq. (13) holds.

Similarly, we can further prove following properties of \( ed_i^{min}(C, n) \) (Proof is omitted here due to the space limit).

Property 1. 2. (Containing property) Given the available next-hop node set \( C \) with \( N \) nodes,

\[
F_n^* \subset F_n^* + 1, \quad \forall 2 \leq n \leq N
\]

Property 1. 3. (Strictly increasing property) \( ed_i^{min}(C, n) \) is a strictly increasing function of \( n \).

\[
ed_i^{min}(C, n + 1) - ed_i^{min}(C, n) > 0 \quad \forall 2 \leq n < N
\]

Property 1. 4. (Concavity property)

\[
ed_i^{min}(C, n + 1) + ed_i^{min}(C, n - 1) \leq 2e_i^{min}(C, n)
\]

B. Maximum one hop packet advancement

Definition 2. Define \( ea_i^{max}(C, n) \) be the maximum expected one hop packet advancement achieved by selecting \( n \) forwarding candidates from \( C \).

In [18], it has been proven that \( ea_i^{max}(C, n) \) has following properties:

1) Strictly increasing property, which indicates that the more nodes get involved in the forwarding candidate set, the larger the \( ea_i^{max}(C, n) \) will be.

2) Relay priority rule, which means the maximum \( ea_i(\pi_j(F)) \) can only be achieved by assigning the relay priority to each candidate based on their distances to the destination, that is, the larger the packet advancement, the higher its relay priority.

3) Containing property, which means \( ea_i^{max}(C, n - 1) \) is a subset of \( ea_i^{max}(C, n) \).

4) Concavity property, which means \( ea_i^{max}(C, n) \) is a concave function of \( n \), although the maximum \( ea_i(\pi_j(F)) \) keeps increasing when more nodes get involved, the gained extra advancement becomes marginal.

C. Maximum one hop packet advancement per candidate

Definition 3. Define \( \frac{(ea_i^{max}(C, n))}{n} \) be the maximum expected one hop packet advancement per candidate achieved by selecting \( n \) forwarding candidates from \( C \).
VI. EGOR ALGORITHM DESCRIPTION

A low computational cost is required for an efficient EGOR algorithm implementation, which can help reduce the processing time. Thus, in this section, we will present a heuristic algorithm called the Efficient EGOR (EGOR) algorithm for node- and packet-routing problems in WSNs.

The EGOR algorithm is designed to select a candidate set of nodes that can balance the three objectives of energy consumption, processing power, and memory space, while ensuring a high success rate and minimizing the packet delivery ratio.

The algorithm works as follows:

1. Select a candidate set of nodes based on the energy consumption and processing power constraints.
2. Assign priorities to each node in the candidate set based on its energy consumption and processing power.
3. Select the node with the highest priority as the next hop.
4. Repeat steps 1-3 until all packets are delivered.

Algorithm Description

The algorithm is divided into three main steps:

1. Selecting the candidate set of nodes:
   - Calculate the energy consumption and processing power for each node.
   - Select a subset of nodes that meet the constraints.

2. Assigning priorities to nodes:
   - Calculate the priority of each node based on its energy consumption and processing power.
   - Assign priorities to nodes in descending order.

3. Selecting the next hop:
   - Select the node with the highest priority as the next hop.
   - Repeat steps 1-3 until all packets are delivered.

The EGOR algorithm is designed to be efficient in terms of computation and communication, making it suitable for use in WSNs.
A. Motivation

In [17], the authors propose a heuristic candidate selection and prioritization algorithm, which runs in \( O(|C|^3) \). However, this algorithm only addresses the tradeoff between packet advancement and coordination delay, and is not designed for WSNs. Because it involves too much forwarding candidates at each hop, a numerical example is given below. Besides, when \(|C|\) is large, the computation delay of this algorithm at each hop is too high for the resource constrained sensor devices, which is shown in next section.

<table>
<thead>
<tr>
<th># of available next-hop nodes</th>
<th>Avg. # of forwarding candidates</th>
<th>Standard Deviation</th>
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<td>0.902</td>
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<td>20</td>
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<td>1.511</td>
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<tr>
<td>25</td>
<td>22.15</td>
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</tr>
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</table>

### Table II

**NUMBER OF FORWARDING CANDIDATES INVOLVED IN THE PROPOSED ALGORITHM IN [17].**

![Graph](image)

(a) Ratio of the expected one hop packet speed to the optimal value

(b) The expected one hop reliability

The pareto principle (also known as the 80-20 rule in the field of economics) states that, for many events, roughly 80% of the effects come from 20% of the causes [27]. 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 \( F \). This indicates that it may only need to order very small number of candidates to obtain a suboptimal solution in our design, by which the algorithm’s time complexity can be greatly reduced.

Here, we give an example illustrating the similar pareto principle in GOR, as shown in Fig. 5. We vary the number of available next-hop nodes \(|C|\) from 10 to 25. For each potential relay node, the packet advancement per hop 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 potential relay node (see Eq. 27 and Eq. 28 in the next section). Each result is averaged over 100 rounds. Table II illustrates the number of forwarding candidates involved in the proposed algorithm in [17]. We can see that it involves too much forwarding candidates, e.g., when \(|C| = 10\), the algorithm will choose 8.87 forwarding candidates from \( C \) on average. We choose only the first 20% of the available next-hop nodes, in which candidates are descendingly sorted according to “Advancement \( \times \) PRR”. It is seen that the first 20% of \( C \) can achieve more than 80% of the optimal value.

B. EGOR algorithm description

The above theoretical analysis and observations motivate us to propose the EGOR algorithm for QoS provisioning in WSNs. The heuristic candidate selection and prioritization scheme is provided in Algorithm 1, in which candidates in \( C \) are descendingly sorted according to “Advancement \( \times \) PRR”. There are two adjustable parameters \( \alpha \) and \( \beta \), which are the minimum and maximum number of candidates to be prioritized, respectively. EGOR will only prioritize the first \( k \) available next-hop nodes based on the observation of the similar pareto principle in GOR. 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 \( F \). When the number of available next-hop nodes increases in dense networks, the time complexity of EGOR is approximate \( O(|C|) \). In Algorithm 1, note that although the first node in \( C \) is included into \( F \) directly, it is not necessary the first candidate of \( F \). This is because the newly added nodes may still have higher priority.

```plaintext
Input: the available next-hop node set \( C ([C] \geq 2) \), partitioned hop Qos requirements: \( speed_i, r_i \)
Output: the forwarding candidate set \( F \)
1 \( F = \{c_1\}; k = \max(\alpha, \min(\beta, 20\%|C|)) \);
2 \( \text{while } C \neq \emptyset \) do
3 \( \text{if meet Qos requirements then} \)
4 \( \text{return } F; \)
5 \( \text{else if CheckRange } (F, c_1) = \text{false then} \)
6 \( \text{// } c_1 \text{ is always the first node in } C, \text{ it should be} \)
7 \( \text{within the transmission range of any node in } F; \)
8 \( C = C - \{c_1\}; \)
9 \( \text{continue;} \)
10 \( \text{else if } |F| \leq k \) then
11 \( C = C - \{c_1\}; \)
12 \( \text{for } i=0 \text{ to } |F| \) do
13 \( \text{temporarily insert } c_1 \text{ between } F(i) \text{ and} \)
14 \( F(i + 1); \text{ get the optimal insert position } i^* \)
15 \( \text{in term of } espeed_i(\pi_j(F)); \)
16 \( \text{end} \)
17 \( \text{Insert}(c_1, i^*, F); \)
18 \( \text{//Insert } c_1 \text{ as the } i^*_t \text{ item in } F; \)
19 \( \text{else} \)
20 \( \text{Append}(c_1, F); \text{//Append } c_1 \text{ as the last item in } F; \)
21 \( C = C - \{c_1\}; \)
22 \( \text{end} \)
```

**Algorithm 1**: Candidate selection and prioritization at forwarding node \( i \) in EGOR

VII. Evaluation

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

A. Simulation settings

In the implementation of our simulation, $N \times N$ sensor 
nodes are uniformly placed in a $200m \times 200m$ field, forming 
a two dimensional grid. A sink node is positioned at bottom 
left $(0m, 0m)$, and the source node is located at the top right 
$(200m, 200m)$. A data packet generated by the source node 
is forwarded toward the sink over multiple hops. The sensor 
transmission range $r$ is taken $40m$. $\alpha = 2$, $\beta = 5$. Let $\gamma$ 
denote the packet size ratio between a control message and 
a data packet. In our simulation, $\gamma$ is 0.1. The MAC layer 
protocol is a modified version of IEEE 802.11 MAC in ns-2, 
$T_{SIFS} = 10us$, $T_{DIFS} = 50us$. The data packet length is 
300bytes and $t_k \approx (2.95 + 0.316 \cdot k)ms$.

We use the Nakagami distribution defined as Eq. 27 to 
describe the power $x$ of a received signal:

$$f(x, m, \Omega) = \frac{m^{mx}e^{-mx}}{\Gamma(m)m^{m}} \exp\left(-\frac{mx}{\Omega}\right)$$

(27)

where $\Gamma$ is the Gamma function, $m$ denotes the Nakagami 
fading parameter and $\Omega$ is the average received power. We set 
$m = 1$ in our simulation. Assuming TwoRayGround signal 
propagation, $\Omega$ can be expressed in Eq. 28 as a function of $d$, 
the distance between the sender and receiver.

$$\Omega(d) = \frac{P_tG_tG_rh_t^2h_r^2}{d^nL}$$

(28)

where $P_t$ is the transmission power, $G_t$ and $G_r$ are the antenna 
gains, $h_t$ and $h_r$ are the antenna heights, $L$ is the loss factor, 
and $n$ is the path-loss exponent. We set $G_t = G_r = 1$, $h_t = 
h_r = 1.5m$, $L = 1$, and $n = 4$ in our simulation. We assume a 
packet is received successfully if the received signal power 
is greater than the receiving power threshold. Then by using Eq. 
27 and Eq. 28, we can derive the PRR at a certain distance $d$ 
[17].

B. Evaluation metrics

We select three evaluation metrics to evaluate the 
effectiveness of EGOR for QoS provisioning in WSNs: 1) On-
time packet delivery ratio; 2) End-to-end delivery delay; 3) 
Normalized sending cost; The on-time packet delivery ratio is 
the number of rounds satisfying the QoS requirements to the 
total number of rounds. The end-to-end delay metric measures 
how long it takes for a data packet to arrive at the sink 
from the source node. The cost of a transmission consists 
of the sending cost of the sender, and the receiving cost 
of one-hop neighbors. Given an evenly distributed network, 
the transmission cost is proportional to the sending cost. 
Hence, the sending cost metric measures the communication 
overhead and energy efficiency to some extent. We define the 
normalized energy cost for sending a data packet as one cost 
unit. Therefore, the energy cost for sending a control packet 
is 0.1 ($\gamma = 0.1$) cost unit.

C. The balance achieved by EGOR

We compare EGOR with two extreme solutions under 
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 node density in this work is defined 
as the number of nodes deployed in a $200m \times 200m$ field. 
The reliability requirement is set 0.99. For the extreme solutions 
(exhaustive 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 ordered.

Fig. 6(a) plots the average packet speed achieved by EGOR 
and the two extreme solutions under different node densities. 
We can see that EGOR provides very close packet speed to 
the Max-Speed. Fig. 6(b) shows that EGOR involves a little 
more forwarding candidates than the Min-F scheme, which 
serves as the lower bound of $|F|$. From Fig. 6, we can see that 
EGOR provides a good balance between the packet speed 
and the energy cost for GOR.

D. The effectiveness of EGOR for QoS provisioning

In term of the effectiveness for multiconstrained QoS pro-
visioning in WSNs, we compare EGOR with the multipath 
routing approach$^3$ [9] [10] and the single path routing with up 
to 3 times retransmission recovery mechanism (GPSR) [28].

1) Impact of the reliability Qos requirement: In this compar-
ison, $14 \times 14$ sensor nodes are uniformly placed in the field, 
we examine the performance differences of EGOR, MPQP and 
GPSR under different reliability requirements. The end-to-end 
delay requirement is set $0.10s$. Fig. 7 shows the results when 
we vary the reliability requirement.

Fig. 7(a) illustrates the changes of the on-time packet 
delivery ratio of three different approaches at increasing the 
reliability requirement. EGOR can always meet the reliability 
and end-to-end delay requirements. While MPQP can only

$^3$Since our aim is to compare the multipath routing approach with 
the opportunistic routing approach for multiconstrained QoS provisioning 
in WSNs, and the basic ideas behind [9] and [10] are similar, thus, we implement 
their common function, which we refer to as MPQP in our simulations.
provide 50% to 80% on-time packet delivery guarantee. For GPSR, about 70% packets can arrive at the destination within 0.10s. We also observe that MPQP behaves unsatisfactory as the reliability requirement increases. The reason is that MPQP is more likely to choose the neighbor(s) with higher PRR when the reliability requirement is larger. However, a neighboring node with higher PRR may possibly has less packet advancement. Thus, with an increase of the reliability requirement, more hop-counts are required to complete the packet delivery task.

Fig. 7(b) and Fig. 7(c) show the average end-to-end delay and normalized sending cost as the reliability requirement changes, respectively. In the end-to-end delay metric, it is seen that EGOR provides more than 50% improvement over the other approaches on average. Compared with EGOR and GPSR, we observe that MPQP spends several times more on energy cost. This confirms our argument that the multipath routing approach for QoS provisioning in resource constrained WSNs is not suitable. Although EGOR behaves a little better than GPSR in the normalized sending cost metric, EGOR can provide much higher on-time packet delivery ratio and less end-to-end delay.

2) Impact of the node density: In this test, we evaluate the performance of EGOR under different node densities by varying the number of nodes from 10×10 to 20×20. The end-to-end reliability and delay requirements are set 0.95 and 0.10s, respectively.

Fig. 8(a) reports the on-time packet delivery ratio under different node densities. It is interesting to see that MPQP and GPSR are influenced by different node densities. As the node density increases, their on-time packet delivery ratios fluctuate. This is partly because GPSR always chooses the neighbor with maximum packet advancement without considering the link quality. Thus, such scheme may incur more retransmissions, consequently degrade the performance. Similarly, for MPQP, more hop-counts is required with the increase of the node density.

Fig. 8(b) and Fig. 8(c) depict the average end-to-end delay and normalized sending cost as the node density increases, respectively. For these two metrics, EGOR shows obvious superiority to MPQP and GPSR.

From Fig. 7 and Fig. 8, we can see that EGOR is less influenced by the changes of the reliability requirement and node density. Compared with the multipath routing approach, all the performances are greatly improved by exploiting the GOR for QoS provisioning in WSNs.

E. The time complexity of EGOR

We evaluate the computation delay of EGOR on MICAz 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 $r_1 = 1.0$, the average computation delay of EGOR grows linearly and slowly as the number of available next-hop nodes increases. When $|C| = 10$, the delay is around 10ms, however, the candidate selection and
The prioritization algorithm proposed in [17] introduces a computation delay on average. When the required reliability goes to 0.99, the EGOR’s computation delay under different number of available next-hop nodes has very little change, from 2.29ms to 2.74ms. Thus, we conclude that EGOR 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. 5 and Fig. 6.

VIII. CONCLUSION

In this paper, we proposed to exploit the geographic opportunistic routing (GOR) for multiconstrained QoS provisioning in WSNs, which is more suitable than the multipath routing approach. We found that existing GOR protocol cannot be 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 (EGQ) in WSNs. We formulated the EGQ problem as a multiobjective multiconstraint optimization problem and analyzed the properties of EGQ’s multiple objectives. Based on our analysis and observations, we then proposed an efficient GOR (EGOR) algorithm for QoS provisioning in WSNs. EGOR achieves a good balance between these multiple objectives, and is specifically tailored for WSNs considering the resource limitation of sensor devices. We conducted extensive evaluations to study the performance of the proposed EGOR. Evaluation results demonstrate that it has a very low time complexity and it can significantly improve the QoS metrics in WSNs, e.g., the on-time packet delivery ratio, end-to-end delivery delay and energy efficiency.

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