TIEGeR: An Energy-Efficient Multi-Parameter Geographic Routing Algorithm

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Abstract—**Geographic routing algorithms conventionally use one-hop greedy forwarding as their primary routing technique, which might lead to routing voids. Secondary routing schemes used to circumnavigate such routing voids are unfortunately not efficient in terms of throughput and energy consumption. Moreover, node residual energy and link quality are not considered during the routing process. This paper presents Two-hop Information based Energy-efficient Geographic Routing (TIEGeR) scheme to achieve effective energy balancing throughout the network, while preventing routing voids by proactively avoiding "local maxima" nodes. Distance to reach destination, node connectivity, link quality, and node residual energy are employed to formulate the routing metric for the TIEGeR. Besides, secondary routing scheme dealing with routing voids is supplemented by the reverse progress mode. Simulations verify the advantages of TIEGeR against conventional geographic routing schemes.**

I. Introduction and Related Work

Wireless sensor networks (WSNs) made up of wireless nodes configurable for various sensing and processing tasks, have found widespread acceptance in numerous applications [1, 2, 3]. With the availability of low power and low cost position tracking devices like GPS (Global Positioning System) and UWB (Ultra-Wideband) localization, geographic routing algorithms have been widely employed for WSNs. Recently, Lichtensteiger *et al*. [4] proposed using geographic routing for Smart Metering Mesh Systems. Most geographic routing algorithms including GPSR [1], GAF [5] and GOAFR [6] adopt distance-based greedy forwarding where packets are forwarded to the one-hop neighbour closest to the destination. This technique often leads to a "routing void" or "deadlock" situation [1, 6]. In this situation, all one-hop neighbours have greater physical distance towards the destination than the current node. Such nodes, also referred to as "local maxima" nodes, necessitate the need for effective void-handling schemes. In order to navigate the packets around these "routing voids", the use of Face routing algorithms [1, 5, 6] is prevalent in most geographic routing algorithms.

Geographic routing protocols in the literature are commonly based on one-hop information [1, 2, 5, 6]. The possibility of using two-hop neighbourhood information was first proposed in GEDIR-2 [7]. Using two-hop information in [8] leads to higher packet delivery rate and shorter hop counts as compared to simple one-hop Greedy forwarding [1] by predicting and avoiding routing voids. The complexity analysis for a network of n nodes presented in [8] indicates that every node can obtain the knowledge of its two-hop neighbourhood nodes in a total of $O(n)$ messages, each message being $O(\log n)$ bits in size. Liu *et al.* [9] present an improved version of GEDIR-2 called NIGRA, which uses only the second hop neighbour location for routing decision.

A very important limitation of WSNs is the nodes' limited energy resources. Hence, energy efficiency becomes a prime concern to be addressed by the algorithm design. This is a major limitation of two-hop information based schemes presented in [7, 9]. In GEAR [10], a distance and residual energy based routing protocol to route around voids is proposed. HobyCan [11] presents another location and residual energy based scheme that constructs multiple paths for packets. This, in turn, distributes the load onto the alternate paths around the hole, thus preventing fast depletion of nodes around the routing void. EAGR [12] proposed a cost metric based on distance, fraction of energy consumed and rate of energy consumption to improve energy consumption of the nodes. e-GPSR [13] presents a residual charge and angle-of-propagation based approach for the greedy forwarding mode.

The distance based greedy forwarding techniques in [1, 2, 5, 6, 7, 9] and the energy aware algorithms in [10-13], assume a simplified binary link layer model, where the radio range is mapped as an ideal sphere. However, the validity of this idealized assumption has been challenged in many research studies [14-16]. Choosing the next hop closest to the destination node may lead to poor link quality because of the increased distance between the sending and the receiving nodes. The product of link quality, measured as PRR (Packet Reception Rate) and distance from destination has been shown to be a good routing metric for geographic routing [16]. More recently, a weighted sum of *PRR*D* product along with the node residual energy has been shown to achieve higher network lifetime [17,18]. In [19], a modified version of *PRR*D* routing metric is used over k-hops for routing, which shows an improvement in terms of packet delivery rate and hop count as compared to conventional geographic routing algorithms. In [20], Li presents a distance and node connectivity based geographic routing scheme. The routing metric comprises of a weighted sum of the distance from destination and the connectivity factor, computed over all the neighbourhood nodes to choose the next hop.

Different from [7, 9], the proposed TIEGeR algorithm employs different combinations of the network parameters obtained using the additional information of the two-hop neighbourhood nodes. For the first hop, a combination of link quality, geographic distance and node residual energy is used. For the second hop, a simple node-connectivity based model is

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utilized. This leads to improved efficiency and reduced metric decision computational time. This is primarily due to the reduced second-hop computational complexity by using only the connectivity factor for the second hop.

Motivated by these arguments, a new routing metric that takes into account link quality, node residual energy, distance to destination and second-hop forward connectivity information is proposed in this paper. The contributions of the proposed scheme are as follows:

- Dedicated secondary routing algorithm is not required. Instead, TIEGeR initiates its *reverse progress mode*, where packets are still forwarded in a greedy fashion using the proposed routing metric.
- The proposed multi-parameter based routing metric reduces the likelihood of encountering routing voids by using the node connectivity information to forewarn about the local maxima nodes. This leads to the *reverse progress mode* initiated sparingly, thus improving the overall routing efficiency of the TIEGeR.
- By using the node residual energy parameter, the TIEGeR achieves effective and efficient energy balancing throughout the network. This helps prevent the network partition due to battery-depleted nodes.
- The TIEGeR proves its effectiveness in both static and mobile network scenarios. The simulation results illustrate the superior performance of TIEGeR even in mobile networks.

The rest of the paper is organized as follows. Section II presents routing parameters considered in this paper. Section III explains the new two-hop neighbourhood information based routing metric along with the steps in the working of TIEGeR Algorithm. In Section IV, simulation results are discussed. Finally, Section V concludes this paper.

II. ROUTING PARAMETERS

A. Link Quality

We consider the log-normal shadowing model [21]. The propagation loss over the link between nodes i and j, is

$$L(d_{i,j})_{dB} = L(d_0)_{dB} + 10\gamma\, log\left(\frac{d_{ij}}{d_0}\right) + X_{dB} \qquad (1)$$

where γ is the path loss exponent, d_0 is the reference distance, d_{ij} is the distance between nodes i and j, and X_{dB} denotes the log-normal shadowing with zero mean and σ^2 variance. Based on the path loss component, we model the link quality estimation as a function of distance between two nodes as:

$$p_{i,j} = \left(\frac{d_0}{d_{ij}}\right)^{\gamma} \qquad (2)$$

B. Node Connectivity

It has been observed that nodes close to the void or along edge of the network topology suffer from low neighbour density [3,20]. This makes such nodes susceptible to a deadlock situation. We consider a new connectivity model that incorporates the number of *forward progress* neighbours for a node as a measure of its connectivity.

Let the set of neighbours of node i be denoted by N_i. A *forward progress* neighbour of node i is defined as the one that is closer to the destination than node i. A *reverse progress* neighbour of node i is defined as the one that is farther away from the destination as compared to node i. Let N_i^{FP} and N_i^{RP} denote the set of *forward progress* neighbours and the set of *reverse progress* neighbours of node i, respectively. In other words, $N_i^{FP} = \{j \in N_i : d_j \leq d_i\}$, $N_i^{RP} = \{j \in N_i : d_j > d_i\}$, and $N_i^{RP} \cup N_i^{FP} = N_i$. Then the normalized connectivity of node i, denoted by c_i is defined as follows:

$$c_i = \frac{|N_i^{FP}|}{|N_i|} \qquad (3)$$

where |A| is the cardinal number of set A.

C. Node Residual Energy

Normalized residual energy of node i, $\bar{E_i}$ is defined by

$$\bar{E_i} = \frac{E_i}{E_{max}} \qquad (4)$$

where E_i is the residual energy level of node i and E_{max} is the maximum start-up energy level of all nodes. This paper assumes that the major factors utilizing the node's energy are the packet reception and transmission.

III. TIEGER ALGORITHM

The TIEGeR employs weight $w_{i,j}$ to replace geographic distance as a sole contributing factor towards routing decision. Prime importance is given to the energy balancing term in the routing metric to aid in higher network lifetime. The steps to follow under the modified algorithm are presented in Subsection A.

A. TIEGeR: Two-hop Information based Energy-efficient Geographic Routing Algorithm:

Objective: Select next hop j^*

Proposed Routing Metric

$$w_{i,j} = \left[\alpha_1 . p_{i,j} + \alpha_2 . c_j + \alpha_3 . \bar{E_j}\right] \qquad (5)$$

where,

$$(\alpha_1 + \alpha_2 + \alpha_3 = 1)$$

$p_{i,j}$ denotes the quality of the link between i and j,
c_j represents the connectivity of node j,
$\bar{E_j}$ is the normalized residual energy of node j.

TIEGeR Algorithm – Steps

Beacon Exchange Protocol

a. Sending hello packets: All nodes periodically broadcast hello messages containing node ID (Identity), node's location, residual energy, connectivity factor.
b. Receiving hello packets: On receiving a hello packet from node j, node i updates its neighbour table with values carried in the received hello packet.

Routing Protocol

a. When node i receives a data packet, compute $w_{i,j}$ using (5).
b. ***Forward Progress Mode***: If $|N_i^{FP}| \geq 1$, choose next-hop j^* such that:
$$j^* = \arg \max_{\forall\, j \in N_i^{FP}} w_{i,j}$$
c. ***Reverse Progress Mode***: If $|N_i^{FP}| = 0$, choose next-hop j^* such that:
$$j^* = \arg \max_{\forall\, j \in N_i^{RP}} w_{i,j}$$

Even though TIEGeR reduces the possibility of encountering a routing void, there still might exist some situations leading to voids. Under such circumstances, the

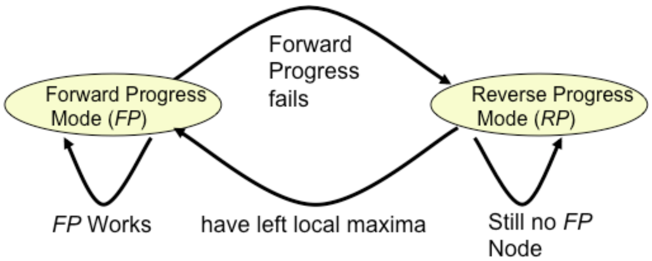

Fig. 1. TIEGeR Algorithm Routing Mode Flow.

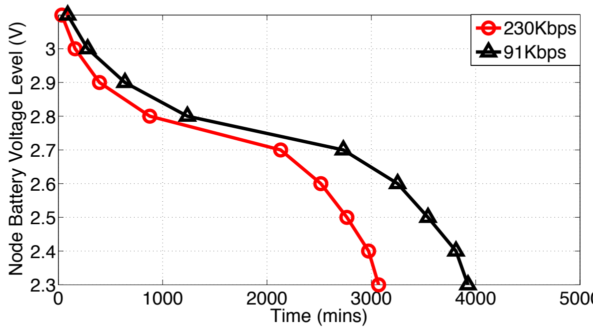

Fig. 2. Experimental Result – Battery Decay Behavior of TI CC2530 nodes.

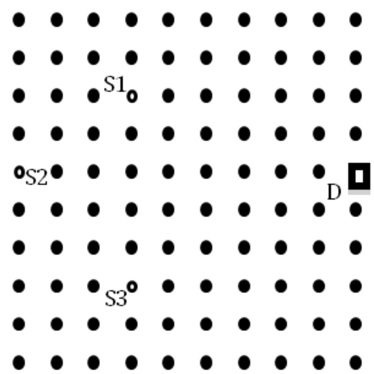

Fig. 3. Network Topology 1 - All static nodes, multiple source nodes.

algorithm switches to *reverse progress* mode. The major difference between the traditional secondary routing schemes and the *reverse progress* mode of TIEGeR lies in the fact that secondary routing schemes like face routing fail to capitalize on the additional node information like link quality, connectivity and residual energy level. Whereas, using the weight factor $w_{i,j}$ during reverse progress mode ensures that even in deadlock situations the packet is forwarded in an energy- and link-aware fashion. This behavior, as shown in Fig. 1, is continued until the packet reaches a node where *forward progress* mode can be re-applied. Hence, TIEGeR eliminates the need for a dedicated secondary routing scheme.

IV. Simulation Results

TIEGeR is compared to existing geographic routing schemes like GPSR, GRR, PRR*D and GEAR by simulating different network topologies using NS-2 [22]. The IEEE 802.15.4 MAC (Medium Access Control) and PHY (Physical) layers are employed for all simulations. Each node is set to have a maximum transmission range of 40 meters. The weight parameters α_1, α_2 and α_3 for the routing metric $w_{i,j}$ are set as 0.3, 0.3 and 0.4, respectively, laying prime importance onto the residual energy parameter. These values were obtained by varying the weight parameters for different simulation runs in order to get the optimal values. The optimal values were computed keeping in mind the three prime objectives, i.e., energy balancing, utilizing good quality of links for packet forwarding, and avoiding the deadlock nodes. The path loss exponent γ and the shadowing deviation X_{dB} for the link quality model are set to 3 and 4 dB, respectively. In order to have a realistic energy model, we simulated the energy level decay function based on the experimental testbed setup. For this, two Texas Instruments CC2530ZDK nodes are used to setup a point-to-point link. Fig. 2 shows the energy decay with time for the CC2530 nodes. The energy decay function in NS-2 is modified accordingly to have a non-linear battery level depreciation as shown in Fig. 2. Also, in order to reduce the time taken to simulate a powered-out node, the maximum battery level is scaled down so that each node can process the transmission and reception of upto 300,000 packets. The evaluation parameters considered for effectively comparing the performance of TIEGeR with the existing geographic routing protocols are:

- **Packet Delivery Ratio:** This is defined as the ratio of number of packets successfully delivered at the destination node to the total number of packets generated at the source node.
- **Network Lifetime:** This is the time before the first node in the network dies out due to depletion of its energy resources. The objective is to measure the time before the network partitions due to energy depleted nodes.

A. Network Scenario 1: Improvement due to Node Residual energy Level Information

Fig. 3 displays the network scenario 1, where the objective is to demonstrate the advantage of the TIEGeR algorithm in terms of achieving effective energy balancing throughout the network. All the nodes are placed equidistantly and identically in a square network topology. To test and verify this behavior, we begin with only one source node, increasing the number of source nodes to three during subsequent simulation runs. The destination is the same for all three traffic sources. Each active source node generates Constant Bit Rate (CBR) traffic, effectively simulating a typical WSN environment with periodic updates being sent to the destination. Increasing the rate of CBR data packets from 9 to 230 kbps for each source node increases the load on the network.

To evaluate the effect of increasing load onto the overall network lifetime, TIEGeR is compared with GPSR and GEAR. As shown in Table 1, TIEGeR clearly outperforms both GPSR and GEAR in terms of network lifetime. GPSR uses the same static path through the network towards the destination node, hence leading to a much faster energy depletion of the nodes along the path. This depletion of energy is accelerated with increasing rate of packet generation for a fixed source destination pair. Similarly, GEAR also tends to forward the packets in a distance based greedy fashion, not considering the energy efficiency parameters until the pure greedy forwarding fails to navigate towards the destination. At this point, GEAR

TABLE I. NETWORK LIFETIME FOR INCREASING LOAD

Traffic Pattern	Network Lifetime (seconds)		
	GPSR	***GEAR***	***TIEGeR***
One 9 kbps Source	9302	9600	10260
Two 9 kbps Sources	9028	9385	10115
Three 9 kbps Sources	8755	9156	9980
One 45 kbps Source	3464	3690	3917
Two 45 kbps Sources	3322	3595	3842
Three 45 kbps Sources	3187	3519	3767
One 91 kbps Source	1198	1240	1384
Two 91 kbps Sources	1126	1181	1349
Three 91 kbps Sources	1061	1119	1321
One 230 kbps Source	605	620	670
Two 230 kbps Sources	572	595	648
Three 230 kbps Sources	538	580	632

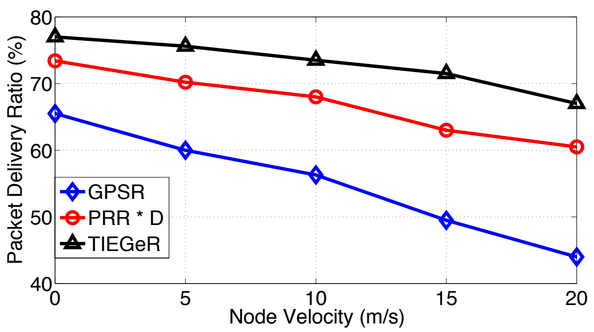

Fig. 4. Packet Delivery Ratio versus Node Velocity (V_{max}) in Network Topology 2.

initializes its estimated-cost function, which is a weighted sum of distance and residual energy level. On the contrary, TIEGeR mitigates the effect of increased rate of packet generation by balancing the packet flows evenly among the various alternate paths towards the destination node.

B. Network Scenario 2: Improvement due to Link Quality Information

In network scenario 2, a 200×200 meters square network topology with 100 mobile nodes using the random waypoint mobility model is presented. In the random waypoint mobility model, each node travels towards a randomly chosen destination at a speed uniformly distributed between [0, V_{max}]. Upon arrival, the node pauses for a small time interval before repeating the process. The objective is to measure the effect of increasing node velocities on the packet delivery ratio of the three routing algorithms – GPSR, PRR*D and TIEGeR. The intention is to highlight the importance of additional link quality information in choosing links with better link quality as opposed to selecting the farthest node from the current node towards the destination node. Simulations are conducted by randomly choosing a source-destination pair generating CBR data packet traffic at 45 kbps. The maximum node velocity V_{max} is increased subsequently from 0 to 20 m/s to inspect the limitation of GPSR and PRR*D during high mobility cases. As illustrated by Fig. 4, TIEGeR maintains a higher packet delivery ratio in all the node velocity cases. GPSR tends to select the forwarding node along the boundary of the radio range, leading to poor link quality. Furthermore, the possibility of the chosen next hop node moving out of the transmission range before the packet is actually forwarded leads to packet drops. Even though PRR*D takes link quality estimation into account, it still selects nodes in the transitional region rather than the connected region. On the contrary, TIEGeR chooses nodes in the connected region. This leads to a reduced packet delivery ratio for both GPSR and PRR*D as compared to TIEGeR.

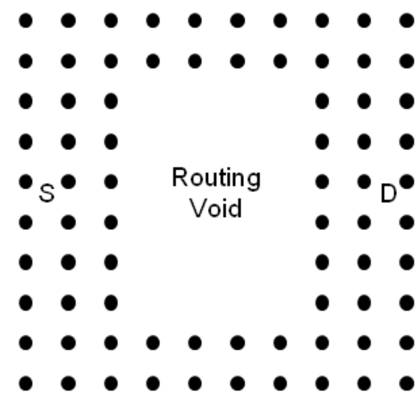

Fig. 5. Network Topology 3 - All static nodes, routing void between Source S and Destination D.

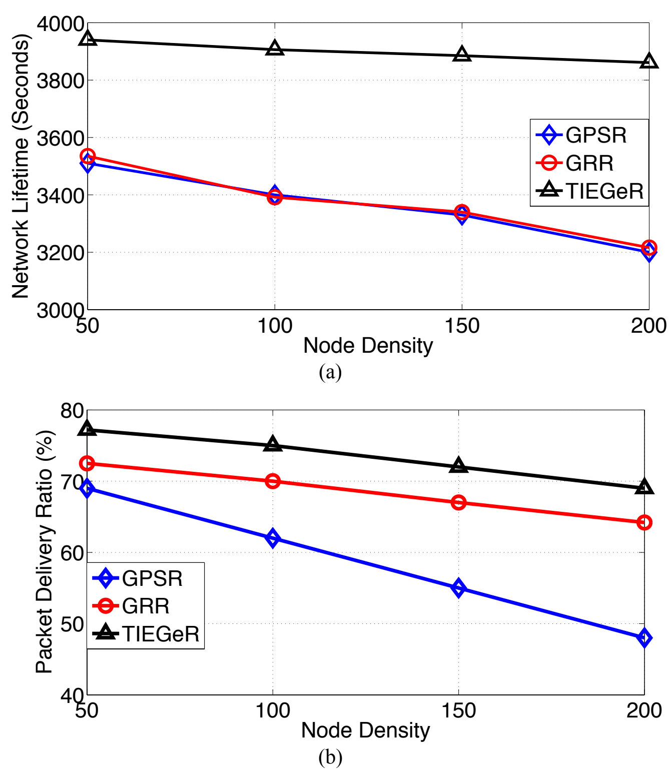

Fig. 6. Plot of (a) Network Lifetime versus Node Density; (b) Packet Delivery Ratio versus Node Density in Network Topology 3.

C. Network Scenario 3: Improvement due to Second-Hop Forward Connectivity Information

Fig. 5 shows the network scenario 3, consisting of a square network topology of static nodes with a void area in the middle of source and destination node. The simulations are executed with the number of nodes in the network gradually increased from 50 to 200. This is done to increase the density of nodes in the network and subsequently observe the effect of the increased neighbour density on the second-hop connectivity factor. The aim of this network topology is to measure the energy balancing effects of the proposed scheme during a typical void scenario. This is achieved by not routing packets towards the routing void. Fig. 6(a) shows that TIEGeR has a higher network lifetime than GPSR and connectivity-based GRR. Due to the lack of energy balancing mechanisms, both GPSR and GRR continuously forward packets over same path, depleting path-nodes faster as compared to the rest of the nodes. Further, with increased neighbor density, the amount of hello messages exchanged is also increased, leading to a drop in the network lifetime as compared to lower node density cases. This explains the slight drop in the network lifetime for TIEGeR with increasing network density, even though the number of alternate paths increases.

In Fig. 6(b), we show the comparison of GPSR, GRR and TIEGeR in terms of the packet delivery ratio. Due to the additional connectivity information, GRR delivers more packets than GPSR. TIEGeR has a higher packet delivery ratio than both GRR and GPSR. Furthermore, the difference in packet delivery ratio between TIEGeR and GPSR increases with increased density in the network. This is due to the increased connectivity leading to effectively predicting and avoiding the "deadlock" nodes. TIEGeR, by using only the *forward progress* nodes to compute the connectivity factor, has the advantage over GRR, which takes into account all the neighbour nodes as its connectivity. Due to this, TIEGeR is better suited to predict the routing void as compared to GRR, leading to a considerably higher packet delivery ratio. Besides, the multi-parameter *Reverse Progress Mode* enables TIEGeR to still navigate the void in an energy efficient way for lower node density cases.

V. CONCLUSIONS

In this paper, we introduce TIEGeR, a multi-parameter two-hop information based energy efficient Geographic Routing algorithm. TIEGeR, due to its *Forward Progress Mode* and the *Reverse Progress Mode*, eliminates the need for a dedicated secondary routing algorithm for geographic routing schemes. We utilize a combination of Node Link Quality, Distance towards Destination, Node Forward Connectivity and Node Residual Energy Level to compute an energy-efficient and link-aware routing metric. This metric is used by TIEGeR to achieve effective and efficient energy and load balancing among the nodes in the network. Furthermore, the presence of link quality in the routing metric ensures that TIEGeR outperforms other comparable geographical routing schemes including GPSR, PRR*D and GRR in terms of packet delivery ratio. Simulation results exhibit the performance superiority of TIEGeR in terms of packet delivery ratio and network lifetime.

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