Customizing a Geographical Routing Protocol for Wireless Sensor Networks

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***Abstract*— Several problems are required to be fixed in order to apply geographical routing protocol Greedy Perimeter Stateless Routing (GPSR) in wireless sensor networks. First, GPSR is designed under the assumption of symmetric links (i.e., *bidirectional reachability*) which is not realistic for many practical sensor networks, since wireless links in sensor networks often are asymmetric. Second, in sensor networks, packet destinations are often marked with locations instead of identifiers like IP address. Therefore, packets are routed to the *home node* which is the node geographically closest to the destined location. Under GPSR, when the target location is outside the exterior perimeter of the sensor network, each packet has to visit all nodes on the boundary of the sensor network topology before it identifies the home node, which results in *energy inefficiency*. Third, due to the dynamic nature of sensor networks, maintaining *data consistency*, that is, data retrieved from the home node for a location should be consistent with the data sent to the same location, becomes a challenge when home nodes change. We propose *On-demand GPSR* (OD-GPSR), a data driven geographical routing protocol customized for sensor networks with solutions to the above three problems. Simulation results show that OD-GPSR performs well in terms of energy efficiency and packet delivery rate at the cost of a little bit more packet delivery delay.**

Keywords: Sensor Networks, Geographical Routing Protocol, Energy-efficient, Link Asymmetry, Data Consistency.

I. Introduction

As a strongly geographical routing protocol allowing nodes to send packets to a particular location, GPSR[5] is holding promise in providing routing support in wireless sensor networks. For instance, many recent research works on in-network data-centric storage such as [9] build applications atop GPSR. However, because GPSR is not originally designed for sensor networks, several problems are required to be fixed before it is applied in sensor networks.

- First, GPSR is designed under the assumption of symmetric wireless links. That is, whenever a node receives a beacon from another node, it considers that node as its neighbor as it assumes they are *bidirectional reachable*. Such an assumption may not be realistic for practical sensor networks, since wireless links in sensor networks often are asymmetric [3].
- In sensor networks, packet destinations are often marked with locations instead of identifiers like IP addresses and packets finally reach the node geographically closest to the destination, the *home node* of the target location. Because sensor nodes may become irregular after running for a period of time or due to unattended deployment, it is highly possible that the target location in a packet is located outside the exterior perimeter of the sensor network. In such cases, GPSR's Planar Perimeters Algorithm does not work efficiently in that all such packets have to visit all nodes on the border of the network topology before returning and recognizing the home node. This process is very energy expensive.
- *Data consistency* problem, which means data retrieved from a location in sensor networks should be consistent with data sent to the same location, becomes a challenge due to the dynamic nature of sensor networks. Sensor nodes including the current home nodes for locations may often fall into disfunction state or even die due to hardware failure and energy exhaustion, or are intermittently reachable as a result of the impact of various factors, e.g., environmental effects.

Based on the implementation of GPSR, we propose *On-demand GPSR*(OD-GPSR), a data-driven geographical routing protocol. OD-GPSR not only works more efficiently than GPSR under the same circumstance but also is able to take advantage of the unidirectional links when non-uniform transmission ranges exist in sensor networks. This property would be very useful in practical sensor networks. In OD-GPSR, the destination in a packet is identified with location instead of node IP address. Packets are routed to the node nearest to the target location(i.e. the home node for that location). Following is a briefly explanation on how OD-GPSR works.

OD-GPSR is a data-driven reactive routing protocol under which, only those nodes with data flowing over solicit location information from neighbors. As a result, unnecessary communication between neighbors is avoided and the valuable energy is saved. When a node needs to forward packets but has no neighbor information, the node caches the packets first and then broadcast a one-hop *beacon-request* packet to all neighbors seeking neighbor information. In response, neighbors send back *beacon* packets including location information using either a *broadcast* packet or a *unicast* packet as specified in the beacon-request packet. Unicast beacon packet is used to discover potential unidirectional links to neighbors.

The routing decision for packets is made using the same algorithm as of GPSR but based on different neighbor information. Packets are forwarded greedily whenever possible based on both bidirectional and unidirectional neighbor information. The packet is always forwarded to the neighbor geographically closest to the target location in *greedy* mode. When a packet reaches a dead end with no closer neighbor, the packet switches to *perimeter forwarding* mode and uses right-hand rule to circumnavigate the void in a planarized network graph. This planarized graph is constructed only based on information of bidirectional neighbors.

After a packet takes a tour of the enclosed perimeter around the target location and returns to the closest node to the destination, the node is recognized as the home node for that location. To maintain data consistency and improve robustness to node failures, OD-GPSR has the home node of a location recruit all neighbors as replica to cope with the dynamic property of sensor networks. The home node keeps broadcasting refresh packets to refresh the timers on neighbors. If the home node dies, a replica node will transfer data to the new home node after its timer expires. Also the current home node periodically sends special packets targeted to the represented location to check the existence of the possibly newly emerged closest node to the location.

OD-GPSR uses a *temporary boundary* method to deal with the boundary problem. The first time a packet is sent to an outside location and identifies its home node after visiting the boundary will trigger the protocol to send a special packet to set all border nodes. With the boundary knowledge in border nodes, following packets targeted to outside locations are able to identify their home nodes at border nodes without extra traversals of the border. Considering the dynamic nature of sensor networks, the state in each border node is a *soft* state which is removed when the timer associated with it expires.

We evaluate the performance of OD-GPSR through simulations in comparison with the GPSR version used in [9]. Results show that OD-GPSR has better performance in energy efficiency and packet delivery success rate at the cost of a little more packet delivery delay.

The rest of the paper is organized as follows. Section 2 presents related work. In section 3, we describe in detail the algorithm and implementation of our protocol. Section 4 gives simulation results. Section 5 is discussion and section 6 concludes with some future directions.

II. Related Work

GPSR[5] is one of the most well known geographic routing algorithms in wireless networks. So far, several applications in sensor networks including GHT[9] are built atop GPSR. GHT proposes the data-centric storage approach in sensor networks, in which notable events and data are stored by name in a distributed hash table(DHT). The implementation of DHT requires substantial routing support and is built atop GPSR. GPSR is modified to fit the needs: First, packet destination is marked with locations instead of identifiers like node IP address. Second, the home node for the target location is identified by the *home perimeter traversal* method. *Home perimeter* is composed of all nodes surrounding a location in which home node is the nearest to the location. After taking a tour of the enclosed home perimeter of the target location and returning to the nearest node to the target location, a packet notices the loop and recognizes it as the home node of the target location. Third, to solve the data consistency problem, the home node recruits all nodes on the home perimeter as replica nodes. Fourth, it points out the boundary problem but does not give solutions. Some problems of this implementation are: First, the design is based on the assumption of symmetric links and does not utilize unidirectional links. Second, using all nodes on the home perimeter is not efficient when the target location is outside the sensor field and therefore the home perimeter is composed of all nodes on the exterior border.

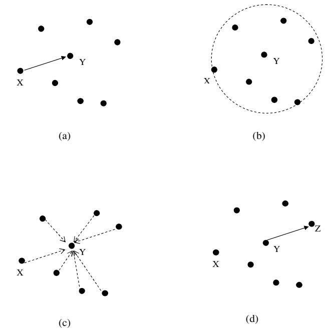

Fig. 1. The process for a node to solicit neighbor information

Several papers address the boundary problem. [6] proposes a geometric routing protocol which considers the performance of face routing used for recovery from greedy forwarding failures. [4] outlines a spectrum of possible solutions to the boundary problem encountered in data-centric storage.

[10], [11] study the impact of radio irregularity on wireless sensor network including geographic routing protocols. [2] points out the impact of non-uniform transmission range on GPSR. [1] proposes methods to guarantee successful perimeter routing for those geographic routing methods based on planar graph by adding virtual edges in cases of instable transmission ranges. [7] extends this result towards efficiency.

III. Algorithms and Implementation

We consider a network of *static* (e.g. immobile) energy-constrained sensors that are deployed over a flat region with each node knowing its own location.

A. Soliciting Beacons from Neighbors

OD-GPSR is a reactive data-driven routing protocol and only those nodes over which data is flowing seek neighbor information for making routing decision. An example of the process to solicit beacons from neighbors is illustrated in Fig. 1. When a node Y gets a packet to forward and finds itself with no reachability information of neighbors, the node broadcasts a beacon-request packet to its neighbors seeking location information in which a parameter is included to specify the type of packet for beacons (either *broadcast* or

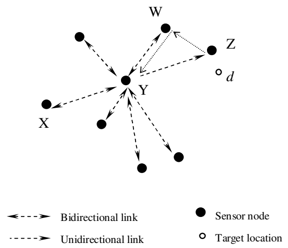

Fig. 2. An example of unidirectional links

unicast), as shown in Fig. 1(b). In response, a neighbor node sends back a beacon including its location via either a broadcast packet or a unicast packet as specified in the request packet, as shown in Fig. 1(c). In Fig. 1(d), after collecting all neighbor location information, node Y makes a greedy forwarding to Z.

Bidirectional links between neighbors are discovered by specifying *broadcast* beacon packets. In particular, when broadcast beacon packets are always specified, the process to solicit beacons would preclude asymmetric links to neighbors and no unidirectional links would be utilized.

Unicast beacon packets are used for detection of unidirectional links. When a neighbor receives notification of delivery failure for unicast beacon packets(we assume the MAC layer has such capability) for several times, the neighbor believes the link is unidirectional and then sends a special *unidirectional_notification* beacon via a local broadcast packet with a predefined value of *ttl* which defines the maximum hops allowed. When the target node receives such a beacon, it realizes the link to that neighbor is a unidirectional link. In a node, there are two neighbor tables. One is for neighbors of bidirectional links and the other is for neighbors to which unidirectional links exist. A neighbor entry of a bidirectional link is removed when a timer associated with it expires. The neighbor entry for a unidirectional link has no such a timer. It is not removed until this unidirectional neighbor is selected for a packet as the next hop and fails to forward the packet, or neighbor tables are removed totally after a certain period of time without data flowing over the current node.

Fig. 2 shows an example of the process to discover unidirectional links, in which link Y→Z is a unidirectional link. After failures to send the beacon to Y directly upon receiving beacon request from Y, node Z turns to deliver the beacon with the help of W via broadcasting. This is also an example for a potential benefit of exploiting unidirectional links. In Fig. 2, *d* is the target location and Z is the home node for *d*. By discovering the unidirectional link from Y to Z, packets on node Y will quickly reach node Z, the home node of the destination. Otherwise, the packet has to make a detour before reaching Z.

OD-GPSR takes the strategy of conditional usage of unidirectional links because unicast packets give rise to more energy consumption than one-hop broadcast packets. First, a node does not detect and exploit unidirectional links when a packet being forwarded is in *perimeter* mode. If the current node already has unidirectional neighbor entries, they are only

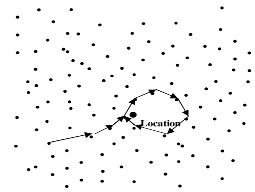

Fig. 3. An example of a packet to find the home node of its target location

used for packets in *greedy* mode and not used for constructing the localized planar graph which is for perimeter routing for packets in perimeter mode. Second, even for packets in greedy mode, a node conditionally specifies unicast beacon packet based on the current network conditions of its vicinity such as the number of neighbors, the geographic distribution of neighbors, the energy level of neighbors and others.

B. Greedy Forwarding and Right-Hand Rule

Greedy forwarding in OD-GPSR uses the same algorithm as GPSR. A forwarding node is always trying to make a greedy choice, selecting the neighbor geographically closest to the destination as the next hop. The neighbor information is from both neighbor tables which include neighbors of unidirectional links and bidirectional links. Greedy forwarding fails when reaching a node which has no neighbors closer to the destination. Then the packet is forwarded using the *right-hand rule* to circumnavigate this region. OD-GPSR routes *perimeter forwarding* mode packets on a planarized subgraph of the network connectivity graph, in which there are no crossing edges. This planarized graph is constructed only based on neighbor information of bidirectional links.

C. Data Consistency Problem

With the destination marked with location, a packet reaches the home node of the destination. Home nodes are categorized into two types: *transient home node* and *persistent home node*. For transient home node, it does not matter if the same data can be retrieved from the same location in different time. In contrast, data consistency is required for persistent home node, meaning that the same data sent to a location before should be retrieved later from the home node of the same location regardless the possible changes of the home node for the location.

A transient home node is identified when a packet reaches a node whose distance from the target location is less than half of its radio range and no neighbor nodes are closer to the destination. The other way to identify a transient home node is the perimeter traversal method in [9] as shown in Fig. 3. After the packet returns to the nearest node to the destined location and finds itself traversing a loop, the node is recognized as the home node for the location.

For persistent home node, the first time a packet is sent to a location, OD-GPSR identifies the target home node using the perimeter traversal method. Following packets to the same destination reach destination as they arrive at the marked home node for the target location without the traversal of the perimeter. Due to the dynamic nature of sensor networks, OD-GPSR has special mechanism for persistent home node to

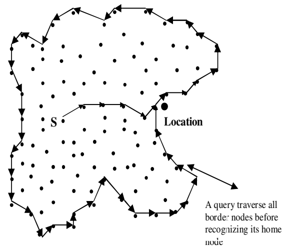

Fig. 4. Destination located outside of the network topology

keep the data consistency. The first time a node is identified and marked as a persistent home node for a location, it recruits all neighbors as replica nodes. Each replica node has a timer associated with it. The primary home node broadcasts refresh packets periodically to refresh timers on all neighbors. When the home node is dead, the timer in a replica node will expire and the replica node will keep sending a special packet to the target location reporting the death of the primary home node until receiving response. To handle the problem of new emerging home node for persistent home node, the current primary home node sends packets to the target location periodically to check the existence of new home node.

D. Boundary Problem

We propose *temporary boundary*, a solution to the boundary problem, which is composed of three steps. The first is the detection of a packet with outside target location. Such a packet traverses the boundary of the network topology in counterclockwise direction before identifying the home node, as shown in Fig. 4. Next is to collect boundary information after a packet is determined with outside destination. The third is to inform all border nodes of the collected boundary information. The border node state is *soft* state and removed after a certain period of time because of the dynamic nature of sensor networks. After a temporary border is formed, when a packet in *greedy* mode reaches a border node, the node is able to make a decision whether or not the target location is outside the current boundary based on its boundary knowledge. If the target location is outside the network topology and no other border nodes are geographically closer to that location, the current node is recognized as the home node for that location. Otherwise, the packet is forwarded. As a result, energy is saved by avoidance of unnecessary traversal of the boundary.

Under OD-GPSR, when a packet switches to perimeter forwarding mode, it starts recording coordinates of several special hops(actually at most 8 hops which include the nodes located at the top, bottom, left and right of the boundary of the perimeter it travels) and their visited time until switching back to greedy mode or identifying the home node. If it switches back to greedy mode, all records are discarded. Otherwise, if a packet finally identifies the home node for its destination, it is easy to determine its traversal direction and then figures out whether it traverses the boundary or not.

After a packet with outside destination is detected, a *border_collect* packet marked with the same target location, is sent to visit all nodes on the boundary in perimeter forwarding mode and returns with all border nodes' location in the sequence of visited time. Afterwards, a *border_set* packet is sent to inform all border nodes of the boundary information. This method works efficiently when the topology change of the network is not much and therefore the time to keep the border state can be set longer.

IV. Simulation Results and Evaluation

We implement the design of the modified version of GPSR proposed in [9](We use the term GPSR to refer this modified version of GPSR.) in order to compare its performance with OD-GPSR.

A. Simulation Environment

We simulated OD-GPSR in ns-2[8]. We use the CMU wireless extensions which includes full simulation of the IEEE 802.11 physical and MAC layer. Our simulations are for networks of 256 nodes with 802.11 WaveLAN radios. The radio range is changed to 40 meters to make it closer to the real situation. The nodes are randomly deployed in a 256m by 256 m rectangle area.

Three metrics are used for evaluation of performance. **Average energy consumption** is defined as the ratio of the total dissipated energy per node in the network to the number of packets successfully received by the sink. This metric defines the energy efficiency of the protocol. **Packet delivery success rate** is defined as the ratio of the number of data packets successfully received by the sink to the number of data packets sent by the data sources. This metric defines the effectiveness of data delivery. **Average delay** is defined as the average time between the moment a data packet is sent by a data source and the moment the sink receives the data packet. This metric defines the freshness of data packets.

B. Simulation Results

In this subsection, we show two series of simulation results to demonstrate the performance of OD-GPSR in comparison to GPSR. Since the latter works under the assumption of known boundary, we limit traffic destinations inside the network topology for the convenience of comparison. Error model is introduced in the simulation to make it close to the real situation, in which 10 percent randomly selected nodes keep switching between disabled state and normal state with intervals of 100 seconds. Simulations with various beacon interval parameter are run for both GPSR and OD-GPSR implementations to study the performance. Note that in the following figures, GPSR-bint5 means GPSR with beacon interval of 5 seconds and ODGPSR-bint5 means OD-GPSR with beacon interval of 5 seconds, and so on.

1) Case 1: precluding unidirectional links: In this simulation, unicast beacon packets are not used and all beacon packets are specified as broadcast packets. Therefore, unidirectional links are precluded from being detected and utilized. The simulation result is to show how the energy efficiency is achieved and the performance is improved even not taking advantage of unidirectional links. Fig. 5, Fig. 6 and Fig. 7 show results of this simulation.

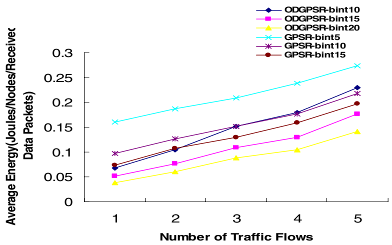

Fig. 5. Average Energy Consumption

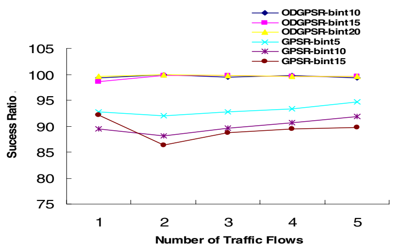

Fig. 6. Packets Delivery Success Rate

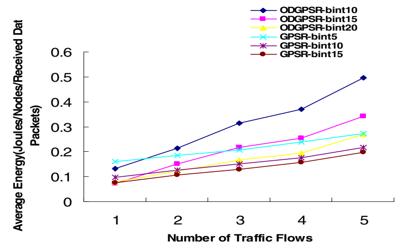

Fig. 8. Average Energy Consumption

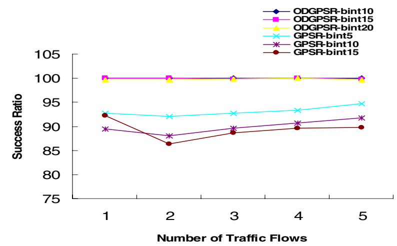

Fig. 9. Packets Delivery Success Rate

From Fig. 5, ODGPSR-bint10 expends less energy than GPSR-bint10 when the traffic is less, although the delivery rate of ODGPSR-bint10 is higher than GPSR-bint10 as shown in Fig. 6. The difference of the energy consumption is incurred by those unnecessary communications among nodes in GPSR. This result is also demonstrated by comparing ODGPSR-bint15 and GPSR-bint15. In OD-GPSR, only nodes with traffic solicit neighbor information and thus saves energy by avoiding unnecessary communications. Imagine a large-scale sensor network with not much traffic at most time, the energy saving is significant. As traffic involves more nodes, the saving becomes less as shown in Fig. 5, in which, when the number of traffic flows increases, the difference between GPSR-bint10 and ODGPSR-bint10 decreases. In OD-GPSR, neighbor information is required to be collected within the beacon interval upon receiving request, which intends to incur high traffic collisions when traffic is high. This is a disadvantage of OD-GPSR than GPSR in which each node randomly sends beacons to neighbors periodically with better desynchronization effect. Therefore, a small value of beacon period is not good for OD-GPSR. As shown in Fig. 5, when the number of traffic is high, the ODGPSR-bint10 is not better than GPSR-bint10 in terms of energy efficiency, while ODGPSR-bint15 is still much better than GPSR-bint15.

As shown in Fig. 6, the delivery rate of OD-GPSR is much better than GPSR. The reason is that GPSR always uses the home perimeter traversal algorithm for recognition of the home node, while OD-GPSR makes improvements for both types of home nodes and therefore the home node of the target location could be determined earlier in many cases especially when the density of nodes is relatively high.

As shown in Fig. 7, the average delay for packet delivery in OD-GPSR is higher than that in GPSR. The delay in OD-GPSR is caused by the delay of the first several packets in each traffic flow. When packets reach nodes not visited recently, they are cached in the nodes until the nodes get neighbor information. When a node already has the neighbor information, following packets are forwarded immediately resulting in comparable delay with GPSR. Under OD-GPSR, the average delay will drop correspondingly as the number of consecutive packets in a flow increases. So we can conclude that the average packet delivery delay of OD-GPSR is a little higher than(but very close to) that of GPSR when the number of consecutive packets in a flow is sufficiently large.

2) Case 2: exploitation of unidirectional links: We study the worst case of OD-GPSR in terms of energy efficiency when unicast beacon packets are introduced. Therefore all beacon packets are specified as unicast packet in the simulation. Fig. 8, Fig. 9 and Fig. 10 show results of this simulation.

By comparing the simulation data in Fig. 8 and Fig. 5, it is obvious how much extra energy consumption is incurred by using unicast beacon packets, which illustrates why we take the strategy of conditional detecting and utilizing unidirectional links.

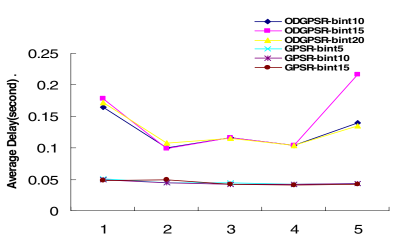

Fig. 7. Packets Average Delay

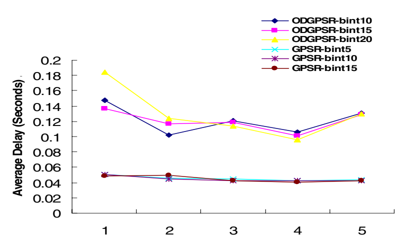

Fig. 10. Packets Average Delay

The simulation results verify that the energy saving by avoidance of unnecessary beacons among neighbors can offset at least part of the extra energy cost of unicast beacon packets in OD-GPSR. In Fig. 8, the difference of energy cost between OD-GPSR and GPSR for the same beacon interval decreases as the traffic decreases because more nodes are kept from sending beacon in OD-GPSR when less traffic exists. Because our simulation scenario is not a large sensor network, the energy saving by this way is not evident and therefore the average energy consumption in OD-GPSR is higher than GPSR for the same beacon interval as shown in Fig. 8. Another reason is that we take the worst case of OD-GPSR by using unicast packets for all beacons and therefore spend more energy than GPSR which uses broadcast beacon packets.

Next is to compare the packet delivery rate for the case when the energy cost is comparable between OD-GPSR and GPSR. From Fig. 8, we can see that the energy cost for OD-GPSR-bint20 is a little bit less than GPSR-bint5. However, from Fig. 9, we can see the successful delivery rate for OD-GPSR-bint20 is higher than GPSR-bint5. The reason is that most traffic destinations in the simulation are inside the network topology and therefore packets take less hops to reach the destination in OD-GPSR than GPSR except the first packet in each flow which uses the home perimeter traversal method to identify the home node as GPSR does.

From Fig. 10, we can see that the packet average delay in OD-GPSR is larger than GPSR. All three lines of OD-GPSR are above the three lines of GPSR. As stated in the above subsection, it is incurred by the first several packets in each traffic in OD-GPSR. Because a node without traffic flowing over recently has no neighbor information in OD-GPSR, the first several packets in a traffic reaching such nodes are cached to wait for the neighbor information for making routing decision, which incurs delay. Following packets in the same traffic do not experience such delay if they come not too late. As the number of packets in the traffic increases, the average delay decreases.

In this simulation study, we do not introduce unidirectional links in the environment at this time. We expect that, by taking advantage of unidirectional links which are not included here, OD-GPSR will perform much better. We leave this study as future work.

V. Discussion

As GPSR, OD-GPSR guarantees the delivery of packets if it is applied to an environment where all nodes have the same transmission range, but performs better than GPSR in terms of energy efficiency and data delivery rate at the cost of a little bit more delay. When it is applied to an environment where link asymmetry exists, the delivery is guaranteed if the planarized graph constructed based on the bidirectional links is connected and also the performance is better than GPSR.

OD-GPSR distinguishes the bidirectional links from the unidirectional links. The planarized graph for perimeter routing to circumnavigate the void is constructed based on only bidirectional links. Even the graph composed of only bidirectional links is connected, using the algorithm as that in GPSR to construct the planar subgraph could lead to partition of the graph. To tackle this problem, we consider two potential solutions.

The first possible solution is using methods proposed in [1] by adding virtual edges to those edge not existing to guarantee the correctness of the planar subgraph. An in-depth study is required to find an efficient localized algorithm for constructing a planar subgraph.

We expect the unidirectional links could also help in solving this problem. But how these unidirectional links can be utilized for such cases is one of our future works.

VI. Conclusion and Future Work

We present an on-demand data-driven geographical routing protocol, OD-GPSR, which adapts to the unique requirements for applications in sensor networks and therefore can be better applied in sensor networks. There are several future works we would like to focus on. First, how to guarantee the delivery of packets under situations where non-uniform transmission ranges exist. Second, we will improve our protocol to decrease the delay. Third, we propose a solution to boundary problem which is suitable for sensor networks relatively stable. An optimal solution to this problem especially for mobile sensor networks is still an open question.

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