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Querying on Federated Sensor Networks

Zuhal Can * and Murat Demirbas

Department of Computer Science and Engineering University at Buffalo, SUNY, Buffalo, NY 14260, USA; demirbas@buffalo.edu
* Correspondence: zuhaltep@buffalo.edu

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Abstract: A Federated Sensor Network (FSN) is a network of geographically distributed Wireless Sensor Networks (WSNs) called islands. For querying on an FSN, we introduce the Layered Federated Sensor Network (L-FSN) Protocol. For layered management, L-FSN provides communication among islands by its inter-island querying protocol by which a query packet routing path is determined according to some path selection policies. L-FSN allows autonomous management of each island by island-specific intra-island querying protocols that can be selected according to island properties. We evaluate the applicability of L-FSN and compare the L-FSN protocol with various querying protocols running on the flat federation model. Flat federation is a method to federate islands by running a single querying protocol on an entire FSN without distinguishing communication among and within islands. For flat federation, we select a querying protocol from geometrical, hierarchical cluster-based, hash-based, and tree-based WSN querying protocol categories. We found that a layered federation of islands by L-FSN increases the querying performance with respect to energy-efficiency, query resolving distance, and query resolving latency. Moreover, L-FSN's flexibility of choosing intra-island querying protocols regarding the island size brings advantages on energy-efficiency and query resolving latency.

Keywords: Federated Sensor Networks; Wireless Sensor Networks; in-network querying

1. Introduction

Wide usage of Wireless Sensor Networks (WSNs) with various application purposes necessitates the federation of WSNs located at geographically distant locations. For example, in a campus environment, each building can be monitored by a WSN of several gas detectors, and a mechanic may send a gas leak query into the building complex in order to receive the geographical location of the gas leak area as a response [1]. In the same campus, each parking lot can be monitored by a WSN [2] and parking lots can be federated in order to allow distance-sensitive queries such as: "Where is the nearest available parking space". A single campus authority may demand to federate all WSNs in a campus environment, whether they are deployed on a building or a parking lot while still providing autonomous management of each WSN.

We call a network of geographically distant WSNs a Federated Sensor Network (FSN), and call each WSN in an FSN an island. Within an FSN, a querying unit needs to be able to gather data from nearby or any island. While providing communication among islands, an FSN management needs to handle queries by running island-specific querying protocols at each island, so that each island can be operated as an autonomous system and connected to FSN with a degree of privacy.

For improving scalability, including distance-sensitivity and increasing regional autonomy, a layered FSN management is beneficial for the federation of islands. For the layered management of an FSN, we develop the Layered Federated Sensor Network (L-FSN) Protocol for the federation of islands, inspired by the Border Gateway Protocol (BGP), which was developed for the federation of autonomous systems on the internet. On the internet, connection among autonomous systems is established by BGP in which a path vector algorithm is used for route selection according to the reachability of autonomous systems. BGP ensures that data is sent to the destination without communication loops with the best possible latency and provides an additional path if a path failure occurs. Due to these benefits, BGP principles correspond to the requirements of the layered FSN management.

Applicability of BGP on FSN has several challenges. We will refer to some of these challenges, and clarify the corresponding adaptations on FSN by L-FSN protocol. BGP protocol uses local route preferences (path, network policies and/or rule-sets) for routing decisions. For L-FSN, we consider wireless link costs and cluster levels of gateways in addition to network policies. Since routers in BGP use the longest-prefix matching for forwarding packets, IP-based routing of BGP is not directly applicable for FSN. Gateways may not have IP-based addresses and cannot aggregate domain members by a suitable prefix. In addition, L-FSN targets rather a smaller network; therefore, forwarding packets according to unique gateway IDs is sufficient for FSN. We prefer to use geographical information along with gateway identifiers in order to aggregate island members.

L-FSN consists of inter-island and intra-island querying protocols. Inter-island querying protocol of L-FSN establishes communication among islands according to a layered management of islands. Inter-island querying protocol enables packet routing regarding several path selection policies, such as the shortest path selection policy while considering privacy of the islands. By L-FSN, an island node can send a query packet directly to a specific island. For example, a miner can query the air pollution level in the next tunnel before relocating [3]. Depending on the application and use-case or management policy, each island can run an island-specific intra-island querying protocol for providing data indexing, caching, and replication functions. There are several in-network querying protocols in the WSNs literature to be adopted as an intra-island querying protocol of L-FSN. As intra-island querying protocols, we discuss the adoption of querying protocols in the literature which are selected from each of categories of geometrical, hierarchical cluster-based, hash-based, and tree-basedcategories [4].

We found that a layered FSN management by L-FSN protocol provides efficiency in terms of energy-efficiency, query resolving distance, and querying latency compared to the flat management. We found that, as intra-island querying protocols of L-FSN, running infrastructure-free protocols in small islands while running infrastructure-based protocols in large islands provides a benefit on both energy-efficiency and query resolving latency.

2. Methods

Layered and flat FSN federations are two methods for federating islands. By layered federation, each island can be managed as an autonomous system and run an island-specific querying protocol. While layered federation allows each island to run different querying protocols, flat management allows the same querying protocol to run on an entire FSN. According to the flat FSN model, an FSN is a geographically large WSN with communication holes.

In our layered FSN model, islands are connected by gateways. Both gateways and island nodes gather data by in-network data processing and indexing techniques for data storage and retrieval. Using in-network data processing and indexing techniques, a gateway or a node either forwards a packet to the next unit (gateway or node) or replies back to a query source unit if it has valid data. We assume that gateways and nodes are initially pre-assigned in each island and have a capability of storing, aggregating and forwarding data.

For the layered FSN model, we divide gateways into exterior gateways (EGs) and interior gateways (IGs). Each island is assigned with at least one EG to be connected to the rest of the FSN. While EGs perform communication among islands, IGs route packets within islands. Two EGs are neighbors if they can communicate directly, or, if their islands are adjacent, in such a way that at least one of the IGs in each island is neighbor with the one in the adjacent island. Two IGs are neighbors if they can communicate directly. In a layered FSN model, the exterior and interior gateway topology is demonstrated in Figure 1.

For the flat FSN model, both gateways and nodes run the same querying protocol. For example, if this querying protocol is a hierarchical cluster-based querying protocol, in the flat FSN model, an island node can become the clusterhead of a gateway, and gateways, as well as island nodes have the same priority and privilege with respect to packet routing.

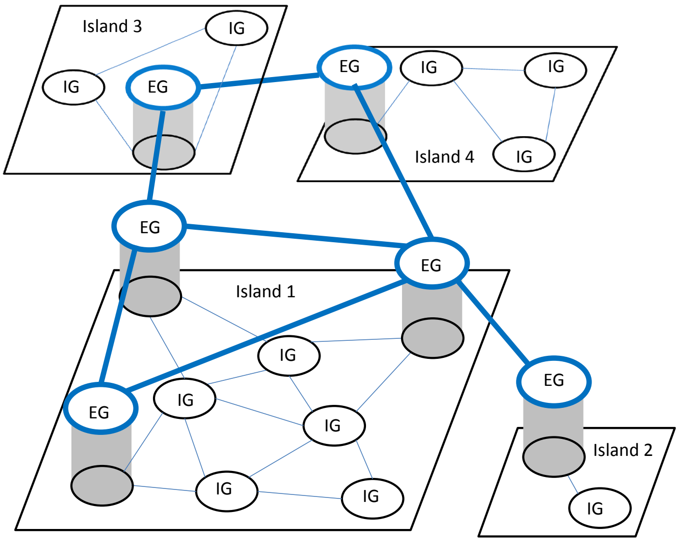

Figure 1. A layered federated sensor network topology.

3. L-FSN Protocol

Layered Federated Sensor Network (L-FSN) Protocol is a querying protocol that is designed for the layered FSN management. By L-FSN, the routing information is exchanged among islands through gateways. L-FSN Protocol consists of three components: routing tables, the inter-island querying mechanism, and the intra-island querying mechanism.

3.1. Routing Tables on Gateways

This section explains the initialization of routing tables, failure detection and recovery mechanisms.

3.1.1. Initialization of Routing Tables

EGs exchange routing tables at the beginning of network construction and whenever a change occurs on an EG's routing table. Exchanging of routing tables continues until no more information is exchanged between EGs.

At first, EGs send routing tables to their neighbor EGs by single broadcast in order to detect their neighbors. Receiver IGs on the broadcast path continue routing packets to the neighbor island's EGs. A receiver *EG z* replies back to the sender *EG x* with its routing table. After receiving a routing table from *z*, *x* declares *z* as one of its neighbors. Next time, when *EG x* propagates a routing table to its neighbor *EG z*, it sends these routing tables directly to the geographical coordinates associated with its neighbor *EG z* instead of broadcasting.

During routing table exchanges, EGs update routing tables according to the path selection policies. For example, for the shortest path selection policy, EGs exchange and update routing tables with the distance-vector algorithm as explained in Appendix A. With the distance-vector algorithm, every EG maintains the least-cost path information. Let D_x(x,y) be the distance from EG *x* to EG *y* on the routing table of *x*. For each neighbor *z*, EG *x* updates its routing table for all EG *y* in FSN using the Equation (1):

$$D_x(x, y) = min\{D_x(x, y), c(x, z) + D_z(z, y)\}, \tag{1}$$

where *c(x,z)* is the cost from *x* to *z*. If *z* is *x*'s direct neighbor, *x* assigns *c(x,z)* to be 1. If two EGs cannot directly communicate, *c(x,z)* is assigned to be the number of gateway hops between *x* and *z*.

Fields of a routing table are shown in Table 1. EGs exchange destination gateways' *id*, *island id* and *geographical coordinates* along with the *area boundary information* with northeast (NE) and southwest (SW) coordinates. EGs build routing tables according to the path selection policies; which are defined by the *metric* field of routing tables. According to the path selection policy, EGs provide the *next neighbor* and the *weight* value. Status can be either public or private. An EG does not propagate a private EG's routing information into FSN in order to prevent the network flow through this private island.

Table 1. Fields of a routing table.

Identifier
Island identifier
Latitude
Longitude
Latitude of the North-East boundary
Longitude of the North-East boundary
Latitude of the South-West boundary
Longitude of the South-West boundary
Metric
Next neighbor
Weight
Status

Instead of managing a large island under a single EG, islands can be managed under multiple EGs. Dividing an island with multiple EGs increases the querying efficiency within an island. In this way, each IG forwards queries to the closest EG within the island. This decreases the query resolving time compared to querying with a single EG. In addition, dividing of islands into regions improves the scalability of the inter-island querying protocol.

3.1.2. Failure Detection and Recovery

In a layered FSN topology, in case an EG fails, EGs can select alternative paths based on their routing table. After routing tables are established on each EG, each EG can provide multiple path information to each destination EGs. In case of path failures, EGs can forward packets through alternative paths.

Each time a gateway receives a packet, it replies back with an acknowledgement message to the sender gateway. If a gateway does not receive an acknowledgement message, it initiates the failure-recovery mechanism as follows. If a failed node is an EG, failure information of the EG is propagated into FSN by routing table exchanges. If a failed node is an IG, this information is propagated among IGs based on the intra-island routing protocol.

3.2. Inter-Island Querying

For inter-island communication, upmost-tier gateways form a backbone tree. Gateways perform both as a router and as a protocol translator. Gateways know where to direct a given packet using their routing tables and convert packets according to the protocol in which data is navigating with respect to the data formats and data rate.

While BGP uses longest-prefix matching to inform subnets on the internet, L-FSN uses the area boundary information. Using the area boundary information, query packets are forwarded to the corresponding EG(s) covering the geographical area of destination. Each IG calculates its area boundary according to the geographical coordinates of its underlying WSN nodes. IGs forward their boundary information to their assigned EG. An EG's boundary is the total boundary of its underlying IGs.

By L-FSN, a query packet includes the data information along with the source and destination information as follows. The source information includes the source island identifier (id) and the source node id. The destination information includes the geographical coordinates of the destination node.

Appendices B and C demonstrate the message processing algorithms. Appendix B explains the new message processing algorithm at a gateway. Gateway receive beacon, query and event messages. Sensor nodes join to gateways by sending beacon messages. Gateways send beacon messages periodically to other gateways to inform their existence. When a gateway receives a beacon message from a gateway, it updates its gateway routing table. Other than beacon messages, gateways receive query and event messages. By L-FSN, an island node can send query and event messages to either several islands or a specific island through gateways. Each time a gateway receives a query or an event message, it updates its records for further message propagation. A gateway can propagate a query into the entire FSN if a broadcast address is assigned for the query destination. Instead of a broadcast address, queries can be directed to specific islands by assigning NE and SW points of the destination area. If both NE and SW points are assigned to be same coordinates, query is routed to a destination point instead of a destination area. According to the destination address, gateways determine the next unit and forward query packets to the next unit on the query propagation path. Similarly, if a gateway receives an event message, it forwards event message to the next unit on the query propagation path. Appendix C explains the new message processing algorithm at a sensor node. A sensor node receives beacon messages from gateways. A sensor node records received query and event message information. Sensor nodes initiate query messages and receives corresponding event data. Moreover, sensor nodes replies to a query message if they have relevant data.

Query and event data message flows on an FSN are demonstrated in Figure 2. By L-FSN, queries are sent to a destination as described below.

Figure 2. Query and event data message flow among Federated Sensor Network units.

Query's Destination Is Assigned to be Unspecified:

If destination geographical information is unspecified, queries are initiated to be sent to the entire FSN. L-FSN allows data packets to be routed to upper-tier clusterhead EGs in a distance-sensitive manner. Meanwhile, data is stored at each data forwarding EG on this path. The query packet follows a hierarchical path similar to the data forwarding path until being resolved at the closest clusterhead gateway that stores the relevant data without being propagated to other islands. In addition to distance-sensitive querying, if data need to be collected from the entire FSN, all upmost-tier EGs receive the query. For example, in a campus environment, a mechanic may send a gas leak query. The query follows a path through the mechanic's building's IG to upper-tier clustered EGs in a distance-sensitive manner. As a response from the first EG that stores the relevant data, the mechanic receives the closest gas leak area's geographical location. Moreover, the mechanic may demand to receive all gas leak areas in the campus, and, send a query to entire FSN. In this case, all upmost-tier clusterhead EGs receive the query packet and reply back to the mechanic's query if their underlying island sensor nodes had detected a gas leak event.

Query's Destination Is Assigned to Be Specified:

L-FSN queries can be directed to specified islands. L-FSN makes island-aware indexing and advertises data to a selected island or subset of islands instead of advertising to all FSN islands. Based on the destination node's geographical information in a query packet, query forwarding EGs determine the destination EG(s). The destination EG is found to be the one that includes the geographical coordinates of the query destination area. If more than one EG is covering the query destination area, the source EG routes the query packet to each of these EGs. Event data packets follow the reverse path of the query propagation. For example, in a campus, each parking lot can be monitored by sensors, and, parking lots as FSN islands can be federated under an FSN. A driver in a parking lot can send a query for an empty parking spot for the destination parking lot before relocating. In this case, the driver's query is first sent to current parking lot's IG, and then propagated to the next EGs based on the destination parking lot's geographical information. An EG that includes the destination parking lot's geographical coordinates replies back to the driver with the availability of parking spots.

3.3. Intra-Island Querying

To optimize for efficiency and achieve a large scale querying system, the layered FSN management by L-FSN provides opportunities to use different intra-island querying protocols on each island. For intra-island querying, query packets follow a path depending on the intra-island querying protocol. Intra-island querying protocols are seamlessly connected with EGs. If an intra-island querying protocol uses the EG of an island as a root structure of the algorithm, EG will automatically catch up with the island information. In this way, an EG will not consume extra effort to retrieve network data.

Intra-island querying protocols of L-FSN can be developed according to directions of querying protocols designed for WSNs. We categorize querying protocols in the WSNs literature according to their underlying data routing mechanisms, as geometrical, hierarchical cluster-based, hash-based, and tree-based [4]. In this section, we select a querying protocol from each of these categories and discuss how an EG can be related with these protocols.

Geometrical querying protocols allow packets to be routed according to the geometrical directions of a destination location for storage and retrieval. As an example protocol to this category, Rumor Routing [5] is built on the intersection probability of query paths and data paths. In Rumor Routing , query and data packets are propagated through a random path. In geometrical protocols, data can be collected in EGs while propagated. If an EG has received the data information previously, it replies back to the querying node.

Hierarchical cluster-based querying protocols allow packets to be routed through clusterheads. Distributed quad-tree (DQT) [6] has a hierarchical cluster-based infrastructure that is built according to the geographical coordinates of the deployment area. In DQT structure, the deployment area is divided into geographical cells, and there is a hierarchical relationship among cells up to root clusterhead cells. For applying hierarchical cluster-based querying protocols into islands as intra-island querying protocols, we can assign an EG as the root clusterhead of the island.

Hash-based querying protocols route data to a destination location for storage and retrieval using a hashing mechanism. Geographic Hash Table (GHT) [7] is an example protocol for hash-based querying protocols, in which a query packet is propagated to the corresponding hashed location where relevant data packet is advertised. On hash-based approaches, an EG can be selected as the rendezvous point. For applying hash-based querying protocols into islands as intra-island querying protocols, we can assign an EG as the rendezvous point for both query and data packets.

Tree-based querying protocols use the message flooding technique to maintain a tree-like routing structure among network nodes. Directed Diffusion protocol [8] is an example protocol for tree-based approaches, which uses the query flooding technique. When a query message is received by a data source node, this node replies back along a reverse query propagation path. Tree-based querying protocols can be adopted as intra-island querying protocols considering an EG as the root of the tree.

4. Results

4.1. Simulation Environment

We evaluated querying protocols on an FSN topology designed according to the north campus buildings of University at Buffalo (UB), State University of New York. We name our FSN topology *UB topology*, which is demonstrated in Figure 3. In this figure, each set of buildings is representing an island that is shown by blue circles. We assume that a WSN is deployed in each building, and WSN nodes in each building are assigned to the corresponding IG that is assumed to be deployed on the building roof. We use the Network Routing API [9,10] of ns-2 [11] for our simulations. Table 2 lists our simulation parameters.

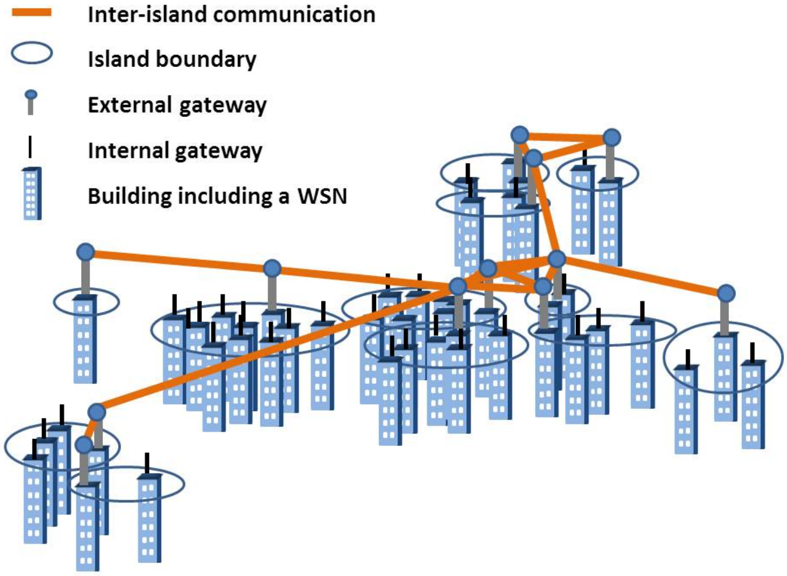

Figure 3. FSN topology in University at Buffalo, State University of New York.

Table 2. Simulation parameters for the layered and flat Federated Sensor Network models.

Parameter	Value
Querying Protocols	Rumor R. [5] DQT [6] GHT [7] D. Diffusion [8] L-FSN
Island size by gateway{# of islands}	1{1} 2{3} 3{3} 4{2} 6{1} 9{2}
Path policy	The shortest path selection
Area	1500 meter × 2000 meter
Sensor node range	100 meter
Gateway range	400 meter
Simulation time	300 second
Number of buildings	48
Number of nodes in each building	9
Number of gateways on each building	1
Number of repeater gateways	5
Event start time	50.th second
Query start time	100.th second
Preamble packet length	271 bytes
Packet length	36 bytes
Low-Power-Listening power for one second	0.263 milliWatt
Transmit power for 1 byte	59.73 milliWatt
Receive power for 1 byte	44.73 milliWatt

4.2. The Comparison of the Layered and Flat FSN Models

We compared L-FSN with querying protocols running on the flat federation model with respect to the querying efficiency. In the flat FSN model, both building nodes and gateways are running a common querying protocol. For flat FSN simulations, we applied querying protocols described in Section 3.3 on the entire FSN. For evaluating the flat FSN management, we ran Rumor Routing, DQT, GHT and Directed Diffusion protocols. Then, we ran L-FSN protocol on the same topology for evaluating the layered FSN management. For this experiment, L-FSN's intra-island querying protocol was selected to be similar to its inter-island protocol.

We implemented each querying experiment by increasing the number of buildings between the query and data source. We evaluated our experiments using three performance metrics, which are described below:

Success rate: Percentage of resolved queries over all query attempts for various distances between the query and data sources. Query and data sources are selected randomly for all query attempts. We ran 10 queries for each 10 distances between the query and data sources for all protocols.

Query resolving cost: Total energy spent on the entire FSN for a querying experiment.

Query resolving latency: The time difference between the query initiation time and data receiving time on a querying node.

For Rumor Routing and DQT protocols, the query resolving cost and latency results are given as an average of results taken from success rate experiments performed up to the distance of three building hops since these two protocols could support querying up to a distance of three building hops. For the rest of the protocols, these results are given as an average of results taken from success rate experiments performed up to 10 building hops.

4.2.1. The Success Rate Results

We observe that both L-FSN and Directed Diffusion protocols support querying distances of 10 building hops with a 100% success rate, as demonstrated in Figure 4.

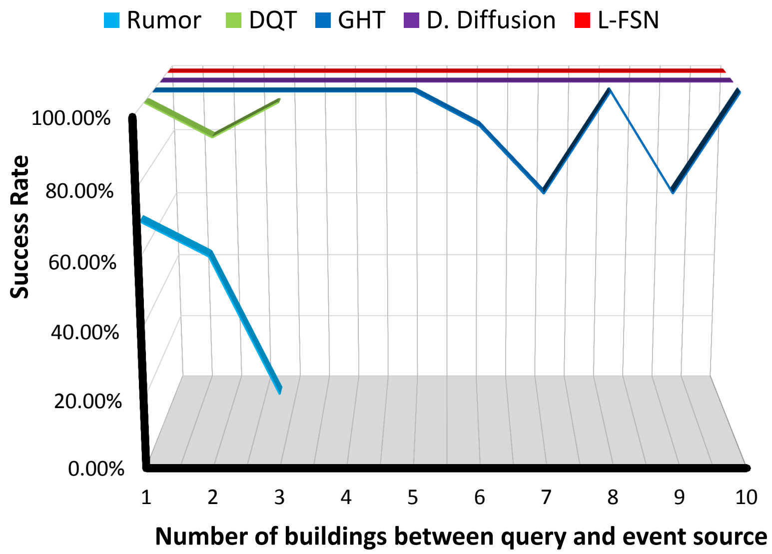

Figure 4. Query success percentage.

Querying protocols evaluated for the flat FSN model suffer from various characteristics of FSN deployment. In this experiment, we observe that both Rumor Routing and DQT cannot support querying up to a distance of 10 building hops. Rumor Routing suffers from communication loops on the flat FSN model due to random forwarding of packets that have a limited *time to live* period. Instead of flat management, a layered management of FSN alleviates occurrence of packet forwarding loops by bounding the packet forwarding area into islands. On the flat FSN model, the location-based infrastructure of DQT cannot support querying when data source is found in another island. The reason is that, when DQT is built over the entire FSN topology, a geographical clusterhead cell may not include a node due to communication holes on the sparsely-connected FSN deployment. Therefore, location-constraint protocols are not directly applicable to the entire FSN using the flat FSN model.

GHT suffers from geographical forwarding. The geographical forwarding method directs a packet to the closest neighbor of a destination location. If none of the neighbor nodes are found to be closer, a packet cannot be forwarded to a destination. This is why some of the query packets are not resolved in FSN and this situation is observed with an oscillation of the success rate data of GHT for values between seven and 10 building hops in Figure 4. Therefore, querying protocols using geographical forwarding require an efficient reliability mechanism to guarantee packet delivery on a sparsely-connected flat FSN model.

4.2.2. The Energy Consumption Results

By L-FSN protocol, gateways consume energy on initialization of routing tables. After initialization of routing tables, the energy consumption on building nodes running L-FSN is very low compared to other protocols as shown in Figure 5. The layered federation by L-FSN prevents building nodes to consume additional energy for inter-island communication.

By this experiment, we found that flooding-based packet routing causes a large energy consumption on the flat FSN model looking at the Directed Diffusion result. Due to network-wise flooding, Directed Diffusion has a higher energy consumption compared to other querying protocols. By flooding-based protocols, even though a query is resolved in the closest island, query messages are received by all island nodes. Therefore, flooding-based querying protocols devised for flat FSN model require additional mechanisms to limit the packet flooding.

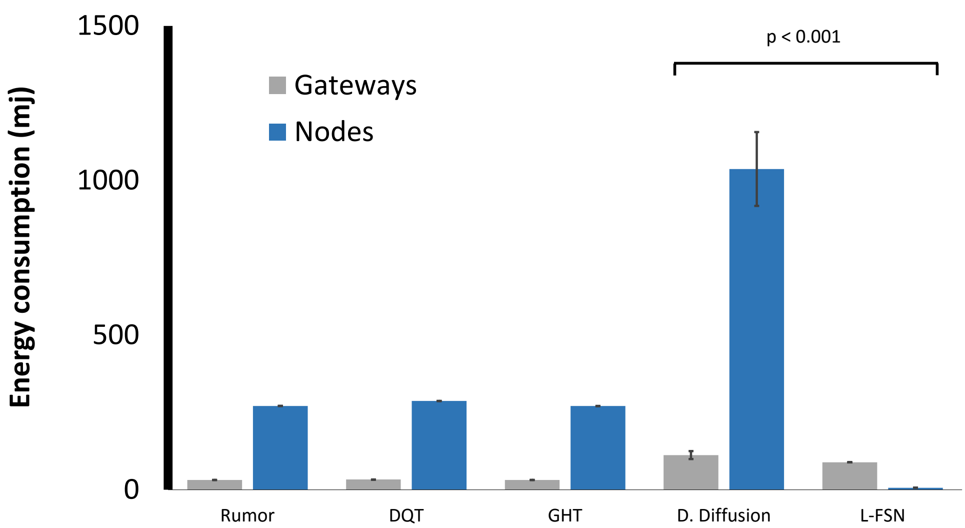

Figure 5. Energy consumption on FSN.

4.2.3. The Querying Latency Results

As shown in Figure 6, Rumor Routing has a large latency compared to other protocols because of the occurrence of packet forwarding loops on the flat FSN model. We also observe that this query resolving latency increases as the distance between query and data source increases. This result indicates a need for an efficient loop detection mechanism for querying protocols running on a flat FSN model.

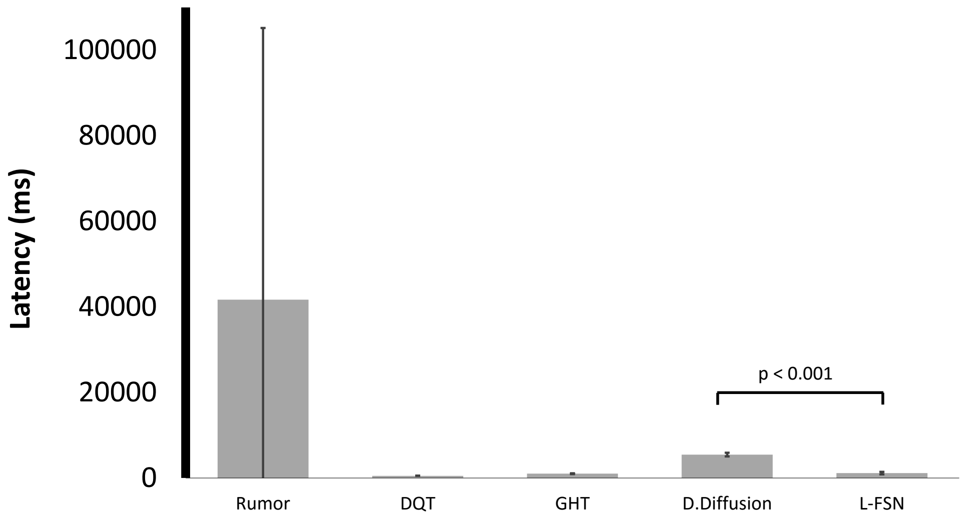

Figure 6. The data delivery latency.

4.2.4. Hypothesis Testing (*t*-test)

We did hypothesis testing (*t*-test) to reveal significant improvements caused by the layered FSN management against the flat management. We previously observed that all queries are resolved by both Directed Diffusion and L-FSN with a 100% success rate as shown in Figure 4. Therefore, we compare the flat management by Directed Diffusion and the layered management by L-FSN using their energy consumption (total consumed energy by gateways and nodes) and latency results as given in Sections 4.2.2 and 4.2.3. This test evaluates the hypothesis stating that the mean values of a variable (energy consumption or latency) observed over time are equal for both of the protocols. We used 0.001 level of significance for *t*-tests. We found that the means of energy consumption and latency results of these two protocols are significantly different at $p < 0.001$. Thus, *t*-test results prove the observation of performance improvement using the layered FSN management by L-FSN compared to flat management.

4.3. Evaluation of L-FSN According to the Island Size

For this experiment, we applied protocols described in Section 3.3 as intra-island querying protocols of L-FSN. We sent a single query from a random node within all islands in order to measure consumed energy and query resolving latency. When we applied the same querying protocol into each island as an intra-island querying protocol of L-FSN, we observed that GHT protocol is the most energy-efficient protocol, and query resolving time is the lowest by the DQT protocol. Since we assume that gateways have enough storage capacity, we do not run the structured replication of GHT, which is a technique that distributes the data storage load, hierarchically. Without the structured replication, we categorize GHT as an *infrastructure-free* querying protocol in which data and query packets are following a geographical path to the hash location, whereas DQT protocol is an *infrastructure-based* protocol due to the construction of a quad-tree structure.

As a second step of this experiment, we first ran L-FSN on the UB topology while running GHT protocol as the intra-island querying protocol of L-FSN for all islands, and, recorded the average consumed energy per node and the average query resolving time. Then, we repeated this experiment each time running DQT as an intra-island querying protocol on several islands depending on island sizes.

Figure 7 demonstrates the percentages of additional energy consumption per node and the decrease on query resolving time at each DQT-GHT combination as intra-island querying protocols. In this figure, a data point label DQT n:m represents the DQT-GHT combination, where DQT protocol is running on islands of size n to m while GHT protocol is running on the rest of the islands. For example, data point DQT 4:9 represents that DQT protocol is running on islands of size 4, 6 and 9 while GHT protocol is running on the rest of islands in the UB topology. The size of islands and number of islands for each island size in the UB topology are shown in Table 2.

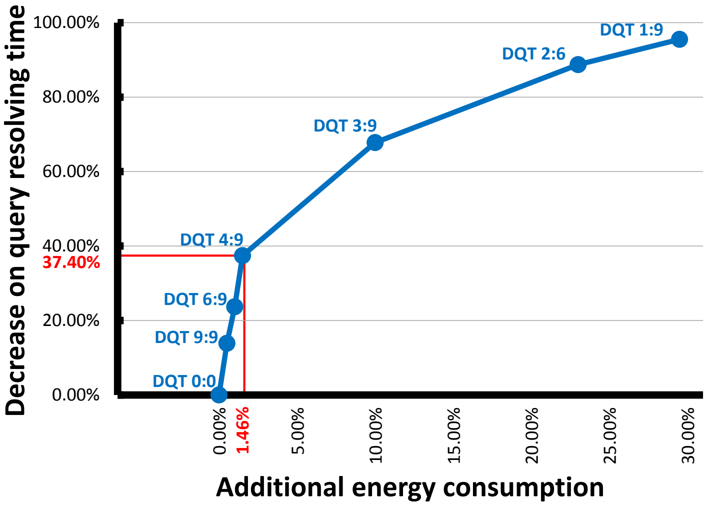

Figure 7. Running both Distributed Quad-Tree (DQT) and Geographic Hash Table (GHT) protocols as intra-island querying protocols of the Layered Federated Sensor Network (L-FSN) protocol. A data point label DQT n:m represent the DQT-GHT combination, where DQT protocol is running on islands of size n to m while GHT protocol is running on the rest of the islands. The size of islands in terms of gateways is given in Table 2.

We observed that if we ran DQT on all islands, we had 29.04% additional energy consumption per node with a 95.53% decrease on query resolving time compared to the case that GHT protocol was running on all islands, as shown with the DQT 1:9 point in Figure 7. While the rest of the islands are running GHT protocol, statistical variance of additional energy consumption per node as we increase the number of islands running DQT protocol is 0.91%, and statistical variance of decrease on query resolving time as we increase the number of islands running DQT protocol is 10.34%.

Due to the tradeoff between energy-efficiency and query resolving time, we can select running DQT on some islands as an L-FSN intra-island querying protocol depending on island size. We observed that a high gain on query resolving time with a low additional energy consumption is achieved when we ran DQT protocol on large islands and GHT protocol on small islands, as shown with DQT 9:9, DQT 6:9 and DQT 4:9 points in Figure 7. If we run DQT on islands of size four and more, we had a low additional energy consumption "1.46%" with a high decrease on query resolving time "37.40%", as shown with DQT 4:9 point. Therefore, we suggest that, as intra-island querying protocol of L-FSN, *infrastructure-free* protocols can be selected on small islands for conserving energy while *infrastructure-based* protocols can be selected on large islands to gain benefit on query resolving time.

5. Related Work

Due to recent technological advances and wide-range application opportunities, in-network querying and indexing on FSN is a promising research area to achieve efficient communication. Recent technological advances enable distant WSNs to be connected under an FSN in various ways. For example, improvements on smartphone technologies allowed smartphones to be able to establish communication among distant WSN deployment areas [12]. Deployment opportunities of FSNs in various environment from urban areas to underwater allowed diverse applications to be developed including power monitoring, intruder detection, environmental monitoring, localization and tracking [13–15].

As an opportunity of studies of more than a decade, gained experience of in-network querying and indexing techniques can be improved to be adapted on FSNs. On a WSN, nodes interact with each other for data processing, aggregation and dissemination purposes [16]. Gathered data is routed to the querying or indexing unit by multi-hop routing techniques. Based on the underlying routing techniques, Can and Demirbas categorize in-network querying techniques as geometrical, hierarchical cluster-based, hash-based, and tree-based with a discussion of WSN design metrics, such as energy-efficiency, distance-sensitivity, scalability and fault-tolerance [4].

One of the FSN concepts is connectivity of geographically distant islands. These islands may occur due to partitioning of an existing WSN or prebuilt due to application purposes. A WSN can be partitioned because of node breakdowns caused by some environmental factors such as disasters or caused by device-related factors such as depletion of energy sources. Several related studies focus on on how to restore connectivity among islands when such a damage occurs [17]. Other than network partitioning, there are studies that focus on the island occurrences as part of the application use-case [18,19]. In these studies connectivity of islands is established by static or mobile relay nodes.

Mobility on an FSN can be investigated on three units: the event mobility, island and relay node mobility [20]. An event can be static such as temperature, or mobile such as an intruder. Island and relay nodes can be static like cameras or mobile like vehicles. Relay nodes can randomly scattered on the gaps among islands as well as optimally replaced. Islands can be connected with mobile devices which move randomly or deterministically. For instance, people-centric island federation is an example of mobile federation [21].

6. Conclusion

For querying on the Federated Sensor Network (FSN), we developed the Layered Federated Sensor Network (L-FSN) Protocol. L-FSN allows layered management of islands by inter-island and intra-island querying protocols according to the path selection policies. We evaluated the applicability of L-FSN with a comparison of various querying protocols running on the flat FSN model. For comparison, we selected a querying protocol from geometrical, hierarchical cluster-based, hash-based, and tree-based categories and ran these protocols on the entire FSN topology in order to evaluate the flat management. We found that the layered management of FSN by L-FSN increases the querying performance with respect to energy-efficiency, query resolving distance, and querying latency compared to flat management. Then, we ran these protocols, which were evaluated for flat federation, as intra-island querying protocols of L-FSN. We found that L-FSN's performance regarding energy-efficiency and query resolving latency can be improved with a selection of intra-island querying protocols according to the size of each island.

In this paper, we evaluated L-FSN protocol on the UB topology. In order to observe protocol behavior on different scenarios, various simulation environments can be developed for evaluation of L-FSN protocol. L-FSN requires authentication of each sensor node to a gateway. This property of L-FSN supports some degree of mobility of island nodes. For improving the performance of L-FSN, investigation of node mobility, heterogeneity, availability and reliability effects on intra-island routing protocol selection were left for future work. In this paper, we evaluated shortest path selection policy for inter-island communication. For future work, various diverse path selection policies can be developed and evaluated.

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Appendix A.

Algorithm A1: Distance-Vector Algorithm

```
At each gateway x;
forall the gateways y in FSN do
    if y is a neighbor of x then
        D_x(x,y) = c(x,y);
    else
        D_x(x,y) = ∞;
    end
end
foreach neighbor gateway z do
    D_x(z,y) = ∞;
end
Send distance vector D_x to all neighbor gateways;
repeat
    if Distance vector D_z is received from a neighbor gateway z then
        foreach gateway y in FSN do
            D_x(x,y) = min{D_x(x,y), c(x,z) + D_z(z,y)};
        end
    end
    if there is link cost change in D_x then
        Send distance vector D_x to all neighbor gateways;
    end
until forever;
```

Appendix B.

Algorithm B1: Processing New Message Algorithm at a Gateway

```
Extract message info;
if message is a beacon message from a sensor node then
    Update sensor member info at the gateway;
end
else if message is a beacon message from a gateway then
    Update gateway routing table;
end
else if message is a query message then
    Update query info at the gateway;
    if query destination is broadcast address then
        Send query message to all neighbor gateways and member sensor nodes;
    else
        Send message to next node on the destination path;
    end
end
else if message is an event message then
    Update event info at the gateway;
    Send message to next node(s);
end
```

Appendix C.

Algorithm C1: Processing New Message Algorithm at a Sensor Node

```
Extract message info;
if message is a beacon message then
    Update gateway info at the sensor;
end
else if message is a query message then
    Update query info at the sensor;
    if self is an event agent then
        Send event data to the requesting node(s);
    else
        Send query message to next node(s);
    end
end
else if message is an event message then
    Update event info at the sensor;
    if self is an query agent then
        Query is resolved;
    else
        Send event message to next node(s);
    end
end
```

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