GRMR: Greedy Regional Multicast Routing for Wireless Sensor Networks

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SUMMARY Information Centric Networking (ICN) is a promising architecture as an alternative paradigm to traditional IP networking. The innovative concepts, such as named data, name-based routing, and in-network caching bring lots of benefits to Wireless Sensor Networks (WSNs). Simple and robust communication model of ICN, based on interest/data messages exchange, is appealing to be deployed in WSNs. However, ICN architectures are designed for power supplied network devices rather than resource-constrained sensor nodes. Introducing ICN-like architecture to WSNs needs to rethink the naming scheme and forwarding strategy to meet the requirements of energy efficiency and failure recovery. This paper presents a light weight data centric routing mechanism (GRMR) for interest dissemination and data delivery in location-aware WSNs. A simple naming scheme gives assistance for routing decision by individual nodes. Greedy routing engaging with regional multicast mechanism provides an efficient data centric routing approach. The performance is analytically evaluated and simulated in NS-2. The results indicate that GRMR achieves significant energy efficiency under investigated scenarios.

key words: data centric routing, greedy routing, multicast tree construction, flooding, Internet of Things (IoT)

1. Introduction

Internet of Things (IoT) is a novel paradigm that frames a new architecture for large scale sensing ecosystems, where all possible devices could be connected to Internet. Wireless Sensor Networks (WSNs) are deemed to be promising components in IoT. However, some challenges still impede the connection of huge amount of various devices to worldwide interconnected networks, such as protocol complexity, diversified addressing schemes, communication incompatibility, security, and privacy. To face the great diversity of sensor nodes and to provide a general named data centric architecture to WSNs, simple and efficient naming schemes and routing mechanisms need to be designed to figure out these issues.

The dynamics and low reliability features of sensor nodes may result in frequent links failure and lead to high packet loss rate and latency. Benefiting from high data redundancy in WSNs, many applications prefer to apply data centric or location-based routing mechanisms to improve data availability. Those routing mechanisms usually focus on data itself rather than the location of this data. Data can be addressed in various strategies, such as sensor ID, data type or regional information. Intelligible naming could enable sensor nodes within the network to recognize, transmit, compress, aggregate and store data transparently.

Many applications require data should be collected with supplement of location information. In geographic routing, nodes depend on a sense of its neighbors’ location for cooperative tasking and routing decision. Its own location of node can be acquired either by absolute form (from GPS) or by the relative to reference points (anchors aware of their own geographic locations [1]). Generally, information of neighbors can be acquired by receiving periodic “beacon” messages, or exchanging “hello” messages.

Host centric routing mechanisms access data by seeking a path from sink to the exact target node. For the reasons of high probability of node outage caused by node sleeping, energy depletion or movement, it is difficult to establish and maintain a reliable path in dynamic and energy constrained WSNs. Other than a single destination, data centric routing mechanisms normally search for a specific data on a set of nodes or on a region of the network. Therefore, the problem of data centric routing is actually a query problem - it must seek out paths to those nodes which have the queried data. Path discovery is achieved with dissemination of query messages penetrating the network.

This paper focuses on a common scenario of data accessing in WSNs: “Report events X that detected in the geographical region Y for a time period Z”. To accomplish this task, query messages (interests) could be propagated to all active sensors (flooding); or a group of sensors (multicasting); or those sensors inside a specific geographic region (geocasting). Under this scenario, a data centric greedy regional multicast routing (GRMR) mechanism is proposed which offers energy efficient routing for WSNs. GRMR utilizes greedy routing within Relative Neighborhood Graph (RNG) [2] to find the optimal path between sink and the event region. To guarantee the reachability of source nodes, a multicast tree is built on Gabriel Graph (GG) [3]. A perimeter face routing algorithm is designed to ensure interest traverse the region and suppress propagation ratio.

Since the dissemination of interests direct to a region rather than to a single node, multiple nodes may have or be able to collect the queried data. Data from different nodes with high redundancy is probably sent along multiple paths to the same sink. This is a critical issue if data needs to be transmitted in high frequency with high bandwidth...
consumption. In this situation, data aggregation is quite important and necessary before data sent to remote sink in the view of energy efficiency. In ICN, intermediate nodes are usually deployed with high-performance hardware, which perform data aggregation and in-networking caching. However, it is impractical in WSNs for capacity-constrained sensor nodes to conduct complicated data aggregation process. In this paper, an efficient naming scheme facilitates the realization of simple data aggregation.

The rest of this paper is organized with following structure: Sect. 2 is an overview of the literature about data centric and geographic routing mechanisms in WSNs. The proposed mechanisms in GRMR on naming scheme, greedy regional multicast routing and data aggregation are presented in Sect. 3. Prospective of performance is analytically evaluated and simulated by comparison with other mechanisms in Sect. 4. Finally, conclusion is given in Sect. 5.

2. Related Work

Data centric models in sensor networks have been studied for many years. The basis is that sensor data is named by some useful attributes such as event type, geographic location, and time period. Many data centric routing paradigms [4] enabled energy-efficient design for data accessing in large-scale WSNs. Prior researches [5]–[7] introduced light-weight ICN architecture to WSNs to satisfy the tight energy constraints, and had been proved energy efficiency to apply attribute-based naming scheme. Directed diffusion (DD) [8] is an often cited data centric routing approach for data accessing from multiple sources. Sinks construct a set of attribute/value pairs in interests and propagate the initial interests penetrating the network using blind flooding. Every node who receives the interest, records the interest and setup gradients towards sink. Although it is an on-demand localized approach that does not require prior “hello” messages, the scalability is questionable because of the flooding of initial interest. In addition, several literatures [9]–[11] aimed to improve the scalability and reduce the protocol complexity of DD.

Geographic routing mechanisms [12]–[18] had been widely studied in location-aware WSNs. Therein, the most popular and efficient approaches are greedy routing mechanisms [15]–[18]. GPSR [15] with its variation [16] utilizes greedy routing for message forwarding to the node that is always progressively closer to destination. When greedy routing fails to find the next hop, perimeter face routing is applied to get out of communication void problem [19]. Network partitioning methods [17], [18] divide network into convex pieces, find the sequence of pieces to visit destination and apply greedy algorithm to deliver the message to next piece. Geocast is a type of geographic routing mechanism for messaging and advertising to certain geographic region. The challenging of geocast mechanisms is how to distribute queries to all nodes within a geographic region with high reachability and low overhead. Survey on typical geocast approaches [20] reveals that most of them cannot guarantee delivery to all nodes inside a region. This is usually caused by either the partitioning of network inside the region [21], [22] or routing failure [23]. Geographic-Forwarding-Geocast (GFG) and Geographic-Forwarding-Perimeter-Geocast (GFPG) [24] guarantee reachability by flooding queries to a specific region.

In WSNs, for the reason of high data redundancy, data aggregation is necessary to reduce traffic overhead. Recent works [25], [26] exploit the data correlation for data aggregation along multi-hop paths. The complexity and the high computation capability requirements are the restriction for wide deployment in WSNs.

3. Greedy Regional Multicast Routing (GRMR)

Recall the specific scenario: “Report events X that monitored in the geographical region Y for a time period Z”.

The routing mechanism should achieve following functionalities: 1) Sink sends interest to region Y with high reliability and low overhead to corresponding nodes; 2) Corresponding nodes receive this interest, and send the collected data to sink. Meanwhile, energy efficiency, reliability, latency and scalability should be taken into account.

GRMR is proposed as data centric geographic routing approach to realize those functions. GRMR is mainly composed by several components. Firstly, interest is named following a simple naming scheme including useful information, which can be used to make routing decision by individual node. Secondly, greedy routing is adopted to establish the path between sink and requested region. Thirdly, a border node is selected and multicast tree is built automatically as the dissemination of the initial interest around requested region. Finally, data is sent to the border node along the reverse path of multicast tree. Data aggregation is implemented at the border node.

In GRMR, interest/data communication model is reserved, while Pending Interest Table (PIT) and Forwarding Information Base (FIB) of ICN architecture are suppressed. An interest table is preserved on every node to cache interest information. A neighbor table stores neighbors’ IDs and locations. Content Stores (CSs) could be deployed at energy abundant nodes or databases distributed in the network.

3.1 Region-Oriented Naming Scheme

Naming scheme is essential for architecture design of data centric networks. An efficient naming scheme is conducive to routing, data caching, data aggregation, and security. ICN architectures implement naming scheme in different ways. Some architectures, such as DONA [27] and PURSUIT [28], use a non-human readable flat naming scheme (a series of binary numbers). It is also difficult to design interpretation algorithm for sensor nodes. CCNx [29] and CONET [30] use human readable hierarchical naming scheme, where useful information can be extracted from the unencrypted name space.

In GRMR, it is necessary for every node have the
ability to parse name space for interests comparison and data aggregation. Different from multifarious data in current Internet, data from specific sensor network is generally confined in limited types. For example, audio sensors record voice data for specific area in fixed data format; while temperature sensors sample temperature of a site only. Interest and data are named by a uniformed format, which need to predefine naming scheme on each node. Given a typical example, ID of an interest for a regional audio sampling can be described as follows.

Message Type = 3
Region = [50, 50; 100, 150]
Last Hop ID = 3485
Sink ID = 3500
Sink Location = [150, 150]
Content Type = aud
Time Stamp = 1427990400
Duration = 10 sec
Interval = 10 sec
Level = 0
Nonce = 15853212

The information in this naming space shows that sink (ID: 3500) requests audio data from a specified rectangular region [−50, 50; 100, 150]. Data should be sampled from time (00:00:00 03/04/2015) with duration 100sec and sampling time interval 10sec. Message Type represents the type of interest and determines the format of following fields. Message format should be pre-configured to each node during the network creation. For example, here we simply define three message types: 1 represents Sensor ID, 2 represents Content ID, and 3 represents Regional Request. Region field is the indication of requested area, which could be in various shapes but delimited by a rectangle for ease of exposition. Last Hop (ID: 3485) is used in perimeter face routing against node failure. Sink ID and Sink Location are necessary for data delivery and failure recovery. Content Type indicates the attribute of queried data. Time Stamp is a Unix time should be synchronized in the network. Level stands for the depth of the node on multicast tree which will be elaborated in Sect. 3.3.2. Nonce is a randomly generated number for uniqueness detection. The whole ID of the interest can be expressed in URL format:

³/³/[−50,50,100,150]/3485/3500/[150,150]/aud/
1427990400/100/10/0/15853212

When a corresponding node receives the interest, it tasks audio sensor to sample data from the time recorded in interest. For example, if sampled data needs to be sent out every 10sec with 10 times, the naming for the first piece of data can be expressed as below.

Message Type = 3
Region = [50, 50; 80, 100]

Sink ID = 3500
Sink Location = [150, 150]
Content Type = aud
Time Stamp = 1427990400
Duration = 10 sec
Level = 3
Nonce = 52364980

Region is the coverage of the sampled data, which might be partial or whole of the requested region of interest. Level is the depth of the node on multicast tree. Other fields have the same property of that with interest.

3.2 Planarized Graphs

A planar graph of network is drawn in GRMR to guarantee efficient and reliable interest/data delivery. In this graph, intersection of edges should be suppressed to ensure the correctness. Greedy routing, perimeter face routing, and multicast tree construction only use links that appeared in the graph. To meet the requirements of various applications in different network environment, some planarization algorithms have been proposed, such as RNG [2], GG [3], UDG [31], and PLDel [32]. RNG and GG are commonly used to draw subgraph locally by each node, which is suitable for neighbors’ location-aware WSNs. Other algorithms either need information of multi-hop neighbors or inadaptable for realistic WSNs. Literature [15] has proved that RNG is a subset of GG, which means RNG is sparser than GG. We employ RNG for the greedy routing outside the requested region and GG for multicast tree construction.

The work principles of GG and RNG are explained as below. We assume that three nodes (u, v, w) present in a network graph with same signal range, and d(u, v) is the distance between vertices u and v. GG criterion removes an edge (u, v) if Thales’ circle on [uv] contains another node w, as illustration in Fig. 1(a) and Eq. (1). In RNG criterion, an edge (u, v) is eliminated if the intersection of two circles with radius |uv| centered at u and v contains another node w (Fig. 1(b) and Eq. (2)).

In this paper, to eliminate the crossing links and provide a sparse network graph for greedy routing, RNG is applied to build subgraph for outside part of requested region. GG generates a relative denser graph to provide sufficient links to reach as many nodes as possible inside requested region.

Fig. 1 Graph algorithms, must no witness w inside the shadow
Algorithm 1: greedy perimeter face routing

Variables: $u$: current node, $N$: a list of $u$’s neighbors, $N_r$: node selected by right-hand rule, $N_l$: node selected by left-hand rule, $N_p$: next hop node, $N_i$: previous node, $D$: center location of requested region.

For all $v \in N$ do
def $d(u, D) \leq \min(d(v, D))$ // perimeter face routing
apply right-hand rule, get node $N_r$ (if absent, $N_r = 0$)
apply left-hand rule, get node $N_l$ (if absent, $N_l = 0$)
if $(N_r \neq 0 \& N_l \neq 0)$
$N_p = d(N_r, D) \leq d(N_l, D) \& N_r \& N_l$
else if $(N_r = 0 \& N_l = 0)$
$N_p = (N_r = 0) \& N_l$
else $N_p = N_l$
else $N_p = v: \min(d(v, D))$ // greedy routing
endif
forward packet to $N_p$

\[\forall w \neq u, v: d^2(u, v) < [d^2(u, w) + d^2(v, w)] \tag{1}\]
\[\forall w \neq u, v: d(u, v) \leq \max[d(u, w), d(v, w)] \tag{2}\]

3.3 Geographic Greedy Regional Multicast Routing

Geographic greedy routing mechanisms provide close-to-optimal paths from source (sink) to destinations (target nodes) in location-aware WSNs. In this paper, destination is a specific region with multiple target nodes located inside randomly. It is inefficient to build individual path between sink and each target if sink is far away from destination region. Instead, the path between sink and border of the destination region, can be merged to one path. Inside the region, interest is inclined to reach all the nodes to find the most satisfied target. Multicast tree construction and perimeter face routing algorithm are proposed to improve reachability and communication reliability inside the region.

3.3.1 Greedy Perimeter Face Routing outside the Region

Sink sends the first interest to one of its neighbors following greedy routing (destination set to the center point of requested region). The neighbor closest to destination in distance is selected as the next-hop node. Upon receiving an interest, node forwards the interest to one of its neighbors in greedy mode except the last-hop node. If greedy mode fails, right-hand rule will be applied to find a neighbor $N_r$ and left-hand rule is used to find another neighbor $N_l$. If both $N_r$ and $N_l$ exist, next-hop $N_p$ will be selected by comparing this two neighbors’ respective distance to $D$ as in Eq. (3). If only $N_r$ (or $N_l$) exists, it will set the next-hop node to $N_r$ (or $N_l$). If neither $N_r$ nor $N_l$ exists, the interest will be sent back to its previous-hop $N_p$. After that, previous-hop $N_p$ applies greedy routing to find another neighbor. This process is called as perimeter face routing algorithm and expressed in Algorithm 1.

$$N_p = d(N_r, D) \leq d(N_l, D) \& N_r : N_l \tag{3}$$

3.3.2 Multicast Tree Construction inside the Region

The objective of this section is to build a multicast tree during the dissemination of initial interest. Procedure of multicast tree construction is illustrated in Fig. 2. By virtue of the multicast tree, GRMR provides an efficient routing for subsequent interest and data delivery. As elaborated in Sect. 3.2, nodes run planarization algorithms locally (GG for nodes inside requested region and RNG for outside) to draw its subgraph.

When border node $b$ who has some neighbors inside requested region receives interest first time, it forwards this interest to its all neighbors inside the region (node $N_1$ and $N_2$). Notice that the interest is not sent to all its physical neighbors but only to those who have connected links with $b$ in its planar graph. Links across border of the region are planarized by this rule: links enter into the region use RNG; links come out of the region use GG.

When node $N_1$ receives this interest, it changes Level value of the interest to 1 ($L_1$ in Fig. 2) and sends the modified interest to its all neighbors. $N_1$’s neighbors inside the region forward the interest to all their neighbors with Level value plus 1. If neighbors outside the region receive the interest, they will forward it to its neighbors inside the region except the last-hop node and add 1 to the value of Level. If no neighbor inside the region, node applies right-hand rule to find next-hop if it locates at the left side of radial $S_b$, and applies left-hand rule if it locates at the right side, as illustrated in Fig. 2. Finally, some surrounding nodes outside the region also receive the interest, and join the paths towards the region. Nodes always check the value of Level first before sending the interest. Only the interest with lowest level is forwarded and recorded in interest table. This algorithm greatly guarantees the reachability of target nodes and improves reliability of message delivery.

Finally, interest reaches three targets (black solid dotted nodes in Fig. 2) and multicast tree is completed. Target nodes send data to border node $b$ respectively along the
multicast tree. This multicast tree is used for subsequent interests distribution from same sink to same region with same data type but different time period. If node failure happens and causes insufficient data acquisition, this multicast tree will be reconstructed.

3.4 Data Aggregation

Tasks toward a region may trigger a group of sensors with same attributes to collect correlated data. Those data are sent to same sink separately if data aggregation doesn’t take effect. High redundancy may exist in those individual data transmission. Some nodes, at intersection of transmission path, possibly gather several pieces of correlated data and merge them into a single report. Data aggregation reduces delivery cost and relieves traffic congestion.

In the proposed scenario, border node \( b \) is the best candidate for data aggregation, since all data is gathered at this point. The native feature of simple naming scheme in our mechanism enables every node to interpret content ID. Through this ability, nodes can work out some simple data aggregation. For example, data aggregation can be simply realized in our scenario by comparing geographic coverage (Region field) of data from different nodes corresponding to the same interest.

Data aggregation has three situations: 1) Any piece of the data is sufficient to the demand of interest; 2) Combination of several pieces of data can be sufficient to the demand; 3) Combination of all pieces of data can meet the demand maximally. For the first case, only the first arrived data is sent to sink by node \( b \), and all following arrived data is discarded. For the second case, the aggregated data is sent by node \( b \) to sink when arrived data pieces are sufficient to cover the entire region, which may cause slight delay. For the third case, timer is set to wait for all possible arrivals of data pieces. Moreover, tradeoff among latency, redundancy, and energy efficiency should be considered.

4. Analytic Evaluation and Simulation

In this section, analytic evaluation and simulation are presented on data delivery cost of GRMR and compared with other approaches. For analytic tractability, we assume that the network contains \( N \) nodes in a square grid, and the signal range of each node exactly covers eight neighbors. Therefore, the number of nodes on each edge of the grid is \( \sqrt{N} \). The sink is \( m \)-th (\( 1 \leq m \leq \sqrt{N} \)) node from the top on the left edge of the network. Requested region is a square located at the right bottom field with edge length \( r \) (\( l < r < \sqrt{N} \)), as shown in Fig. 3.

Energy consumption is intensively considered for performance evaluation of WSNs. Signaling is the overriding portion of power expenditure besides data gathering. The cost of transmission and reception of all messages related to the mechanisms is calculated and evaluated. Although power dissipation for transmission is higher than reception [8], the disparity doesn’t impact the evaluation results in order of magnitude. Therefore, we simply assume that single message transmission (or reception) can be represented by a unit.

4.1 Comparison between Greedy and Flooding Routing

GRMR, similar with many existing approaches, builds path during the dissemination of initial exploratory message (interest). Many routing mechanisms flood initial interest and restrict broadcast for subsequence. Therefore, it is meaningful to compare delivery cost of initial interest among GRMR, flooding and restricted flooding. Greedy routing cooperating with regional multicast is adopted in GRMR (Fig. 3(c)). In greedy routing phase, next-hop selection is the best progress on the distance to the center of requested region without preliminary route discovery. Whole network flooding (Fig. 3(a)) and restricted flooding (Fig. 3(b)) are the contrast to GRMR in analytic evaluation. Whole network flooding broadcasts interest to all nodes in the network while restricted flooding eliminates broadcast by sending interest directionally to requested region.

Flooding approaches broadcast every interest to every node throughout whole network. Delivery cost for sending an interest is \( N \) since every node sends the same interest only once. If a node receives a replicated interest, it simply discards rather than forwards it. Conversely, each node receives the same interest from its all neighbors. Thus, the
cost of reception is determined by 2 times the number of links in the network. Total number of links \( N_l \) in the network can be calculated by Eq. (4). Equation (5) produces overall delivery cost of flooding approach \( C_f \).

\[
N_l = 2(\sqrt{N} - 1)(2\sqrt{N} - 1) \quad (4)
\]

\[
C_f = N + 4(\sqrt{N} - 1)(2\sqrt{N} - 1) = 9N - 12 \sqrt{N} + 4 \quad (5)
\]

The flooding region of restricted flooding is limited to the region directional to destination as in Fig. 3 (b). The delivery cost of restricted flooding \( C_{rf} \) can be calculated by Eq. (6).

\[
C_{rf} = (1 - m\sqrt{N})C_f \quad (6)
\]

In GRMR, the first \textit{interest} is sent to a border node of requested region following greedy routing. Afterwards, it constructs multicast tree by propagating \textit{interest} to its neighbors inside the region (Fig. 3 (c)). From sink to destination, the next hop is always selected by a diagonal link if it leads to the shortest path directionally; otherwise, a horizontal link is selected. This process is iterated until \textit{interest} reaches requested region. Each node on this path receives and forwards the \textit{interest} only once. Cost of Transmitting \textit{interest} from sink to requested region \( C_g \) can be calculated by twice the number of forwarding nodes by Eq. (7).

\[
C_g = 2(\sqrt{N} - r - 1) \quad (7)
\]

For multicast tree construction, nodes send \textit{interest} one time, and receive the \textit{interest} from its all neighbors inside the region. The delivery cost \( C_r \) for multicast tree construction can be estimated by Eq. (8) and overall delivery cost of GRMR can be generated by Eq. (9).

\[
C_r = r^2 + 4(r - 1)(2r - 1) \quad (8)
\]

\[
C_{grmr} = C_r + C_g = 9r^2 - 14r + 2\sqrt{N} + 2 \quad (9)
\]

Assume \( r = \alpha \sqrt{N} \) and \( m = \beta \sqrt{N} \), \( 0 < \alpha + \beta \leq 1 \). Then, Eq. (6) and Eq. (9) can be transformed to Eq. (10) and Eq. (11) respectively.

\[
C_{rf} = (1 - \beta)(9N - 12 \sqrt{N} + 4) \quad (10)
\]

\[
C_{grmr} = 9\alpha^2N + (2 - 14\alpha)\sqrt{N} + 2 \quad (11)
\]

According to the calculation above, the delivery cost of flooding is \( O(9N) \), while restricted flooding is \( O(9(1 - \beta)N) \). If \( \alpha \) is a constant and network size is infinite, the delivery cost of GRMR is \( O(9\alpha^2N) \). If \( r \) is constant, the delivery cost of GRMR is \( O(2\sqrt{N}) \). Therefore, with increasing of network size, GRMR is much more energy efficient and scalable than aforementioned approaches.

4.2 Simulation and Analysis

GRMR and several comparable approaches were simulated in NS-2 [33]. GRMR was implemented based on the built-in routing protocol - directed diffusion (DD) [8], [34], which is a data centric routing paradigm for sensor networks. A number of modifications were put into effect to realize functionalities of GRMR. Multicast tree construction was implemented to support efficient \textit{interest} distribution, data delivery and aggregation. Besides, flooding function, gradient setup and reinforce process of DD were disabled. GFG [24], which adopts similar greedy routing and geocasting mechanism to GRMR, was simulated by disabling multicasting tree construction and data aggregation of GRMR. GFG is significant for the evaluation of data aggregation effect of GRMR. Only high-level network characteristics were considered in this simulation, such as nodes’ connectivity and message delivery. Other simulation parameters were set following default options of DD, such as MAC layer protocol, signal propagation, and collision strategies.

In the simulation, network size was switched from 50 to 400 nodes in increments of 50 nodes. Network field was step-increased along with the number of nodes to keep stable node density. At first, 50 nodes were generated by randomly placed in a 160m by 160m square. Every node had 40 meters radio range. A modified 802.11 MAC from DD was applied to imitate real sensor network radio. Power dissipation for reception was set to 395mW and 660mW for transmission, so that the transmission cost is computed by 1.67 times to reception cost in the simulation. Simulation time was 350sec, and 5 \textit{interests} were injected to the network with time interval (60sec). All \textit{interests} had same fields except \textit{Time Stamp} and \textit{Nonce} fields. Corresponding nodes returned 5 pieces of \textit{data} for each \textit{interest} with time interval (10 sec). A node at the center of the left edge of the network was selected as sink. Requested region located at the bottom right with 30% coverage to whole network. Inside requested region, three nodes were selected indiscriminately as corresponding nodes to reply data. \textit{Interest} with 42 bytes length were diffused to requested region and \textit{data} with 64 bytes length was replied to sink by corresponding nodes.

Data aggregation was realized by utilizing the application-specific filter API of DD. Filter API provides matching functions of data attributes. We defined a new attribute set to meet the naming scheme of GRMR. A matching function was provided to compare the new defined attributes. Uniformed naming scheme and simple matching function was provided to compare the new defined attributes. Unified naming scheme and simple matching function enabled the filter incur little network cost to interact with directory or mapping services. Although three aggregation approaches were discussed in Sect. 3.4, only the first approach was implemented until now. More complex aggregation algorithms on merging multiple data pieces to one message will be realized in the future.

As discussed in Sect. 4.1, delivery cost of initial \textit{interest} should be primarily evaluated due to its broadcast property in many mechanisms. The delivery cost of flooding, restricted flooding (RF), DD and GRMR on initial \textit{interest} is plotted in Fig. 4. The cost of DD is nearly equal to that of Flooding, because DD broadcasts initial \textit{interest} to whole network to establish paths and setup gradient. Greedy routing with regional multicast in GRMR produces much
lower delivery cost than others.

In Fig. 5, overall cost for disseminating 5 interest and transmitting replied data is displayed. Flooding isn’t presented in this graph, because it apparently leads to considerable higher cost than other approaches due to its broadcast manner for every interest. The cost of DD increases rapidly due to its additional exchange messages for the maintenance of gradient. The cost of GFG is higher than GRMR for the lack of efficient multicast tree construction and data aggregation mechanisms.

In congestion avoidance networks, latency has tight relationship with the hops from source to destination. The average delay is shown as a function of network size in Fig. 6. GRMR gets a pretty comparable latency to DD and flooding. Flooding has the highest latency deriving from random delay of MAC signal propagation to avoid broadcast collision. Similar to Flooding, DD uses broadcast for diffusion of the initial interest. This is the reason why the average delay larger than GFG and GRMR. Although GFG applies greedy routing engaging with regional broadcast mechanisms, the absence of multicast tree construction results in slightly higher latency. That is because the subsequent messages cannot take benefits from multicast tree.

To evaluate the impacts of network dynamics on average delay, we turned off a fixed fraction of nodes randomly in the 400 nodes network scenario. Delay of data transmitted from a source to sink was measured 10 times to provide higher probability that at least one node on the path is offline. The result reveals that GRMR conducts more stable connectivity than GFG and DD in low reliability networks, which is benefit from rapid failure recovery and efficient multicast tree construction.

Foregoing simulations were all conducted on the assumption of requested region covers 30% area of whole network. Since broadcast is used for multicast tree construction, size of requested region distinctly impacts the overall delivery cost of GRMR. The simulation with fixed requested region size as the function of network size is shown in Fig. 8. Requested region was restricted in a 80m × 80m square at the center of the network. GRMR manifests superior delivery cost to other approaches, because the proportion of cost on multicast tree construction decreases progressively along with the growth of network size.

Simulations have been only carried out on a fixed workload consisted of one sink and three sources. The number of sinks and sources would affect the performance on account of more data propagation. Figure 9 presents the delivery cost variation of GRMR on multiple sinks with multiple sources in the 400 nodes network. The result reflects a increasing cost in direct proportion to the number of sinks. The rea-
The feature of GRMR include per-node routing state, low naming complexity, simple routing mechanism, and efficient data aggregation. Performance evaluation results reveal that GRMR has significant lower delivery cost and less latency for both interest diffusion and subsequent data delivery. Further investigations are under way, including design efficient data aggregation algorithms for WSNs with multiple sinks and multiple sources, carry out simulation with more network conditions, and study the influence of node position error on routing mechanisms.

5. Conclusion

This paper presented greedy regional multicast routing mechanism (GRMR), which merges greedy routing with regional multicasting to provide energy efficient data centric routing for WSNs. The features of GRMR include per-node routing state, low naming complexity, simple routing mechanism, and efficient data aggregation. Performance evaluation results reveal that GRMR has significant lower delivery cost and less latency for both interest diffusion and subsequent data delivery. Further investigations are under way, including design efficient data aggregation algorithms for WSNs with multiple sinks and multiple sources, carry out simulation with more network conditions, and study the influence of node position error on routing mechanisms.

Acknowledgments

This work was supported by ICT R&D program of MSIP/IITP, Republic of Korea [No. B0126151078-0002003, Creation of PEP based on automatic protocol behavior analysis and Resource management for hyper connected for IoT Services].

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