A Novel Quorum Based Location Management for Wireless Sensor Network with Mobile Sinks

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Abstract—Location service provides position of mobile destination to source node so that position based routing can be applied. Several quorum-based location services have been proposed. These location service protocols suffer from complex structure with high overhead or host location foreknowledge and difficulty in quorum construction. To overcome those deficiencies, we propose a novel quorum-based location service. In the proposed scheme, location databases are stored in the network nodes themselves, which form a self-organizing virtual backbone network. Quorum system is constructed on the virtual backbone network in conformity to irregular grid rule. Every mobile node will notify its location update information to irregular grid quorum system so that other hosts can obtain the mobile node location through irregular grid quorum system. The simulation results show that our proposed location service leads to high success rate, appropriate quorum size and good load.

Keywords—wireless sensor network, quorum, irregular grid.

I. INTRODUCTION

In a mobile wireless sensor network, mobile hosts move freely from place to place. The location of a mobile host must be identified before a conversation to the mobile host can be established. One of the most important issues is location management in such highly dynamic environment because mobile host may roam in arbitrary manner.

There are two basic operations in location management: location update and paging. Location update is the process that the mobile host reports its up-to-date location information dynamically while its position has changed. The searching host process is referred to as paging. When an incoming call arrives, the system initiates paging process for the mobile host. To perform location update or paging will incur a significant amount of cost, which would improper limited resource (e.g., wireless bandwidth and power at the mobile host, the processor and databases for location) and bring on performance depravation of network.

Specially, wireless sensor networks (WSN) are unstable multi-hop networks in which nodes often disconnect the network in an arbitrary manner; the location scheme is often faced with the failure of locating the up-to-date position of mobile nodes. Thereby, failure probability should be considered. Availability is also an important reference criterion, because each node has limited processing and communication ability. Load measure should be considered as well.

Some traditional protocols [1, 2, 3] deal with this service using flooding-based methods, which involve all nodes, located inside a region, in data accessing. The location of destination can be retrieved locally, but the communication complexity of a location update by each node scales with. Large amount of interchanges among nodes will consume considerable cost and even cause many collision problems at MAC layer. There have been several research efforts on locating mobile sensors in different wireless sensor networks environment. In cellular construction [4], the system coverage area is partitioned into cells. Sensor system utilizes home location registers (HLR) and visitor location registers (VLR), both residing within the wire backbone, to keep track of user locations. Grid Location Scheme (GLS) [5, 6] divides the area that contains the sensor network into a hierarchy of squares. In this hierarchy, \( n \)-order squares contain exactly \( 4^{n-1} \) order squares, forming a so called quad-tree. Each node maintains a table of all other nodes within the local first-order square. A node makes a bootstrapping mechanism to discover other node’s position through quad-tree. [7, 8] both introduce a virtual homezone to store location information in its database. The positions of a node in someone homezone can be derived by applying a hash function to the node identifier.

In this work, we propose an efficient location management using quorum system, where quorum may provide quick query about the host location. A mobile host receives distributing location information from location databases which form a virtual backbone that is dynamically distributed among the network. These databases serve only as containers for location information storage and retrieval. Every host will report its location information to the nearest databases. Every database belongs to different quorums which intersect and connected with each other, where mobile host may get the location information of every node through paging process. Irregular Grid Quorum (IGQ) scheme is proposed in this work. The backbone nodes are logically arranged in rows of varying width. A quorum is the union of one full row and a representative from every row below the full row. It manifests its high quality for all universe sizes, so it is a good choice not only for systems with thousands or millions of nodes but also for systems with as few as several nodes. The quorum system-based scheme is distributed in operation and uses the databases of an entire quorum to hold
a replica of a mobile host’s location information. There is no fixed association between any particular quorums to any mobile host. First, the assignment of a location database to reside in any mobile host is flexible, contingent upon the network node stability and traffic and mobility patterns. Second, during the location update of a mobile host or when a call arrives to a mobile host, location of the mobile can be written to or read from any randomly chosen quorum of databases.

The merits of our scheme are summarized as the following. First, our location management scheme, IGQ, is fully distributed and fault tolerant. Second, IGQ scales well to a large number of nodes. Finally, IGQ could meet the challenges presented by node mobility. Similar to UQS [9], in our scheme, the entire network dynamically choose members to constitute virtual backbone. However, our scheme uses a different and original approach to construct quorum system.

The remainder of this paper is organized as follows. In Section II we analyze several existing quorum systems for location management and some proposed quorum algorithms. Section III illustrates the Irregular Grid Quorum-based location management. A comparative performance evaluation through simulation is presented in Section IV. Section V concludes this paper.

II. RELATED WORK

Quorum systems have been used for benign fault tolerance, maintaining data availability in the presence of distributed services. Quorum systems are defined as follows. A set system is a collection of sets over an underlying universe. A set system is said to satisfy the intersection property, if every two sets have a nonempty intersection. Set systems with the intersection property are known as quorum systems and the sets in such a system are called quorums.

Traditional quorum systems are typically represented by Byzantine quorum system [10], Crumbling Wall quorum system [11], Grid quorum system [12], Tree quorum [13] and Diamond quorum system [14]. Their topology covers regular grid, tree and diamond.

Quorum systems have been used in the study of distributed control and management problems such as data replication protocol [15], name servers [16], selective dissemination of information [17] and distributed access control and signatures [18]. In the field of wireless sensor network (WSN) several distributed mobility management scheme using quorum system are proposed. In [9], a distributed location management scheme is proposed that utilizes location databases that form a virtual backbone, which is dynamically distributed among the network nodes. These databases serve as containers for location storage and retrieval. However, there is an unsolved problem in this work which does not provide pertinent quorum construction method: it assumes that the virtual backbone nodes maintain quorum intersections among themselves by a arbitrary method; yet, the method is not clear how to guarantee the intersection of selected nodes, how to dominate the size of quorum intersection and the quorum size. These ambiguous factors will result in uncertain performance of location process. The basic idea of SQLS [19] is that destination node registers its location along a ‘column’ to form an update quorum. Source node makes a query along a ‘row’ to form a search quorum. The destination location is detected at the intersection between the update and search quorums. However, when node failure probability is considered, it becomes less availability and efficient. Also, it need to know the comparatively position between nodes by the support of geographical information, which is difficult to implement in WSN.

III. IRREGULAR GRID QUORUM BASED LOCATION MANAGEMENT

A. Virtual Backbone Framework for Quorum Scheme

In order to implement the mobility management scheme, a set of mobile hosts is chosen to contain the nodes location databases. This set comprises a self-organizing virtual backbone. It dynamically assigns memberships to mobile hosts in the network depending on the communication environment and the network node density. Under ideal conditions, all nodes in the virtual backbone are interconnected, and every non-backbone node is connected with at least one other backbone node, such that communication between any two nodes is possible. Although logically a two-level hierarchy is in place here, the flat network structure is used, such that a connection can be a multihop link that spans both the backbone and non-backbone nodes. Thus, routing of the actual traffic is carried by all nodes in the network. In particular, the virtual-backbone nodes can communicate between each other through routes that pass through the non-backbone nodes. [9] demonstrate for detailed descriptions of the formation and maintenance of the virtual backbone in the presence of node disconnections. When a database fails, the node in which it resides detaches from the network for a long time, such that the location information stored in it is lost. We say that a database is inaccessible when it retains the location information but cannot be accessed for a short period of time, due to node instabilities.

Moreover, the location of a mobile host is defined in terms of the positional relationships between the mobile host and the other nodes. The identity of the neighboring nodes of a mobile host can provide an indication of how a message could be routed to the mobile host. In particular, we will define the location of a mobile host as the ID number of its nearest location database. Nodes containing the location databases can dynamically detach and reattach to the network at any time due to mobiles’ movements or changes in the communications environment.

The virtual backbone nodes maintain interconnection among themselves by any routing methods. As will be shown later, with the quorum-based mobility management scheme the optimal number of databases in the virtual backbone is usually small compared with the size of the network. Therefore, for a large wireless sensor network, the
cost of routing among the virtual-backbone nodes is typically very small compared with routing within the entire network. Besides location service, the virtual backbone can also perform other network functions on which we will not elaborate in this paper, such as channel assignment, flow control, and multicast routing. Thus, the cost of virtual backbone maintenance can be far be offset by the advantages that it brings with it. During the initial setup, some form of full-network routing, such as flooding, is performed once to find the set of nodes that best serve as the virtual backbone. Afterwards, we only need to ensure that when a backbone node has detached from the network, a nearby nonbackbone node is recruited to take its place in the virtual backbone. In [22] and [23], examples are given on how backbone sets of nodes in an ad hoc network can be determined in a distributed fashion without the use of a central-controlling entity. Here we emphasize that, in this scheme, since a connection can be a multihop link through both the backbone and nonbackbone nodes, the backbone does not have to maintain direct radio contact with every node in the network. Therefore, the algorithm to construct the virtual backbone has much lower complexity than those proposed in [22] and [23].

B. Selection Algorithm for Virtual Backbone

For each network node, we define an r-zone, which consists of the node itself and all nodes or less hops away, where is the guaranteed maximum hop count from a node to its nearest database. Then, this problem can be described as: find a set of databases with minimum cardinality, such that every node in the network is in at least one database’s r-zone. Namely, the virtual backbone “covers” the entire network.

The computation of a virtual backbone can be reduced to the following minimum set covering problem: given a set of objects V (i.e. nodes) and a E collection of sets of these objects C (i.e. r-zones), find a subset (i.e. r-zones induced by virtual backbone) ∈ E of minimum cardinality, such that every element v ∈ V belongs to at least one of the sets in C.

The MSC (Minimum Set Covering) problem is known to be NP-hard, and the greedy algorithm provides the best known approximation to the optimal solution [22]. However, the greedy algorithm is a centralized one, which is not suitable for use here due to the lack of stability in the ad hoc environment. [24] presents a Distributed Database Coverage Heuristic (DDCH) for virtual backbone generation. DDCH generates a virtual backbone with only local information exchange and local computation. Due to space reasons, we don’t describe the problem in detail.

C. Irregular Grid Quorum Construction on Backbone

1) Preliminaries

A coterie is a family of subsets such that every pair of subsets in it has at least one element in common but neither is a subset of the other.

Definition 1: A coterie C under an underlying set \( U = \{1,2,\cdots,n\} \) is a family of subsets (called quorums) of U satisfying the intersection property (i.e. for any pair \( S, R \in C, S \cap R \neq \emptyset \) holds), and minimalism (i.e. no quorum in C contains any other quorum in C) [25]

Definition 2: A coterie D is said to dominate another coterie C if, for \( \forall Q \in C \), there exists a quorum \( Q' \in D \) satisfying \( Q' \subseteq Q \). A coterie C is non-dominated (ND) if no other coterei dominates it. ND coteries are important in practical applications, since they have maximal efficiency in some sense. Let NDC denote the class of all ND coteries. The following propositions come from [26].

A definition of IGQ (Irregular Grid Quorum) is as follows.

Definition 3: Let \( n = (n_1,\cdots,n_d) \) be such that \( \sum_{i=1}^{d} n_i = n \).

Let \( U_1,\cdots,U_d \) be nonempty disjoint subsets of the universe U with \( |U_i| = n_i \). Then, \( \text{IGQ}(n) = \{ U_i \cup \{a_1,\cdots,a_d\} \mid U_i \in J \} \) for \( i = 1,\cdots,d \).

The set \( U_i \) is called the \( i \)-th row and \( n_i \) is its width. A quorum that uses row \( i \) as the full row is called based on row \( i \).

Proposition 1:
if \( n_i = 1 \) and \( n_i \geq 2 \) for all \( i \geq 2 \), then \( \text{IGQ}(n) \in \text{NDC} \).

Lemma 1: if \( n_i = 1 \) for some \( i \geq 2 \), then \( \text{IGQ}(n) \) is not a coterie. [11]

Proof: Assume that there exists some \( i \) such that \( n_i = 1 \), then any quorum \( S \in \text{IGQ}(n) \) that is based on row \( i \) contains the single element in row \( i \). But then \( S \) contains some other quorum \( R \in \text{IGQ}(n) \) (that is based on row \( i \)), violating the Minimalism property, so \( \text{IGQ}(n) \) is not a coterie.

Quorum1= \{ 1,2,5,7,11 \} Quorum2= \{ 2,3,6,8,9 \}  
Quorum3= \{ 4,5,6,7,12 \} Quorum4= \{ 9,10,11,12 \}  
Figure 1. Sample of irregular grid system

Fig.1 shows a sample of IGQ system containing 12 elements. These elements have an ID number respectively. Except the first row, other rows contain at least 2 elements. It is determined by the principle of NDC. If non-first-row
only has one element, the non-dominated property of coterie can not be ensured. Quorum 1 contains the first row, one element 2 from the second row, one element 5 from the third row, one element 7 from the fourth row and one element 11 from the fifth row. As the same principle, quorum $i$ contains the whole elements of $i$th row and one element of each row below $i$th row.

2) Irregular Grid Quorum Construction Algorithm with Backbone Nodes

For each backbone node, we define an ID number with every node. A node selected by random will initiate an ID granting process which award every nodes a unique number. The initial node broadcast an ID.MSG with the number 1. Nodes which receive ID.MSG will set and rebroadcast ID.MSG. If node receives ID.MSG secondly, the message will be discarded. The process does its best to ensure backbone nodes with sequential ID. Row-head (the first node in a row) choose nodes to form a row, while row-tail (the last node in a row) assigns the head of next level row. For example, node 1 acts as the first row and assign node 2 as the row2 head. Node2 will choose several closest nodes (≥ 2) to construct row2.

Quorum assignment follows the principle of Definition 3. Every row-head will carry out the duty of selecting an element from each row which is a part of a quorum. The row-head needs to contact any $n$ nodes out of $n$ rows ($n$ equals to the number of rows below the row-head). It floods the request to these rows. The row-head only select the first reply node out of one row to form quorum. If the rows of irregular grid equal to $r$, then the size of quorum is $r - 1$.

D. Mechanism and Sample of Irregular Grid Quorum Based Location Management

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1
2 3
4 5 6
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Quorum1={1,2,5}
Quorum2={2,3,6}
Quorum3={4,5,6}

Figure 2. Virtual Backbone and the Location Databases

Fig. 2 shows an example of the virtual backbone structure in a sensor network. The yellow circles represent the backbone nodes, and the gray circles represent the nonbackbone nodes.

The location databases are arranged into quorums. In Fig. 2, an example irregular grid based quorum system is $\{\{1,2,5\},\{2,3,6\},\{4,5,6\}\}$. When a mobile host, $A$ for example, updates its location, it contacts the closest node that belongs to the backbone set, the one with location database 5, in this case. The backbone node then sends out a location-update message, containing $A$’s ID number, the node’s location (e.g., identity of the database 5), and a sequence number that indicates the time of update to one of the quorums, e.g. $\{4,5,6\}$. When a mobile host $B$ initiates a call to $A$, it first contacts the node with location database 1, which in turn queries (through multicasting) a quorum, e.g. $\{1,2,5\}$, for $A$’s location. Location database 2 then sends back to $B$ the location information of $A$. It is possible that location database 1 has an older copy of $A$’s location information and sends it to $B$ as well. Then it is up to check the time-sequence numbers in both messages and pick up the latest one. Because of the intersection property of the quorum system, $B$ can ideally always receive the most current location information of $A$.

However, in a mobile environment, nodes often detach from the rest of the network without warning. The connectivity of the nodes in the backbone set is maintained by a procedure as shown in Fig. 3. A backbone node may detach from the network, in which case the topology of the backbone will be rearranged. If a backbone node has been disconnected from the network for more than a threshold amount of time, a new node will be chosen as the replacement. For example, the mobile host $C$, as shown in Fig. 3, may be chosen to replace the detached node containing location database 3. $C$ will set up a new location database with the ID number 3 and become a new member of the backbone set. If the node originally containing location database 3 later reconnects to the network, it will delete the database when it is aware of its long absence and the existence of another database with the same ID. With the replacement, location information stored in the original location database is lost. Therefore we say that a location database fails when the node in which it resides detaches from the network.

IV. PERFORMANCE EVALUATION AND SIMULATION

A. Performance Metrics

1. Quorum Size- The different number of nodes with each row induces different number of rows, which is related with quorum scale, with the same element size. Having small quorums has obvious advantages such as a low message...
complexity of the protocol or a low number of database replicas kept. In this case, more backbone nodes mean more big size of quorum.

2. Availability- Assuming that each element fails with probability $p$, $F_p$ denotes the surviving elements do not contain any quorum. Having small $F_p$ means low probability of locating failure. One node stopping its work doesn’t predicate system failure; however, one quorum losing life denotes the failure of whole locating system. So we would like $F_p$ to be as small as possible. Availability can be induced from the failure probability of IGQ quorum location system.

3. Load- It reflects an access probability of quorum system. Load denotes the whole time an element is used. For a given quorum system $S$, the load $L(S)$ is the total engaged time on the busiest element in quorum system. The load measures the quality of a quorum system in the following sense. If the load is low, then each element is accessed rarely, thus it is free to perform other unrelated tasks.

We use a probabilistic model of the failures in the system. We assume that the nodes fail independently with a fixed uniform probability $p$. We assume that the failures are transient that the failures are crash failures (i.e., a failed element stops to function rather than functions incorrectly) and that they are detectable.

Note that this model implicitly assumes that the communication links are perfect, and that the network is fully connected, hence the network never partitions off. In general this is an oversimplification of real communication networks. However we believe that such a model is reasonable for some important cases and especially for a well maintained wireless sensor network. We use $q = 1 - p$ denotes the probability of a node survival.

B. The Quorum Size of Irregular Grid Quorum

Any quorum based on row $i$ has size $n_i + d - i$. So the smallest size of quorum is $\min(n_i + d - i)$. The number of quorums lies on the rows of IGQ. That is, more rows denote more number of quorums. A large quorum has obvious disadvantages such as a high message complexity of the protocol and low redundancy with low fault-tolerance. Therefore a moderate size of quorums is advocating.

C. The Availability of Irregular Grid Quorum

To calculate the failure probability of a given irregular grid system considers the following procedure to search the grid for either a complete quorum or a failure configuration. We go over the rows from the bottom up, starting with row $d$.

If a fully live row is found, its union with all the live elements in rows below it gives a live quorum. On the other hand, if a fully failed row is found then it is pointless to search rows above it and we know that all rows below it contain a failed element, so no live quorum exists. If no row is fully live then obviously no live quorum exists. Thus stopping decisions are correct. Let $F_p(i)$ denote $F_p$ of the sub grid of the top $i$ rows. The failure probability $F_p(i)$ obeys recurrence

$$F_p(i) = 1 - q^n_i,$$

$$F_p(i) = p^n_i + (1 - p^n_i - q^n_i)F_p(i-1), i > 1$$

When $n_i = 1$, then $1 - q^n_i = p$, so we can expand the recurrence get the failure probability of irregular grid $IGQ(n)$ on $d$ rows with $n_1 = 1$

$$F_p(IGQ(n)) = \sum_{j=1}^{d} p^n_j \prod_{j=i+1}^{d} (1 - p^n_j - q^n_j)$$

$d$ denotes the number of rows of irregular grid.

D. The load of Irregular Grid Quorum

Proposition 2: Let $c$ denote the size of smallest quorum in a IGQ with $d$ rows. Then, $L(S) \geq \max\left(\frac{1}{c}, \frac{1}{d}\right)$.

Proof: $L(S) \geq 1/c$ is just a re-statement of Proposition in [27]. Since every quorum contains at least one coterie, any strategy must access some coterie with probability $\geq 1/d$.

E. Simulation Results

In this section, we use simulation to compare the availability and load of IGQ system with those of several other quorums (UQS, SQLS) that are based on different logical organization of the quorum nodes. We also consider the different arrangements of the UQS by setting one intersection between quorums, and make similar quorum size versus the system availability.

The performances of all protocols are measured in three metrics: load, quorum size and availability. Load can be measured by the access time/sec on each element, which is the sum of the access time of all quorums it belongs to (an access rate on each quorum is given). Availability can be induced from the failure probability of IGQ location system.

The simulation is conducted in a $1000*1000$ 2-D free-space by randomly placing 500 nodes by OPNET. The size of backbone nodes range from 10 to 100 according to the experiments require. The quorum size rest with the number of IGQ rows, which is conducted by self-determination of each backbone node, so that the rows size is not fixed. For the sake of simplicity, we only consider the monotone increasing number of elements of rows, where backbone nodes choose the nearest elements as coterie.
The first sets of experiments are carried out at different backbone node number and quorum size. Uniform mobility of one special receive host is assumed. Fig. 4 shows average access time per second between different quorum sizes. \( d \) denotes the quorum size of IGQ system. Access probability 100/sec on each quorum is given. As expected, the average access time of each node decreases as either node number \( n \) and quorum size \( d \) increases. Because when backbone node number increases, the idle time of quorum will reduce. As quorum size increase, the time of quorum returning result will increase at the same time.

The second set of experiments was carried out at different backbone node number and quorum size. Assuming 10% nodes failure, Fig.5 depicts that IGQ system improves system alive probability with the increase of backbone node number. Alive probability reflects the availability of quorum-based system while some nodes invalidate and lost ability to communicate with other nodes. With the increase of rows of IGQ, quorum system have good fault-tolerance characteristic. That means IGQ system with bigger quorum size will not stop even if several nodes pass away.

Two experiments are reported in Fig. 6 and Fig. 7. Node number will affect total cost and success rate in the same direction. In comparing different quorum-based location management schemes, we note that with the step-up of size of nodes, the stability of IGQ total cost is better than UQS and SQLS, which ascribe the structure of IGQ. In the condition of same backbone nodes, IGQ has the smallest quorum size, which results in low routing cost and little time. Simulation results show that IGQ outperforms UQS and SQLS in average success rate. Fig. 7 also represents that IGQ improves the performance by 20 ~ 40 % in the aspect of average success rate.

V. CONCLUSION

We presented architecture for irregular grid quorum scheme designed for location management in WSN with mobile sinks. This system handles challenges that arise due to the stringent requirements imposed by mobility, multihop and wireless. The IGQ system provides a new approach for advanced research to decrease the time for location while mobile node’s location changes. IGQ system does not require any special processes for positioning node and network topology. By reducing the calculation complexity in quorum construction procedure, it is possible to apply our
proposed scheme to provide location management services in mobile wireless sensor networks.

One of drawbacks of quorum based scheme is that it requires searches and updates in the whole network even when source and destination are relatively close to each other. Possible extension of our protocol to address this issue is the hierarchical quorum based protocol. It generally follows doubling circle method, with updates and searches limited to bounding circles areas. Two perimeters (made from Gabriel graph of the entire graph) of two circles, update and search one, have normally two rendezvous points. If destination search fails in one circle size (loop detected on perimeter) then search proceeds to the double circle size (next level hierarchy). Further study will consider the two circle scheme to address the deficiency problem.

VI. ACKNOWLEDGMENT

This work was supported by National Natural Science Foundation of China (NSFC) under grants No.60673178, No.60873241, and Hi-Tech Research and Development Program of China under grants No.2008AA01Z217, No.2009AA01Z210.

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