A scalable quorum-based location service in ad hoc and sensor networks

Ivan Stojmenović*

Department of Electronic, Electrical and Computer Engineering,
The University of Birmingham,
Birmingham B15 2TT, UK

SITE, University of Ottawa,
Canada
E-mail: stojmenovic@storm.ca
*Corresponding author

Dandan Liu

Computer School,
Wuhan University,
Wuhan, China
E-mail: liudd2004@hotmail.com

Xiaohua Jia

Department of Computer Science,
City University, Hong Kong,
Kowloon, PR China

Computer School,
Wuhan University,
Wuhan, China
E-mail: csjia@cityu.edu.hk

Abstract: Location service provides position of mobile destination to source node so that position-based routing can be applied. Previous location service protocols suffer from partial flooding overhead, and/or location failure in group movement scenarios. To overcome those deficiencies, we propose a quorum-based location service. The basic idea 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. The overhead of each routing task, including location service, is $O(\sqrt{n})$, where n is the number of nodes in the network. Four strategies are proposed to adjust the quorum system and improve it's performance. To guarantee the success of location retrieval, both search and update quorums are extended by face routing which traverses outer boundary of the network. The simulation results show that our proposed location service has high success rate and good scalability.

Keywords: location service; quorum; ad hoc networks; sensor networks.

Reference to this paper should be made as follows: Stojmenović, I., Liu, D. and Jia, X. (2008) 'A scalable quorum-based location service in ad hoc and sensor networks', *Int. J. Communication Networks and Distributed Systems*, Vol. 1, No. 1, pp.71–94.

Biographical notes: Ivan Stojmenović is a Professor at the University of Ottawa (www.site.uottawa.ca/~ivan) and Chair Professor of Applied Computing at the University of Birmingham, UK. He received the UK Royal Society Wolfson Research Merit Award. His current research interests are mostly in the design and analysis of algorithms for wireless ad hoc and sensor networks.

Dandan Liu received a BS in Computer Science and Technology from Wuhan University of China in 2003, and she is a PhD candidate in Computer School in Wuhan University of China now. Her research interests include wireless networks, mobile computing and distributed systems.

Xiaohua Jia received his BSc in 1984 and ME in 1987 from the University of Science and Technology of China, and a DSc in 1991 in Information Science from the University of Tokyo, Japan. Currently, he is a Professor in the Department of Computer Science at City University of Hong Kong and School of Computing, Wuhan University, China. His research interests include distributed systems, computer networks, WDM optical and wireless networks, internet technologies and mobile computing.

1 Introduction

We consider two basic scenarios in this paper. Mobile ad hoc networks (Giordano, 2002) consist of wireless nodes that communicate with each other in the absence of a fixed infrastructure. In wireless sensor networks, sensor nodes are static and route reports on event discovery to a special node (base station or actuator) that can be mobile. The task of finding and maintaining routes in the network is non-trivial since node mobility causes frequent unpredictable topological changes. Location-based routing (Giordano and Stojmenovic, 2004) is therefore introduced to reduce the communication overhead imposed by flooding-based solutions. Each node operates autonomously with no central control. It determines its own location through the use of GPS or some other type of positioning service. Location-based routing problem is generally divided into two phases that may be investigated separately as follows:

Phase 1: Location service that comprises of location update and location retrieval.

Phase 2: Routing data traffic from source to a destination whose location is known.

We focus on addressing the first phase in this paper. Because of frequent mobility, the location of a destination should be identified before efficient data transmission could be accomplished. Mobile nodes should register their current position with location service. When a source node has no information about the location of a desired communication recipient, it contacts the service and requests that information. This paper aims at developing energy efficient location service, so that routes between source and destination can be found.

Traditional protocols (Basagni et al., 1998; Ko and Vaidya, 1998; Stojmenovic et al., 2006) deal with this service using flooding-based methods, which involves 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 $O(n)$. Large amount of interchanges among nodes will consume considerable energy and even cause many collision problems at MAC layer. The main goal of this paper is to describe a scalable localised location update scheme, by controlling the overhead of each routing task to $O(\sqrt{n})$, where n is the number of nodes in the network. Another goal is to present a method that does not require nodes to remain in a fixed region, which is the case with other known methods. In other words, the proposed method is applicable when all nodes move in more or less same direction (e.g. rescue team or soldiers). This feature is lacking in another scalable, home-agent and hashing-based scheme, proposed independently in five papers (Blazevic et al., 2001; Morris et al., 2000; Pei and Gerla, 2001; Stojmenovic, 1999b; Woo and Singh, 2001). They have low fault tolerance in the presence of nodes failures or dynamic environment.

In this paper, we propose a scalable quorum-based location service based on a localised approach. It relies on multiple location servers replicated on several geographical positions to form a quorum. In a *localised* algorithm, each node makes the decision to which neighbour(s) to forward the message-based solely on the location of itself, and its neighbouring nodes and fixed amount of additional information (e.g. destination position for routing). Localised algorithms avoid communication overhead needed for distributed solutions that need global knowledge, such as full networks information, including position of all nodes and activity status of all nodes. A survey of existing localised protocols for location updates for efficient routing is given in Stojmenovic (2002a), while a survey on position-based routing can be found in Giordano and Stojmenovic (2004) and Stojmenovic (2002b).

Most previously proposed position-based routing algorithms for mobile ad hoc networks were based on forwarding the actual message along multiple paths toward an area where destination is hopefully located. The significant communication overhead can be avoided if the routing strategy is changed. We first propose to apply a variant of well-known route discovery scheme. The source node issues several search ‘tickets’ (each ticket is a ‘short’ message containing sender’s id and location, destination’s best known location and time that location is reported and constant amount of additional information) that will look for the exact position of destination node. When the first ticket arrives at the destination node D, D will report back to source with brief message containing its exact location, and possibly creating a route for the source. The source node then sends full data message (‘long’ message) toward exact location of destination.

The novel quorum-based location service reduces the overhead of each update and search task to $O(\sqrt{n})$, where n is the number of nodes in the network. Nodes report their new positions to their neighbours whenever a link is broken or created. After certain number of such link changes, nodes forward their new position to all nodes located in its ‘column’, that is, to the north and south of their current location with certain ‘thickness’ of reporting. The destination search then begins with two tickets being sent in the east and west direction, with certain ‘thickness’, looking for the most up to date information of destination’s position. When the tickets reach each end of current ‘row’, the search is continued toward best reported destination position, with corrections along the path as better information becomes available closer to destination. One of the tickets can be sent from the source directly toward destination, to take advantage of possibly correct information on destination location. We also propose four strategies for the quorum construction to increase the success rate, and improve the energy efficiency. The intersection of 'row' and 'column' can be guaranteed by adding outer face of the ad hoc network to both of them. We describe a strategy based on face routing along perimeter of outer boundary of the network.

We show through simulation that the proposed routing and location update schemes provide scalable routing scheme with high success rates and reasonable communication overhead. The proposed method is also applicable in scenarios when all nodes move out of original region, preserving connectivity. For instance, our location update scheme works well when all nodes move together to a new area (e.g. group of vehicles or soldiers). The columns and rows defined in our location update scheme are relative, not absolute. It also adapts well to synchronous node movements (such as vehicles on a highway), keeping mutual distances but moving at high speed. In this case, the edge disconnection is predicted based on estimated node position, using their reported speed and direction of movement.

Ad hoc networks are best modelled by *unit disk* graphs constructed in the following way. Two nodes A and B in the network are neighbours (and thus joined by an edge) if the Euclidean distance between their coordinates in the network is less than the transmission radius R, which is equal for all nodes. The unit graph is valid model when there are no obstacles in the signal path (e.g. a building). Ad hoc networks with obstacles can be modelled by subgraphs of unit graphs.

The rest of this paper is organised as follows. Section 2 gives the literature review. Section 3 summarises the basic idea of quorum-based location service. We specify the location update and destination search in Sections 4 and 5, respectively. We extend four variants for quorum-based location service in Section 6. In Section 7, simulations are given to compare the performances among different variants, and show their efficiencies. We also present some discussion about other existing protocols in this section. Finally we conclude this paper in Section 8.

The preliminary version of this paper appeared as technical report (Stojmenovic, 1999a) from 1999. The report was revised several times, and two students attempted simulations for several years (Bosko Vukojevic at University Ottawa, and Pedro E. Villanueva-Peña at UNAM Mexico and University Sheffield, UK). A summary of it was also given in book chapter (Stojmenovic, 2002a). It was not submitted previously to conferences or journals because of lack of satisfactory experimental data. In the meanwhile, the quorum-based method from Stojmenovic (1999a) was widely cited (several versions were cited in Google Scholar together about 60 times), and applied in several papers to solve other related problems. Variants of it were also experimentally compared (with other known methods) by other researchers. Details are given at the appropriate places in this paper. Here, we only mention two independent rediscoveries of basic horizontal-vertical greedy quorum-based method (without face routing part for guaranteed service) in 2002 (Aydin and Shen, 2002) and in 2004 (Tchakarov and Vaidya, 2004) (this paper also describes an enhancement) in the context of efficient content location in location-aware ad hoc networks. Short conference version of this paper appeared in Liu et al. (2006a,b).

2 Literature review

We briefly describe position-based routing schemes that are used in this paper. *Greedy* method (Finn, 1987; Stojmenovic and Lin, 2001) selects neighbour *A* that is closest to the destination *D*. A routing algorithm that guarantees delivery in unit graphs is described in Bose et al. (2001). It applies greedy routing until either message is delivered, or a node having no closer neighbour to destination than current node is encountered (called failure node). In latter case, face routing is applied to recover from failure. Face routing requires the network topology to be a *planar graph* (i.e. no edges intersect each other); the one used in Bose et al. (2001) is the Gabriel graph. *Gabriel graph* (Gabriel and Sokal, 1969) contains edges between nodes *u* and *v* if and only if no other nodes are located within the circle centred in the middle of edge (*u*, *v*) and with diameter $\|uv\|$. It has some desirable properties when used for routing in wireless networks, such as localised message free computation, planarity and preserving connectivity (Bose et al., 2001). Gabriel graph divides the network into faces. The one that contains the line *SD*, where *S* is failure node and *D* is destination, is traversed by right-hand or left-hand rule (placing a virtual hand on the 'walls' of the face) until node *A* closer to destination than *S* is encountered (existence of such a node for unit disk graphs is recently confirmed in Frey and Stojmenovic (2006). Greedy routing continues from *A* until delivery or another failure node.

A detailed literature review on location update schemes for efficient routing in ad hoc networks is given in a survey (Stojmenovic, 2002a). The survey includes the DREAM algorithm (Basagni et al., 1998), LAR schemes (Ko and Vaidya, 1998), Voronoi diagram and convex hull based approaches (Stojmenovic et al., 2006) and doubling circles scheme (Amouris et al., 1999), among others. We will restrict the review only to results directly related to this paper.

Given a set *S* of *n* servers, a quorum system is a set of mutually disjoint subsets of *S* whose union is *S*. When one of the servers requires information from the other, it suffices to query one server from each quorum. It is possible to form quorums of size approximately $\sqrt{n}$ (Maekawa, 1985). For example, 25 servers can be organised into 5 rows and 5 columns. Each column serves as a quorum. Thus each node (i, j) (located in *i*th row and *j*th column) replicates its data to all servers (i', j) in its column. To extract the information from server (i, j), server (i', j') may inquire within its i'th row, and the server (i', j) will provide requested information. Variations of this scheme are used in fixed networks, where the set of queried servers contains at least one server that belonged to the quorum that received the latest update. Hence, each query returns the latest value of the queried data. Such a query and update strategies has been previously employed for location management in cellular networks (Krishnamurthy et al., 1998; Prakash and Singhal, 1996; Prakash et al., 1997).

The authors in Karumanchi et al. (1999) discussed information dissemination in partitionable mobile ad hoc networks. They use a well known approach for information dissemination by replicating information at multiple nodes acting as repositories, and employing quorum-based strategies to update and query information. In Karumanchi et al. (1999), *n* nodes are divided into $n^{1/2}$ groups with $n^{1/2}$ nodes in each in two ways and preserve such quorums while nodes move. They also discussed the question when to update location, and argued that distance-based updates (based on absolute distance travelled since last update) and movement-based updates (based on the velocities of nodes) may have limited usefulness in ad hoc networks (such location updates are used in Basagni et al. (1998) and Ko and Vaidya (1998)). For instance, nodes may move within a small circle, causing unnecessary location updates. They concluded experimentally that the best strategy is to update when a certain prespecified number of links incident on a node have been established or broken since the last update (Karumanchi et al., 1999). We decided to apply this strategy in our paper. However, the quorum organisation in our paper differs from one in Karumanchi et al. (1999). The quorums applied in this paper refer to nodes currently located on a north-south or east-west route from a source/destination, while quorums from Karumanchi et al. (1999) consist of very same nodes, whose movement makes them difficult to find by an algorithm more efficient than flooding.

Modifications of quorum-based strategy for use in dynamic or partitionable servers has been considered in Karumanchi et al. (1999), Haas and Liang (1999a,b) and Liang and Haas (2000). The main idea in Karumanchi et al. (1999) is that each server (or node) selects one of quorums at random, to increase the chance of obtaining relatively up to date information in several 'columns'. Haas and Liang (1999a,b) and Liang and Haas (2000) proposed another variant of quorum-based distributed mobility management scheme. First, virtual backbone is initiated and maintained (Liang and Haas, 2000). Two 'neighbouring' backbone nodes may be up to $2r + 1$ hops away. A distributed scheme for initiating is based on selecting, repeatedly, a node with maximal number of unassigned r hop neighbours as backbone nodes, and assigning all its r hop neighbours to that node. We observe that this is, in fact, a well-known clustering algorithm (Lin and Gerla, 1997) generalised to r hops. The maintenance of cluster structure is known to require significant communication overhead (for instance, local changes may cause global updates by chain effect) (Gerla et al., 2000; Wu and Li 2001). A significantly better backbone structure, one that does not require any communication overhead and provides connectivity between nodes, is described in Wu and Li (2001), and can be also generalised to r-hop case. Nodes in virtual backbone are database servers for location information. They define a quorum system, which is a set of subsets such that any two subsets intersect in small number of preferably constant number t of databases. Each subset then has the same size k. In Haas and Liang (1999b) the choice of subsets is uniform and is performed by applying a centralised balanced incomplete block design algorithm. The selection of these subsets at random was discussed in Haas and Liang (1999a). When a node moves, it updates its location with one subset containing the nearest backbone node. Each source node then queries the subset containing its nearest backbone for the location of destination, and uses that location to route the message. The routing algorithm is not discussed in Haas and Liang (1999a,b) and Liang and Haas (2000). It can be easily observed that location updates, destination searches are not local, and that they involve routing between backbone nodes. Thus backbone nodes must exchange their location information in order to perform their duties. It is not clear whether subset querying or backbone node communication can be done more efficiently than by flooding all nodes. Taking the entire overhead into account, it is not clear whether the whole routing algorithm will perform better than a simple flooding algorithm, with redundant retransmissions eliminated (roughly half nodes suffice to retransmit to achieve reliable flooding) (Stojmenovic et al., 2002). The flooding-based routing algorithm does not require any location updates, requires no quorum-based structure for its maintenance (which, in turn, relies on flooding anyway), and does not require communication overhead for its own backbone structure, which is dominating set as defined in Stojmenovic et al. (2002) and Wu and Li (2001).

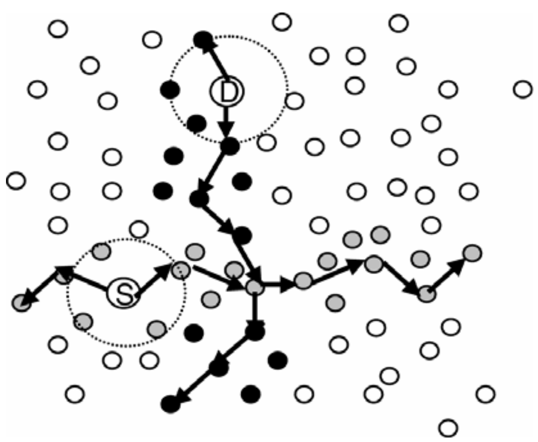
Location update technique that is most relevant to this paper is the home agent-based scheme, which has been independently proposed in Blazevic et al. (2001), Morris et al. (2000), Pei and Gerla (2001), Stojmenovic (1999b) and Woo and Singh (2001). In this scheme, each node selects a home region, known to other nodes, and sends location updates to nodes currently located in its home region. In order to locate destination, nodes send destination search message (or full message in some variants) toward home agent region of destination, and redirect search or message from the region to current location of destination. The main advantage of proposed quorum-based scheme over home agent-based one is its flexibility when all nodes move to new region (in this case, all home regions become empty).

3 Quorum-based location service

To enable an efficient quorum-based location service, mobile nodes should occasionally intelligently update their current location information to a subset of nodes in the network to form an update quorum. When a node wants to communicate with another node whose current location is unknown, it makes a query to a subset of nodes, which form a search quorum. Common node in both update and search quorums provides the location information to the querying node as desired. The challenge is how to collect appropriate members for matching quorums to produce rendezvous with smaller cost.

We propose a novel quorum-based location service for mobile ad hoc networks, and for sensor networks with mobile sinks. The basic idea is that when a node needs to update its location information, it propagates its location information in both north and south directions to reach the north and south boundaries of the network. All nodes that receive the update packet form a north-south column. When a querying node wants the position of the destination node, it first checks whether the location recorded in its database is outdated. If so, the node propagates its search packet in both east and west directions to reach the boundaries. All nodes involved form an east-west row. The search packet is bound to obtain the required location from a rendezvous node between a pair of column and row quorums (see Figure 1).

Figure 1 Quorum construction



There are several options to get the exact location of destination, and they are not the primary goal of this paper. For example, the request, after reaching the ends of the row, can be forwarded to the destination according to the information obtained from rendezvous node. Finally, destination will reply back its accurate location to satisfy the search request. Alternatively, rendezvous node may report back immediately the destination position, if it is clear that the information gained is sufficiently 'fresh'.

In this location service, the overhead of each quorum task is $O(\sqrt{n})$, where n is the number of nodes in the network. The advantage of this method compared to existing solutions is that nodes can announce and find their locations without any sort of flooding or broadcasting throughout the whole network. Also, the method uses relative positions of nodes and thus is suitable for use when all nodes move in the same direction.

4 Location update

We adopt the quorum-based idea to enable efficient routing in mobile ad hoc and sensor networks. Clearly, nodes in ad hoc network do not stay in the same 'column', and the distributed information may easily disperse due to node movement. Moreover, it is not clear what the 'column' is, and how all the nodes in a column, once defined, will receive latest updates. Nevertheless, we believe that this idea is worth pursuing, and much more promising than the one proposed in Haas and Liang (1999a,b) and Liang and Haas (2000).

The basic update procedure is performed by each moving node whenever it observes that, due to its movement, an existing edge will be broken (i.e. the distance between two nodes becomes $>R$). Similarly, the same action may be taken when a new neighbour is detected (i.e. in response to a message arriving from a new neighbour). The availability of geographic position information enables nodes to estimate the connection time with other nodes, as proposed in Stojmenovic et al. (2000) and Su et al. (2000). The connection time is defined as the estimated duration of a connection between two neighbouring nodes. Neighbouring nodes frequently update their location to each other, and this information may be used to estimate the direction and speed of their movements. In turn, this suffices to estimate the connection time. Let A and B be the two neighbouring nodes which move at speeds a and b, respectively. Here, A and B are position vectors while a and b are directional vectors. At time t, they move to new positions $A' = A + at$ and $B' = B + bt$. They loose their connection when the distance between them becomes $>R$, where R is the radius of corresponding unit graph. The time t when the connection will be lost can be estimated by solving quadratic equation $|A'B'|=|B-A+(b-a)t|=R$ (Stojmenovic et al., 2000; Su et al., 2000). Note that this adopted criterion allows nodes to move with the same speed and in the same direction (e.g. a road) without generating any location update message.

In response to the detected broken link, each node A will broadcast a message containing its new location information to all neighbours. In response to newly detected neighbour, neighbouring nodes will reply. Note that nodes do not transmit their location in response to location update received from already existing neighbours, in order to control the overhead, and restrict updates to actions caused by moving nodes.

The main location update method is to forward the new location information (and node's identifier) within a 'column' in the network, in the following way. Each node uses a counter to count the number of previously made changes in edge existence (the number of created or broken edges). When the *counter* reaches a fixed threshold value *e*, location information is forwarded along the 'column', and *e* is reset to 0. Node *A* that reaches threshold value will initiate location update within column as follows. *A* transmits update information to all its neighbours (within transmission radius *R*). The same message also includes location or ID of the northernmost neighbour *B* of *A* (and similarly southernmost neighbour *C*). The selected neighbour *B* will find the *next* forwarding neighbour in the same fashion (but in the north direction only). This search continues until a node *B* has no neighbour that is more to the north than *B*. The initiator of location update *A* sends the update in both directions (dir includes both north and south), while other nodes follow only one of directions. The main location update route, in north-south direction, is created in the process. It consists of all nodes on the route and all of their neighbours. This is refereed to as the column with thickness $p = 1$. This method is used in our experiments. Neighbouring nodes may retransmit to enlarge the thickness to $p = 2$ (some of nodes may not retransmit if an optimisation (Stojmenovic et al., 2002) is applied). The process may continue until arbitrarily selected thickness *p* is reached.

The frequent problem with the scheme is that the northernmost node as determined by the northward update may be only locally northernmost. A 'horizontal' destination search can miss such a node, which can remain 'below' it. To overcome this problem, each locally northernmost node may switch to FACE mode (Bose et al., 2001) until another node, more northern, is found on a face. Such node may return back to regular upward move. The switch between regular and face modes can be repeated few times. The process terminates when the first edge of the outer face in the same *face_time* is about to be repeated. The two ends of the edge are denoted as *farthest_nb* and *farthest_nb_next*. The FACE algorithm can be improved by applying a short-cut scheme (Datta et al., 2002). The final result will be that all nodes at the outer face of the network will receive location update. This method guarantees that 'horizontal' destination search and 'vertical' location update will intersect at one of the nodes on the outer face. The drawback is that these nodes will have more traffic demands. Figure 2 presents the pseudo-code for quorum construction in location update.

Each node receiving new location information for *A*, by means of any of transmissions, will record it, together with date of update. Moreover, each node transmitting any kind of message will include its own location with the message, thus providing an update on its own position to its neighbours within the selected transmission radius.

Figure 2 Quorum construction in location update

```
for eachnode do
  if (counter > threshold e) then
    dir ← {north, south }
    farthest_nb ← this
    GFG(PKT<dir, next, farthest_nb, farthest_nb_next,
          face_time>)
    if (next is found) then
      bcast PKT<dir, next, farthest_nb,
            farthest_nb_next, face_time>

Event handler:
upon receive PKT<dir, next, farthest_nb,
            farthest_nb_next, face_time> do
  if (this = next) then     /*I'm the forwarding node*/
    /*selecting next forwarding node*/
    GFG(PKT<dir, next, farthest_nb, farthest_nb_next,
          face_time>)
    if (next is found) then
      bcast PKT<dir, next,farthest_nb, farthest_nb_next,
            face_time>

Function:
GFG (PKT<dir, next, farthest_nb, farthest_nb_next,
        face_time>)
  local_info ← node n∈ neighbors ∪ {this}
  temp ← u∈ local_info ∧
        u is the farthest node in direction dir ∧
        u is farther than farthest_nb
  if (temp ≠ this) then       /*greedy algorithm*/
    next ← temp
    farthest_nb ← next
    face_time ← first
  else    /*face algorithm*/
    if (face_time = first) then /*first time into face*/
      temp ← u∈ local_info-{this} ∧ u is the
            neighbor with the smallest clockwise
            angle with respect to direction dir.
    else   /*keep in the same face*/
      temp ← u∈ local_info-{this} ∧ u is the
            neighbor with the smallest clockwise
            angle with respect to incoming packet
            direction.
    /*when the first edge of the face is about to
    repeat again, stop face routing*/
    if (farthest_nb=this ∧farthest_nb_next=temp) then
      next=NULL
    else
      next ← temp
      if (face_time = first) then
        farthest _nb_next ← next
      face_time ← follower
```

5 Destination search

The search for destination is performed in the following way. When a source node *S* intends to send data to a destination node *D*, it first checks the location information about *D* in its own database. If the position of *D* is not outdated, actual data is simply transmitted according to this best-known location. Otherwise, the source *S* broadcasts search request among neighbours that are located at most *q* hops away, where *q* is another network parameter. If destination is $q + 1$ hops away, it will be located (the destination could be neighbour of a node *s* hops away). The search messages always carry the location of sender (and time), and nodes receiving the information will update sender's location in their tables.

If there is no reply, the search continues in east-west direction, in similar way as for the location update (i.e. easternmost and westernmost neighbours will extend the search in corresponding directions). The search message includes time of last available information, and other nodes are requested to provide more up to date information, if they have. This process proceeds as follows. Let *A* be a node of east-west search route. If *A* has more recent information about *D*, it will replace it in the message. The information is then forwarded in given direction (eastward or westward) to furthest possible neighbour, and forwarded similarly until a node is reached that has no neighbour followed in east or west direction. Figure 3 provides the pseudo-code of quorum construction in destination search.

When easternmost and western most nodes are reached, the search strategy changes. The message search is then oriented towards the destination, using the latest available information for each search message. There are three searches initiated. The first one originates at sender node *S*, using the best information collected within the neighbours at most *q* hops away. This search does not need to wait for the result of searches in the east and west directions. The other two searches are initiated by easternmost and westernmost nodes in a given 'row'. Each of the three search tasks follows a path towards destination, using *greedy* strategy (Finn, 1987; Stojmenovic and Lin, 2001) or *GFG* (Bose et al., 2001) (to guaranty process continuation). That is, at each step, the neighbour closest to destination is selected to forward the message. Since any of the messages between two nodes can be heard by all nodes within the radius *R*, if any of them has a better information about destination, it may respond, and the new information will take precedence over the former one in forwarding decision. Note that the location of source node is updated at each node that hears any of destination search or path creation messages.

We now illustrate the extension that guarantees the intersection of 'row' and 'column' using an example in Figure 4. The 'Row' *SUV-SW* constructed by destination search from *S*, and 'column' *DJ-DF*, constructed by location update by *D*, do not intersect. They are constructed by applying the described greedy mode in east/west and north/south directions. This means that the constructed quorums are of insufficient size and do not meet general criteria for guaranteeing the intersection. However, the row/column end nodes *V*, *W*, *J* and *F* may switch to the boundary mode, and extend their search and update following GFG algorithm (Bose et al., 2001) with destinations set at infinity nodes in east, west, north and south directions. Node *V* applies face routing *VUQKT* until reaching node *T* that is located east of *V*, meaning that the recovery was achieved and construction may continue in greedy mode. Note that recovery can be also called earlier, at node *Q*, since it has neighbour *T* that is to the east of *V*. From *T*, greedy routing continues eastward *TGEHA* until reaching another local maximum in the east direction. Node *A* is not aware of its global east position until face routing along outer boundary, initiated at *A*, returns back to *A*. This means that nodes on the outer boundary (indicated by 'heavy' bold lines) are part of any quorum. Face routing uses edges of planar Gabriel graph, indicated by 'normal' bold lines. The unit graph in Figure 4 consists of all indicated edges. The plane is divided into faces. All but one of them is closed, and the only open face can be used as the resource for sharing the information.

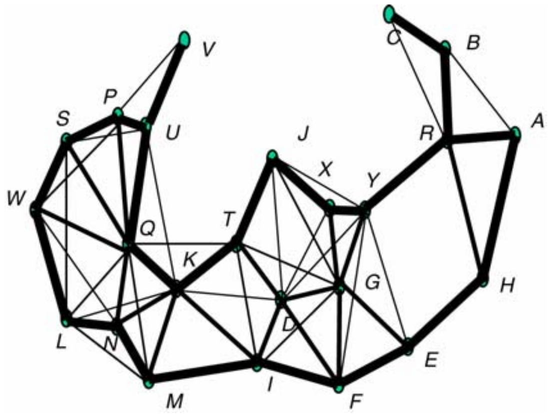
Figure 3 Quorum construction in destination search

```
locate (destination D_id)
 if (database[D_id] = NULL ∨ is outdated) then
   dir ← {east, west}
   search[D_id] ← database[D_id]
   farthest_nb ← this
   GFG (PKT<dir, next, farthest_nb, farthest_nb_next,
          face_time>)
   if (next is found) then
     bcast SEARCH<search[D_id], dir, next,
             farthest_nb,farthest_nb_next,
             face_time>

Event handler:
upon receive SEARCH<search[D_id], dir, next,
             farthest_nb, farthest_nb_next,
             face_time> do
  /*if information of D in search packet is fresher, update
  the information in database*/
  if (search[D_id] is newer than database[D_id]) then
    database[D_id] ← search[D_id]
  if (this = next) then     /*I'm the forwarding node*/
    /*if information of D in database is fresher, update
    the information in packet */
    if (database[D_id] is newer than search[D_id]) then
      search[D_id] ← database[D_id]
    /*selecting next forwarding node*/
    GFG (PKT<dir, next, farthest_nb, farthest_nb_next,
           face_time>)
    if (next is found) then
      bcast SEARCH<search[D_id], dir, next,
              farthest_nb, farthest_nb_next,
              face_time>
Function:
GFG (PKT<dir, next, farthest_nb, farthest_nb_next,
       face_time>)   /*provided in   Fig.2 */
```

Since *F* could be a local maximum, the location update should continue from it. Suppose that the outer boundary is to be followed in clockwise direction. Node *F* switches to the boundary node, and finds neighbour *I* (among all GG neighbours *I*, *D*, *G* and *E*) with the smallest clockwise angle with respect to the south direction. The receiving node *I* similarly finds the neighbour with the smallest clockwise angle $\angle FIM$, with respect to incoming packet direction *FI.* Node *M* then forwards to neighbour *N* having the closest clockwise direction with respect to direction *MI* among GG neighbours of *M* (thus *L* is ignored). Finally, when packets arrive at node *F* again, the update operation terminates. This is because the following edge *FI* is the first edge of the outer face that will be reached twice. Therefore, the boundary follows *LWSPUVUQKTJXYRBCBRAHEF* in Figure 4.

Figure 4 'Row' SUV-SW and 'column' DJ-DF, and outer boundary in 'heavy' bold lines



The elegance of the proposed method is that it is adaptable to 'surprises' along the route. Consider, for example, the node *J* as the one switching to face mode. It forwards the packet to neighbour *X* with the closest direction with respect to the north direction. It is then forwarded to *Y* and *R*. Node *R*, however, is north of node *J* and may switch back from the face mode to the greedy mode, then forward packet to *C* (all neighbours considered) etc.

We now prove that the proposed quorum-based location service, supported by GFG, can guarantee destination search so long as source and destination are connected, and the impact of mobility is eliminated.

Theorem: *The quorum-based location service guarantees to obtain most up-to-date location information of destination, if the source and destination nodes are connected and the network is static.*

Proof: In the quorum-based location service, location update is propagated along north (south) direction, applying Greedy-Face-Greedy algorithm. Since nodes only have local information, the target of face routing is assumed to be at the infinite north (or south, respectively) direction. Thus after reaching the northernmost (and/or southernmost) node, message will be still propagated along the outer face of the network, and be dropped upon return to the first edge of that face (i.e. between the first and second visit to the northernmost node, message will visit all boundary nodes). Note that if destination is disconnected from source, they will have distinct outer boundaries. Therefore, all nodes located along the unique outer face containing both source and destination nodes serve as location servers for the network. In fact, it suffices that only these nodes memorise the locations of all nodes from the network.

Later, location search is propagated along east (and/or west) direction in the similar way. It will also go through all nodes along the same outer boundary according to GFG algorithm. The search quorum can obtain the most up-to-date information after comparing data along common outer face. The Theorem is then proved.

Note that both quorum constructions, one towards the east and one towards west, will continue traversing outer boundary. This implies almost doubling the communication overhead with respect to a version that will only follow quorum construction in the east direction. The overhead can be reduced if only one of destination search or location update follows the outer boundary, while the other is not needed at all. In fact, during the quorum construction that searches easternmost node, the westernmost, northernmost and southernmost nodes may also be discovered. In order to propose reactive algorithm, we suggest that location update messages stop at the first recognised outer boundary node, without following the boundary. This, however, is possible only if outer boundary is stable.

Since nodes on the boundary may move and thus loose their status, a mechanism is needed to transfer the location database to one of remaining outer boundary nodes when moving nodes loose such status. This can be achieved by transmitting location database upon moving out of boundary, with information being picked up by all neighbouring nodes. The thickness of the boundary may also be increased to increase method reliability. This assumes a good mechanism for recognising border status of nodes following local changes, other than full face traversal.

Finally, the protocol also needs to handle node mobility between two location updates. The destination search will reach the area where node was located when it last initiated 'column' location update. Therefore, moving node needs to maintain 'connection' with nodes remaining in that area. The best method may depend on the size e of 'breakage' counter. Reactive protocols being preferred, we suggest that the node closest to reported destination position initiates geocasting up to distance of e hops. That is, all nodes up to distance of e hops from it will receive the destination search message. The parameter can be increased for better reliability.

6 Variants of quorum-based location service

We consider here several variants of quorum-based location service, for both greedy only and greedy-face-greedy quorum construction methods. They have different tradeoffs between communication overheads and success rates. We describe four strategies to construct quorum system.

1. Column for location update, row for destination search, denoted by $C + R$.
2. This is the basic quorum method used in location service. Node updates its current location along the column in north-south direction, using greedy only routing. When other node searches the destination, it sends retrieve packet along the row in east-west direction by greedy only routing. In our experiments we adopt $p = q = 1$.
3. Both columns and rows are used for location updates and destination searches, denoted by CR + CR.
4. To increase the member of quorums, location update and destination search can be performed on both column and row, that is, in both north-south and east-west directions. There may be two sets of rendezvous between update and search quorums generally, increasing the probability of finding quorum intersections since greedy only routing is applied in their construction. We compare this variant with others in the experiments. Another option is to perform location update and search in two arbitrary but mutually orthogonal directions. Moreover, they can be executed in four different lines, such as row, column and two lines at angles $\pi/4$ between them, in order to produce more rendezvous between quorums.

5 By applying GFG method, update and search packets are transmitted along north-south and east-west directions, respectively. Since GFG is applied for both update and search, it is denoted by CF + RF.

6 Quorums can be extended to reach the extreme points of network when GFG (Bose et al., 2001) is triggered when packet forwarding stops at the local maximum. Face routing will increase communication overhead, because all the hosts located in the perimeter have to be involved. However, such overhead is inevitable if we need to guarantee success in quorum-based protocol.

7 By applying GFG method, update and search packets are transmitted along north only and east only directions, respectively. It is a new variant of strategy CF + RF and denoted by CF + RF(N).

Since Face routing guarantees packets to traverse the outer perimeter of the network, we can further reduce communication overhead by performing update and search in only one direction. Specifically, location updates are going along north only direction and search packets are going along east only direction. Both are forwarded by GFG. The searches and updates are guaranteed to meet on the common outer boundary (see Theorem).

7 Performance evaluation

7.1 Simulation

In this section, we will study the performance of quorum-based location service through the simulation. Four strategies ($C + R$, CR + CR, CF $\pm$ RF and CF + RF(N)) are introduced to construct different quorum system. The simulation compares their performances to show the different tradeoffs. The performances of all protocols are measured in two metrics. Success rate is the probability of the existence of at least one rendezvous node between update and search quorum, or equivalently the probability of successful delivery of data packets to the destination. Communication overhead is the number of nodes required to forward update or search packets when the extreme points of the network are arrived. Since the costs of update and search operation in the four strategies are similar, we only measured the cost of update operation in diagrams.

We studied the case of static networks, in order to verify the methods effectiveness under ideal circumstances, and to provide proof of concept. We use the simulation programs written in C++ program language to evaluate the performance of the service in an ideal network environment. We assume the unit disk graph model with the transmission radius R. Two network parameters are varied over a wide range: the number of nodes in the network (N) and the average node degree (k) to address the scalability issue.

The simulation is conducted in a 100 × 100 2D by randomly placing N nodes. First, we fix $N = 500$, while changing k from 8 to 20. The corresponding value for transmission radius R is calculated as follows (Stojmenovic and Lin, 2001): sorting all possible edges and choosing R to provide exactly $nk/2$ edges. Then we set $k = 10$, the number N of nodes is varied from 100 to 500. In each run of the simulations, for given N and k, we randomly place N nodes in the square, and randomly pick two nodes (one sending location update and the other destination search). All unconnected topologies are discarded. We present average of 100 separate runs for each result shown in Figures 5–8.

Figure 5 Success rate versus node degree

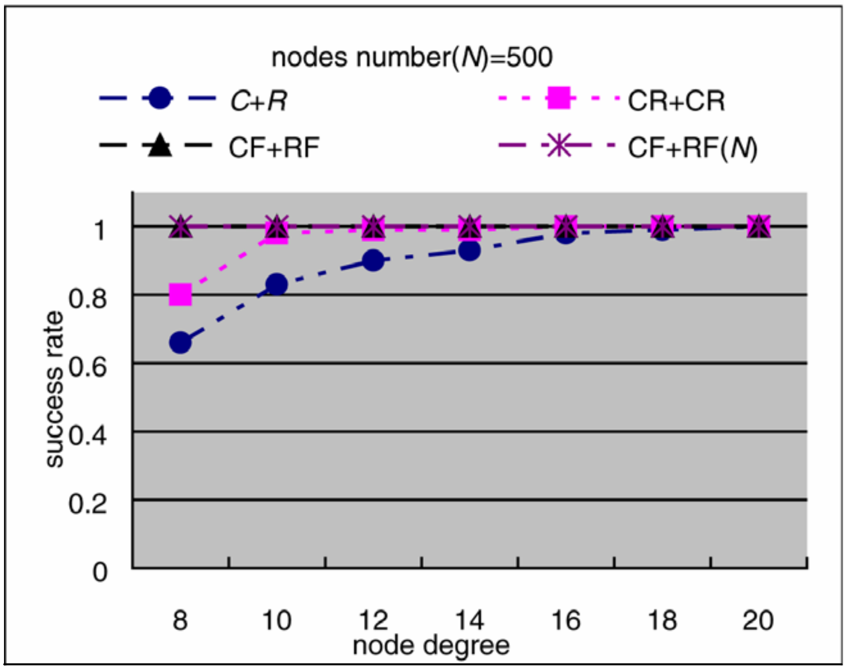


Figure 6 Success rate versus nodes number

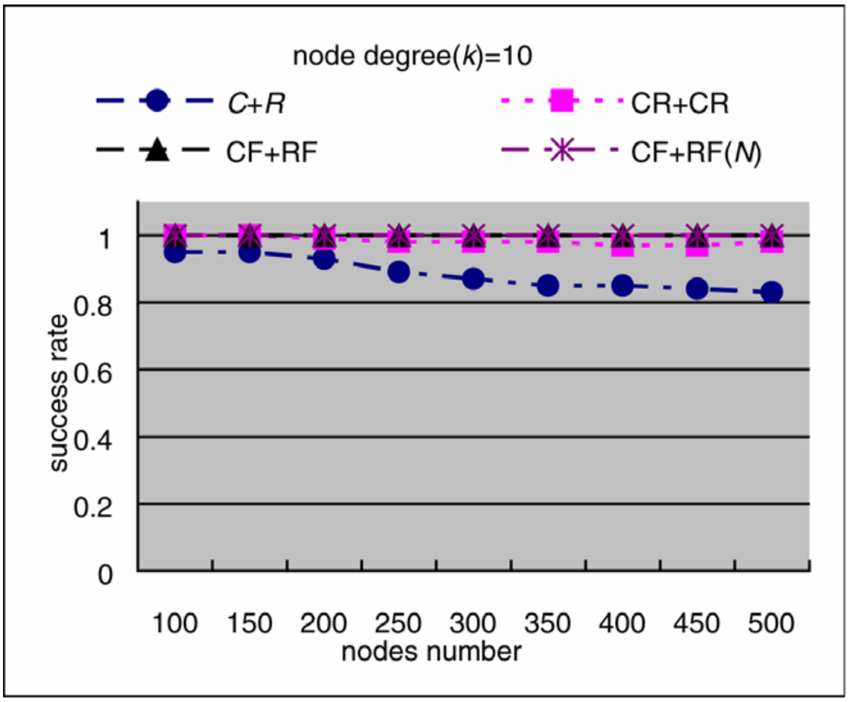


Figure 7 Update messages versus node degree

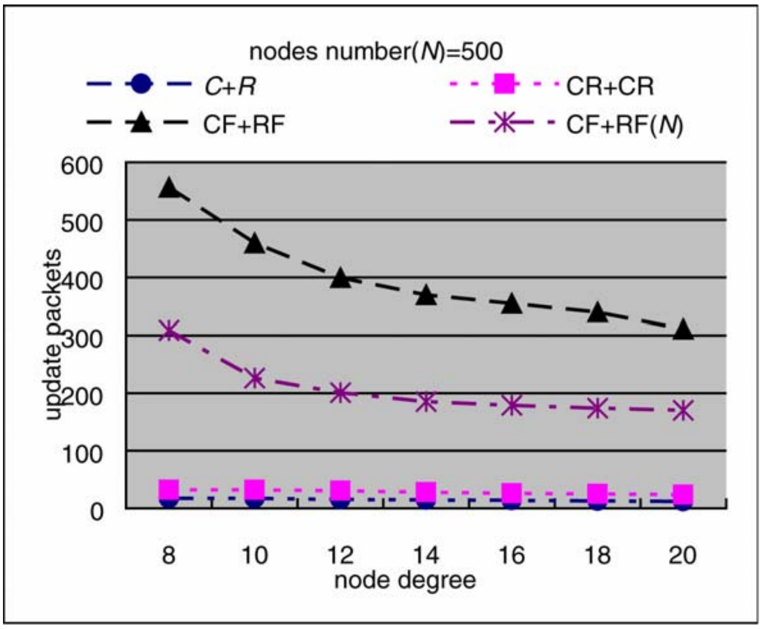
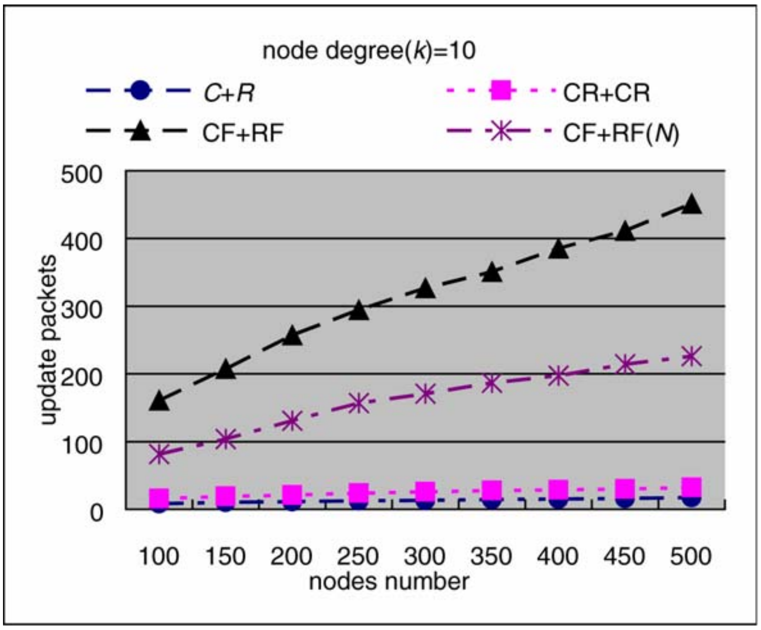


Figure 8 Update messages versus nodes number



CF + RF and CF + RF(*N*) guarantee the successful data delivery to destination. The destination is set to be an infinite node with respect to given directions. Since there is no path to that destination node *D*, the packets will eventually traverse the outer face containing the *D* without detecting a face providing progress towards *D* (Frey and

Stojmenovic, 2006). Because both update and search packets traverse the same perimeter of the network, those nodes located on the outer perimeter can be interpreted as location servers where two quorums intersect.

Figure 5 shows that the success rates of $C + R$ and CR + CR increase as node degree k increases. Figure 6 shows that the success rates of $C + R$ and CR + CR drop when N increases.

We show the communication overhead of location service by four strategies in Figures 7 and 8. The number of nodes involved to forward update packets by the strategy CF + RF is quite high. This is because face routing requires many forwarding nodes. It is executed on the Gabriel Graph that always chooses short edges along a face. The number of forwarding nodes required by the strategy CF + RF(N) has similar tendency. But the number is only about half of that required by CF + RF, because packets are transmitted along only one direction. Figure 7 shows that the number of forwarding nodes required by both CF + RF and CF + RF(N) decreases as k increases. Figure 8 shows that the number of forwarding nodes required by CF + RF and CF + RF(N) increases as N increases.

7.2 Simulations by other researchers

Several papers have already given comparisons between quorum-based location service and some other rendezvous-based location service, such as hashing (home agent) based ones. Das et al. (2005) gave performance comparison among three location services through analysis and experimental evaluation. The three protocols are Column-Row Location Service (XYLS), Grid Location Service (GLS) and Geographic Hashing Location Service (GHLS). XYLS is similar to our quorum-based one except not using face routing as recovery strategy.

They concluded that GLS, a hierarchy hashing-based location service, benefits from maintaining a hierarchy when the source and destination nodes are close to each other, since the query traversal can be limited to the lower levels of the hierarchy. But the GLS has a very high complexity of maintaining a hierarchy of grids and the consequent maintenance due to nodes moving across grid boundaries. The scalability of GLS is not as good as for the other two. They also claimed that XYLS exhibits near perfect load balance because, regardless of where the nodes are, their updates and queries are sent across the network along the x- and y-dimensions. Although XYLS has high protocol overhead in static networks as the network scales, the overhead stays roughly the same in a mobile network. As a result, XYLS provides better performance in terms of overhead than GLS in a mobile scenario. Finally, they claim that GHLS, an extreme case of flat hashing-based location service, outperforms the other two in both protocol overhead and success rate.

However, the authors in Mauve et al. (2001) concluded that the flat hashing-based location services that use the concept of home zone have two main drawbacks. Firstly, if the home zone is sparsely populated, the zone radius may have to be increased. Secondly, a node may be hashed to a distant home agent, leading to increased communication and time complexity, as well as problems if the home agent cannot be reached.

Compared to the other location services, our quorum-based location service has many unique features. Firstly, by applying GFG method, the successful data delivery to destination can be guaranteed. Secondly, the overhead of each routing task is controlled at $O(\sqrt{n})$. Finally, the protocol is applicable when all (or a subset of) nodes move in more or less the same direction (e.g. rescue team or soldiers). Because when nodes are moving together towards new area, the relative positions of nodes are not changed, which helps to avoid frequent location updates and maintain quorum members.

8 Follow-up and future work

In this paper, we proposed a quorum-based location service in wireless ad hoc and sensor networks. Node registers its location along a 'column' to form an update quorum. Other node makes a query to the nodes along a 'row' to form a retrieve quorum. The intersection between the update and retrieve quorum provides the location. There is trade-off between the system consumption and success rate of location accessing. GFG (Bose et al., 2001) may be applied to guarantee the intersection between update and search quorums.

Our location update scheme works well even if nodes move together to a new area (e.g. group of vehicles or soldiers). The columns and rows defined in our location update scheme are relative, not absolute. It also adapts well to synchronous node movements (such as vehicles on a highway), keeping mutual distances but moving at high speed. In this case, the edge disconnection is predicted based on estimated node position, using their reported speed and direction of movement.

After the technical report (Stojmenovic, 1999a) version of this paper, a number of other relevant papers on location service were published in literature, and we mention few of them. Basic row-column quorum-based location service presented in this paper was named in several subsequent papers (e.g. Chen et al., 2006; Jiang and Ling, 2007) as XYLS protocol.

In Ziviani et al. (2002), it is proposed to send the initial packets of a flow to learn the position of their destination instead of adopting a dedicated query packet. Nikaein and Bonnet (2002) proposed to rely on multiple location servers replicated on several geographic positions. The distribution of location servers and the destination search follow an Archimedean spiral. Cheng et al. (2002) proposes also to use multiple home regions, but distributed uniformly over the area in which the nodes move about.

In Dolev et al. (2003) a sophisticated geoquorum system for implementing atomic memory in mobile ad hoc networks is proposed. In Bhattacharya (2003), two quorum-based schemes are presented. In the first scheme, node selects k other nodes, connected to it, at random for either queries or updates. However, it is not clear how this selection can be made with local knowledge only. In the second scheme, a node initiates a random walk of length k, for either query or update. In quorum-based scheme (Lee et al., 2003), node also selects k connected other nodes at random to dynamically form a quorum of size k. The efficiency of the method is not clear since selected nodes may move, and an efficient method (other than flooding) to find one of them is needed.

An application of quorum-based protocol is given in Niculescu and Nath (2003) as follows. 'Generalising an idea presented in Stojmenovic (1999a), a replacement scheme using trajectories is as follows: possible destinations (servers S) advertise their position along arbitrary lines and clients C will replace their flooding phase with a query along another arbitrary line which will eventually intersect the desired destination's line. The intersection node then notifies the client about the angle correction needed to contact the server directly. In order to guarantee that the server and client lines intersect inside the circle with diameter CS, it is in fact necessary for the nodes each to send in four cardinal directions'.

Melamed et al. (to appear) describe Octopus location service scheme. Octopus divided the network area into horizontal and vertical strips, and stores the location of each node at all the nodes residing in its horizontal and vertical strips. A single packet updates the location of many nodes at many other nodes. While the number of messages is reduced, each message becomes longer and thus overhead reduction is questionable. The other difference with quorum-based system described here is the division into grids and propagation within grids. However, in low-density scenarios, this reduces the change of propagating in desired directions. Finally, the movement of individual nodes to new grids may still require individual location updates. Comparison is done with GLS.

Li and Santoro (2006) proposed a distributed zone-based sensor relocation protocol, ZONER, for mobile sensor networks on the basis the quorum-based technique in this paper. ZONER is able to effectively discover previously-deployed redundant sensors without being concerned with obstacles or network ununiformity, and it relocates them in a shifting way to replace failed non-redundant ones without changing network topology. In ZONER, each redundant node registers itself with all the non-redundant nodes inside a vertical *registration zone* across the entire network; when a node fails, its specified neighbours inquire all the non-redundant nodes inside a bounded horizontal *request zone* for redundant nodes; because the request zone intersects with a number of registration zones, the non-redundant nodes in the intersection areas can provide the requester with redundant node information. Face routing (Bose et al., 2001) is applied similarly as in this paper to deal with void areas.

A quorum-based distributed and efficient information dissemination and retrieval system for wireless sensor networks has been described by Liu et al. (2006a,b). It is also enhanced by face routing (Bose et al., 2001) to guarantee the success.

Sarkar et al. (2006) describe a location service scheme that makes use of mapping from plane to three-dimensional sphere and applying quorum-based analogy on diameter circles of that sphere, thus guaranteeing their intersections.

Liu et al. (2007) gave a generalisation of basic quorum-based strategy. Their 'comb-needle' discovery support model resembles an ancient method: use a comb to help find a needle in sands or a haystack.

The basic quorum-based location service was enhanced by different type of backbone, obtained when network is partitioned into equal size squares, and one server was selected in each square (Zhang et al., to appear). The main advantage is that the overhead caused by location updates was controlled by restricting them to border crossing events. However, when grid leaders move outside their grid, significant message exchange was needed to elect new leader. When all nodes move in a certain direction, this overhead appears quite unnecessary. We are developing an alternative scheme using connected dominating sets as backbone instead of leaders in a grid division.

Jiang and Ling (2007) proposed SEEKER location service based on aggregate update, which integrates a group of position updates. Network is divided into grids. Position updates are aggregated and forwarded in the east and west directions. Location queries are sent in north and south directions.

One of the 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 (Amouris et al., 1999), 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).

Unsuccessful searches for destination may be converted into full flooding at termination nodes, if guaranteed delivery is required, and nodes have high mobility rates such that presented methods become unreliable. If this event occurs very rarely, it should have no significant impact on communication overhead. In case of frequent failures, the quorum-based strategy may need further improvements. At very high speed, it may not be possible to do anything better than flooding, as observed in Ho et al. (1999). We also believe that any location update method, no matter how clever it is, will only work well up to a certain speed limit. Nevertheless, it remains a challenge to push that limit as far as possible, with a loop-free and scalable method that does not resort to flooding, too often.

We believe that quorum-based idea for routing in ad hoc networks has the potential to be very efficient, in terms of small hop counts, almost guaranteed delivery, and small communication overhead, compared to other existing schemes. It is expected that the candidate methods will be compared in future with a common simulator and appropriate medium access layer.

Acknowledgements

This work was supported by a grant from Research Grants Council of Hong Kong (No. CityU 114505), NSF China Grant (No. 60633020), the UK Royal Society Wolfson Research Merit Award and NSERC Canada Strategic Grant 33406.

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