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Quorum and connected dominating sets based location service in wireless ad hoc, sensor and actuator networks

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Abstract

Location service provides position of mobile destination to source node to enable geo-routing. In existing quorum-based location service protocols, destination node registers its location along a 'column' while source node makes a query along a 'row'. Grid and quorum-based location service is based on division of network into square grids, and selecting 'leader' location server node in each grid. Location updates, leader reelection and information transfer are performed whenever destination and leader nodes are moving to a different grid. We propose here to apply connected dominating sets (DS) as an alternative to grids. We also improved basic quorum, and applied on DS-quorum (DS based quorum) better criterion for triggering local information exchanges and global location updates, by meeting two criteria: certain distance movement and certain number of observed link changes with (DS) nodes. Backbones created by DS nodes (using 1-hop neighborhood information) are small size, do not have a parameter like grid size, and preserve network connectivity without the help of other nodes. Location updates and destination searches are restricted to backbone nodes. Both methods use 'hello' messages to learn neighbors. While this suffices to construct DS, grid leader (re)election requires additional messages. Simulation results show that using DS as backbone for quorum construction is superior to using grid as backbone or no backbone at all. The proposed DS-quorum location service can achieve higher (or similar) success rate with much less communication overhead than grid-based approaches.

Keywords: Location service; Connected dominating sets; Backbone; Ad hoc networks; Sensor networks

1. Introduction

We consider two basic scenarios in this article. Mobile ad hoc networks 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 nontrivial since node mobility causes frequent unpredictable topological changes. Location-based routing [14] 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 absolute location through the use of GPS or relative location with a collaborative protocol [2]. Location-based routing problem consists of two complementary tasks, location service (that comprises of location update and location retrieval), and routing data traffic from source to a destination whose location is known. We focus on addressing the first task in this paper. Because of frequent mobility, the approximate location of a destination should be identified before efficient data routing could be accomplished. Mobile nodes should register their current position with a 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

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at developing energy efficient location service, so that routes between source and destination can be found.

Traditional protocols (see [16] for a survey and references) deal with location service using flooding-based methods, which involves all nodes, located inside a region, in data accessing. Large amount of interchanges among nodes will consume considerable energy and even cause many collision problems at MAC layer. The problem becomes even more difficult when nodes are mobile. The first path-based location update service is 'home-agent' based (see [16] for an overview and references). It does not properly addresses group movement, since nodes rely on absolute coordinates e.g., by applying a hash-based function that maps each node to its 'home', with an absolute address. When the whole group moves, 'home' becomes remote and unaccessible. To overcome those deficiencies, [15] proposed a quorum-based location service in 1999. 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 found at the intersection between the update and search quorums. Several strategies were proposed to adjust the quorum system. To guarantee the success of location retrieval, both search and update quorums are extended by face routing [4] which traverses outer network boundary. In the sequel we will only discuss quorum-based location services.

One of observed drawbacks of the original quorum-based location service is the performance in dense networks, as too many nodes become involved in processing requests, and outer faces contain too many short edges. This problem was addressed recently in [13,22] by proposing the network division into equal size squares, and selecting one 'leader' node in each square to participate in the backbone. Quorum-based location service then continues mainly on the backbone nodes. Other nodes may be used to connect backbone nodes. The main advantage is that the overhead caused by location updates was controlled by restricting them to border crossing events. However, this frequently used grid division approach for constructing backbones has some drawbacks. Grid partitioning can disconnect the originally connected network, as discussed and illustrated in [18]. Further, the choice of square size for partitioning is a parameter to be tuned, and studies show that all choices have weaknesses. Finally, nodes need to learn exact grid boundaries they belong to, which requires additional overhead and adds to imprecision problems. 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, since relative node coordinates may not change at all. In fact, a closer look at group movement with fixed grid boundaries reveals an 'exploding' overhead as all nodes constantly change grids and grid leader reelection is constantly ongoing even without any data traffic.

We propose here to apply a different backbone concept which does not have listed drawbacks. It is based on connected dominating set (DS) construction [7,5,18,21]. We propose a scalable and energy efficient quorum-based location service based on this DS concept, which has further advantages. In the proposed service, a connected dominating set (DS) is first created as backbone for quorum construction. Each node decides whether or not it is a dominating node by a self-pruning scheme [7,5,18,21]. All the location update and destination search operations are made upon the nodes that belong to the constructed DS. Specifically, we propose an enhanced variant that has better performance than all the variants in [12], called CRFCRF. In this variant, both columns and rows are used for location updates and destination searches. Face routing is applied when packet forwarding stops at the local maximum. Face routing causes large communication overhead, because all the nodes located in the perimeter have to be involved. To save energy, we apply a *stop-duplicate forwarding policy* to avoid the redundant packets transmission by same nodes (see details in Section 4).

Our new DS based quorum method addresses drawbacks of grid and quorum-based location service methods [13,22]. The CRFCRF variant achieves very high success rate since each update and search quorum system is constructed along four orthogonal directions by GFG [4] protocol, while communication overhead can be controlled at a low level by the *stop-duplicate forwarding policy*. It is adaptive to group movement scenarios, since all decisions are made based on relative rather than absolute coordinates. Nodes react to topological changes rather than to change in their absolute coordinates. For instance, when all nodes move in a certain direction synchronously then DS based solution does not require any messages and updates (relative network structure remains unchanged). If they are aware of planned movement then even 'hello' messages are not required (until a deviation from planned movement occurs). This then does not change DS set and invokes no backbone maintenance messages. On the other hand, grid-based solution invokes significant amount of control messages each time any leader crosses grid borders which are tight to absolute coordinates. Thus DS backbone and quorum-based location service preserves the main advantage of basic quorum-based method originally proposed in [15], handling efficiently group mobility scenario with low overhead, while grid-based approaches 'loose' it. Additionally (like in grid-based approaches), DS and quorum-based approach handles location service and routing around void areas and preserves path rather than flooding-based searches.

We simulated the proposed service in scenarios with both static and mobile sensors/nodes and destinations. The performance of the proposed quorum and DS based location service, CRFCRF, is assessed by comparing with grid-based Anchor Location Service (ALS) [22], proposed for static sensor networks with mobile sinks, and Octopus [13], proposed for mobile ad hoc networks. Since we wanted to study only the impact of DS vs grid as backbones, ALS and Octopus are slightly modified so that there are no other differences in the protocol. For instance, ALS applies face routing in both directions around void areas, while here it follows strictly GFG [4] suggesting traversal in only one direction. Octopus applies an aggregation technique and end nodes initiate the location update for the whole row by appending information to a single packet, while here it doesn't use aggregation and individual node will send update packets along its horizontal and vertical strip when the update criterion is met. In addition, performances are compared between the original quorum system [15,12] without backbone and with quorum system obtained by DS or replaced DS by grid partitions, using the same variants as in [12]. The results demonstrate that the proposed quorum-based location service based on DS provides more energy efficient and scalable service than location service enhanced by grids.

The rest of this paper is organized as follows. Section 2 gives the literature review. Section 3 describes the new DS backbone based quorum location service protocol. We list several variants for construction of quorum and backbone based location services in Section 4. Section 5 presents the simulations results. Finally we conclude this article and give the future work and references.

2. Literature review

In a *localized* algorithm, each node makes the decision to which neighbor(s) to forward the message based solely on the local information it obtained by using simple beacon message, such as the location of itself, its 1-hop neighborhood information, and other fixed amount of additional information (e.g., destination position for routing). Localized algorithms avoid communication overhead of distributed solutions that need global knowledge, including position and activity status of all nodes.

While the network model for proposed quorum and backbone based location service can be arbitrary, the simulations are based on the widely adopted unit disk graphs (UDG). UDG is defined by $G = (V, E)$, where V represents the set of sensor nodes in the network and there is an edge $e = (u, v) \in E$ between nodes u and v if and only if the Euclidean distance between them $\|uv\| \leqslant R$, where R is the transmission radius, equal for all nodes.

2.1. Routing

We briefly describe position based routing schemes that are used in this article. In the *greedy* method [8], node currently holding packet will forward it to the neighbor A that is the closest to the destination D. A routing algorithm that guarantees delivery in 2-D UDG is described in [4]. It applies greedy routing until either message is delivered, or a node having no closer neighbor to destination than current node is encountered (called failure node). In later 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 [4] is the Gabriel graph. *Gabriel graph* contains edges between nodes u and v if and only if no other nodes are located inside the circle centered 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 localized message free computation, planarity, and preserving connectivity [4]. Gabriel graph divides the network into faces. The one that contains the line SD, where S is the 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 a node A closer to destination than S is encountered (existence of such a node for unit disk graphs is recently confirmed in [9]). Greedy routing continues from A until delivery or another failure node. Detailed survey on position based routing schemes in given in [14].

2.2. Connected dominating sets

Each node either belongs to a dominating set or has a neighbor in the dominating set. The problem of computing the smallest possible connected dominating set is known to be a NP-complete even if the knowledge of the global topology is available. Dai and Wu [7] introduced a generalized dominating set concept, where coverage can be provided by an arbitrary number of connected 1-hop neighbors. Node A is covered by its 1-hop neighbors $B, C, D, \ldots$ if the neighbors $B, C, D, \ldots$ are connected, any neighbor of A is a neighbor of at least one of nodes $B, C, D, \ldots$ and $key(A) < min\ (key(B), key(C), key(D), \ldots)$. The definition is modified (see [19]) to avoid similar message exchanges between neighbors. It is then further computationally simplified by Carle and Simplot-Ryl [5], as follows. First, each node checks if it is an intermediate node. Then each intermediate node A constructs a subgraph G of its neighbors with higher *key* values. If G is empty or disconnected then A is in the dominating set. If G is connected but there exists a neighbor of A which is not a neighbor of any node from G then A is in the dominating set. Otherwise A is covered and is not in the dominating set. Dijkstra's shortest path scheme can be used to test the connectivity. We have applied this concept to construct DS for quorum-based scheme. Ingnelrest et al. [11] gave an enhanced definition to obtain smaller CDS over the connected graph by using 2-hop topological or positional information. However, such a strategy is not applicable to the networks with constrained resource nodes, such as sensor networks, because too much neighboring information are exchanged via HELLO message. An important property for this backbone is that its construction does not require any communication overhead (after learning neighbors via 'hello' messages) and preserves network connectivity.

2.3. Quorum-based location service

A survey of existing localized protocols for location updates for efficient routing is given in [16]. We will restrict the review only to results directly related to this paper.

Reader may also consult [15] for a survey of other methods for ad hoc networks declared as 'quorum' based. These methods in fact have substantially different notion of 'quorum' which is inefficient when applied to ad hoc networks, as argued in [15].

We now summarize the quorum-based method [15,12] that enables efficient scalable and localized location service in wireless mobile ad hoc and static sensor (with mobile sinks) networks. It relies on multiple location servers replicated on several geographical positions to form a quorum. Nodes report their new positions to their neighbors whenever a link is broken or created. Such link status can be decided by each node according to the geographic position information, as proposed in [17,20]. 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. The process is illustrated in Fig. 1. The intersection of 'row' and 'column' can be guaranteed by adding outer face of the ad hoc network to both of them. This strategy is based on face routing along perimeter of outer boundary of the network. Several variants were described in [12], and we selected the following ones.

2.3.1. C + R

Column location update, *row* destination search. Face routing is not applied.

2.3.2. CF + RF

By applying GFG method, update and search packets are transmitted along north–south and east–west directions, respectively. Quorums can be extended to reach the extreme points of network if GFG [4] is triggered when packet forwarding stops at the local maximum. Face routing will increase the communication overhead, because all the nodes located in the perimeter have to be involved. However such overhead is inevitable if we need to guarantee the success in the quorum-based protocol.

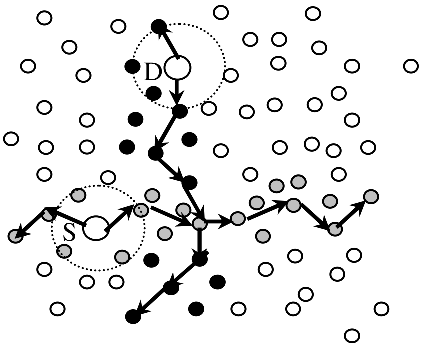


Fig. 1. Quorum construction.

2.3.3. CF + RF (N)

By applying GFG method, update and search packets are transmitted along north only and east only directions, respectively. Both are forwarded by GFG. The searches and updates are guaranteed to meet on the common outer boundary.

2.4. Grid-based quorum location service

Zhang, Zhao and Labrador [22] introduced the Anchor Location Service (ALS), a grid-based location service designed for large-scale wireless sensor networks. A global grid structure is first built as the backbone, and one node in each grid (if any) will be selected as sink location server (anchor). The anchor selection process is achieved by means of propagating anchor setup messages by the sink along four orthogonal directions (North, South, East and West). Intermediate nodes between two neighboring grid nodes will relay the setup messages and only the recruited anchors store and retrieve the active sink location. A similar method, called Octopus, but applied to mobile ad hoc networks, is given in [13]. Octopus divides the space into horizontal and vertical strip. Each strip's end nodes initiate the location update. Location of each node will be updated at both its horizontal and vertical strips. In addition, Octopus applies aggregate updates. The locations of all nodes along the strip will be appended to the packet and stored at all nodes in the same strip. The construction of anchor system in [13,22] is similar to the construction of quorum system proposed in [15,12]. We will now elaborate on differences. ALS [22] uses both right-hand and left-hand rules when setup message encounters the border or a void area. While in Octopus [13], the bypass mechanism forwards the packet to a node that is in the same direction but in an adjacent strip. These differ from [15,12] where face routing by only one of the rules is applied to route around void areas. The main differences are in the triggering mechanisms. In the original quorum-based system [15,12], destination nodes count the number of topological changes with their neighbors and send updates along their columns when the count reaches a threshold value. In some scenarios, nodes in quorum-based service [15,12] may be active in small local neighborhood, thus triggering global column updates unnecessarily. In grid-based methods [13,22], such updates are instead triggered whenever destination node enters new grid, regardless of other topological changes. This is a better method for described scenario. The other difference is in information transfer mechanisms. In grid-based methods [13,22], when a leader node changes its grid, new leader is elected for the grid, and the destination location information is transferred to the new leader. Thus during the destination search the information that is searched remains in given row. This mechanism does not exist in quorum-based method [15,12], where mobile nodes (or sleeping sensors) may do not remain available at given location to inform about destination location, when required.

Grid-based quorum approaches have some drawbacks. Grid leaders alone do not preserve network connectivity [18]. Thus update and search messages should be sometimes relayed by other nodes, which then do not store necessary information. If the intersection of row and column is at such node, the destination information is not found because it was not stored there. Thus the overall design has additional problems to be studied. Neither of the papers [13,22] deal with this problem. Second, the choice of square size α for partitioning is a parameter to be tuned. In ALS, if α is large, the space will be divided into fewer grids, each of which will take more area. Thus the message exchange within each grid will be large. Moreover, since fewer grid nodes are selected, the location information can only be stored at fewer servers, which will reduce the rate for successful destination search. But if α is small, since the setup packets have to go through each grid node along the direction even if multiple grid nodes are within one transmission radius, more grid nodes will be selected as anchors, thus making more hops while routing for update or search purposes. Similarly, in Octopus, the strip width ω should be carefully tuned. As presented in [13], setting $\omega = R$ can reduce the per node packet and byte complexities while it does not reduce the reliability compared to choosing $\omega \leqslant \frac{\sqrt{3}}{2}R$. Next, nodes need to learn exact grid boundaries they belong to, which requires additional overhead and adds to imprecision problems. Further, grid leader selection requires each node to send and receive additional messages. To select grid leaders, every node must compare its location with location of nearby candidates, and the 'winner' must announce its decision.

3. Backbone based quorum location service

One of drawbacks of the original quorum-based location service [15,12] is the performance in dense networks, as too many nodes become involved in processing requests, and outer faces contain too many short edges. We address this issue here by proposing to apply DS concept of backbones.

A connected dominating set (DS) is first constructed on network G. Each node decides whether or not it is dominant. Nodes exchange 1-hop neighbor information through HELLO messages periodically. To achieve a better performance, we configure the key of a node u as follows: $Key(u) = \{degree(u), energy(u), id(u)\}$. This means that nodes with higher neighbor degree have a larger probability to be selected as dominant. In static sensor networks, the construction of DS is done at the beginning and is maintained only when sensors change activity status from sleeping to active and vice versa (periodically, every ΔT time). However, mobility imposes more challenges for maintaining such backbone structure. According to the local information, each node determines periodically whether or not it is a dominating node by the scheme every ΔT time (that is, whenever a new series of hello messages are sent). The selection of optimal maintenance interval ΔT is tricky, as it depends on local and global mobility and stability. The status change may occur long before ΔT expires. Therefore we opted for additional local reevaluation based on creation and breakage of links of considered node with current backbone nodes. The topology change counter *BThre* is first fixed. Whenever a dominating node oversees a change in its backbone status that is over the *BThre*, neighbors are informed by a message. The node as well as all its direct neighbors updates their backbone status immediately. Link status evaluations can be made any time appropriate information is available, such as observing topological change based on direction and speed of movement, or reception of message from neighbor with piggybacked position information, or a round of hello messages.

During the update procedure, only dominating nodes are considered as candidates for message transmission and information storage. This is different from the anchor system construction in [13,22], in which all nodes are candidates for message propagation. The advantage of using only backbones instead of all nodes along paths is that intersections of row search and column update paths is guaranteed to be in backbone node having stored information. The path lengths can be increased because of restriction to backbone nodes. However, the experiments in [6] show that this increase is not significant. Note that non-DS nodes could be used on path since neighboring backbone nodes may overhear messages and store the information or respond. However, they may also have collisions at the same time, while acknowledged communication avoids this problem. Thus backbone nodes are used for forwarding messages for every hop in our location service scheme. This in general reduces the number of hops. Note that non-backbone nodes may even temporarily sleep to preserve energy, while preserving overall functionality. This is not possible in grid-based approaches [13,22].

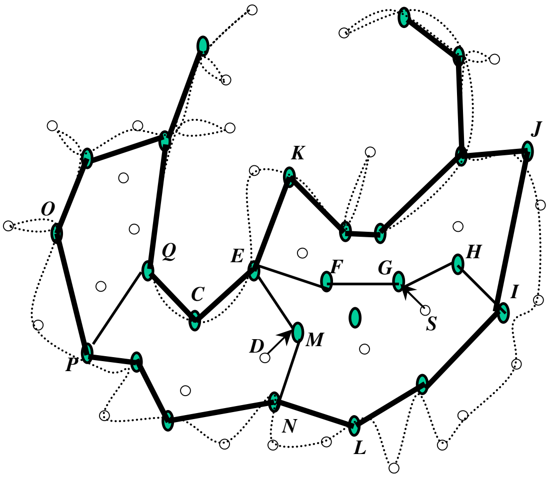


Fig. 2. Update and search with or without backbone nodes.

After selecting (or self-selecting) backbone nodes, the details of quorum-based location service become identical to its original scheme, as elaborated in [15], and reader can find them there. The difference is that only backbone nodes participate. Fig. 2 gave an example to illustrate this point, showing path with and without applying backbone enhancement. In Fig. 2, all solid (green) nodes indicate backbone nodes, and all hollow (white) nodes including source S and destination D indicate regular nodes. We first explain the DS based quorum location service. The destination search from S is forwarded along the 'row' '*SGHIJ-SGFECQPO*' and location update by D is forwarded along the 'column' '*DMEK-DMNL*' (indicated by bold lines). The 'row' and 'column' are constructed by applying the greedy mode in east–west and north–south directions until reach the border of the network. If face routing is applied, the row/column end nodes J, O, L and K will switch to the boundary mode, and continue to extend their update/search following GFG algorithm [4] with destinations set at infinity nodes in east, west, north, south directions. Since only backbone nodes are considered as candidates for forwarding, the update/search packets will traverse the outer boundary of DS as indicated in the 'heavy' bold lines in the figure, and all the green nodes along the line will be recruited as location servers.

As a comparison, the route of the inefficient face routing in the original quorum system presented in [12] is also shown in Fig. 2 (in short dash curve). Since all nodes can participate in the forwarding, the overall system overhead will be considerable large. The impact of face routing on the consumption is the most. Because face routing always uses short edges among nodes from the Gabriel Graph, the perimeter of the entire topology will be gone through, and those boundary nodes will have more traffic demands. Apparently, the route is much longer. Thus using backbone as an enhancement for quorum construction can significantly reduce the consumption caused by perimeter transmission (the route is in heavy bold line compared with the short dash curve). It can also improve the storage usage of the network, as fewer nodes need to record the information.

We now discuss additional details for completing this scheme. The original quorum-based scheme applied certain number *Thre* of topological changes (links made and broken) with neighbors as signal for destination nodes to trigger global updates. In our new technique, that can be conveniently named DS-quorum, this counter is again applied, but only with respect to nodes that are known to be backbones. In addition, to account for a drawback of basic quorum scheme, one more criterion is added (both criteria must be satisfied). Node should also move certain distance *Dist* away from its original location. This can be applied in both static sensor networks, and mobile ad hoc networks, including group mobility to new area. We adopt the $Thre = 8$ (the number counts both when an existing edge is broken and when a new neighbor is detected) and $Dist = R$ (transmission radius) in the experiments.

The grid-based methods have also the advantage of transferring information to new grid leader from the current leader when the later moves out of the grid. Similar mechanism would be desirable in case of DS backbone replacing grids, since, in mobile networks, the information stored in location servers may be easily lost due to nodes' absolute or relative movement. The criterion for information transfer may be the same one applied for triggering global updates. However, applied thresholds for distance moved and for number of link changes might differ. Also, the thickness of the information transfer may also be increased to increase method reliability. To take the high mobility into the account, we still use $Thre = 8$, $Dist = R$ as the double criterions for transfer in our experiments. But the transfer starting time is different from the update starting time. To have a fair comparison, the grid-based methods transfers only when the grid leader leaves its current grid and the moving distance is $Dist = R$.

4. Variants of DS and grid-based quorum-based location service methods

Several variants of quorum-based routing protocols are considered in [12]. As presented in [12], the variant CFRFN achieves best performance in static networks. CFRFN transmits update/search packets along only one direction by GFG routing protocol while always guarantee the destination search. We adopt this variant in some groups of the experiments. Since we focus on the comparison of quorum using different backbones, we still use CFRFN as routing protocol in mobile scenarios. While a much higher success rate can be obtained by applying CFRF [12] as the routing protocol.

Moreover, we propose an enhancement to all the variants in [12], called CRFCRF.

CRFCRF: both columns and rows are used for update/search quorum construction. That is the update/search packets are transmitted along four orthogonal directions. To achieve a better performance, a new face routing with *stop-duplicate forwarding policy* is used when greedy fails at local maximum in all directions. When a node is selected as the next forwarding node, it will first check whether it has already been requested to forward this same message before. If so, it will simply drop the packet (called *stop-duplicate forwarding policy*). Under this policy, any message will be forwarded at most $|V| - 1$ times where V is the set of vertices in the network G. Notice that this is different from the original face routing methods in [4,12]. Simulation results show that the protocols achieve very high successful data retrieval in almost all the scenarios with this stop-duplicate forwarding policy. Since location update and destination search can be performed in four directions, north–south and east–west, there are four sets of rendezvous between update and search quorums generally, and the probability of finding quorum intersections can be greatly increased.

We also consider three variants for backbone construction.

(i) *DS*: Dominating set is the backbone. Only dominating nodes are candidates to forward the update packets, as well as store the information. The variant with all nodes forwarding (and only DS nodes storing) has also been tested, but the performance is shown to be inferior (it has lower success rate and more transmission cost than DS-variant).
(ii) *G*: Global grid is constructed as backbone. Only grid nodes are candidates to forward the update packets, as well as store the information.
(iii) *N*: No backbone is used for quorum construction.

Furthermore, the maintenance for backbone includes two options as well:

(i) *D*: Dynamic backbone maintenance with additional inform messages. In DS-quorum, dominating nodes send notice to neighbors and invoke the backbone maintenance mechanism only when current topology change counters are over. In G-quorum, only when the grid leaders change grid, they send notice to neighbors and invoke a new leader competition within the previous and current grid, respectively.
(ii) *P*: Periodic backbone maintenance with beacon messages. In DS-quorum, DS is constructed each ΔT time and according to periodic hello message. In G-quorum, local flooding is used for new leader decision each ΔT time.

Each variant of backbone construction and maintenance options can be combined with the quorum construction protocols, respectively. Specifically, the names for each option are shown in Tables 1 and 2.

The major difference between ALS and Octopus is that in ALS, all nodes participate in packets forwarding but only grid nodes can store the updated information; while in Octopus, all nodes reside in the grid (strip) can forward and store the updated information. Thus, the ALS and Octopus can be also characterized as follow: ALS = G-D-CRFCRF with additional changes in face routing rule and forwarding candidates. Octopus = G-D-CRFCRF with major differences in bypass mechanism and forwarding candidates.

5. Performance evaluation

In this section, we will study the performance of quorum-based location service through the experiments. First, performances are compared between the DS-D-CRFCRF and G-D-CRFCRF (Table 1.1) to show the efficiencies of replacing grid with DS as the backbone, which are constructed dynamically. In addition, we compare the performances of the original quorum system (N-P-CFRFN) with quorum system obtained by DS or by grid partitions (DS-P-CFRFN and G-P-CFRFN) (Table 2.2), with periodically beacon messages applied.

Table 1
With CRFCRF as routing protocol

	N	DS	G	
D	None	DS-D-CRFCRF	G-D-CRFCRF	1
P	N-P-CRFCRF	DS-P-CRFCRF	G-P-CRFCRF	2

Table 2
With CFRFN as routing protocol

	N	DS	G	
D	None	DS-D-CFRFN	G-D-CFRFN	1
P	N-P-CFRFN	DS-P-CFRFN	G-P-CFRFN	2

Four metrics are assessed while varying the node degree and node velocity.

(i) *Success rate*: The probability of the existence of at least one rendezvous between update and search quorums. Since we only focus on the impact of different backbones on quorum construction, i.e., the differences of how update and search quorums are constructed and whether they have intersections or not, the routing protocol used after the quorum intersection for all location services is the same (all use GFG to destination). Thus they will have the same probability to reach the destination after the intersections.
(ii) *Update cost*: The number of transmissions divided by *n*, where *n* is the number of nodes in the network. It measures the average transmissions (trans/node) required to forward update/search packets when the update/search process terminates. Since the costs of update and search operation are symmetric, we only show the results of update operation in diagrams.
(iii) *Maintenance overhead*: The overall overhead of message exchange (pkt/node) to maintain the backbone (DS or Grid) during the whole simulation time. It is closely related to topology change counter *BThre* or square size α.
(iv) *Update times*: How many times the location update is triggered during the simulation period. It is closely related to update thresholds *Thre* and *Dist*, or square size α.

We use the Network Simulator 2 (*ns*-2.30) to evaluate the performance. In order to verify the methods effectiveness under ideal circumstances, an ideal MAC model is used to avoid collisions on physical layer. Two hundred uniformly mobile nodes are randomly deployed in a two-dimensional 1000×1000 m network area.

We evaluate all the performances in both sensor networks and mobile ad hoc networks. The first set of simulation is done with static sensors and static sinks, and all disconnected topologies are discarded. The average node degree d is varied from 10 to 30 in 5 increments. Transmission radius is calculated from d at beginning, and thus is tuned from 89.206 m to 218.51 m accordingly. The entire area should be fully partitioned by the grid edge α. Since the network area is fixed at 1000×1000 m, α is fixed at 200 m as a result.

Then we assess the performances in sensor networks with mobile sinks and ad hoc networks with all mobile nodes. Each moving node uses a "Random Waypoint" model [3], toward a random destination with a constant velocity selected between zero and a maximum speed. After the destination is reached, a new destination will be set and moved towards to immediately. Such behavior will be repeated during the simulation. There is no pause time for the nodes. Each simulation runs for 100 simulated seconds.

The second set of simulations is done with static sensors and few mobile sinks. The moving sink will update its current location throughout the network. First we set node transmission radius $R = 200$ m (to be equal to the square size α). The sink moves toward a random destination with a constant velocity v, v is varied from 5 m/s to 25 m/s in 5 increments. Then we fix the velocity $v = 10$ m/s, the average node degree d is varied from 5 to 30 in 5 increments to explore the scalability.

The third set of simulation is done with all nodes moving with a constant velocity selected during the interval $(v-2, v+2)$, where the average velocity v varied from 5 m/s to 25 m/s in 5 increments. R is fixed at 200 m. Then we vary the d from 5 to 30 and keep the average velocity $v = 10$ m/s.

Each scenario is randomly generated for 3 times in case nodes were very close or very far apart from each other. For the reasons stated in the literature review, we set the grid square size and strip width as $\alpha = \omega = R = 200$ m. Unless otherwise stated, we utilized these parameters in all our experiments.

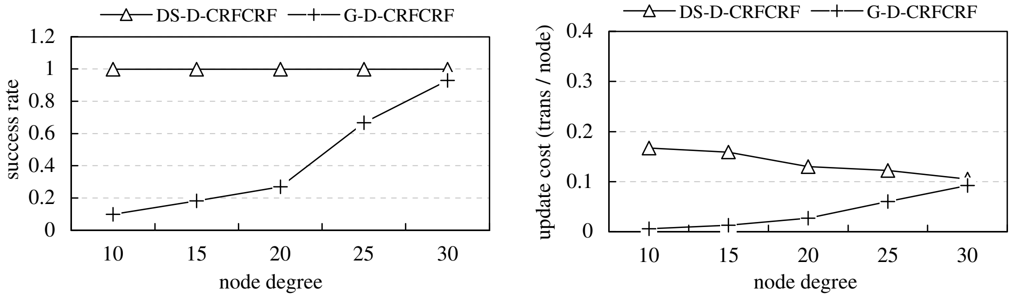
In each simulation scenario, every node sends "hello" message, including 1-hop neighbors' information, every 3 s. The backbone status is checked just after the "hello" process each 3 s. If dynamic maintenance is applied, the backbone update is invoked by only backbone nodes when the criterion is met. In DS-D-quorum, the criterion for maintenance is configured as $BThre = 8$. In G-D-quorum, only when leader changes grid, new leaders in current and previous grids are selected. Otherwise, in P-options, a global backbone are constructed each 3 s without test. Each 6 s, node will check local information before deciding for an update, starting at 35 s. The two criterion for update mechanism in DS-quorum are configured as $Thre = 8$, $Dist = R$. If using grid as backbone, the update will be triggered if node changes grid and moving away from current position by more than R distance. We also use the transfer mechanism to increase the success rate. Only backbone node checks whether to invoke the transfer each 6 s. The criterions are set as that used for update. Three CBR (Constant Bytes Rate) connections are randomly generated. Each source node tries to send one packet with a 512 byte data payload each 6 s, starting at 44 s. If the source does not have the current location of the destination, it initiates a location search. Each point drawn in the diagrams below is an average of 30 trials, with 95% confidence intervals.

5.1. Simulation with static sensors and static sinks

5.1.1. Efficiencies of using different backbones

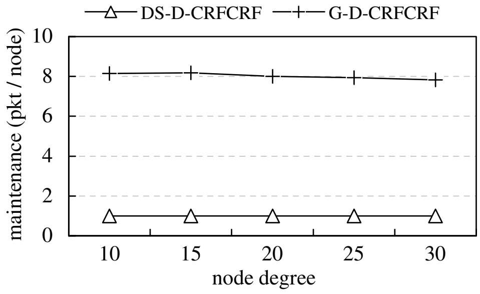
We compare the proposed DS based quorum location service DS-D-CRFCRF with grid-based quorum location service G-D-CRFCRF, in static case in Fig. 3. CRFCRF is used as the strategy for quorum construction. As expected, the DS-D-CRFCRF achieves 100% success rate while each node requires less than 0.2 transmissions in the average (Fig. 3(a) and (b)). Since the backbone is always connected, DS-D-CRFCRF can always guarantee the destination search in the sensor networks with all static nodes. Note that although the update cost of G-D-CRFCRF is less than the DS-D-CRFCRF at first, it increases as degree increases, and finally exceeds DS-D-CRFCRF whose cost decreases as degree increases. The different tendency is due to the different connectivity. Increasing degree means increasing transmission radius. It yields a smaller DS (according to CDS definition). Moreover, DS-CRFCRF only chooses the furthest one of the backbone nodes as next forwarding node in each transmission. Thus when nodes have more neighbors, the number of hops to the extreme of a direction can be reduced. However, in grid-based strategies, the backbone can frequently partition the network. Therefore, packets will be easily dropped before reaching the border. When the connectivity of grids increases as degree increases, the quorum construction in each direction can be extended further. Thus more grid nodes can be collected as quorum members for location retrieval. It suffices to increase the success rate as a result.

Note that although the update cost of DS-D-CRFCRF is a little more than that of G-D-CRFCRF, the cost in backbone maintenance is much less and only about 12.5% of the latter. The dynamic backbone maintenance overhead is presented in Fig. 3(c). It shows that to maintenance a global grid, each node will send about eight packets during the simulation time. It can be explained mathematically by the size of square area and network density. The average network density in our simulation is $D = \frac{200}{10^6}$ node/m^2, while each square area size is $A = \alpha \times \alpha = 200 \times 200$ m^2. Thus about $D \times A = 8$ nodes exist within one square. Since nodes are stationary during the simulation period, each node requires backbone maintenance only once. This is a much more communication overhead comparing to only one packet for constructing DS. It is because to select grid nodes, every node must compare its location with all nodes within the four small squares around the grid point. Moreover, the neighboring grid nodes must exchange information with each other to update the neighbor grid node table periodically, so that the global grid information stored in each node is able to keep consistent. Apparently, if the square size α increases, the maintenance will be larger. The number is almost independent of node degree, thus the curve fluctuates little with the degree in the figure. On the contrary, DS maintenance broadcasts only one packet to inform all neighbors at the



(a) success rate

(b) update cost



(c) maintenance

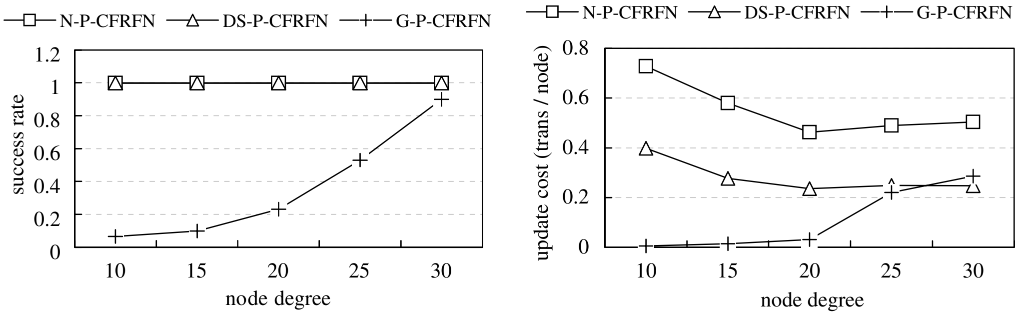
Fig. 3. Performance of DS-quorum and G-quorum vs node degree *d*.

initial time. This is a significant energy savings for wireless ad hoc and sensor networks.

5.1.2. *Efficiencies of quorum and backbone based quorum methods*

Fig. 4 shows the difference of original quorum without any backbones as addition to using DS or grid as backbone. Since in static networks, variant CFRFN is the best choice because it guarantees the destination search while the communication overhead is almost half of the cost by variant CFRF (proved in [12]), the three location services all use this routing protocol for the quorum construction in the simulation in sensor networks. Additionally, original quorum method uses only the periodic beacon message to route packets, thus we just change the method to DS-quorum and G-quorum while still use beacon message to construct the backbone. The average node degree is varied from 10 to 30. The connectivity of each topology is verified with corresponding transmission radius.

As stated in Fig. 4(a), both the N-P-CFRFN and DS-P-CFRFN can guarantee the location retrieval, while the success rates of the G-P-CFRFN are much lower. This is because quorum-based location service can achieve a superior performance when quorum system is constructed upon a connected topology. N-P-CFRFN stores information in all nodes that are connected. In DS-P-CFRFN, message information is only stored in backbone nodes. Since the selected DS can always preserve existing connectivity, there will always exist at least one rendezvous between the update and search quorums. However, when using grid as the backbone, the backbone nodes may easily be disconnected from each other due to the configuration of square size α and transmission radius R. Thus the location of destination may be stored without the reach of the search quorum. In addition, packets are more likely dropped due to



(a) success rate

(b) update cost

Fig. 4. Performance of quorum with or without backbone vs node degree *d*.

the link broken. But when node has more neighbors, it has more alternatives which help increasing the probability of finding a backbone one. Therefore, the success rate of G-P-CFRFN increases as degree increases.

As we can see from Fig. 4(b), the update cost by the DS-P-CFRFN is much lower than the N-P-CFRFN without any backbones. This is because only backbone nodes, which are subset of all nodes in the networks, are considered as candidates to forward message. Although the G-P-CFRFN involves the least transmission cost, it is at the sacrifice of lowest success rate.

The maintenance for the three location service can be analyzed as follows. The N-P-CFRFN has no backbone overhead. DS maintenance requires no extra message exchange among nodes. Each node only use the information from "hello" message to be self-pruned from the dominant set, and use the next "hello" message to make an announcement to neighbors. While the G-P-CFRFN uses periodic about eight packets to maintenance the grid. The overall overhead is closely related to the interval of backbone re-construction. To avoid confusion with the overall cost when dynamic maintenance is applied, we do not show the diagram here.

5.2. Simulation with static sensors and few mobile sinks

5.2.1. Efficiencies of using different backbones

In this section, we consider the sensor networks with only few sinks moving around the area with constant speed $v = 10$ m/s. As sink moves, it will intelligently update its current location to inform other nodes reside in the network.

The increasing in average node degree improves the success rates of both DS and grid-based quorum location service. When degree rises up, each update process will collect more backbones as servers to store the information as more nodes are involved in each 1-hop broadcasting during the update. The improvement in G-D-CRFCRF is more obvious, while it can hardly success when node has few neighbors.

Fig. 5(b) shows that the transmission cost of G-D-CRFCRF increases much when degree increases. This is because when d increases, a node has more neighbors and more choices to select one of them to be the next forwarding node. Thus each direction can be extended much further. As a result face routing is more likely to be triggered on the outer boundary, on which more and more nodes will be added to the quorum as well. On the contrary, DS based location service has a counter-effect. As degree increases, fewer and fewer nodes will be selected as backbone nodes (according to the definition of DS). Moreover, since DS-D-CRFCRF applies stop-duplicate forwarding policy, nodes will not transmit the same packet more than once, the cost can be controlled.

The curves in Fig. 5(c) are similar to that in Fig. 3(c). When only sink moves, most nodes reside in each square keep in the same place during the simulation time. There is few chance for leaders to cross the grid, thus the dynamic maintenance is hardly invoked after the initiation.

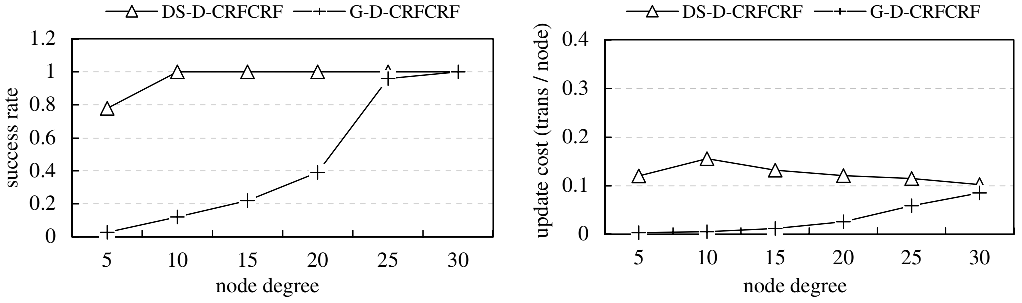
The impact of node degree on the update times of different backbones in such scenarios is also investigated and the results are presented in Fig. 5(d). It can be observed that both DS-D-CRFCRF and G-D-CRFCRF send updates less frequently as node degree increases. Moreover, using DS as backbone incurs fewer number of update times. This thanks to the double criterion for update. To invoke an update, the sink should at least move away from current distance by more than $Dist = R$ m. Obviously, when R increases as d rises up, such criterion is harder to be met. Note that the update chances of DS-D-CRFCRF is quite small when degree $d = 5$. This is mainly because of the other criterion. DS-D-CRFCRF updates when the number of link change with only backbone nodes is about to reach the threshold *Thre*. When degree is small, the sink has little dominating neighbors. Thus the link changes rarely. This is also in accordance with intuition. When a node gets more neighbors around, there will be more information given to network and more chance of finding the destination. Thus fewer times of update are needed.

We also study the impact of average sink velocity on the performance of DS and grid-based quorum location service in Fig. 6. As we can see from the figures, the DS-D-CRFCRF achieve 100% success rate when sink moves from 5 m/s to 25 m/s. This is because the scenarios only have few sink moves around the network. The backbone constructed upon the network is not changed much and thus preserves connectivity. It is also the reason for the little changes in update cost and maintenance overhead as sink moves. However, the success rate of G-D-CRFCRF decreases badly when sink moves faster and faster. The reason is that the location information stored in location servers is easily out of date to the movement. More importantly, mobility imposes more challenges for maintaining grids connectivity when the grids easily partition networks in itself. Thus the constructed quorums are of insufficient size and do not meet general criteria for guarantying the intersection, which in turn results in fewer transmission cost.

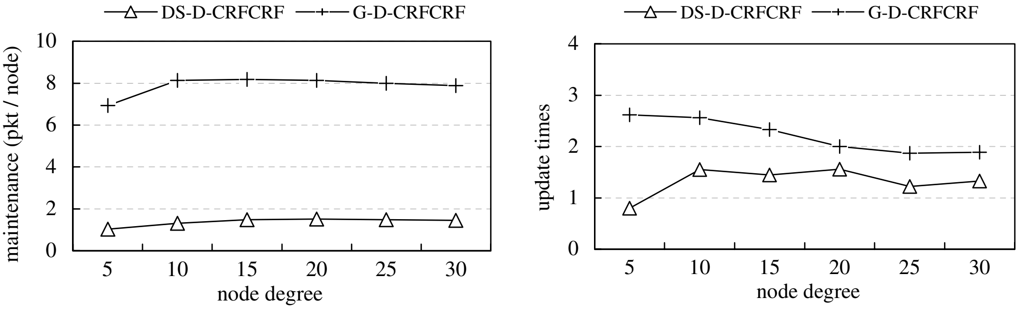
It is shown when nodes moves faster, the updates are triggered more frequently in Fig. 6(d). This is intuitive. The higher speed nodes are moving with, the more frequently it needs to send out its current location to inform other nodes in the network. But the total round is controlled below 4 times, since there are double criterions to check the update.

5.2.2. Efficiencies of quorum and backbone based quorum methods

In this section, we also looked at the performance of quorum with or without backbones when sinks are moving at the constant velocity 10 m/s. Since most nodes in the network are stationary, the curves of success rate and update cost (Fig. 7(a) and (b)) under the quorum location services with DS or grid as backbone have similar tendencies with that in Fig. 5(a) and (b), even though different

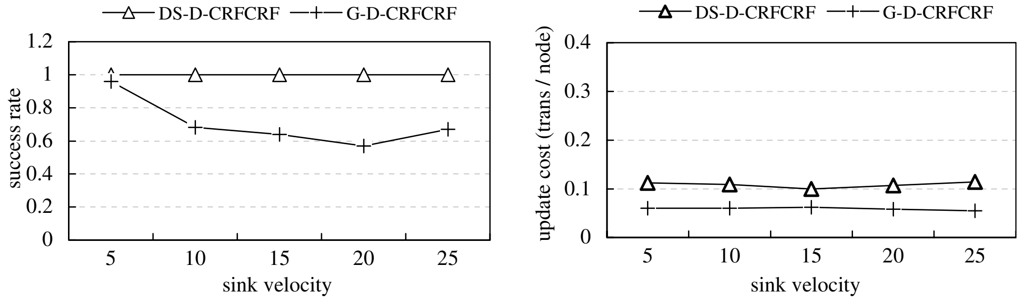


(a) success rate (b) update cost

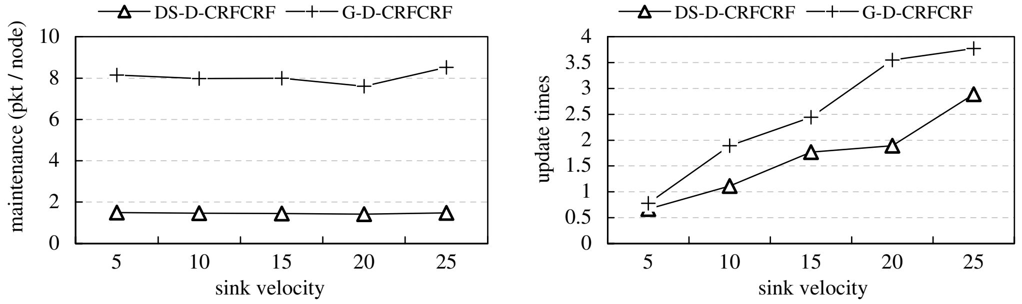


(c) maintenance (d) update times

Fig. 5. Performance of DS-quorum and G-quorum vs node degree d, sink $v = 10$ m/s.



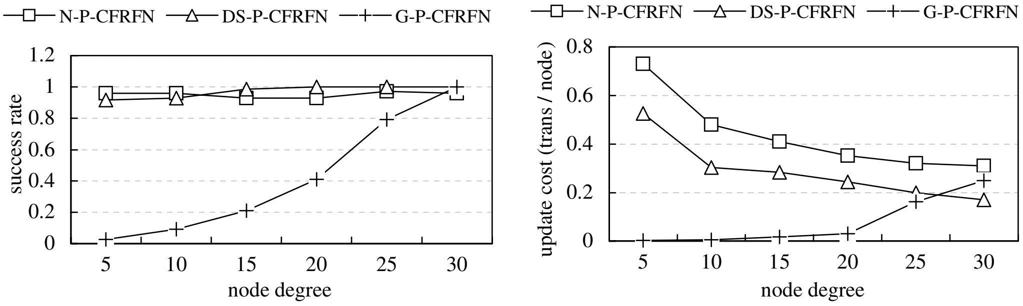
(a) success rate (b) update cost



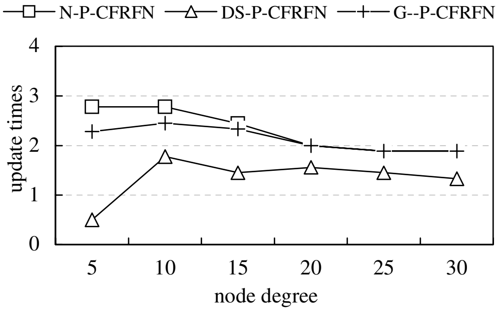
(c) maintenance (d) update times

Fig. 6. Performance of DS-quorum and G-quorum vs sink velocity v, $R = 200$ m.

protocols (CRFCRF and CFRFN, respectively) are applied. This indicates that the backbone selection has more crucial effect for quorum-based location service than routing protocols. Note that the N-P-CFRFN has almost the same success rate with that of DS-P-CFRFN, while the update cost and update times (Fig. 7(b) and (c)) is the most of the three. This is because in backbone based services, all packets are transmitted by only backbone nodes that are subset of all nodes in the networks. Moreover, the neighboring link changes in update triggering mechanism counts number of link with merely the backbone nodes that does not depend much on density. When losing the backbone, all the criterions should count on all nodes in the network.



(a) success rate (b) update cost



(c) update times

Fig. 7. Performance of quorum with or without backbones vs node degree d, sink $v = 10$ m/s.

Fig. 8 is to evaluate the impact of sinks mobility on backbones. The transmission radius is fixed at $R = 200$ m. The G-P-CFRFN is influenced badly by the mobility, even when the global grid is constructed periodically. Although the update cost in G-P-CFRFN is little lower than that in DS-P-CFRFN, it is because of the unsuccessful quorum extension. The DS or grid-based services has similar curves as in Fig. 6. But due to the backbone properties, the N-P-CFRFN obtains almost the same success rate with much higher update cost than DS based one.

Given the results from Figs. 3–8, we conclude that the performance in sensor networks with few mobile sinks is similar to that with all static nodes.

5.3. Simulation with all mobile nodes

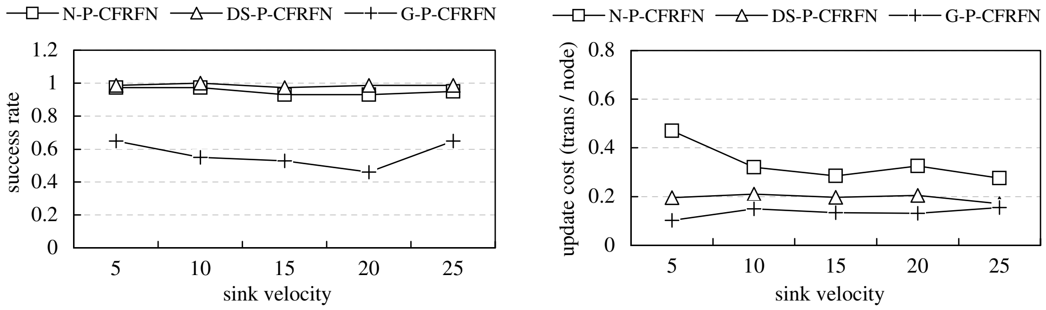
All results presented so far consider our base scenarios where most nodes are stationary in the sensor fields. In order to test the performance in a network with frequent topology changes, we run several simulations where all nodes are move with high mobility.

5.3.1. Efficiencies of using different backbones

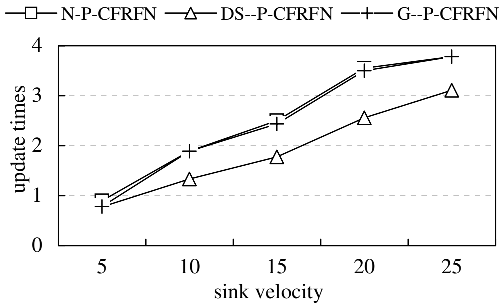
Fig. 9 shows the performances of quorum-based location service with different backbones in the mobile cases where nodes are moving at the average velocity $v = 10$ m/s. The success rate of strategies DS-D-CRFCRF increases as degree increases, and reaches almost 100% quickly, while the success rate of G-D-CRFCRF is much lower. The curves are similar with the one in Fig. 5(a) but with a little drop due to nodes mobility.

All the curves in Fig. 9(b) increase as node degree increases. On one hand, when node degree increases, node has more neighbors and more choices to select one of them to be the next forwarding node. Thus each direction can be extended much further. On the other hand, FACE algorithm only terminates when the same face is about to arrive the second time. As nodes move, if they have more neighbors, the routing has more chances to change face. Thus the FACE algorithm may traverse more faces before it terminates. Note that the grid-based one cost less, but at the sacrifice of lower success rate.

We investigate the maintenance overhead of using DS or Grid as backbone during the simulation period in Fig. 9(c). In DS-D-CRFCRF, the backbone maintenance is invoked dynamically according to the link changes where only links to backbone neighbors are counted. Although there are more chances to switch neighbors when degree increases, we only count the link change with backbone nodes. While in G-D-CRFCRF, the maintenance is triggered when grid leader changes grid. Thus both of the change does not depend much on nodes degree. So the curves in Fig. 9(c) do not fluctuate much. But the G-D-CRFCRF requires much more overhead to maintain the global grid. This is because in DS-D-CRFCRF, when dominating nodes finds that the link change is over the threshold, it only needs to send one packet to direct neighbors. The node, as well as all its neighbors will announce their backbone status by just appending 1 bit to the next hello message. In G-D-CRFCRF, when grid leaders change grid, they will send a packet to neighbors too. However, a restricted flooding will be called up within its current and previous grids to

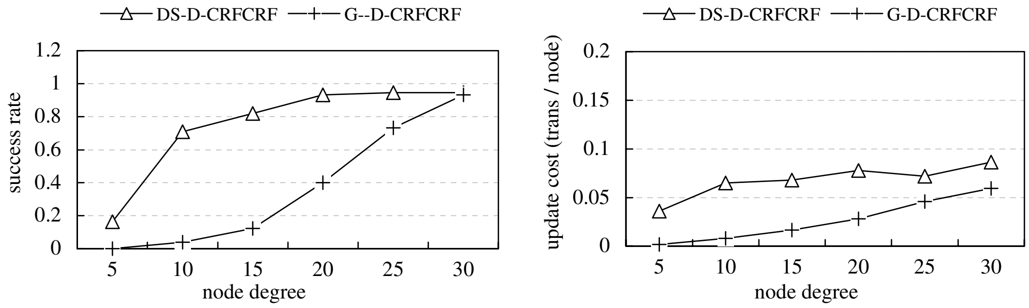


(a) success rate (b) update cost

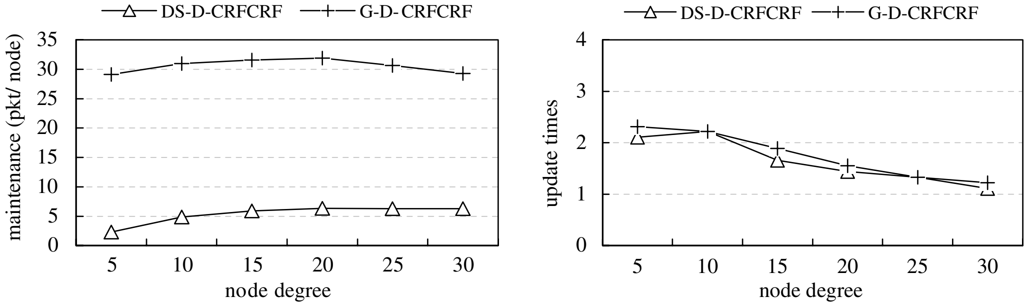


(c) update times

Fig. 8. Performance of quorum with or without backbones vs sink velocity v, $R = 200$ m.



(a) success rate (b) update cost



(c) maintenance (d) update times

Fig. 9. Performance of DS-quorum and G-quorum vs node degree d, $v = 10$ m/s.

compete for the new leaders. The message exchanges during the flooding will take significant consumption.

The update times of using DS or grid as backbone is similar and decreases as degree rises up. This is because of the parameters used in the double criterion for invoking update. When nodes move at a fairly high speed, the transmission radius becomes the major criterion for update. So long as the moving distance is more than R, the other threshold is bound to arrive. When R increases as degree increases, the criterion becomes harder to meet.

We also studied the impact of high mobility rate on different backbones when $R = 200$ m. The rate of DS-D-CRFCRF achieves almost 100% and drop little as nodes move faster in Fig. 10 (a). This is because the location information of neighbors in node's table may be out of date due to the movement. The packets may be sent to a neighbor that is already out of the sender's transmission range, leading to an undesired packet loss. When the velocity increases, the packet loss increases. As a result, update/search routing is more likely to terminate before extending to the end of the column/row, which decreases the probability of intersection of update and search column. Luckily, since all services store the location information along four orthogonal directions and face routing that achieves very high date delivery rate is used, the decrease is not obvious. However, as G-D-CRFCRF uses the grid as backbone, the frequent topology changes impose high difficulty to provide a connected backbone. It incurs a high probability of search failure as the result.

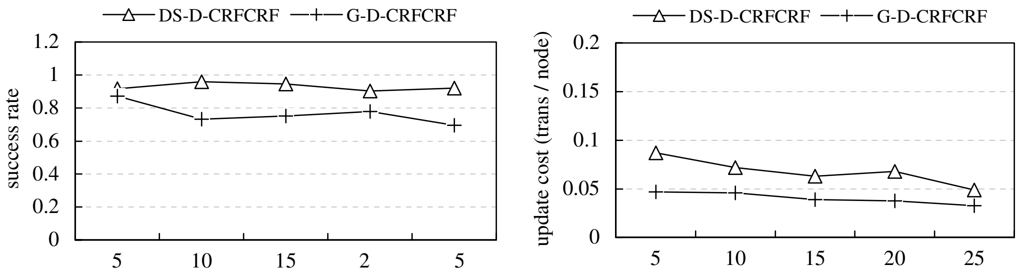
In Fig. 10(b), the number of update packets decrease as node velocity increases. The packets are likely to be sent to a nonexistent neighbor due to the movement, so the packets will be dropped in advance.

In Fig. 10(c), the maintenance overhead of G-D-CRFCRF increases rapidly as velocity rises up. This is because when nodes move faster, it will cause more events of border crossing by leaders. Thus more rounds of backbone maintenance are invoked. As there are flooding within two squares, the overhead increases multiply. But in DS-D-CRFCR, nodes only count the link changes with dominating neighbors. Since the number of such link is quite small, even when nodes move faster, the number of the link changes including new link detection and previous link breakage can only slowly arrive at the threshold *Thre*. Granted that maintenance is invoked, there will be only one packet by 1-hop broadcast. Thus the DS maintenance is influenced little by the nodes mobility.

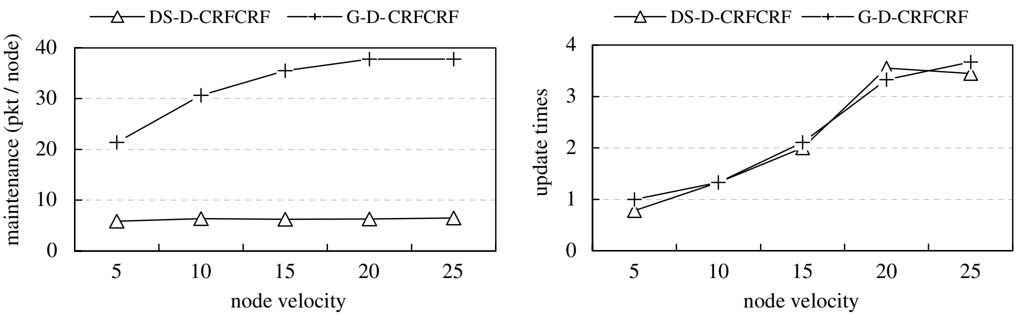
In Fig. 10(d), all services invoke the update procedure less than 4 times during the 100 simulated seconds. This is also because of the parameter used in criterion. The threshold of the counting to the number of neighbors *Thre* and the moving distance *Dist* can be tuned to adjust the update times.

5.3.2. Efficiencies of quorum with or without backbone

As we can see from Fig. 11(a), the success rate of DS-P-CFRFN is a little higher than that of N-P-CFRFN. This is because when periodically update the backbone status according to the beacon message, most dominating nodes in the DS are connected. As degree increases, the topology is more and more likely to be connected as a consequence. Moreover, the success rate of destination search increases as degree becomes larger. While by N-P-CFRFN, since the nodes for packets transmission are selected from all nodes, the connectivity of the entire topology may be disturbed due to the high mobility, the quorum system constructed upon such topology may have no intersection as a result. Note that grid-based strategies has much lower success rate and can rarely retrieve location when degree is smaller than 15, even when the backbone is constructed periodically. This is due to its unconnected backbone characteristic.

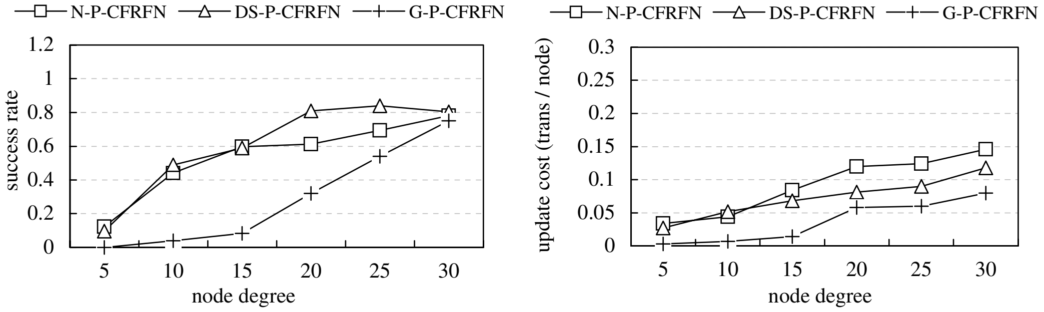


(a) success rate (b) update cost

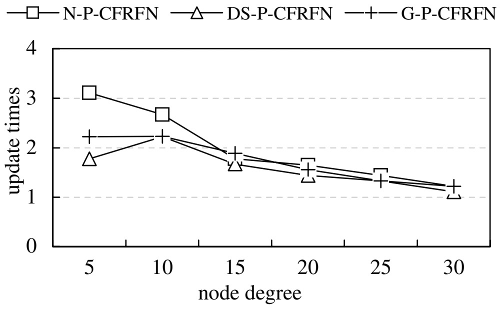


(c) maintenance (d) update times

Fig. 10. Performance of DS-quorum and G-quorum vs node velocity v, $R = 200$ m.



(a) success rate (b) update cost



(c) update times

Fig. 11. Performance of quorum with or without backbones vs node degree d, $v = 10$ m/s.

The update cost of three location services increases as degree increases, but the N-P-CFRFN involves more nodes for message forwarding (Fig. 11(b)). This is because in face routing, increasing R yields a denser network. A node has more neighbors and more choices to select one of them to be the next forwarding node. Thus, each direction can be extended much further. Moreover, as R increases, face routing is more likely to be triggered on the outer boundary, on which more and more nodes will be added to the quorum as well. But, after R increases enough so that face routing can be applied to all nodes on the perimeter of the network, the number tends to become steady eventually. The N-P-CFRFN is influenced much by these impacts. However, the DS-P-CFRFN has a counter-effect. There will be fewer nodes recruited as dominant when degree increases. Note that the G-P-CFRFN requires little transmission cost, because the update cost can easily be dropped due to the disconnection between two backbone nodes.

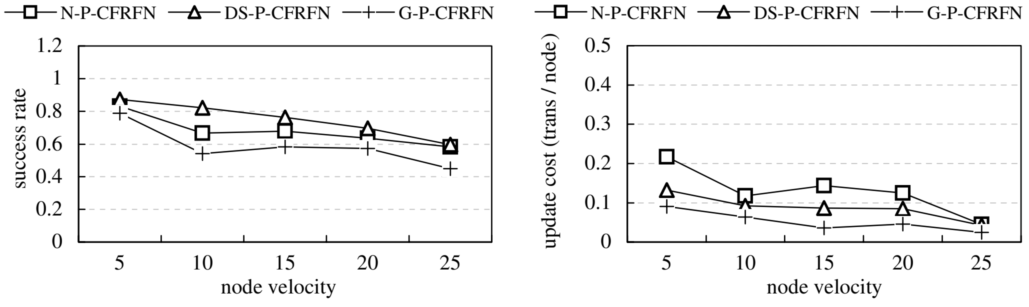
The N-P-CFRFN invoke update more frequently than that of the other two when degree is smaller than 10 (Fig. 11(c)). This is because the criterion for update in N-P-CFRFN is counted on all direct neighbors. Thus there will be more link changes comparing to that in DS-P-CFRFN where only backbone nodes are counted.

We also evaluate the performance of N-P-CFRFN on the impact of node velocity in Fig. 12(a) to (c). It obtains lower success rate than DS-P-CFRFN because quorum system is constructed upon the entire topology of networks, which may easily disconnected when nodes move at a high speed. Once more, the update cost is the most as all nodes can participate in packets forwarding. The update times are almost the same for the three location services. This is because when nodes moves fast, the transmission radius becomes the major criterion for update as explained above.

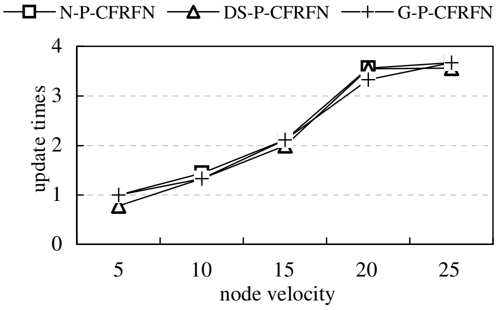
6. Future work

In this paper, we proposed DS based quorum location service in wireless ad hoc and sensor networks. DS as backbone is calculated and updated in the network periodically. The columns and rows defined in our location update scheme are relative, not absolute. It 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. As demonstrated in the paper, using DS as backbone for quorum construction is superior to using grid as backbone or when no backbone is applied. The proposed DS-D-CRFCRF location service can achieve higher (or similar) success rate with much less communication cost than G-D-CRFCRF. Moreover, it requires much less overhead to maintain the DS than maintain grid in both dynamic and periodic options.

One of drawbacks of quorum-based scheme is that it requires searches and updates visit the quorum system built on the DS induced from 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 [1], with updates and searches



(a) success rate (b) update cost



(c) update times

Fig. 12. Performance of quorum with or without backbones vs node velocity v, $R = 200$ m.

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 [10]. We also believe that any location update method, no matter how clever is, will only work well up to a certain speed limits. 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.

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