Int. J. Autonomous and Adaptive Communications Systems, Vol. 1, No. 1, 2008 41

Depth First Search-based and power-aware geo-routing in *ad hoc* and sensor wireless networks

Bosko Vukojevic

School of Information Technology and Engineering,
University of Ottawa,
800 King Edward Avenue,
Ottawa, Ontario K1N 6N5, Canada

Nishith Goel

Cistel Technology Inc.,
30 Concourse Gate, Unit 40,
Ottawa, ON K2E 7V7, Canada
E-mail: ngoel@cistel.com

Kalai Kalaichevlan

Eion Inc.,
320 March Road, Suite 500,
Ottawa, Ontario K2K 2E3, Canada
E-mail: kalai@eion.com

Amiya Nayak*

School of Information Technology and Engineering,
University of Ottawa,
800 King Edward Avenue,
Ottawa, Ontario K1N 6N5, Canada
E-mail: anayak@site.uottawa.ca
*Corresponding author

Ivan Stojmenovic

EECE,
University of Birmingham,
Edgbaston, Birmingham B15 2TT, UK
E-mail: stojmenovic@storm.ca

Abstract: Depth First Search (DFS) and position-based routing algorithms were proposed in literature. These are localised algorithms that guarantee the delivery for connected *ad hoc* and sensor wireless networks modelled by arbitrary graphs, including inaccurate location information for a destination node. This article first optimises an existing DFS-based routing scheme by eliminating from the candidate list neighbours whose messages to other nodes were overheard. We then introduce a new set of localised routing algorithms. The new DFS routing protocol is integrated with power metrics minimise total power for routing of a message. These DFS Power Progress-based algorithms are combinations of known greedy power ad DFS routing algorithms. All algorithms are further enhanced by applying the concept of connected dominating sets, which greatly reduced the search path without impacting significantly the length of effectively constructed path for real traffic. Experiments confirm the efficiency of the new enhanced DFS, power-aware and connected dominating set-based routing algorithms and ability to guarantee the delivery in arbitrary model due to the DFS routing framework.

Keywords: *ad hoc* and sensor networks; depth first search routing; power aware geo-routing.

Reference to this paper should be made as follows: Vukojevic, B., Goel, N., Kalaichevlan, K., Nayak, A. and Stojmenovic, I. (2008) ‘Depth First Search-based and power-aware geo-routing in *ad hoc* and sensor wireless networks’, *Int. J. Autonomous and Adaptive Communications Systems*, Vol. 1, No. 1, pp.41–54.

Biographical notes: Bosko Vukojevic completed his Master Degree in Computer Science at the University of Ottawa, Canada, in 2007.

Nishith Goel has holds a BE (honours) in Electronics and Telecommunications Engineering from the University of Jodhpur, India; a Masters of Applied Sciences in Electrical Engineering and a Doctor of Philosophy in Systems Design Engineering from the University of Waterloo, Canada. In 1984, he joined Bell-Northern Research (Nortel Networks) as a member of the Scientific Staff. He worked at Nortel Networks for over 12 years. In 1995, he founded Cistel Technology which now has over 130 employees and consultants with offices in Ottawa, Toronto, Atlanta (USA) and New Delhi (India). He has over 50 publications in various conferences and journals.

Kalai Kalaichelvan earned his PhD from the University of Toronto. He joined Bell-Northern Research/Nortel Networks, where he was a Platinum talent advancing to executive ranks. He won several prestigious awards during his 15 years service. In 2001, he founded EION Inc, a Wireless networking company. In 2004, he won the ‘Canadian Innovator of The Year’ award from CATA/NRC for his contributions to Business Innovations. In 2005, he was awarded the Wireless Communications Association International (WCA) Wemmie Award for ‘Advanced Technology for the Underserved: Community Services’. He is the sole Canadian on the Advisory Board to the Chairman of Samsung, South Korea.

Amiya Nayak received his BMath degree in Computer Science and Combinatorics and Optimisation from the University of Waterloo, Canada, in 1981 and PhD in Systems and Computer Engineering from Carleton University, Canada, in 1991. Currently, he is a Full Professor at the School of Information Technology and Engineering at the University of Ottawa, Canada. His research interests are in the areas of mobile *ad hoc* and sensor networks, fault tolerance, and distributed systems/algorithms, with over 100 publications in refereed journals and conference proceedings.

Ivan Stojmenovic received all degrees in Mathematics. He published over 200 different papers, and edited four books on wireless *ad hoc* and sensor networks and applied algorithms with Wiley. He is currently an Editor of Dozen, and Founder and an Editor-in-chief of three journals. He is in the top 0.56% most cited authors in Computer Science (Citeseer 2006). One of his articles was recognised as the Fast Breaking Paper, for October 2003, by ISI. He is Recipient of the Royal Society Research Merit Award, UK. He chaired and/or organised more than 30 workshops and conferences. He is an IEEE Fellow

1 Introduction

The architecture of *ad hoc* mobile wireless networks is characterised by the lack of fixed infrastructure. They rely on multi-hop communications among peers that would be typical in emergency situations, remote and environment monitoring, search and rescue operations, battlefields, radar networks, conferences and other similar cases. Wireless sensor networks are made up of a number of sensor nodes that are positioned within a limited and defined geographical area. Recently, a whole set of wireless sensor networks applications have been considered and various deployments have been tested. Sensors detect an event (movement, presence of chemicals, rise of temperature, etc.) and report it to a sink node. They are typically characterised as networks with nodes that do not move or have insignificant movement patterns. Sensor nodes are capable of processing gathered and exchanged data in real time.

Ad hoc and sensor networks are comprised of wireless hosts. Each network host is capable of communicating directly with other network hosts in its neighbourhood. A message sent by a node will reach all neighbouring nodes that are located at the distances less than the transmission radius. We assume symmetric communication links between nodes, but not necessarily equal transmission radii. Due to limited transmission radius, the routes between the nodes are usually formed through several hops. The routing problem is the problem of finding a route for sending a message from a source node to a destination node. Each network node can be a source or a destination of the communication link. In addition, nodes are asked to participate in routing other nodes packets, i.e. to act as routers. The problem of finding and maintaining routes has proven to be a significant challenge in wireless *ad hoc* networks.

One possible solution to the routing problem would be the well-known Shortest Path (SP) algorithm. This non-localised scheme requires that each network node possesses global knowledge about the network. It is an unrealistic and hypothetical requirement for the global knowledge to be fully distributed to all network nodes. The information about changes in network topology, in the SP scenario, due to node mobility or changes in node activity, would need to be distributed across the network. In addition to the activity status and the location updates for all the nodes in the network, the updates on the status of every possible link in the network to guarantee the availability of SP, which is unacceptable quadratic communication overhead.

Localised schemes are based on non-global behaviour. Each node makes routing decisions based only on the information about neighbouring nodes and the position of the destination. Localised routing addresses mobility and changes in the availability of network nodes. In existing greedy routing algorithm, each node forwards messages to the neighbour that is closest to the destination. This algorithm is not efficient for low-degree graphs (a low average number of neighbours). However, it offers a performance that is close to the SP-based routing, whenever the routing of the message is successful.

In most of the cases, the sensor use position information in their decisions. The availability of position information for proper sensor functioning was widely recognised as highly desirable; however, it is a non-trivial problem and the precision of the location information may impact the performance of a protocol. There exists a variety of position determination protocols, with a variety of message complexities. The position information for *ad hoc* networks is also feasible, since nodes are located on a device (such as handheld devices and cars) which can increasingly afford satellite communication.

DFS-based routing scheme is introduced in Stojmenovic, Russell and Vukojevic (2002). It was the first localised algorithm that guarantees delivery for connected *ad hoc* wireless networks even in case of inaccurate location information for the destination node. This is enabled by an algorithm internal design that is built upon the fact that DFS is not a stateless routing scheme. Memorising information about past traffic, at the node level, helps the routing logic to keep switching between greedy and recovery modes, providing the message delivery even in a case of inaccurate location information.

Hop count performance of the original DFS algorithm (Stojmenovic, Russell and Vukojevic, 2002) was not too far from the SP benchmark for a well-connected network. However, sparse networks, with network density parameter values less than seven, left room for further improvements. This article investigated several possible ways to resolve the issue of DFS hop count performance. We introduce and analyse a set of various DFS-based routing strategies and evaluate their performance. Our improvements are in three directions: enhancing the basic DFS routing algorithm by observing that overheard traffic from neighbours can be used to eliminate some candidate neighbours from depth-based search, applying metric different from hop count (we apply power-aware metric, but other metrics can be used as well) and reducing the search traffic to nodes from a connected dominating sets.

The major difference between DFS and power-aware DFS protocols is that nodes use different priority metrics for sorting best neighbours. Instead of distance to destination, the appropriately defined power- or cost-aware metric is used.

Preliminary conference version of this article appeared in Vukojevic et al. (2007).

2 Background and related work

Finn (1987) proposed a greedy routing scheme that chooses the successor node that makes the best progress toward the destination. The distance to destination is used to measure the progress. The algorithm fails when no node is closer to the destination than the current node that holds the message. A similar protocol, a variant of greedy-based algorithm, called Geographical Distance Routing (GEDIR), is presented in Stojmenovic and Lin (2001b). The algorithm stops if the best choice for the current node is to return the message to the previous node. Several other existing location-based routing algorithms are reviewed in Stojmenovic and Lin (2001b). A survey of existing position-based routing schemes is given in Stojmenovic (2002a).

A localised FACE routing algorithm, described in Bose et al. (1999) guarantees the message delivery in connected unit graphs. It can be combined with the greedy routing to yield an efficient greedy-face-greedy routing algorithm (Bose et al., 1999). Hop count metric in greedy mode can be replaced by other metrics, such as power or reluctance to forward traffic, to give other schemes (Stojmenovic and Datta, 2004). The advantage of these algorithms, compared to DFS-based approaches, is that they offer guaranteed delivery without memorising past traffic (stateless behaviour). However, disadvantage is that they are very sensitive to the accuracy of position information, small movements while routing is in progress, and work in restricted unit disk graph model (all nodes have the same transmission radius) and in two dimensions. Therefore, while they can be deemed better under severe restrictions, they are not competitive to DFS-based approaches under a wide range of realistic scenarios, including communication model imperfections due to realistic physical layer, imprecise position information, reasonable movements while search is in progress, work in both 2D and 3D, and with different transmission ranges at different nodes. For these reasons, we did not compare them with DFS approaches in this article.

Stojmenovic, Russell and Vukojevic (2002) proposed to use DFS method for routing decisions. Each node *A*, upon receiving the message for the first time, sorts all its neighbours according to a criteria, such as their distance to destination, and uses that order in DFS algorithm. It is the first localised algorithm that guarantees delivery for (connected) wireless networks modelled by arbitrary graphs, including inaccurate location information. They then propose the first localised Quality of Service (QoS) routing algorithm for wireless networks. It performs DFS routing algorithm after edges with insufficient bandwidth or insufficient connection time are deleted from the graph, and attempts to minimise hop count. This is also the first article to apply position information in QoS routing decisions, and to consider the connection time (estimated lifetime of a link) as a QoS criterion. The average length of the measured QoS path in experiments, obtained by DFS method (Stojmenovic, Russell and Vukojevic, 2002) was between 1 and 1.34 times longer than the length of QoS path obtained by SP algorithm. The overhead is considerably reduced by applying the concept of connected dominating sets.

The details of DFS algorithm (Stojmenovic, Russell and Vukojevic, 2002) are as follows. DFS creates a path in the graph without making any jumps from a node to another node that is not its neighbour. In DFS-based algorithm, nodes are 'coloured' as white or grey (because of distributed behaviour of our algorithm, the third colour is not needed). Initially, all nodes are white (that is, if message *id* is not found in local memory, white colour is assumed). The process of visiting nodes coincides with sending messages among nodes. There is always only one copy of message in the graph, and thus a path is created. The sender node S begins routing and colours itself as a grey node. Grey nodes are nodes that are visited (that is, they received message at least once). Each message that is sent from a node *B* to a node *A* has one bit that indicates whether the message is forwarded or returned. Node A receiving the message then acts according to that bit. White node *A*, upon receiving forwarded message for the first time, changes its colour to grey, and orders its neighbours according to distance from destination (the neighbours which are closer to destination are preferred). The only exception is that node *B*, that sent message to *A*, is ignored. Thus, node *A* should memorise together with the message id, also neighbour *B* that forwarded that message. The message is then forwarded to the first choice *C* among neighbours. If there is no choice, message is returned to *B*. Grey node *A*, upon receiving forwarded message from any node *B*, will reject the message immediately. That is, the message will be immediately returned to *B*. If node *A* sends message to node *B*, and node *B* rejects the message, it is counted as two hops in the simulation ($A - B$ and *B* back to *A*). Grey node *A*, upon receiving a returned message from node C, will forward the message to the next choice *E* in its sorted list of neighbours, if such a neighbour exists. If *A* has no more neighbours in its list, message will be returned to the neighbour *B* which sent the message to *A* (and which was memorised for that purpose).

Jain, Puri and Sengupta (2001) proposed, independently of Stojmenovic, Russell and Vukojevic (2002) a single-path strategy that guarantees delivery called Geographic Routing Algorithm (GRA). It requires nodes to partially store routes toward certain destinations in routing tables. GRA applies greedy strategy in forwarding messages. However, sometimes node *S* may discover that it is closer to the destination *D* than any of its neighbours. That is, the packet may be 'stuck' at *S*. Under this condition, it starts the route discovery protocol. The route discovery finds a path from *S* to *D* and updates the routing tables toward *D* at any node on the path, with this information. After that the route discovery protocol is successfully completed, the stuck packet can be routed from *S* to *D*. The authors propose two route discovery strategies: *breadth first search* (which is equivalent to flooding) and DFS. DFS yields a single acyclic path from *S* to *D*. Each node puts its name and address on the route discovery packet *p*. Then, it forwards *p* to a neighbour who has not seen *p* before. This neighbour is one of all the neighbours which minimise $\mathrm{d}(S, y) + d(y, \mathrm{D})$, where $d(x, y)$ is Euclidean distance between nodes *x* and *y*. If a node has no possibilities to forward the packet, it removes its name and address from the packet and returns the packet to the node from which it originally received it. Route discovery packets are kept for some time. If a node receives twice the same packet, it refuses it. The authors investigate routing table sizes and present methods for taking into account positional errors, node failures and mobility.

Routing based on the dominating set approach, as presented and defined in Wu and Li (1999) and Stojmenovic, Seddigh and Zunic (2002) offers an innovative and promising improvement for potential solutions to the *ad hoc* network's routing problem. A set of nodes, a subset of all network nodes, is considered to be a dominating set if all nodes in the network are either in the set or are direct neighbours of nodes in the set. Nodes that belong to the dominating sets are called internal nodes. Different definitions for dominating sets generate different set of internal nodes.

The substance of this approach is to exclusively use internal nodes for routing of messages throughout the *ad hoc* network. The consequence is that the search space for a route is reduced to corresponding internal nodes. If a source is not an internal node, it forwards the message to one of its neighbouring internal nodes. This internal node represents a new source point of the routing problem that happens only along a reduced graph based on internal nodes of the network. As routing gets to the end of the route, the message reaches the internal node that is either the destination node or a direct neighbour of the destination node. In a later case, an additional forward toward the destination is required.

Wu and Li (1999) proposed a simple and efficient distributed algorithm for calculating connected dominating set in *ad hoc* wireless networks. Stojmenovic, Seddigh and Zunic (2002) and Stojmenovic (2004) introduce a major improvement in a way these dominating sets are calculated and formed. Stojmenovic, Seddigh and Zunic (2002) proposed improving (Wu and Li, 1999) rules for building dominating sets by replacing node ids with a record: key = (degree, *x*, *y*) where degree is the number of neighbours of a node and *x* and *y* are its two coordinates. The novelty in Stojmenovic, Seddigh and Zunic (2002) and Stojmenovic (2004) is that process of determining dominating set status of the *ad hoc* network nodes requires zero communication overhead. This is a significant improvement over previous ways of building dominating sets. A node is marked as an intermediate node if it has two unconnected neighbours. A node *A* is covered by neighbouring node *B* if each neighbour of *A* is also neighbour of *B*, and $\mathrm{key}(A) < \mathrm{key}(B)$. Nodes not covered by any neighbour are defined as inter-gateway nodes. A node *A* is covered by two connected neighbouring nodes *B* and *C* if each neighbour of *A* is also neighbour of either *B* or *C* (or both), $\mathrm{key}(A) < \mathrm{key}(B)$, and $\mathrm{key}(A) < \mathrm{key}(C)$. An intermediate node not covered by any neighbour becomes an inter-gateway node. An inter-gateway node not covered by any pair of connected neighbouring nodes becomes a gateway node. Dominating set generated by Stojmenovic, Seddigh and Zunic (2002) and Stojmenovic (2004) is identical to a dominating set generated by Wu and Li (1999).

The optimal power-saving algorithm, that minimises the total energy per routing task for a message, can be calculated by applying Dijkstra's single-source shortest weighted path algorithm. Each edge has the weight $u(d) = d^{\alpha} + c$, where d is the length of the edge (Rodoplu and Meng, 1999). This represents the (proportional to message length) power needed for transmission between two nodes. We refer to this algorithm as SP power algorithm and it is mainly used to compare the performance of various new localised algorithms.

Localised power-aware routing algorithms were first studied in Stojmenovic and Lin (2001a). Kuruvila, Nayak and Stojmenovic (2004) proposed progress-based localised power-aware routing algorithms, including projection power-based, iterative power progress-based and iterative projection power progress ones. Current node in these algorithms chooses one of its neighbours that are closer to destination than itself. In addition, a selected neighbour is required to minimise the ratio of power to reach that neighbour, and the progress made, measured as the reduction in distance to destination (or projection along the line to destination). The power-aware localised schemes are shown to be conceptually simpler than algorithms presented in Stojmenovic and Lin (2001a) and have similar or better performance. Let us assume that the destination node is D. Node S currently holds the message and one of its neighbours is node A. Let $r = |SA|$, $d = |SD|$ and $x = |AD|$. Kuruvila, Nayak and Stojmenovic (2004) considers measure of the proportional progress and the actual power used to make that portion of the progress. The power spent on transmission of the message from node S to A is $(r^{\alpha} + c)$. The portion of the progress made with this power is $(d - x)$. With similar advancing through the network, there would be $d/(d - x)$ steps, and the total power cost would be $(r^{\alpha} + c) * d/(d - x)$. Therefore, this progress-based routing algorithm will select a neighbour that will minimise: $(r^{\alpha} + c)/(d - x)$. This is the neighbour that minimises the power spent per unit of progress made, in terms of getting closer to the destination.

3 Proposed DFS improvements

The first contribution of this article is a special enhancement of the internal design of DFS. The idea is to avoid communication between neighbouring nodes that is not necessary, since this knowledge could be extracted from the past traffic. Each node will memorise some of the traffic related to ongoing routing task. More precisely, they will memorise traffic of their neighbours. It has been noticed that the basic DFS algorithm considers all neighbours at each node. All neighbours are initially candidates for forwarding, except one from which the message came from for the first time following DFS algorithm. However, this is not necessarily the very first time the message has been overheard. Some neighbours may forward the message to another nodes, and such forwarding is an indication that these neighbours have already been visited, and will reject the message in the future if the same message is forwarded to them. Thus, nodes can simply eliminate them from their forwarding lists. In order to support proposed improvement, each node is required to create and maintain a list of neighbouring nodes that should be ignored for the ongoing routing task.

Figure 1 DFS routing before and after enhancements give paths **SABC**A**C**SCB**A**CA SC**SEFGHID** and **SAB**CBA**SEFGHI**D

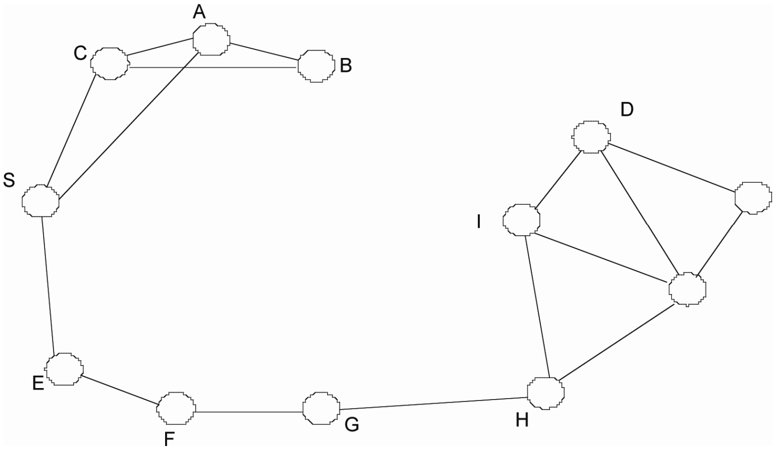
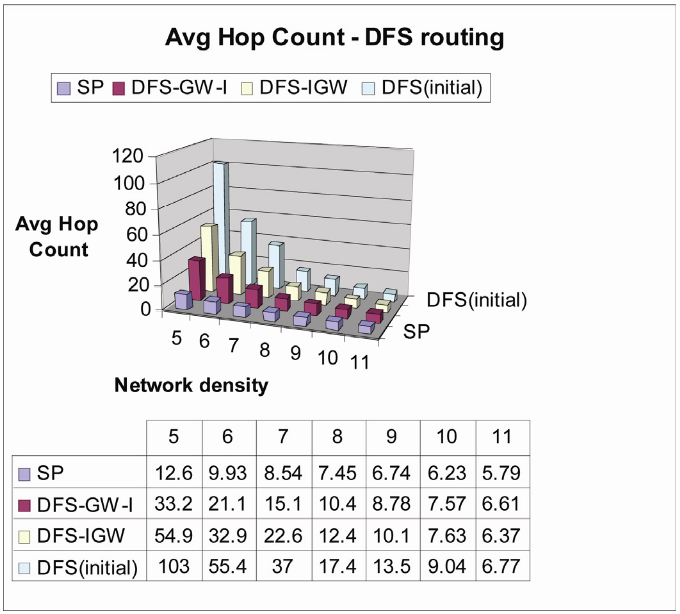


Figure 1 gives an example of a DFS routing path: **SABC**A**C**SCB**A**CA**S**C**SEFGHID**, where bold and regular letters correspond to forwarded and returned/rejected messages, respectively (sender node is marked). Consider now the enhanced version. When S forwards to A, C eliminates both A and S from its forwarding list. When A forwards to B, C eliminates both A and B. When B forwards to C, A eliminates C from its forward list. Thus, after initial path SABC, node C has empty forward list, and returns the message to B (S then eliminates C from its list), which in turn returns it to A. A then returns it to S, which then explores the other component of the graph. The improved version of DFS applied in this section of the network would generate the following route: **SAB**CBA**SEFGHI**D, which is significant improvement, in terms of hop count, over the initial DFS algorithm proposed path.

This enhanced DFS routing scheme is further improved by applying the concept of connected dominating sets. Several definitions of dominating set and internal nodes were used. The basic principle of dominating set theory, the reduction of the network to the subset of nodes that belong to the dominating set, is the core of the improvement strategies that were used. DFS is extended to route messages only across internal nodes that form dominating sets. Dominating sets, as proposed and defined by Wu and Li (1999) and Stojmenovic, Seddigh and Zunic (2002) were based on one of the selected set of internal nodes: intermediate, inter-gateway and gateway. The goal is to reduce the number of nodes that are used for routing messages throughout the network.

Traditionally, in addition to the information about the delivery rate, hop count was the most important measure of the quality of the routing solution. This metric assumes fixed transmission radii and therefore fixed energy per hop. However, nodes may have capability to adjust their transmission radii. In such case, hop count is not an appropriate metrics. Instead, the minimal power needed to transmit between the two neighbouring nodes is considered. We also address this model and metric in this article by introducing a new set of power-aware algorithms, which are built upon a framework of DFS guaranteed delivery routing. These new algorithms are generated by integrating the improved version of the DFS algorithm with progress-based power-aware algorithms. The essence is to combine algorithms (Kuruvila, Nayak and Stojmenovic, 2004) with the improved version of the DFS algorithm. The improved version of DFS scheme includes both previous modifications to DFS, i.e. one that uses dominating set principles and a modification that requires nodes to memorise past traffic for messages. The DFS routing algorithm sorts all neighbours (edges) at each visited node according to their progress over power cost ratios. The next neighbour for forwarding is then selected based on these ratios (Figure 2).

Figure 2 Graphical representation of data from Table 1 (see online version for colours)



	5	6	7	8	9	10	11
SP	12.6	9.93	8.54	7.45	6.74	6.23	5.79
DFS-GW-I	33.2	21.1	15.1	10.4	8.78	7.57	6.61
DFS-IGW	54.9	32.9	22.6	12.4	10.1	7.63	6.37
DFS(initial)	103	55.4	37	17.4	13.5	9.04	6.77

Table 1 Average hop counts (includes reject and return messages) for DFS – $n = 250$ nodes

Degree (d)	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*labels*
DFS (initial)	Connected graphs could not be generated		102.61	55.412	37.012	17.428	13.456	9.044	6.766	Average hop
			32.695	17.228	11.215	3.849	2.657	1.053	0.313	Reject count
			8.764	2.939	1.294	0.262	0.127	0.038	0.004	Return count
			250	250	250	250	250	250	250	Internal nodes
DFS-Int			86.438	48.692	33.499	16.317	12.817	8.783	6.662	Average hop
			27.017	14.781	9.897	3.436	2.412	0.956	0.276	Reject count
			6.762	2.298	1.007	0.188	0.098	0.028	0.002	Return count
			214	222	230	235	238	240	242	Internal nodes
DFS-IGW			54.946	32.889	22.563	12.384	10.105	7.632	6.367	Average hop
			13.436	7.841	5.051	1.717	1.215	0.463	0.156	Reject count
			5.467	1.935	0.79	0.145	0.078	0.021	0.002	Return count
			169	173	177	181	184	187	189	Internal nodes

Table 1 Average hop counts (includes reject and return messages) for DFS – $n = 250$ nodes (continued)

DFS-IGW-I	37.745	22.869	16.11	10.278	8.585	7.069	6.189	Average hop
	4.836	2.832	1.825	0.664	0.455	0.181	0.066	Reject count
	5.467	1.935	0.79	0.145	0.078	0.021	0.002	Return count
	169	173	177	181	184	187	189	Internal nodes
DFS-GW	42.266	26.613	18.441	11.641	9.636	7.986	6.753	Average hop
	7.352	4.439	2.696	1.031	0.711	0.36	0.126	Reject count
	5.524	2.308	1.057	0.29311	0.154	0.062	0.018	Return count
	147	142	137	33	129	123	120	Internal nodes
DFS-GW-I	33.168	21.147	15.119	10.417	8.784	7.566	6.608	Average hop
	2.803	1.706	1.035	0.419	0.285	0.15	0.053	Reject count
	5.524	2.308	1.057	0.293	0.154	0.062	0.018	Return count
	147	142	137	133	129	123	120	Internal nodes
SP	12.57	9.927	8.541	7.447	6.736	6.227	5.79	

4 Performance evaluation

The custom network simulator was designed and implemented in Java programming language and used to construct *ad hoc* wireless networks and required routing of messages through randomly formed networks. Experiments have been carried only on connected graphs. Each of n network nodes was chosen by selecting its x and y coordinates at random in the interval (0, 100). In order to control the average node degree k (the average number of neighbours per node), all potential $n^* (n-1)/2$ edges in the network were sorted by their length, in increasing order. Selected node radius R that corresponds to chosen value of k was equal to the length of $nk/2$th edge in the sorted order (Stojmenovic and Lin, 2001b).

The following protocols were simulated: DFS (initial) (Stojmenovic, Russell and Vukojevic, 2002) DFS-Int (modified DFS), DFS-IGW (basic DFS (Stojmenovic, Russell and Vukojevic, 2002) with inter-gateway nodes), DFS-GW (basic DFS with gateway nodes), DFS-IGW-I: (modified DFS with Inter-Gateway nodes), DFS-GW-I (modified DFS with gateway nodes) and SP routing. A set of simulation experiments demonstrated associated improvements of the proposed amended routing schemes.

We measured average hop count (includes reject and return messages), average reject count (as per DFS algorithm) average return count (as per DFS algorithm) and average number of nodes in considered dominating set.

Improvements to the DFS routing algorithm hop count numbers are evident as different dominating set notions are applied. The lesser network density, the improvements are bigger. For example, the improvement is ~68% for $n = 250$ and $d = 5$. A larger density, for the same network size, gives ~9% ($n = 250$ and $d = 11$). Small improvements are delivered in those network scenarios where the basic DFS routing algorithm performance is quite similar to the best possible routing solutions. For example, the improvement of ~1% ($n = 40$ and $d = 11$) is delivered for basic DFS performance which is only ~1.3% worse from SP hop count. Improved versions of the DFS algorithm greatly help the hop count performance to converge to the ideal solution. This gap is dramatically narrowed for those network scenarios where basic DFS routing algorithm performance is far from established (SP hop count) baseline – networks with small network density values. At the same time, these improved algorithms deliver their benefits even in those network cases where basic DFS performance is quite close to the ideal one – networks with higher network density.

5 Performance evaluation of DFS QoS routing

This section evaluates the performance of the DFS QoS routing algorithm. The DFS-based routing framework is reused for analysis of DFS QoS routing. QoS routing requirements, when applied on the DFS algorithm, result in some edges being removed from the used DFS resulting paths. The DFS QoS analysis did not require a separate set of QoS routing experiments to be executed since the remaining subgraph is also represented by pair (n, d) (d is the average degree of the remaining subgraph).

Instead of a regular hop count, a so-called Effective Hop Count (EHC) was measured. In a nutshell, this is the DFS path without edges that were marked as those that rejected or returned messages. The path created by eliminating these unnecessary hops is required QoS path. The EHC of resulting QoS path can be calculated as:

$$\text{EHC}=\text{hopCount} - 2 * \text{rejectCount} - 2 * \text{returnCount}.$$

Table 2 Effective Hop Counts for Depth First Search Quality of Service routing (n = 40)

Degree (d)	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
DFS (initial)	6.938	5.713	4.596	3.876	3.225	2.859	2.551	2.356	2.189
DFS-Int	6.739	5.548	4.485	3.807	3.183	2.835	2.542	2.356	2.187
DFS-IGW	6.614	5.342	4.319	3.658	3.101	2.792	2.524	2.342	2.182
DFS-IGW-I	6.614	5.341	4.319	3.657	3.1	2.794	2.525	2.343	2.181
DFS-GW	6.624	5.363	4.378	3.751	3.24	2.914	2.661	2.461	2.309
DFS-GW-I	6.625	5.363	4.377	3.75	3.239	2.914	2.663	2.461	2.31
SP	6.33	4.955	4.012	3.445	2.994	2.708	2.488	2.318	2.171

Table 3 Power consumption for all routing tasks for n = 100

Degree (d)	*4*	*6*	*8*	*10*
DFS (initial)	9.2	4.845	2.199	1.791
DFS-Int	7.23	4.224	2.073	1.7
DFS-IGW	4.965	2.976	1.625	1.312
DFS-IGW-I	4.005	2.293	1.376	1.135
DFS-GW	4.277	2.45	1.503	1.216
DFS-GW-I	3.725	2.117	1.367	1.15
Power progress DFS	3.615	2.029	1.294	1.077
SP power	1.884	1.308	0.993	0.867

As per Table 2 ‘EHC for DFS QoS routing’ the it is evident that EHC results are significantly improved. This is evident for the various DFS-routing algorithms. DFS QoS-routing performance improvement is greatest for those DFS routing protocols that are characterised by the most return and reject messages. The best DFS routing protocols, DFS-GW and DFS-GW-I, as expected, offer better EHC performance.

Table 2 results demonstrate other interesting characteristics of the DFS QoS routing scheme. QoS performance of all listed DFS algorithm variations fall in the same range (for a certain network configuration (n, d)), i.e. QoS performance of the worst DFS performer gets quite close to QoS performance of the best DFS performer (hop count performance). It should be noted that these data prove that DFS QoS routing offers almost the SP route for QoS routing in localised manner. Excellent results are present for low-degree networks. Dense connected networks (higher values of d) offered equally good results (quite close to SP performance).

6 Performance evaluation of DFS progress-based power-aware routing algorithm

For this set of routing experiments, DFS-GW-I was selected and merged with Power Progress scheme. This is the best DFS candidate for $d < 7$ (both analysed network sizes, $n = 40$ and 100). We applied HCB power model (Heinzelman, Chandrassekaran and Balakrishnan, 2000) where the energy needed for one transmit and receive event is: $u(r) = r^2 + 1{,}000$ (for nodes at distance r). This energy was split between the sender node ($r^2 + 1{,}000$) and the fixed power for reception is charged to the receiving node (1,000).

All numbers in Table 3 are ten to the power of eight.

It appears that the contribution to the saving of power spending appears to be greater for networks with higher density. The total power consumption is quite close to the ideal spending for smaller networks and higher values of network density. The deviation of DFS Power Progress for $n = 100$ and $d = 10$ is ~20 and ~23% for $d = 8$.

7 Conclusions and future work

This article focused on two goals. Foremost, various improvements to the initial DFS were described and simulated. Proposed improvements of initial DFS routing algorithm succeed in delivering significant benefits to the hop count performance. The performance is close to the performance of the SP metrics for dense connected networks.

The best DFS routing candidates were merged with power-aware schemes. A new set of power-aware DFS-based algorithms appears to have several important features. The DFS framework extends its ability to guarantee delivery on power-aware routing algorithms that, as expected in their original greedy form, do not deliver all of the time. At the same time, the power metric performance of the DFS routing is also improved.

It is fair to assume that the selected best candidate DFS algorithm(s) will easily integrate with location update protocols. A source node which is about to start DFS routing can use available location update scheme(s) (Stojmenovic, 2002b) to determine the correct location of the destination node. Once the destination information is available, DFS routing would initiate the routing task independently of the location update component, and based on the data provided by these location update mechanisms.

Researched DFS-routing algorithms prove to be ideal candidates with their guaranteed delivery capability, even for special cases, where location information is not fully correct.

There are several possible directions for associated research of potential improvements to introduced DFS-based power-aware routing algorithms. One direction is to study reluctance of nodes to forward traffic because of low remaining energy they have. This has been studied already in Stojmenovic and Lin (2001a) and Kuruvila, Nayak and Stojmenovic (2004) and these greedy routing schemes can be also combined with DFS approach to guarantee delivery. The goal is to extend network life, not to minimise the energy per path. Potentially interesting and related future directions could be also based on further improvements of used dominating set definitions. The inevitable problem of routing algorithms based on dominating sets is caused by the fact that dominating set nodes execute many more tasks than other nodes. Wu et al. (2002) as a solution to this problem, proposed to power-aware dominating set definition. In this definition, each dominating set node has a key (power level, degree, id) for deciding its dominating set status. Thus, nodes use their power levels as the primary criterion. Nodes with more power are preferred in the dominating set selection process. If power levels are same, degrees are used as secondary key, and finally node ID would be used to break ties. The further improvements are proposed in Shaikh et al. (2003).

Further improvements can be obtained by reducing the number of links to be explored by DFS using a sparse connected subgraph of the original graph. Two notable candidates are Gabriel graph and relative neighbourhood graphs. Reduced density is associated with reduced reduced search space and faster recovery from ‘bay’ areas. Connected dominating sets can then also be applied on these structures for further (but expected major) improvements.

References

Bose, P., Morin, P., Stojmenovic, I. and Urrutia, J. (1999) ‘Routing with guaranteed delivery in *ad hoc* wireless networks’, *ACM Wireless Networks*, 7, 6 November 2001, 609–616; Paper presented in the Proceedings of the *3rd ACM International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications DIAL M99*, Seattle, August 20, pp.48–55.

Estrin, D., Govindan, R., Heidemann, J. and Kumar, S. (1999) ‘Next century challenges: scalable coordination in sensor networks’, Paper presented in the Proceedings of the *MOBICOM*, Seattle, pp.263–270.

Finn, G.G. (1987) ‘Routing and addressing problems in large metropolitan-scale internetworks’, *ISI Research Report ISU/RR-87-180* (p.1).

Heinzelman, W.R., Chandrassekaran, A. and Balakrishnan, H. (2000) ‘Energy efficient routing protocols for wireless microsensor networks’, Paper presented in the Proceedings of the *Hawaii International Conference on System Sciences*.

Jain, R., Puri, A. and Sengupta, R. (2001) ‘Geographical routing using partial information for wireless *ad hoc* networks’, *IEEE Personal Communication*, Vol. 8, pp.48–57.

Kuruvila, J., Nayak, A. and Stojmenovic, I. (2004) ‘Progress based localized power and cost aware routing algorithms for *ad hoc* and sensor wireless networks’, *Third International Conference on AD-HOC Networks and Wireless ADHOC-NOW*, Vancouver, BC, July 22–24, LNCS 3158, pp.294–299, *Int. J. Distributed Sensor Networks*, 2, pp.147–159.

Rodoplu, V. and Meng, T.H. (1999) ‘Minimum energy mobile wireless networks’, *IEEE Journal on Selected Areas in Communications*, Vol. 17, pp.1333–1344.

Shaikh, J., Solano, J., Stojmenovic, I. and Wu, J. (2003) 'New metrics for dominating set based energy efficient activity scheduling in *ad hoc* networks', Paper presented in the Proceedings of the *WLN Workshop at IEEE Conference on Local Computer Networks*, Bonn, Germany, pp.20–24.

Stojmenovic, I. (2002a) 'Position-based routing in *ad hoc* networks', *IEEE Commmunications Magazine*, Vol. 40, pp.128–134.

Stojmenovic, I. (2002b) 'Location Updates for Efficient Routing in Ad Hoc Networks', *Handbook of Wireless Networks and Mobile Computing* (pp.451–471)., Wiley.

Stojmenovic, I. (2004) 'Comments and corrections to 'dominating sets and neighbor elimination-based broadcasting algorithms in wireless networks'', *IEEE Transactions on Parallel and Distributed Systems*, Vol. 15, pp.1054–1055.

Stojmenovic, I. and Datta, S. (2004) 'Power and cost aware localized routing with guaranteed delivery in wireless networks', *Wireless Communications and Mobile Computing*, Vol. 4, pp.175–188.

Stojmenovic, I. and Lin, X. (2001a) 'Power-aware localized routing in wireless networks', *IEEE Transactions on Parallel and Distributed Systems*, Vol. 12, pp.1122–1133.

Stojmenovic, I. and Lin, X. (2001b) 'Loop-free hybrid single-path/flooding routing algorithms with guaranteed delivery for wireless networks', *IEEE Transactions on Parallel and Distributed Systems*, Vol. 12, pp.1023–1032.

Stojmenovic, I., Russell, M. and Vukojevic, B. (2000) 'Depth first search and location based localized routing and QoS routing in wireless networks', *IEEE International Conference on Parallel Processing*, August 21–24, Toronto, pp.173–180; 2002, *Computers and Informatics*, Vol. 21, pp.149–165.

Stojmenovic, I., Seddigh, M. and Zunic, J. (2002) 'Dominating sets and neighbor elimination based broadcasting algorithms in wireless networks', *IEEE Transactions on Parallel and Distributed Systems*, Vol. 13, pp.14–25.

Vukojevic, B., Goel, N., Kalaichevlan, K., Nayak, A. and Stojmenovic, I. (2007) 'Power aware depth first search based geo-routing in *ad hoc* and sensor wireless networks', *The Ninth IFIP/IEEE International Conference on Mobile and Wireless Communications Networks*, Cork, Ireland, 19–21 September, pp.141–145.

Wu, J., Dai, F., Gao, M. and Stojmenovic, I. (2002) 'On calculating power-aware connected dominating set for efficient routing in *ad hoc* wireless networks', *IEEE/KICS Journal of Communications and Networks*, Vol. 4, pp.59–70.