MAP : A Balanced Energy Consumption Routing Protocol for Wireless Sensor Networks

Mohamed Mostafa A. Azim*

Abstract—Network lifetime is a critical issue in Wireless Sensor Networks (WSNs). In which, a large number of sensor nodes communicate together to perform a predetermined sensing task. In such networks, the network life time depends mainly on the lifetime of the sensor nodes constituting the network. Therefore, it is essential to balance the energy consumption among all sensor nodes to ensure the network connectivity. In this paper, we propose an energy-efficient data routing protocol for wireless sensor networks. Contrary to the protocol proposed in [6], that always selects the path with minimum hop count to the base station, our proposed routing protocol may choose a longer path that will provide better distribution of the energy consumption among the sensor nodes. Simulation results indicate clearly that compared to the routing protocol proposed in [6], our proposed protocol evenly distributes the energy consumption among the network nodes thus maximizing the network life time.

1. INTRODUCTION

A Wireless Sensor Network (WSN) is a specific class of wireless Ad-Hoc networks in which hundreds or thousands of sensor nodes are collaborating together to accurately measure a physical phenomenon from the environment or to monitor a remote site. The sensor nodes constituting the network are battery-powered devices with limited energy, computation capability and storage. In a WSN, if one node dies, it could lead to a separation of the sensor network. Thus, every sensor node should live as long as possible to maximize the lifetime of the wireless sensor network.

Several routing protocols have been proposed in the current decade that considers the energy consumption problem attempting to balance the energy consumption in the sensor network and maximize the network lifetime. For example, Low-Energy Adaptive Clustering Hierarchy(LEACH) protocol [1], Threshold-sensitive Energy Efficient Network (TEEN) Protocol [2], Energy-Aware On-Demand Routing [3], Energy-Aware Routing [4], Power Aware Organization protocol [5] and Minimum-Hop Routing [6].

LEACH [1] is a cluster-based routing protocol that randomly selects a few sensor nodes as cluster heads and circulates this role to evenly distribute the energy load of sensor nodes. In

TEEN [2], sensor nodes sense the medium continuously, while data transmission is done in less frequency for saving energy. A cluster head sends its members two thresholds namely, the hard threshold and soft threshold. The node will transmit data only when the current value of the sensed attribute is greater than the hard threshold. The Energy-Aware On-Demand Routing [3] increases the lifetime of a network by routing around the nodes that are running low in battery. In addition, it turns off the radio interfaces dynamically during the periods when the nodes are idle. In Energy-Aware Routing [4], a set of sub-optimal paths are used. These paths are chosen by means of a probability function, which depends on the energy consumption of each path. In Power Aware Organization protocol [5], the sensor nodes are divided into disjointed sets covering the area to be monitored. In every set a single node can be activated while other nodes are set to a low-energy sleep state. With the Minimum-Hop Routing [6], an optimal path to the sink node is determined based on two metrics, the hop count and the energy level. The node with minimum hop count to the sink node is selected. When several nodes having the same hop count exist, the sensor node with the most energy should be chosen as the next recipient to relay data packets.

The use of minimum hop count or equivalently the shortest path routing protocol as the main criteria for selecting a route for data forwarding has the following drawbacks.

Firstly, nodes along different shortest paths become over utilized than other nodes. This uneven energy consumption results in energy holes in the monitored area, causing network partitioning. In this case, the sensed data will not be delivered to the sink. Thus, the network life time will be potentially decreased [7], [8]. Secondly, from both the energy consumption point of view and the capacity point of view, it is better to communicate using short multi-hop routes than using a long single hop route [9]. Therefore, we are motivated to propose our MAP routing protocol that overcomes the above mentioned shortcomings of the minimum hop protocol.

In this paper, we propose an energy-efficient, routing protocol for wireless sensor networks. Our proposed routing protocol is considered an enhanced version of the minimum hop routing protocol. Our approach is similar to that in [6] in flooding a special setup packet to establish a local routing table for every node in the network before data transmission actually takes place. The routing table consists of parent, sibling, and child nodes, together with their identification numbers and energy levels, within one hop distance. In contrast to [6], the proposed routing protocol may choose a longer path that will provide better distribution of the energy consumption among the sensor nodes.

The rest of the paper is organized as follows: Section 2 is a brief review on the related work. In section 3 we present our proposed routing scheme. The simulation environment and experimental results are discussed in Section 4. Conclusions are given in Section 5.

2. RELATED WORK

The authors in [6] proposed a min hop routing protocol. The proposed routing protocol chooses hop counts and battery power levels as criteria for determining the route between sensor nodes to save as much energy as possible in both computations and data communications.

In this protocol, nodes are given IDs based on their hop distance from the sink node as shown in Fig. 1. Nodes which are 1 hop apart from the sink are named as hop1. Those which are 2 hops away from sink are called hop2 and so on.
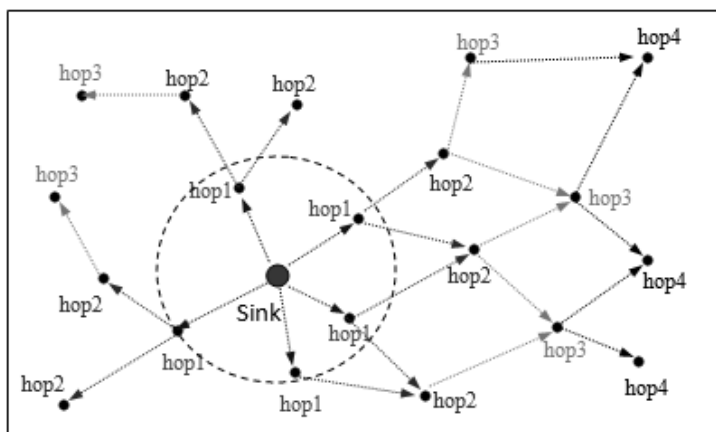
Fig. 1. The setup packet is flooded one more hop away[6]

Nodes in the routing table are classified into three categories namely, *parent node*, *sibling node* and *child node*. A parent node is a node in the transmission range of another sending node and having a hop count one less than the sending node. A sibling node is a node in the transmission range of another sending node having the same hop count as the sending node. A child node is a node in the transmission range of another sending node having a hop count one more than the sending node.

The min hop routing algorithm searches for an optimal path to the sink node by forwarding the data packet to a parent node (to guarantee a minimum hop path) that has the highest energy level among the parent nodes in its routing table. When several optimal paths exist, the sensor nodes that have the most energy should be chosen as the next recipient to relay data packets. Otherwise, if there is no parent node available, the sensor node forwards the data packets to a sibling node, which has the highest energy level among the sibling nodes in its routing table. Otherwise, if there is no sibling node available, the sensor node returns the data packet to its predecessor, i.e. the node where the packet came from. In this case, the predecessor removes the dead route by deleting the former designated node from the routing table and tries to find an alternative path. Although the minimum hop routing protocol improves the average energy consumption in the network, it has the following shortcoming.

Firstly, it is essential to balance the energy consumption among the sensor nodes to avoid early depletion of the network. However, in the minimum hop protocol [6] whenever the sensor node sends an event, the same route from the source node to the sink node is used. This leads to over utilizing some sensor nodes (along the minimum hop routes) while having other sensor nodes less exploited. This will potentially drain all the energy from nodes that are on several shortest paths thus leading to a loss of sensor nodes in some regions and the network's becoming partitioned.

Secondly, it is desirable to use short-range communication instead of long-range communication between sensor nodes because of the transmission power required [9]. To clarify this idea let's consider the case shown in figure 2. Suppose node *u* must send a packet to node *v*, which is at distance *d*. Node *v* is within *u*'s transmitting range at maximum power, so direct communication between u and v is possible. However, there exists also a node *w* in the region *C* circum-
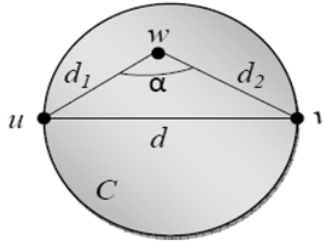
Fig. 2. The case for multihop communication

scribed by the circle of diameter d that intersects both u and v. let $\delta(a,b)$ be the distance between nodes a and b, respectively. Since $\delta(u,w) = d_1 < $ d and $\delta(v,w) = d_2 < d$, sending the packet using w as a relay is also possible. Which of the two alternatives is more convenient from the energy-consumption point of view?

For simplicity, assume the radio signal propagates according to the free space model and that we are interested in minimizing the transmit power only. With these assumptions, the power needed to send the message directly from u to v is proportional to d^2; in case the packet is re-layed by node w, the total power consumption is proportional to $d_1^2 + d_2^2$.

Consider the triangle $\widehat{uwv}$, and let α be the angle opposite to side uv. By elementary geometry, we have $d^2 = d_1^2 + d_2^2 - 2d1d2 \cos\gamma$. Since $w \in C$ implies that $\cos\alpha \le 0$, we have that $d^2 \ge d_1^2 + d_2^2$. It follows that, from the energy-consumption point of view, it is better to communicate using short, multi-hop paths between the sender and the receiver.

Finally, the amount of interference between concurrent transmissions is strictly related to the power used to transmit the messages [9]. We refer to Figure 3 to clarify this important point with an example. Assume that node u must send a message to node v, which is experiencing a certain interference level I from other concurrent radio communications. For simplicity, we treat I as a received power level, and we assume that a packet sent to v can be correctly received only if the intensity of the received signal is at least $(1 + \eta)I$, for some positive η. If the current transmit power P used by u is such that the received power at v is below $(1+ \eta)I$, we can ensure correct
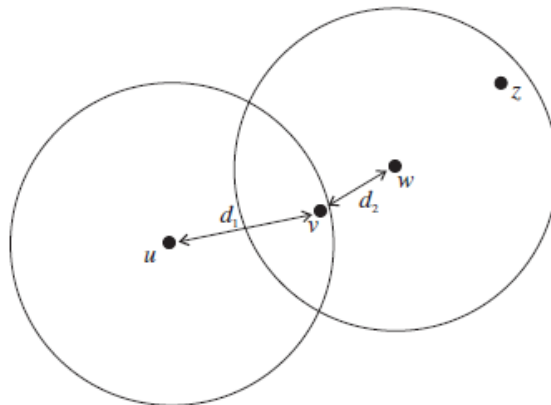

Fig. 3. Conflicting wireless transmissions [9]. The circles represent the radio coverage area with transmit power P

message reception by increasing the transmit power to a certain value $P' > P$ such that the received power at v is above $(1 + \eta)I$. This seems to indicate that increasing transmit power is a good choice to avoid packet drops due to interference. On the other hand, increasing the transmit power at u increases the level of interference experienced by the other nodes in u's surroundings. So, there is a trade-off between the 'local view' (u sending a packet to v) and the 'network view' (reducing the interference level in the whole network): in the former case, a high transmit power is desirable, while in the latter case, the transmit power should be as low as possible. The following question then arises: how should the transmit power be set, if the designer's goal is to maximize the network traffic carrying capacity?

The author in [9] proved that, from the network capacity point of view, it is better to communicate using short, multi-hop paths between the sender and the destination.

Therefore, due to the above mentioned limitations, we have been motivated to propose our MAP routing protocol that overcomes the above mentioned shortcomings of the minimum hop protocol.

3. PROPOSED MAXIMUM AVAILABLE POWER PROTOCOL

In this paper we propose an efficient energy-aware routing protocol for wireless sensor networks. The main idea of the proposed protocol is based on selecting the route with Maximum Available Power (MAP). Our proposed protocol overcomes the shortcomings of the minimum hop protocol described above.

In our protocol, to establish the routing tables, the sink node broadcasts a setup packet to all sensor nodes within its one-hop distance. All the receiving nodes within one hop from the sink node increase the hop count by 1 and mark the sink node as their parent by registering its hop count, ID number and energy level on their routing tables. Then, each of the recipient nodes will broadcast a setup packet to its neighbors to update their routing tables and hop counts. Similar to the minimum hop count protocol [9], nodes in the routing table are classified into three categories namely, parent nodes, sibling nodes and child nodes.

Unlike the minimum hop count protocol, in the proposed MAP routing protocol each node selects its next hop from the list of parent nodes as well as the list of sibling nodes of the routing table based on the energy level. The node with maximum power will be selected. Therefore, instead of using the same route (min-hop) from a node to the sink node, MAP may find an alternate route to the sink node through one of the sibling nodes that has a better energy level than all available parent nodes. Thus, distributing the routing load between parent nodes and sibling nodes equally based on their energy level. To clarify this idea let's consider the following example shown in figure 4. In which, the source node A needs to send a message to the sink nodes S.

Consider the routing table at node A as shown in table 1 and the power level at each node is set as follows:

$P_A = 7$, $P_B = 5$, $P_C = 7$, $P_D = 8$, $P_E = 4$.

According to the minimum hop protocol, node A has two parent nodes; node B and node E. Node A also has one sibling node; node C. Note that, node D is out of the radio range of node A.

Then node B will be selected as the next hop because it is the parent node with maximum
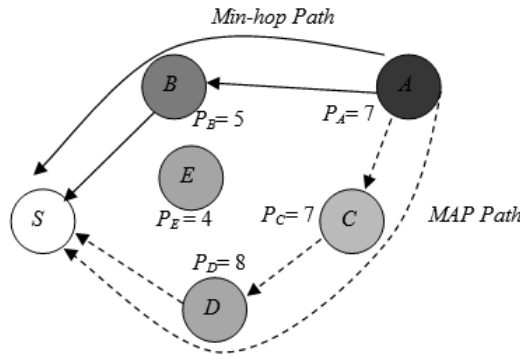
Fig. 4. A sample network scenario

Table 1. The routing table at node A

Next Node ID	No. of Hops to Sink	Energy level	Node classification
B	1	5	Parent
E	1	4	Parent
C	2	7	Sibling

power. Thus the selected path is (A➔B➔S).

Alternatively, in MAP protocol, we choose the next hop from the list of parent and sibling nodes based on the maximum power. In other words, regardless of whether the classification of a node is a parent node or a sibling node, we select the node with maximum available power. In this way, we guarantee that all parent nodes and sibling nodes will be employed in the routing process evenly.   Hence, all sensor nodes will almost have the same rate of battery depletion and the network life time is maximized. Moreover, the nodes will be communicating through multiple short hops-- one of the potential advantages of our proposed scheme.

In our protocol, when the energy level of a node goes below a certain threshold, it indicates that the node is dying out. In this case, the dying-out node sends a delete packet to all the sensor nodes in its routing table. Each of the receiving nodes reacts to the delete packet by deleting the dying-out node from its routing table.

Therefore, we can conclude that, the main advantage of the Min-hop protocol is the ability to forward data within a predetermined maximum number of hops while, in the MAP protocol, forwarding data back and forth between two sibling nodes due to their having similar energy levels (which we call "data bouncing") may result in longer communication paths. Therefore in our simulation if data is received from a sibling node it cannot be returned back to the sending node again. The main advantage of the MAP protocol is its ability to evenly distribute the routing load among all network nodes thus maximizing the network lifetime.

4. EXPERIMENTAL RESULTS

In this section, we compare the performance of our proposed method with Min-Hop Routing [6]. In this comparative experiment, we used a simple abstract energy model rather than a par-

ticular one to compute energy consumption in one data packet delivery. It is well known that in wireless sensor network communications, idle listening or signal transmitting/receiving consumes much more energy of a sensor node than does the calculation of an optimal path or memory accessing. Therefore, in our simulations, the energy consumption of calculation and memory accessing is not considered. This model assumed that, from a pure energy/bit standpoint, the sensor nodes spent 1.0 and 2.0 energy units respectively, for transmitting and receiving one data bit. Thus, for a data packet 1 Kbit long, the energy for relaying (transmitting and receiving) one data packet is 3000 energy units.

Experiments were carried out using a random network topology. In which sensor nodes were randomly scattered in a fixed 50×50 m2 deployed area, and the sink node was located at the lower left corner. The number of sensor nodes changed from 50 to 150 with increments of 25. Each sensor node had a maximum transmission range of 10 m and a detection range of 5 m. Before data delivery, the routing table has been set up at each sensor node. The energy dissipated in the routing table establishment process was not included in the total energy consumption, because both of the MAP protocol and Minimum-Hop protocol use a technique similar to the classic flooding method to establish the routing table.

To make a fair comparison, in each test, each scheme used exactly the same network topology where we introduce a fire in a random location. Sensors that are close to the fire location detect an increase in temperature and report this increase to the base station by sending one data packet to the sink node, using the two different schemes under comparison. The size of the data packet was 1 Kbit, including the header.

Meanwhile, we registered different performance metrics and we will demonstrate these results hereafter. The performance metrics used are the number of successful packet transmissions from nodes detecting the fire to the base station, the average hop length of a connection, the normalized energy consumption in the network and the number of sensors remaining alive (2 cases) and their corresponding results are shown in Fig 5, Fig 6, Fig. 7, Fig. 8, Fig. 9, respectively.

Note: When the number of sensors is 50 only one sensor could detect the fire. When the number of sensors is between 75 and 100, two sensors were in the fire range. When the number of sensors is between 125 and 150, three sensors could sense the existence of a fire.

The number of successful transmissions shown in Fig. 5, is an indication of the network lifetime. Networks with a greater number of successful transmissions indicate a longer lifetime. On the other hand, networks with fewer numbers of successful transmissions imply shorter lifetime due to the early depletion of the unchangeable batteries of its sensor nodes.

The results in Fig. 5 show that, when the number of sensors is 50, the number of successful transmissions from the sensing node to the sink node is 16 and 32 when using the Min-hop routing and the MAP routing protocols, respectively. This indicates that our proposed protocol balances the energy consumption all over the network, thus prolonging the network lifetime.

Another interesting observation is that, with MAP routing, by increasing the number of sensors from 75 to 100, the number of successful transmissions increased from 43 to 58. However, for the same numbers of sensors, using the Min-Hop count routing provides the same number of accepted transmission in both cases. This is due to the fact that, when the number of sensors is 75, only two sensors were close to the fire location and only these two sensors could detect the fire. By increasing the number of sensor nodes from 75 to 100 we expect that more sensors will
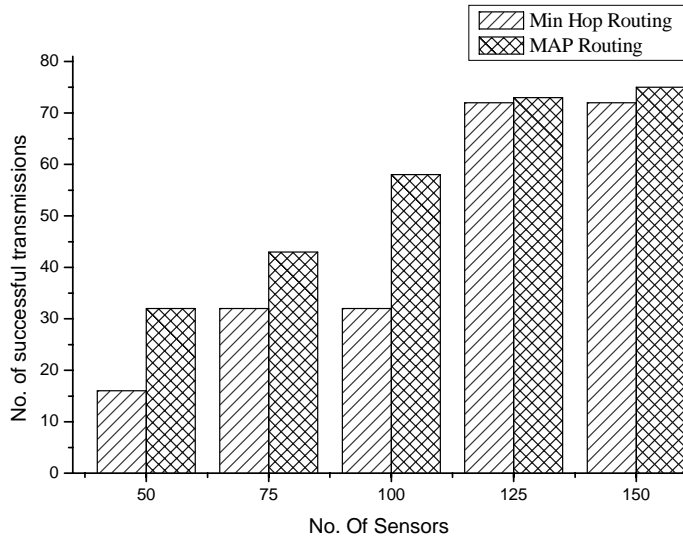
Fig. 5. The number of successful transmissions to sink node

detect the fire. However, due to the random generation of the sensors' locations, we found that, the fire was out of the sensing range of the newly added sensors. In this case, the Min-Hop protocol did not make use of the topology changes due to its selection of the route with the minimum number of hops (i.e. the number of successful transmissions was the same) while, the MAP protocol could benefit from these changes in the topology by evenly distributing the routing load among all nodes (including newly added nodes) and hence the number of successful transmissions was increased.

The same scenario happens when the number of sensors increases from 125 to 150, except that 3 sensors have detected the fire instead of two.

The results shown in Fig. 6 indicate that, with Minimum hop count routing, the increase in the hop length with the increase in the number of sensors is slight. This is because of using a set of shortest paths that might not change with increasing the number of sensor nodes in the network. Hence, nodes along these shortest paths will have their batteries depleted before the other less-utilized network nodes and the network will become disconnected at some regions.

On the other hand, the results in Figure 6 show that, with MAP routing protocol, the average hop length increases by increasing the number of sensors. This confirms that our proposed routing protocol balances the routing load on larger numbers of sensor nodes hence utilizing their batteries evenly. Thus, with our proposed MAP routing protocol the network lifespan can be significantly maximized.

The results shown in Fig. 7 show that, the normalized energy consumed in the network employing MAP protocol is generally higher than that employing the Min-Hop routing protocol. This is due to the fact that, referring to Fig. 4, the total number of packets that are successfully delivered to the sink node when using the MAP protocol is more than that using the Min-hop protocol. Thus, this increase in energy consumption is used to deliver more data packets.
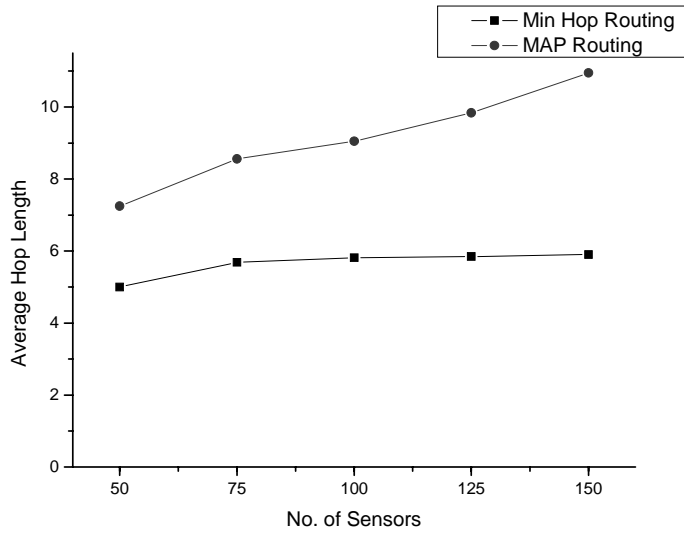
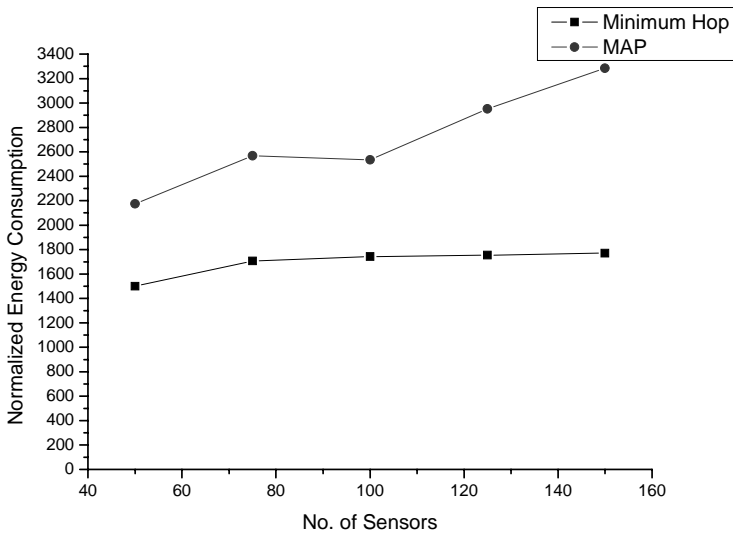Fig. 6. The Average Hop Length

Fig. 7. Normalized Energy Consumption

To fully understand the performance of our proposed protocol, we have to estimate the network lifetime. Therefore, we simulated the performance of both protocols in terms of the number of nodes alive versus the simulation time or number of simulation rounds in the following two cases. When the number of sensor nodes in the network is 100 and only one sensor can detect the fire due to its randomized location, the corresponding result is shown in Fig.7. Similar results are also reported in Figure 8, where 2 sensor nodes can detect the fire.

In the result shown in Fig. 8, it is clear that, the death of the first sensor node happens at round 16 and round 44 for the networks employing the Min-Hop and MAP routing protocol,
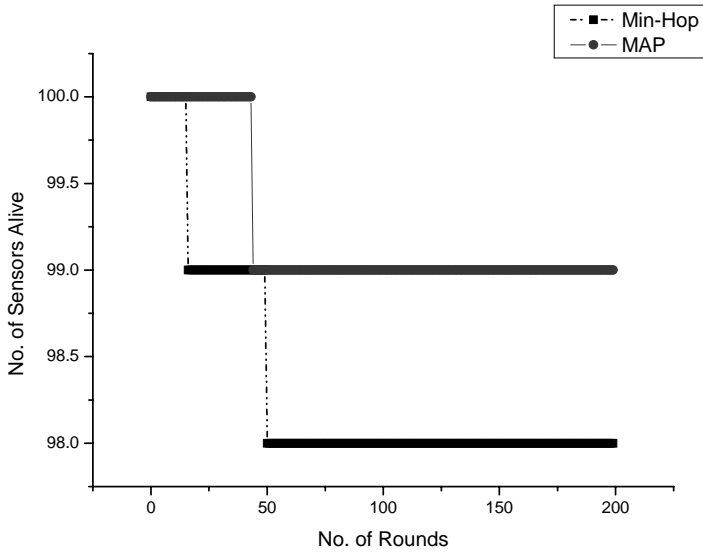
Fig. 8. No. of Sensors Alive (with a network of 100 sensors-- 1 sensor detects the fire)

respectively. This clearly shows the ability of the MAP protocol to enable networks to survive for a longer time.

Note that, when the number of nodes alive reaches its steady state value this indicates that one or more of the sensors along the path has died-out and the network has become disconnected and thus no further packets can be delivered to the sink node.

The results shown in Fig. 9 demonstrate that, with the MAP protocol the number of nodes
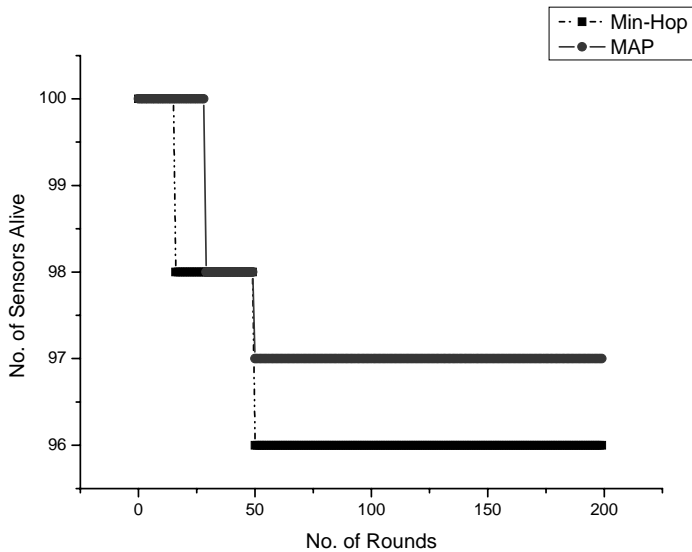

Fig. 9. No. of Sensors Alive (with a network of 100 sensors-- 2 sensor detect the fire)

alive is higher than that with the Min-Hop protocol in most of the simulation rounds. This demonstrates the ability of our proposed protocol to prolong the network lifetime by evenly distributing energy consumption among all sensor nodes.

5. CONCLUSIONS

We have presented an energy-efficient routing scheme for the wireless sensor networks. In this protocol, we choose the route with maximum available power for data forwarding.

Extensive simulations show that, in comparisons between the minimum hop protocol and the MAP routing protocol, the number of data packets delivered successfully to the sink node is significantly increased and the depletion rate of the sensor nodes is reduced. In summary, with the MAP routing protocol, the battery power of the network is utilized efficiently and evenly among all the sensor nodes. Therefore, we conclude that WSNs employing MAP routing protocol will have longer life spans.

REFERENCES

[1] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks," IEEE Transactions on Wireless Communications, Vol.1, No.4, pp.660-670, Oct., 2002.

[2] A. Manjeshwar and D. P. Agrawal, "TEEN : A Protocol for Enhanced Efficiency in Wireless Sensor Networks," in the Proceedings of the 1st International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing, San Francisco, CA, April, 2001.

[3] N. Gupta and S. R. Das, "Energy Aware On-Demand Routing for Mobile Ad Hoc Networks," Proc. 4th International Workshop on Distributed Computing, pp.164-173, Dec., 2002.

[4] R. Shah and J. Rabaey, "Energy Aware Routing for Low Energy Ad Hoc Sensor Networks," in the Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), Orlando, FL, March, 2002.

[5] Mihaela Cardei, Ding-Zhu Du, Improving Wireless Sensor Network Lifetime through Power Aware Organization, ACM Wireless Networks, Vol.11, 2005.

[6] Shao-Shan Chiang, Chih-Hung Huang, Kuang-Chiung Chang, "A Minimum Hop routing Protocol for Home Security Systems Using Wireless Sensor Networks," IEEE Transactions on Consumer Electronics, Vol.53, Issue 4, pp.1483-1489, Nov., 2007.

[7] J. Li, P. Mohapatra, "Analytical modeling and mitigation techniques for the energy hole problem in sensor networks," Pervasive and Mobile Computing, Vol.3, pp.233-254, 2007.

[8] M. Marta, M. Cardei, "Improved sensor network lifetime with multiple mobile sinks," Elsevier Journal of Pervasive and Mobile Computing Vol.5, pp.542-555, October, 2009.

[9] Paolo Santi, "Topology Control in Wireless Ad Hoc and Sensor Networks," John Wiey & Sons, 2005, ISBN: 978-0-470-09453-2

Mohamed Mostafa A. Azim

He received a BSc degree in electrical engineering from Cairo University in 1994, an MS degree from the Technical University Eindhoven, Netherlands, in 1997, and his PhD degree in computer science from Tohoku University, Japan, in 2006. He is the author of several research papers published in the most reputable journals and conferences. His current research interests are optical networks survivability, routing and security protocols for wireless sensor networks.