Wireless Sensor Networks – Routing Impact on Energy Distribution and Energy Hole Formation

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Abstract

In this paper we investigate the impact of different routing techniques on energy consumption in sensor networks with a central node. When multi-hop transmissions are used the sensors stationed closer to the central node will have to relay a large amount of traffic and expend their batteries faster. This leads to the "energy hole" problem ultimately resulting in reduced network life. We use a sensor network simulator to test the effectiveness of several routing techniques for homogenous networks and compare them to heterogenous networks using relay nodes to determine the best approach in terms of network life.

Keywords: Smart routing, sensor networks, energy hole problem, many-to-one communication model, energy consumption, green communication.

1 Introduction

A lot of research has been done recently on wireless sensor networks and this trend will continue as they are becoming a more and more important part of our life [1, 2]. Sensor networks are typically formed from a number of nodes in order to monitor a specific kind of activity. These range from

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home environment applications [3], mapping applications [4], weather and seismic measurements [1] or even battlefield monitoring. Such nodes are usually limited foremost by size and the need to operate without infrastructure like power lines or communication lines. This leads to fundamental limitations in battery power (network life), computational power and transmission capabilities (communication range). Much effort is directed today towards pushing these limitations [5–7], although battery power remains the biggest concern. This paper focuses on uneven energy consumption in large scale sensor many-to-one networks with a central data-gathering node.

Sensor networks can be categorized by their data traffic pattern into one-to-many or many-to-one networks. One-to-many network has each node disseminating its data towards other interested nodes. A special case is a many-to-many communication network where data is transferred between pairs of nodes. In a many-to-one sensor network all of the nodes are sending their sensing data towards a central node, typically a base station. This central node then either stores this information or carries specialized relay-communication equipment (such as a satellite dish or long range wireless modem). Such networks are typically used for environment monitoring and surveillance [8, 9].

Scalability problems in routing and energy consumption occur when such many-to-one networks are used to cover a large area requiring more than one hop in communication as well as a large number of devices in order to adequately monitor the environment. One of the problems occuring in such large scale sensor networks is an uneven energy consumption rate, particularly around the central node. Nodes close to the central one have to relay more traffic than the outlying nodes, resulting in faster energy consumption. These nodes are then the first to drain their energy supply leading to a dead battery area around the central node. This is called an “energy hole” problem [10].

Different routing techniques can partially mitigate this problem by sending some nodes to sleep in order to spread the routing load, however this does not completely remove it. Clustering and data aggregation have most often been proposed as a solution. Such networks can easily be scaled due to their multi-hierarchy architecture used to channel data to local relay nodes which then proceed to transmit information directly to the central base station or by relaying it between themselves [11, 12].

We have developed a sensor network simulator for real-case scenario simulations in both physical and mac layer, supporting many different routing techniques, including greedy forwarding, multi-hop smart routing, shotgun forwarding and flooding [13]. We use it to investigate the impact of the energy hole problem on different routing techniques and to investigate how clustering affects such networks. Of particular interest are data congestion and total network life in terms of time and reported events per unit of energy. We have done extensive simulations on the performance of different routing techniques, some of which are presented in [14]. This paper expands on that work and gives new simulations showing the effects of clustering.

Section 2 of this paper gives a short background on the energy hole problem and typical solutions used in sensor networks. Section 3 details simulation setup, assumptions and parameters used. Section 4 presents simulation results in terms of network lifetime, energy efficiency and battery usage through different parts of the network. Section 5 contains concluding remarks.

2 Background

2.1 The "Energy Hole" Problem

Data in many-to-one networks is transmitted to the central base station using multi-hop routing. If we assume maximum range R of an individual node, then nodes within R circle radius around the central base station can transmit their data with a single direct link (Figure 1). However, nodes with distance between R and $2R$ from the central node (second circle) have to transmit their information through the nodes within the first circle. This creates additional load on the first circle nodes as they need to spend additional energy to first receive the data packets and then to forward them towards the central node. It is clear that nodes within this circle will run out of battery power first, thus creating a no-pass zone around the central node and preventing any data gathering even if the central node is still operational and outlying nodes continue to monitor the environment. We assume here that packets can traverse the first circle using a single hop which may not always be the case in real-case scenarios.

Assuming same node density within both circles it follows that for each packet generated within the first circle there are three packets generated within the second circle as it has three times the surface area. That means that nodes within the first circle have to relay three times as many events as they themselves generate. This problem is further compounded if the nodes within first circle are not in sleep mode and have to receive parts of each

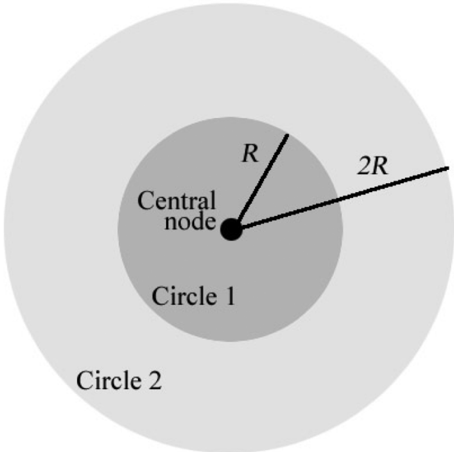

Figure 1 Simplified energy hole problem with nodes in first circle having to relay the second circle information on top of their own data.

incoming data packet before they can determine whether they belong to its multi-hop transmission path.

Sensor network lifetime is usually defined as the time period within which the network can maintain its functionality by covering the designated area and sending data with good reporting rate. In this paper it is defined as the time until the first node dies. It is of big importance to see where the first nodes cease to function and to compare that to the energy distribution through the network. A better network will drain the batteries of its nodes more evenly. Other big factors are to see how many events the network is able to report during its lifetime and how long can it keep actively monitoring the environment.

2.2 Energy Conservation Approaches

The very basic form of network uses unguided routing and simply spreads the sensed data to the whole network (flood routing). This is a very inefficient form of communication so other approaches like location aware routing where nodes forward the packet only if they are closer to the destination from the previous hop (location aware routing) are used, but this still results in a large number of excessive transmissions. Targeted transmissions such as greedy forwarding are typically employed in sensor networks. A node wishing to transmit uses maximum transmission power in order to send the

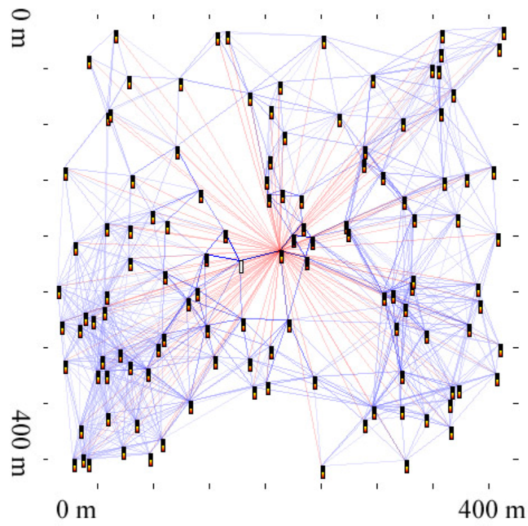

Figure 2 Smart routing in an ad-hoc network. Lines represent data transmission paths with stronger lines representing paths used more often.

packet as far towards its destination as it can. This however causes a lot of interference and often uses more power than necessary.

Smart routing algorithms consider network topology and select the best possible multi-hop transmission path, employing only the minimal required power in each of the hops. However, these are most computationally intensive out of the mentioned routing protocols and require dissemination of up-to-date network topology to operate efficiently. Figure 2 shows an implementation of smart routing in an ad-hoc network. Lines represent connections between the nodes, and strength (intensity) of each line shows how often it is used for communication – stronger lines are used more often. Lines typically run from outside nodes towards nearest nodes and the middle. Nodes are represented by small rectangle bars placed at their positions showing current battery status (the more empty the battery becomes, the lower its battery level indicator will be).

Deployment assistance in the form of clustering is often used to combat the energy hole problem. Several relay nodes are distributed around the network area, each receiving a sub- region from which to collect data and forward to the central node using its own (often enhanced) transmission power. These can be used in conjunction with any of the mentioned routing proto-

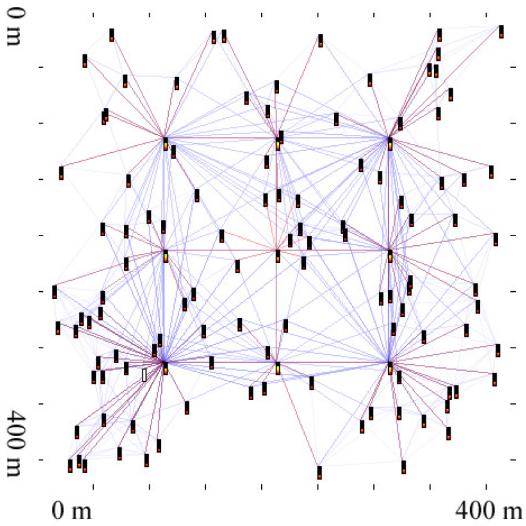

Figure 3 Routing in a hierarchial network. Connections run towards the nearest relay nodes from where they are routed towards the central node.

cols. In this paper we will focus on relay nodes using the same transceiver cirquits as the rest of the network, but having enhanced batteries to cope with the additional load. Such networks utilizing relay nodes are hierarchical in nature and have distinctive traffic patterns, as can be seen in Figure 3. Connections in such a network typically run from regular nodes towards the nearest relay node, and then from them towards the central base station.

3 EnVO Simulator and Network Parameters

EnVO network routing simulator was developed in MATLAB programming language with the purpose of testing the influence of various routing protocols in a realistic ad-hoc wireless network [15]. It was further developed into encompassing hierarchical approaches. EnVO routing simulator incorporates the common routing schemes – flood routing, shotgun routing, greedy forwarding, and two smart power control routing algorithms – one based on best hop routing, the other on two-hop path-finding. A general review on current routing methods in ad-hoc networks can be found in [13, 16]. It also enables simulation of hierarchical networks using local relay nodes.

Data transfer rate, environment interference levels, network throughput, node battery levels and network life are monitored using same network topography and simulation parameters with different routing protocols.

Several assumptions have been used in simulation:

- Nodes are randomly distributed over simulation area using a uniform distribution.
- Network is well connected.
- Routing tables have been established, relay nodes selected, and network data required for specific routing protocol disseminated to every node.
- Each sensor node starts in idle mode monitoring the environment and sensing radio traffic in its area.
- Events occur randomly through network with uniform distribution.
- Network is event driven, although simulation results are valid for time driven networks as events are generated at the same rate.
- Each sensor node has the same likelihood to notice an event while operating in monitoring mode. A report is generated in the form of a data packet and sent to the central node.
- All sensor nodes have the same transceiver circuits requiring same signal levels for successful reception.
- All regular nodes have the same batteries, fully charged, while relay nodes and the central node carry batteries with three times higher capacity.

In our simulations we consider a square area of 400 by 400 m with a base station located in the center of the map and 200 nodes spread through the environment equalling node density of 1 node per 800 m^2 (approximately 28 m average distance between neighbouring nodes). Same node locations have been used for all routing protocols.

Communication protocols include collision avoidance using radio sensing and random back-off time. Network operates using 1 Mbps data rate, with each event report carrying 1 kb of data. Events are randomly generated at the average rate of 10 events per second. Nodes are able to operate with transmission levels between 1 and 100 mW and have −95 dBW receiver sensitivity resulting in a maximum range of 169 m. Nodes are categorized into four concentric circles equalling half a hop distance radius increase (85 m) to better follow battery levels. The central node's battery levels are monitored separately.

Nodes have 1 J battery capacity, while central and other relay nodes have 3 J battery capacity. Energy consumption of each node is as follows:

- 1 mW while idle.
- 60 mW during packet negotiation sensing.
- 135 mW while receiving data.
- 45 mW for transmission processing.
- Between 1 and 100 mW during data transmission.

4 Simulation Results

Simulations have been run on the same network topology for each of the routing schemes to determine the best approach for large scale networks. Average battery levels relative to their starting value for each of the concentric circle areas around central node at the end of network lifetime are shown in Table 1. As expected, there is an uneven distribution of energy between circles, especially in the case of flood routing, shotgun routing and SLAM routing. Shotgun routing and SLAM routing in particular suffered network failure with still very high battery levels, indicating large variety in energy consumption between different nodes within the network. Both greedy forwarding and and optimal multi-hop routing benefitted from the use of clustering, spreading the load within the network more evenly.

Table 2 shows network parameters at the end of network lifetime. Time before first node battery failure measured in seconds is displayed in the first column. Greedy forwarding and optimal multi-hop routing are clearly the best routing methods regarding network lifetime, with similar results. Optimal multi-hop with clustering achieved the best network lifetime of 645 seconds. This is for a communication network operating in 5% load range with 1 J stored energy per battery at the start of simulation. The number of reported events during network life, both as absolute and as a percentage of actual occured events is given in column 2. It is clear from this that flood routing did not benefit from clustering, quite the opposite. Shotgun routing had a small reduction in required energy per reported event, but also performed badly with less than half events reported. These are the results of a too high network load for these routing protocols. It is clear that they cannot handle a 5% network load (average data stream of 50 kbps in a 1 Mbps network). Greedy forwarding and optimal multi-hop performed much better and benefited further from clustering. Optimal multi-hop in particular achieved a very high network life time with nearly perfect event report record at 99% without and 96% with clustering. The difference was lost in packet collisions, mostly at the relay nodes, and can be further avoided by aggregating data into bigger packets.

Table 1 Average relative battery levels in each of the circle at the end of network lifetime.

	Central node	First circle (R/2)	Second circle (R)	Thirdcircle (3/2 R)	Fourth circle (2R)
Flood routing	65%	33%	30%	17%	8%
Flood + clustering	78%	32%	35%	15%	8%
Shotgun routing	46%	10%	17%	46%	71%
Shotgun + clustering	53%	14%	35%	57%	76%
SLAM routing	59%	50%	76%	85%	88%
SLAM + clustering	68%	54%	53%	56%	60%
Greedy forwarding	55%	19%	30%	41%	45%
Greedy + clustering	43%	7%	23%	25%	30%
Optimal multi-hop	53%	30%	43%	47%	49%
Optimal + clustering	38%	16%	25%	25%	26%

The third column shows the amount of energy used per successfully reported event. Flood routing and shotgun routing – both a very basic routing protocols, performed poorly, requiring an order or even two orders of magnitude more power per reported event compared to the more advanced routing schemes. SLAM routing had good energy consumption rate, especially with clustering as it greatly reduced the load off the nodes close to the central base station. However, better results were achieved with greedy forwarding

Table 2 Network parameters at the end of the simulation for each of the routing algorithms.

	Network lifetime	Reported events	Energy used per event	Interference levels
Flood routing	55s	166 (30%)	900 mJ	-68 dBW
Flood + clustering	56 s	28 (5%)	5240 mJ	-68 dBW
Shotgun routing	79 s	341 (43%)	400 mJ	-68 dBW
Shotgun + clustering	78 s	345 (44%)	330 mJ	-68 dBW
SLAM routing	99 s	869 (87%)	53 mJ	-72 dBW
SLAM + clustering	319 s	2385 (74%)	37 mJ	-70 dBW
Greedy forwarding	470 s	4548 (96%)	28 mJ	-68 dBW
Greedy + clustering	553 s	5227 (94%)	29 mJ	-68 dBW
Optimal multi-hop	479 s	4767 (99%)	23 mJ	-75 dBW
Optimal + clustering	645 s	6228 (96%)	24 mJ	-77 dBW

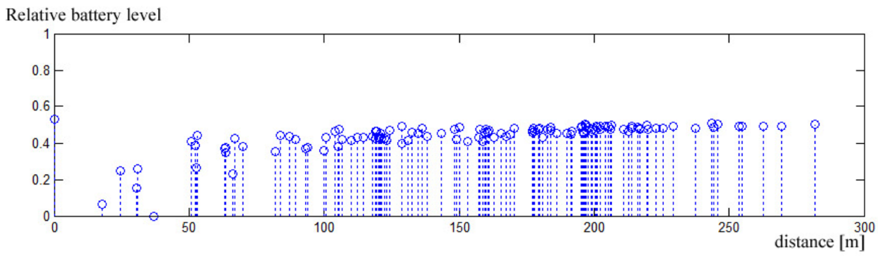

Figure 4 Battery levels at the end of simulation using optimal multi-hop routing without clustering. Nodes with shorter distance from the central node lose battery power faster, resulting in network outage while most of the batteries are still around 50%.

and even more so with optimal multi-hop, requiring only 23 mJ per reported event (1 kb of relayed data).

Finally, the fifth column shows the average interference level through the area covered by network, an important information if the network is to operate below a certain treshold so as not to disrupt existing communication networks within the area, or to stay below detection levels during a conflict. While most routing protocols had similar interference levels, optimal multi-hop achieved a 7–9 dB lower level of interference through the network area, a significant improvement.

Figure 4 shows node relative battery levels for optimal multi-hop routing at the end of network life plotted against the distance from the central base station. Without clustering the nodes closer to the central base station lose energy faster, resulting in much lower battery levels and inevitable drop of nodes from the network. Nodes within the first 50 m from the central base station all had under 30% of battery energy left, while those farther than 50 m (approximately one third of the maximum transmission range) still had on average around 50% battery energy left.

Figure 5 shows the same routing protocol combined with node clustering. A much lower overal battery level can be observed through the network at the end of its lifetime. The node that caused the dropout for this case was actually at a distance of 160 m, practically at the maximum transmission range from the central base station. The few nodes with high battery levels positioned around 100 and 140 m are in fact the relay nodes which start with three times higher battery capacity and levels which they need in order to handle the increased amount of traffic occuring over them. The average node in the network had only around 15–30% energy left in its battery, practically avoiding the energy hole problem.

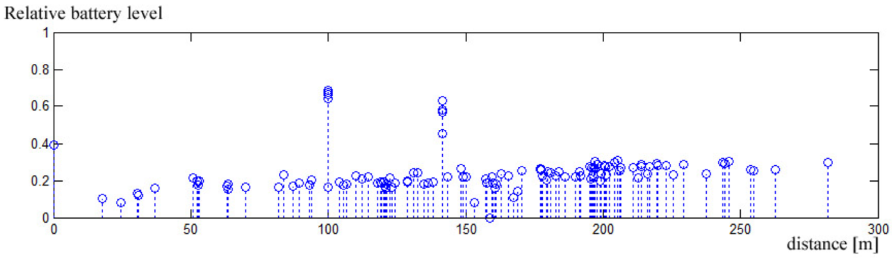

Figure 5 Battery levels at the end of simulation using clustering with optimal multi-hop routing. Remaining battery levels in the network are much lower when compared to the case without clustering, averaging at 15–30%. Several peaks in remaining battery power occurring around 100 and 140 m are from relay nodes which start with three times higher battery capacity.

5 Conclusion

In this paper we addressed the energy hole problem of uneven energy consumption in large scale wireless sensor networks. Several common routing protocols were compared with the advanced smart routing and multi-hop optimization in regards to network lifetime, efficiency of energy use, interference and battery consumption. Impact of clustering on each routing scheme and on reduction of the energy hole problem was considered.

The best results with and without clustering were obtained by optimal multi-hop routing which calculates the best direct path towards the target node and then optimizes it for multi-hop transmission. It achieved a network lifetime of 645 s (20% higher from greedy forwarding) with an average useful data rate of 50 kBps relayed over distance of up to 300 m and only 1 J starting battery power (average energy use of 24 mJ per each 1kb packet). It had an even energy consumption throughout the whole network and practically avoided the energy hole problem.

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Biographies

Damir Zrno received his dipl.ing. degree in electrical engineering from the University of Zagreb, Croatia in 2002, and his joint Ph.D degree from both University of Zagreb, Croatia and Aalborg University, Denmark in 2010. Since 2002, he has worked at Faculty of Electrical Engineering and Computing in Zagreb, Croatia as a research assistant on several projects in the area of radio communications including network planning, SAR measurements, radio propagation modeling, radio localization, cognitive network simulation and optimization.

Dina Simunic is a full professor at the University of Zagreb, Faculty of Electrical Engineering and Computing in Zagreb, Croatia. She graduated in 1995 from the University of Technology in Graz, Austria. In 1997 she was a visiting professor in Wandel & Goltermann Research Laboratory in Germany, as well as in Motorola Inc., Florida Corporate Electromagnetics Laboratory, USA, where she worked on measurement techniques, later on applied in IEEE Standard. In 2003 she was a collaborator of USA FDA on scientific project of medical interference. Dr. Simunic is a IEEE Senior Member, and acts as a reviewer of *IEEE Transactions on Microwave Theory and Techniques*, *Biomedical Engineering and Bioelectromagnetics*, *JOSE*, and as a reviewer of many papers on various scientific conferences (e.g., IEEE on Electromagnetic Compatibility). She was a reviewer of Belgian and Dutch Government scientific projects, of the EU FP programs, as well as of COST-ICT and COST-TDP actions. She is author or co-author of approximately 100 publications in various journals and books, as well as her student text for wireless communications, entitled: *Microwave Communications Basics*. She is co-editor of the book *Towards Green ICT*, published in 2010. She is also editor-in-chief of the *Journal of Green Engineering*. Her research work comprises electromagnetic fields dosimetry, wireless communications theory and its various applications (e.g., in intelligent transport systems, body area networks, crisis management, security, green communications). She serves as Chair of the "Standards in Telecommunications" at Croatian Standardization Institute. She servers as a member of the core group of Erasmus Mundus "Mobility for Life".

Ramjee Prasad (R) is currently the Director of the Center for TeleInfrastruktur (CTIF) at Aalborg University (AAU), Denmark and Professor, Wireless Information Multimedia Communication Chair. He is the Founding Chairman of the Global ICT Standardisation Forum for India (GISFI: www.gisfi.org) established in 2009. GISFI has the purpose of increasing the collaboration between European, Indian, Japanese, North-American, and other worldwide standardization activities in the area of Information and Communication Technology (ICT) and related application areas. He was the Founding Chairman of the HERMES Partnership – a network of leading independent European research centres established in 1997, of which he is now the Honorary Chair.

Ramjee Prasad is the founding editor-in-chief of the Springer *International Journal on Wireless Personal Communications*. He is a member of the editorial board of several other renowned international journals, including those of River Publishers. He is a member of the Steering, Advisory, and Technical Program committees of many renowned annual international conferences, including Wireless Personal Multimedia Communications Symposium (WPMC) and Wireless VITAE. He is a Fellow of the Institute of Electrical and Electronic Engineers (IEEE), USA, the Institution of Electronics and Telecommunications Engineers (IETE), India, the Institution of Engineering and Technology (IET), UK, and a member of the Netherlands Electronics and Radio Society (NERG) and the Danish Engineering Society (IDA). He is also a Knight ("Ridder") of the Order of Dannebrog (2010), a distinguishment awarded by the Queen of Denmark.