Research Journal of

Information Technology

ISSN 1815-7432

Academic
Journals Inc.

www.academicjournals.com

Research Journal of Information Technology 3 (3): 167-180, 2011
ISSN 1815-7432 / DOI: 10.3923/rjit.2011.167.180

Energy Holes Mitigation Techniques in Sink's Proximity using Sensor Deployment in Wireless Sensor Networks

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ABSTRACT

Traffic patterns in WSNs follow a converge-cast (M:1) pattern, wherein nodes closer to a sink carry heavy traffic loads compared to those on peripheries. Such excess load results in depletion of available energy at an increased rate and ultimately leads to formation of energy holes around the sink. This implies non-deliverance of data to sink along certain paths and the residual total network lifetime is affected. A study on the residual network lifetime and data delivery for uniform deployments is suggested. The results show that 80% of the accumulative network energy can be left unused if the network lifetime ends. Two strategies have been proposed so as to maximize network lifetime by reducing hot-spots in sink vicinity. First, for Gaussian deployments, a correlation between network lifetime and quantity of sink-neighboring nodes has been observed. Second, for heterogeneous deployments, a correlation between network lifetime and increased energy levels of sink-neighboring nodes has been observed. In both cases, the network lifetime is capped beyond a certain threshold. Simulation results confirm both the proposed strategies by recording an increased network lifetime.

Key words: Wireless sensor networks, energy holes, network lifetime, lifetime optimization, deployment strategies

INTRODUCTION

Advancements in Micro-Electric Mechanical Systems (MEMS) and wireless communications have facilitated in development of low cost smart sensors. In addition to being physically small, these sensors have limited energy as well as limited computing resources. They are used typically for sensing and gathering information from an environment which is forwarded to a decision server. This process is carried out by self-organization of sensors into an agreed hierarchy in an ad-hoc fashion, upon formation of which sensors cooperate with one another. A WSN with hundreds or thousands of nodes operating in this manner are anticipated (Kahn *et al*., 1999).

Conceptually, as discussed by Hempstead *et al.* (2008), a smart sensor mote may consist of MEMS sensors, power source, micro-controller, memory units, event processor and transceiver units. The power source is typically a battery but in some cases photo voltaic cells can also be used. The micro-controllers are usually CPU or DSP chips with a limited instruction set like z80 IS. The transceiver unit is usually a single omni-directional RF antenna. The event processor is a programmable state machine which can process basic data transfers and power management instructions. An interrupt controller and timer counters are also inherent in the device.

There is an inherent trade-off in each of these components. For instance, the memory size can influence buffering capabilities and transient traffic handling capabilities of the mote. The battery size influences the network-lifetime and data processing capabilities of the network. The transceiver unit determines the transmission range of the network and the capacity of the transmission channel (Chen *et al.*, 2002). As such, optimization of these units can significantly influence the longevity of the network.

A taxonomy based on traffic patterns is given; for 1:M traffic flow, sensing data received at a node is dispersed to multiple receivers in the network, whereas for M:1 traffic flow, data moves through different sources and converges upon a single base station for further processing. M:1 networks are usually used for data harvesting, monitoring and surveillance (Duarte-Melo and Liu, 2002; Marco *et al.*, 2003; Duarte-Melo and Liu, 2003).

For a M:1 flow, nodes nearer the sink bear heavier traffic load and thus their residual energy depletes quickly, leading to formation of energy holes. With the loss of critical data paths, data can no longer be delegated to the decision server. Consequently the network's lifetime ends sooner than anticipated and significant amount of overall residual network energy remains non-utilized. Experimental results (Lian *et al.*, 2006) show when the network lifetime is over in a normal node deployment, up to 90% of the total initial energy of the nodes is left unused.

Directed Diffusion (DD) is energy efficient data dissemination scheme in order to extend the lifetime of wireless sensor network based on shortest path routing. The nodes lying on the optimum path will deplete their energy quickly. To avoid local hotspot which possibly form by DD, a new scheme Source Routing Directed Diffusion (SR-DD) is proposed. In this scheme when all nodes in all possible paths have sufficient residual energy then the sink select the optimum path based on the residual energy, a path with minimum total transmission energy among these paths is chosen and if all paths have nodes with low energy, max-min residual energy path is chosen which tries to achieve a balance between the minimum transmission energy and the energy consumption equivalence (Hu and Zhang, 2006).

Cross layer joint routing and MAC-PHY achieve energy balance and energy efficiency at the same time in WSN. The energy balance routing dissipate the levels of residue energy evenly throughout the network while the optimal transmission power control achieves further energy saving by adjusting transmission power to meet communication quality requirement at the receiver. The experimental results show that cross layer approach with energy balanced routing scheme and optimal power control improves energy efficiency while achieving energy balance as well (Wang *et al.*, 2007).

Another power saving scheme is to dynamically adjust the length of the beacon interval based on the communication demand. Due to this dynamic adjustment of the beacon interval, mobile nodes can sleep longer if they are not involved in any active communication and achieve both high energy-efficiency and high network throughput. This scheme conserve about 40% of battery power without compromising throughput compared to IEEE 802.11 power saving scheme (Youn and Kang, 2008).

This study addresses the minimization of uneven energy usage in M:1 traffic patterns. The impact of strategically placed sensor nodes on network lifetime, data delivery and throughput is assessed.

RELATED WORK

Lifetime model: A definition of network lifetime appears in different forms throughout literature. A simple approach refers to the time until the first node fails or runs out of energy (Chang and Tassiulas, 2000). For a directed graph G(N, A) where N is set of all nodes and A is set of all directed links, this approach is given in as $T_{sys} = \min(T_i)$ in Eq. 1 where T_i is the lifetime of node i, E_i is the initial energy, e_{ij} is energy required for transmission of single unit, q_{ij} is information generation rate at i and S_i is the set of neighbor nodes j for node i. A link ij exists only if j belongs to S_i. Since node failures in WSN are a common occurrence, such a definition would be most suitable for mobile ad-hoc networks rather than WSN. Along similar lines, a variant definition of $T_{sys} = \max(T_i)$ can also be derived:

$$Ti=\frac{Ei}{\sum eij\sum qij} \tag{1}$$

Other alternatives are references to a) the time until the network is disconnected or divided into two or more sub graphs, b) the time until a certain number of nodes fail (Vieira *et al.*, 2004), or c) the time when an observed region is no longer covered by any node (Karl and Willig, 2005). For b, the premise is that if a single node dies, it would be expected that its immediate neighbors will share extra load.

Bhardwaj *et al.* (2001) provided an analytical model for upper bounds on the network lifetime of trigger-based M:1 sensor networks. In Bhardwaj and Chandrakasan (2002), the authors further presented a role assignment technique in constructing the upper bounds on sensor network lifetime. To the best of our knowledge, these studies are among seminal efforts in this field. However, they do not identify the problem of uneven energy consumptions in M:1 sensor networks.

Lifetime optimization: Lifetime elongation using optimization of some fixed parameters such as traffic control (Cheng *et al.*, 2008), load balancing and energy balance maintenance has also been covered.

A cell-based energy conservation technique is proposed by Ye *et al.* (2002), wherein nodes in the same cell are selectively switched on/off collaboratively in order to save energy. Blough and Santi (2002) investigated this technique's performance on energy conservation and lifetime extension. Their simulation results show that this cell-based technique can extend network lifetime significantly. However, their work is based on uniform network density and random distributed peer-to-peer traffic which is different from the many-to-one traffic pattern in our work.

To extend the lifetime of network the study is proposed to balance energy consumption for homogenous sensor network with high node density. Rectangular grid partitions are made of sensor network. To monitor each grid and relay data from other grids, at any time one node is scheduled to be active in grid. To make energy stored in a grid proportional to the total power consumption of the grid, the lifetime of all individual grids is equalized. The algorithm not only extends the lifetime but also improves the performance of the sensor network (Wei *et al.*, 2007).

Liang *et al.* (2011) proposed an in-network data aggregation scheme to maximize network lifetime. With a random coefficient each node multiplies its reading and sends result to the next hop to calculate weighted sum of all messages. The base station will receive weighted sum instead of individual node reading and restore the original data. All nodes consume the same energy because to calculate weighted sum each node only perform one addition and one multiplication.

Load balancing can be achieved through a combination of intelligent routing and transmission power control (Singh *et al.*, 1998). The authors state that metrics other than energy consumed per packet need to be used measuring the life of all nodes in a network. Examples given are an optimum path where nodes with depleted energy reserves are at a minimum. An alternative load balancing approach is a scheduling based scheme, where some nodes take turns in monitoring an area while the remaining go into sleep mode. Such a scheme has also been proposed in Tian and Georganas (2002) wherein only sink vicinity nodes perform sleep scheduling.

Luo and Hubaux (2005) use a mobile sink to improve the network lifetime. The nodes near the sink would change over time with a sink moving in the network, thus mitigating the energy imbalance around the sink. They prove that for network lifetime elongation, the best position for a static sink is the center of the circle when the WSN covers a circular area. The authors further demonstrate that using a mobile sink is beneficial and that the mobility trajectory should follow the periphery of the network. A joint mobility and routing scheme is also devised. Shiue *et al.* (2005) propose an energy hole healing protocol using mobile sensors when an energy hole appears.

A technique for maximizing system lifetime using flow (traffic) control is given in Chang and Tassiulas (2000), wherein it is the responsibility of every node to maintain a balance between the sum of information generation rate and the total incoming traffic to that of the total outgoing flow. EEHCA (an energy-efficient hierarchical clustering algorithm for wireless sensor network) achieves a good performance in terms of lifetime by minimizing energy consumption for communication and balancing the energy load among all the nodes. EEHCA adopts a new method for cluster head election which can avoid the frequent election of cluster head. In order to improve the performance of fault-tolerance, the concept of backup cluster head was introduced. When nodes finished the communication within their own clusters and the cluster heads have finished the data aggregation, the head clusters will transmit aggregated data to the sink node by a special multi-hop mode. Results show that EEHCA has better than LEACH (low energy adaptive clustering hierarchy) and HEED (hybrid energy efficient distributed clustering) in terms of network lifetime (Xin *et al.*, 2008).

To minimize total energy consumption an energy efficient protocol named CTPEDCA (Cluster-Based and Tree Based Power Efficient Data Collection and Aggregation Protocol for WSNs) is used. For cluster heads CTPEDCA use Minimum Spanning Tree (MST) routing strategy. In each round only one cluster-head communicate directly with the faraway sink which improves the transmission routing mechanism between cluster-heads. From results it's clear that CTPEDCA is better than LEACH, it's prolong the network lifetime by balance the energy consumption of all nodes. The complexity of algorithm is O (ElogV) where V is the set of cluster-heads, the complexity show that the algorithm is very fast (Wang *et al.*, 2011).

Energy equilibrium routing algorithm based on cluster-head prediction for wireless sensor network (CP-EERP) uses the cluster head prediction to improve lifetime of cluster-head, balances the energy among nodes and extends network lifetime. Network initialization phase, cluster building phase, data transmission phase and cluster prediction phase are included in CP-EERP. As compared to classic routing algorithm CP-EERP perform better in term of energy efficiency and the number of communication neighbors (Guo *et al.*, 2010).

Transmission range optimization can influence the ability to directly send traffic in single hops as compared to indirect transmissions using multiple hops. In former case, no energy hole will be created but the consumption of energy by a node would be very high (Perillo *et al.*, 2004). The authors propose a technique for determining how a node should distribute its outgoing data packets over multiple distances by using minimum transmission power. Two conclusions are reached for variable transmission range. In the first instance; nodes farther away from the sink have greater transmission range and can communicate with the sink in a single hop. When relaying data, only their own energy will be reduced, eventually dying out. In the other instance, if multiple hops are used to communicate with the sink, there will be increased traffic load on sink-neighbor-nodes, the direct result of which would be the early demise of these nodes.

An N-policy M/G/1 queue has been reported by Jiang *et al.* (2009) for alleviating power consumption. According to this scheme, a queue threshold N is specified for the concept of queued wake up. This threshold is used to control the number of times the data radio is turned on and the latency delay for the buffered data packets. In the queued wake up scheme, when the queue holds N packets, the sensor node triggers its data radio, conducts the process of medium-contention and transmits the queued packets in a burst.

DEPLOYMENT STRATEGIES

A taxonomy of deployment strategies along the lines of six points of Cheng *et al.* (2008) is given. We assume that similar energy level, transmission range, energy consumption pattern and transmission bandwidth among different nodes define the homogeneity of nodes:

- **Single static sink:** Deployments using this strategy are made with uniformly generated traffic, homogeneous sensors, uniform energy and a single but static sink with no extra costs
- **Mobile data sink:** Such deployments have an added cost of a mobile data sink as was proposed in Shah *et al.* (2003). The deployments also are made using uniformly generated traffic, homogeneous sensors and uniform energy
- **Multiple data sink:** The deployment strategy is the same as in single static and mobile data sinks, but with an additional deployment of a data sink
- **Non uniform energy:** The node energy of all nodes is non-uniform, even though they are homogeneous. The energy assignment to an individual node is based on multiple factors such as position or workload
- **Non uniform placement:** Deployment under this strategy is usually performed for heterogeneous nodes, where nodes have different responsibilities such as computation, relaying, or sensing
- **Non uniform traffic:** This is usually application dependent. An example of which is evident by Chakrabarty *et al.* (2002) which is based on intrusion detection. In such scenarios, node density is usually greater away from the sink; hence these outlier nodes will be generating more traffic as compared to those located close to the sink

The root classification is based on Uniform and Gaussian deployment. Each is further sub-divided into two additional categories for Engineered and Random deployment (Fig. 1).

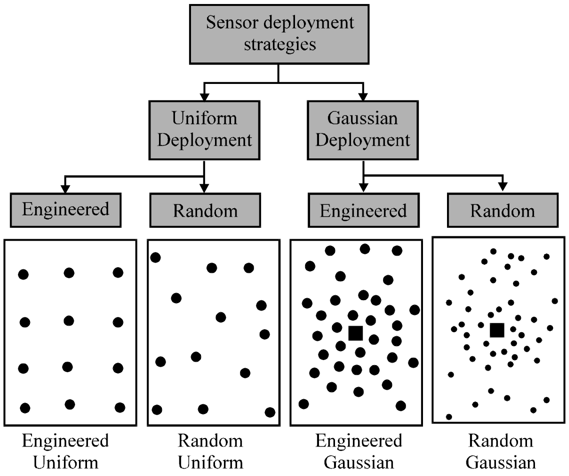

Fig. 1: Sensor nodes deployment strategies

SIMULATION AND RESULTS

Simulations have been performed for Uniform-Random and Gaussian-Random deployments with homogeneous nodes, random traffic and stationary sink at center of topology. Simulations have also been performed for instances where nodes are heterogeneous (differentiating in energy level only). Performance of network is evaluated using metrics such as network lifetime, throughput and data delivery.

Uniform random deployment strategies: We will consider uniform deployment strategy. Along with this, we assume that our sink will be stationary and placed in the center of our topology as show in Fig. 2. The nodes used would be homogeneous and traffic generation would be random. The result shows the network-lifetime and data delivery of uniform deployment strategies.

Network lifetime: In contrast to Cheng *et al.* (2008), we will define the network life-time for our model as the total period of time that nodes can communicate with the sink until this link is broken. In other words, when all of the immediate sink neighbor-nodes energy levels are drained out, such that there is no path available for communicating with the sink, then this will culminate the total network life-time. Figure 3, shows the total network lifetime against an energy depletion of sink neighboring node. We find that the total network lifetime gradually increases as the number of sink neighbor nodes energy are depleted. When the neighboring nodes die out then no packets will be delivered to the sink and there will be no increase in network lifetime.

Ratio of packets sent and received: Figure 4 shows the ratio of packets sent and received for each sink-neighbor-node increment. According to the graph, the ratio of packets sent and received is approximately the same, but once the neighbor nodes of the sink die out, we notice that even though the sensing nodes are sending packets, the sink is not able to receive them. Here, it is confirmed that up to 90% of the energy of the network is left unused when the network lifetime is over if the nodes are uniformly distributed in the network (Lian *et al.*, 2006). If we gradually increase the number of sink-neighbors to 45, we notice greater energy stability in our network and all nodes die at around the same time.

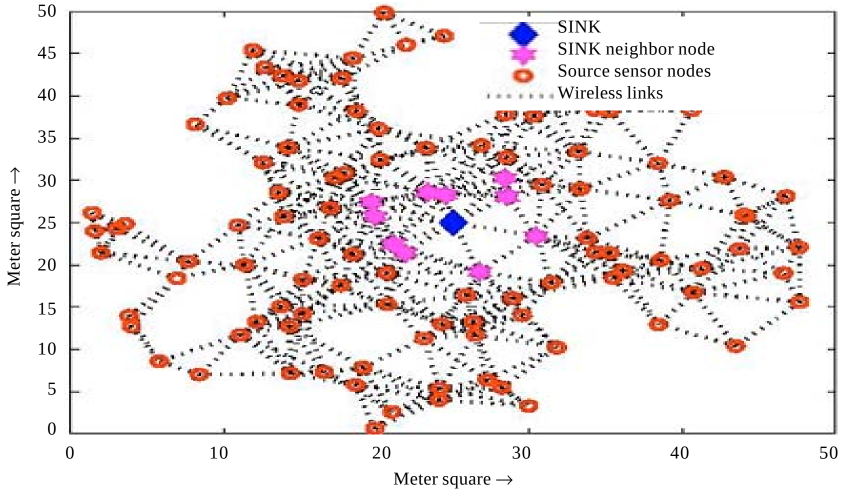

Fig. 2: Uniform deployment strategies

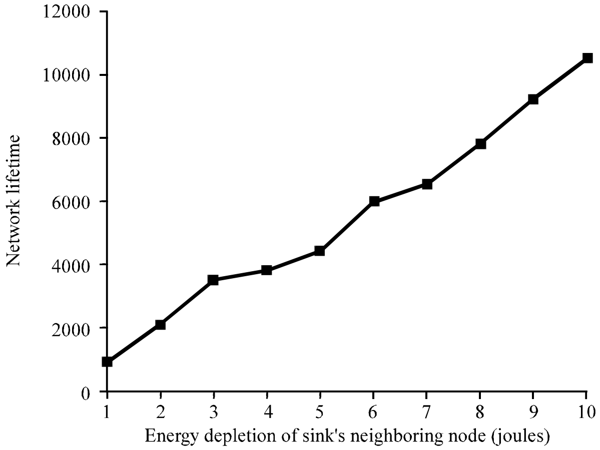

Fig. 3: Network lifetime of uniform random deployment strategy

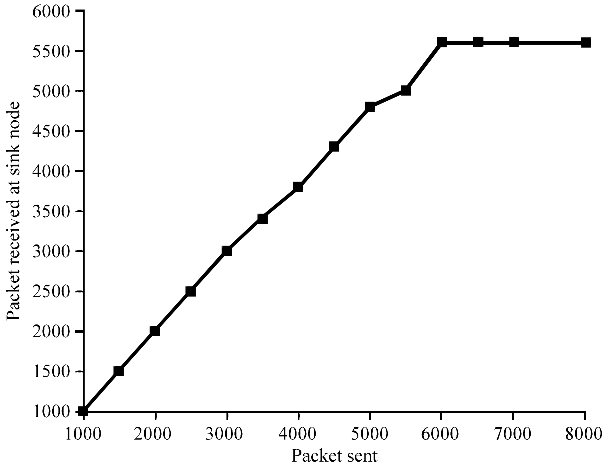

Fig. 4: Data delivery of uniform random deployment strategy

Table 1: Parameters for strategy I

Parameters	Values
Area	50×50 m^2
Sink neighbors	10-45
No of source node	100
Transmission range	10 m
Initial node energy	10 J
Energy consumption (during transmission)	10 mJ

Gaussian deployment strategies: Network was deployed in a geographical area 50×50 m^2. We increment the number of sink neighbors from 10 to 45 as shown in Fig. 5, 6. The number of sensing nodes is 100 and their transmission range is 10 m. We assigned the initial energy of each node as 10J whereas the energy consumption during transmission is 10 mJ (Table 1).

Network lifetime: In contrast to Cheng *et al.* (2008), we will define the network life-time for our model as the total period of time that nodes can communicate with the sink until this link is broken.

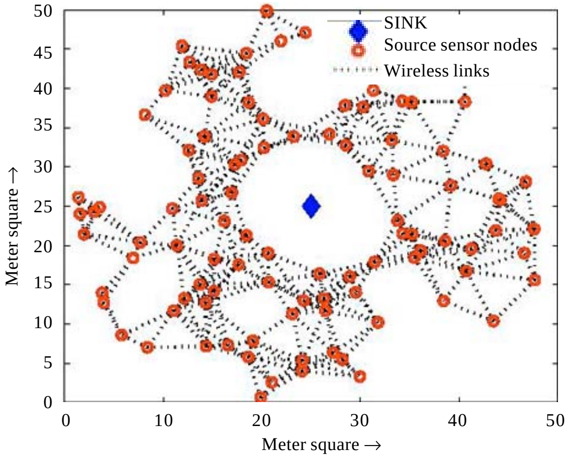

Fig. 5: No sink neighbors

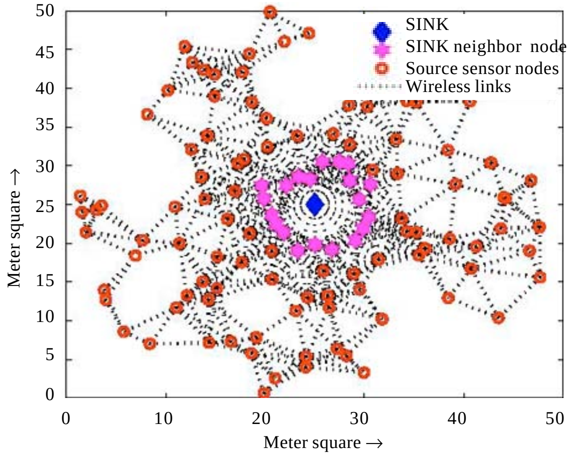

Fig. 6: Twenty sink neighbors

In other words, when all of the immediate sink neighbor-nodes energy levels are drained out, such that there is no path available for communicating with the sink, then this will culminate the total network life-time. Figure 7, shows the total network lifetime against an incrementing number of sink neighboring nodes. We find that the total network lifetime gradually increases as the number of sink neighbor nodes are increased. The sharp steps noticeable in the graph are due to the uniform random deployment strategy used for each increment. However, there is a cap on this life-time increase beyond a certain limit. This is due to the fact that the neighbors of the sink-neighbor nodes start dying.

Throughput: Throughput of the network is the number of packets delivered to the sink in a given time frame. Figure 8 shows that the throughput records almost a linear increase as the number of node neighbors are increased.

Ratio of packets sent and received: Figure 9 shows the ratio of packets sent and received for each sink-neighbor-node increment. According to the graph, the ratio of packets sent and received

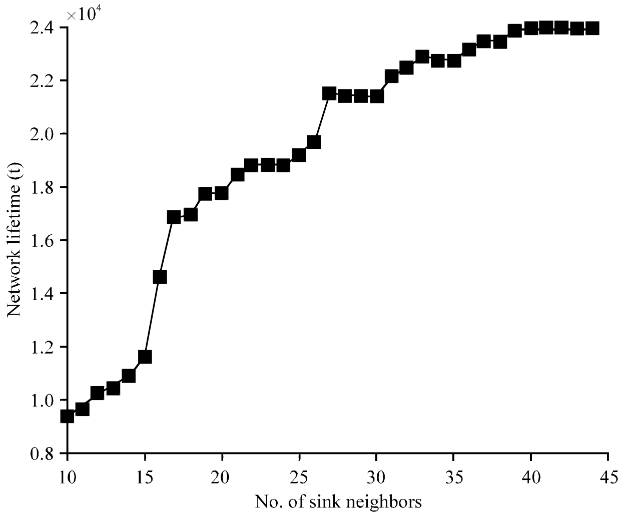

Fig. 7: Impacts of incrementing sink neighbors nodes on network lifetime

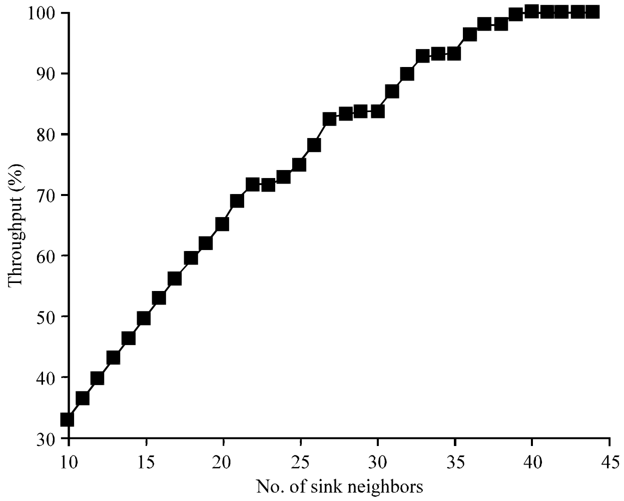

Fig. 8: Impact on network throughput for increment of sink neighbor nodes

is the same, but once the neighbor nodes of the sink die out, we notice that even though the sensing nodes are sending packets, the sink is not able to receive them. Here, it is confirmed that up to 90% of the energy of the network is left unused when the network lifetime is over if the nodes are uniformly distributed in the network (Lian *et al.*, 2006). If we gradually increase the number of sink-neighbors to 45, we notice greater energy stability in our network and all nodes die at around the same time.

Heterogeneous node deployment strategies

Increasing energy of sink neighbors: Our network was deployed in a geographical area 50×50 m^2. We assigned the number of sink neighbor nodes as 10 whereas the number of sensing nodes is 100. The total transmission range is 10 m. For sink-neighbor nodes, the initial energy is incremented gradually from 10 to 45 joules, whereas the initial energy for non-sink-neighbor nodes

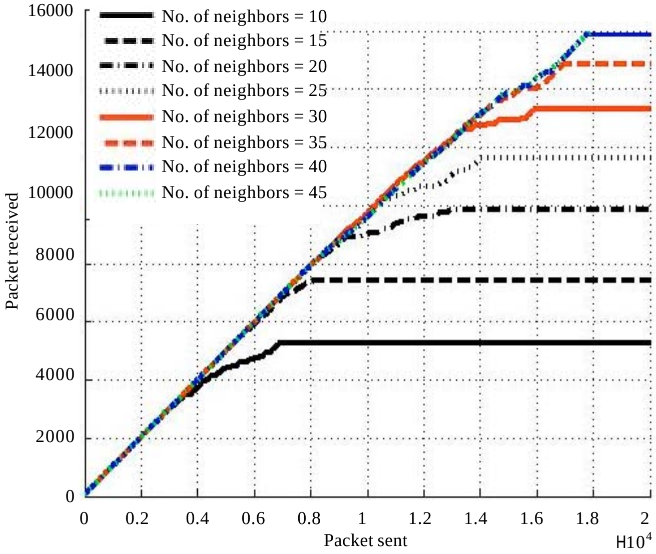

Fig. 9: Impacts of incrementing sink neighbors nodes on packets sent/received ratio

Table 2: Parameters for strategy II

Parameters	Values
Area	50×50 m^2
Sink neighbors	10
No of source node	100
Transmission range	10 m
Initial non sink neighbors node energy	10 J
Energy consumption (during transmission)	10 mJ
Initial sink neighbors node energy	10-45 J

is fixed at 10 joules. The energy consumption during transmission for all nodes is set at 10 milli-Joules (Table 2).

Network lifetime: Figure 10 shows the total network lifetime against an incrementing energy level of sink neighbors. We find that the total network lifetime shows a sharp increases as the energy level is increased. However, we notice that the network lifetime achieves a peak for an energy level of 20-25 Joules. Any subsequent increase in energy level has virtually no impact on the network lifetime. This is due to the fact that the neighbor of the sink-neighbor nodes starts dying.

Throughput: Throughput of the network is the number of packets delivered to the sink in a given time frame. Figure 11 shows that the throughput records almost a sharp linear increase as the energy of neighbors' node are increased.

Ratio of packets sent and received: Figure 12 shows the ratio of packets sent and received for each increment of sink-neighbor node energy level. According to the graph, the ratio of packets sent and received is the same, but once the neighbor nodes of the sink die out, we notice that even though the sensing nodes are sending packets, the sink is not able to receive them. This also shows

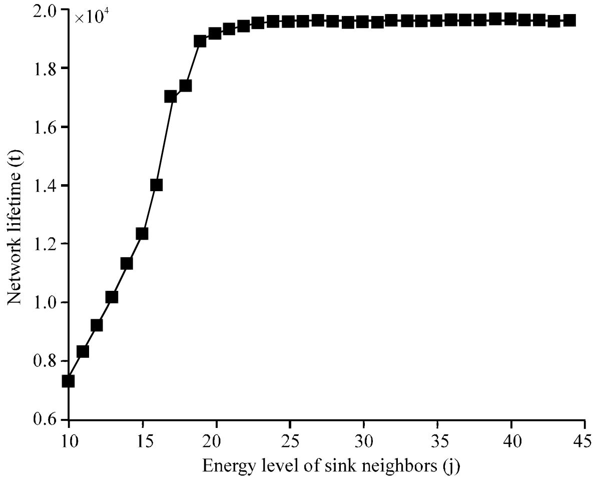

Fig. 10: Impact of incrementing sink neighbors nodes energy on network lifetime

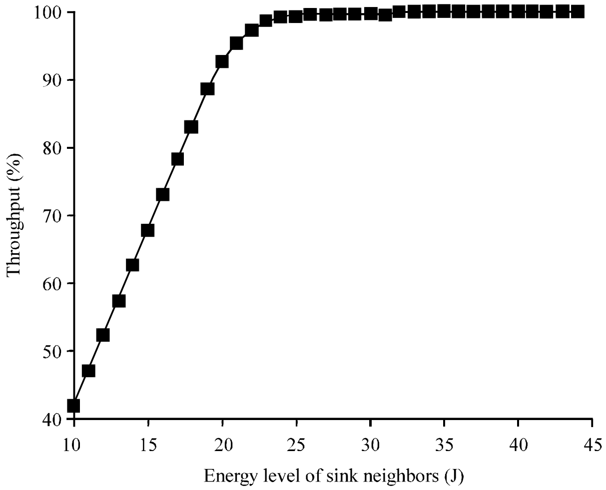

Fig. 11: Impact on network throughput for increment of sink neighbor energy

that upto 90% of the network energy can be wasted (Lian *et al.*, 2006). If we gradually increase the energy level to 45 J, we notice greater energy stability in our network and all nodes die at around the same time.

Comparison of Gaussian and Heterogeneous node deployments and its impact on network lifetime: Figure 13, shows a comparison of the network lifetime for both strategies 1; increment of sink neighbor nodes and strategy 2; increment of sink neighbor node energy levels. The figure shows a variable which is used to denote the network lifetime. For the first strategy, we assign the value of by multiplying it with 'n' while energy level is static at 10 joules. The value of 'n' is the incrementing number of sink-neighbor nodes from 10 to 45. For the second strategy, we assign the value of by multiplying it with 'e' while sink-neighbor node number is fixed at 10. The value of 'e' is the incrementing initial energy level of sink-neighbor nodes from 10 to 45 milli Joules. We notice that the maximum network lifetime achievable is by incrementing the number of sink

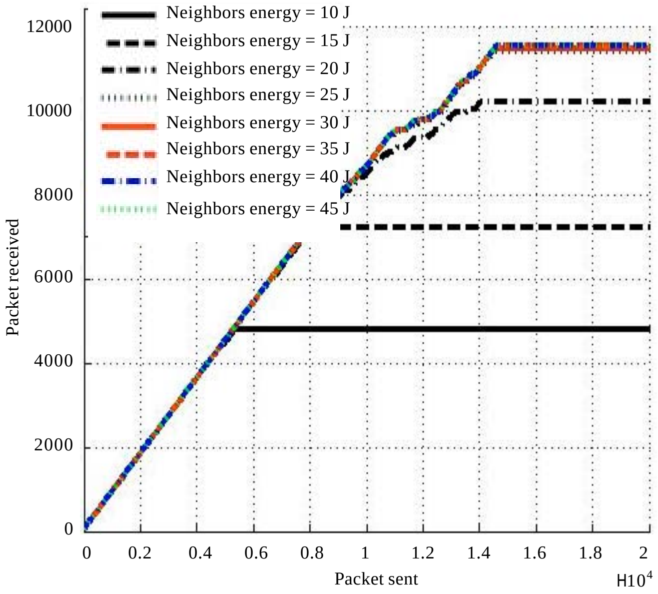

Fig. 12: Impact on incrementing sink neighbors' nodes energy on packets sent/received ratio

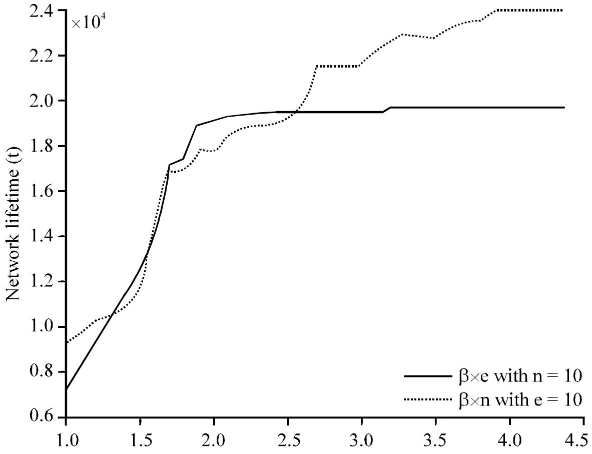

Fig. 13: Comparison of gaussian and heterogeneous node deployments and its impact on network lifetime

neighbor nodes, as compared to increasing the energy level. However, when the energy level of both the strategy is around 10 milli Joules range, we see that the network lifetime of both strategies converge upon one another.

CONCLUSION AND FUTURE WORK

Energy efficiency is the most important design consideration for wireless sensor network and its optimum utilization is a challenge in its own regard. The deployment model is Simple, efficient and less costly and can scale well to large networks. A good sensor deployment strategy is one that achieves an energy balance in the network. The main factor for energy balance is the optimum number of sink neighbor nodes, rather than other performance enhancing factors such as increased energy level of all the sensor nodes. Both implemented strategies suggest increased energy efficiency and energy balance. Our strategy is simple to implement and involves less cost as compared to other intelligent techniques for achieving maximum lifetime. Our work can be extended to analyze the performance for other deployment strategies.

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