“How long is the lifetime of a wireless sensor network?”

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Abstract

Wireless sensor networks (WSNs) are known to be highly energy-constrained and each network’s lifetime has a strong dependence on the nodes’ battery capacity. As such, the network lifetime has been a critical concern in WSN research. While numerous energy-efficient protocols have been proposed to prolong the network lifetime, various definitions of network lifetime have also been used for the different scenarios and protocols. The lifetime of a sensor network is most commonly defined as the time to the first sensor node failure – seemingly over-pessimistic in many envisaged deployment scenarios. While other definitions exist, there has not been any consensus on which quantitative lifetime definition is most useful. In this paper, we aim to provide as objectively as possible, a comparative study of WSN protocols based on various network lifetime definitions. We also discuss the implications of these metrics and their applicability in evaluating the effectiveness of WSN data delivery schemes.

Keywords: *Network Lifetime, Wireless Sensor Network*

1. Introduction

Rapid advancement in the wireless communication and embedded systems technologies has enabled the realization of wireless sensor networks (WSNs) which composed of many inexpensive, low-power, and disposable tiny sensor nodes. Each node has the capability for sensing, simple computing, data processing, and communicating with neighbouring sensor nodes. Exploiting the collaborative effort of a large number of nodes, WSNs can be deployed for monitoring a physical phenomenon and reporting it to depository nodes where the end-user can access the data, thus greatly extending our ability to monitor and control the physical environment from remote locations. As a whole, WSNs are expected to be self-configuring, scalable, reliable and robust in the presence of changing topologies due to node failure and environment changes. A wireless sensor node’s compact size also means that they are usually equipped with a small battery having finite power supply and hence a short operational life. A critical concern in the design of WSNs is the network lifetime, and how to extend the lifetime of WSNs remains a hot topic in sensor networks research.

It has been aptly stated in [1] that the “Network lifetime is the time span from the deployment to the instant when the network is considered non-functional. When a network should be considered non-functional is, however, application specific.” However, this definition easily translates into multiple quantitative metrics, thus motivating the work presented in this paper. In this paper, we present an objective survey and analysis of the different types of network lifetime definitions for different types of network protocols. In the following sections, we first identify common quantitative definitions of network lifetime. Similarly, we classify a selected list of WSN protocols and identify suitable candidates for our study. Using simulations, we then evaluate the performance of the selected protocols under different lifetime definitions. We also discuss the implications of these metrics and their applicability before concluding the paper.

2. Lifetime Definitions and Classification

With the many different lifetime definitions, there has yet to be a definition which is most satisfactory and appropriate to adopt. For simplicity, the lifetime of a sensor network is most commonly defined as the time from the instant the network starts operating to the first sensor node failure. However, this definition seems too pessimistic for WSNs, since the failure of one node does not prevent the rest of the nodes from providing appropriate functionality due to the redundancy of deployed nodes, and the self-organizing and fault tolerance capabilities of WSN. Other definitions have also been used in the literature but they are rather subjective as well.

To the best of our knowledge, such a comparison of protocols using different lifetime definitions has yet to appear and our motivation of doing so is several-folds.

Firstly, knowledge of which definition is more satisfactory and thus allows one to calibrate the performance of protocols based a more reasonable lifetime definition. This also provides a fairer basis for performance comparisons among similar network protocols. Secondly, such study allows one to gain an insight into the various proposed network lifetime definitions which aids in further investigation or proposal of more realistic definition of network lifetime for WSNs. Thirdly, a better understanding of the various types of lifetime definitions can facilitate the research of new energy-efficient protocols for WSN, as well as to help in the selection of the appropriate protocol for a desired application.

Unlike traditional communication networks where *connectivity* is the key requirement, WSNs also need to provide sensing *coverage*. Traditionally, a network is fully *connected* if there is a route between every pair of nodes. However, in WSNs, the main goal of the sensor nodes is to sense and transmit data back to the sink where the end-users can access the data and perform further processing. Hence, a WSN is fully connected as long as each sensor node is within the transmission range of at least one other node, and all the sensor nodes are able to report their collected data back to a sink through any communication path. Sensing *coverage*, on the other hand, characterizes the monitoring quality provided by a sensor network in a designated region. The definition of coverage usually is based on the sensing range of the nodes, and complete coverage in a WSN refers to the network's capability to monitor every area in the sensing region. In a simplified but widely used model, all the nodes sense a circular area of radius *rs*, and the monitored region ***R*** is completely covered if every point of ***R*** is a distance of at most *rs* from at least one sensor.

Connectivity and coverage are two important aspects in WSNs closely tied to the usefulness of the network, and they are essential considerations in defining the network lifetime. Nevertheless, we argue that connectivity must be achieved in order for sensed data to be transmitted to the sink for processing. Hence, in this paper, we focus on lifetime definitions that are connectivity-related. This does not, in any way, imply that coverage is not crucial. The various connectivity-related network lifetime definitions proposed and reported in the literature include:

i) Time till the first sensor node failure [1][2][3][4].
ii) Time till certain percentage of sensor nodes failure OR surviving nodes in the network (falls below a given application-dependent threshold) [5][6][7].
iii) Time till the network becomes disjoint; network partitions emerge [8].
iv) Time till size of the largest connected component drop below a threshold [9].
v) Time till the packet delivery rate falls below a certain threshold [11].
vi) Time till all the sensor nodes dies [12].
vii) Time till number of errors exceeds a threshold [7].
viii) Time till the number of packets that can be (successfully/correctly) delivered by the network falls below a threshold [13].
ix) Time till no sensor has enough energy for transmission during a data collection; the first failure in data collection [1].
x) Time till the notification latency (delay between event detection to reception at the closest sink) exceeds a threshold [10].
xi) Time till no communication backbone exists [13].

The 11 definitions listed above share various similarities and we can categorize them as shown in Table 1 below. This helps us focus our study on those definitions that are more distinguishable, from which we can then perform meaningful comparisons.

Table 1: Categorization of network lifetime definitions

Class	Representative	References
1	Time to which percentage of failed sensor nodes exceeds a threshold.	[1][2][3][4] [5][6][7][12]
2	Time to emergence of first partition in the network.	[8][9][13]
3	Time to which the packet delivery rate falls below a threshold.	[7][10][11]

3. WSN Protocol Classification

In this section, we identify some known WSN protocols, comprising data dissemination and routing protocols [14], as candidates for our study. Data dissemination protocols consider the sources and sinks in the network in bringing the sensory data across from the sources to the sinks, whereas routing protocols focus more on efficiently forwarding the data towards a destination. We first compare them, and based on the various definitions of network lifetime and the possible factors that could affect the lifetime, we group them (in Table 2) based on network structure (i.e. layered or clustered) and routing method (i.e. proactive, reactive or hybrid). One representative from each group (viz., Directed Diffusion [15], LEACH [12] and SPEED [16]) is then selected for the performance analysis.

4. Comparative Performance Evaluation

4.1 Simulation Platform and Parameters

We use GloMoSim (ver 2.03) for our simulations. The three protocols, Directed Diffusion (DD), LEACH

Table 2: Classification and comparison of WSN protocols

Class ID	Protocol Class	Protocols	Data-aggregation	Data-negotiation	Energy resource adaptive	Optimal/ energy efficient	Load-balancing	Layered/ Clustered	Proactive/ Reactive routing	Multi-path/ Single-path
A	Layered and Hybrid	***Directed Diffusion***	yes	yes	no	yes	no	Layered	Hybrid	Multi-path
		SAR	no	no	yes	yes	yes	Layered	Hybrid	Multi-path
B	Clustered and Proactive	***LEACH***	yes	no	no	no	yes	Clustered	Proactive	Single-path
		TEEN, APTEEN	yes	yes	no	no	no	Clustered	Proactive	Single-path
		PEGASIS	yes	no	no	yes	yes	Clustered	Proactive	Single-path
		Virtual Grid Architecture Routing	yes	no	no	yes	no	Clustered	Proactive	Single-path
		Fixed-Size Cluster Routing	yes	no	no	no	yes	Clustered	Proactive	Single-path
		Hierarchical Power-Aware Routing	No	no	yes	yes	yes	Clustered	Proactive	Single-path
C	Layered and Reactive	***SPEED***	no	yes	no	yes	yes	Layered	Reactive	Single-path
		Flooding	no	no	no	no	no	Layered	Reactive	Multi-path
		Gossiping	no	no	no	no	no	Layered	Reactive	Single-path
		SPIN	yes	yes	yes	no	yes	Layered	Reactive	Multi-path
		MCFA	no	no	no	yes	no	Layered	Reactive	Multi-path
		Rumour Routing	yes	yes	no	yes	no	Layered	Reactive	Multi-path
		SAFE	no	yes	no	yes	no	Layered	Reactive	Single-path
		Two-Tier Data Dissemination	no	yes	no	no	no	Layered	Reactive	Multi-path

and SPEED, are implemented in GloMoSim and the network lifetimes achievable by these protocols based on the three lifetime classes (cf: Table 1) are studied. A typical WSN power usage model comprises sensing, transmitting, receiving (including overhearing), idling, sleeping, and computation. With current technology, the energy consumption of wireless communication is several orders of magnitude higher than that required for computation, dominating the energy consumption.

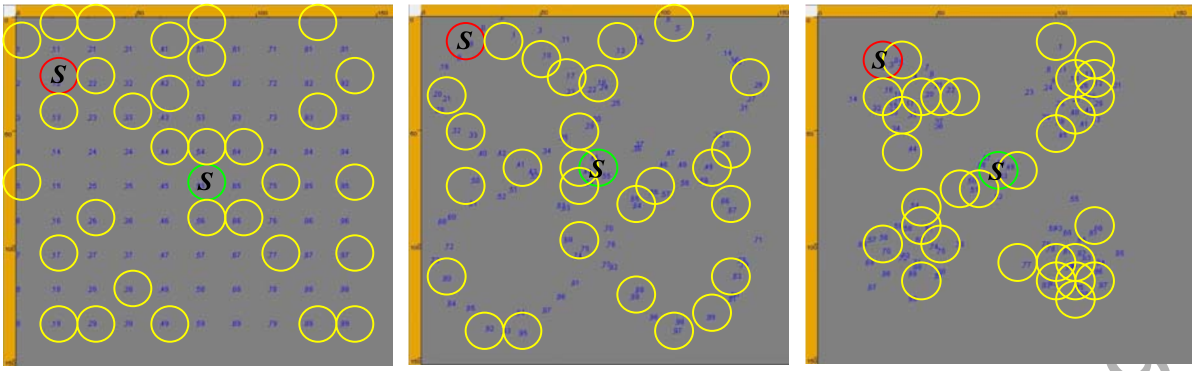
Hence, for our simulations, we consider only the power consumption incurred by a sensor for data transmission and reception, idle mode operation and any network initialization or start-up cost incurred is accounted for under these three components. It is also worthwhile to note that the sensing range and the communication range of a senor node are generally not the same, and the power consumption in sensing an event and transmitting data also differs. The simulation setup details and parameter values for our simulations are listed in Table 3.

Network Lifetime Metrics

All the nodes in our simulation are energy-constrained as specified by the parameter, Battery Capacity, in Table 3. In our simulations, when the energy level in a given node has dropped to a level at which it is unable to transmit, that node is considered dead for the remainder of the simulation. The battery capacity is chosen such that results obtained can be within the comparable range across the different protocols under the specified simulation scenarios (simulation time, network size, etc), and such that all

Table 3: Simulation Parameters

Parameters	**Value**
Simulation Time	100 sec
Radio Type	Accnoise
Terrain Dimensions	140m × 140m; 420m × 420m
Txn Range, R_c	50 m (open terrain)
MAC protocol	CSMA
Propagation Model	Free Space
Energy Model	660mW in transmission; 395mW in reception; 35 mw in idle mode [17]
Battery Capacity	3000 mJ
No. of Sinks	1 sink
Sources	30 sources randomly distributed over the terrain
Data Rate	2 events/sec
Random No. Seed	1 – 10
No. of nodes	100, 150, 200, and 250
Node Placement Topology (Figure 1)	Random, Grid , Topology 1 (sparse regions) and Topology 2 (clustered)
Sink node position	Random, Upper left corner, Centre



(a) Grid (b) Topology 1 (Sparse regions) (c) Topology 2 (Clustered)

Figure 1. Network Topologies used in the simulations (locations of the sink node ***S*** is circled in red, at upper-left corner, and green at centre, and the locations of various source nodes are circled in yellow)

the nodes will expire latest by the end of the simulation time of 100 seconds which is more than adequate for the network to stabilize and protocols to be evaluated. Note that currently available commercial motes are usually powered by a pair of AA batteries and their manufacturers claim operational lifetimes that last from days to months or even years.

The thresholds that determine the expiration of network lifetime based on the three classes are 10% node failure (Class #1) and delivery rate of 150m/s (Class #3). For Class #2, the network lifetime expires as soon as any set of nodes becomes disconnected from the sink. The delivery rate used in the Class #3 network lifetime definition refers to the end-to-end delivery speed along a straight line from the source to the sink node, and specifically refers to useful data packets originated from the source nodes only. Unless a packet is routed exactly along a path that is the Cartesian straight line joining the source to the sink, this delivery rate is larger than the actual rate of the packet in the network. Furthermore, unlike the other lifetime definitions, the Class #3 definition deals with the degradation of a property which may not begin as a whole. In particular, the delivery rate in Class #3 may be expected to be low and unstable in the beginning. As such, we have to specifically capture the time to the first persistent drop in the rate of delivery below the threshold, instead of merely taking the time to which the delivery rate appears below the threshold.

5. Results and Analysis

5.1 General Case: 100 nodes, uniform random

We first present the results obtained from our simulations for the case where the network size is 100 nodes and nodes are deployed uniformly random across the terrain. The sink is randomly placed within the terrain. This set of results (as shown in Figure 2) serves as a general case that is typically assumed by most studies. The uniform grid topology serves as a control case. However, in an actual deployment scenario, the nodes are less likely to be evenly distributed and tend to be clustered together, which we model with Topology 1 (Sparse Regions) and 2 (Clustered) in Figure 1(b) and (c) respectively. Unless otherwise stated, the network lifetime is measured in seconds, and each result has been averaged over 10 simulation runs with different seeds, executed over a simulated time of 100s which was sufficient for all definitions of network lifetime to be reached. In the high density ("dense") network, the 100 nodes are deployed in an area of 140m-by-140m and the same number of nodes is deployed in a larger area of 420m-by-420m to model a low density (sparse) network.

As we can observe from the results, SPEED leads in almost all the definitions of network lifetime when the network density is high. When the network density is lowered, all the three protocols' network lifetimes improve. In particular, LEACH slightly outperforms SPEED in the low density scenario, and has the longest lifetime for all the definitions. We can observe from the raw simulation results that there is a significant drop in the number of collisions and packet lost in the

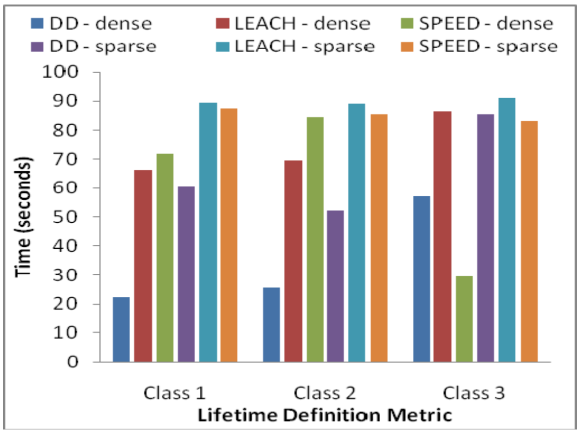


Figure 2. Uniformly Random Node Distribution

network. This enhances the performance of the protocols in terms of their lifetimes, and is particularly true for Class #3, which also signifies a more stable network and the data flow through the network more smoothly. These observations suggest that, with the transmission range and the number of nodes in the network being kept the same, a less dense network is able to lead to longer lifetimes of the network as compared to a denser network.

The reason behind SPEED's better lifetime performance could be traced to its design, which specifically aims to detect congestions in the network and divert the traffic away, in order to maintain a desired single hop delivery speed across the sensor network so that the end-to-end delay is proportional to the distance between the source and destination. By balancing the traffic and reducing congestion, SPEED is apparently able to balance the power consumption in the network and prevent some nodes from dying faster than the rest. This is also evident in the raw simulation results, in which almost all the nodes are utilized and they exhaust their power supplies at around the same time. We also observed that SPEED has almost no data lost due to buffer overflow. This is distinctively better than Directed Diffusion and even LEACH, which have considerable packet loss. Furthermore, SPEED is a reactive protocol that creates and repairs routes on demand, and as such generates less control packets for route discovery. This is especially true in our case where all the nodes are static, and therefore the beaconing rate for location update is very low. The benefit of this is more obvious in a dense network where nodes are in closer proximity and have a higher chance of contending with one another for the wireless channel. However, SPEED has a short lifetime in a dense network for the Class #3 definition, which is the time to which the delivery rate of the data packet falls below a threshold. This is as expected because SPEED is a reactive protocol which does not have a predetermined routing path before the delivery of the actual data packets. Although SPEED can divert traffic to reduce congestions and is able to maintain the desired single-hop delivery rate of the packet across the network, it does not guarantee a desirable end-to-end delivery rate.

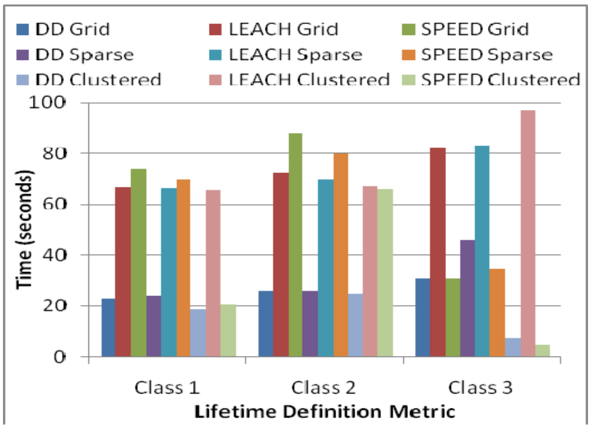
LEACH also does load-balancing by rotating the role of the cluster heads. However, as a proactive protocol, it tends to disseminate more control packets in the network than a reactive protocol like SPEED. For example, even if all the sources eventually happen to be in the same cluster for this round, LEACH still attempts to setup the clusters for the other the nodes regardless of whether a node is the source. Moreover, LEACH assumes that every node has something to send and allocates bandwidth for each cluster member even though it may not be the source node, and the transmission of such unnecessary packets accounts for some of the energy dissipation in the nodes.

However, there is no load-balancing in Directed Diffusion which uses flooding for interest dissemination and this consumes a large amount of energy. This led to its short lifetime as compared to the other two protocols, and we have observed in the raw simulation results that almost all the nodes exhaust their power approximately at the same time early in the simulation – a phenomenon of the flooding process.

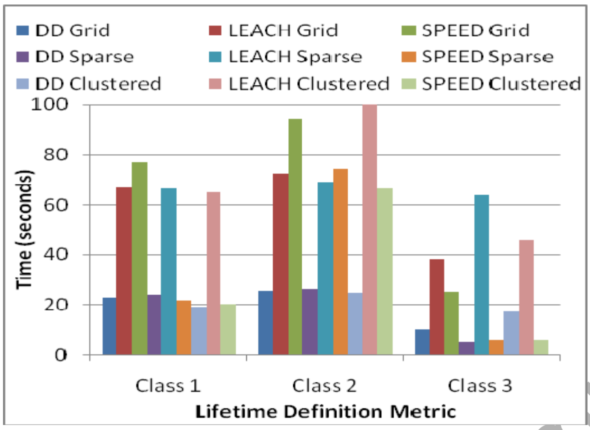
5.2 Topology Variations

It has been analyzed and pointed out [12] that the most energy-efficient protocol to use depends on the network topology. The topology model used by a protocol in a simulation can have a critical impact on the results, and the results can be distorted if the simulation model is unrealistic [18]. Furthermore, in order to better analyze the impact of the different sink positions, we have two different scenarios: one in which the sink is positioned near the upper left corner of the terrain, and another in which the sink is located at the centre of terrain. For the corner placement, we assume the symmetry effect of the mirror pattern will produce similar results, as such, we do not consider the cases in which the sink is positioned at the other three corners of the terrain in our simulation. We rerun our simulations for the two different sink positions with the three different topologies, and the results are shown in Figure 3.

We observe that the clustered network (Topology 2) gives shorter lifetimes for Directed Diffusion and SPEED, which is expected since clustering of nodes will naturally result in network congestion for a non-cluster-based protocol. In this scenario, SPEED is unable to relieve congestion fast enough by diverting traffic. We have observed that some nodes expired much earlier than others in this topology, unlike in the Grid topology where SPEED is able to evenly balance the load across the network. Moreover, the results for SPEED show a significant number of packets lost due to overflow in the clustered network as compared to the low number of packet lost in the network with sparse regions (Topology 1) and the near zero packet loss in the Grid topology; the same observations also apply to Directed Diffusion. These observations explain the shorter lifetimes for both SPEED and Directed Diffusion in the clustered network, which imply that non-cluster-based protocols tend to have shorter lifetimes in a non-uniform topology where the nodes are physically clustered in groups.



(a) Sink at corner of the network



(b) Sink at the centre of the network

Figure 3. Different Topology Variations

On the other hand, the cluster-based LEACH protocol is able to achieve the longest lifetimes in a clustered network (Topology 2) as compared to when it is applied in the other two network topologies. The physical clustering of the nodes facilitates the grouping of the nodes into clusters, and thereby reduces the total transmission energy required in the setup as well as in the transmission of data packets from the cluster members to the cluster head. This is further enhanced and made prominent when the sink node is positioned at the centre, as shown in the results in Figure 3(b).

In contrast, SPEED performs better and obtains longer lifetimes in the Grid topology, where there is no clustering of the nodes, and especially so for Class #2 lifetime when the sink is at the centre. However, the network lifetimes of achieved by SPEED deteriorates in the other two network topologies where the nodes are non-uniformly placed, even when the sink is located at the centre. This clearly shows that network topology can have a great impact on the performance of the protocols and having the sink at the centre does not necessarily improve the lifetimes as predicted.

5.3 Scalability – Increasing Network Sizes

Scalability is a key criterion of any WSN protocol. To observe the impact of network size on network lifetime, we repeat our simulations using network sizes ranging from 100 to 250 nodes, in steps of 50, with the general case scenario. From Figure 5, we observe that there is a general trend of decreasing network lifetimes as network size increases (with density unchanged.) The number of collisions and packets lost increases as the network size increases. Moreover, the range of variations in the node expiration times increases for SPEED and LEACH as the network size increases, suggesting that they are less efficient in balancing the load among the nodes and controlling congestion as the network size increases.

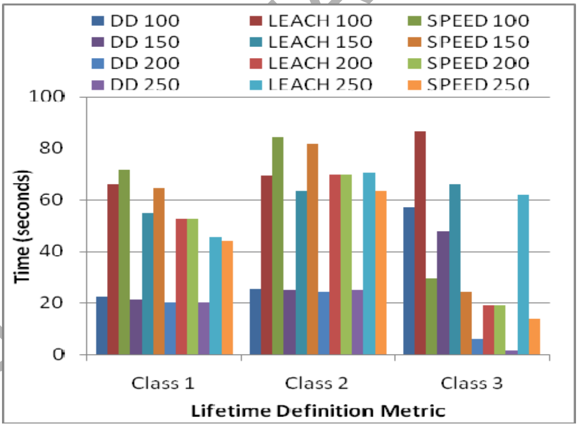


Figure 4. Scalability -- Increasing Network Sizes

For LEACH, there is an increase in the number of control and data packets in the network due to the increase in communications load and packets in the network. In particular, there will be more members in each cluster and/or more clusters. Hence, even though the number of source nodes (which generates useful data for the Sink) remains unchanged, each cluster head will have to handle more members and data, which will involve more packets and communication, thereby increasing energy consumption and traffic in the network. Similarly, SPEED incurs more control overhead for managing a larger network, which adds up to increased energy consumption for the network. With an increased network size, there will be more beaconing traffic from the Neighbour Beacon Exchange component of SPEED used for exchanging location information between nodes.

However, Directed Diffusion exhibits relatively constant lifetimes for the different network sizes, which can be attributed to the flooding of interest packets that consumes a large amount of energy and quickly depleting the nodes, leaving little opportunity for the increase of network size to make an impact in the lifetimes of the network. Nonetheless, we can observe the drop in the Class #3 network lifetime as the network size increases.

6. Analysis and Implications of "Lifetime"

Before we analyze the various lifetime definitions and discuss the implications, it is useful to study the successful delivery ratio of data packets to the sink over time in relation to the protocols' performance under the different lifetime definitions. The percentage of data packets received at the sink node over the simulation period for the General Case (Section 5.1) for the different protocols are shown in Figure 5.

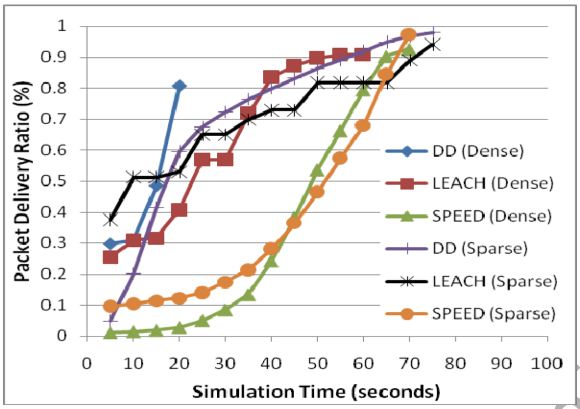


Figure 5. Packets Successfully Delivered to Sink

As the network scenario for our simulations is basically time-driven with a fixed data rate at each source and the primary objective is to send the sensed event data to the sink, this implicitly suggests the level of usefulness of the network at the different point of time in the simulation. Moreover, as we have set the simulation time to be longer than the effective period during which the network and protocol can support the successful delivery of the sensed data, it is reasonable to analyze the different lifetimes based on such a relationship. In other words, when no sensed data is able to reach the sink node when the network is still operational according to the lifetime definitions, the network has lost its usability regardless of the definition of network lifetime.

Although there is no drastic difference in the results of the protocols between the different lifetimes, we are able to observe and study the characteristics of both the lifetime definitions for WSNs and the network protocols under the various scenarios. In particular, the following conclusions can be drawn:

- The time to which the percentage of failed nodes exceeds a threshold (Class #1 lifetime definition) tends to give relatively pessimistic results – the current most commonly used definition for network lifetime sets the threshold at one node. While this is unambiguous and simple, it does not in any way reflect the two critical aspects of WSNs, namely, connectivity and coverage.
- Protocols with well implemented load-balancing mechanism are more likely to prolong the lifetimes of the network. However, scalability remains an issue; as the network size increases, the protocols tend to be less efficient in balancing the load among the nodes and in diverting the traffic away from congested regions.
- With the transmission range and number of nodes in the network kept the same, a sparse network is able to lead to longer network lifetimes as compared to a denser network. This suggests that good topology management which is able to pick a subset of nodes to be awake while keeping the rest asleep can extend the network lifetime concurrently from different aspects.
- Non-cluster-based protocols tend to have shorter lifetimes in a non-uniform topology where the nodes are physically clustered in groups, but perform better when used in the Grid topology. Cluster-based protocols perform best in physically clustered topology and further enhanced when the sink is at the centre of the clusters. Considering that in actual deployment scenarios, it is much more likely for the nodes to be non-uniformly distributed across the terrain (unless they are manually deployed in specific locations,) cluster-based protocols may be eventual candidates for use in actual deployments.
- The network topology can have a great impact on the performance of the protocols and having the sink at the centre of the terrain does not necessarily improve the lifetimes as predicted. The central placement of the sink is beneficial only when connectivity is the criterion that determines the network lifetime (i.e. Class #2 lifetime definition.) This is further reinforced when the topology is favoring to the protocol, e.g. a cluster-based protocol applied to a clustered network. In other words, the placement of the sink node at the centre tends to give better network lifetimes only when the topology is favoring to the protocol, but tends to deteriorate the lifetimes in other topologies.
- The network lifetime that is based on the time to which the packet delivery rate falls below a threshold (Class #3 lifetime definition), can be affected by the stability of the delivery rate and tends to inaccurately reflect the usefulness of the network.

7. Conclusions and Future Work

The envisaged deployment scenarios for WSNs lead to cost and size considerations which severely limit the resources that can be built into the sensor nodes. While computation and memory resources may be considered temporary constraints, energy constraints remain a tough challenge to address. While there have been many different energy-efficient protocols proposed to address the energy constraints on WSNs with the common goal of prolonging network lifetime, there are also different definitions of network lifetime that have been used for different scenarios and by different proposals. In this paper, we have presented an objective survey and analysis of the different network lifetime definitions applied to different types of WSN protocols.

There are still many aspects of network lifetimes left for further study, e.g. those related to coverage. Unlike wireless ad hoc networks where connectivity is the key concern, the effectiveness of WSNs is also measured by their ability to provide the required coverage to sense events and acquire data. The work presented in this paper is by no means comprehensive. An immediate extension would be to include the energy consumed by sensing, processing and the sleeping mode of the nodes to reflect a more realistic network for more accurate lifetime results. A more critical need is, in our opinion, a new quantitative definition of the network lifetime which takes into consideration the key characteristics of WSN and, most importantly, both connectivity and coverage attributes of the network.

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