

On the Sensitivity of Sensor Network Simulations

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Abstract - The availability of simulators and emulators that are tailored for wireless sensor networks (WSNs) is a necessary step in allowing accurate evaluation, but simply having the right tools is not sufficient to ensure that the results of experiments actually correspond to what might be expected in realistic deployments. The critical issue is what models are available in these tools, and if these are used in an appropriate manner. In this paper we review the current approaches to WSN experimentation and identify a serious shortcoming in common simulation methodology, specifically in regard to the choice of network topologies and traffic models. We hypothesize that this mismatch has an important impact on the sensitivity of published sensor network simulations. We support our hypothesis using an analysis of the *Directed Diffusion* protocol.

I. INTRODUCTION

The subject of wireless sensor networks (WSNs) is relatively young, and at this juncture two key observations can be made. The first observation is that the majority of results to-date rely on basic analytical models for sensor node behaviour that are evaluated using discrete-event simulations. While providing valuable and early insight into the efficiency of WSNs, these simulations have very simple models of the real world, especially in relation to wireless link behaviour, traffic and topology models, and failure modes. The second observation is that, while there have been only a handful of published reports on deployments of testbeds, they are characterised by unexpected and often unexplained behaviour in terms of both performance and failures. See for example [1,2].

Of course it is to be expected that there will be some mismatch between the results of simulation and actual implementations. A simulator represents an idealised view of the target environment and network, and as such cannot be expected to capture all the various nuances of a real deployment. However it behoves the research community to strive for simulations that mitigate this mismatch, by taking steps to validate simulation assumptions and incorporate models that are more realistic. As an alternative, or sometimes complementary, approach, emulation environments typically offer a more realistic representation than used in simulators. They achieve this by running very similar or identical code as will be used in subsequent deployment. But precisely because of this feature, emulators are limited in the scale of experiments, an important factor when considering wireless sensor networks with hundred or thousands of individual nodes.

The special demands on WSN simulation and emulation are reflected in the volume of relevant literature. *SENS* [3] is a simulator designed to offer considerable flexibility in composing different models of the application, network and physical environment. Extensions of the *J-Sim* and *ns-2* simulators to support wireless sensor networks are presented in [4] and [5] respectively. While suitable for large-scale modelling, simulators fail to capture lower-level details that relate to the performance of individual nodes. In sensor networks this information is often important because of the need to understand the impact of hardware and software design choices on energy efficiency and other metrics. A number of hybrid tools [6, 7, 8] exist in which individual nodes are emulated and network communication between nodes is simulated. The key theme for emulation is balancing the accuracy and precision of the models against the need for reasonable performance.

The availability of simulators and emulators that are tailored for wireless sensor networks is a necessary step in allowing accurate evaluation, but simply having the right tools is not sufficient to ensure that the results of experiments actually correspond to what might be expected in realistic deployments. The critical issue is what models are available in these tools, and if these are used in an appropriate manner. In this paper we review the current approaches to WSN experimentation and identify a serious shortcoming in common simulation methodology, specifically in regard to the choice of network topologies and traffic models. We hypothesize that this mismatch has an important impact on the sensitivity of published sensor network simulations. In the next section we provide a synopsis of the common methodology for conducting WSN simulation experiments. This is followed in Section III by a discussion of the shortcomings of the methodology and presentation of our hypothesis. A sensitivity analysis is presented in Section IV to support the hypothesis. The paper concludes in Section V.

II. SYNOPSIS OF COMMON METHODOLOGY

When designing a simulation experiment there is a range of decisions that need to be made regarding the values of input parameters. The decisions on parameters are largely determined by the scope of the experiment and the interests of the researcher, however it is the case that to-date, many simulations of wireless sensor networks share common choices for key parameters and metrics, particularly when those experiments study the same type of component such as

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MAC or routing. There is a range of typical parameters that must be predetermined.

In this paper our focus is on the settings that are used for network topologies and the traffic models. In reviewing the literature, the approach to topology that is taken above for Directed Diffusion is most commonly encountered – a square sensor field populated with a collection of sensor nodes placed at random points – a uniform random graph. Commonly used dimensions range from 100m to 500m square. The selected density of nodes is influenced by node communication and sensing ranges, and set so as to ensure a certain level of sensing coverage or connectivity. Settings for connectivity range are usually between 10-50m, with sensing ranges being set at proportionally lower values, such as one-third. Good practice is to generate a set of such random topologies over which the experiments are repeated and the results averaged. However, a number of papers use a regular square grid, with nodes evenly spaced at each intersection point on the grid.

The traffic that occurs in a sensor network is a key parameter and governs both downstream, from sink(s) to source(s), and upstream from source(s) to sink(s). The quantity of downstream traffic is typically assumed to be much greater than that of upstream traffic, and easily determined by the rate at which the sink issues requests – most papers seem to use a fixed period with settings that vary considerably from several seconds to several minutes. Upstream traffic is characterised by spatial and temporal dimensions. The spatial distribution of traffic determines those nodes in the network from where the traffic emanates and is typically one of:

1. Ubiquitous – all nodes in the sensor field;
2. Random node – a given node selected at random, and possibly its neighbours;
3. Random region – nodes that lie in a randomly selected region of the sensor field;
4. Mobile – nodes that are within sensing range of an object that moves through a sensor field according to some mobility model (e.g. Random Waypoint).

For mobile nodes the temporal dimension of traffic generation is determined by the parameters to the mobility model and of course the rate of appearance of objects. For the other traffic models the temporal dimension in most papers is dominated by the frequency at which the sink(s) generates requests.

III. DISCUSSION AND HYPOTHESIS

WSN simulations can be characterized for our purposes by considering their models for network topology and traffic. Drawing on the presentation in the previous section, topology is typically constrained by a square area of a specified physical dimension, in which nodes are deployed in random locations. Traffic is commonly generated by all or some subset of nodes producing messages either at fixed intervals or at random. This methodology is used because it simplifies the design and

repetition of experiments, and matches the intrinsic desire for stochastic validation by using uniform models.

Much of this methodology was originally developed for simulating ad-hoc networks and is perhaps a good match for the early battlefield-oriented scenarios for sensor networks. However, sensor network applications go well beyond military battlefields with nodes being dropped from aircraft, and lead us to question whether the accepted simulation methodologies are widely appropriate, and what impact these choices are having on simulation experiments. For example in many real world situations the topology will not be random (or a grid) but may be structured or semi-structured, reflecting the manual placement of nodes at points of special interest or that are easily accessible, or to avoid obstacles. In fact clusters of nodes will likely occur near to areas of interest. Unlike traditional data networks and ad-hoc networks, WSN networks will be constrained by physical reality.

In regard to traffic, today’s models of generation seem especially contrived and artificial, appealing in their simplicity but not taking into account the underlying physical phenomena. Of course we cannot yet define a set of “standard” phenomena models because of a lack of experience with real deployments and applications. But it seems desirable that simulation models for physical phenomena are needed that would allow nodes to determine if they can sense an event, as opposed to the researcher simply selecting nodes which he/she deems to have sensed. The work on mobile objects is promising but should be expanded to deal with the evolution of other more complex phenomena such as chemical plumes and forest fires with impact of wind and obstacles.

We believe that the physical nature of WSNs behoves us take a pragmatic approach to simulation that will allow us to understand and quantify the impact of topology and traffic models. There are two issues. The first is to develop a toolkit of topologies and traffic models that are more appropriate for WSN environments. The second is to study the impact of *multiple* different such models on performance and behaviour. We believe that the methodology for WSN simulation must be altered to evaluate new algorithms and protocols with multiple such models, and not just one model for traffic and topology, as is the norm today. For work that is already published we don’t know whether a re-evaluation using multiple models would yield results that are better or worse than those already published. It may be that by constraining the models it will show that previous results actually represent worst-case scenarios and we can expect better theoretical performance in practice. Or it may highlight unexpected failures due to the non-uniformity of realistic models. Our contribution is to highlight this mismatch in methodology, and to evaluate our hypothesis that the choice of topology and traffic models can have a significant impact on performance.

Our research is encouraged by several recent papers that, in the process of evaluating their own work, have observed the

impact of topology or traffic in sensor network simulations. In [9], the authors present a number of new models that they have added to the *Qualnet* simulator. One of these models allies with a concern of ours by providing a richer model for the occurrence and detection of phenomena. Others relate to the models of node battery and CPU. They report briefly on an experiment using two well-known ad-hoc routing protocols (DSR and AODV) running on a 100 nodes square grid. They use a traffic model in which a source and destination pair are randomly selected, and compare with a new traffic model that selects a random region of size 2-6 nodes. The same volume of traffic is generated for both traffic models. Using the random-pair traffic model they observe that both routing protocols perform equally well, but when using the random region model the performance of AODV deteriorates rapidly with increasing group size. No root-cause analysis is given for this result.

In [10], the authors address the issue of optimal placement of sink nodes, discussing a number of different strategies. As part of their evaluation they use three different network topologies – regular grid, uniform random graph, and a random graph with preferential attachment i.e. clustered. They demonstrate that the effectiveness in terms of power is very sensitive to the location of the sinks, which in turn is constrained by the choice of underlying topology. Hence establishing a link between topology and efficiency.

In [11], the authors report on a systematic comparison on different variants of Directed Diffusion. They use 60 nodes randomly distributed in a square field of 50m x 50m. The number of sinks and sources is varied, with their locations being selected at random. Two traffic models are used. One uses exponential inter-generation times with a fixed mean rate - set so that the aggregate event rate is independent of the number of sources. This exponential model was chosen to avoid synchronization effects. The other model uses a fixed mean inter-generation time, so that the traffic grows in proportion to the number of sources. The typical mean value is 10 seconds. The analysis is primarily focused on the impact of numbers of sinks and sources in guiding the choice of one or other of the various approaches, but of interest to us is the clear effect of traffic and topology (via location and number of sources and sinks) on the amount of control overhead messages and hence efficiency.

Other researchers have raised general concerns about the level of detail that is available in wireless simulators, especially in respect to models of signal propagation and node energy consumption. For example see [12,13]. Clearly the availability of detailed and accurate models is an essential foundation for conducting rigorous simulation experiments. In particular the wireless community urgently needs a much greater understanding of the variable reliability of short-range outdoor wireless links. Going beyond these issues of detail, our contribution is not to identify a need for greater detail in simulations *per se*, but rather to highlight the importance of

assessing the sensitivity of simulation experiments when using multiple topology and traffic settings that coincide with realistic settings for sensor networks.

IV. SENSITIVITY ANALYSIS

In order to evaluate our hypothesis that sensor network simulations are sensitive to settings for topology and traffic, we conducted a series of simulations using ns-2 and with one-phase Directed Diffusion. We selected Directed Diffusion because it is widely used in simulation studies. An extended sensitivity analysis for this protocol was reported in [14], but does not consider the issues we consider in this paper. Note that our objective in this paper is to identify and justify our hypothesis. It is not to try to identify weaknesses in Directed Diffusion. We select Directed Diffusion simply to illustrate our hypothesis; we believe the problem we identify has wide implication for the WSN community.

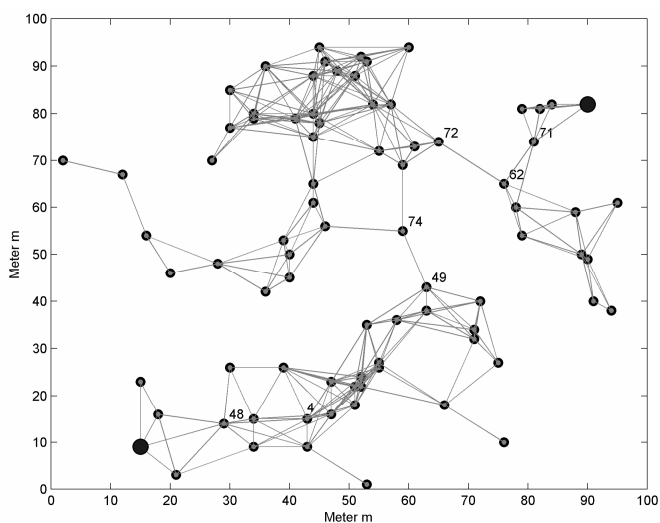


Figure 1. Cluster Topology

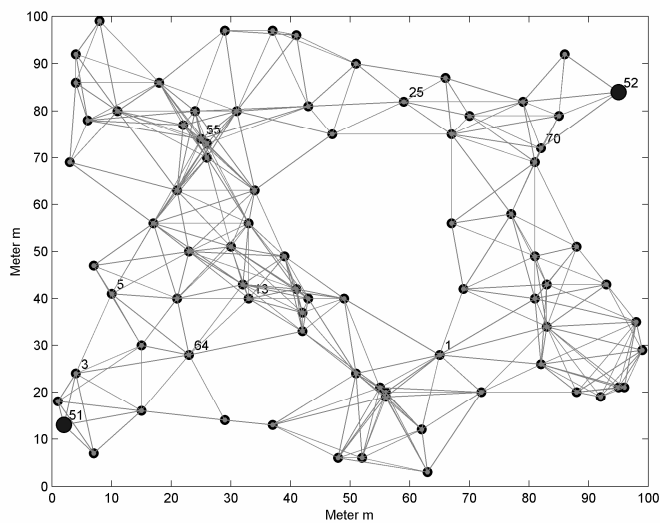


Figure 2. Random Topology

We are interested in several traffic models and topologies. In regard to topologies we identify uniform random graph, regular grid, and clustered. We are especially interested in the impact of clustering, because that appears to correspond with the informed placement of nodes at important locations during deployment. In regard to traffic, we are interested in four models. The first is what we previously called ubiquitous – according to some fixed period all nodes issue a message. The second is what we previously called random region, where we select a node at random and have it and its neighbors each generate a message. The third is what we call linear spreading, such as with a forest fire or wind-blown release of chemicals. In that case a location is chosen at random and the phenomenon spreads throughout the network. The final traffic model is a single mobile object or group of mobile objects, corresponding for example to an animal or herd traversing the sensor field. In our current analysis we selected a subset of these models.

A. Simulation setup

At the initial stage of our work, we analyzed the effect of random and periodic traffic models with uniform random and cluster topologies. We generated five uniform random topologies and five cluster topologies with 81 nodes in each network placed in a 100m x 100m area. One topology of each type is shown in fig. 1 and fig. 2. In both of the figures, the locations of sinks are marked with big solid black circles. Each node was configured with the initial energy of 50 Joules. Two sinks were chosen manually for each topology such that these sinks lie at the opposite peripheries of the network. For each of these topologies, two separate simulations were run corresponding to the two selected traffic patterns: random and periodic. We ensured that same amount of data was transmitted in each of the traffic patterns. The average sending rate in each of the traffic patterns was around 26 packets/sec. For each of the simulations we observed the time when the first node dies i.e. when the network starts to partition, the order in which the first few nodes die and the average delivery rate per sink.

B. Simulation results

We will first discuss how the two different topologies behaved in the presence of random traffic because it is the most widely used traffic model in sensor network simulations and we observed that the effect of topology is more pronounced under this traffic model. Then we will look at the same topologies under periodic traffic model and afterwards we will do a general comparison of the two traffic models. The results for one of the random and cluster topologies with periodic and random traffic models are shown in Table 1 and Table 2 respectively. The results for other simulations were similar but omitted as lack of space.

Under random traffic model, the uniform random and cluster topologies showed a clear difference. We observed that the random topology almost always lasted longer than the

cluster topology. Fig. 3 shows the energy plot of the two topologies under this traffic model. In random topology, generally the nodes that are one or two hops away from the sinks die first while both the cluster heads and the nodes a few hops away from sinks are the first ones to die in cluster topology. This can be inferred intuitively because in cluster topology, cluster heads forward all the traffic originating in the cluster and thus get depleted quickly. The first few nodes that die in a random topology generally include the sinks but in a cluster topology, sinks die much later than other nodes. The average delivery rate per sink is also slightly higher in random topologies as compared to cluster topologies. Both of these can be attributed to the early partitioning of the network in a cluster topology resulting in dropped packets. Thus the cluster topology exhibits a slightly lower delivery rate and the sinks in cluster topology last longer because they receive fewer packets as compared to random topology.

Random and cluster topologies did not show a clear marked difference under periodic traffic model. Simulation results show that the time when the network starts to partition is close together for both types of topologies. The nodes that are one or two hops away from sinks die first in random topology and in cluster topology both the nodes that are few hops away from sinks and the cluster heads are the ones that die just like the scenario with random traffic model. The average delivery rate per sink is also similar for both types of topologies. It seems that the effect of periodic traffic model is more dominant in this case and under this traffic model both the topologies exhibit similar behavior.

	Random Topology	Cluster Topology
Time when first node dies	207s	229s
Order in which nodes die	3, 64, 13, 1, 5, 55	4, 48, 62, 71, 72, 49
Packets sent before partition	5293	5925
Average number of packets/sec	25.5	25.8
Packets received before partition	4300	5648
Average delivery rate per sink	0.40	0.47

	Random Topology	Cluster Topology
Time when first node dies	323s	248s
Order in which nodes die	3, 25, 5, 70, 51, 52	72, 62, 71, 74, 49, 48
Packets sent before partition	8586	6561
Average number of packets/sec	26.5	26.4
Packets received before partition	17127	12544
Average delivery rate per sink	0.99	0.95

Comparing between periodic and random traffic models, an interesting point observed is that the lifetime of the network under random traffic is always longer than the one with periodic traffic, although the average rate at which the data is transmitted is same in both cases. Furthermore, the average delivery rate per sink with random traffic pattern is much higher than with periodic traffic. Although the volume of data transmitted is same for both types of traffic, however, each traffic model has its own inherent traffic nature. The traffic in periodic model is burstier where all the nodes send a packet after a fixed interval (3s in our case). However, in random model, nine nodes are selected at random every second and asked to send three packets resulting in smoother traffic.

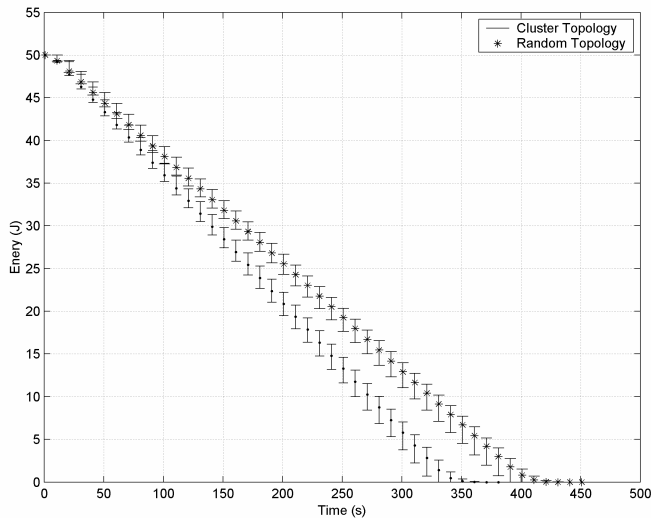


Figure 3. Min, Avg. and Max. Energy with Random Traffic Model

V. CONCLUSION

This paper considers the hypothesis that the choice of network topologies and traffic models has significant impacts on sensor network simulations. From the simulation results, we realize that traffic pattern is a dominant factor on network performance. However, when a particular traffic pattern is used, the effect of different topologies starts to become more apparent.

Our current analysis considered only a subset of traffic models and we plan to extend it to all the listed models in future work. With this work, we hope to draw the attention of sensor network research community to current simulation methodology mismatch with real world models. We encourage the development of more realistic models and the use of multiple models in sensor network simulations.

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