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Application of Particle Swarm Techniques in Sensor Network Configuration

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ABSTRACT

A decentralized version of particle swarm optimization called the distributed particle swarm optimization (DPSO) approach is formulated and applied to the generation of sensor network configurations or topologies so that the deleterious effects of hidden nodes and asymmetric links on the performance of wireless sensor networks are minimized. Three different topology generation schemes, COMPOW, Cone-Based and the DPSO-based schemes are examined using ns-2. Simulations are executed by varying the node density and traffic rates. Results contrasting heterogeneous vs. homogeneous power reveal that an important metric for a sensor network topology may involve consideration of hidden nodes and asymmetric links, and demonstrate the effect of spatial reuse on the potency of topology generators.

Keywords: Sensor Networks, Network Topology, Swarm Intelligence, Particle Swarm Optimization.

1. INTRODUCTION

Current topology control algorithms¹⁻⁵ try to minimize the power used by radio transceivers while ensuring connectivity of the network. A common theme in energy-aware sensor network operation is that reducing transmit power of the nodes extends the network lifetime. The question, however, is whether a reduction of unnecessary links (from the connectivity perspective) will actually translate into energy savings. Note that, among other problems, fewer links may lead to fewer choices of routes, more collisions and packet drops. This paper aims at investigating network properties that are critical for true energy efficient topology control.

Park and Sivakumar⁶ have demonstrated that in networks with a common transmit power allocation to all nodes, the optimum node transmission power varies with traffic load on the network. While common power for all the nodes may be a relatively easier scheme to implement, it is, however, intuitively restrictive in terms of energy savings since most likely, there will be nodes that can use less transmission power than others to perform the same networking tasks. Topology generation schemes that result in heterogeneous power, on the other hand, may introduce "hidden nodes" and "asymmetric links." The study by Liu and Li¹ highlights the existence of asymmetric links as a part of their distributed topology control algorithm. The number and impact of the asymmetric links, however, is not addressed in depth. We assert that there are desirable topological attributes that should be considered when generating a configuration. Identifying these appropriate metrics may lead to development of better topology control schemes. More specifically, we will argue that topology control schemes should account for the hidden nodes and asymmetric links, so as to induce better network performance in terms of network capacity and energy efficiency for a wide range of network loads.

In Section 2 we justify examining hidden nodes and asymmetric links as a metric for topology generation. Section 3 summarizes the three topology generators that are compared. Section 4 compares and contrasts properties of topologies generated by these approaches. Section 5 details how our simulations are constructed in ns-2⁷. The results of the simulations are presented and discussed followed by concluding remarks in Section 6.

2. NETWORK MODEL, HIDDEN NODES AND ASYMMETRIC LINKS

We consider a collection of N nodes deployed statically in \mathfrak{R}^2 , where d_{ij} denotes the Euclidean distance between node i and node j . A topology control scheme will determine the transmission radius $r_{\min} \leq r_i \leq r_{\max}$ for each node i where $i=0,1,\dots,N-1$, and r_{\min} and r_{\max} are the minimum and maximum transmission ranges respectively for any node in the network. A set of nodes without the transmission radii being defined is referred to as a deployment, and will be referred as a network topology once the transmission radii is determined by the topology control algorithm. We

assume that node i can transmit to a neighboring node j if and only if $d_{ij} \leq r_i$, and define Ω_i as the neighborhood of node i . Consistent with most other work in the literature, we have assumed the transmission range of a node to be independent of direction even though it may not be so in reality. However, this simplified assumption suffices for our study to investigate the impact of asymmetric links and hidden nodes and allows us to have a “controllable” environment to define asymmetric links and hidden nodes.

In general, an energy efficient topology control scheme aims at reducing the transmission power of the nodes. It is well known that the transmission range is positively correlated to the transmission power. Let $C(\mathbf{r})$ be a function that returns 1 if all nodes are connected and 0 otherwise given the transmission radii vector $\mathbf{r} = [r_1, r_2, \dots, r_N]$. A general formulation of the topology control problem can then be stated as follows.

$$\min \left(\sum_{i=1}^N r_i \right) \quad \text{subject to, } C(\mathbf{r}) = 1, \quad r_{\min} < r_i < r_{\max} \quad (1)$$

$$\{d_{ij} < r_j \mid j \in \Omega_i(r_i)\}$$

Note that the objective stated in (1) focuses on minimizing the sum of the transmission radii, which while not equal to the total transmission power of all nodes, nevertheless varies with it. Other objective functions such as minimizing the maximum transmission radius may be used, but we focus on topology control algorithms that have similar objectives as that stated in (1).

We may now formally define asymmetric links and hidden nodes. A node has an asymmetric link with one of its neighbors j if and only if $r_i \geq d_{ij}$ and $r_j < d_{ij}$, i.e., i can talk to j but j cannot talk to i . We denote the number of asymmetric links for node i as n_i^a . In a network where there are no asymmetric links, the definition of hidden node is well known: a node (say A) is hidden from another node (say B) if the two nodes can communicate with a common node (say C) but they cannot sense each other. Hidden nodes impact spatial reuse in the following sense: if node A transmits to C while B is transmitting to C, the resulting collision at C will cause loss of data from both A and B. In the case where there are asymmetric links, the traditional definition of hidden nodes is not enough to define the spatial reuse. Consider an asymmetric link from node i to j , and one would notice that node i 's transmission can interfere with node j 's transmission even though there is no common node in between the two where they can talk to. In this case, the RTS/CTS solution from CSMA/CA will have no effect and unforeseeable collisions can happen and lead to energy waste or even protocol failures. A topology generator allowing heterogeneous power among nodes may have significant number of asymmetric links and hidden nodes. We will look into these two metrics in examining network performance in Sections 4 and 5.

3. TOPOLOGY GENERATORS

3.1 COMPOW power control

The COMPOW^{3,8} power control algorithm, which targets on minimizing a common power used by all nodes subject to the connectivity constraint, offers an ideal baseline scenario for analyzing the impact of hidden nodes and asymmetric links. Simply, when all nodes communicate with the same power, there are no asymmetric links. Furthermore, if the carrier sensing range is more than two times the transmission range, there will be no hidden node, either. In COMPOW, all nodes back off their power until the network becomes partitioned. The nodes then communicate using the power just prior to the partitioning. There are a couple of noteworthy observations. The COMPOW algorithm is relatively easy to implement in a centralized fashion, but may not be as easy if it were to be implemented in a distributive manner. The COMPOW algorithm performs well when the deployment is regular. For example, if all nodes are equally spaced in a regular lattice, one can do no better than COMPOW in terms of minimizing power and the number of hidden nodes and asymmetric links. This suggests to us that a relevant measure for comparing results across different deployments will be the uniformity of the deployment or the topology resulting from the topology control algorithm.

3.2 Cone-based topology generation

The Cone-Based⁴ approach to topology generation is a distributed heuristic for minimizing the total node transmission power subject to the connectivity constraint. The algorithm can form provably connected networks (assuming that the network is connected when all nodes are transmitting at maximum power) while allowing nodes to reduce the power to different levels. The basic idea of the algorithm is that each node will increase its transmit radius until for any angle, α , there exists at least one neighbor within the area subtended by the angle. It is shown that as long as $\alpha \leq 5\pi/6$, the network is guaranteed to be connected. Nodes are required to continue to increase their transmit radius during the first “cone” phase of the algorithm until they satisfy the requirement that there is a neighbor in any cone about them. Some nodes may not be able to locate a neighbor in every cone about them and will eventually be using their maximum power or transmit radius. After the “cone” phase, any node using maximum power is assumed to be an edge node and hence goes through a “back-off” phase. The edge nodes decrease power just to the point where they detect that their “coverage” has decreased. Each edge node then uses the power recorded just before its coverage decreased. The last phase of the algorithm uses the triangle inequality to remove redundant edges in the topology, possibly further reducing the transmit power of some of the nodes. The Cone-Based approach yields heterogeneous power topologies, which leads to non-zero hidden nodes and asymmetric links. The algorithm makes no attempt to minimize hidden nodes or asymmetric links. We reproduced the Cone-Based algorithm using $\alpha = 5\pi/6$ and generated topologies by executing the “cone” phase followed by both the “back-off” and “redundant-edge removal” phases.

3.3 Distributed particle swarm optimization (DPSO)

We have introduced the concept of distributed particle swarm optimization (DPSO) previously in a couple of different contexts including that of sensor coverage⁹. We developed DPSO as a distributed variation of particle swarm optimization (PSO). In PSO, the solution to an optimization problem is developed using a number of particles each of which obtains its own solution. Assuming the optimization to be a minimization, the process can be summarized as follows:

1. Let $f(\mathbf{x})$ be an M -dimensional objective function that is to be minimized.
2. Let there be several particles in the PSO scheme each of which generates an M -dimensional solution vector. If $\mathbf{x}_i^{(n)}$ is the solution of the i -th particle at the n -th iteration then the fitness value of the particle is $f(\mathbf{x}_i^{(n)})$.
3. At the $(k+1)$ -th iteration, each particle’s solution $\mathbf{x}(k)$ is updated as

$$\begin{aligned} \mathbf{v}(k+1) &= \mathbf{v}(k) + \phi_1(\mathbf{x}_p(k) - \mathbf{x}(k)) + \phi_2(\mathbf{x}_n(k) - \mathbf{x}(k)) \\ \mathbf{x}(k+1) &= \mathbf{x}(k) + \mathbf{v}(k+1) \end{aligned} \quad (2)$$

where $\mathbf{v}(k)$ is its “velocity,” $\mathbf{x}_p(k)$ is the particle’s own best recorded position in terms of smallest $f(\mathbf{x})$ value and $\mathbf{x}_n(k)$ is the best recorded position among particles in its neighborhood. Thus each particle belongs to a suitably defined neighborhood. ϕ_1 and ϕ_2 are random variables that are uniformly distributed.

4. Convergence is achieved when the best solution does not change substantially from iteration to iteration.

We now attack the topology generation problem with each node behaving as a particle (hence the distributed version) with the objective being connectivity maintenance, asymmetric link minimization and power minimization. In the process we find that the fitness function involves three major topological properties, transmission radius, number of hidden nodes and number of asymmetric links. Furthermore, the fitness function for each node is different, a major difference between DPSO and PSO. Our approach involves a heuristic search through the space of possible topologies for topologies that optimize these quantities. During the search we allow individual nodes to autonomously adjust their transmission radius in an attempt to optimize their own individual fitness. We define the i -th node’s fitness as

$$f_i = \frac{(N_{2,i} - N_{2,i}^A + 1)}{(N_{2,i} + 1)} + \frac{(N_i^A + 1)}{(N_{neigh,i}^A + 1)} + \frac{r_i}{r_{MAX}} + \frac{2\pi}{cov_i} \quad (3)$$

In (3), r_{MAX} is maximum communication radius of any given node, cov_i is the coverage of node i , $N_{2,i}$ is the number of 2-hop neighbors of node i , $N_{2,i}^A$ is the number of 2-hop neighbors that are also asymmetric links and

$$N_{neigh,i}^A = \sum_{j \in \Omega_i} N_j^A \quad (4)$$

Each term in (3) is scaled by an appropriate factor so that each term has about the same order of magnitude as the other terms. Since any given node cannot compute a count of hidden nodes, the number of hidden nodes is approximated by $N_{2,i} - N_{2,i}^A$, which approximates an upper bound on the number of hidden nodes for node. The fitness expression of (3) encourages nodes to reduce their transmission radius, hidden nodes and asymmetric links while maximizing their coverage. The coverage maximization encourages spontaneous formation of connected graphs during the optimization. We may define the best topology in terms of any desired metric: hidden nodes, asymmetric links, sum-transmit-radius, $\sum_i r_i$, or max-transmit-radius, $\max\{r_i\}$. We choose to track the topology with the minimum number of asymmetric links. This is done because we believe that a lower sum-transmit-radius topology need not out-perform a higher sum-transmit-radius topology and when minimizing the number of asymmetric links, the number of hidden nodes resulting from the DPSO algorithm was usually fewer than the number present in a Cone-Based topology.

4. COMPARING THE TOPOLOGIES

We first discuss the properties of the topologies generated based on the three afore-mentioned topology generators. Twenty random deployment of 80 nodes and nine random deployments of 200 nodes are tested. The nodes are uniformly distributed on a circle. For each deployment, the topology generator determines the vector \vec{r} that contains the transmission radii for the nodes. From each topology generated, we derive and record various statistics, such as the average distance between neighbors, the sum of the transmission radii (sum-transmit-radius), and the number of hidden nodes and asymmetric links. Figures 1 and 2 highlight the different topological properties exhibited by the three topology generators. We show the results for the 200 node deployments only, because for 80 nodes, the topological properties are qualitatively identical to the 200 node results, differing mainly in scale. The figures show that the average sum-transmit-radius is lowest in the Cone-Based topologies and highest in the COMPOW topologies while the number of hidden nodes and asymmetric links is smallest for COMPOW topologies and largest for Cone-Based topologies. Topologies generated by DPSO offers a good compromise between the two. Intuitively, and as we will show in the next section these two properties closely correlate to the performance exhibited by these different topologies although the deployment is the same. More specifically, the higher the sum-transmit-radius is, it is more costly to transmit a packet. However, more asymmetric links and hidden nodes mean more re-transmissions and unsuccessful route establishments, and therefore waste of energy.

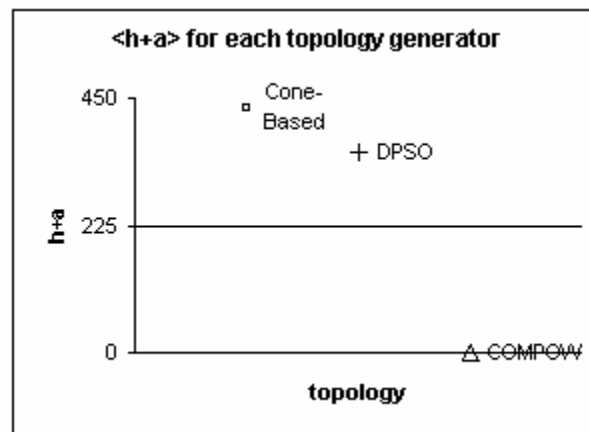


Figure 1 The average # hidden nodes plus asymmetric links (h+a) for each topology generator (over 9 deployments of 200 nodes).

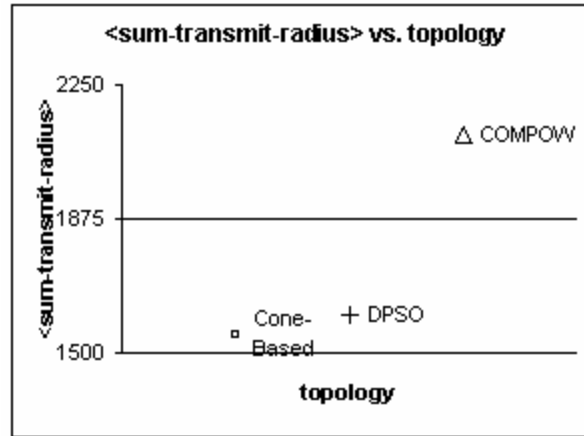


Figure 2 The average sum-transmit-radius for each topology generator (over 9 deployments of 200 nodes).

5. NETWORK PERFORMANCE EVALUATION

5.1 Simulation setup

The afore-mentioned topologies (generated by the three topology generators from the random deployments) are simulated in ns-2, with AODV^{10,11} and 802.11 being the routing and MAC protocol. The target performance metrics we examine are “network capacity” and “energy efficiency.” The network capacity is defined as the percentage of offered load that reaches the destinations. Notice that not all packets will reach the destination successfully, due to failure on route establishments and MAC protocol reaching the maximum retries. The energy efficiency (joules/bit) is defined as the energy required in delivering one bit of data from the source to the destination (regardless how far they are from each other).

Our simulations choose the sources and the destinations from the “internal” nodes and the “external” nodes, respectively. The philosophy behind this choice is to imitate the case where the sensors in the sensing field will send the data to exterior processing gateways. The external nodes (which are not the exterior gateways) in this case are the ones that the data will pass through to reach the exterior gateways. Recall that the nodes are deployed uniformly within a circle. Figure 5 illustrated the traffic patterned created based on this model. The next questions then are how to determine which nodes are internal and which nodes are external. We define the external nodes as the ones located in the “shell” of the circle, and the internal nodes as those located within the internal circle – see Figure 5. The size of the shell (D) is determined by ensuring that data generated from internal nodes will need to pass through the shell to reach to the exterior of the circle. We accomplish this by choosing D roughly equals to the average transmission radius based on the COMPOW algorithm over the random deployments. With the radius of the circle $R = 50$, we choose $D = 10$ for the 200-node cases and $D = 16$ for the 80-node cases.

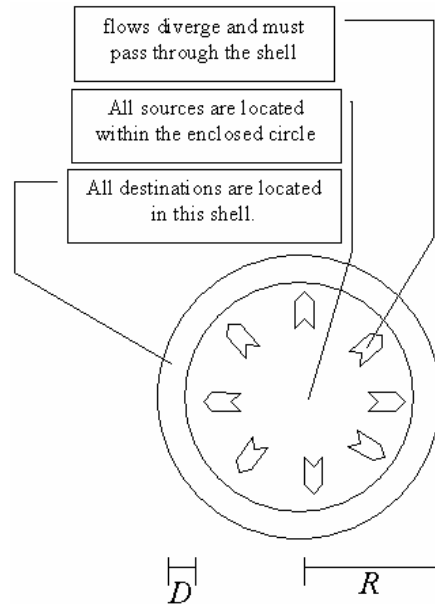


Figure 3 The traffic patterns force packets to diverge from the internal circle outward through the shell with width D .

With the source and destination nodes determined, we now turn our attention to the choice of data rate from each source. Note that the total maximum possible data rate the simulated network can generate is approximately the product of “the number of destinations that can simultaneously receive data” and “the transmitting/receiving capacity of the nodes” (set as 2 Mbps for our simulations). Note that the number of destinations that can simultaneously receive depends on the transmission range chosen, and therefore is topology-generator dependent and particularly different for the 80-node and 200-node cases. With the protocol overheads, multi-hop load factors and re-transmissions, we determine our “heavy-load” for the 80-node and 200-node cases, and summarize in Table 1. Also shown in Table 1 are two other lower offered-load cases we simulated. Note that the medium load is $1/4^{\text{th}}$ of the heavy load and the light load is $1/16^{\text{th}}$ of the heavy load. The traffic is generated with UDP. We examine the simulation statistics and verify that these choices are indeed representative a wide range from heavy to light load situations for the network. We also note that the offered data rate can be higher if more-suited routing and MAC protocol were chosen for the simulation. The purpose of this paper, however, is to examine the shortcoming of having asymmetric links and hidden nodes, and therefore the choice of AODV and 802.11 suffice to represent the cases where the protocols somewhat depend on symmetric links.

Table 1 summary of offered loads simulated for 80 and 200-node deployments

	80 nodes	200 nodes
light load	2 64-byte packets per source per second	1 64-byte packets per source per second
medium load	4 128-byte packets per source per second	2 128-byte packets per source per second
heavy load	8 256-byte packets per source per second	4 256-byte packets per source per second

Our final note on the simulation setup is a modification we made for AODV^[10, 11]. Note that AODV broadcast route discovery packets from the source to the destination. The route will be built when the acknowledgement traversed back to the source following the path visited by the route discovery packet. If any link in the route were asymmetric, then the returning packet would be stranded at a node using insufficient power to reach the node that broadcast the original route request. To ensure that all AODV routing packets can return routing information to the requesting source, we modified the ns-2 source code such that any node receiving a route request packet measures whether it has sufficient power to reach the originating node. If it cannot reach the originating node, then the packet is dropped. This simple modification is what we foresee to be a natural fix that will be adopted by many routing protocols. We believe that this change will allow us to focus more on the effect of asymmetric links on reasonable network protocols for wireless ad hoc/sensor networks.

5.2 Network capacity and energy efficiency

We begin our discussion on the network performance by presenting the results for 200 node deployments. Figure 4 and Figure 5 show the network capacity and energy efficiency achieved (averaged over the 9 random deployments), respectively, when different topology generator is used for the three different offered load cases.

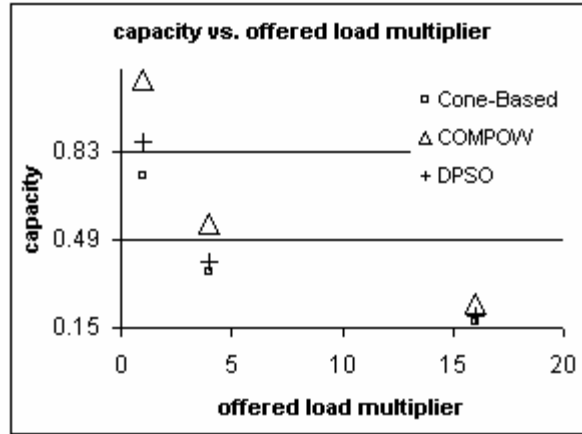


Figure 4 Average network capacity (over 9 deployments of 200 nodes) for the different topology generators.

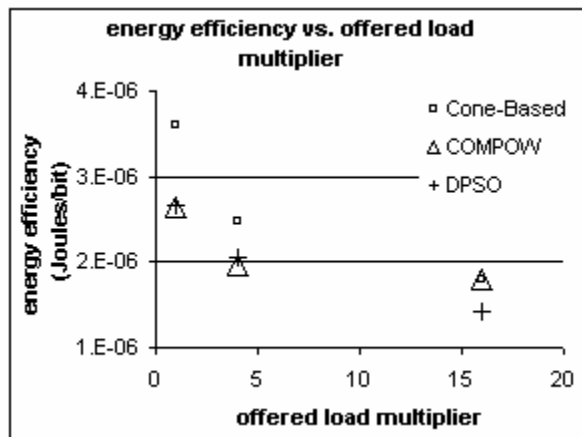


Figure 5 Average energy efficiency (over 9 deployments of 200 nodes) for the different topology generators.

We observe that COMPOW always results in higher capacity, followed by DPSO and then the Cone-Based. With respect to energy efficiency, the Cone-Based topologies always result in the worst energy efficiency, approaching the efficiency of COMPOW at high loads. In contrast, the DPSO topologies result in energy efficiency approximately the same as COMPOW and surpass the COMPOW efficiency at high loads. In the sequel, we present detailed results to provide explanations of these trends.

To understand the performance of these 3 topology generators, we tracked and counted every dropped packet from the ns-2 trace. The drops related to MAC operation were grouped together and summed. Those relating to routing were grouped together and summed (RTR). We are particularly interested in learning if there is any benefit to minimizing the number of hidden nodes/asymmetric links when generating a topology. We present below the correlation between MAC and RTR drops and the sum of hidden nodes and asymmetric links (h+a) for all the topologies generated. We focus our attention on the lowest offered load data.

Figure 6 shows the RTR drops versus “h+a” for different topologies generated. One can easily observe the positive correlation between the “h+a” to the RTR drops. In fact, we believe that the RTR drops is the dominate factor leading to the plunge of network capacity. Figure 7 exhibits the correlation between RTR drops and the network capacity. These

results suggest relationship from the hidden nodes and asymmetric links to the RTR drops, which somewhat reflect “no route to host” and therefore significantly degrade network capacity.

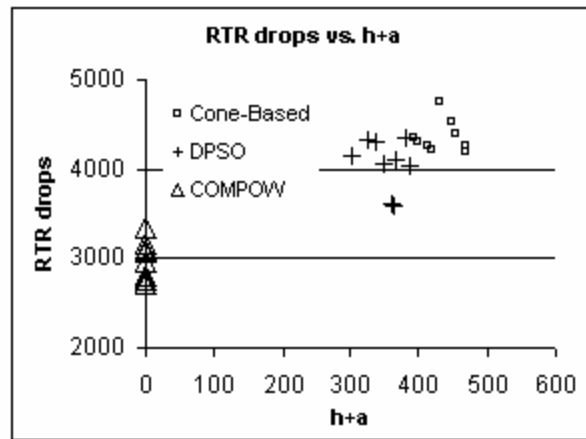


Figure 6 The correlation between RTR drops and “h+a” for the topologies generated (200-node, light-load).

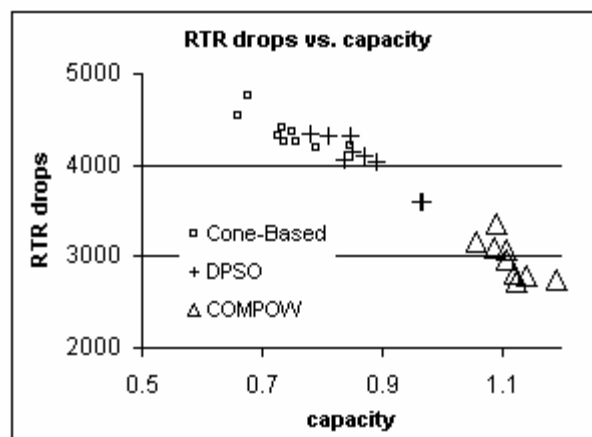


Figure 7 The correlation between RTR drops and network capacity for the topologies generated (200-node, light-load).

For a given deployment, if all 3 types of topologies used the same amount of energy to deliver their data to the sinks, then the Cone-Based and DPSO topologies would be less energy efficient because they operate at a lower capacity, delivering fewer bits to the sink over the simulation. However, for a given deployment, the 3 types of topologies do not use the same amount of energy. COMPOW uses the most energy followed by DPSO and Cone-Based. If we assume that the loss in capacity is due to routing failures, then we are left with (at least) two factors contributing to the interesting variation in the energy efficiency of the 3 types of topologies across different loads. These factors are the difference in the transmission power (or transmission radii) of the nodes and the MAC drops. Excess power uses more energy, as do MAC drops.

Let us consider each data load separately. Figure 8 shows the MAC drops versus the various loads for different types of topologies. Based on Figure 5 and Figure 8, we observe that, at the lowest data rate, COMPOW and DPSO have about the same energy efficiency and MAC drops. This means that the lower power consumption of the DPSO topology, combined with its lower than COMPOW capacity, causes the energy efficiencies to be approximately equal. However, the Cone-Based topology, also having around the same number of MAC drops, does not operate at that much lower power than the DPSO topologies (see Figure 2) and thus its energy efficiency drops with its capacity, which is significantly lower than that of the DPSO topology. The energy efficiency data for the medium-load case can be

similarly explained. With the highest offered load, we see that the capacities are approaching the same value although the Cone-Based capacity is still significantly lower than the COMPOW capacity. However, at the highest data rate, the COMPOW topologies experience (see Figure 8) much higher MAC drops than DPSO and Cone-Based, allowing them to approach, and even surpass, in the case of DPSO, the energy efficiency of the COMPOW topologies.

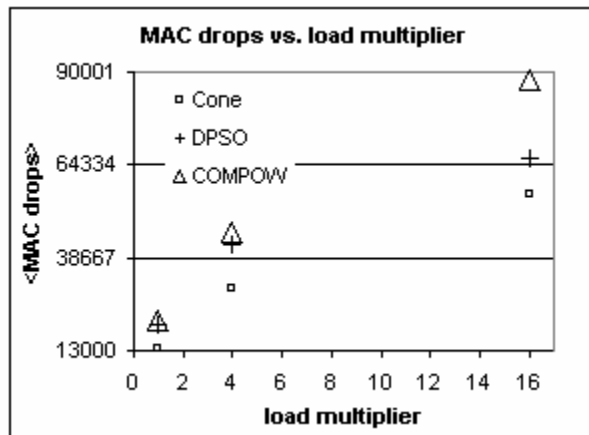


Figure 8. The MAC drops averaged over the deployments of 200 nodes for the 3 topology generators across different offered loads.

5.3 Effect of spatial reuse

Above we focus mainly on the 200-node cases. The network capacity and energy efficiency results for the 80 node simulations are qualitatively similar to those for the 200-node cases. However, the fraction of the offered load delivered is substantially lower even though the offered load was scaled to be in the same proportion as that offered in the 200-nodes simulations. Also, it appears that the different topology generators have a diminished impact on the performance of the network. This can be explained by considering the spatial reuse of the topology.

Recall that the 80 nodes are uniformly deployed in the same area with 50-unit radius. Hence the 80 node deployments were less dense than the 200 node deployments. The smallest average transmit radius for the 80 nodes deployments is 12, resulting from the Cone-Based algorithm. This leads to a large carrier sensing range that occupies a big portion of the entire area, especially if the transmitter is near the center of the circle. This severely restricts the number of possible simultaneous transmissions in the network. With 200 nodes, the problem is less severe, with the smallest average transmit radius is 7.76 (also resulted from the Cone-Based generator). Because of the restriction on spatial reuse, the correlation between the routing failures to the network capacity become less significant, since routes have fewer hop counts and are easier to be found. Similarly, the plummet of energy efficiency due to MAC drops will be less significant since there cannot be too many simultaneous transmissions anyway. Figures 9 and 10 exhibit the correlations between the network capacity and “h+a” for the 200-node and 80-node cases, respectively. As can be seen, the correlation still exists for the 80-node cases, but is less clear as compare to the 200-node – denser deployment cases.

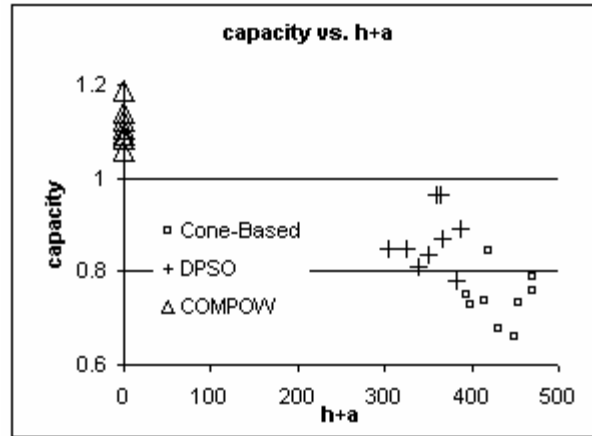


Figure 9 The correlation between network capacity and “h+a” for the 200-node cases.

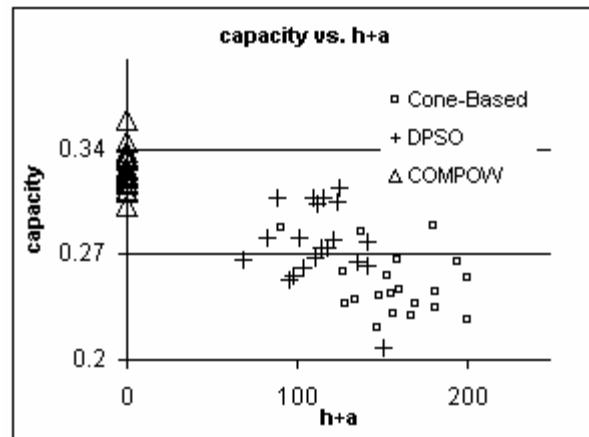


Figure 10 The correlation between network capacity and “h+a” for the 80-node cases.

6. CONCLUSION

Many factors contribute to the average energy usage of wireless sensor nodes in a real network environment. This work suggests that the existence of asymmetric links and hidden nodes have an impact on network performance, especially for networks with much spatial reuse (i.e., many nodes can transmit at the same time). An approach, based on distributed particle swarm optimization or DPSO, was provided for topology generation aimed at minimizing asymmetric links and hidden nodes. We finally note that AODV and 802.11 are not the best suited for wireless sensor networks and were adopted for the studies more by default than anything else. The results may need to be re-examined if new alternative protocols become widely available.

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