Topology Maintenance: Extending the Lifetime of Wireless Sensor Networks

Pedro M. Wightman[1] and Miguel A. Labrador
Department of Computer Science and Engineering
University of South Florida
Tampa, Florida 33620
{pedrow,labrador}@cse.usf.edu

Abstract— **Topology control is a well-known strategy to save energy and extend the lifetime of wireless sensor networks. In the literature, it is usually referred as the process that, given a set of nodes, builds a reduced topology that still guarantees connectivity and coverage. Here, we extend this definition. We consider topology control as two processes: topology construction and topology maintenance. Topology construction encompasses those algorithms that build the reduced topology. Topology maintenance is the process that changes the reduced topology from time to time when the current one is no longer optimal. In this paper we define topology maintenance and present different strategies and triggering criteria that can be used to switch the network topology. We also implement static and dynamic global topology maintenance strategies using two well-known topology construction algorithms and time- and energy-based triggering criteria, and compare their performance via simulations on sparse and dense networks. Our results demonstrate that the appropriate use of topology maintenance techniques extends the network lifetime versus the option of not doing topology maintenance at all. In sparse networks, while dynamic global techniques improve the network lifetime, static techniques may improve or degrade the performance. However, all results are fairly similar. On the other hand, topology maintenance is very well justified in dense networks where important performance improvements can be achieved. In this case, the superiority of dynamic global techniques is evident, and even more as the density of the network increases.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) is a very popular technology due to the variety of applications in which a lightweight, ad hoc, and relatively cheap communication infrastructure can be used. At the same time, the constraints imposed by these networks are very well-known: very limited computation, communication, storage capabilities, and energy resources. This last aspect, which limits the lifetime of the network and therefore its utility, has received considerable attention by the research community over the last several years. The design of energy-aware protocols, algorithms, and mechanisms, with the goal of saving as much energy as possible, and therefore extending the lifetime of the network, has been the topic of many research studies.

One known strategy to save energy in WSNs is that of *Topology Control*. Topology control, as it is usually defined in the literature, is the process of changing, normally reducing or simplifying, the topology of the network to save energy while preserving important network characteristics, such as connectivity and coverage. However, the current definition of topology control usually does not include the maintenance of the network topology, which might not be optimal after some time, or may no longer contribute to achieve other network-wide goals, such as the even consumption of the energy resources.

In this paper we change and extend the definition of topology control. We consider topology control as two processes that work in an iterative manner. On the one hand, there is the same process of building the reduced topology, that we now call *Topology Construction*. On the other hand, we introduce the concept of *Topology Maintenance*, which is the process in charge of switching the reduced topology from time to time when the current one is not optimal anymore. This iterative process of building and switching topologies until there is no new reduced topology capable of providing the expected service is our definition of topology control.

This work makes two important contributions. First, it includes a new taxonomy for topology maintenance along with different strategies and triggering criteria that can be used to switch the network topology. To the best of our knowledge, this is the first formal effort in this direction in wireless sensor networks. Further, the evaluation of different topology maintenance strategies, although non-existent in the literature, it is necessary, as topology maintenance can either improve or degrade the network lifetime of the network. Therefore, our second contribution is the performance evaluation of dynamic and static global topology maintenance techniques in sparse and dense networks using two well-known topology construction algorithms and two different triggering criteria. Our results demonstrate that the appropriate use of topology maintenance techniques extends the network lifetime versus the option of not doing topology maintenance at all. In sparse networks, while dynamic global techniques improve the network lifetime, static techniques may either improve or degrade the lifetime. Experiments in dense networks show similar results; however, the superiority of dynamic global techniques is evident, and even more as the density of the network increases.

The rest of the paper is organized as follows. Section II includes the related work on topology control. Section III describes the new taxonomy for topology maintenance. Sec-

---

[1] Professor on leave from Universidad del Norte, Barranquilla, Colombia.

978-1-4244-4388-8/09/$25.00 ©2009 IEEE

tion IV presents the performance evaluation. Finally, Section V concludes the paper.

II. RELATED WORK

Topology construction can be exercised in different ways. The initial topology can be reduced by solving the Critical Transmission Range (CTR) problem, which reduces the transmission range of all nodes by the same minimum amount, or by solving the Range Assignment Problem (RAP), which sets the minimum transmission range for each node [8]. Other techniques are based on the assumption that nodes have information about their own positions and the position of their neighbors [6], or that they have directional antennas that are used to determine the orientation of the nodes [5], [7]. Although both assumptions are valid, they are costly and not easy to implement. Other topology construction algorithms are based on the Connected Dominating Set (CDS) paradigm. Here, the idea is not to change the transmission range of the nodes but to turn unnecessary nodes off while preserving important network properties, such as connectivity and communication coverage.

The CDS approach has been utilized in several papers [1]–[3], [5], [13]–[15]. Most CDS-based mechanisms work in two phases: in phase one they create a preliminary version of the CDS, and in phase two they add or remove nodes from it to obtain a better approximation to the optimal CDS. Two relevant CDS-based mechanisms are the CDS-Rule-K [13] and the A3 [11] algorithms.

The CDS-Rule-K algorithm utilizes the marking algorithm proposed in [15] and the pruning rule included in [14]. The idea is to start from a big set of nodes that accomplishes a minimum criterion and prune it according to a specific rule. In the first phase, the nodes exchange their neighbor lists. A node remains active if there is at least one pair of unconnected neighbors. In the second phase, a node decides to unmark itself if it determines that all its neighbors are covered by marked nodes with higher priority, which is given by the level of the node in the tree: lower level, higher priority. The final tree is a pruned version of the initial one with all redundant nodes with higher or equal priority removed.

The A3 algorithm produces an approximate solution to the Minimal Connected Dominating Set problem, which is proved to be NP-Hard in [10]. The A3 algorithm assumes no prior knowledge about the position or orientation of the nodes; therefore, the nodes do not have an exact geometric view of the topology. However, nodes determine how far they are based on the strength of the signal received, and this information is enough to select a close-to-optimal CDS tree, based on the belief that farther nodes will offer better area of communication coverage. A3 only needs one-hop information and was shown to provide a low linear message complexity, making it an excellent choice for global topology maintenance techniques (explained later).

In the literature of topology control, it is very common to see that researchers are mainly concerned about producing an optimal reduced topology; however, they usually oversee the known fact that the energy in the network drains over time and the optimal topology, built based on the initial state of the network, is not optimal anymore, or it may no longer contribute to network wide goals, such as the even consumption of the energy. Although some studies include mechanisms for maintaining the network, changing the topology from time to time, they usually embed these mechanisms in their topology construction algorithms, and neither formally include the concept of topology maintenance nor provide any guidance as to what type of other topology maintenance strategies might be possible. Further, they do not quantify the energy savings provided by each algorithm. For example, the cluster-based topology control algorithm described in LEACH [9] uses a global scheme for updating the clusters, which executes in *rounds*, periodically. However, is this time-based technique the only possibility? Why not changing the clusters and clusterheads based on energy? or node failure? If we use one of these alternate methods, do we obtain better (or worse) performance? How much longer does the network work compared with the option of not switching the clusterheads? Similar questions can be asked in most of the existing topology control algorithms. Other algorithms that somehow include some sort of topology maintenance can be found in [2], [4], [16], [17].

III. TOPOLOGY MAINTENANCE

We define topology maintenance as the process that restores, rotates, or recreates the network topology when the current reduced one is no longer optimal. Topology maintenance can be exercised in different ways depending on when the topologies are built, their scope, and the type of triggering event or metric. These options are explained next.

A. When are the reduced topologies built?

Topology maintenance techniques can be subdivided as static, dynamic, or hybrid, according to the time when the new reduced topologies are built. *Static topology maintenance techniques* calculate all different topologies during the first topology construction process. These topologies are built and stored in memory and switched when needed. As such, static techniques have “pre-planned” topologies. The best example to describe these techniques is making the analogy with the lights of a Christmas tree: the entire set of lights contains a number of pre-defined subsets that cover the entire tree and take turns over time. As it can be inferred, static techniques take additional time during the initial topology construction phase to calculate all additional topologies, but once this process is finished, the switching process is faster than if a new topology construction phase had to take place. Further, the communication overhead of each subsequent topology construction phase is also saved. Static topology maintenance techniques may have some drawbacks too. For example, it is difficult to know a priori how each of the topologies and their nodes will consume their energy. Therefore, the mechanism may choose to use some nodes in more than one topology that may not be available or will make the topology to last shorter than expected.

Dynamic topology maintenance techniques, on the other hand, calculate a new reduced topology "on the fly", triggering the topology construction mechanism when necessary. Dynamic topology maintenance mechanisms have the advantage of having more and better information about the network to find a better new reduced topology. The disadvantage of these mechanisms is that they consume additional resources every time they are run, therefore, it is extremely important that the topology maintenance and the topology construction mechanism be both very energy efficient.

Finally, *hybrid topology maintenance techniques* use both, static and dynamic techniques. Hybrid techniques calculate all different reduced topologies during the first topology construction phase (static approach) but if the coming topology can not be established because the sink has no connectivity with the nodes (dead topology), the mechanism finds a new topology on the fly (dynamic approach). This approach inherits some of the advantages and disadvantages of the static and dynamic techniques.

B. Scope of the network

The second question is related to the scope of the network, or which nodes are involved in the execution of the topology maintenance algorithm. The scope can be global or local. While *global techniques* consider all the nodes in the network in order to take a global-optimal decision, *local techniques* only consider a small subset of the nodes in order to take a decision in a local-optimal fashion. Therefore, global techniques switch the entire topology, and local techniques only switch a portion of the network, such as a branch of a tree, a cluster, or even just one node.

C. Triggering criteria

Whether the topology maintenance mechanism is static, dynamic, or hybrid, there is one important question related to all: what is the criterion or criteria that will be used to trigger the process of changing the current topology? The triggering criteria, which may have important implications in terms of energy savings as well as coverage, reliability, and other important metrics, may be based on one of the following choices:

- *Time-based:* In time-based topology maintenance, the current topology is changed every time a timer expires. The amount of time is usually fixed and pre-defined, and a very critical variable. A very short time may cause unwanted extra overhead as a consequence of switching the topology more often than necessary. On the other hand, a very long time may use a suboptimal network longer than necessary, with the possibility of losing important events given it s poor coverage.
- *Energy-based:* Given the energy limitations of wireless sensor devices, it makes sense to switch the topology when the energy level of the nodes goes below a certain threshold. Again, the choice of the energy threshold is very critical for the same reasons explained before. Changing the topology too often may end up spending more energy than the energy that is supposed to be saved by topology maintenance, defeating its purpose. A very low threshold, on the other hand, will make certain critical nodes unavailable for upcoming topologies.

TABLE I

SIMULATION PARAMETERS.

	Sparse Topologies	**Dense Topologies**
Deployment area	200m x 200m	
Number of nodes	50	100 and 400
Number of sinks	1 sink	
Transmission Range	1xCTR(50) equivalent to: 37m ([8])	
Node Distribution	Uniform (200,200)	
Time Threshold	1000 time units	
Energy Threshold	10% of total energy	
Max number of reduced topologies (static and hybrid schemes)	3 reduced topologies	
E_{max}	1 Joule	
A3 Weights	$W_E = 0.5, W_D = 0.5$	
Energy Consumption	Eelec = $50nJ/bit$; Eamp = $10pJ/bit/m^2$ Short Messages = $25Bytes$ Long Messages = $100Bytes$ Idle state energy consumption assumed negligible	

- *Random:* In random-based topology maintenance, the current topology is switched using a random variable, such as time, or a random number that picks the next topology, like in the case of several available topologies in static topology maintenance.
- *Failure-based:* A failure-based technique triggers the process of changing the current topology after a node, or a number of nodes, has failed. These techniques require the existence of failure detection and notification mechanisms.
- *Density-based:* Another metric might be based on the density of the network. A similar metric might be the node degree of the network or the node degree of some important nodes.
- *Combinations:* Combinations of these variables can be used as well. For example, the topology maintenance can be activated based on energy and failure, or time and energy.

In this paper, we evaluate static and dynamic global topology maintenance techniques using the A3 and CDS-Rule-K topology construction mechanisms, and energy- and time-based triggering criteria in sparse and dense networks.

IV. PERFORMANCE EVALUATION

The purpose of the experiments in this section is to determine the benefit of implementing topology maintenance techniques in both sparse and dense networks, and compare their performance versus the choice of not implementing topology maintenance at all. In the performance evaluation, we made the following assumptions:

- All nodes are located in a two dimensional space and have a perfect communication coverage disk.

- Nodes have no information about their position, orientation, or neighbors.
- The initial graph, the one formed right after the deployment, is connected.
- Distances can be calculated as a metric perfectly proportional to the Received Signal Strength Indicator (RSSI).
- There is no packet loss at the Data Link Layer.
- There is a way in which a node can be awaken when its radio is off.

In these experiments, sparse topologies are defined as topologies in which the communication radius is calculated based on the Critical Transmission Range (CTR) formula of Penrose-Santi [8]. This guarantees that the node degree is very low, creating a weakly-connected topology. Dense topologies are defined as sparse topologies in which we doubled the original number of nodes.

In the simulations, we implemented the following topology maintenance techniques and triggering criteria:

- No topology maintenance: The initial reduced topology works permanently until the sink detects that it does not have any more active nodes in range. This is the same termination policy for the rest of the algorithms.
- Dynamic Global Time-based Topology Recreation - DGTTRec: Every time interval the topology maintenance algorithm terminates the previous reduced topology and invokes the topology construction algorithm to create a new one.
- Dynamic Global Energy-based Topology Recreation - DGETRec: Similar to DGTTRec, but the recreation is triggered every time a node reaches a critical energy threshold.
- Static Global Time-based Topology Rotation - SGTTRot: Every time interval the topology maintenance algorithm rotates the active reduced topology for one of the pre-planned ones.
- Static Global Energy-based Topology Rotation - SGETRot: Similar to SGTTRot, but the rotation is triggered every time a node reaches a critical energy threshold.
- Hybrid Global Time-based Topology Recreation and Rotation - HGTTRecRot: Every time interval the topology maintenance algorithm rotates the active reduced topology for one of the pre-planned ones. When a sink detects that it is isolated in the current active reduced topology, it will try to recreate that reduced topology.
- Hybrid Global Energy-based Topology Recreation and Rotation - HGETRecRot: Similar to HGTTRecRot, but the rotation triggered every time a node reaches a critical energy threshold. The recreation is executed also when a sink detects that it is isolated in the current active reduced topology.

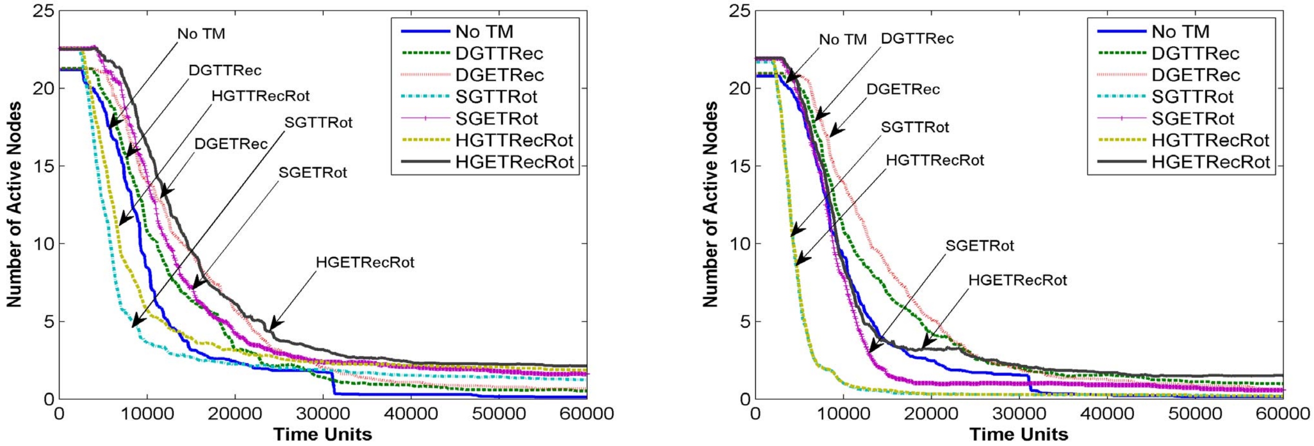
As stated before, all these topology maintenance strategies were tested using the A3 and CDS-Rule K topology construction algorithms. The implementations were coded and tested in a simulation tool called Atarraya [12], designed with the purpose of testing topology control algorithms. In the case of dynamic global techniques, the sink broadcast a *Reset Message* to let the nodes know that the topology construction algorithm will be run again. Also, a *Notification Message* is implemented so that nodes can notify the sink when they are running out of energy, so the sink knows it is time to send the Reset Message and initiate the recreation of the topology. In the case of static global techniques, the Notification Message is used when needed (energy-based criteria) and the Reset Message is sent to appropriate nodes so the new pre-planned topology becomes active.

For simplicity, in our experiments we limit the number of pre-planned topologies to three. A more complex mechanism that finds as many as possible disjoint topologies can be found in [4]. The process of selecting these three topologies is different depending on the underlying topology construction mechanism. In the case of A3, we manipulate A3's selection metric to lower the probability of selecting one node in more than one topology. However, since the same topology construction algorithm is run every time, if a particular node that has been used before in another topology is needed to guarantee topology connectivity, it may be selected again. In other words, the static global technique based on A3 may produce shared-disjoint topologies. In the case of the CDS-Rule-K topology construction algorithm, since it does not include any numerical metric to select the nodes, the algorithm is left unchanged, meaning that it may produce very similar trees.

In all simulations, each active node in the current reduced topology is scheduled to send data messages directed to the sink every 10 time units. Since both topology construction algorithms produce a tree-based reduced topology rooted at the sink, a very simple routing algorithm was implemented in which nodes forward the data messages to their respective parents. In our experiments, no data aggregation or similar strategy is implemented. Energy is drained when a packet is either sent or received according to the well-known energy model presented in [9]. Table I shows a summary of the most important simulation parameters for each scenario.

A. *Sparse networks*

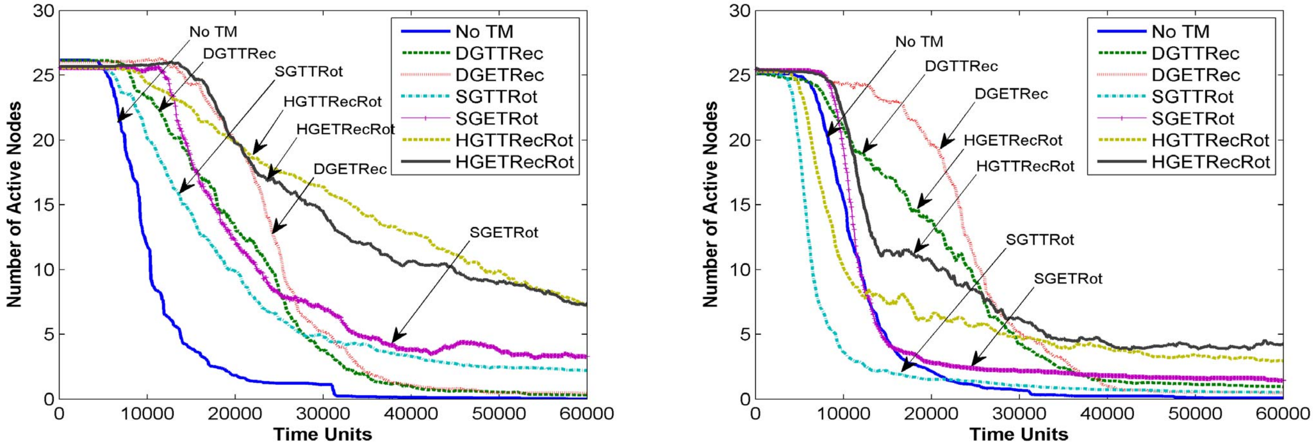
Figures 1(a) and 1(b) show the lifetime of the network in number of active nodes over time in sparse networks using static, dynamic and hybrid global topology maintenance techniques with energy- and time-based triggering criteria, and no topology maintenance at all. The trends are clear: regardless of the topology construction algorithm used, dynamic techniques improve the lifetime of the network compared with the no topology maintenance option. The Static technique only showed improvement when it was using the energy-based in A3; the time-based Static technique degrades the performance of both A3 and CDS-Rule-K compared to not having topology maintenance. The energy-based Hybrid approach produced the best performance for A3, while the time-based one showed to be similar to the time-based Static technique in both topology construction algorithms.



(a) A3

(b) CDS-Rule-K

Fig. 1. Experiment 1: topology maintenance in sparse networks.



(a) A3

(b) CDS-Rule-K

Fig. 2. Experiment 2: topology maintenance in dense networks.

Two observations are worth mentioning here. First, it can be seen that, in general, topology maintenance techniques have no major impact in the lifetime of the network in sparse networks. This behavior is expected given that there are not many options to create disjoint topologies, if more than one. This means that the topology maintenance procedure just activates the same or a very similar reduced topology every time and the overhead related to the changing process drains extra energy from the nodes in the topology, killing them earlier. The impact of not having disjoint subsets can be appreciated in the CDS-Rule-K algorithm, as both static and hybrid techniques did not even reach the performance of having no topology maintenance. Second, the performance of the static and hybrid techniques may change according to the value of the triggering mechanism. However, the effect of changing either the time or the energy threshold in the lifetime of the network is beyond the scope of this paper and part of our current investigation.

B. Dense networks

Figure 2 shows the performance of the topology maintenance techniques in dense networks. As it can be seen, the gains provided by topology maintenance in this case can be considerable, compared with the case of not using topology maintenance at all and the sparse networks case seen before. Here, dynamic techniques also improve the lifetime of the network regardless of the topology control algorithm. However, it can be noticed that the performance in dense networks depends on the topology construction mechanism used. For example, it can be seen that, while in the case of A3 all hybrid, dynamic and static techniques improve the performance -being the hybrid the one that extended the most the network lifetime-, the performance of CDS-Rule-K with the hybrid and static techniques continues to be very close to the option of not performing topology maintenance at all, with a very small advantage from the hybrid technique. This last aspect, again, is caused by the fact that CDS-Rule-K may be using very similar topologies over and over, and the time and energy thresholds chosen might not be the optimal ones.

The behavior of the hybrid in A3 can be explained by the fact that in dense networks the possibility of having disjoin trees increases, and that some of the nodes that were not included in any of the pre-planned trees can be used for maintenance in the future during the recreation stages, fact that is not possible in the static one. However, even though the average performance of the hybrid technique is superior to the one showed by the dynamic technique, the main problem of the hybrid approach seen on each individual topology separately is that the sink must reach total isolation before recreating the reduced topology, which leads to having lapses of time in which the network is working poorly; in other words, if the network can handle no-service periods, then the hybrid will offer a longer lifetime, but if the network cannot tolerance no-service periods, another triggering mechanism should be considered to guarantee a minimum level of service.

V. CONCLUSION

This paper extends the definition of topology control to include topology construction, or building a new reduced topology (former topology control definition), and topology maintenance, or changing the reduced topology from time to time when the current one is no longer optimal. The paper introduces a taxonomy for topology maintenance that did not exist before, which frames some existing and new topology maintenance techniques and strategies. The techniques are classified as static, dynamic or hybrid, with local or global scope. We also include a non-exhaustive list of triggering criteria, or when to switch the topologies. Time-, energy-, failure-, random-, and density-based criteria are included in the list.

In addition to the taxonomy, the paper includes a performance evaluation of static, dynamic and hybrid global topology maintenance techniques in sparse and dense networks using energy- and time-based triggering criteria and the A3 and CDS-Rule-K topology construction algorithms. We compare these techniques against the common topology control strategy of not performing topology maintenance at all. Our simulation results clearly show that, from the network lifetime point of view, dynamic techniques always extend the lifetime of the network regardless of the network density and the topology construction algorithm. The static techniques showed that they may actually degrade the performance, specially when it is triggered by time, when the pre-planned topologies are not disjoin, and when the network density is low. In the case of the hybrid approaches they showed a better performance in A3 that in CDS-Rule-K because of its similarities with the static technique. In addition, the energy-based technique produce good results in both scenarios, while the time-based techniques produced mixed results, not having very good results in sparse networks but generating the best result for A3 in dense networks.

Another important conclusion is that the performance of static and hybrid techniques need further investigation in two fronts. First, a sensitivity analysis is needed to determine better time and energy thresholds. Second, the limit in the number of disjoint topologies needs further analysis, as more disjoint topologies can be found with the network density. In the near future, we will investigate these issues along with dynamic local topology maintenance techniques.

REFERENCES

[1] S. Butenko, X. Cheng, C. Oliveira, and P. M. Pardalos. *A New Heuristic for the Minimum Connected Dominating Set Problem on Ad Hoc Wireless Networks*, pages 61–73. Kluwer Academic, 2004.

[2] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris. Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks. *Wireless Networks*, Vol. 8, No. 5:481–494, 2002.

[3] S. Guha and S. Khuller. Approximation algorithms for connected dominating sets. *Algorithmica*, 20(4):374–387, 1998.

[4] R. Iyengar, K. Kar, and S. Banerjee. Low-coordination Topologies for Redundancy in Sensor Networks. In *Proceedings of the 6th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, pages 332–342, 2005.

[5] V. Kumar, T. Arunan, and N. Balakrishnan. E-span: Enhanced-span with directional antenna. In *Proceedings of IEEE Conference on Convergent Technologies for Asia-Pacific Region*, volume 2, pages 675–679, 2002.

[6] L. Li, J. Y. Halpern, P. Bahl, Y-M. Wang, and R. Wattenhofer. Analysis of a cone-based distributed topology control algorithm for wireless multi-hop networks. In *Proceedings of the Annual ACM Symposium on Principles of Distributed Computing*, pages 264–273, 2001.

[7] N. Li, J. C. Hou, and L. Sha. Design and analysis of an mst-based topology control algorithm. In *Proceesdings of IEEE INFOCOM*, volume 3, pages 1702–1712, 2003.

[8] P. Santi. *Topology Control in Wireless Ad Hoc and Sensor Networks*. John Wiley & Sons, September 2005.

[9] A. Chandrakasan W. R. Heinzelman and H. Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *HICSS '00: Proceedings of the 33rd Hawaii International Conference on System Sciences-Volume 8*, page 8020, Washington, DC, USA, 2000. IEEE Computer Society.

[10] P. J. Wan, K. Alzoubi, and O. Frieder. Distributed well connected dominating set in wireless ad hoc networks. In *Proceedings of IEEE INFOCOM*, 2002.

[11] P. Wightman and M. Labrador. A3: An topology construction algorithm for wireless sensor networks. In IEEE, editor, *Globecom08: Proceedings of the IEEE Global Communication Conference*, New Orleans, USA, November 2008.

[12] P. M. Wightman. Atarraya: A topology control simulator. http://www.cse.usf.edu/˜pedrow/atarraya/.

[13] J. Wu, M. Cardei, F. Dai, and S. Yang. Extended dominating set and its applications in ad hoc networks using cooperative communication. *IEEE Trans. on Parallel and Distributed Systems*, 17(8):851–864, 2006.

[14] J. Wu and F. Dai. An extended localized algorithm for connected dominating set formation in ad hoc wireless networks. *IEEE Transactions on Parallel and Distributed Systems*, 15(10):908–920, 2004.

[15] J. Wu and H. Li. On calculating connected dominating set for efficient routing in ad hoc wireless networks. In *Proceedings of the 3rd ACM international Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications*, pages 7–14, 1999.

[16] Y. Xu, J. Heidemann, and D. Estrin. Adaptive Energy-Conserving Routing for Multihop Ad Hoc Networks. Research Report 527, USC/Information Sciences Institute, October 2000.

[17] Y. Xu, J. Heidemann, and D. Estrin. Geography-informed Energy Conservation for Ad Hoc Routing. In *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking*, pages 70–84, 2001.