2009 International Conference on Advanced Information Networking and Applications Workshops

A Topology Control Protocol for 2D Poisson Distributed Wireless Sensor Networks

Waltenegus Dargie and Alexander Schill
Chair for Computer Networks
Faculty of Computer Science
Technical University of Dresden
01062 Dresden, Germany
Email: (waltenegus.dargie, alexander.schill)@tu-dresden.de
Rami Mochaourab
Communications Theory, Communications Laboratory
Dresden University of Technology, 01062 Dresden, Germany
Email: mochaourab@ifn.et.tu-dresden.de
Lin Guan
Department of Computer Science
Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK
Email: L.Guan@lboro.ac.uk

***Abstract*—Topology control in a wireless sensor network is useful for ensuring that the network remains connected in the presence of nodes that exhaust their energy or become altogether dysfunctional (for whatever reasons). It also ensures that all the link that can be established are energy-efficient links and the nodes utilize their energy fairly. In this paper, we propose a fair and energy efficient topology control protocol for a two-dimensional random sensor deployment in which the nodes can estimate the distances to their neighbors and vary their transmission power accordingly. The protocol applies a neighbor eligibility metric in order to ensure a fair distribution of energy in the network. We introduce the notion of weighted relaying regions defined over the plane of a searching node to drop out inefficient links. Unlike most topology control protocols that rely on nearest neighbor approaches, we use a distance measure that is radio characteristic and channel condition dependent. We verify the performance of the protocol through simulation results on network graph properties and energy consumption.**

I. Introduction

In wireless sensor networks, communication (receiving as well as transmitting) consumes a significant amount of energy. Since routing involves several nodes, its energy demand is by far bigger than all the rest communication and data processing tasks. As to the exact number of nodes that should participate in a routing task, so far the research community is not one mind. There are those who argue that multi-hop communication is preferred over single hop communication. The premises for this assumption is that as the distance of communication increases, the probability of getting a line-of-sight (LOS) link decreases, in which case the path loss index can no longer be assumed to be 2 but between 2 and 4, and in some cases, even 6. By reducing the distance of communication to a shorter length, it is possible to keep a LOS link, which significantly reduces the transmission cost.

On the other hand, there are those (for example Ephremides [7] and Haenggi [13]) who argue that this is an oversimplified analysis that does not take into account the cost of routing overhead, delay, channel coding/decoding, end-to-end reliability, efficiency of transmission power amplifier, etc., and advocate long-hop routing. For densely deployed networks in which there are sensors that are placed randomly (such as in pipelines with several turns in short distances), short-hop routing is quite unsuitable. Apparently, long distance communication has also its disadvantages besides path loss, including interference.

A topology control protocol is necessary to set an upper and lower bound on the number of links that can be active in the network. This ensures that the network remains connected and its lifetime is optimized. Moreover, it guaranties an available link to a higher-level routing protocol that is defined based on an application-specific metric (such as minimum hop, minimum delay, minimum energy consumption, maximum available power, etc.).

In wired networks, the way the network elements are physically interconnected directly influences the network's topology. Routing protocols take into account this fact when routes are computed. In wireless networks, however, as long as the communication range suffices, essentially, all nodes can establish a link with each other, creating a mesh-topology networks [7], which is not energy efficient. Another problem is that during the operation of the network, some nodes may exhaust their energy more rapidly than others and others may become dysfunctional. A topology control protocol deals with all these problems and ensures that the network is connected with energy efficient links.

The main challenge is to develop a topology control that is simple, scalable, and less resource intensive. Ideally, it

978-0-7695-3639-2/09 $25.00 © 2009 IEEE
DOI 10.1109/WAINA.2009.63

should function based on local information only. In most cases, additional knowledge such as the location of placement and the relative position to the sink node can be obtained from layout information or from blueprints and can be employed to determine relative neighborhood. We propose a localized algorithm that enables nodes to autonomously create and maintain energy-efficient links. The protocol defines proximity and eligibility metrics to ensure network connectivity and to optimize lifetime.

This paper is organized as follows. First, we discuss related work in Section II. Section III, we present the Fair and Efficient Topology Control (FETC). Evaluation of the protocol is discussed in Section IV. Finally, in section V, we provide concluding remarks and future work.

II. Related Work

Most existing approaches to topology control apply computational geometry techniques and proximity graphs to build sparse, but connected links.

Bhardwaj et al. [9], provide a model for computing the most energy efficient number of hops to relay data from any source in a linear topology network to a fixed base station. The number of hops depends on a *characteristic distance* and the distance of the source to the base station. The *characteristic distance* itself is dependent on the propagation environment and radio parameters. Jeng et al. [16] use Neighborhood Graphs to compute adjustable neighborhood regions and to optimize the node degree. A similar work that optimizes a node degree is proposed in [27] - their constructed graph is a subgraph of the Relative Neighborhood Graph [15] and the protocol uses local information (signal strength information).

Wattenhofer et al. [5] propose a topology control protocol to dynamically adjust transmission power based on local decisions. Accordingly, a node increases its transmission power until it finds a neighbor node in every direction. But the question how a node trims off inefficient links in case it discovers several neighbors is not addressed.

The topology control protocol of Kung et al. [6] selects suitable communication nodes, adjusts service loads of critical nodes, and manages sleeping schedules. The protocol principally divides the topology operation into topology formation phase and topology adjustment phases. In the topology formation phase, a link is set up while during the topology adjustment phase, the links are adjusted with an optimal balance of critical nodes in backbone.

III. Fair and Efficient Topology Control

We consider a 2-dimensional, randomly distributed network. The detail description of the network can be found in [4] and [1]. Given such deployment, the research goal is to develop a topology control that ensures that the network remains connected and the established routes are energy efficient.

Three basic eligibility metrics play roll in selecting a link, among many contending links. The aim is to utilize energy more efficiently, but also to enable nodes consume energy in a more uniform fashion. By so doing, we ensure that the networks's life time is optimized and the network itself remains connected. We achieve these two goals by defining weighted relaying regions and by defining eligibility metric. Whereas the weighted relaying region estimates the most energy efficient route between a source node and the sink, the eligibility metric ensures that no node is disadvantaged in being situated in the most optimal link. The eligibility metric therefore takes into account the energy reserve of a node with respect to the available energy of its neighbors. Both metrics require local knowledge only, i.e., neighboring nodes cooperate to exchange information pertaining to their location and their available energy.

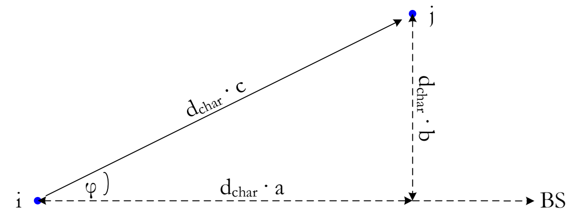

Fig. 1. An illustration of the hop model

A. Weighted Relaying Regions

We introduce the notion of the weighted relaying regions in a plane. It enables to determine the eligibility of a neighboring node, positioned in the defined regions of a transmitting node, to become a relaying node. The aim is to increase the overall energy efficiency of a multi-hop link. Because we want the decision to be based on local information only, the efficiency model is an estimation model.

Bhardwaj et al. [9] estimate the upper bounds of the lifetime of a wireless sensor network based on the notion of the *characteristic distance*. The characteristic distance enables to compute the link that consume the minimum energy in a linear topology [3], [2]. It is a function of the path loss index and the energy consumed to process and transmit a single bit of information. We refer the reader to [4], for the complete treatment of the issue.

Given a source node and a sink node, a multi-hop communication is most energy efficient, if all intermediate nodes are located a characteristic distance, d_{char}, away from each other, in the direction of the sink. In a linear random deployment, this may not be possible, therefore, nodes closer to the characteristic distance are chosen, such that the link that consumes the minimum energy is established. Such a link, however, cannot be used forever, as the relaying nodes will consume their energy more quickly than others. Given a 2-dimensional, random deployment, that can be modeled as a 2-dimensional Poisson distribution, the weighted relay region considers all nodes that are near to a straight line link between a source and a sink, and this link is a function of the characteristic distance.

In order to formulate the weighted region in the plane of a searching node, we define a hop model which represents the position of a neighboring node with respect to an optimal position. Hence, in a multi-hop link between an arbitrary node in the network and the base station, a single hop can be modeled as illustrated in Figure 1. Assuming node i is the searching node, the position of the relaying node j is represented in terms of its deviation from an optimal relaying position from node i.

Suppose D, is the distance between the source node and the sink, d_{char}, the characteristic distance, and K_{opt}, is the optimal number of hops such that:

$$K_{opt} = \left\lfloor \frac{D}{d_{char}} \right\rfloor \; or \; K_{opt} = \left\lceil \frac{D}{d_{char}} \right\rceil \tag{1}$$

In a randomly deployed linear network, the nodes may not be optimally placed to satisfy the equations above. In which case, the number of hops, K'_{opt}, is greater by one hop than or equal to K_{opt}, if equal distances of d_{char} are taken from each node to its relaying node in the direction of the base station. Noting that the characteristic distance is a function of the path loss index, γ, such that $2 \leq \gamma \leq 6$, the overall link efficiency measure, Λ, of a multi-hop link can be formulated as:

$$\Lambda \leq \frac{\tilde{a} \cdot \gamma}{\bar{c}^{\gamma} + \gamma - 1} \tag{2}$$

where $\bar{c}$ is the normalized average link distances over d_{char}.

B. Node Eligibility Metric

The link efficiency metric, Λ_j, does not count out those nodes which are used as relay nodes frequently, and hence, are depleting their energy reserve more quickly than others. This will lead to disconnected links. To avoid this condition, we define a node eligibility metric that takes the energy reserve of a node into account.

We define the metric $\Upsilon_j = \frac{e_j}{E}$. Similar to the overall efficiency metric Λ, Υ_j is applied on a neighboring node to reveal the relative amount of energy it has with respect to the other nodes. Combining both metrics, we can achieve overall link efficiency and fairness through a common eligibility measure of a neighboring node. Thus, we define:

$$\Psi_j = \Lambda_j \cdot \Upsilon_j \tag{3}$$

A node i with node j as its neighbor calculates Ψ_j, $0 \leq \Psi_j \leq 1$. This determines a measure for node j, for which node i can estimate how eligible it is to be a neighbor.

In the presence of node failures and node mobility, the topology control protocol adapts to the changes by periodically computing the two metrics. Therefore, message exchange between the nodes is to be done regularly. Hence, information on energy reserves can be as well interchanged, and the topology is updated correspondingly. This update shows that the topology of the network might change over time and is dynamic. Depending whether the nodes have information on the direction of the base station, the topology of the network differs. We denote the graph where the nodes have direction information to the base station with FETCD, else, the developed graph is denoted as FETC.

C. Protocol Description

In this section, we describe our topology control protocol, which is divided in two phases. The first phase is the neighbor discovery phase where each node selects k nodes in its neighborhood. The neighbor selection is carried out according to the node eligibility criterion. The network graph that is created after this phase is not symmetric. The second phase of our protocol is concerned in building a symmetric graph of the already built graph in phase 1. The symmetry is obtained by adding the reverse edge to every asymmetric link. The phases of the graph are represented as follows:

Phase 1: Choosing k Neighboring Nodes (For a generic node i)

1) Node i wakes up at time t_1, and announces its identity (id_i) and energy reserve ($e_i^{t_1}$) at maximum power (P_{t-max}).
2) Node i receives the messages from the neighboring nodes and stores their identities in its neighbor list $\mathcal{N}(i)$.
3) Node i estimates the distance to each node in $\mathcal{N}(i)$. Node i has the energy reserves of the neighboring nodes (e_j) as well as the distances to them ($d(i,j)$), where $j \in \mathcal{N}(i)$.
4) Node i calculates Ψ_j, for each neighbor in its list.
5) Node i chooses the k neighbors in its list $\mathcal{N}(i)$ that have the highest value of Ψ. If originally node i has less than k neighbors, then all nodes are chosen.
6) Node i updates its neighbor list according to the chosen nodes in step 5.

The developed graph according to phase 1 of the protocol, has directed links and the graph is a directed graph, $\mathcal{G}_{digraph}$. Hence, a symmetry phase is necessary to enforce symmetry in the graph. In this phase we build the symmetric super-graph of $\mathcal{G}_{digraph}$.

The symmetric super-graph of $\mathcal{G}_{digraph}$ is defined as the undirected graph $\mathcal{G}$ obtained from $\mathcal{G}_{digraph}$ by adding the undirected edge $[i \leftrightarrow j]$ whenever edge $[i \rightarrow j]$ or $[i \leftarrow j]$ is in $\mathcal{G}_{digraph}$. That is, $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{E} = \{[i \leftrightarrow j] | [i \rightarrow j] \in \mathcal{E}_{digraph}$ or $[i \leftarrow j] \in \mathcal{E}_{digraph}\}$.

Phase 2: Enforcing Graph Symmetry (For generic node i)

1) At time t_2, node i announces its identity (id_i) and list of Neighbors ($\mathcal{N}(i)$) at maximum power (P_{t-max}).
2) Node i receives the neighbor lists, and calculates the set of symmetric neighbors. Node i checks all neighbor lists and finds if it exists there. When that is the case, it checks if the neighbor list originates from a neighbor in its neighbor list. If not, the corresponding neighbor is added to its list $\mathcal{N}(i)$.

After the symmetric graph is constructed, node i determines for each neighbor in $\mathcal{N}(i)$ the minimum required transmission power to reach it and stores it in it neighbor table list $\mathcal{N}_L(i)$. On communication with a node in its neighbor list, the messages are transmitted at the corresponding power level. The selected neighbors of a node i are surely its logical neighbors. That is, there exist nodes in its maximum assigned transmission range that are not selected in its neighbor list.

These nodes in $\mathcal{N}(i)$ are used for the purpose of routing. That is, in order to determine the routes in the communication graph, only the nodes in the neighbor list are considered.

IV. Evaluation

A. Experimental Set Up

In order to perform comparisons between the network topologies developed through different protocols and our protocol, we run simulations using MATLAB®. First we generate the node deployment which mainly determines the positions of the nodes. Then, by using these positions and the channel characteristics, we build the topologies which define for each node a set of neighbors with whom it can communicate directly with.

We denote the Disk Graph, with disk radius equals to the maximum transmission range, d_{max}, as the original topology (Original). Each node in the network has in its neighbor list the nodes within its maximum transmission range. The name "Original" is given for two reasons. First, in a topology control protocol, the main criteria of choosing a neighbor of a node is that this node lies within transmission range. Hence, taking the original topology and trimming it in relation to the used topology control protocol satisfies this aspect. Second, the original topology has the property that it contains all possible communication links.

Of the proximity graph topologies, we choose the Gabriel Graph [15] and the Relative Neighborhood Graph, represented as GG and RNG respectively, as network topologies to compare with. Starting from the original topology, the GG and RNG topologies do not necessarily contain all the links as in the theoretically built graphs on the deployment. Links that are longer than the highest transmission range do not exist. Hence, the graph may lose some of its properties if the density of the nodes is low. The KNeigh protocol, as described in [10], builds the topology based on the k nearest neighbors. The preferred value of k is as well derived in that work and set to 9. We include for the simulations the introduced optional pruning phase.

The simulations can be divided in two categories. First, is the study made in graph theoretical aspects such as the graph connectivity and node degree. Second, is the aspect of energy conservation made when events take place in the network and a flow between the nodes and the final destination is generated. Starting with the deployment phase, we define our region of deployment having 500 $m \times 500$ m dimensions. The number of nodes deployed in this region is taken as 100, 200, 300, 400, and 500. In turn, different deployment densities are examined. The base station is chosen to be the furthest node with the highest x-coordinate in the deployment. This leaves the base station at the edge of the deployment which is the case in many deployment scenarios. Furthermore, in a real scenario, the base station has usually infinite energy supply. This is interesting since our protocol considers the energy capacities remaining in the nodes in order to determine the eligibility of building the links. Therefore, the base station gets a definite high eligibility if it is within transmission range, which in turn increases the number of nodes that are directly connected to it.

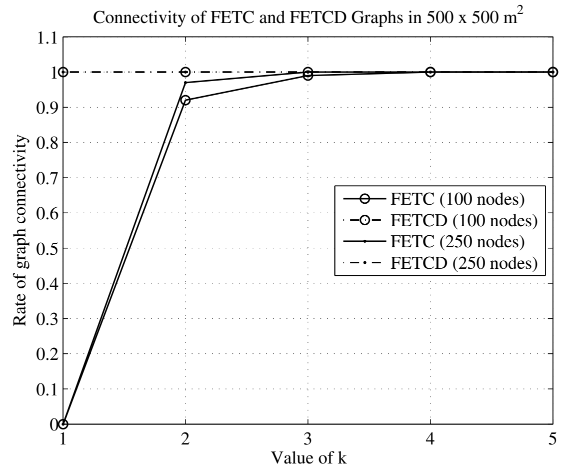

Fig. 2. The connectivity of a network as a function of node density

The path between each node and the base station is determined and stored in each node. We use Dijkstra's algorithm to find the shortest path from each node to the base station. On this level, experimentation on the network can be done. We denote a period of time as a time step where 100 nodes are randomly chosen from the deployment and one bit of information is sent from them to the base station. In this case, for each event starting from node i, the nodes that are along the path decrease their energies respective to our energy model. A relaying node consumes reception power as well as transmission power according to the distance to its next hop neighbor. The path-loss exponent γ is chosen as either 2 or 4 according to the required transmission distance. Here we introduce the crossover distance, $d_{crossover}$, as in [14]. If the transmission distance is less than $d_{crossover}$, γ is taken as 2. Else, γ is taken as 4. In Table I, the parameter values used for simulations are represented.

B. Simulation Results

We choose two values of n to test the connectivity of our graph. We generate 100 random graphs for each k and the specified node density and we calculate the rate of connectivity of the graphs. In Figure 2, the connectivity rate for deployments of 100 and 250 nodes is plotted. We observe that the connectivity rate is high for high density deployments, such that choosing $k = 1$ can lead to a high rate of connectivity. However, for $k = 5$ the connectivity of the graph is secured even for low densities, and this measure is taken as sufficient to make sure of the connectivity of the graph. We use this value of k for further simulations in this section.

The node degree refers to the average number of neighbors with which a node directly interacts. It indicates the probability of collusion at the MAC layer, end to end delay and connectivity - Minimizing the node degree in the network reduces the overhead in finding routes in the topology. In Figure 3,

TABLE I
PARAMETER VALUES.

Description	Parameter	Value
Initial Battery Capacity	E	2 J
Path loss exponent	γ	2 or 4
Relay Rate	r	1 bits/s
Maximum transmitting distance	d_{max}	137 m
Crossover distance	$d_{crossover}$	86.2 m
Transmitter electronics energy	α_{11}	50 nJ/bit
Receiver electronics energy	α_{12}	50 nJ/bit
Radio amplifier energy	α_2	10 pJ/bit/m^2 ($\gamma = 2$) 0.0013 pJ/bit/m^4 ($\gamma = 4$)
Characteristic Distance	d_{char}	100 m ($\gamma = 2$) 71 m ($\gamma = 4$)

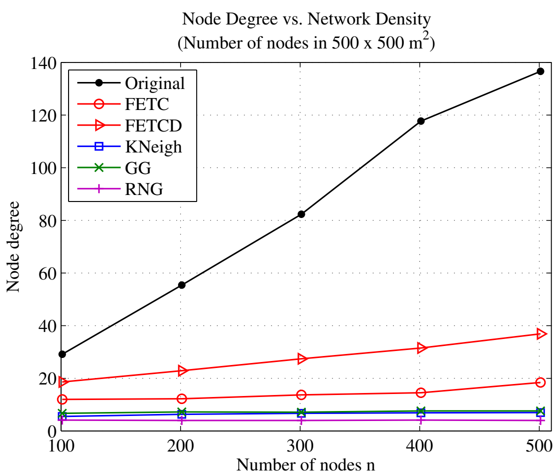

Fig. 3. The node degree as a function of the network's density

we compare the node degrees of the different topologies to increasing values of the deployed nodes. According to our simulations, the RNG graph has the lowest node degree with respect to the other topologies as is expected. Whereas, the KNeigh and GG graphs have a slightly higher node degree. Interesting, in all of these three graphs, the node degree is constant regardless of density. The FETC and FETCD topologies have higher node degrees than the rest. Since the FETCD protocol has directional information to the base station, each node selects in the first phase of the protocol k nodes that are in the direction of the base station almost exclusively. In the second phase of the protocol where graph symmetry is made, the links that are behind the nodes with respect to the base station are added. With the directional information property, more links are added in the symmetry phase of FETCD graph than the FETC graph which explains these results.

The second aspect of comparison between the different topologies is the variance in the energy reserves between the nodes with increasing time steps. The variance in the energy reserve of a nodes at a specific time is calculated by reducing the square of the energy reserve of a node from the square of the mean energy reserves of all nodes and by squaring this result. We plot the average of all variances of all nodes at the corresponding time step. In Figure 4, the variance of the nodes energy reserves after 100 time steps is plotted. We have chosen the same number of events in a time step for all network densities. In doing so, no analysis can be made between the variance in energy reserves corresponding to different node densities of the same graph. Hence, we compare only the results of the network graphs for the corresponding node density. The KNeigh, GG, RNG achieve lower fairness between the nodes compared to our topology control protocols for network densities other than 100. In sparse topologies, nearest neighbor routing has an efficient transmission distance which leads to comparably good results. For different densities, the FETCD accomplishes the lowest variances between the nodes. In comparison to the other topologies, the FETC and FETCD topologies have a good distribution of the energy dissipation. Hence, the distances between the nodes in the FETC and FETCD graphs are energy efficient and fair. The FETCD has its nodes with the least difference in energy capacities. This shows, that the longer hops in the original topology can be unfair for the corresponding nodes in reducing their energy capacities considerably. In that case, fewer nodes relaying the messages leads to unfairness in the network.

Decreasing both the overall energy consumption in the network as well as maintaining similar energy levels between the nodes in a network is a prerequisite for system lifetime maximization. According to the simulation results, this issue has been achieved and fulfilled.

V. CONCLUSION

The energy efficiency of a wireless sensor network and the lifetime maximization problem is tackled by considering two aspects: The overall network energy consumption efficiency and fairness. Based on theoretical work on upper bounds of the network lifetime, we exploited the notion of a characteristic distance, d_{char}, that is dependent on the radio characteristic and the channel condition. From a node's view point, an estimation is made over the neighboring nodes on their overall link efficiency in relaying a message. This is done according to their positions relative to an optimal relaying position and the position of the base station. The efficiency estimation is made hop by hop. Fairness in energy utilization, and thereby connectivity, is addressed by taking the energy reserves of the

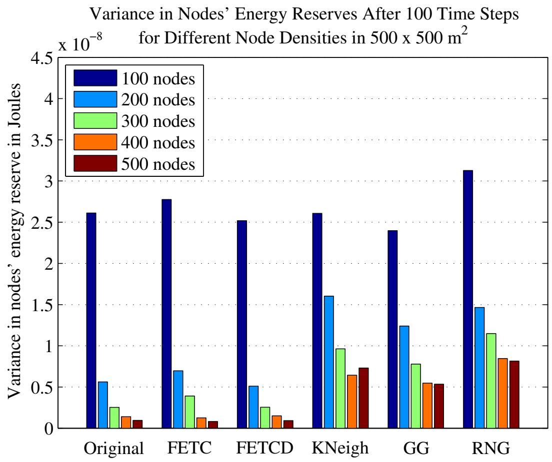

Fig. 4. Variance in the energy reserves of the nodes after 100 time steps.

nodes in the neighbor selection criteria into account.

The simulation results confirmed that our topology is not as sparse as the RNG, GG, and K-Neighbor topologies. However, with respect to the original topology (the mesh topology), the node degree is slightly increased with network density. Interesting results are obtained concerning the energy dissipation rate in the overall network. Unlike the other topology control protocols, the transmission rates are not affected by increasing network densities. Moreover, concerning the energy reserves between the nodes, contrary to the RNG, GG, and KNeigh topologies, we have minimized imbalance. The results showed that nearest neighbor topologies are energy inefficient for high network densities. The original topology, on the other hand, contains inefficient long links which significantly decreased the energy efficiency of the network. These results show that our network topology suits to prolong the lifetime of the network.

REFERENCES

[1] X. Chao, W. Dargie, and G. Lin Energy Model for H2S Monitoring Wireless Sensor Network. *,Proceedings of the 11th IEEE International Conference on Computational Science and Engineering*, 2008.

[2] M. Zimmerling, W. Dargie Localized Power-Aware Routing in Linear Wireless Sensor Networks . *,The 2nd ACM Workshop on Context-Awareness for Self-managing Systems*, 2008.

[3] M. Zimmerling, W. Dargie Energy-Efficient Routing in Linear Wireless Sensor Networks. *,The Fourth IEEE International Conference on Mobile Ad-hoc and Sensor Systems*, 2007.

[4] R. Mochaourab, W. Dargie A fair and energy-efficient topology control protocol for wireless sensor networks. *,The 2nd ACM Workshop on Context-Awareness for Self-managing Systems*, 2008.

[5] R.Li. Wattenhofer, L. Bahl, and P.Y.-M. Wang. Distributed topology control for power efficient operation in multi-hop wireless ad hoc networks. *Proceedings of Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies, Infocom*, 2001.

[6] H.-Y. Kung, C.-M. Huang, H.-H. Ku, and Y.-J. Tung. Load Sharing Topology Control Protocol for Harsh Environments in Wireless Sensor Networks. *In proceedings of the 22nd IEEE International Conference on Advanced Information Networking and Applications*, 2008.

[7] A. Ephremides. Energy concern in Wireless Networks. *IEEE Journal of Wireless Communication*, 2002.

[8] V. Rodoplu and T. Meng. Minimum Energy Mobile Wireless Networks. *IEEE Journal of Selected Areas in Communications*, vol. 17, No. 8, 1999.

[9] M. Bhardwaj, T. Garnett, and A. Chandrakasan. Upper bounds on the lifetime of sensor networks. *Communications, 2001. ICC 2001. IEEE International Conference on*, 3:785–790 vol.3, 2001.

[10] D. M. Blough, M. Leoncini, G. Resta, and P. Santi. The k-neigh protocol for symmetric topology control in ad hoc networks. In *MobiHoc '03: Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing*, pages 141–152, New York, NY, USA, 2003. ACM.

[11] J.-H. Chang and L. Tassiulas. Energy conserving routing in wireless ad-hoc networks. *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, 1:22–31 vol.1, 2000.

[12] Chipcon, SmartRF CC2420, 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver. Chipcon Product data sheet.

[13] M. Haenggi. Twelve reasons not to route over many short hops. *Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th*, 5:3130–3134 Vol. 5, 26-29 Sept. 2004.

[14] W. Heinzelman. *Application-specific protocol architectures for wireless networks*. PhD thesis, Cambridge: Mass. Inst. Technol., 2000.

[15] J. Jaromczyk and G. Toussaint. Relative neighborhood graphs and their relatives. *P-IEEE*, 80:1502–1517, 1992.

[16] A. A.-K. Jeng and R.-H. Jan. The r-neighborhood graph: An adjustable structure for topology control in wireless ad hoc networks. *IEEE Trans. Parallel Distrib. Syst.*, 18(4):536–549, 2007.

[17] B. H. Liu, Y. Gao, C. T. Chou, and S. Jha. An energy efficient select optimal neighbor protocol for wireless ad hoc networks. In *LCN*, pages 626–633. IEEE Computer Society, 2004.

[18] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson. Wireless sensor networks for habitat monitoring. In *WSNA '02: Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, pages 88–97, New York, NY, USA, 2002. ACM.

[19] N. Patwari, I. Hero, A.O., M. Perkins, N. Correal, and R. O'Dea. Relative location estimation in wireless sensor networks. *Signal Processing, IEEE Transactions on [see also Acoustics, Speech, and Signal Processing, IEEE Transactions on]*, 51(8):2137–2148, Aug. 2003.

[20] D. Puccinelli and M. Haenggi. Wireless sensor networks: applications and challenges of ubiquitous sensing. *Circuits and Systems Magazine, IEEE*, 5(3):19–31, 2005.

[21] R. Ramanathan and R. Rosales-Hain. Topology control of multihop wireless networks using transmit power adjustment. *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, 2:404–413 vol.2, 2000.

[22] T. S. Rappaport. *Wireless Communications: Principles and Practice*. IEEE Press, Piscataway, NJ, USA, 1996.

[23] V. Rodoplu and T. Meng. Minimum energy mobile wireless networks. *Selected Areas in Communications, IEEE Journal on*, 17(8):1333–1344, Aug 1999.

[24] C. Savarese, J. Rabaey, and J. Beutel. Location in distributed ad-hoc wireless sensor networks. *Acoustics, Speech, and Signal Processing, 2001. Proceedings. (ICASSP '01). 2001 IEEE International Conference on*, 4:2037–2040 vol.4, 2001.

[25] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie. Protocols for self-organization of a wireless sensor network. *Personal Communications, IEEE [see also IEEE Wireless Communications]*, 7(5):16–27, 2000.

[26] D. Stoyan, W. S. Kendall, and J. Mecke. *Stochastic Geometry and its Applications*. John Wiley and Sons, Chichester, 1987.

[27] R. Wattenhofer and A. Zollinger. Xtc: a practical topology control algorithm for ad-hoc networks. *Parallel and Distributed Processing Symposium, 2004. Proceedings. 18th International*, pages 216–, 26-30 April 2004.

[28] L. Yu, N. Wang, and X. Meng. Real-time forest fire detection with wireless sensor networks. *Proceedings of the International conference on Wireless Communications, Networking and Mobile Computing*, 2:1214–1217, 23-26 Sept. 2005.