

01 Dec 2007

## Collaborative Routing Algorithm for Wireless Sensor Network Longevity

Shishir Bashyal

Ganesh K. Venayagamoorthy  
*Missouri University of Science and Technology*

Follow this and additional works at: [https://scholarsmine.mst.edu/ele\\_comeng\\_facwork](https://scholarsmine.mst.edu/ele_comeng_facwork)



Part of the [Electrical and Computer Engineering Commons](#)

---

### Recommended Citation

S. Bashyal and G. K. Venayagamoorthy, "Collaborative Routing Algorithm for Wireless Sensor Network Longevity," *Proceedings of the International Conference on Intelligent Sensors, Sensor Networks and Information, 2007. ISSNIP 2007*, Institute of Electrical and Electronics Engineers (IEEE), Dec 2007. The definitive version is available at <https://doi.org/10.1109/ISSNIP.2007.4496896>

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in Electrical and Computer Engineering Faculty Research & Creative Works by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact [scholarsmine@mst.edu](mailto:scholarsmine@mst.edu).

# Collaborative Routing Algorithm for Wireless Sensor Network Longevity

# Shishir Bashyal<sup>1</sup>, Ganesh Kumar Venayagamoorthy<sup>2</sup>

*Real-Time Power and Intelligent Systems Laboratory,*

*Department of Electrical and Computer Engineering, University of Missouri – Rolla*

*141 Emerson Electric Co. Hall, 1870 Miner Circle Rolla, MO 65409*

*<sup>1</sup>sbashyal@ieee.org, <sup>2</sup>gkumar@ieee.org*

## ABSTRACT

This study proposes a new parameter for evaluating longevity of wireless sensor networks after showing that the existing parameters do not properly evaluate the performance of algorithms in increasing longevity. This study also proposes an ant inspired Collaborative Routing Algorithm for Wireless Sensor Network Longevity (CRAWL) that has scalability and adaptability features required in most wireless sensor networks. Using the proposed longevity metrics and implementing the algorithm in simulations, it is shown that CRAWL is much more adaptive to non-uniform distribution of available energy in sensor networks. The performance of CRAWL is compared to that of a non-collaborative algorithm. Both algorithms perform equally well when the available energy distribution is uniform but when the distribution is non-uniform, CRAWL is found to have 20.2% longer network life. CRAWL performance degraded by just 10.1% when the available energy was unevenly distributed in the sensor network proving the algorithms adaptability.

## 1. INTRODUCTION

Wireless Sensor Networks are being proposed, developed and used for different fields of applications like wild-fire monitoring [1], smart farming/harvesting [2], habitat monitoring [3], structural health monitoring [4], surveillance [5] and emergency response systems [6]. A significant amount of work has already been done in different aspects of wireless sensor network. In [7], authors have surveyed a number of such research efforts in wireless sensor network. The futuristic application scenarios bring out two key requirements of sensor networks: support for very large number of unattended autonomous nodes and adaptability to environment and task dynamics [8]. As more success stories of sensor networks in different application domains are being reported, the number of nodes in a wireless sensor networks is also growing. Similarly, sensor networks are now subjected to perform in extreme environments like forests and vineyards where they come across variations in operating conditions and node failures. Scalability and adaptability are existing challenges in wireless sensor networks with out which their application will be severely limited.

Sensor nodes in a wireless sensor network almost always operate on battery occasionally backed by solar or wind

energy sources. Sensor nodes therefore have to make optimal use of the available energy resources. The major portion of the energy budget in a sensor node is spent for transmission and reception of the sensor data. It is therefore possible to minimize communication related energy usage in a sensor node by using a suitable communication protocol and several such algorithms have already been proposed. The readers are referred to [9], and the references there, for a survey of such protocols specifically designed for sensor networks where energy awareness is an essential consideration.

Most power aware communication protocols follow a cluster based approach in which a group of nodes in a region select a cluster head (CH) that gather the information from nodes in the cluster and forward it to the sink. The most interesting research issue regarding such protocols is how to form the clusters so that the energy consumption and contemporary communication metrics such as latency are optimized [8]. Figure 1 shows a typical cluster based wireless sensor network.

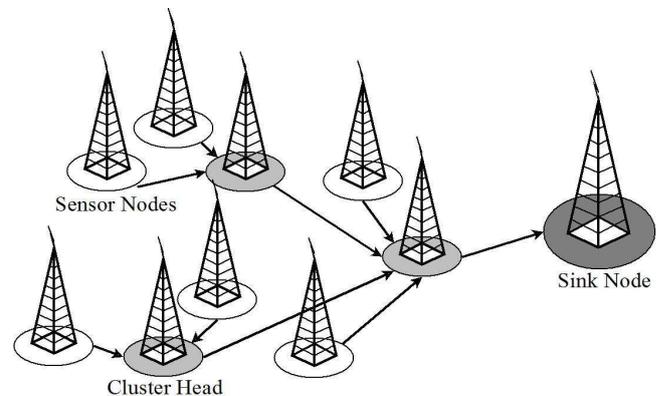


Fig. 1: Cluster Based Wireless Sensor Network

Most of the communication protocols proposed for power aware wireless sensor networks often make one or more of the following assumptions which make them non-optimal for most real-life applications:

- **Homogeneous distribution of nodes in the network**  
Nodes can be randomly initialized (for example thrown from an aircraft) and hence might be unevenly distributed in the coverage area

- **Homogeneous distribution of energy resources**  
Energy resources may be unevenly distributed in a sensor network for several reasons: unequal energy consumption in different nodes, sensor node battery replacement in multiple phases and unequal energy input from secondary sources (for e.g. solar or wind energy sources)
- **Single hop access to the sink**  
In a large sensor network, all nodes can not reach the sink even at the maximum transmission level and would have to find multi-hop routes to the sink
- **Priori network information**  
Network features like size, density and topology change with time hence should not be relied on initial information.
- **Reliable communication**  
Two neighbouring nodes may not always be able to communicate with each other due to radio channel properties and other physical obstructions in between.

In this study a completely different approach, inspired by collaborative defensive behaviour in ants, is proposed for wireless sensor network routing. Each node is treated as an intelligent agent (like an ant) capable of functioning based on the local available information thereby inheriting the scalability and adaptability of ant colonies. The nodes in the wireless sensor colony collaborate using the ant inspired collaboration algorithm proposed in [10] to come-up with a dynamic routing scheme based on the available energy ensuring that the energy resources are properly utilized to achieve network longevity. The algorithm is not only capable of adapting to changing operational conditions but also offers scalability that makes it suitable for next generation of real-life wireless sensor network applications.

Rest of the paper is organized as follows: the concept of longevity in sensor network is presented in section 2 and the ant inspired collaboration algorithm is introduced in section 3. The proposed Collaborative Routing Algorithm for Wireless Sensor Network Longevity (CRAWL) is detailed in section 4. After summarising the observations of the study in section 5, section 6 concludes the paper.

## 2. WIRELESS SENSOR NETWORK LONGEVITY

Power aware wireless sensor network algorithms proposed in literature so far do not always result in desired performance. For example one of the cluster based power aware algorithm called LEACH (Low Energy Adaptive Clustering Hierarchy) proposed in [3] randomly rotates the cluster head position such that each node in a cluster takes its turn as a cluster head at some point in time. While rotating the cluster head position, the algorithm does not consider the remaining energy level in the newly selected cluster head and thus it is possible that a candidate least suited to act as a cluster head will be selected as a cluster head for the time interval. Several modifications to LEACH have been proposed in literatures

that improve the longevity of the network to some extent but most of them have one or more of the following limitations:

- Sink node performs routing optimization for the whole network [12][13] and as a result the system is vulnerable to failure of the sink node. Furthermore, as the number of nodes in the network increases, the optimal route computation becomes more and more difficult for the sink node.
- Location awareness is required in individual nodes [12][13] which is not practical in most wireless sensor networks due to cost factors. Moreover, positioning related circuitry further increases battery consumption, adversely affecting network longevity.
- Ego-centric self-election as a cluster head [14] based on random probabilities have problems like more suitable candidates not being selected or multiple cluster heads being selected in a region.

A measure of longevity of sensor networks commonly used in literature is the set of parameters: the number of sensor updates after which the First Node Dies (FND), Half Nodes Alive (HNA) and Last Node Dies (LND) [11]. Some literature instead use the number of sensor updates after which 1%, 50% and 100% of the sensor nodes die as the measure of sensor network longevity [14]. Though these measures provide some idea about the longevity of sensor networks, they do not reveal the effectiveness of the sensor network after the node deaths. Let us consider a wireless sensor network installed for monitoring forest fire in a certain area. Knowing how many of the nodes in the sensor network are still alive does not reveal how effective the system is, except when all or none of the sensor nodes are alive. What should also be known is the distribution of the surviving nodes in the sensor network so that the area that is being monitored could be estimated. What this means is that two sensor networks having same number of surviving nodes can still have different effectiveness in monitoring the environment based on their sensor node distribution. For example in [14], the authors point out that “the uneven distribution of dead nodes would lead to information vacuum in a certain region, which decrease the network quality and thus shorten the network lifetime” but still follow the old metrics that does not account for the information vacuums while evaluating the performance of their sensor network. This study proposes the effectiveness of the sensor network after certain number of sensor node failures as the measure of network longevity. The measure of the effectiveness of a wireless sensor network at any given time is a function of the number of surviving nodes as well as their distribution in the desired coverage area. Figure 2 and the discussion following it show the importance of sensor node distribution for effectiveness of the wireless sensor network. Figure 2(b) shows a possible uneven distribution of surviving nodes while using existing algorithms that may occur due to unequal availability of energy sources, for example, due to the sun shining on only one region of the network coverage area.

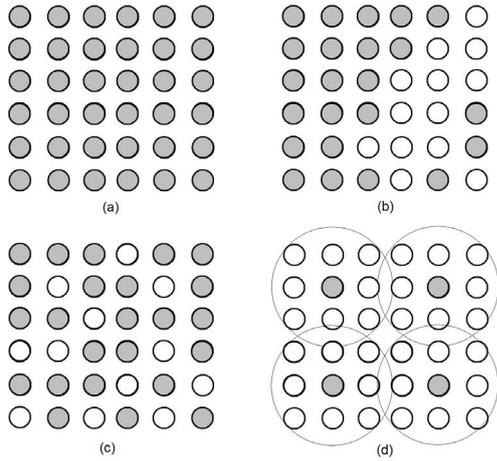


Fig. 2: Different possible sensor node distribution: (a) initial network with all surviving nodes, (b) uneven distribution of surviving sensor nodes, (c) more uniform distribution of surviving sensor nodes and (d) optimal distribution for the last four surviving nodes for area coverage.

The distribution of surviving nodes in Fig. 2 (c) is much better as the information vacuum is minimal. Figure 2 (d) presents the optimal distribution for last 4 remaining sensor nodes for the given network size.

In a wireless sensor network, a number of sensor nodes are used to obtain information from a certain geographical region. How many sensor nodes are required for a purpose depends on two parameters: the area to be monitored and the desired spatial resolution. The spatial resolution is low when a large area is monitored using a small number of sensor nodes. Similarly, if all nodes are placed close to each other, the resolution is high but the area coverage is compromised. Therefore the remaining number of sensors in a wireless sensor network alone is not a proper measure of the functioning of the sensor network. Whether the sensors are evenly distributed in the area of interest affects the effectiveness of the network. Information vacuums created due to dead sensor nodes lead to under-performance of the sensor network. For example, in a forest fire monitoring wireless sensor network, it is necessary that the surviving nodes be evenly distributed in the area being monitored rather than all of them getting accumulated in a certain region or else fire can not be detected until it has already spread to a large area. The longevity of the network should therefore be the measure of time-span for which the wireless sensor network performs satisfactorily. Loss of a sensor node degrades either resolution or coverage area but they should both be degraded uniformly so that wireless sensor network performs satisfactorily for the longest possible time. In this work, to define longevity, we first define wireless sensor network *Effectiveness* as:

$$Effectiveness = \sqrt{\frac{AreaCovered \times SurvivingNodes}{TotalArea \times TotalNodes}} \quad (1)$$

From the above definition, the wireless sensor network is fully effective when all of the sensor nodes are alive and they

cover the entire region of interest. As more nodes die due to battery exhaustion, the effectiveness decreases, finally reaching 0 when all of the nodes die. The longevity of the network is then defined as the time for which the network effectiveness is more than 70%. One possible case for the value of *Effectiveness* in equation 1 to be 0.7 is when 50% of the sensor nodes are dead and still 100% of the area is covered by the sensor network. Coverage of 100% of the area by just 50% of the nodes is possible because a unit area is still considered to be covered after the death of the sensor node if the dead node still has at least four surviving neighbour nodes. This is considering the fact that in most sensor network applications, it is possible to obtain satisfactory estimate of the sensor readings at the dead node by interpolating or voting (based on the nature of the data) among the neighbours. Also, the initial node distribution is usually heterogeneous owing to the fact that sensors are densely placed at locations that are more important. In order to take this importance into account, the unit area is defined as the area covered by a sensor node. So the same spatial area is considered to be 1 unit or multiple units based on the number of sensor nodes used to cover that area.

Applying equation 1 to the networks shown in figure 2(b) and 2(c), *Effectiveness* values of 0.6 and 0.78 is obtained respectively. Though the number of dead nodes in the two networks are almost same (12 and 13), the *Effectiveness* varies a lot owing to the dead-node distribution differences in the two networks. The network in 2(c) is performing satisfactorily whereas the *Effectiveness* of the network in 2(b) is below threshold. The proposed measure of network longevity is therefore much more meaningful than the ones based on just the counting of dead nodes.

### 3. ANT INSPIRED COLLABORATIVE ALGORITHM

The collaborative routing algorithm proposed and used in this study has been inspired by the defensive behavior in ant colonies. The nest building, foraging and defense in ant colony are all executed in collaboration but without any central control. The fascinating simple behaviors of the individual ants resulting emergence of intelligence in the colony has inspired several algorithms in computer science. Studies show that the formation of a colony in ants and the emergence of social behavior are due to their ability to communicate using their antennae when they are physically together or using chemical called pheromones in which case they have to be in the same territory within a time frame as the pheromone concentration decreases with time due to evaporation. The temporal nature of the communication helps the ants to come up with complex behaviors. For example, while out on foraging, ants need to find out the shortest path to the food source and this they achieve by measuring the pheromone strength while returning.

In [15], authors present a detailed analysis of defense mechanism of *Lasius Niger* ant species concluding that the defense system of this ant species consists of three processes:

- i. A recruiting system that allocates more workers to more valuable resources;
- ii. Individual ants following a simple decision rule to become more aggressive in response to increased numbers of nest-mates nearby (hence aggressive behavior reflecting the importance of each area to the colony); and
- iii. Variability in individual responses causing a gradual change in the proportion of fighting ants responding to a threat.

The ant inspired collaboration of intelligent agents based on ant's defensive behavior was first proposed in [10] where the algorithm is used for multi-robot collaboration. Collaborative multiple robots are shown to perform better compared to ego-centric team of robots for obstacle removal/avoidance task. In this study, the collaboration algorithm is being used for collaborative routing in wireless sensor network to improve the network longevity.

As [15] suggests, the aggressiveness of an ant depends considerably in the number of ants in the neighborhood. The more the ants present in an area, the more aggressive the ants become. Individual ants can assess the number of ants in an area simply by sensing the pheromone concentration in that area. If ants are present in a larger number, the pheromone concentration will be high in that area as a result of more ants depositing pheromone on the surface. The lower pheromone concentration in an area implies lower number of ants in the area. More ants in an area also signify the importance of the area. When ants sense danger, they react based on the pheromone concentration in the area and hence important areas like nests and primary food-sources, where more ants are recruited, are strongly protected. If an isolated ant detects some danger, it is much more likely to run away as the low pheromone concentration indicates that the area is not worth the fight.

Individual nodes in a wireless sensor network already have the required capability to communicate with their immediate neighbors and therefore it is possible for them to collaborate with each other. As proposed in [10], the "aggressiveness" of ants is related to the "eagerness" of individual nodes in this study such that the more the eagerness of a node, the more likely it is to become the cluster head.

#### 4. CRAWL

Scalable and adaptive routing algorithm that is capable of making good use of the available energy resources is the requirement of practical energy constrained wireless sensor networks. Central control or dependence of any sort makes the network vulnerable to complete failures and adversely affects the scalability of the system. In this section we present a collaborative routing algorithm that enables individual nodes to discover appropriate routes based on available local information.

Each individual node is assigned an eagerness value to perform tasks. Like in ant colonies, the eagerness of the nodes is varied from time to time based on the number of nodes in

the neighbourhood and the energy available to them. As a result, the nodes that are in a region where energy availability is high have higher eagerness to act as a cluster head than nodes in a region with lower energy availability. As the algorithm considers the energy availability in neighbouring nodes while computing eagerness, two nodes having equal remaining battery life may have different eagerness based on whether they are located in an energy abundant region or energy scarce region. The consequence is that nodes with lower energy availability in the region start behaving thrifty while the nodes in higher energy region perform energy-intensive tasks by becoming cluster heads. The algorithm therefore does not ensure optimal energy consumption in the network by selecting short routes but effectively manages the available energy so that all nodes can survive for a longer period.

The eagerness computation, cluster formation and routing is carried out in the following way:

- i. Nodes broadcast their energy availability (battery and other sources of energy) to their neighbours
- ii. Nodes compute their eagerness based on the energy availability information received from the neighbours.

$$Eagerness = Self\_Battery\_Capacity + \sum \frac{Neighbours\_Battery\_Capacity}{10} \quad (2)$$

- iii. Nodes broadcast their eagerness information back to their neighbours.
- iv. Nodes select the neighbour from which it received maximum eagerness value as their parent node.
- v. The node which did not receive eagerness values higher than its own becomes a cluster head.
- vi. The sink then floods the cluster heads to develop a route among the sink and the cluster heads
- vii. Cluster heads adjust their power level to be able to communicate to the sink either directly or through other cluster heads.
- viii. The process is repeated at regular intervals to adapt to the changing energy availability.

The eagerness broadcast by nodes let the neighbours know the energy availability in the region and find the candidate with the best eagerness locally. The messages therefore follow the available energy gradient until a node does not find any neighbour that has eagerness higher than its own. In this case, the node becomes a cluster head and looks for long distance communication to other cluster heads or preferably the sink node. The messages might be flowing in the opposite direction from the sink in cases where the available energy gradient ascends toward the opposite end. However, as the opposite end node has higher eagerness (due to higher energy availability), the messages will be forwarded by the energy abundant cluster head to the sink node. Therefore the algorithm is sub-optimal in minimizing energy usage but is optimal in making use of available energy resources to achieve network longevity. When nodes start dying, the algorithm ensures that the surviving nodes are evenly distributed in the coverage area which is essential, as discussed in the previous section, for the network to be

effective. The even distribution is because of a node with dead neighbours having lower eagerness values (the summation being low in equation 2) and therefore being less likely to be selected as a parent node or cluster head.

## 5. RESULTS AND DISCUSSION

Power consumption model suggested in [3] for the commonly used Mica mote is used in this study. The estimated power consumption for different operations in a Mica mote is tabulated below:

TABLE 1: POWER CONSUMPTION OF MICA MOTES ESTIMATED IN [3]

Operation	nAh
Transmitting a packet	20.000
Receiving a packet	8.000
Radio listening for 1 ms	1.250
Operating analog sensor for 1 sample	1.080
Operating digital sensor for 1 sample	0.347
Reading a sample from ADC	0.011
Flash Read Data	1.111
Flash Write/Erase Data	83.333

Following the suggestion in [3], the initial battery capacity is considered to be around 2200mAh. To make the simulation more realistic, the initial battery capacity in sensor nodes is randomly varied from 1000mAh to 2400mAh. Moreover, some of the nodes in the network, including the sink node, are supplied with a secondary source of energy to reflect the ability of the algorithm to adapt to different energy availability conditions. The battery capacity of those nodes therefore remains constant overtime.

The algorithm is simulated using the Matlab based Probabilistic wireless network simulator called Prowler [16]. Prowler is an event-driven simulator that can run either in deterministic mode or in probabilistic mode that simulates the non-deterministic nature of the communication channel and the low-level communication protocol of the motes. As Prowler also targets the Mica motes, the battery model that has been used and the simulation environment adopted in this study match each other.

100 nodes are uniformly distributed in a grid initialised with certain battery capacity (for normal nodes, initial battery capacity is initialized to values up to 2400mAh but some nodes have secondary energy sources in which case the capacity is higher) and signal strength of 1. Upon execution, each nodes start by broadcasting their battery capacity and then compute their own eagerness based on equation (2). Figure 3 shows the initial eagerness distribution in the network and the collaboratively computed route for the distribution. The algorithm comes up with a routing scheme in which each node knows whether or how to forward the received messages until the messages do not finally reach the destination. The performance of CRAWL is compared with that of a non-collaborative algorithm in which nodes know the battery level of the neighbouring nodes and the message is

forwarded to the neighbour with maximum remaining battery capacity. The only difference between the two algorithms is that CRAWL considers the energy distribution in the region to compute the cluster heads and the routing scheme whereas the non-collaborative algorithm forwards messages greedily to the neighbour with the highest remaining battery.

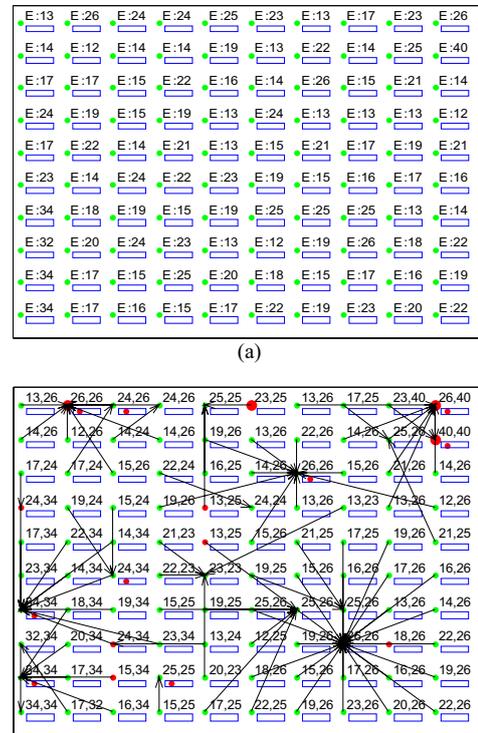


Fig. 3: (a) Initial eagerness distribution and (b) collaboratively computed routing scheme for the wireless sensor network

In simulation, it is observed that both algorithms perform almost equally well when there is uniform energy distribution in the network. When the initial battery capacity in the nodes is varied between 2000mAh and 2400mAh, the network operated using CRAWL lasts on average 4.7% longer but when the initial variation is increased to between 1500mAh and 2400mAh, CRAWL lasts on average 26.6%. When the variation is further increased to between 1000mAh and 2400mAh; CRAWL lasts on average 20.2% longer. This clearly shows that CRAWL selects more suitable routes for network longevity when the energy distribution is fairly heterogeneous but as the heterogeneity is further increased, the longevity of CRAWL starts to degrade. The longevity of CRAWL degraded by 10.1 % due to the severe change in energy level variation when the non-collaborative algorithm degraded by 21.3%. This result proves that CRAWL is twice more adaptive to severe system heterogeneity as compared to the non-collaborative algorithm.

## 6. CONCLUSION

The parameters commonly used in literature to describe network longevity are not meaningful as the parameters do

not properly reflect the duration for which the wireless sensor networks perform satisfactorily. This study introduces a new parameter, Effectiveness, of the wireless sensor network using which the performance of a network can be quantified. The longevity of the network is then defined as the duration of time for which the network is at least 70% effective. This proposed definition of longevity is then used in evaluating the performance of the proposed algorithm.

Simulation results clearly show that CRAWL performs much better than the non-collaborative algorithms in achieving network longevity when the energy distribution in the network is non-uniform. CRAWL performance degraded by just 10.1% when the energy distribution heterogeneity was substantially increased in a wireless sensor network proving adaptability of the algorithm. As the entire routing is based on local energy availability information, the algorithm is highly scalable. With both scalability and adaptability, CRAWL is a suitable algorithm for coming generation of wireless sensors networks.

#### REFERENCES

- [1] Liyang Yu; Neng Wang; Xiaoqiao Meng, "Real-time forest fire detection with wireless sensor networks," in Proceedings of International Conference on Wireless Communications, Networking and Mobile Computing, vol.2, pp. 1214-1217, Sept. 2005.
- [2] Burrell, J.; Brooke, T.; Beckwith, R., "Vineyard computing: sensor networks in agricultural production," *Pervasive Computing*, IEEE, vol.3, no.1, pp. 38-45, Jan.-March 2004.
- [3] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson, "Wireless Sensor Networks for Habitat Monitoring," in First ACM Workshop on Wireless Sensor Networks and Applications, Atlanta, GA, USA, September 2002.
- [4] Wendi Rabiner Heinzelman, Anantha Chandrakasan, Hari Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks," 33rd Hawaii International Conference on System Sciences-Volume 8, p. 8020, 2000.
- [5] Tian He, Suda Krishnamurthy, John A. Stankovic, Tarek F. Abdelzaher, Liqian Luo, Radu Stoleru, Ting Yan, Lin Gu, Jonathan Hui, and Bruce Krogh. "An Energy-Efficient Surveillance System Using Wireless Sensor Networks." in the Second International Conference on Mobile Systems, Applications, and Services (MobiSys), June 2004.
- [6] Konrad Lorincz, David Malan, Thaddeus R. F. Fulford-Jones, Alan Nawoj, Antony Clavel, Victor Shnayder, Geoff Mainland, Steve Moulton, and Matt Welsh, "Sensor Networks for Emergency Response: Challenges and Opportunities", *IEEE Pervasive Computing*, Special Issue on Pervasive Computing for First Response, Oct-Dec 2004.
- [7] Akkaya K., Younis M., "A survey on routing protocols for wireless sensor networks", *Ad Hoc Networks*, Vol. 3, pp. 325-349, 2005.
- [8] D. Estrin, R. Govindan, J. Heidemann, S. Kumar, "Next century challenges, "Scalable Coordination in Sensor Networks", Proceedings of MOBICOM, 263-270, Seattle, 1999.
- [9] Akkaya K., Younis M., "A survey on routing protocols for wireless sensor networks", *Ad Hoc Networks*, Vol. 3, pp. 325-349, 2005.
- [10] Bashyal Shishir, Venayagamoorthy Ganesh K., "Ant Inspired Algorithm for Multi-robot Collaboration", in Proceedings of ANNIE Conference, in Press, 2007.
- [11] Wendi Rabiner Heinzelman, Anantha Chandrakasan, Hari Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks," 33rd Hawaii International Conference on System Sciences-Volume 8, p. 8020, 2000.
- [12] Heinzelman, W.B.; Chandrakasan, A.P.; Balakrishnan, H., "An application-specific protocol architecture for wireless microsensor networks," *Wireless Communications*, IEEE Transactions on, vol.1, no.4, pp. 660-670, Oct 2002.
- [13] Takehiro Furuta, Mihiro Sasaki, Fumio Ishizaki, Atsuo Suzuki, Hajime Miyazawa, "A New Cluster Formation Method for Sensor Networks Using Facility Location Theory", Technical report of the Nanzan Academic Society, August 2006.
- [14] Liang Ying, Yu Haibin, "Energy Adaptive Cluster-Head Selection for Wireless Sensor Networks", In Sixth International Conference on Parallel and Distributed Computing Applications and Technologies, pp. 634-638, 2005.
- [15] Hiroshi Sakata, Noboru Katayama; "Ant defence system: A mechanism organizing individual responses into efficient collective behavior", *Ecological Research* 16 (3), 395-403, 2001.
- [16] Simon, G.; Volgyesi, P.; Maroti, M.; Ledeczi, A., "Simulation-based optimization of communication protocols for large-scale wireless sensor networks," *Aerospace Conference Proceedings*, IEEE, vol.3, pp. 3\_1339-3\_1346, March 2003.
- [17] C. Behrens, O. Bischoff, M. Lueders, and R. Laur, "Energy-efficient topology control for wireless sensor networks using online battery monitoring", *Adv. Radio Sci.*, vol. 5, pp. 205-208, 2007.
- [18] Kay Römer, Oliver Kasten, Friedemann Mattern, "Middleware Challenges for Wireless Sensor Networks", *ACM Mobile Computing and Communication Review*, Vol. 6, No. 4, pp. 59-61, October 2002.
- [19] Chipara, O.; Zhimin He; Guoliang Xing; Qin Chen; Xiaorui Wang; Chenyang Lu; Stankovic, J.; Abdelzaher, T., "Real-time Power-Aware Routing in Sensor Networks," *IWQoS*, pp.83-92, June 2006.