A WIRELESS SENSOR NETWORK AIR POLUTION MONITORING SYSTEM

M.Prithiviraj[1], B.Ramkumar[2], Mantu Sarkar[3], Mrs.Queen Mary Vidya[4]

Department of Computer Science and Engineering

123 UG students,4Asstproffessor

1.,2,3,4Vel Tech High Tech Dr Rangarajan Dr Sakunthala Engineering college, Avadi,

Mail id:prithvimpr@gmail.com, ram.rockers7@gmail.com, mantusarkar@hotmail.com,queenmaryvidya@velhightech.com

ABSTRACT

Sensor networks are currently an active research area mainly due to the potential of their applications. Inthis paper we investigate the use of Wireless Sensor Networks (WSN) for air pollution monitoring inMauritius. With the fast growing industrial activities on the island, the problem of air pollution isbecoming a major concern for the health of the population. We proposed an innovative system namedWireless Sensor Network Air Pollution Monitoring System (WAPMS) to monitor air pollution inMauritius through the use of wireless sensors deployed in huge numbers around the island. The proposed system makes use of an Air Quality Index (AQI) which is presently not available in Mauritius. In order toimprove the efficiency of WAPMS, we have designed and implemented a new data aggregation algorithmnamed Recursive Converging Quartiles (RCQ). The algorithm is used to merge data to eliminateduplicates, filter out invalid readings and summarise them into a simpler form which significantly reduce the amount of data to be transmitted to the sink and thus saving energy. For better power management weused a hierarchical routing protocol in WAPMS and caused the motes to sleep during idle time.

KEYWORDS

Sensor Networks, Routing Protocol, Data Aggregation, Air Pollution Monitoring, Data Fusion

1. INTRODUCTION

Sensor networks are dense wireless networks of small, low-cost sensors, which collect anddisseminate environmental data. Wireless sensor networks facilitate monitoring and controllingof physical environments from remote locations with better accuracy [1]. They haveapplications in a variety of fields such as environmental monitoring, indoor climate control, surveillance, structural monitoring, medical diagnostics, disaster management, emergencyresponse, ambient air monitoring and gathering sensing information in inhospitable locations [2,3, 4, 5]. Sensor nodes have various energy and computational constraints because of their inexpensive nature and ad-hoc method of deployment. Considerable research has been focusedat overcoming these deficiencies through more energy efficient routing, localization algorithmsand system design.

In this paper we proposed a wireless sensor network air pollution monitoring system (WAPMS)

for Mauritius. Indeed, with the increasing number of vehicles on our roads and rapid urbanization air pollution has considerably increased in the last decades in Mauritius. For thepast thirty years the economic development of Mauritius has been based on industrial activitiesand the tourism industry. Hence, there has been the growth of industries and infrastructureworks over the island. Industrial combustion processes and stone crushing plants hadcontributed to the deterioration of the quality of the air. Further, the economic success of

Mauritius has led to a major increase in the number of vehicles on the roads, creating additionalair pollution problem with smoke emission and other pollutants.Air pollution monitoring is considered as a very complex task but nevertheless it is veryimportant. Traditionally data loggers were used to collect data periodically and this was very

time consuming and quite expensive. The use of WSN can make air pollution monitoring less complex and more instantaneous readings can be obtained [6, 7]. Currently, the Air Monitoring

Unit in Mauritius lacks resources and makes use of bulky instruments. This reduces the flexibility of the system and makes it difficult to ensure proper control and monitoring.WAPMS will try to enhance this situation by being more flexible and timely. Moreover,accurate data with indexing capabilities will be able to obtain with WAPMS. The mainrequirements identified for WAMPS are as follows:

1. Develop an architecture to define nodes and their interaction

2. Collect air pollution readings from a region of interest

3. Collaboration among thousands of nodes to collect readings and transmit them to a gateway,

all the while minimizing the amount of duplicates and invalid values

4. Use of appropriate data aggregation to reduce the power consumption during transmissionof large amount of data between the thousands of nodes

5. Visualization of collected data from the WSN using statistical and user-friendly methodssuch as tables and line graphs

6. Provision of an index to categorize the various levels of air pollution, with associatedcolours to meaningfully represent the seriousness of air pollution

7. Generation of reports on a daily or monthly basis as well as real-time notifications duringserious states of air pollution for use by appropriate authorities

At present, our scientific understanding of air pollution is not sufficient to be able to accuratelypredict air quality at all times throughout the country. This is where monitoring can be used tofill the gap in understanding. Monitoring provides raw measurements of air pollutantconcentrations, which can then be analysed and interpreted. This information can then beapplied in many ways. Analysis of monitoring data allows us to assess how bad air pollution isfrom day to day, which areas are worse than others and whether levels are rising or falling. Wecan see how pollutants interact with each other and how they relate to traffic levels or industrialactivity. By analysing the

relationship between meteorology and air quality, we can predict
which weather conditions will give rise to pollution episodes.

2. RELATED WORKS

Wireless Sensor Network (WSN) is an active field of research due to its emerging importance inmany applications including environment and habitat monitoring, health care applications,traffic control and military network systems [8]. With the recent breakthrough of Micro-Electro-Mechanical Systems (MEMS) technology [9] whereby sensors are becoming smaller and moreversatile, WSN promises many new application areas in the near future. Typical applications ofWSNs include monitoring, tracking and controlling. Some of the specific applications arehabitat monitoring, object tracking, nuclear reactor controlling, fire detection, traffic monitoring, etc.Initial development into WSN was mainly motivated by military applications. However, WSNsare now used in many civilian application areas for commercial and industrial use, including environment and habitat monitoring, healthcare applications, home automation, nuclear reactorcontrolling, fire detection and traffic control [8]. This transition from the use of WSN solely inmilitary applications has been motivated due to the nature of WSNs which can be deployed in wilderness areas, where they would remain for many years, to monitor some environmentalvariables, without the need to recharge/replace their power supplies. Such characteristics help toovercome the

difficulties and high costs involved in monitoring data using wired sensors. Below are some areas where WSN have been successfully deployed to monitor the environment.

2.1. Fire and Flood Detection
Large number of environmental applications makes use of WSNs. Sensor networks are deployed in forest to detect the origin of forest fires. Weather sensors are used in flood detectionsystem to detect, predict and hence prevent floods. Sensor nodes are deployed in theenvironment for monitoring biodiversity.The Forest-Fires Surveillance System (FFSS) [10] was developed to prevent forest fires in the
South Korean Mountains and to have an early fire-alarm in real time. The system senses
environment state such as temperature, humidity, smoke and determines forest-fires risk-levelby formula. Early detection of heat is possible and this allows for the provision of an early alarmin real time when the forest-fire occurs, alerting people to extinguish forest-fires before it grows.
Therefore, it saves the economical loss and environment damage. Similarly, a typical application of WSN for flood detection and prevention is the ALERT system [11] deployed inthe US. Rainfalls, water level and weather sensors are used in this system to detect, predict andhence prevent floods. These sensors supply information to a centralized database system in a
pre-defined way.

2.2. Biocomplexity Mapping and Precision Agriculture

Wireless sensor networks can be used to control the environment which involves monitoring air,soil and water. Sensors are deployed throughout the field and these sensors form a network that communicate with each other to finally reach some processing centre which analyse the datasent and then accordingly adjust the environment conditions (e.g., if the soil is too dry, theprocessing centre send signals which actuators recognise accordingly and thus can start thesprinkling system. Biocomplexity mapping system helps to control the external environment.

Sensors are used to observe spatial complexity of dominant plant species [12]. An example isthe surveillance of the marine ground floor where an understanding of its erosion processes isimportant for the construction of offshore wind farms [13].

Precision agriculture is an emerging WSN application area to monitor and control the amount ofpesticides present in drinking water, monitor the level of soil erosion and the level of airpollution [14].

Precision agriculture encompasses different aspects such as monitoring soil, crop and climate in a field. Huge amount of sensor data from large-scale agricultural fields arefrequently generated in such an application.

2.3. Habitat Monitoring

Concerns associated with the impacts of human presence in monitoring plants and animals infield conditions have to a large extent been overcome by WSNs [15]. Sensors can now bedeployed prior to the onset of the breeding season and while plants are dormant or the ground is

frozen as well as on small islets where it is unsafe or unwise to repeatedly attempt field studies.Such deployment represents a substantially more economical method for conducting studiesthan traditional personnel-rich methods where substantial proportion of logistics andinfrastructure must be devoted to the maintenance of field studies, often at some discomfort and occasionally at some real risk.Perhaps the best known application demonstrator for WSN in this domain is the Great Duck Island project at Berkley [15]. Sensors monitored the microclimates in and around nestingburrows used by the Leach's Storm Petrel in a non-intrusive and non-disruptive manner. Moteswere deployed on the island, with each of them having a microcontroller, a low-power radio,memory, and batteries. Readings such as Infrared levels, humidity, rainfall and temperaturewere monitored on a constant basis to better understand the movements of the petrels. Motesperiodically sampled and relayed their sensor readings to computer base stations on the islandwhich in turn fed into a satellite link that allows researchers to access real-time environmentaldata over the Internet.

Researchers at University of Florida and University of Missouri, Colombia are studying the roleof wildlife in maintaining diversity, tracking invasive species and the spread of emergingdiseases by obtaining unobtrusive visual information. They are using DeerNet [16] which is aWSN-based system for analysing wildlife behaviour by tracking deer's actions. The overall goal is to develop a long-lived and unobtrusive wildlife video monitoring system capable of real-timevideo streaming. The captured

video will be transmitted over to a remote monitoring center forreal-time viewing and camera control. Advanced scene classification and object recognition algorithms together with fusion of data from other sensors like GPS and motion can be appliedto remove essential visual information from the captured video. Then, statistical models aboutanimals' food selection, activity patterns and close interactions can be made consequently.

3. RECURSIVE CONVERGING QUARTILES (RCQ) DATA AGGREGATIONALGORITHM

Most wireless sensor networks involve the collection of high amounts of data. For this reason,during last years considerable research effort has been devoted to data fusion and aggregationalgorithms [17, 18]. In general, if we consider the problem to route data packets, representingmeasurements collected by sensors, to a single managing entity, i.e., a network sink, it is oftenefficient to exploit the correlation among similar data collected by the sensors in order todecrease overhead [19, 20]. At this point, however, a trade-off arises between the amount oftransmitted data in the aggregated flows and their reliability. Data aggregation is a technique which tries to alleviate the localized congestion problem. It attempts to collect usefulinformation from the sensors surrounding the event. It then transmits only the usefulinformation to the end point thereby reducing congestion and its associated problems. We havedeveloped a

new data aggregation algorithm for WAPMS named Recursive Converging Quartiles (RCQ). The algorithm includes two basic operations namely duplicate elimination and
data fusion.

3.1. Duplicate Elimination Technique

In WAPMS a packet consists of two parts: the data, which is the reading collected by the sourcenode, and an id, which identifies the node uniquely in the network such as a network address.The cluster head collects readings from every node and stores them in a list. After collection, itgoes through each item in the list and check for the occurrence of packets with the same id,thereby detecting the presence of duplicate packets. It then keeps only one instance of them.
Figure 1and figure 2 illustrate our proposed duplication elimination technique.
Figure 1. Multihop routing of data during a collection instance
Figure 2. Illustration of duplicate elimination technique

3.2. Proposed Data Fusion Technique

There are several statistical methods to summarise a list of data. We have considered the use ofthe three quartiles - lower, median and upper. We have considered the use of quartiles since they are unaffected by extreme values; this is required in our system whereby extreme and invalidvalues can sometimes be transmitted to the cluster head and these should not influence the datafusion mechanism. Moreover, quartiles reduce the amount of data to only three values while still

reflecting the original data in an accurate way. The novel data fusion algorithm works asfollows:

1. The list is partitioned into several smaller groups

· We consider the length of the list

· We find its multiples in the form $(x1, y1)$, $(x2, y2)$…

· E.g., length = 200, multiples = $(1, 200)$, $(2,100)$, $(4, 50)$, $(5, 40)$, $(10, 20)$, $(20, 10)$, $(24, 5)$

· We choose the pair which will give the highest number of groups (Maximise x) and theminimum number of elements per group, while keeping it above a threshold (Minimisey, y > threshold value)

E.g., length = 50, multiples = $(1, 50)$, $(2,25)$, $(5, 10)$, $(10, 5)$, threshold = 5, optimal pair = $(10, 5)$.

2. We calculate the quartiles for each of the smaller lists

3. Merge the resulting quartiles for the sub lists into one list

4. Repeat the whole process until the eventual number of groups, in which the list can bebroken, becomes one and the final list obtained has only three values.

Figure 3 below shows our proposed data fusion algorithm, Recursive Converging Quartiles, at

work to achieve 3 values out of the original 33.

Figure 3. Using RCQ to aggregate a list of 33 values to only 3 values

4. WAPMS: THE PROPOSED AIR POLLUTION MONITORING SYSTEM

The proposed wireless sensor network air pollution monitoring system (WAPMS) comprises ofan array of sensor nodes and a communications system which allows the data to reach a server.The sensor nodes gather data autonomously and the data network is used to pass data to one or more base stations, which forward it to a sensor network server. The system send commands tothe nodes in order to fetch the data, and also allows the nodes to send data out autonomously.Figure 4 shows the architecture diagram of WAPMS.Figure 4. Architecture diagram of WAMPS.

Below is a brief description of each component of WAMPS:

· *Reading Sensor:* generates a random value whose range is set based on the value of"seriousness" variable.

· *Reading Transmitter:* gets the generated value from the reading sensor and transmits itthrough the communicator.

· *Power Controller:* Each node will have a method called "turn on" that will start the nodeand we just call it. As for power-saving modes, this will depend on what the simulator willprovide to us.

· *Communicator:* this is implemented by the simulator. Inter-Process communication is usually done using sockets; so, we expect the simulator to provide us with sockets as wellas methods such as "send" and "receive".

· *Launcher:* informs the data collector to start collection based on the delivery mode set bythe user.

· *Data Collector:* gets a list of nodes from which it has to collect readings, then sends messages to inform them and finally receives the required values.

· Aggregator: implements the RCQ algorithm for data aggregation that we will discuss in thenext section.

· *Data Extractor:* Use SQL queries to extract data from database

· *Data Displayer:* This extracts data as required by the user and displays them in a table aswell as evaluates the AQI for the selected area.

· *Trend Analyser:* Gets previous readings and determines relationship between them to beable to extrapolate future readings.

· *Nodes Deployment Viewer:* Displays deployment of nodes in the WSN field and their AQIcolours.

· *Connection Initiator:* The java DriverManager allows for a method to open a database,providing it the name of the database, user name and password as parameters. So, thiscomponent just has to make a call to this method and store the return reference to theconnection.

· *Connection Destructor:* Connection object, in java.sql package, usually provides for a close method that closes the latter safely and frees associated memory as well as save the state of the latter. Therefore, this component just has to call this method.

The following table shows the various types of nodes that are present in WAPMS:

Table 1. Types of Nodes

Type   ofNodeEnergyRequirements Location Role

Source(sensornode)Constrained Random Sensing andmultihoproutingClusterHead (collector)Not-Constrained FixedCollectionandaggregationSink/Gateway Not-Constrained Fixed CollectionThese nodes will form a hierarchy that is shown in figure 5 below:

Figure 5. Hierarchy of nodes

The strategy to deploy the WSN for our system is as follows:

o We first partition our region of interest into several smaller areas for better management ofhuge amount of data that will be collected from the system and for better coordination of the

various components involved

o We deploy one cluster head in each area; these will form cluster with the nodes in theirrespective areas, collect data from them, perform aggregation and send these back to thesink.

o We, then, randomly deploy the sensor nodes in the different areas. These will sense the data,send them to the cluster head in their respective area through multihop routing

o We will use multiple sinks that will collect aggregated from the cluster heads and transmit

them to the gateway. Each sink will be allocated a set of cluster heads.

o The gateway will collect results from the sinks and relay them to the database and eventually to our application.

Figure 6 illustrates our deployment strategy:

Figure 6. Deployment strategy

The system is simulated over a small region as a prototype and then it will be extended to thewhole island. The town of Port Louis, the capital of the country, is chosen for the prototypeimplementation as it is an urban area and therefore, more exposed to air pollution than ruralareas. The site is partitioned the site into 6 smaller areas as shown in figure 7. With this small

number of areas, we will use a single sink and we further simplify the system by allowing thegateway to play the role of the

latter.Figure 7. Partition of Port Louis into smaller areasAn Air Quality Index (AQI) is used in WAMPS. The AQI is an indicator of air quality, based onair pollutants that have adverse effects on human health and the environment. The pollutants are

ozone, fine particulate matter, nitrogen dioxide, carbon monoxide, sulphur dioxide and totalreduced sulphur compounds. Figure 8 and figure 9 illustrate the AQI range.Figure 8. The range of AQI values

The AQI consists of 6 categories, each represented by a specific colour and indicating a certainlevel of health concern to the public and is it shown in figure 9. The Ambient Air Quality

Standards for Mauritius reports that the safe limit for ozone is 100 micrograms per m3 and thesafe AQI value set is also 100. Therefore, the AQI itself can, indirectly, be used to measureozone concentration in Mauritius.Figure 9. Description of AQI categories

5. SIMULATIONS AND RESULTS

WAMPS has been simulated using the Jist/Swans simulator [21]. JiST is a high-performancediscrete event simulation engine that runs over a standard Java virtual machine. It converts anexisting virtual machine into a simulation platform, by embedding simulation time semantics atthe byte-code level. SWANS is a scalable wireless network simulator built atop the JiSTplatform. SWANS is organized as independent software components that can be composed toform complete wireless network or sensor network configurations. Its capabilities are similar tons2 and

GloMoSim but it is able to simulate much larger networks. SWANS leverages the JiSTdesign to achieve high simulation throughput, save memory, and run standard Java networkapplications over simulated networks. In addition, SWANS implements a data structure, calledhierarchical binning, for efficient computation of signal propagation.The DSR protocol [22] has been used for data transmission in WAPMS. The Dynamic SourceRouting protocol is a simple reactive routing protocol designed specifically for use in multi-hopwireless ad hoc networks. DSR allows the network to be completely self-organizing and selfconfiguring,without the need for any existing network infrastructure or administration. DSR

contains two phases: Route Discovery (find a path) and Route Maintenance (maintain a path).These only respond on a request. The protocol operates entirely on-demand, allowing therouting packet overhead of DSR to scale automatically to only that needed to react to changes in

the routes currently in use.After a collection, the system displays the nodes in their corresponding AQI colour as shown in

figure 10. The following is an example of such a screen:

Figure 10. Nodes' Deployment after a collectionGiven an area and a date, the system display the corresponding AQI readings and the healthconcern in this area as shown in figure 11 below.

Figure 11. AQI for a selected area

Furthermore, the WAPMS system allows fast analysis of received data through line graphs ofselected areas.Figure 12. Line

graph generated for selected areasThe performance of WAPMS has been evaluation with increasing load. We have varied thenumber of areas simulated from 1 to 6 and for each case, we have varied the number of nodesper area from 50 to 200 and the execution time of the system has been recorded. The results areshown in table II and figure 13.Table 2. Execution Time of WAPMS

As shown in the above table, the maximum running time of our simulator is less than 20 minutes in the worst case of 6 areas and 200 nodes in each area. The short execution time ofWAPMS is massively advantageous comparing to the existing air pollution monitoring unit ofMauritius that often takes days to measure pollution in an area. Moreover, WAPMS allows

timely monitoring of an area and an abnormal situation can be detected almost immediately.

6. CONCLUSION

As discussed in this paper, recent technological developments in the miniaturization ofelectronics and wireless communication technology have led to the emergence ofEnvironmental Sensor Networks (ESN). These will greatly enhance monitoring of the naturalenvironment and in some cases open up new techniques for taking measurements or allow

previously impossible deployments of sensors. WAPMS is an example of such ESN. WAPMSwill be very beneficial for monitoring different high risk regions of the country. It will providereal-time information

about the level of air pollution in these regions, as well as provide alerts in

cases of drastic change in quality of air. This information can then be used by the authoritiestotake prompt actions such as evacuating people or sending emergency response team.WAPMS uses an Air Quality Index to categorise the various levels of air pollution. It alsoassociates meaningful and very intuitive colours to the different categories, thus the state of airpollution can be communicated to the user very easily. The major motivation behind our study

and the development of the system is to help the government to devise an indexing system tocategorise air pollution in Mauritius. The system also uses the AQI to evaluate the level ofhealth concern for a specific area.

WAPMS uses a novel technique to do data aggregation in order to tackle the challenge of powerconsumption minimisation in WSN. We have named this novel technique as RecursiveConverging Quartiles. It also uses quartiles to summarise a list of readings of any length to justthree values. This highly reduces the amount of data to be transmitted to the sink, thus reducing

the transmission energy required and at the same time representing the original values accurately.Another strength of WAPMS is the high quality of results it produces. The collected readingsare saved in a database and these can be accessed individually in a table or summarisedareawisein a line graph. The table uses the AQI to provide the results using the associated colours

and it also provided the level of health concern for a particular area. The line graph allows theuser to view the trend of air

pollution for several areas at a time. WAPMS also displays a map

of the town of Port Louis, showing the locations of the deployed sensors nodes and the readingscollected by each one. Thus, WAPMS is very flexible, very easy and yet very powerful due toits ability to providehighly summarised results as well as fine-grain results at the level of sensors.

7. REFERENCES

[1] H. Karl and A. Willig, Protocols and Architectures for Wireless Sensor Networks, John Wiley andSons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, England, 2005.

[2] D. Culler, D. Estrin, and M. Srivastava, "Overview of Sensor Networks", *IEEE Computer*, August2004.

[3] K. Martinez, J. K. Hart, and R. Ong, "Environmental sensor networks", *IEEE Computer Journal*,Vol. 37 (8), 50-56, August 2004.

[4] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson, "Wireless sensor networksfor habitat monitoring", Proceedings of the 1st ACM International workshop on Wireless sensornetworks and applications, Atlanta, Georgia, USA, 88-97, 2002.

[5] I. F. Akyildiz, D. Pompili and T. Melodia, "Underwater acoustic sensor networks: research challenges", *Ad Hoc Networks*, Vol. 3 (3), 257-279, May 2005.

[6] Y. Ma, M. Richards, M. Ghanem, Y. Guo and J. Hassard, "Air Pollution Monitoring and MiningBased on Sensor Grid in London", *Sensors 2008*, Vol. 8(6), 3601-3623.

[7] G. Hassard , M. Ghanem , Y. Guo , J. Hassard , M. Osmond , and M. Richards, "Sensor Grids For Air Pollution Monitoring", in the Proceedings of 3rd UK e-Science All Hands Meeting, 2004.

[8] I. Khemapech, I. Duncan, and A. Miller, "A survey of wireless sensor networks technology," inPGNET, In the Proceedings of the 6th Annual Postgraduate Symposium on the Convergence ofTelecommunications, Networking & Broadcasting , Liverpool, UK, EPSRC, June 2005.

[9] B. Warneke and K.S.J. Pister, "MEMS for Distributed Wireless Sensor Networks," 9th International Conference on Electronics, Circuits and Systems, Croatia, September 2002.

[10] B. Son, Y. Her, J. Kim, "A design and implementation of forest-fires surveillance system based onwireless sensor networks for South Korea mountains", *International Journal of Computer Scienceand Network Security (IJCSNS)*, 6, 9, 124–130, 2006.

[11] ALERT, Available from: http://www.alertsystems.org/, Accessed on: 14 August 2009.

[12] T.H. Keitt, D.L. Urban and B.T. Milne, "Detecting critical scales in fragmented landscapes,"*ConservationEcology(online)*, Vol. 1, 1997.

[13] J. Heidemann et al., "Underwater Sensor Networking: Research Challenges and Potential Applications," USC/ISI tech. rep. ISI-TR-2005-603, 2005.

[14] I. F. Akyildiz, W. Su, Y.Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: ASurvey", *Elservier Computer Networks*, Vol.38 (4), pp. 393-422, March 2002.

[15] A. Mainwaring , D. Culler , J. Polastre , R. Szewczyk , J.Anderson, Wireless sensor networks forhabitat monitoring, Proceedings of the 1st ACM international workshop on Wireless sensornetworks and applications, Atlanta, Georgia, USA, September 2002.

[16] DeerNet, Available from: http://blog.xbow.com/xblog/2007/10/deernet ---caugh.html, Date Accessed: 27 August 2009.

[17] R. Rajagopalan and P.K. Varshney, "Data-Aggregation Techniques in Sensor Networks: A Survey," *IEEE Communication Surveys and Tutorials*, Vol. 8 (4), pp. 48-63, December 2006.

[18] H. Albert, R. Kravets and I. Gupta, "Building Trees Based On Aggregation Efficiency in SensorNetworks," *Ad Hoc Networks*, Vol. 5 (8), pp. 1317-1328, November 2007.

[19] O. Younis and S. Fahmy, "Distributed Clustering in Ad-hoc Sensor Networks: A Hybrid, Energy-Efficient Approach", In Proceedings of IEEE INFOCOM, Vol. 1, 629-640, March 2004.

[20] Q. Cao, T. He, L. Fang, T. Abdelzaher, J. Stankovic, and S. Son, "Efficiency Centric Communication Model for Wireless Sensor Networks", in Proceedings of IEEE INFOCOM, pp. 1-12, 2006.

[21] JiST/SWANS, Java in Simulation Time / Scalable Wireless Ad hoc Network Simulator, Available from: http://jist.ece.cornell.edu/index.html, Cornell University.

[22] D. Johnson, D. Maltz, and J. Broch, "DSR: The Dynamic Source Routing Protocol for Multi-Hop Wireless Ad Hoc Networks", *In Ad Hoc Networking*, Chapter 5, 139-172, Addison-Wesley, 2001.