

Reliable and Energy Efficient Backup Clustering Scheme for Wireless Sensor Networks

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Abstract – One of the major challenges in wireless sensor networks (WSN) is to meet the energy constraint of its sensor nodes while ensuring reliability of the system. Clustering is an effective self-organization approach to offer energy-efficient communication for WSNs. However, energy of a sensor node dynamically decreases when it plays a role of a cluster head. As a result some nodes die faster that shorten overall network lifetime and reduce reliability. Existing clustering techniques even with backup cluster head (BCH) consumes huge energy due to frequent re-clustering and inefficient backup cluster head selection and switching. In this paper we propose a new approach for backup cluster head scheme to reduce the frequency of re-clustering and thus to increase the network lifetime. We introduce the selection of an optimal set of backup cluster heads from the cluster member nodes and the calculation of their optimum switching time. To evaluate the efficacy of the proposed scheme we extend the HEED clustering protocol to backup cluster head. Simulation results demonstrate that our proposed approach is effective in prolonging the network lifetime that outperforms both HEED and backup clustering proposed in [10] considerably. Proposed scheme also enhances data reliability by reducing re-clustering overhead.

Index Terms – Wireless sensor networks, backup cluster head, reliability, energy consumption, network lifetime.

I. INTRODUCTION

Wireless Sensor Network (WSN) has emerged as an active research area mainly due to its potential of numerous cutting edge applications. The primary tasks of a sensor node within a WSN are sensing, data processing and communication. In WSN, spatially distributed autonomous tiny devices (nodes) collaborate to monitor physical or environmental phenomenon such as temperature, lighting, sound, vibration, pressure, motion and pollutants at different locations. In many applications, nodes are deployed in a remote and harsh environment or in disaster areas where recharging would be expensive and time consuming or even impossible.

Since the energy required for transmitting data is always higher than computation, it is advantageous to organize sensors into clusters [1]. Clustering is used not only in WSN, but also in other domains [2][3]. In WSN clustering techniques, a subset of nodes becomes cluster head (CH) nodes that receive data from a group of nodes, and process and transmit them to the base station (BS), or to another CH in the case of a multi-level network.

Although clustering can reduce energy consumption, its main problem is that energy consumption is concentrated on the CHs. The CH nodes deplete energy faster than non-CH nodes as they need to perform more tasks like data aggregation, compression and encryption before forwarding

data. Moreover, due to the multi-hop routing nature of a sensor network, the nodes along the routing paths tend to have heavier workload and consequently deplete their energy faster than other nodes. Therefore, periodic re-clustering is introduced to select a new set of nodes with higher residual energy to act as CHs [1][5]. However, CHs spend energy at different rate due to unequal cluster size, node density and random distribution of nodes. Even though healthier nodes exist in a cluster, sometimes a node having less energy continues to serve as a CH till its death or before re-clustering takes place in the network. The inefficient and excessive usage of energy by certain nodes often causes energy imbalance in a cluster. As a result, some CHs may face faster death. Frequent failures of CHs demand frequent re-clustering incurring large re-clustering overhead of energy.

Many WSN applications are critical in nature, where the data loss can not be tolerated such as chemicals leakage and sudden rise of temperature in industry, abnormal reading of medical devices attached to the patient's body, and detection of enemy operation etc. Therefore, these applications demand a reliable network. Sudden break down of a CH due to energy depletion disconnects the cluster from the whole network resulting loss of sensed data. Moreover, the sensing operation of the whole network remains suspended during re-clustering. Consequently, reliability of the entire network decreases drastically.

To solve the energy consumption problem of the clustering protocols and to provide a greater fault tolerance from a CH break down situation, backup or proxy node has been proposed [8][12] which assumes the role of the current CH. However, the effectiveness of [8] is limited due to exploiting the average remaining energy of all nodes in a cluster to bring the proxy node in the place of a CH. Single and double backup CH concept introduced in [12] has shown that it could improve data transfer reliability in exchange of network lifetime.

Efficient use of energy is one of the recent challenges in clustered WSN. Much of the research [1-7][12] has attempted to overcome the challenges in reducing energy consumption and extending system lifetime through cluster based routing techniques. However, none of these approaches could improve network lifetime and reliability simultaneously [10].

To address this major issue, in this paper we propose a new technique for selecting an optimal set of BCHs for a particular cluster based on the residual, average reachable, and switching energy, and energy for data aggregation and communicating other clusters (inter-cluster) or the BS.

The remainder of this paper is organized as follows. Section II presents a survey on related works. In section III

we address the problem statement which discusses the clustering problems and sensor network energy model. The proposed backup clustering protocol is presented in section IV. Section V shows simulation setup and Section VI describes performance evaluation. Finally concluding remarks and directions for future work are provided in Section VII.

II. RELATED WORKS

A clustering refers to a grouping of sensor nodes that are usually within a geographic neighbourhood to form a cluster which is managed by a CH. A number of energy-efficient hierarchical clustering algorithms have been proposed in the literature to prolong the network lifetime [1-5]. Heinzelman et al. [1] introduced a clustering technique called low-energy adaptive clustering hierarchy (LEACH) for mainly periodical data gathering applications. To distribute energy consumption over all nodes in the network, LEACH uses randomized rotation of CHs. The TDMA time schedule is adopted between the CH and the member nodes to avoid collision, and the base station communicates the CHs by CDMA schedule. Each CH assumes direct communication to the base station. Random selection of CHs incurs faster death of some nodes and consequently, their frequent failures result in large re-clustering overhead. It generates clusters based on network size and does not work well in dynamic network. In [4], the authors proposed distributed algorithms for organizing sensors into a hierarchy of clusters to minimize the energy spent in communicating information to the sink. However, minimizing the total energy consumption is not equivalent to maximizing coverage time, as the former criterion does not guarantee balanced power consumption at various CHs [14].

Younis and Fahmy proposed Hybrid Energy Efficient Distributed clustering (HEED) [5] which does not make any assumption about the network such as its density and size. Every node runs HEED individually. At the end of the clustering process, each node either becomes a CH or a child of a CH. The initial probability for each node to become a tentative CH depends on its residual energy, and final CHs are selected according to the intra-cluster communication cost. HEED terminates within $O(1)$ iterations, and achieves fairly uniform distribution of CHs across the network. However, HEED has not addressed the situation where the CH nodes die, which renders data loss [12]. Also clusters generated by HEED are not well balanced and the cluster topology fails to achieve minimum energy consumption in intra-cluster communication [15].

In EECS [6], a distance-based cluster formation method is proposed to produce clusters in unequal size. Clusters farther away from BS have smaller sizes, thus some energy could be preserved for long-haul data transmission to BS. However, CHs are chosen here based on only residual energy and less energy consuming inter-cluster multi-hop communication technique is not considered. Energy-efficient multi-hop routing protocol for wireless sensor networks (EEMR) [7] presented an uneven clustering mechanism and inter-cluster multi-hop routing selection. Clusters which are closer to the base station (BS) have smaller cluster size than those farther

from the BS, thus they can preserve some energy for the purpose of inter-cluster data forwarding. EEMR improves the network lifetime over HEED. However, uneven cluster size consisting of nodes with different residual energy can cause energy imbalance in the cluster resulting faster die of some nodes.

PEACH (Proxy-Enabled Adaptive Clustering Hierarchy) [8] selects a proxy node which can assume the role of the current CH during one round of communication. PEACH uses healthy nodes for the detection and management of any CH failure. Although the protocol claims improvement in network lifetime over LEACH, it couldn't extend the lifetime until the first node falls. Energy-driven adaptive clustering hierarchy (EDACH) [9] proposes a new approach which evenly distributes the energy dissipation among the sensor nodes to maximize the network lifetime. This is achieved by replacing the CH having low battery power with a proxy node and forming more clusters in the region relatively far from the BS. However, more clusters formed far from the BS rather increases energy consumption with the single hop communication required to reach the BS. In both PEACH and EDACH, authors used a threshold value to determine when the current CH becomes obsolete. However, the calculation of the threshold value as an average energy consumption of all CHs of the network is not an effective approach, as all clusters do not spend energy at equal rate.

Hashmi et al. proposed [12] to reduce the loss due to the failure of a CH in any existing clustering protocol by selecting a backup CH for those CHs whose residual energy level are close to deplete their energy and are expected to die before the next rotation. They achieved more data transfer reliability by reducing data loss only due to the death of CH nodes. For this they used single and double backup CHs. This scheme could increase data transfer reliability to some extent, however, in [10] it was reported that this decreased the network lifetime compared with LEACH.

III. PROBLEM STATEMENT

A. Clustering Problems

The main objective of clustering-based sensor networks is affected due to the overhead incurred in the clustering process. Let T_C be the clustering time of the whole network and T_N be the network operation time. The lifetime of a sensor network is $n(T_C + T_N)$, where n is the number of re-clustering process runs until either first or all nodes die. In the entire lifetime of a network, the clustering process spends a total time of nT_C . We can reduce n , by reducing the frequency of re-clustering. Therefore, it is necessary to optimally select a set of BCHs for a particular cluster and switch them with the current CH according to their optimum switching time so that both reliability and network lifetime increases simultaneously. For this we also need to rank the selected BCHs of a particular cluster so that they can take over the job of the relevant current CH sequentially. This will increase the effective network operation time by reducing the clustering overhead. In this paper we have assumed that the energy depletion is the main cause of a node failure. If a node

continues its role as a CH for a long time, it will eventually loose its precious energy faster than its member nodes.

In a cluster-based multi-hop WSN, CHs play roles such as data sensing, aggregating and routing. Malfunctioning of some CHs due to power failure can cause significant topological changes and might require rerouting of packets and reorganization of the network. Switching the cluster head role also affects the other CHs in the network that use the CH which has been recently replaced to forward packets toward the BS through multi-hop communication. Thus, enhancing data reliability through seamless network operation is essential for WSNs.

B. Sensor Network energy Calculation

Let N be the total number of nodes in the network and K be the total number of clusters in the network. E_{da} be the 1-bit data aggregation energy. If l_1 be the data receiving rate (Bit/sec) from member nodes, l_2 be the data receiving rate (Bit/sec) from M number of multi-hop nodes and l_3 be the data aggregated from member nodes and multi-hop nodes, according to the energy model [16], energy consumed by a CH can be calculated as follows:

$$E_{CH} = E(\text{Receiving member node data}) + E(\text{Receiving multi-hop data}) + E(\text{Aggregating data of CH's own, member nodes and multi-hop nodes}) + E(\text{Transmitting aggregate data to BS/CH})$$

$$E_{CH} = l_1 \left(\frac{N}{K} - 1 \right) E_{elec} + l_2 M E_{elec} + \left(l_1 \frac{N}{K} + l_2 M \right) E_{da} + \left(l_3 E_{elec} + l_3 \varepsilon_{mp} d_{CH,CH/BS}^4 \right) \quad (1)$$

Energy consumed by non-CH node,

$$E_{non-CH} = l_1 E_{elec} + l_1 \varepsilon_{fs} d_{non-CH,CH}^2 \quad (2)$$

Distance between non-CH and CH ($d_{non-CH,CH}$) is small and hence data transmission is dependent on the free space ε_{fs} channel model. Whereas, distance between CHs and CH to BS ($d_{CH,CH/BS}$) is large and hence data transmission is dependent on multipath fading ε_{mp} channel models [16].

IV. PROPOSED BACKUP CLUSTERING PROTOCOL

A. Protocol Operation

In this section we propose a new backup clustering scheme considering the residual energy (E_{RE}), average reachable energy (ARE), switching energy (E_{SW}), sensing energy (E_S) energy for aggregating data (E_{da}), and energy spent to communicate the other CHs (inter-cluster communication) or the BS. ARE of a node represents the expected intra-cluster communication energy consumption if that node is selected as a CH. Therefore, ARE will enforce the selection process to elect a node as a BCH, which will minimise the intra-cluster communication cost. A CH selects a set of BCHs just after the formation of that cluster. To do this, CH uses E_{SW} , and E_{RE} and ARE of each member nodes, that are obtained during their

time of joining. Current CH also calculates the optimal switching time based on nodes' E_{RE} , E_{SW} , E_S and energy consumed by a CH (E_{CH}), which includes energy for data aggregation and transmitting data to the BS, and all energy required for intra and inter-cluster communication. Then it initiates the switching operation by sending a single update message. The sequence of protocol operation can be described as follows:

1. Current CH optimally selects and ranks a set of BCHs from all member nodes and calculates their optimal switching time.
2. At its switching time, current CH chooses the first BCH from its ranked set of BCHs and broadcasts the BCH information by a single update message.
3. All member nodes of that cluster update their current CH information on receipt of the update message.
4. All the member nodes of that cluster including the CH to be replaced join the new CH as its member nodes.
5. Other relevant CHs of the network update their multi-hop routing table on receipt of this update message.
6. Newly selected BCH takes over the role of the CH to be replaced and forwards its aggregated data to the same node as was done by that CH.
7. Newly selected BCH is removed from its set and CH switching process continues until either next round of re-clustering or any more BCH does not exist.

Fig.1 shows the BCH switching process. Here, node 2 hands over the CH role to node 4.

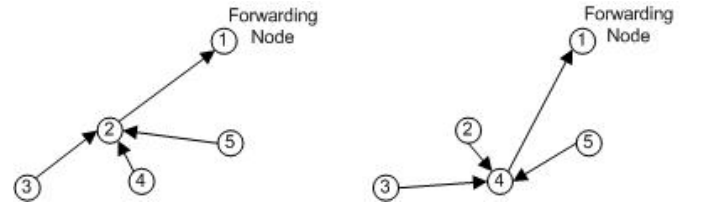


Fig. 1 Switching to backup cluster head.

It is less likely that all clusters in the whole network will start CH switching operation at the same time. Rather only the CH, which reaches to its threshold energy (switching time), triggers the switching process. Although CH switching operation takes place in one cluster, regular network operations in the other clusters remain unaffected. The switching operation takes quite short time compared to the time needed for re-clustering as illustrated in Fig. 2. Thus the protocol considerably reduces re-clustering frequency.

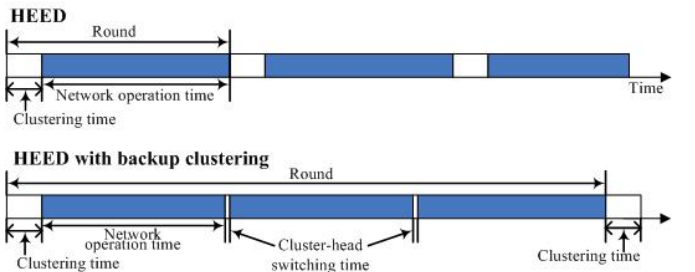


Fig. 2 Time line of HEED with backup clustering.

B. Backup Cluster Head Selection

The objective is to select a set of BCHs by minimising the overall energy spent in a cluster. Therefore, the optimal selection of a BCH can be defined as follows:

$$i = \arg \min_{1 \leq i \leq l} \{ARE_i + C_i E_{SW}\} \quad (3)$$

where i represents the ID of a node to be selected as a BCH, l denotes the number of nodes within a cluster range, and C_i is calculated as follows:

$$\text{if } E_{RE(i)} \geq E_{\min(i)} \text{ then } C_i = \left\lfloor \frac{E_{\max} - E_{RE(i)}}{E_{SW}} \right\rfloor + 1 \quad (4)$$

$$\text{else } C_i = \infty \quad (5)$$

where E_{\max} is the maximum energy of the sensor node and $E_{RE(i)}$ is the residual energy of i^{th} member node in a cluster. $E_{\min(i)}$ is the required minimum energy of a node to play the role of a CH. To be selected as a BCH node, a member node has to have a required minimum energy ($E_{\min(i)}$); otherwise it will be ignored by a very large value of ∞ . In the selection process of a BCH, since a small value of $E_{RE(i)}$, provided that $E_{RE(i)} \geq E_{\min(i)}$, will require more frequent switching, we need to have a parameter which (e.g., C_i) can represent the frequency of switching of a BCH if it were selected with respect to E_{\max} . Therefore, in this case, C_i has been regarded as defined in (4). To ensure that the node whose $E_{RE(i)} < E_{\min(i)}$ is not selected as a BCH, C_i is set to a large number (e.g., $C_i = \infty$) defined in (5). This will ensure selection of a node as new CH with minimum ARE and maximum residual energy within a particular cluster.

C. Calculation of Threshold Energy and Time for Switching

Switching energy represents the energy required to bring a BCH in the role of a current CH such as broadcasting BCH information to its member and the other relevant CH nodes. Since frequent switching consumes more energy, it is necessary to calculate an optimum time to switch from a CH to its respective BCH.

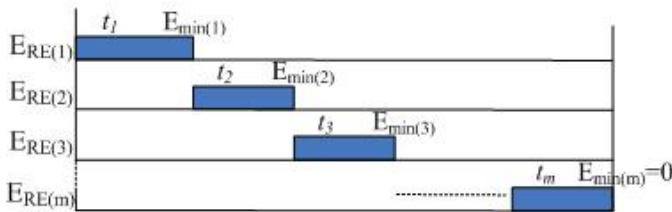


Fig. 3 Time line of backup cluster head switching.

Let t be the optimum time to switch. $E_{CH(i)}$ is the energy consumed by i^{th} node as a CH at unit time. Also let E_S be the energy per second required by non-CH member. Suppose from l member nodes in a cluster, m nodes are selected to perform as backup cluster heads. Then, the cluster life-time will be $t = t_1 + t_2 + t_3 + \dots + t_m$ shown in Fig. 3. Our objective is to maximize t so that the cluster life-time is maximised. The optimal selection of a BCH switching time can be defined as follows:

$$\text{maximise } t \quad (6)$$

$$\text{where } t = \sum_{j=1}^m t_j$$

and subject to:

$$E_{\min(i)} = \sum_{j=i+1}^m t_j \times E_S;$$

$$t_j = \frac{E_{RE(j)} - E_{\min(j)} - E_{SW} - E_S \sum_{k=1}^{j-1} t_k}{E_{CH(j)}};$$

$$\text{and } E_{\min(m)} = 0.$$

It is noteworthy to mention that the proposed backup clustering scheme could be used in any cluster-based routing protocol for wireless sensor networks.

V. SIMULATION SETUP

The simulations are aimed to study the performance of network lifetime and reliability of the entire sensor networks. The simulations have been performed on TOSSIM for TinyOS. Initial energy of sensor nodes is considered 1.0J. We considered symmetric links and no noise or physical obstacles in signal communication. Energy spending due to data aggregation and multi-hop data forwarding by the CH has been considered to get more realistic and practical result. We simulated the HEED clustering protocol and backup clustering scheme introduced in [10] called Backup_Cluster_[10] over HEED. Then, we implemented our proposed backup clustering scheme on top of HEED, and compared the network lifetime and reliability of our proposed scheme with HEED and Backup_Cluster_[10]. For a fair comparison, the network topologies, node distribution, node-energy distribution, channel propagation model and other simulation parameters have been kept identical across all protocols. Simulation is carried out by sensor network topologies with 200 sensor nodes. Each sensor node is uniformly distributed between the point (0,0) and (200,200). A node is considered “dead” if it has lost 99% of its initial energy. Simulation parameters are listed in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Cluster radius (range)	25 m
E_{elec}	50 nJ/bit
ϵ_{fs}	10 pJ/bit/m ²
ϵ_{mp}	0.0013 pJ/bit/m ⁴
E_{da}	5 nJ/bit/signal
E_{sw}	50 nJ/bit
Data packet size	100 bytes
Broadcast packet size	25 bytes
Packet header size	25 bytes

VI. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed backup clustering scheme using simulations. As a performance metric, firstly, we compare the network lifetime

of our single and multiple backup clustering schemes with HEED and Backup_Cluster_[10]. Secondly, we compare data loss ratio (DLR) for our proposed single and multiple backup clustering with HEED and Backup_Cluster_[10]. DLR is a ratio of the difference of total data sent by the sensor nodes and received at the base station to the total data sent by the sensor nodes, as given below:

$$DLR = \frac{TotalDataSent - TotalDataReceived}{TotalDataSent} \quad (7)$$

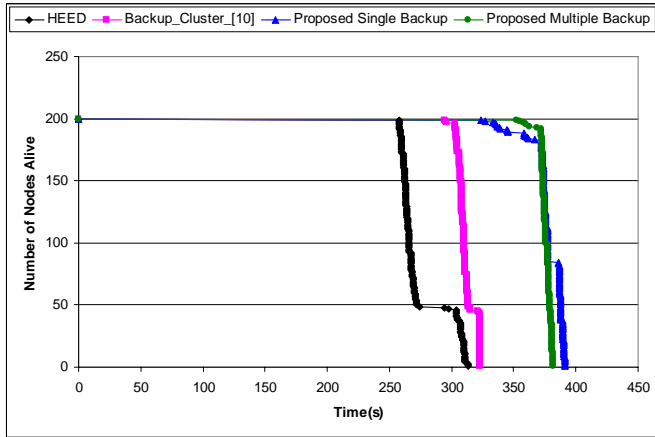


Fig. 4 Network lifetime using HEED vs. backup clustering schemes.

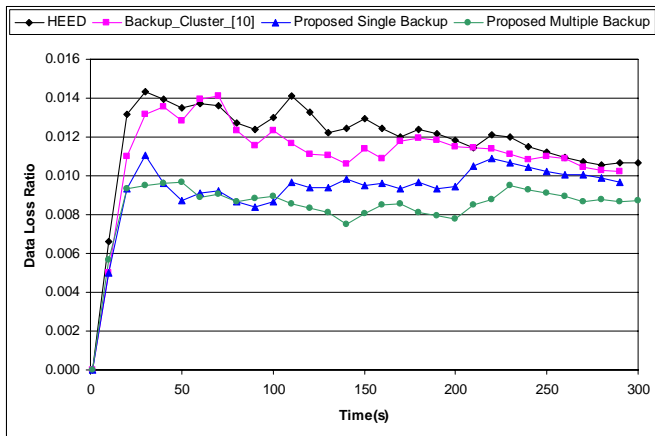


Fig. 5 Data loss ratio of HEED vs. backup clustering Schemes.

We implemented both our proposed backup clustering scheme and the backup clustering scheme as mentioned in [10] over HEED. Simulation results as shown in fig.4 demonstrate that network lifetime with our backup clustering scheme (both single and multiple BCHs) prolongs the network lifetime compared to HEED and [10]. Both first node and last node die earlier in HEED and [10] compared to our BCH rotation scheme. Fig.5 shows that DLR is less in our proposed backup clustering scheme compared to HEED and [10]. During the simulation, multiple backup CHs switching took place 2 to 5 times in each cluster. It is apparent from the simulation results that the proposed scheme has significantly increased the network lifetime in both cases (the time until the first node dies and the time until the last node dies) as

compared to the network lifetime of the HEED protocol. The proposed scheme increases the reliability of a network at the same time by reducing energy depletion of CHs and the frequency of network re-clustering. BCH information in our scheme is broadcasted by a single update message. Hence network traffic due to switching is very low compared to [10].

VII. CONCLUSION AND FUTURE WORK

In this paper, we propose an optimal backup cluster head scheme where the role of cluster head rotates among selected member nodes within the cluster for balanced energy dissipation. This scheme reduces energy consumption and time needed for frequent re-clustering and thus enhances the network lifetime and reliability. We combine rotation of CH role among nodes of a cluster with a suitable clustering algorithm. Simulation results confirm that by rotating the CH in cluster-based networks, the network lifetime can be increased and the network reliability can be improved as compared to those networks not using CH rotation or using existing backup cluster head selection scheme such as [10]. Our technique costs a single message exchanged among the nodes for seamless CH switching and performs better by quickly converging to a new topology.

Entire network re-clustering is not only a resource burden on the nodes, it is often very disruptive to the on-going operation. However, in backup clustering scheme sensed data of a particular cluster may be lost during its switching operation, however, rest of the network continue its regular data sensing and transmission operation. Therefore, our proposed scheme helps better monitor the field by avoiding loss of important data from the sensor. To get better performance goals and optimise use of energy it is necessary to reorganize the member nodes among clusters after CH switching. Therefore, for future work, we propose to extend the backup clustering technique to achieve evenly distributed sensors and equal-sized clusters.

REFERENCES

- [1] W. Heinzelman, A. Chandrakasan and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Transactions on Wireless Communication*, vol. 1(4), pp. 660-670, October 2002.
- [2] J. Kamruzzaman and S.M. Aziz, "A note on activation function in multilayer feedforward learning," Proc. Intl Joint Conf. on Neural Networks (IJCNN), pp. 519-523, Honolulu, USA, 2002.
- [3] T Imam, KM Ting, J Kamruzzaman, "z-SVM: An SVM for improved classification of imbalanced data," *Lecture Notes in Computer Science*, vol. 4304, pp. 264-273, 2006.
- [4] S. Bandyopadhyay and E. Coyle, "An Energy-Efficient Hierarchical Clustering Algorithm for Wireless Sensor Networks," *Proceedings of IEEE INFOCOM*, vol. 3, pp. 1713-1723, April 2003.
- [5] O. Younis, S. Fahmy, "HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Transactions on Mobile Computing*, vol. 3(4), pp. 660-669, 2004.
- [6] M. Ye, C. Li, G. Chen and J. Wu, "EECS: An Energy Efficient Clustering Scheme in Wireless Sensor Networks," *International Performance, Computing, and Communications Conference*, pp. 535-540, April 2005.
- [7] J. Yu, W. Liu, J. Song and B. Cao, "EEMR: An energy-efficient multi-hop routing protocol for wireless sensor networks," *IEEE/ACIS International Conference on Computer Systems and Applications*, pp. 291-298, March 2008.

- [8] K.T. Kim and H.Y. Youn., "PEACH: Proxy-Enable Adaptive Clustering Hierarchy for Wireless Sensor network", *Proceeding of The 2005 International Conference On Wireless Network*," pp. 52-57, June 2005.
- [9] K. T. Kim and H. Y. Youn, "Energy-Driven Adaptive Clustering Hierarchy (EDACH) for Wireless Sensor Networks," *Springer Berlin/Heidelberg*, vol. 3823, pp. 1098-1107, November 2005.
- [10] O. Younis, M. Krunz and S. Ramasubramanian, "Node Clustering in Wireless Sensor Networks: Recent Developments and Deployment Challenges," *IEEE Network*, vol. 20, pp. 20-25, May 2006.
- [11] T. Shu, M. Krunz and S. Vrudhula, "Power Balanced Coverage-Time Optimization for Clustered Wireless Sensor Networks," *International Symposium on Mobile Ad Hoc Networking & Computing*, pp. 111-120, May 2005.
- [12] S.U. Hashmi, H.T. Mouftah and N.D. Georganas, "Achieving Reliability over Cluster-Based Wireless Sensor Networks using Backup Cluster Heads," *IEEE Global Telecommunications Conference, GLOBECOM'07*, pp. 1149--1153, 2007.
- [13] Lee, H., Kim, K. and Youn, H. "A new cluster head selection scheme for long lifetime of wireless sensor networks", *Lecture Notes In Computer Science 3983, Springer*, 2006, pp. 519.
- [14] Shu, T., Krunz, M. and Vrudhula, S. "Power balanced coverage-time optimization for clustered wireless sensor networks," *MobiHoc*, 2005, pp. 111-120.
- [15] Ding, P., Holliday, J. and Celik, A. "Distributed energy-efficient hierarchical clustering for wireless sensor networks," Vol. 3560, Springer, 2005.
- [16] T. Rappaport, "Wireless Communication: Principles & Practice", *Prentice-Hall*, 1996.