Delay and Energy Optimization in Multilevel Balanced WSNs for Landslide Monitoring

Balaji Hariharan, Venkat P Rangan
Amrita Center for Wireless Networks and Applications,
Amrita School of Engineering,
Amrita Vishwa Vidyapeetham University
Kollam, Kerala, India
balajih@am.amrita.edu, venkat@amrita.edu

Simi Surendran, Rekha P, Arya Devi R.D, Maneesha Vinodini Ramesh
Amrita Center for Wireless Networks and Applications,
Amrita School of Engineering,
Amrita Vishwa Vidyapeetham University
Kollam, Kerala, India
{simisurendran,rekhap,aryadevird,maneesha}@am.amrita.edu

Abstract— **In most of the real world wireless sensor network deployments, the energy utilization is a critical factor as the nodes are battery powered. In most of the real-world deployments it is observed that the sensing subsystem consumes higher power. In order to extend the lifetime of such systems it is required to reduce the sensing energy than communication energy. We have deployed a system for monitoring Landslides in India consists of 150 geo-physical sensors and used solar panels to power these sensor nodes. The decision making in favor of Landslide occurrence is based on the maximum values obtained from the high priority sensors. As this maximum value is not frequently changing in the deployment, locating the sensor node with maximum value allows us to switch off the other sensors for a predetermined period of time. This work proposes an optimal balanced network topology for delay minimization by parallelizing data aggregation operation in each sub-network. The sensor node switch off schemes on the top of delay minimized topology enables the optimal utilization of the available solar power. The analysis of these mechanisms shows that, more number of nodes can be powered with the available source of energy and can increase the network life time**

Keywords— Wireless Sensor Network; Energy replenishing; Topology; Balanced networks

I. Introduction

Most of the Wireless Sensor Network (WSN) applications are energy constrained because of two major reasons: 1) The wireless sensor nodes are battery powered 2) It is not possible to change the batteries frequently, as the wireless sensor network may deployed in harsh environments. Hence in almost all application, there is a need to minimize energy utilization by the wireless sensor nodes and thereby increasing energy utilization. In this work, we have considered the WSN application for Landslide monitoring and detection.

Landslides are one of the major threatening natural disasters in India. We have deployed a wireless sensor network for the real-time detection of Landslides in Munnar, Kerala. It is operational from 2009 [1]. For detection of Landslides, this system uses sensors namely, Rain gauge, Dielectric moisture sensor (DMS), Pore pressure sensor, Geophone, Strain gauge and Tilt meter. These sensors integrated with wireless mote constitute a wireless sensor node in our Landslide detection system. Even if, these wireless sensor nodes are solar powered, during rainy seasons, this system experience severe power shortage. Hence optimizing the energy utilization of these wireless sensor nodes have a major impact on the operational efficiency of the system. The total energy consumption in wireless sensor network includes the energy utilization in sensing, transmission, reception and processing. From our analysis it is found that sensing requires more energy compared to all other energy utilization components. The system prioritizes the sensors based on the maximum of the sensed values. Identifying sensors which give maximum values allows to switch off least priority sensors for a predefined period of time. By minimizing the time for computing the maximum of the sensed value, we can switch off the sensors as early as possible. Increasing the OFF time of the sensor nodes contribute to the minimization of the overall network energy utilization.

In our Landslide detection system, a gateway node will collect the sensed data from the wireless sensor network and forward to the remote control station. This acts as a sink node in this network. The sink node may not be in the communication range of all the deployed wireless sensor nodes. Hence intermediate nodes are used to forward packets from the sensor nodes to the sink node. Based on the communication range, we need intermediate nodes in multiple levels. According to [3], the balanced network gives minimum delay for aggregate computation in a tree topology.

The organization of the paper is as follows: Section 2 deals with the works related to the topic. Section 3 and 4 discusses the delay optimization in balanced network topology and energy optimization using the switch off schemes respectively.

Section 5 deals with performance evaluation of the proposed optimization technique followed by conclusion in section 6.

II. RELATED WORK

A wireless sensor network for real time detection and early warning for rain induced landslide has been deployed in Munnar, Kerala[1]. This system consists of more than 150 geophysical sensors each powered by solar power. The main challenge faced by the existing system is to reduce power consumption. Unlike other sensor networks, it is observed that sensing subsystems consumes more power compared to the communication subsystem. An optimum sensor network topology that reduces the network delay named Balanced Sensor Networks has been discussed in the work [2]. Energy optimization using duty cycle control in WSN has been discussed in [3]. Efficient mechanisms for optimizing the energy consumption in link layer have been addressed in [4]. A set of algorithms which focus on the network structure to efficiently reduce the power consumption has been discussed in the works [5 6 7]. There exist several data aggregation techniques, which allow reducing the number of messages exchanging through the intermediate nodes. A set of in-network aggregation algorithms has been discussed in [8]. This technique combines the data received by the node from its neighbors in order to reduce packet length to be forwarded to the sink node. A tree based aggregation technique has been discussed in [9]. This method constructs tree with root node as sink and source nodes as leaves. Parent node aggregates the data from its leaves and sent to the higher level. Efficiency of this method depends on the way we constructs the tree.
Clustering based techniques for aggregating sensor data has been discussed in the work [10]. In this approach, the network can be divided into several clusters and cluster head aggregates the data from cluster members and forward to the sink node. There exist distributed clustering algorithms such as LEACH [11] also achieves energy consumption by the random election of cluster heads based on the balance energy consumption. In this work, we focus on the sensors that provide redundant information to put in an off state in order to save energy. Therefore all these existing TDMA and MAC protocols can't be used to achieve the same. Rezaei. et.al [12] discusses a set of duty cycling and data driven approaches for maximizing the network life-time by reducing the energy consumption. This work also discusses a set of communication protocols that achieves energy reduction by optimizing the MAC layer functionalities. The research work [13] proposes methods to effectively increase the network life-time by introducing data aggregation and traffic shaping in wireless sensor networks.

III. DELAY REDUCTION IN DATA AGGREGATION

Consider a multilevel balanced network in figure 1, where the sensor nodes are equally distributed among the first level intermediate nodes.
In this section, we discuss how the proposed balanced tree topology reduces delay in data aggregation. Computation of optimal number of children for each intermediate node including root node and optimal height of the balanced tree is derived to reduce the data aggregation delay. In each level, the intermediate nodes have equal number of sub-trees. Let T_{net} be the communication delay to forward packet from one node to next higher level node and T_{comp} is the delay for comparing two sensed values. We assume the T_{net} and T_{comp} values are same for all levels of the tree.
Lemma 1: For a network of any height (H) connecting N sensor nodes, in order to minimize the total delay of max computation, each intermediate node as well as the gateway node will have $\sqrt[H]{N}$ subtrees connected under it.

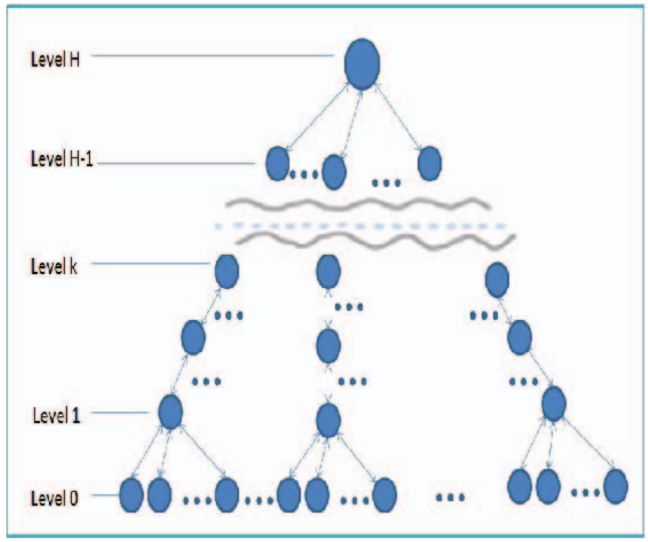

Fig.1. H-level optimal balanced network with N sensor nodes (leaf nodes)

Proof: Since any network with least delay must be horizontally balanced, let us assume x1 is the number of sensors connected to each intermediate node of level 1; similarly, let x2 be the number of subtrees connected to each intermediate node of level 2, …, and finally, xH be the number of subtrees connected to (root) gateway node at level H. The total number of sensor nodes, N, is given by:

$$N = x_1 \, x_2 \dots x_H \qquad (1)$$

The delay in the network is given by,

$$T_{max} = HT_{net} + (x_1 - 1)T_{cmp} + (x_2 - 1)T_{cmp} + \cdots + (x_H - 1)T_{cmp}$$

$$T_{max} = H(T_{net} - T_{cmp}) + (x_1 + x_2 + \cdots + x_H)T_{cmp} \qquad (2)$$

After substituting for x_H from Equation 2 in the above Equation 1 for T_{max}, we will end up with H-1 variables, to minimize which, we take the partial differential with respect to x1, x2…xH-1 and equate them to 0.

$$\frac{d}{d(x_1)}\left(x_1 + x_2 + \cdots + \frac{N}{x_1 x_2 \dots \dots x_{(H-1)}}\right) = 0$$

$$1 - \left(\frac{N}{x_1 x_2 \dots \dots x_{(H-1)}}\right) = 0$$

$$x_1^2 x_2 \dots \dots x_{(H-1)} = N$$

Similarly, after taking partial differential with respect to x_2 we get: $x_1 x_2^2 \dots \dots x_{(H-1)} = N$

Continuing with partial differentials 1 with respect to x_3, x_4, …, $x_{(H-1)}$, and solving, we get,

$$x_1 = x_2 = \cdots x_H = \sqrt[H]{N} \qquad (3)$$

Hence, an H-level network with $\sqrt[H]{N}$ sub trees connected to every intermediate node and the (root) gateway node yields the lowest delay for max computation.

Theorem 1: A (H-1) level network continues to yield the least possible delay for max value computation until the inequality $H\left(\sqrt[H]{N}-1\right) - (H-1)\left(\sqrt[H-1]{N}-1\right) \leq 1 - r_{nc}$ holds.

Proof

A single level network of N sensor nodes will have max computation delay given by Equation 4

$$T_{max}(single\ level) = (N-1)T_{cmp} + T_{net} \qquad (4)$$

The best possible two level network with the same number of nodes N will have max computation delay given by Equation 5

$$T_{max}(two\ level) = 2\left(\sqrt{N}-1\right)T_{cmp} + 2T_{net} \qquad (5)$$

For single level network to be better than two level,

$$T_{max}(single\ level) \leq T_{max}(two\ level)$$

$$(N-1)T_{cmp} + T_{net} \leq 2\left(\sqrt{N}-1\right)T_{cmp} + 2T_{net}$$

$N - 2\sqrt{N} + 1 \leq r_{nc}$, where $r_{nc} = T_{net}/T_{cmp}$

$$\left(\sqrt{N}-1\right)^2 \leq r_{nc}$$

$$N \leq \left(1+\sqrt{r_{nc}}\right)^2 \qquad (6)$$

Similarly for H level network to be better than H-1 level network

$$T_{max}(H\ level) \leq T_{max}(H-1\ level)$$

$$H\left(\sqrt[H]{N}-1\right)T_{cmp} + HT_{net} \leq$$

$$(H-1)\left(\sqrt[H-1]{N}-1\right)T_{cmp} + (H-1)T_{net}$$

$$H\left(\sqrt[H]{N}-1\right) - (H-1)\left(\sqrt[H-1]{N}-1\right) \leq 1 - r_{nc} \qquad (7)$$

When we are given N sensor nodes, the optimal height for generating a balanced network can be computed by solving the above equation. Take the height to be equal to floor (H) and fully populate the network in a horizontally balanced manner, starting with root node. Any residual numbers of sensor nodes are added one per sub tree starting bottom up at level 0, and then continuing upwards one level at a time until all sensor nodes are added to the network. Compute the total delay T_{max} for this network configuration. Next, construct an alternative network by taking the ceiling (H) and proceeding to complete the network in a manner similar to the above step. We get an alternative network configuration, whose height is one more than the network of step 1 above. Compute the total delay T_{max} for this network. Among the above two networks, choose the one that yields lower delay.

IV. Sensor Energy Optimization

In our wireless sensor network deployed for land slide detection, the energy consumption of sensing is much larger compared to the energy consumed during transmission, reception and processing. Hence the total energy utilization in the network is directly proportional to the time duration in which the sensor nodes are in ON state. By switching off suitable sensors based on their sensed values can significantly reduce the energy requirement. Here we propose three mechanisms to switch off the nodes to improve the life of the network. The switch of time the sensor nodes depends on the delay experienced in the data aggregation operation. Here we consider the computation of maximum value among all the sensed data as the data aggregation operation.

A. Broadcast based switch off scheme

Consider an H-level optimal balanced network, the number of nodes at each level is $\sqrt[H]{N}$. All sensor nodes in this network sense the physical parameter and forward it to the higher level nodes. Higher level nodes perform MAX value computation among its children and forward it to their higher level nodes that eventually reach the sink node. Sink node computes the maximum value among the sub-maximums and broadcast a message to switch off all the sensor nodes other than the one who sensed the maximum value. The MAX computation happens in H levels including sink in the H-level balanced network. The computation time at each level is $\left(\sqrt[H]{N}-1\right) T_{comp}$.

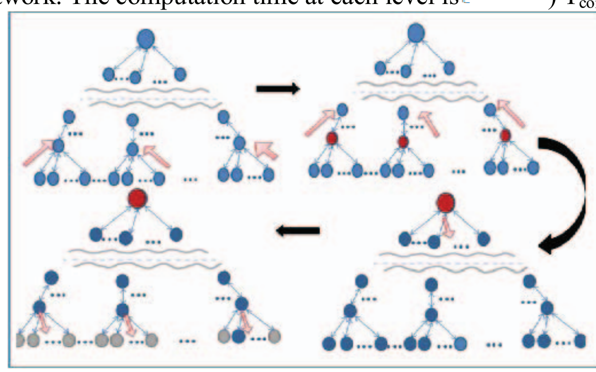

Fig.2. Network stages sink node broadcast switch off method

Hence the MAX computation time in H levels $= H\left(\sqrt[H]{N}-1\right) T_{comp}$. Propagation time for H level balanced network = H× T_{net}. The maximum time required for MAX value computation and propagation of messages from leaf to sink node is,

$$T_{max} = H\left[\left(\sqrt[H]{N}-1\right) T_{comp} + T_{net}\right]$$

After computing MAX value, the sink node will broadcast a switch off message to the sensor node at lower level with the computed max value. The lower level nodes check the MAX value and if it is different from its own sensed value, then go to sleep mode until next epoch.

$$T_{total} = H\left[\left(\sqrt[H]{N}-1\right) T_{comp} + 2T_{net}\right]$$

B. Level based switch off scheme

The sensor nodes at level 0 send the sensor measurement to the 1st level nodes. The MAX value is computed in the first level. After the MAX value computation the 1st level nodes send the MAX value to 2nd level nodes and send SWITCH OFF messages to all the level 0 nodes except the sensor node that measured MAX value. That means all the sensor nodes except one node will get the SWITCH OFF message and will go to sleep state. At each level this procedure continues till the global MAX value is computed in the sink node. After computing the global MAX value, the sink will send the SWITCH OFF message to all sensor nodes that are ON except the sensor node which has measured the global MAX value. We assume that the sensor nodes have unique identifiers. The SWITCH OFF message to lower level and the MAX value to the higher level nodes are send simultaneously. The network stages of this method are shown in figure 3.

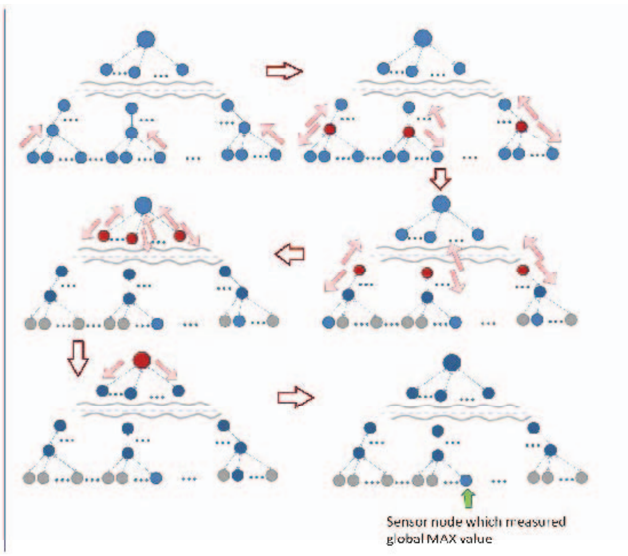

Fig. 3. Network stages in Level Switch off method.

Let N be the total number of sensor nodes at the level 0 and the optimal height of the balanced network be H. The level of the nodes can be represented as 'L' where it takes values from 0 to 'H'. Hence the sensor nodes are at the level L = 0 and the sink node is at the level L = H. After the MAX value computation in level L = 1, all the level 0 nodes, except $(\sqrt[H]{N})^{H-1}$ number of sensor nodes, will go to sleep state. Thus after the MAX value computation at the level L and after sending the SWITCH OFF message, $(\sqrt[H]{N})^{H-L-1} - (\sqrt[H]{N})^{H-L}$ sensor nodes will go to sleep state. The ON time of the sensors which will go to SLEEP state after sending the SWITCH OFF message at Level 'L' is given by,

$$T_{ON} = 2L \times T_{net} + L(\sqrt[H]{N}-1)\, T_{comp}$$

C. *Stay ON Messaging Scheme*

Assume the Balanced Network created for the Landslide detection is a synchronous network. Each node has a unique ID. The channel is ideal-no propagation effects are considered. All the basic assumptions hold for this method. In an H-level optimal balanced network, the number of nodes at each level is $\sqrt[H]{N}$.

This protocol has two rounds. In the first round, the communication happens from the leaf node to the sink. The leaf nodes sense the physical parameter and transmit it to the upper level nodes. After sending the message the leaf node will go to sleep state. In the higher level nodes the maximum value computation takes place and they will record the source and route of the messages. After the MAX computation the higher level nodes will enter into sleep mode. The path of the MAX value from the source to the destination will also propagated to the higher levels, thereby the sink will have the knowledge about the source of the MAX value and the path to reach the sensor node having MAX value. The inclusion of the path in the packet will increase the number of bytes to transmit and also the higher level nodes require sufficient memory for storing the path of all incoming data till the MAX computation. The network stages in the first round are shown in figure 4.

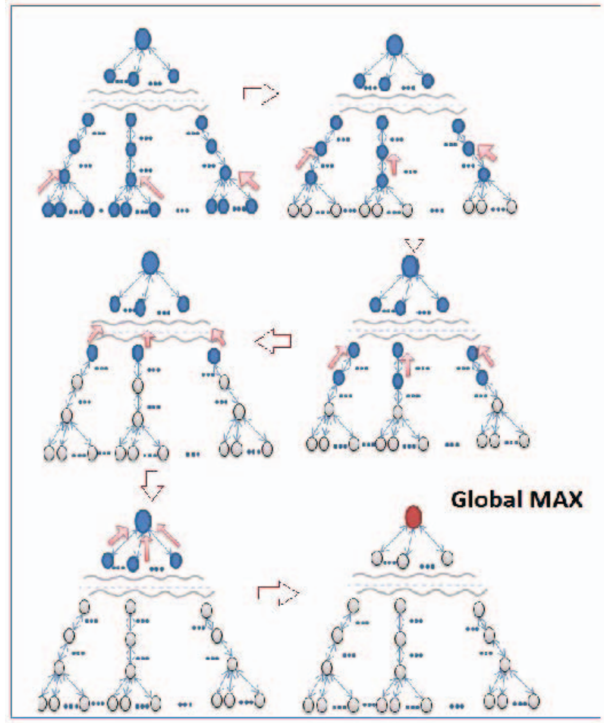

Fig. 4. Network stages in the first round.

The MAX computation happens in H levels including sink in the H-level balanced network. The computation time at each level is $(\sqrt[H]{N}-1)\, T_{comp}$. Hence the MAX computation time in H levels $= H(\sqrt[H]{N}-1)\, T_{comp}$. Propagation time for H level balanced network = H× T_{net}. The maximum time required for MAX value computation and propagation of messages from leaf to sink node is,

$$(T_{max})_{total} = H[(\sqrt[H]{N}-1)\, T_{comp} + T_{net}]$$

The sensor nodes will go to sleep mode after it measured the physical parameter and sent it to the upper level nodes. Hence the maximum time the sensor nodes are in sleep mode in the first round is, $(T_{sleep})_1 = (T_{max})_{total}$.

In the second round, the sink node will send a STAY-ON message to the sensor node at lower level having the MAX value. The STAY-ON message keeps the sensor node ON until the start of the next iteration. The sensor node in the lower level (0^{th} level) of the network will switch to active mode only when the STAY-ON message arrives at the 1^{st} level of nodes from the H^{th} level sink node. The maximum time taken to reach the STAY-ON message at 1^{st} level nodes, $(T_{sleep})_2 = (H-1) \times T_{net}$. Hence the total sleeping time of the sensor node is given by the equation,

$$(T_{sleep}) = H[(\sqrt[H]{N}-1)\, T_{comp} + T_{net}] + (H-1) \times T_{net}$$

After the STAY-ON message reached at the lower level node, all the other sensor nodes will go to sleep mode. The network stages in the second round are shown in the Figure 5. The active mode duration of the sensor nodes,

$$T_{active} = \delta + T_{net}$$

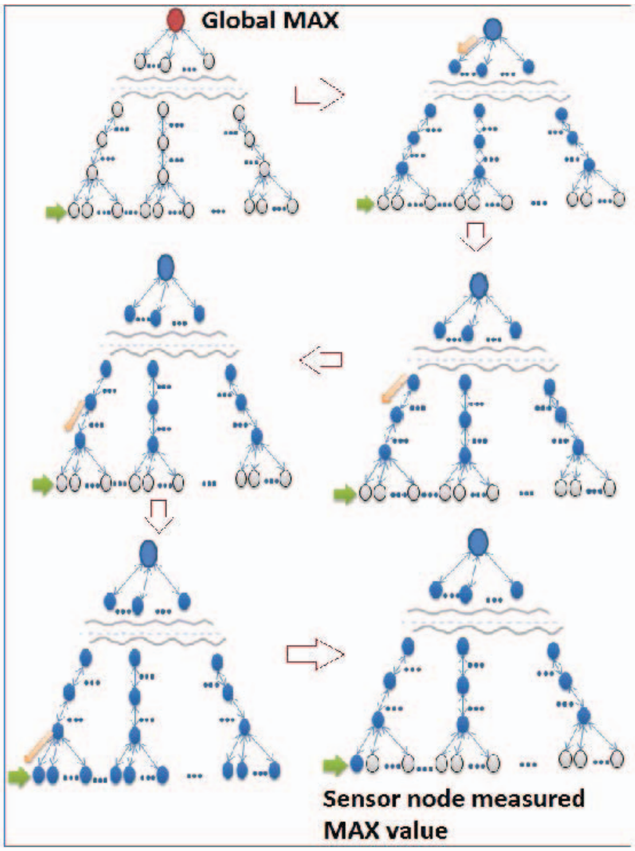

Fig. 5. Network stages in the second round.

V. PERFORMANCE EVALUATION

For analyzing the performance of the balanced topology and the node switch off schemes, we assume that the network delay in all links is uniform. The transmission delay, T_{net} is taken as 4.6 ms which includes the time for transmitting the packet over the air and the time for receiving the packet at destination node based on zigbee stack [14]. Here we use the computational delay, T_{comp} as 1.1 ms which includes time for extracting the data from the packet and the time for max value computation. We assume an epoch time of 100 ms which is divided into ON time and OFF time for the sensor nodes.

Our wireless sensor network deployment for landslide detection in Munnar consists of 150 sensor nodes and it is powered using solar panels. Thus the total available solar energy for our WSN deployment is 777.6 mWh. Each sensor node and its interfacing circuit need 655mW. Without using any node switch off schemes, we can power up to 80 nodes per day using available energy source. Figure 6 shows the remaining energy of the source with different network size.
From the analysis it is found that we can power 150 sensor nodes for half a day. In the switch off scheme specified in section 4.1, in order to switch off the nodes, sink node is broadcasting a message after maximum value computation. All nodes are in ON state until the broadcast message reaches leaf nodes. In each epoch, all nodes will be in ON state up to the time Ton and go to sleep state till the end of that epoch.

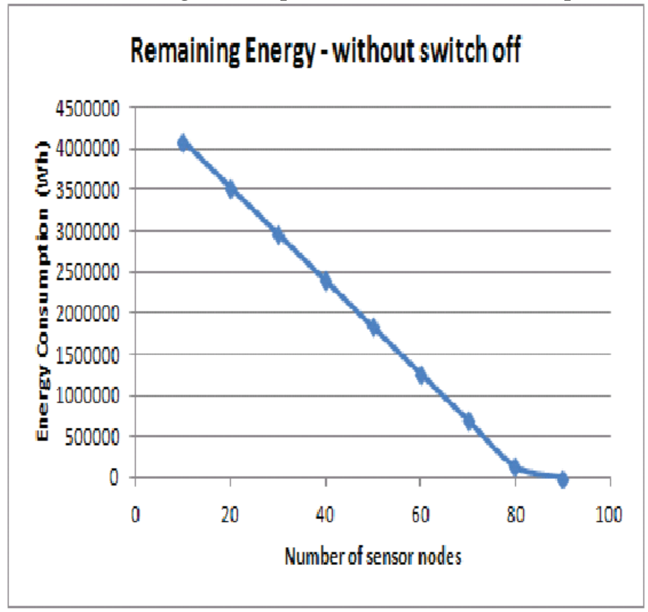

Fig. 6. Remaining Energy graph without switch off scheme

Figure 7 shows the variation in the remaining energy of the source in a day with different network sizes. Using this scheme, we can power up to 150 nodes per day.

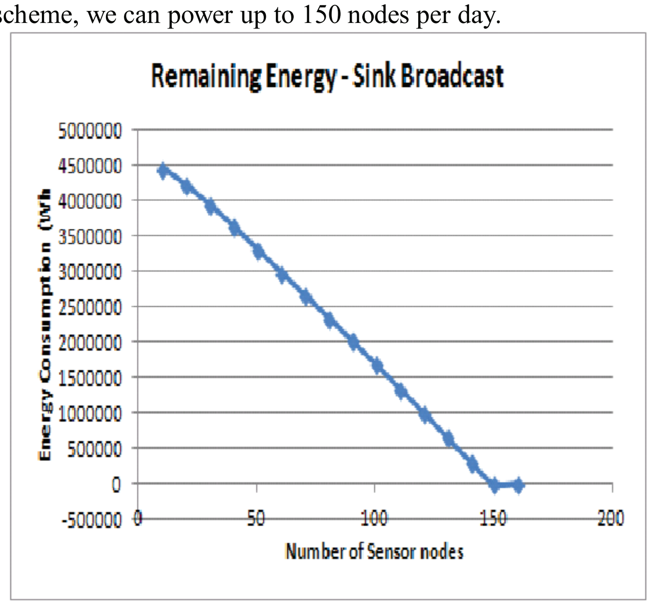

Fig. 7. Remaining Energy with sink broadcast

In the level switch off method, after one level transmission, only $\sqrt[H]{N}$ number of nodes will be in ON state. Figure 8 show that, this scheme enables us to power 650 nodes per day. This can improve the operational time of the network from half a day to 4 days using the same available energy.
In the Stay ON method, all sensor nodes except the node giving max value will be on for a fixed period of time in each epoch. Figure 9 shows the variation in remaining energy of the source with increased network size. Using this method we can power up to 900 nodes and the operational time of the network improved to 6 days.

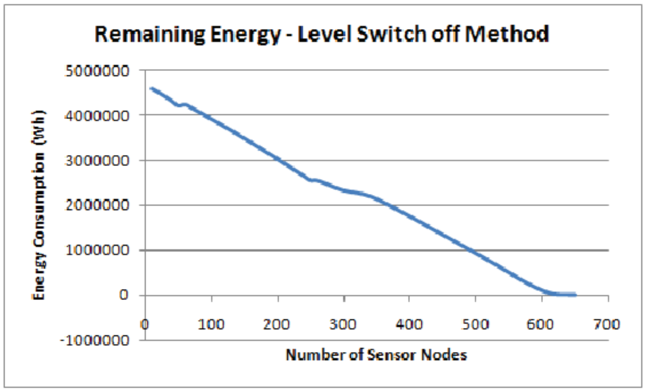

Fig. 8. Remaining Energy Level Switch off Method

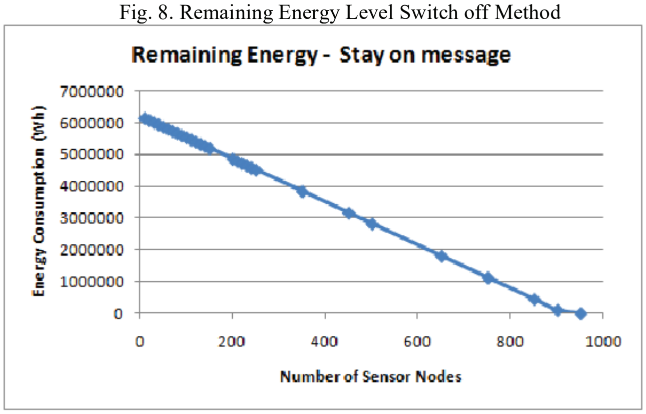

Fig. 9. Remaining energy - stay on message

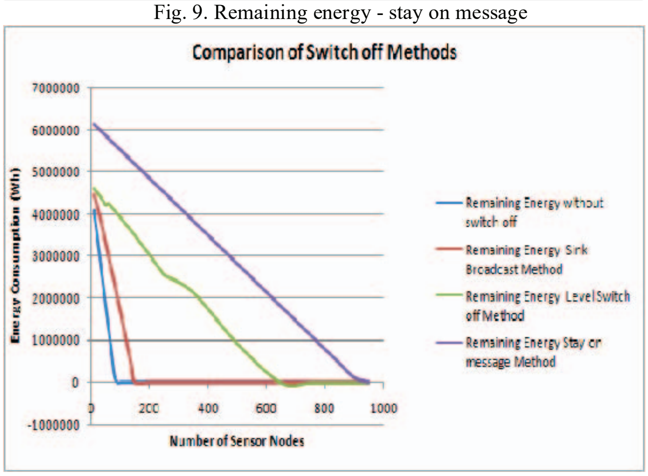

Fig. 10. Comparison of Remaining Energy

The comparison of the three energy optimized network with the one without any sensor node switch is shown in figure 10. It clearly indicates that with the balanced topology with the node switch off schemes improve the lifetime of the wireless sensor network.

VI. Conclusion And Future Work

One of the major constraints in the large scale deployment of wireless sensor nodes is the effective utilization of available source of energy. This paper proposed a delay minimization and energy optimization scheme for wireless sensor network for landslide detection. Delay minimization in data aggregation operation is achieved through the balanced network topology. In order to reduce the energy consumption of sensor nodes, node switch off methods based on the delay function has been implemented. Reducing the delay in data aggregation resulted in the increase of the sleep period of the sensors and hence achieved a reduction in energy consumption. The analysis of results showed that the proposed balanced topology and the three switch off schemes improved two to twelve times the life time of the network. Currently, we are in the process of deploying the wireless sensor network for monitoring Landslides in Himalayan regions. In future, we try to minimize the packet size and optimize the sensor interfacing circuits.

Acknowledgment

We would like to express our immense gratitude to our beloved Chancellor Sri Mata Amritanandamayi Devi (AMMA) for providing the motivation and inspiration for doing this research work. The authors would also like to acknowledge the contributions of Mr. Sangeeth Kumar and many other colleagues and friends as well.

References

[1] Maneesha Vinodini Ramesh, Design, development, and deployment of a wireless sensor network for detection of landslides, International Journal of Wireless & Mobile Networks (IJWMN) Vol. 4, No. 3, June 2012 DOI : 10.5121/ijwmn.2012.4314 205

[2] Kamalanathan Kandasamy, Sreedevi A G, P Venkat Rangan and Maneesha V Ramesh , Node Failures, Data Aggregation Delay And Its Impact On Power Optimization In Balanced Sensor Networks, 2012.

[3] M. Yilmaz, “Duty cycle control in wireless sensor networks,” A Thesis Submitted to the Graduate School of Natural And Applied Sciences Of Middle East Technical University, September 2007.

[4] R. K. Rajgopal Kannan and S. S. Iyengar, “Energy and rate based mac protocol for wireless sensor networks,” SIGMOD Record, vol. 32, pp. 46 – 55, December 2003.

[5] K. Akkaya and M. Younis, “A survey on routing protocols for wireless sensor networks”, Elsevier Ad Hoc Networks 3 (2005) 325–349.

[6] N. H. A. Ababneh, “Energy efficient topology control algorithm for wireless sensor networks,” A thesis submitted at The University of Sydney, vol. 1, pp. 1–177, November 2008.

[7] J. W. Fonda, “Energy efficient wireless sensor network protocols for monitoring and prognostics of large scale systems,” A Dissertation Presented To The Faculty Of The Graduate School Of The University Of Missouri-Rolla, vol. 1, pp. 10 – 211, 2008.

[8] E. Fasolo, M. Rossi, J. Widmer, and M. Zorzi, “In-Network Aggregation Techniques for Wireless Sensor Networks: A Survey”, IEEE Wireless communication 2007

[9] M. Lee and V.W.S. Wong, “An Energy-aware Spanning Tree Algorithm for Data Aggregation in Wireless Sensor Networks,” IEEE PacRrim 2005, Victoria, BC, Canada, Aug. 2005.

[10] K. Dasgupta, K. Kalpakis, and P. Namjoshi, “An Efficient Clustering-based Heuristic for Data Gathering and Aggregation in Sensor Networks”, IEEE 2003.

[11] Wendi Rabiner, Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan, “Energy-efficient Communication Protocol for Wireless MicrosensorNetworks”,In: Proc. of 33rd Annual Hawaii Inter Cord on System Sciences, Hawaii, USA: IEEE Computer Society, 2000.

[12] Z. Rezaei, S. Mobininejad, “Energy Saving in Wireless Sensor Networks”, International Journal of Computer Science & Engineering Survey (IJCSES) Vol.3, No.1, February 2012.

[13] C. Schurgers, M.B. Srivastava, “Energy Efficient Routing in Wireless Sensor Networks”, MilComm2001, IEEE.

[14] Chester Kim and Peder Rand, “Z-Stack Duty Cycle Analysis ", Application Note AN114