

Energy Efficient Model for Data Gathering in Structured Multiclustered Wireless Sensor Networks

Jinran Chen, Shubhalaxmi Kher, Arun K. Somani
Dependable Computing and Networking Lab
Iowa State University
Ames, IA 50010
{jrchen, shubha, arun}@iastate.edu

Abstract

Recent rapid development in wireless sensor networks has enabled their application to surveillance systems both in civil and military area. We develop two energy efficient data gathering models achieving higher reliability in a structured multiclustered topology. Such models are developed for power transmission line monitoring systems and can also be employed for high way speed monitoring systems. The local homogeneous sensor nodes are grouped together to form clusters and a special processing and relaying node is designated to be responsible for communication among local groups. The goal is to achieve uninterrupted monitoring over a long time using power constrained sensor nodes as the replacement of battery is a major issue in an application like power transmission line. Comparison of the two models shows that the two level communication model consumes less power and is more suitable than single level communication model in the power transmission line monitoring systems.

1 Introduction

Advances in VLSI technology have enabled the development of low-cost wireless sensor networks. Wireless sensor networks may consist of hundreds, and potentially thousands of tiny sensor nodes. These sensor nodes, such as MICA motes, have the capability of collecting various measurements such as light, sound, acceleration, magnetism, and temperature [4]. They can be used in various application areas, such as environment and habitat monitoring, ecophysiology, condition-based equipment maintenance, disaster management, and emergency response[5][6][7].

As the networked sensor nodes become smaller and cheaper, they have the potential to be embedded in all consumer devices, in all vehicles, or deployed in continuous monitoring environment [10]. However, the constraints of the sensor nodes, such as limited power, limited computation capability, poor internode communication, limited network bandwidth, and limited storage, have to be taken into considerations when deploying large sensor networks and these problems are not trivial. In this paper, we focus on the issues of collecting data in an application where the application environment dictates that the sensor nodes be deployed in a clustered mode and these cluster communicate with each other using a topology such as a linear chain.

The lifetime of a sensor network primarily depends upon the power consumption of sensor nodes [3] [9] [10] [11]. Our goal is to perform the desired computation and schedule communication to balance the ratio that minimize the power consumption. Data transmission accounts for a large share of power consumption. Sensing and signal processing consume a consistent amount of power[1]. At physical layer, energy efficiency of wireless communication can be achieved by lowering radio duty cycles and dynamic modulation scaling [9]. Energy is wasted at the MAC layer due to collision, control packets overhead and idle listening. Sensor network specific MAC protocols have been developed to reduce power consumption by alleviating the sources of energy waste [11]. Research have been carried out at the network layer to develop routing protocols to prolong the lifetime of the network, for instance, LEACH (Low-Energy Adaptive Clustering Hierarchy)[3]. Some techniques at data management level, such as sampling, prediction, approximation, power-based query optimization, and data centric storage, can be used to reduce the power consumption. In-network processing or data aggregation is another way to help alleviate the problem [10].

In many sensor networks, sensor nodes are distributed randomly in the designated area to gather information to be sent back to the base station for further processing. However, in certain applications, the application dictates that the sensor nodes be deployed in a linear/sub-linear chain manner. For example, as depicted in Fig. 1, sensors are installed on power towers to detect any unusual events in a power transmission line and inform the control center if any significant information is collected. Similarly, sensor nodes can be distributed along the highway to conduct speed monitoring task and these sensors are also forming a linear chain topology. Most research focus on the randomly distributed sensor nodes. Linear/sub-linear chain based sensor networks have different characteristics from these randomly distributed networks. This paper addresses the issues of this type of network. We assume that sensors at a particular location are to be treated as a cluster and information flow is then restricted among the neighboring clusters.

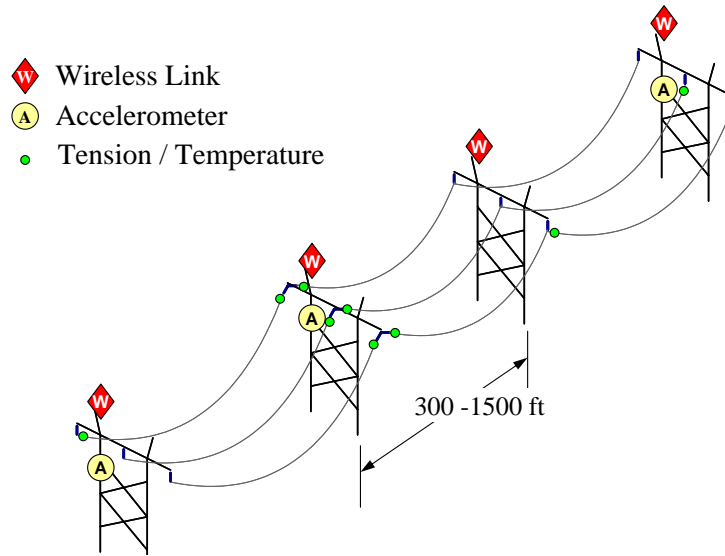


Figure 1. Power Transmission Line Monitoring Using Sensors

The remainder of this paper is organized as follows: Section 2 describes the network model, energy consumption model, and states the problems we address in this work. We present two different models as the single level and two level communication models in Section 3. The analysis of these models is given in Section 4. Section 5 includes the analytical results. Finally, we conclude the paper in Section 6.

2 Models and Issues

2.1 Network Model

For the power transmission line monitoring system as depicted in Fig. 1, we consider sensors distributed on the tower for measurement of various parameters. These sensors carry out only measurements and extract information out of the collected data. They are termed as low end sensors. On each tower, we also propose to deploy one expensive processing and relaying node (PAR node) to form the backbone of the multiclustered topology. A local group consists of one such node and a group of low-end sensors surrounding it as shown in Fig. 2. The group of sensor nodes are further divided into several clusters.

Sensors in one cluster are within the transmission range of each other. Thus every sensor can hear all other sensors in its own cluster. We assume that the distance between two local groups are too long for low-end nodes of the two groups to communicate with each other directly. Therefore, they have to use PAR node as the gateway to

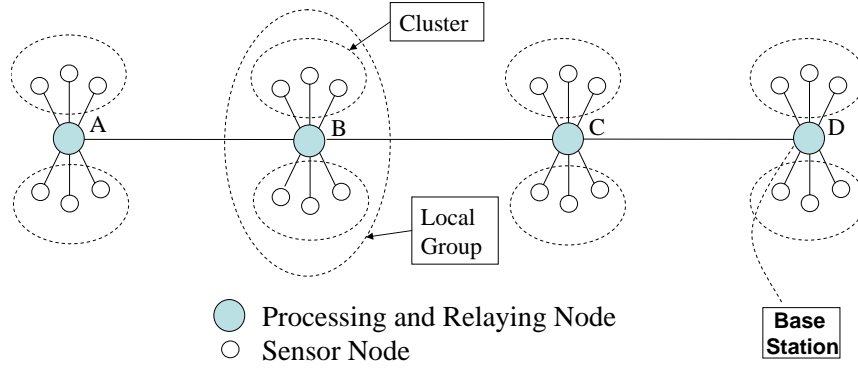


Figure 2. Structured Multiclustered Wireless Sensor Networks

realize data processing and data transmission over the long distance. The end user gets the information collected from the sensors in the network via the PAR nodes. Although the PAR nodes are powerful nodes, their transmission range is still limited. We assume they can only communicate directly with their left and right neighboring PAR nodes along the path. For example, in Fig. 2, PAR node B in the middle can only send or receive data from its left or right neighboring nodes A or C directly.

The lifetime of such a structured multiclustered sensor networks is defined as the time elapsed until the first local group in the network fails. A local group failure occurs only when the PAR node fails (due to energy depletion or physical failure) or the cluster nodes fail to send messages to the PAR node.

2.2 Sensor's Energy Model

We use the same energy model as discussed in [12]. In this model, a typical sensor node consumes energy in communication, computation, and sensing processes. The key energy parameters for communication are energy/bit used by the transmitter electronics (α_{11}), energy dissipated in the transmit op-amp (α_2), and energy/bit used by the receiver electronics (α_{12}). With the assumption of a $1/d^n$ path loss, the energy consumed is:

$$E_{tx} = (\alpha_{11} + \alpha_2 d^n) * r \quad (1)$$

$$E_{rx} = \alpha_{12} * r \quad (2)$$

where E_{tx} and E_{rx} are the energy consumed to send and receive r bits respectively. α_{11} and α_{12} are the energy dissipated in transmitter and receiver electronics per bit (50 nJ/bit). α_2 is the energy dissipated for the transmitter

amplifier (100 pJ/bit/m²). d is the message transmitting distance and r is the number of bits in the message. We assume that the radio channel is symmetric and thus the energy used to send a data packet from node A to node B is the same as the energy consumed to transmit from node B to node A.

Besides the energy dissipated during the communication process, energy is consumed during the computation process as well. We used the following formula to calculate the power consumption in data processing (P_p):

$$P_p = CV_{dd}^2f + V_{dd}(i_s e^{qV/kT} - 1) \quad (3)$$

where C is the total load capacitance; V_{dd} is the voltage swing and f is the switching frequency; i_s is the reverse saturation current; V is the diode voltage; q is electronic charge ($1.602 \times 10^{-19}C$); k is Boltzmann's constant ($1.38 \times 10^{-23}J/K$); T is temperature. The second term determines the current leakage power loss.

We assume a constant energy (α) is consumed to sense one bit. The total energy consumed in sensing r bits is:

$$E_{sensing} = \alpha_3 * r \quad (4)$$

3 Our Protocol

We develop two application specific protocols based on a structured topology for monitoring systems. The aim is to reduce the power consumption of the sensors in the system so that the lifetime of the network can be prolonged as replacement of the sensor nodes/battery is a major concern in a field application. The two protocols employ sensor nodes and PAR nodes for sensing, processing, and relaying of information in a structured multiclustered topology.

3.1 Cluster Head Selection

We use an easy way as discussed in [3] to choose the cluster head in both models. Each member of a cluster selects a random number between 0 and 1. If the number is larger than a system predefined value, the member node becomes the cluster head. If there are more than one nodes competing to be the cluster head of the same group of cluster nodes, then one with the highest energy wins. This can be done through message exchanging. If no node chooses a number higher than threshold, they choose again until cluster head is selected. After the cluster head selection, the cluster head creates a schedule for all cluster nodes to wake up, sense and transmit data.

3.2 Cluster Formation

Each cluster head broadcasts an advertisement message to members of the cluster. Energy consumption for advertisement message for each cluster head is assumed to be same. The members decide which cluster they belong to based on received signal strength of the advertisement. This costs cluster members minimum energy in communicating with the head with strongest advertisement signal strength because we assume symmetric propagation channel.

3.3 Single Level Communication Approach

At the tower, we consider two types of nodes, low-end sensors geographically close to each other forming clusters and one PAR node acting as a processing and relaying node. The PAR node is assumed to have additional processing and power capability as compared to the low-end nodes. This single level communication model is shown in Fig. 3. The sensor nodes (referred as members) in the cluster gets the schedule from the cluster head for waking up, sensing and relaying the data to the cluster head which processes information for all the members and relays it to the neighboring nodes. This relaying continues from one tower to the neighboring tower until it reaches the base station. The PAR node's functions include data aggregation and relaying messages from its neighboring cluster nodes.

The members detect different parameters required by the end users and send them to the PAR node in the local group. The simplest way for the data delivery from sensor nodes to the end user is to let members transmit data to the PAR nodes and each PAR node communicates directly with the end user. However, this direct method wastes the sensors' energy due to collision and redundant data transmission. To conserve energy, a cluster head is chosen randomly in each cluster. The selected cluster head broadcasts its status to the members of the cluster and creates a schedule for all the members including the head node itself. Members can send data directly to the PAR node during the allocated transmission slots only. The radio component is turned off for each member when they do not transmit data. Also, the scheduler, schedules each member either to sleep, wake up and/or sense, send the data. In this way, energy is conserved. Fig. 3 shows the local cluster for each tower composed of a cluster head and a PAR node along with members in a cluster.

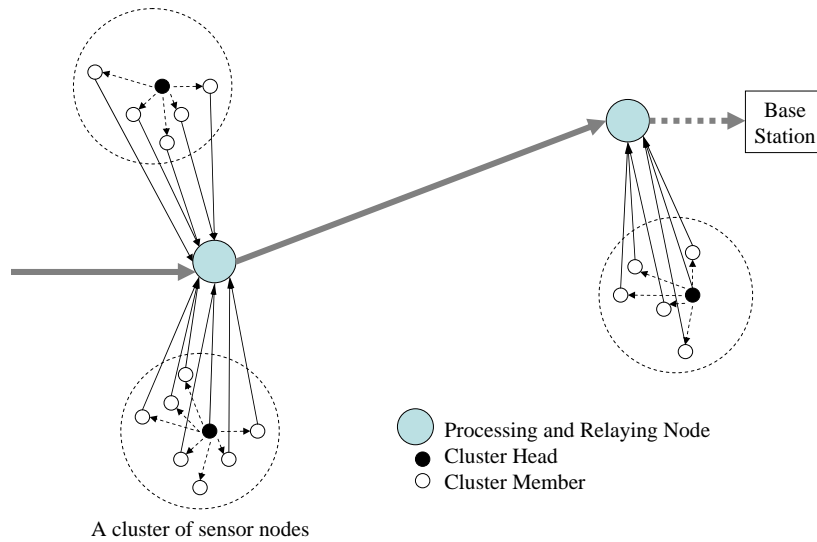


Figure 3. Single Level Communication Model

3.4 Two Level Communication Approach

The difference between the single level and two level model lies in the data relaying within the cluster. In the earlier model, the cluster head only schedules the members and bears no responsibility of gathering data from all the members and the associated processing. All members send data directly to the PAR node where as in this model, members communicate only with the cluster head and cluster head communicates with the PAR node. In other words, processing and transmitting overhead for the cluster head is less. However, the PAR node has two fold functions: processing of data from all members of the cluster and relaying it over the linear chain. Although the processing and relaying node is a high-end powerful node, it is still constrained by energy. In the two level approach, the data gathering is done at the cluster head thereby the processing overhead at the PAR node is reduced.

In the two level hierarchical approach, each member sends messages to its cluster head. This two level hierarchical model is shown in Fig.4. Apparently the cluster head consumes more power in this model than in the single level communication model. Therefore, we want to distribute energy usage evenly among the members in the cluster by rotating the cluster head responsibilities among the cluster members. After the cluster is formed and cluster head is selected, cluster members will send their data during their allocated transmission time to the elected cluster head. After each node in the cluster finishes transmission in its turn, the cluster head will aggregate data and send composite signal the processing and relaying node.

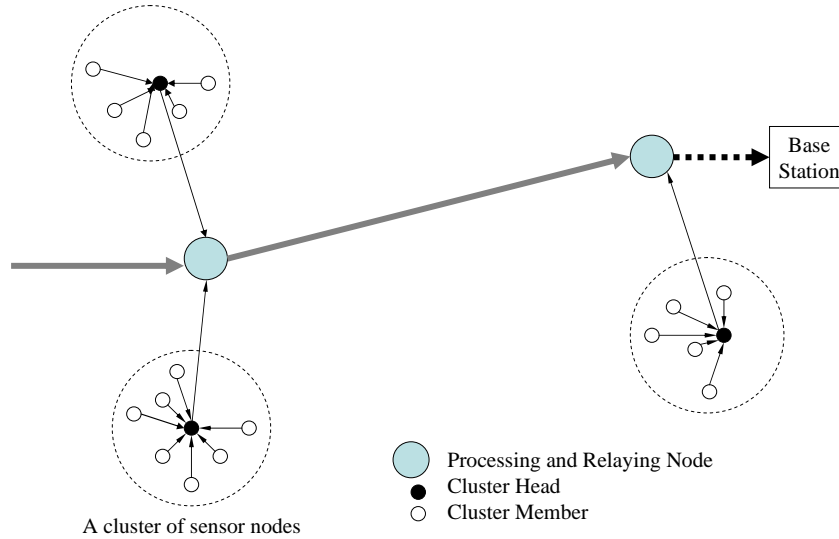


Figure 4. Two Level Communication Model

4 Model Analysis

Given the two models described above we investigate the power consumption profile of the sensor nodes, the cluster head and the PAR node. In each state the power consumption can be defined using power consumption equations. In other words, we can determine the profile of the sensor energy level using the time it spends in each of the states. The sensor node is in one of the three states: inactive, sensing and receiving, transmitting. Similarly, the head node can be in four states: inactive, receiving, processing, and transmitting. PAR node can be in any of the states: inactive, sensing and receiving, processing, and transmitting. Each of the nodes depletes energy continuously till it dies. Thus we can model it as a continuous time Markov model considering discrete states as mentioned above. First, we analyze single level communication model using Markov chain process. Then, we discuss the analysis of two level communication model.

4.1 Single level communication model analysis

In the single level communication model, the cluster head is selected at the beginning of the set up process. The cluster head schedules the members in the cluster once. After scheduling the cluster head behaves identical to other member in the cluster. The schedule for data transmission is created and broadcast to all the other sensor nodes by the cluster head. Because this process may happen only once during the lifetime of a sensor, therefore, we can ignore the power consumption needed for scheduling. In other words, cluster head and the members can be

considered the same for modeling in the state space. A member can be in any one of the following states: inactive, sensing and receiving, and transmitting.

State S_1 : (inactive state) In the inactive state, sensors turn off their sensing and communication circuitry. The power dissipation is minimum and only due to current leakage. Thus, from equation (3) power loss in sleep state can be given by;

$$P_{sleep} = V_{dd}(i_s e^{qV/kT} - 1) \quad (5)$$

State S_2 : (wake up, sensing and receiving) When a node wakes up and starts sensing the target, it is in sensing and receiving state. Power dissipation in this state is due to sensing and receiving data. By combining Equation (4) and Equation (2) together, we can get the total power consumed in this state as;

$$E_{sr} = \alpha_{12} * r_1 + \alpha_3 * r_2 \quad (6)$$

where r_1 and r_2 are the number of bits received and sensed respectively. Since the head node schedules the transmission slots for the cluster nodes, there will not have any collision within the cluster. But collision could occur with nodes in other clusters. In this case, nodes need to contend for the channel. However, if each cluster communicates using different CDMA codes, this type of interference can be reduced and no contention could happen.

State S_3 : (Transmitting) In transmitting state, the node sends message to the processing and relaying node. When the sensor node is in transmitting state, power is consumed to transmit data. the power consumption can be given by (1), $E_{tx} = (\alpha_{11} + \alpha_2 d^n) * r$.

Assume the sensor starts in inactive state, after some time, it wakes up and senses the environment in state S_2 . After collecting data, it tries to transmit data immediately. If it succeeds in occupying the medium, it transits to S_3 , otherwise, it will wait for the elapse of backoff time. We assume different clusters use different CDMA codes so collision will not occur in this case. After the allocated time period elapses the node again resumes state S_1 . While in S_3 either a successful transmission occurs or it fails. If it fails then the nodes waits for the next round to wake up.

Fig. 5 shows the state transition for the cluster member nodes in the single level communication model.

For the PAR node an additional state, processing state is required to model its behavior. The state transition diagram for the PAR node is given in Fig. 6.

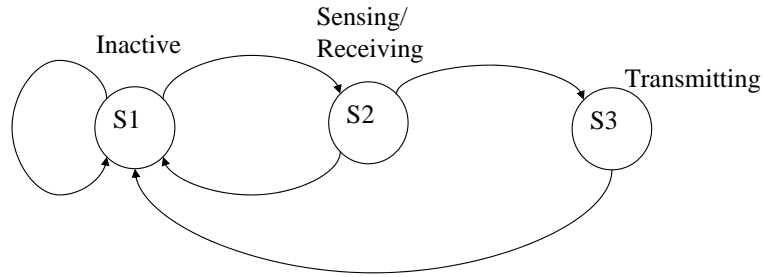


Figure 5. State Transition Diagram for Cluster Members

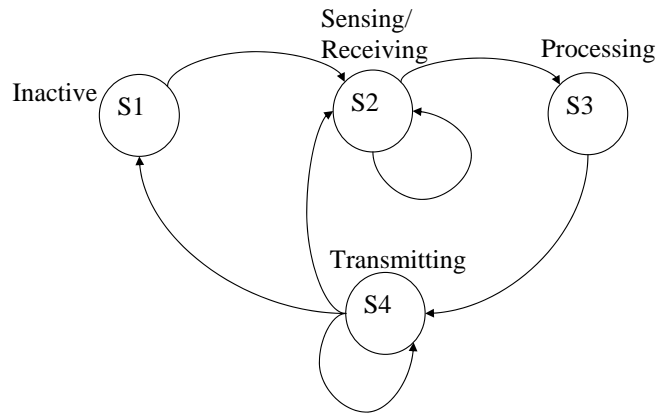


Figure 6. State Transition Diagram for Processing and Relaying Node

Equation (3) can be used to calculate the energy consumed in this processing state. PAR node has a very low probability to remain inactive.

4.2 Two-level Communication Model analysis

The cluster member nodes in the two-level communication model behave similar to cluster member nodes in single level communication model. We can use the same state transition diagram to model them. Their energy consumption can also be calculated the same way as in single level communication model.

The behavior of head node can not be treated the same as cluster head as in single level communication model. The reason is that head node consumes more power than cluster members due to data aggregation and relaying. Power consumed in the process of determining the head node can not be ignored in this model since this process happens much more often than that in single level communication model. State transition diagram for the cluster head is shown in Fig. 7. Calculation of energy consumption for different states remains the same as in single level

communication model. Equation (5) is used for inactive state, Equation (2) is used for receiving state, Equation (3) is used for processing state, and Equation (1) is used for transmit state.

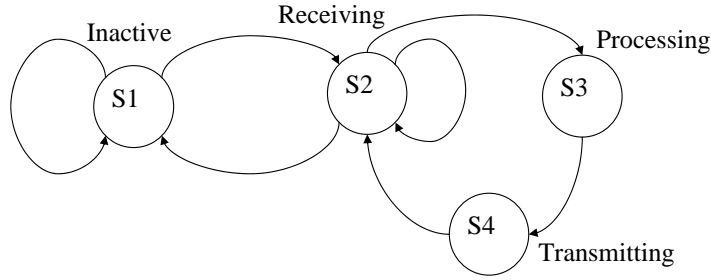


Figure 7. State Transition Diagram for Cluster Head for Two-level Model

For the PAR node, its behavior is the same as in single level communication model. We can apply the same Markov chain to analyze these nodes.

5 Results

In this section, we present our analytical model and theoretical analysis results.

5.1 Single Level Approach

We consider the state transition diagram for each sensor node.

5.1.1 Member node & cluster head

For the member nodes in our single level communication model, the state transition matrix is given by :

$$\mathbf{M} = \begin{pmatrix} p_{11} & p_{12} & 0 \\ p_{21} & 0 & p_{23} \\ p_{31} & 0 & 0 \end{pmatrix}$$

$$p_{11} + p_{12} = 1;$$

$$p_{21} + p_{23} = 1;$$

$$p_{31} = 1;$$

$$0 \leq p_{11}, p_{12}, p_{21}, p_{23}, p_{31} \leq 1.$$

Denote $p_{s_1}^m, p_{s_2}^m, p_{s_3}^m$ as the probability of finding a node in the state s_1, s_2 , and s_3 at a given time t . Let $\mathbf{p}^m(t) = [p_{s_1}^m(t), p_{s_2}^m(t), p_{s_3}^m(t)]$ represent the set of steady state probabilities. The state probabilities for the node at time $t + 1$ are given by $\mathbf{p}(t + 1)^m = \mathbf{p}^m(t)\mathbf{M}$. The steady state probability vector for a member node is, $\mathbf{p}^m(t + 1) = \mathbf{p}^m(t) = \mathbf{p}^m$. Using the above equation we can find the steady state probability of a member node.

5.1.2 PAR node

State transition matrix for the PAR node in single level communication model is given by,

$$\mathbf{M} = \begin{pmatrix} 0 & p_{12} & 0 & 0 \\ 0 & p_{22} & p_{23} & 0 \\ 0 & 0 & 0 & p_{34} \\ p_{41} & p_{42} & 0 & p_{44} \end{pmatrix}$$

$$p_{12} = 1;$$

$$p_{22} + p_{23} = 1;$$

$$p_{34} = 1;$$

$$p_{42} + p_{44} = 1;$$

$$0 \leq p_{12}, p_{22}, p_{23}, p_{34}, p_{42}, p_{44} \leq 1.$$

This matrix can also be used to calculate the steady state probability vector for the PAR node in our Two-level Hierarchical Model. Denote $p_{s_1}^r, p_{s_2}^r, p_{s_3}^r, p_{s_4}^r$ as the probability of finding a processing and relaying node in states, s_1, s_2, s_3, s_4 , let $\mathbf{p}^r(t) = [p_{s_1}^r(t), p_{s_2}^r(t), p_{s_3}^r(t), p_{s_4}^r(t)]$. Then, we obtain the steady state probability vector, $\mathbf{p}^r(t + 1) = \mathbf{p}^r(t + 1) = \mathbf{p}^r$.

5.2 Two Level Approach

The member node state diagram is same as in the single level communication model. The difference lies in the cluster head modeling and the PAR node.

5.2.1 Cluster head

For the cluster head node in the Two-level Hierarchical Model, the state transition matrix is given by;

$$\mathbf{M} = \begin{pmatrix} p_{11} & p_{12} & 0 & 0 \\ p_{21} & p_{22} & p_{23} & 0 \\ 0 & 0 & 0 & p_{34} \\ 0 & p_{42} & 0 & 0 \end{pmatrix}$$

$$p_{11} + p_{12} = 1;$$

$$p_{21} + p_{22} + p_{23} = 1;$$

$$p_{34} = 1;$$

$$p_{42} = 1;$$

$$0 \leq p_{11}, p_{12}, p_{21}, p_{22}, p_{23}, p_{34}, p_{42} \leq 1.$$

Denote $p_{s_1}^h, p_{s_2}^h, p_{s_3}^h, p_{s_4}^h$ as the probability of finding a PAR node in states, s_1, s_2, s_3, s_4 respectively, let $\mathbf{p}^h(t) = [p_{s_1}^h(t), p_{s_2}^h(t), p_{s_3}^h(t), p_{s_4}^h(t)]$. Using the state transition probabilities, we obtain the steady state probability vector, $\mathbf{p}^h(t+1) = \mathbf{p}^h(t+1) = \mathbf{p}^h$.

5.3 Power Consumption Issues

From Section 4, we have the power consumption of each node in each state. Denote λ_{s_i} as the power consumption in state i . For each node, total power consumption is $\sum_i^n \lambda_{s_i} p_{s_i}$, where n is the number of states a node can stay in. The total power consumption of cluster member nodes in the system for both models is:

$$\lambda_{\text{member nodes}} = \sum_{i=1}^3 \lambda_{s_i} p_{s_i}^m \quad (7)$$

The total power consumption of PAR nodes in the system for both models is:

$$\lambda_{\text{PAR nodes}} = \sum_{i=1}^4 \lambda_{s_i} p_{s_i}^r \quad (8)$$

The total power consumption of cluster head nodes in the system for Two-level Hierarchical Model is:

$$\lambda_{\text{head nodes}} = \sum_{i=1}^4 \lambda_{s_i} p_{s_i}^h \quad (9)$$

Finally, the total power consumption for each model can be stated as follows:

$$\lambda_{\text{single-level}} = \sum_{i=1}^n \lambda_{\text{member nodes}} + \sum_{j=1}^m \lambda_{\text{PAR nodes}} \quad (10)$$

where n is the total number of cluster nodes and m is the total number of PAR nodes.

$$\lambda_{\text{two-level}} = \sum_{k=1}^l \lambda_{\text{head nodes}} + \sum_{i=1}^n \lambda_{\text{member nodes}} + \sum_{j=1}^m \lambda_{\text{PAR nodes}} \quad (11)$$

where l, n, m are the total number of cluster head nodes, member nodes, and PAR nodes respectively.

Our analysis is based upon preliminary assumptions on transition probabilities of the sensors. Steady state probabilities for the sensor node are found to be [0.7153, 0.1431, 0.1416]. It shows that at any given time, the probability of sensor node to be in sleep state is highest. Fig. 8 shows the power consumption for each local group, which consists of one PAR node and some cluster nodes. As shown in this figure, the power consumption of the single level communication model is consistently higher than that of the two level communication model. In both models, the power is linear to the number of the nodes in the local group. The more nodes in the cluster, the more power they will consume.

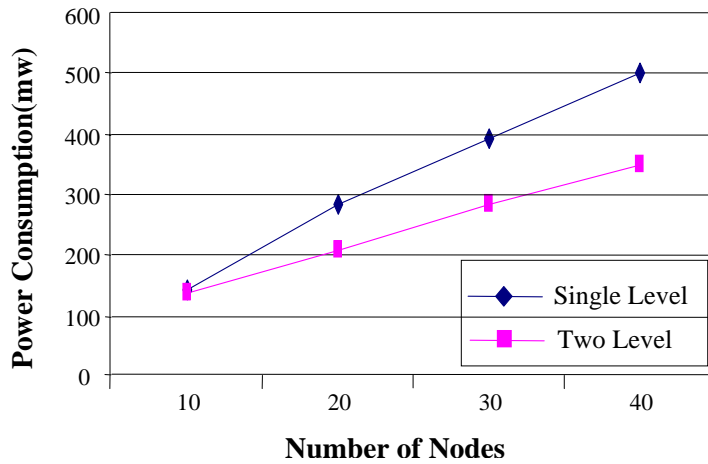


Figure 8. Power Consumption of Local Group

6 Conclusion

In this work, we developed single level and two level communication models for data gathering in a structured multiclustered sensor networks. This type of sensor network could be applied in environment, high way, or power transmission line monitoring systems. Our objective is to minimize the power consumption in the overall networks. We used CTMC(Continuous Time Markov Chain) to analyze the two models and found that two level communication model performed better than single level communication model in terms of total power consumption in a local group. The power consumption for the head node in single level approach is identical to the member nodes whereas in the two level approach it is much higher. Power consumption for the PAR node is higher in single level approach than that in two level approach. We can easily extend our results to the whole sensor network by summing the power consumption of all the local groups.

Future work can be done to extend the model to take into account some aspects that have not been addressed in this work. For example, the end-to-end delay issue, connectivity issue, and coverage issue need to be considered. An error model could be added in the Markov analysis process in future study.

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