Overlapped Layers for Prolonging Network Lifetime in Multi-Hop Wireless Sensor Networks

Hongyan Wang[1], Mei Yang[1], Yingtao Jiang[1], Shupeng Wang[2], Laximi Gewali[3]

[1]*Department of Electrical and Computer Engineering*
[3]*School of Computer Science*
University of Nevada, Las Vegas, NV 89154
[2]*Institute of Computing Technology, Chinese Academy, Beijing, P. R. China*

Abstract

In this paper, the bottleneck problem in PRMC-based wireless sensor networks is studied. This problem can be solved by overlapping neighboring layers. By this way, more cluster head candidates are available for each layer and the intra-cluster communication energy can be reduced, which ultimately helps prolonging network life time. Through analysis and numeric results, the reasonable overlapped ranges are decided such that the energy consumption among the cluster heads of different layers is balanced. Simulation results with the selected overlapped ranges confirm that overlapping neighboring layers balances the energy consumption among cluster heads of different layers and prolongs network life time.

1. Introduction

Wireless sensor networks have been proposed as a practical solution for a wide range of applications due to their benefits of low cost, rapid deployment, self-organization capability, and cooperative data-processing [1]. Many applications, such as military surveillance and habitat monitoring, require the deployment of large-scale sensor networks (with the number of sensor nodes in the order of hundreds or thousands, or even millions) in a large geographic area.

For large-scale sensor networks, the previous research shows that clustered structure [2][12] and multi-hop routing [5][6] achieve better energy efficiency. In [9], a highly scalable and fault-tolerant network architecture, named as the Progressive Multi-hop Rotational Clustered (PMRC) structure is presented, which is suitable for the construction of large-scale wireless sensor networks. In the PMRC structure, sensor nodes are partitioned into layers according to their distances to the sink node. A cluster is composed of the nodes located in one layer and the cluster head in the upper layer closer to the sink node. The cluster head is responsible for forwarding data to its upstream layers. However, when cluster heads cooperate with each other to forward their data to the sink node, the cluster heads closer to the sink node are burdened with heavy relay traffic and tend to die early, which reduces network coverage and causes network partition. We refer this problem as the *bottleneck* problem.

Similar problem has been considered in some research work. In [5], the authors point out that the concentration of data traffic towards a small number of sensor nodes closer to the sink node threats the network lifetime. They propose to let the sink node be mobile such that the nodes close to it change over time. In [9], an unequal clustering model is proposed to balance the energy consumption of cluster heads in heterogeneous multi-hop wireless sensor networks where cluster heads are deterministically deployed at some pre-computed locations. In [3], an Energy-Efficient Unequal Clustering (EEUC) mechanism is proposed to partition the sensor nodes into unequal-sized clusters such that clusters closer to the sink node are expected to have smaller cluster sizes. Thus they will consume lower energy during the intra-cluster data processing, and can preserve some more energy for the inter-cluster relay traffic. A similar problem of unbalanced energy consumption among cluster heads also exists in single-hop sensor networks. The Energy Efficient Clustering Scheme (EECS) [11] is proposed to produce clusters of unequal size in single-hop networks.

However, the existing schemes cannot be directly applied to solve the bottleneck problem in the PMRC structure. To solve this problem, in this paper, we propose to use overlapped layers to balance the relay load at the cluster heads for all layers.

The rest of the paper is organized as follows. Section 2 describes the overlapped layers. Section 3 gives the analysis and numeric results. Simulation results are presented in Section 4. Section 5 concludes the paper.

2. Overlapped Layers for PMRC Structure

In a PMRC structure, sensor nodes are partitioned into layers according to their distances (calculated using hop counts) to the sink node. A cluster is composed of the nodes located in one layer and within the transmission range of the cluster head, which is responsible for forwarding data to its upstream layers. Note that the cluster head is also part of another cluster in an upper layer. In this way, the data is always forwarded to nodes closer to the sink, which guarantees the routing will follow the path with the lowest cost.

The bottleneck problem in the PMRC structure is described as follows. In the PMRC structure, the traffic is more concentrated as the cluster heads are closer to the sink node. It is easy to see that the cluster heads closest to the sink node are burdened with the heaviest traffic load which will deplete their batteries very quickly. When these cluster heads run out of batteries, the network is partitioned. Unfortunately, it is difficult to find replacing cluster heads due to the lack of candidate nodes in the range of the original clusters. The result is that the sink node has no way to collect data any more even though a large part of the network is still alive. The life time of the whole network is limited by the life time of these bottleneck nodes.

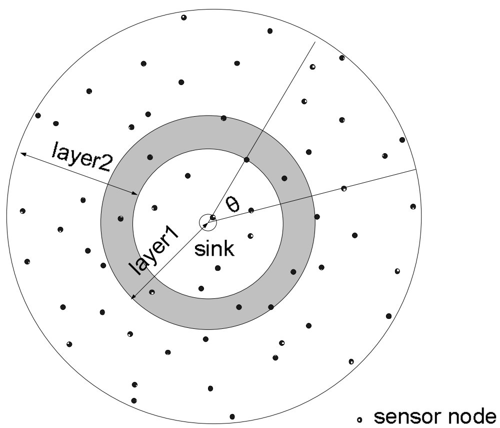

Figure 1 Overlapped layers in a PMRC-based sensor network.

The bottleneck problem in the PMRC structure can be solved through overlapping neighboring layers. Fig. 2 illustrates the idea using a PMRC-based sensor network with two layers in a circular area. The sink node is located at the center of the circular area. As shown in the figure, layer 1 occupies a circular area and layer 2 is shown in a ring shape. The grey area indicates the overlapped area of layer 1 and layer 2. Note that the sensor nodes in the grey area still belong to layer 1 while they are the candidate cluster heads for clusters in layer 2. Enlarging the overlapped area will increase the number of cluster head candidates for clusters in layer 2. By this way, more replacing cluster heads can be found from these candidate nodes. In addition, by overlapping layers, the size of the clusters formed in layer 2 tends to be smaller, which will save the energy consumed in intra-cluster communication. Ultimately, the network life time can be prolonged.

When more than two layers exist in the network, the overlapping between other adjacent layers is also needed. However, overlapping layers may increase the number of layers in the network, which may increase the data delay experienced from the sending node to the sink node. In next section, we will analyze the effect of overlapped layers in average energy consumption and justify the appropriate overlapped ranges.

3. Analysis

3.1 Analysis of Average Load

Without loss of generality, we assume the sensor nodes are distributed uniformly with density ρ in a circular area and the sink node is located at the center of this circular area. The circular area can be partitioned into a set of subareas, each one composed of the clusters formed in consecutive layers. As shown in Fig. 2, each subarea can be represented as a fan shape with angle θ.

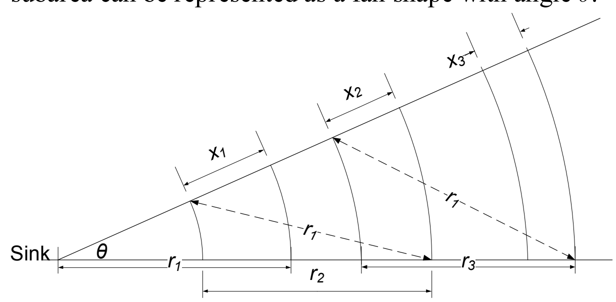

Figure 2 Top view of three overlapped layers.

In this analysis, we only consider the energy consumed in data transmission and receiving, which dominates the overall energy consumption of each node [3]. Assume that all the nodes may send data and there is no data aggregation at all layers.

We use *load* of a node to represent the energy used by the node in transmitting and receiving data. Given that the energy that can be used for each node is limited, higher load will shorten the life time of a node.

The following notations will be used in the analysis.

R: diameter of the circular area.

r: transmission/sensing ranges of all nodes. And r is assumed to be much smaller than R.

n: maximum number of layers in the sensor network area.

ρ: sensor node density.

θ: angle of the fan shape.

ε: the energy needed for a sensor node to send a unit of data.

$\beta*\varepsilon$: the energy needed for a sensor node to receive a unit of data.

L_i: the average load of head nodes at layer i ($1 \le i \le n$) located in the overlapped area of layers i and i+1.

r_i: the range of the ring shape of layer i, where $r_1=r$.

x_i: the overlapped range between layer i and layer i+1.

Fig. 2 shows the relation among r_1, r_2, r_3, x_1, x_2, and x_3 within a fan shape with angle θ.

Consider the cluster head candidates in the overlapped area of layer 1 and layer 2 in Fig. 2. The energy consumed by these nodes consists of two parts:

1) E_r: the energy consumed for receiving the data relayed through layer 2, which is composed of the data collected from all layers outside of layer 1;

2) E_t: the energy consumed to send the data collected at layer 1and the data relayed through layer 2.

And E_r and E_t can be derived as:

$$E_r = (R^2 - r_1^2)\rho\beta\varepsilon\theta / 2,$$

where $(R^2 - r_1^2)\theta / 2$ gives the area outside of layer 1.

$$E_t = (R^2 - (r_1 - x_1)^2)\rho\varepsilon\theta / 2.$$

Therefore, L_1 can be derived as:

$$\frac{(R^2 - (r_1 - x_1)^2)\rho\varepsilon\theta / 2 + (R^2 - r_1^2)\rho\beta\varepsilon\theta / 2}{(r_1^2 - (r_1 - x_1)^2)\rho\theta / 2}$$

For simplicity, we normalize the value of r_1 as 1. Assume $R=n*r_1$, then we get $R=n$. Thus L_1 can be derived as:

$$L_1(x_1) = \frac{(n^2 - (1 - x_1)^2) + \beta(n^2 - 1)}{(2 - x_1)x_1}\varepsilon \qquad (1)$$

We then derive L_2 as follows. To find out the area in the overlapped area of layer 2 and layer 3, we need calculate r_2, which can be obtained by geometry relation as

$$r_2(x_1, \theta) = \sqrt{1 - (1 - x_1)^2 \sin^2\theta} - (1 - x_1)(1 - \cos\theta) \qquad (2)$$

Then we get

$$L_2(x_1, x_2, \theta) = \frac{(n^2 - (1 + r_2 - x_1 - x_2)^2) + \beta(n^2 - (1 + r_2 - x_1)^2)}{(2(1 + r_2) - 2x_1 - x_2)x_2}\varepsilon \qquad (3)$$

We then derive r_3 and L_3 as follows.

$$r_3 = (x_1, x_2, \theta) = \sqrt{1 - (1 + r_2 - x_1 - x_2)^2 \sin^2\theta} - (1 + r_2 - x_1 - x_2)(1 - \cos\theta) \qquad (4)$$

$$L_3(x_1, x_2, x_3, \theta) = \frac{(n^2 - (1 + r_2 + r_3 - (x_1 + x_2) - x_3)^2) + \beta(n^2 - (1 + r_2 + r_3 - (x_1 + x_2))^2)}{(2(1 + r_2 + r_3) - 2(x_1 + x_2) - x_3)x_3}\varepsilon \qquad (5)$$

Generally, we have,

$$r_n(x_1, x_2, \ldots, x_{n-1}, \theta) = \sqrt{1 - (\sum_{i=1}^{n-1}(r_i - x_i))^2 \sin^2\theta} - (\sum_{i=1}^{n-1}(r_i - x_i))(1 - \cos\theta) \qquad (6)$$

$$L_n(x_1, x_2, x_3, \ldots x_n, \theta) = \frac{(n^2 - (\sum_{i=1}^{n}(r_i - x_i))^2) + \beta(n^2 - (\sum_{i=1}^{n}(r_i - x_i) + x_n)^2)}{(2(\sum_{i=1}^{n}(r_i - x_i)) + x_n)x_n}\varepsilon \qquad (7)$$

Ideally, the network lasts the longest time when the life time of the cluster heads at each layer is balanced. That is to say, balance between all loads (L_i's) is preferred, i.e., $L_1=L_2=\ldots=L_n$. The optimal value for each overlapped range x_i can be obtained by solving this equation. However, this equation is too complex to solve. In the following, the numeric results for L_1, L_2, and L_3 are shown, which helps justify the appropriate overlapped range values.

3.2 Numeric Results for L_1, L_2, and L_3

Assume that β=0.7, ε=1.0, n=5, ρ=1.0, then we can calculate the numeric values of L_1. Fig. 3 shows L_1's values vs. x_1, which shows L_1 is decreasing when x_1 increases. And L_1 decreases dramatically when $x_1 \leq 0.4$. That is to say that, the larger the overlapped range between layers 1 and 2, the less average load of the cluster head nodes in layer 1. However, larger overlapped range will increase the number of layers (e.g., when x_1=1, layers 1 and 2 are completely overlapped). Considering the trend shown in the figure, a moderate x_1 value between 0.4 and 0.6 is good enough to achieve significant improvement in L_1.

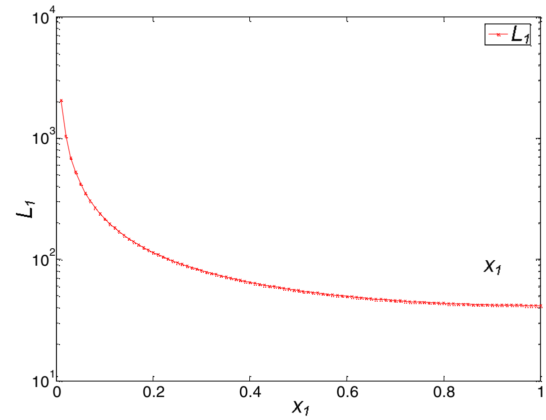

Figure 3 L_1 vs. x_1.

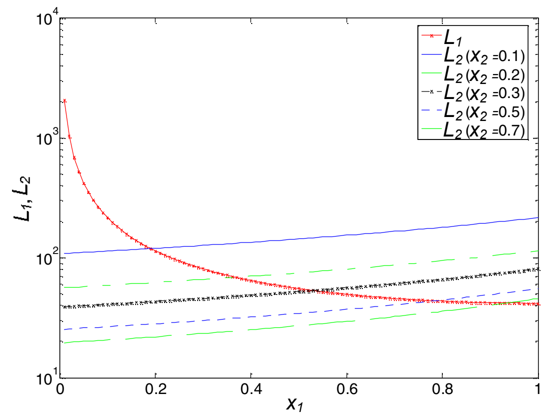

Figure 4 L_2 vs. x_1 and x_2.

To calculate L_2, we assume θ=27°, a moderate fan angle. Fig. 4 shows the values of $L_1$and L_2 vs. x_1 for five x_2 values. It is clear that L_2 is increasing when x_1 increases and decreasing when x_2 increases. Refer to the reasonable range of x_1 (0.4~0.6), a balance between L_1 and L_2 is picked at the crossing point when x_1 is about 0.5 and x_2 is about 0.3.

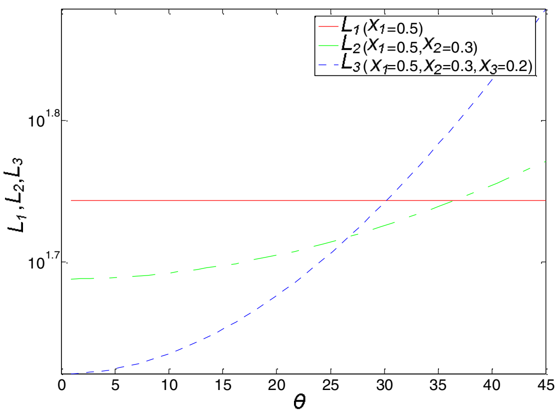

Figure 5 L_1, L_2, and L_3 vs. x_1, x_2, x_3, and θ.

Then, by fixing x_1 = 0.5 and x_2 =0.3, Fig. 5 shows the values of L_1, L_2, and L_3 vs. θ. The figure shows that both L_2 and L_3 are increasing when θ increases. To achieve a balance among L_1, L_2, and L_3, θ=27° and x_3 =0.2 are selected. Following this trend, x_i = 0.1 is decided for i>3.

4. Performance Evaluation

To evaluate the performance of the proposed overlapped scheme, simulations of PMRC with overlapped layers have been conducted on OPNET Modeler network simulator [7] and compared with PMRC without overlapped layers. The simulation model developed in [10] is adopted here and the overlapped scheme is implemented on it.

4.1 Simulation Settings

In the simulation, we assume a 200*m*x200*m* geographical area covered by a network with the sink node located at the center. All the sensor nodes are uniformly distributed in the network. The energy model for data transmission and receiving in [4] is used here. Generally, the transmission energy is decided by the packet length and the distance of transmission and the receiving energy is purely related to the packet length. Tab. 1 shows some basic parameters used in all simulations.

We consider the following performance metrics:

- *Average packet latency*. The latency of a packet includes the delay on each hop, which is composed of the delay on transmission and receiving, the propagation delay, as well as the processing delay on each node.
- *Average energy consumption per packet*. The energy consumption per packet is calculated over all the hops that a packet traverses, including the energy spent on transmission and receiving.
- *Time to first node death*. In our simulations, we only consider the node death due to drained energy. In general, this metric reflects the worst node life time.
- *Time to network partition*. The time to network partition is defined as the time instance when the network is no longer connected due to node failure, i.e, when there is a node cannot find its cluster head.

Table 1 Basic simulation parameters.

Parameter	Value
Sensor field area	200*m* x 200*m*
Node number (N)	{400, 600, 800}
Radio transmission range (R_t)	{20, 40, 60, 80}*m*
Initial energy per node	0.3*J*
Maximum buffer size	1000 packets
Channel bandwidth	1*Mbps*
Processing speed at each node	10*Mbps*
Packet generation rate	1*pkt/s*
Simulation time	Until network partition

In the following, we present the simulation results of the above performance metrics for four different scenarios: 1) PMRC (without overlapped layers) as the baseline; 2) PMRC with overlapped layers with x_1 = 0.5 (i.e., other layers have no overlaps); 3) PMRC overlapped layers with x_1 = 0.5 and x_2 =0.3; 4) PMRC overlapped layers with x_1 = 0.5, x_2 =0.3, and x_3 =0.2. For all scenarios, only one cluster head is selected for each cluster. And in all simulations, the same set of nodes evenly distributed in the most outward layer is selected to sense the data and generate the packets.

4.2 Performance with Different Transmission Range

Figs. 6-9 present the performance metrics of the four scenarios for the number of sensor nodes N=400. Fig. 6 shows that under the same transmission range (R_t), the scenarios of overlapped layers have more average packet latency than the baseline and more overlapped layers yield more delay. This is consistent with our intuition that more overlapping layers will generate more layers, which leads to more packet latency. Fig. 6 also shows that the average packet latency for all scenarios decrease with R_t increasing. The reason is that with R_t increasing, the number of layers in the network is decreased, hence reducing the average hop count and the delay.

Fig. 7 shows the average energy per packet of all scenarios vs. transmission range. Generally, more overlapped layers cause more average energy per packet as the number of layers is increased with more overlapped layers. And the average energy per packet is decreased for $R_t \leq 40m$ due to less number of hops traversed, but it is increased for $R_t \geq 60m$ as higher transmission energy is needed for larger R_t's.

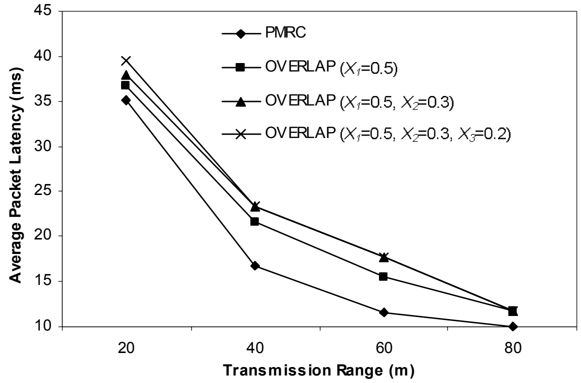

Figure 6 Average packet latency vs. R_t.

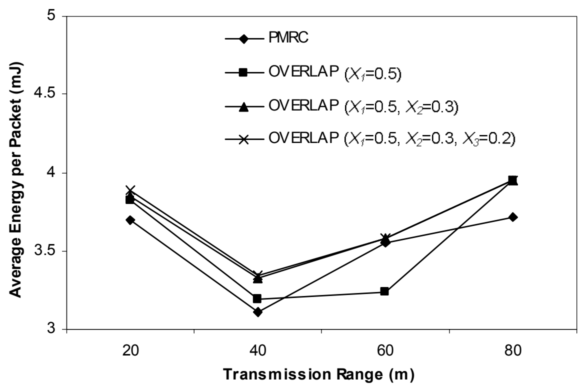

Figure 7 Average energy per packet vs. R_t.

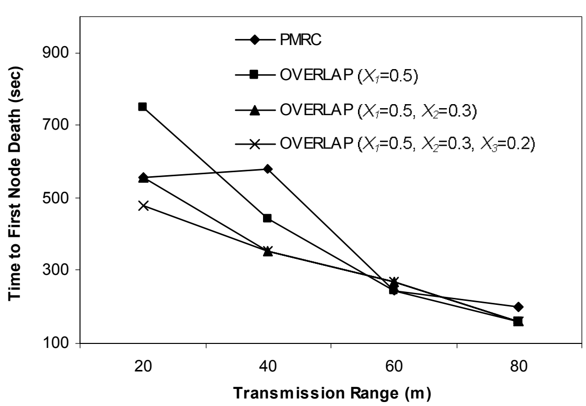

Figure 8 Time to first node death vs. R_t.

Fig. 8 shows that time to first node death of all scenarios vs. transmission range. Generally the time to first node death decreases for all scenarios with R_t increasing. This is due to the fact that more energy is needed to transmit data when R_t increases. The trend among different scenarios under the same transmission range is not consistent as the time to first node death very much relies on the topology.

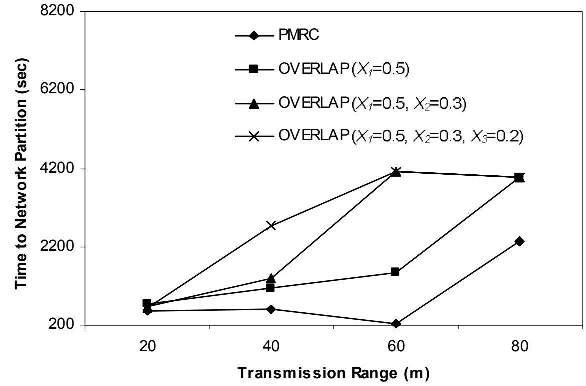

Figure 9 Time to network partition vs. R_t.

However, compared with the baseline, the scenarios with overlapped layers have more balanced energy consumption between layers. This is confirmed by the results shown in Fig. 9 where the scenario with overlapped layers (x_1=0.5) outperforms the baseline significantly (up to 6.3 times at transmission range = 60*m*) in terms of network life time. The scenarios with more overlapped layers further improve the network life time.

4.3 Performance with Different Number of Nodes

Figs. 10-13 show the results of the four performance metrics for the number of nodes N ranging in {400, 600, 800} when transmission range is set as 40*m*. To clearly show the impact of more number of nodes, the same number of sending nodes is used for different N's.

Fig. 10 shows that the average delay of all scenarios does not change much with the number of nodes increasing. Similar to Fig. 6, the more overlapped layers, the more average delay resulted. Fig. 11 shows that the average energy per packet does not differ much with the number of nodes increasing. The trend among all scenarios is consistent with that shown in Fig. 7.

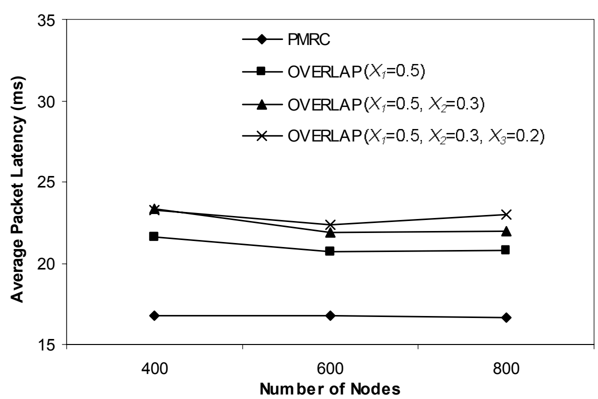

Figure 10 Average packet latency vs. N.

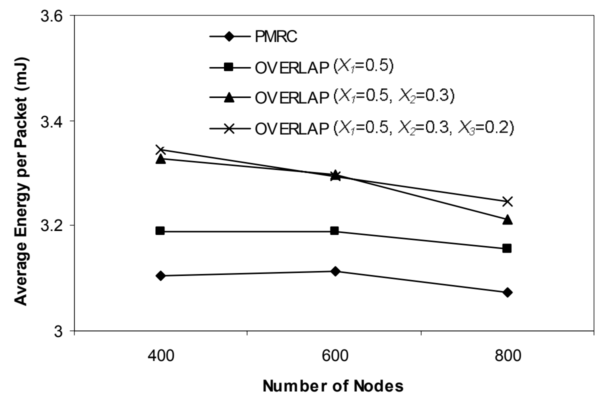

Figure 11 Average energy per packet vs. ***N*****.**

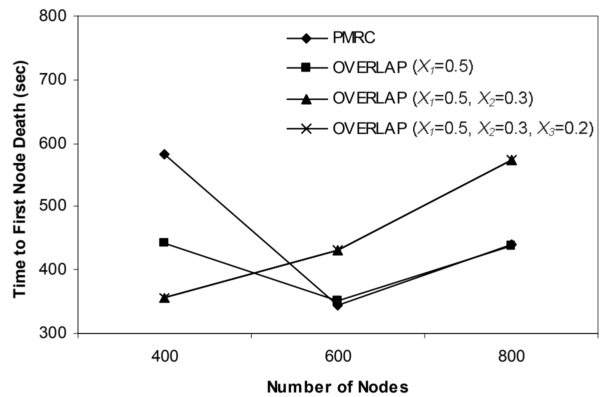

Figure 12 Time to first node death vs. ***N*****.**

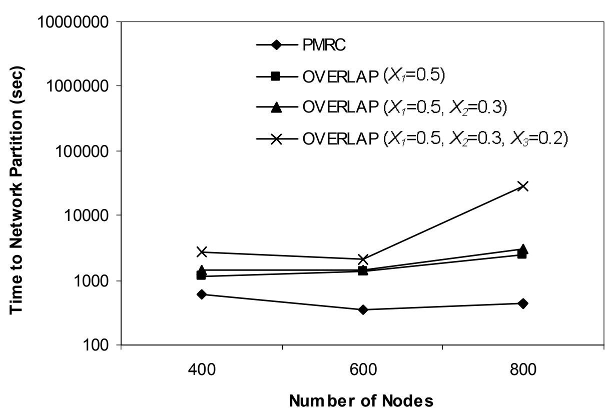

Figure 13 Time to network partition vs. ***N*****.**

Fig. 12 shows that the trend of time to first node death tends to be random as the number of nodes changes for all scenarios. The reason is that this metric is mainly influenced by topology of the sensor nodes.

Fig. 13 shows that the network life time fluctuates with the number of nodes increasing for all scenarios. Intuitively, the number of candidate nodes is increased as the number of nodes increases. However, other factors such as the imbalanced cluster size may impact the network life time. The trend among different scenarios is consistent with that shown in Fig. 9.

5. Conclusion

In this paper, we proposed to overlap neighboring layers to solve the bottleneck problem in PMRC-based wireless sensor networks. Analysis is performed to decide the desirable overlapped ranges. Simulation results show that the scenarios with overlapped layers outperform the scenario without overlapped layers significantly in terms of network life time. The tradeoff of the overlapping scheme is the increase of average delay and average energy per packet due to the increased number of layers. Future work includes the study of other factors, such as topology, cluster size, which have negative impact on prolonging the network life time.

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