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Overlapping layers for prolonging network life time in multi-hop wireless sensor networks

Hongyan Wang
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OVERLAPPING LAYERS FOR PROLONGING NETWORK LIFE TIME IN MULTI-HOP WIRELESS SENSOR NETWORKS

by

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Bachelor of Engineering in Electrical Engineering
Zhejiang University, China
June 1997

A thesis submitted in partial fulfillment of the requirements for the

Master of Science Degree in Electrical Engineering
Department of Electrical and Computer Engineering
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Graduate College
University of Nevada, Las Vegas
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Hongyan Wang

Entitled

OverlappingLayers For Prolonging Network Life Time

In Multi-Hop Wireless Sensor Networks

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering

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ABSTRACT

Overlapping Layers for Prolonging Network Life Time in Multi-hop Wireless Sensor Networks

by

Hongyan Wang

Dr. Mei Yang, Examination Committee Chair
Assistant Professor in Department of Electrical and Computer Engineering
University of Nevada, Las Vegas

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. Many applications, such as military surveillance and habitat monitoring, require the deployment of large-scale sensor networks. A highly scalable and fault-tolerant network architecture, the Progressive Multi-hop Rotational Clustered (PMRC) structure has been proposed, which is suitable for constructing large-scale wireless sensor networks. However, similar to other multi-hop structures, the PMRC structure also suffers from the bottleneck problem.

This thesis is focused on solving the bottleneck problem existing in the PMRC structure. First, the Overlapping Neighbor Layers (ONL) scheme is proposed to balance the energy consumption among cluster heads at different layers. Further, the Minimum Overlapping Neighbor Layers (MONL) scheme is proposed wherein the overlapped area between neighbor layers is gradually increased through network life time to achieve load balance and energy efficiency in the whole network area. Simulation results show that the
MONL scheme significantly prolongs network life time and demonstrates steady performance on sensor networks with uniformly distributed sensor nodes. To further prolong the network life time, traffic-similar sensor nodes distribution combined with the MONL scheme is studied.

The proposed overlapped layers schemes are proven to be effective in solving the bottleneck problem and prolonging network life time for PMRC-based networks. They can also be applied for other multi-hop cluster-based sensor networks. The traffic-similar nodes distribution concept can be applied in optimizing sensor network deployment to achieve desired network life time.
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CHAPTER 1

INTRODUCTION

In this chapter, an introduction to wireless sensor networks and their applications are given first followed by a review of the related work in network architectures. Then the Progressive Multi-hop Rotational Clustered (PMRC) structure is introduced and the bottleneck problem is described. At the end of this chapter, an outline of the thesis is given.

1.1 Wireless Sensor Networks and Their Applications

Continuing advances in wireless communications, computing and sensor technology have fostered the development of a wide variety of Wireless Sensor Networks (WSN) consisting of low cost, low power, and small size sensor nodes that communicate in short distance. With the development of Micro Electromechanical Systems (MEMS), sensors can be made smaller and cheaper [42]. 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].

Wireless sensor networks are emerging paradigms that promise to change the way humans interact with their environments [23]. The applications of wireless sensor networks include industrial control and monitoring; home automation and consumer electronics; military and homeland security; asset tracking and supply chain management; intelligent agriculture; and health monitoring [9].


• Military and homeland security: surveillance and monitoring, target tracking [17] ; battle damage assessment [37] ; Scalable and fault-tolerant sensor networks are often needed in these applications.

• Asset tracking and supply chain management: tracking of shipping [50] ; tracking railroad cars in rail yards; tracking an item in a large warehouse [32].

• Intelligent agriculture and environmental sensing: rain gauge for large farms and ranches [15] ; plants monitoring [28] ; monitoring of soil moisture, temperature [11] [4] ; habitat monitoring [1]. For these applications, the cost and power consumption of the sensor network must be low to make it sustain for sufficient long time.


The characteristics of wireless sensor networks and the specific requirements of aforementioned applications bring the following challenges in designing efficient wireless sensor networks: energy efficiency, scalability, fault tolerance, and security.
1.2 Related Work

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 such large-scale sensor networks, the previous research shows that clustered structure [20] [48] and multi-hop routing [27] [30] achieve better energy efficiency [21] [43].

Clustered architectures include the Low-Energy Adaptive Clustering Hierarchy (LEACH) [18] and its variants, LEACH-C, LEACH-F [19], and M-LEACH [29], the Hybrid Energy-Efficient Distributed (HEED) clustering algorithm [47] [48] and the Robust Energy Efficient Distributed (REED) clustering algorithm [49], the multi-level hierarchical cluster structure [3] [39] [40], and others [13] [24] [26] [38] [44].

The LEACH and its variants [19] [29] deal with single hop clustering [48], (i.e., the cluster heads are within one hop range of the sink node). The HEED protocol is designed for multi-hop clustering [48], which prolongs network life time by the hybrid approach of selecting cluster heads probabilistically and assigning sensor nodes to clusters with communication cost minimized [47] [48].

The REED approach [49] targets to construct k-fault-tolerant networks by selecting k independent sets of cluster heads. In the multi-level hierarchical cluster structure [3] [39] [40], nodes are organized into different levels. All sensor nodes belong to the lowest level (level-1), where the cluster heads in level-1 form level-2. This process is repeated for each level until the sink is reached. However, in the aforementioned clustered architectures, there is no guarantee that a cluster head is physically closer to the sink. As a result, it may take more energy to forward the data from the cluster head to the sink.
In [14], the multi-hop infrastructure network architecture (MINA) was proposed, which partitions sensor nodes into different layers according to their individual hop counts along the path to the sink node. It is guaranteed that data are forwarded from the source to the sink node through those nodes with less hop counts. However, in [14], there is no discussion on how the forwarding nodes are selected such that the overall energy consumption can be balanced among different sensor nodes.

Other research work for large-scale sensor networks include [22] [26], etc. In [22], the SAFE protocol was proposed for data dissemination from stationary sensor nodes to mobile sink nodes in large-scale sensor networks. The major problems of the SAFE protocol are the large number of states to be maintained at intermediate nodes and the multiple rounds of message exchanges required to set up a path. The two-tier data dissemination (TTDD) protocol [26] is another protocol for disseminating data from stationary sensor nodes to multiple mobile sinks by setting up a grid structure. However, the cost of proactively creating/maintaining the grid structure from all sources to the edge of the sensor field tends to be unbearably high for large sensor networks.

1.3 The PMRC Structure

In light of MINA, a highly scalable and fault-tolerant network architecture named as the Progressive Multi-hop Rotational Clustered (PMRC) structure is presented in [38], 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. Figure 1.1 illustrates the PMRC structure. 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.

Figure 1.1 The PMRC structure.

However, like in other multi-hop sensor networks, the PMRC structure suffers from the bottleneck problem which 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.

Similar problem has been considered in some research work. In [27], the authors point out that the concentration of data traffic towards a small number of sensor nodes closer to the sink node threatens the network lifetime. They propose to let the sink node be mobile such that the nodes close to it change over time. In [38], 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 [24], 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) [46] is proposed to produce clusters of unequal size in single-hop networks.

1.4 Contributions and Thesis Organization

The thesis is focused on the study of efficient solutions to the bottleneck problem existing in the PMRC-based sensor networks with the objective of prolonging network life time.
First, the Overlapping Neighbor Layers (ONL) scheme is proposed to balance the energy consumption among cluster heads at different layers. Through analysis and numeric results, the reasonable overlapped ranges are determined 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 lifetime.

Further, the Minimum Overlapping Neighbor Layers (MONL) scheme is proposed wherein the overlapped area between neighbor layers is gradually increased through network lifetime to achieve load balance and energy efficiency in the whole network area. Simulation results show that the MONL scheme significantly prolongs network lifetime and demonstrates steady performance on sensor networks with uniformly distributed sensor nodes.

To further prolong the network lifetime, traffic-similar sensor nodes distribution combined with the MONL scheme is studied. Simulation results that the combination scheme achieves better performance.

The rest of the thesis is organized as follows: Chapter 2 describes the ONL scheme in details and presents the analysis of reasonable overlapped ranges and simulation results; Chapter 3 states the Minimum Overlapping Neighbor Layers (MONL) scheme in details; Chapter 4 presents the analysis of traffic load and describes the traffic-similar sensor nodes distribution combined with the MONL scheme; Chapter 5 summarizes our findings in this thesis and discusses directions for future work.
CHAPTER 2

OVERLAPPING NEIGHBOR LAYERS

In this chapter, we propose to use the overlapping neighbor layers (ONL) scheme to solve the bottleneck problem in PMRC-based sensor networks.

2.1. Overlapped Layers for PMRC Structure

The bottleneck problem in the PMRC structure can be solved through overlapping neighboring layers. Figure 2.1 illustrates the idea using a PMRC-based sensor network with two layers in a circular area.

Figure 2.1 Overlapped layers in a PMRC-based sensor network.
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 the next two sections, we will analyze the effect of overlapped layers in average energy consumption and justify the appropriate overlapped ranges.

2.2 Analysis of Average Load

Without loss of generality, we assume the sensor nodes are distributed uniformly with density $\rho$ 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 sub areas, each one composed of the clusters formed in consecutive layers. As shown in Figure 2.2, each sub area can be represented as a fan shape with angle $\theta$.

In this analysis, we only consider the energy consumed in data transmission and receiving, which dominates the overall energy consumption of each node [24]. 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.

$\rho$: sensor node density.

$\theta$: angle of the fan shape.

$\varepsilon$: 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 $i$ ($1 \leq i \leq n$) located in the overlapped area of layers $i$ and $i+1$. 

Figure 2.2 Top view of three overlapped layers.
$r_i$: the range of the ring shape of layer $i$, where $r_1 = r$.

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

Figure 2.2 shows the relation among $r_1$, $r_2$, $r_3$, $x_1$, $x_2$, and $x_3$ within a fan shape with angle $\theta$.

Consider the cluster head candidates in the overlapped area of layer 1 and layer 2 in Figure 2.2. 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) $E_i$: the energy consumed to send the data collected at layer 1 and the data relayed through layer 2.

And $E_r$ and $E_i$ can be derived as:

$$E_r = (R^2 - r_i^2) \rho \epsilon \phi \theta / 2,$$

where $(R^2 - (r_i - x_i)^2) \rho \epsilon \phi \theta / 2$ gives the area outside of layer 1.

$$E_i = (R^2 - (r_i - x_i)^2) \rho \epsilon \phi \theta / 2.$$

Therefore, $L_1$ can be derived as:

$$\frac{(R^2 - (r_i - x_i)^2) \rho \epsilon \phi \theta / 2 + (R^2 - r_i^2) \rho \beta \epsilon \phi \theta / 2}{(r_i^2 - (r_i - x_i)^2) \rho \phi \theta / 2}$$

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

$$L_1(x_i) = \frac{(n^2 - (1-x_i)^2) + \beta(n^2 - 1)}{(2-x_i)x_i} \epsilon \quad (1)$$

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
\[ r_2(x_1, \theta) = \sqrt{1 - (1 - x_1)^2 \sin^2 \theta} - (1 - x_1)(1 - \cos \theta) \quad (2) \]

Then we get

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

We then derive \( r_3 \) and \( L_3 \) as follows.

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

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

Generally, we have,

\[ r_n(x_1, x_2, ..., x_{n-1}, \theta) = \sqrt{1 - \left( \sum_{i=1}^{n-1} (r_i - x_i) \right)^2 \sin^2 \theta} - \left( \sum_{i=1}^{n-1} (r_i - x_i) \right)(1 - \cos \theta) \quad (6) \]

\[ L_n(x_1, x_2, x_3, ..., x_n, \theta) = \frac{(n^2 - \left( \sum_{i=1}^{n} (r_i - x_i) \right)^2) + \beta(n^2 - \left( \sum_{i=1}^{n} (r_i - x_i) + x_n \right)^2)}{(2 \left( \sum_{i=1}^{n} (r_i - x_i) \right) + x_n)x_n} \varepsilon \quad (7) \]

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.
2.3 Numeric Results for $L_1$, $L_2$, and $L_3$

Assume that $\beta =0.7$, $\epsilon =1.0$, $n =5$, $\rho =1.0$, then we can calculate the numeric values of $L_1$. Figure 2.3 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 2.3 $L_1$ vs. $x_1$.](image)
To calculate $L_2$, we assume $\theta = 27^\circ$, a moderate fan angle. Figure 2.4 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.

Then, by fixing $x_1 = 0.5$ and $x_2 = 0.3$, Figure 2.5 shows the values of $L_1$, $L_2$, and $L_3$ vs. $\theta$. The figure shows that both $L_2$ and $L_3$ are increasing when $\theta$ increases. To achieve a balance among $L_1$, $L_2$, and $L_3$, $\theta = 27^\circ$ and $x_1 = 0.2$ are selected. Following this trend, $x_i = 0.1$ is decided for $i > 3$. 

Figure 2.4 $L_2$ vs. $x_1$ and $x_2$. 

![Graph showing $L_1$ and $L_2$ vs. $x_1$ for different $x_2$ values.](image)
2.4. 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 [31] and compared with PMRC without overlapped layers. The simulation model developed in [45] is adopted here and the overlapped scheme is implemented on it.

2.4.1 Simulation Settings

In the simulation, we assume a 200m x 200m 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 [25]
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.
Table 2.1 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.

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.
Table 2.1 Basic simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor field area</td>
<td>$200m \times 200m$</td>
</tr>
<tr>
<td>Node number ($N$)</td>
<td>${400, 600, 800}$</td>
</tr>
<tr>
<td>Radio transmission range ($R_t$)</td>
<td>${20, 40, 60, 80} m$</td>
</tr>
<tr>
<td>Initial energy per node</td>
<td>$2J$</td>
</tr>
<tr>
<td>Maximum buffer size</td>
<td>1000 packets</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>$1Mbps$</td>
</tr>
<tr>
<td>Processing speed at each node</td>
<td>$10Mbps$</td>
</tr>
<tr>
<td>Packet generation rate</td>
<td>1pkt/s</td>
</tr>
<tr>
<td>Simulation time</td>
<td>Until network partition</td>
</tr>
</tbody>
</table>

2.4.2 Performance with Different Transmission Range

Figures 2.6 - 2.9 present the performance metrics of the four scenarios for the number of sensor nodes $N = 400$. Figure 2.6 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. Figure 2.6 also shows that the average packet latency for all scenarios decreases 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.

Figure 2.7 shows the average energy per packet of all scenarios vs. transmission range. Generally, more overlapped layers lead to 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 2.6 Average packet latency vs. $R_t$. 

Figure 2.7 Average energy per packet vs. $R_t$. 

Figure 2.8 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.

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 Figure 2.9 where the scenario with overlapped layers ($x_1=0.5$) outperforms the baseline significantly (up to 6.3 times at transmission range = 60m) in terms of network life time. The scenarios with more overlapped layers further improve the network life time.

2.4.3 Performance with Different Number of Nodes

Figures 2.10 - 2.13 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 40m. To clearly show the impact of more number of nodes, the same number of sending nodes is used for
Figure 2.9 Time to network partition vs. \( R_t \).

different \( N \)'s.

Figure 2.10 shows that the average delay of all scenarios does not change much with the number of nodes increasing. Similar to Figure 2.6, the more overlapped layers, the more average delay resulted. Figure 2.11 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 Figure 2.7.

Figure 2.12 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.

Figure 2.13 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 Figure 2.9.

Figure 2.10 Average packet latency vs. $N$.

Figure 2.11 Average energy per packet vs. $N$. 
Figure 2.12 Time to first node death vs. $N$.

Figure 2.13 Time to network partition vs. $N$. 
In summary, the simulation results show that the ONL scheme significantly prolongs the network life time. The tradeoff of the ONL scheme is the increase of average delay and average energy per packet due to the increased number of layers.
CHAPTER 3

MINIMUM OVERLAPPING NEIGHBOR LAYERS (MONL)

The ONL scheme provides a solution to balance the load of cluster heads at different layers in the PMRC-based wireless sensor networks. However, in the ONL scheme, the layer boundary and overlap range are static during network lifetime. The network lifetime is still limited by some node which has only one candidate cluster head, which failure will cause the network partition. Figure 3.1 illustrates such an example.

To overcome this limit, we propose the Minimum Overlapping Neighbor Layers (MONL) scheme with gradually changed layer boundary through network lifetime to achieve load balance and energy efficiency in the whole network area.

3.1 The MONL Scheme

Without loss of generality, we assume that a node is not eligible to be elected as a cluster head if its residue energy falls lower than a pre-defined energy threshold. Observe that in the ONL scheme, an overlap between two neighbor layers is not necessary if the cluster head (in the upstream layer) of a cluster (in the downstream layer) has its residue energy higher than certain threshold. As such, the initial overlapped area between neighbor layers in the ONL scheme may be reduced to consist of only the initial cluster head of a cluster in the downstream layer. When the residue energy of the initial cluster head falls below the energy threshold, it will be deliberately “pushed” to its downstream layer (i.e. its layer number will be increased by one). The result is that the overlap
between these two neighbor layers may grow a little larger towards the upstream layer direction on the next round of network recreation. Consequently, throughout the network life time, minimum overlap between any neighbor layers is kept and the cluster size is dynamically changed.

Figure 3.1(a) Initial structure of the cluster in layer 2.

Figure 3.1 illustrates the growing overlap between neighbor layers in the MONL scheme. As shown in Figure 3.1(a), initially, node 2 in layer 1 is selected as the cluster head for the cluster composed of nodes 3, 4, 5, 6 in layer 2. After the residue energy of node 2 drops below the threshold ("retires" from the head position), it will be "pushed" to layer 2. Then the network is recreated and node 1 is selected as the head of a cluster which consists of nodes 2, 3, 4, 5 (see Figure 3.1(b)). And node 6 which is originally within transmission range of node 2 is "pushed" to layer 3 ("resigned" from layer 2 to...
layer 3) as it is out of the transmission range of any node in layer 1. The result is that the overlapped range between layer 1 and layer 2 is growing larger towards layer 1.

3.2 Properties of MONL

The MONL scheme has the following properties: first, it automatically increases the required minimum overlap on demand between any neighbor layers. The number of layers on the routing path between a source sensor node (which generate data) and the sink node is thus increased gradually. Due to the dynamic change of layer boundary and cluster topology, the routing path from a source sensor node to the sink node is changed accordingly. However, the routing path will always have the lowest number of hop counts, which is guaranteed by the basic rule how the layers are formed.

Second, different from ONL, the overlap between neighbor layers is changed from the minimum to the largest gradually during network life time. Also different from ONL,
neighbor layers can be irregularly overlapped. As such, one layer can be in irregularly ring-like shape.

Third, the MONL scheme overcomes the limit caused by static network topology control (as illustrated in Figure 3.1). As such, the MONL scheme can adapt to any randomly deployed network as long as the initial topology is connected (i.e. any sensor node has at least one neighbor node which is within its transmission range). Due to its dynamic feature, the MONL scheme provides fault tolerance against sudden failure of sensor node(s) provided that the remaining topology is still connected. Due to this property, the deployment of the network is made easier.

Fourth, the MONL scheme inherently helps in balancing the energy consumption among cluster heads of clusters within the same layer. Compared with the ONL scheme, the MONL scheme promotes this balance in a dynamic way. In addition, the deliberate change of layer number of “retired” cluster heads will also help reducing their energy consumption in post-retire communication.

Figure 3.2 illustrates such an example. As shown in Figure 3.2(a), as the cluster head for a larger cluster, node 2 drains out its energy faster than node 9 which is the cluster head for a smaller cluster. Figure 3.2(b) shows that after node 2 “retires” from the head position, after network recreation, node 1 takes the turn of a new cluster head while node 9 still acts as a cluster head. Node 4 is switched from its original cluster headed by node 2 to the cluster headed by node 9. As a result, the unequal energy consumption rate among different clusters of the same layer will lead to “unsmooth” overlap border between neighbor layers. Note that after network recreation, node 2 joins the cluster headed by node 1, which is closer to node 2 than its original cluster head (i.e., the sink node). This
Figure 3.2(a) Unequal energy consumption rate with unequal cluster size.

Figure 3.2(b) Relative balanced energy consumption with recombined clusters.
saves the energy needed to communicate from node 2 to its cluster head.

Finally, due to its minimum overlap property, the clusters in the neighbor layers have less radio interference to each other than that in the ONL scheme.

3.3 Comparison of Simulation Results of MONL and ONL

To evaluate the performance of the MONL scheme, simulations of PMRC, ONL and MONL have been conducted on OPNET Modeler network simulator for 400 nodes with transmission range 40m. Other simulation settings here are almost the same as in Section 2.4 except that sensor nodes distribution varies for different schemes.

We consider the same set of performance metrics as in the ONL scheme: average packet latency, average energy consumption per packet, time to first node death, time to network partition.

In the following, we present the simulation results of the above performance metrics for seven different scenarios: 1) PMRC (without overlapped layers) as the baseline; 2) ONL with $x_1 = 0.5$ (i.e., other layers have no overlaps); 3) ONL with $x_1 = 0.5$ and $x_2 = 0.3$; 4) ONL with $x_1 = 0.5$, $x_2 = 0.3$, and $x_3 = 0.2$; 5) MONL based on the same node distribution as scenarios 1)-4); 6) MONL scheme with uniform random node distribution A; 7) MONL with uniform random node distribution B. The first five scenarios are all based on the node deployment used in section 2.4, as shown in figure 3.9. The latter two scenarios assume the node deployment follows a uniform distribution in the 200m \times 200m area, as shown in figure 3.7 - 3.8. For all scenarios, only one cluster head is selected for each cluster. 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.
Figures 3.3 - 3.6 show the results of the four performance metrics for seven different scenarios.

![Average Packet Latency vs. Scenarios](image)

Figure 3.3 Average packet latency vs. scenarios.

Figure 3.3 shows that the average packet latency of the MONL scheme is less than that of the three ONL scenarios but higher than that of the non-overlapped PMRC. As all the data sending nodes locate in the most outward layer, the packet delay is proportional to the number of layers in the network (which is equivalent to the number of hops on the routing path). The number of layers resulted in the MONL scheme is initially the same as in the non-overlapped PMRC but gradually increasing to a value larger than that in the ONL scheme. Yet in the ONL scheme, the number of layers is fixed to a larger value (compared to the non-overlapped PMRC) when the network starts to operate. This explains the trend shown in the figure.
Figure 3.4 Average energy per packet vs. scenarios.

Figure 3.5 Time to first node death vs. scenarios.
As shown in Figure 3.4, the average energy per packet metric for the first five scenarios shows a similar trend as in Figure 3.3. The reason is that the energy consumed per packet is directly related to the number of the hops (i.e., the number of layers based on the simulation assumption).

Figure 3.5 shows that the trend of time to first node death tends to be random as the clusters formed in the first five scenarios are different. The MONL scheme has the same time to first node death as the non-overlapped PMRC, since the initial cluster topology formed in the MONL scheme is the same as that in the non-overlapped PMRC.

Figure 3.6 shows that the MONL scheme achieves the longest network life time among all first five scenarios. This is consistent with our expectation. It is observed that in the MONL scheme, the cluster heads within the initial layer 1 boundary tend to die quicker than the cluster heads in other layers. As such, the number of nodes existing in initial layer 1 boundary generally bounds the network life time.
Figures 3.3-6 also show that the MONL scheme generally shows a steady performance in the four performance metrics excluding the time to first death even when sensor nodes are deployed randomly. The two different sensor nodes deployments used in the last two scenarios are shown in Figure 3.7 and Figure 3.8. As shown in Figure 3.6, the cases A and B of the MONL scheme with random node deployment have longer network life time than the MONL scheme with the node deployment shown in Figure 3.9. The reason for this life time difference among simulations is that case A have 52 sensor nodes in layer 1, and case B has 55 sensor nodes in layer 1, while the other case only has 37 sensor nodes in layer 1. For the same reason, the network life time for different cases of the MONL scheme with different random node deployment also varies.
Figure 3.7 Nodes deployment for *MONLRANDOM_CASE_A*. 
Figure 3.8 Nodes deployment for MONL\_RANDOM\_CASE\_B.
Figure 3.9 Nodes deployment for *MONL*.
As discussed in chapter 3, the network life time of the MONL scheme is generally bounded by the number of the sensor nodes existing in the initial layer 1 boundary. A natural idea to break this constraint is to distribute more nodes in layer 1. An important problem to solve here is how to decide the node distribution. In this chapter, we propose to distribute the nodes in a traffic-similar way such that network life time is prolonged. Before we introduce the traffic-similar sensor nodes distribution, we first analyze the traffic load in a randomly distributed sensor network.

4.1 Network Model and Load Distribution of MONL

Assume a sensor network consisting of static sensor nodes with a uniformly random distribution of density $\rho$ within a circle of radius $R$, and a sink node locates at the centre of the circle. All sensor nodes are homogeneous. The transmission ranges of all sensor nodes are fixed at $r$, which is assumed to be much smaller than $R$ ($r \ll R$). Each sensor node generates data with a constant rate $\lambda$. Other notations used are defined in the same way as in section 2.2.

The MONL scheme is applied to the sensor network. Similar to PMRC, sensor nodes are partitioned into layers according to their distances (calculated using hop counts) to the sink node. The range of a layer in the radius direction is bounded by the transmission
range \( r \). The layers are labeled consecutively from 1 the layer closest to the sink node to \( n \) for the layer with the largest hop count to the sink node.

Nodes in the same layer form clusters within the transmission range of the cluster head, which locates at the inner layer. The sensor nodes that act as cluster heads in layer \( i \) forward data from its cluster to its cluster head in layer \( i - 1 \). No data aggregation is performed in the data forwarding process.

![Illustration of geometry relation of layer \( i \).](image)

Note that cluster heads of clusters in layer \( i \) belong to clusters in layer \( i - 1 \). The minimum overlapped area between layer \( i - 1 \) and layer \( i \) consists of the cluster heads of clusters in layer \( i \), which logically belongs to layer \( i - 1 \). In the MONL scheme, the layer boundary between layers \( i - 1 \) and \( i \) is moving during network lifetime, the overlapped area between layer \( i - 1 \) and layer \( i \) is also changing.
As in section 2.2, we analyze the load of a sensor node which represents the power consumed by the node to transmit and receive data. It is obvious that the higher the load, the shorter the node life time. The average load of nodes in layer i, $L_i$, is an average of the loads of all sensor nodes composing of layer i. The energy consumed by these nodes consists of two parts:

1) $E_r$: the energy consumed to receive the data relayed through layer i, which is composed of the data collected from all layers outside of layer i within circle R;

2) $E_t$: the energy consumed to send the data from all sensor nodes at layer i and the data relayed through layer i.

Figure 4.1 illustrates the geometry relation of layer i (with radius range $r$) within the circular area of diameter $R$. Assume layer i is d distance from the sink node, then we have:

$$E_r = \pi (R^2 - d^2) \rho \beta \lambda \varepsilon$$

$$E_t = \pi (R^3 - (d - r)^2) \rho \lambda \varepsilon$$

Then, we have

$$L_i = \frac{E_r + E_t}{\text{number of nodes in layer i}}$$

$$= \frac{\pi (R^2 - d^2) \rho \beta \lambda \varepsilon + \pi (R^3 - (d - r)^2) \rho \lambda \varepsilon}{\pi (d^2 - (d - r)^2) \rho}$$

When $d \geq r$, that is, $i \geq 2$, $L_i = \frac{(R^2 - d^2) \beta + (R^3 - (d - r)^2)}{d^2 - (d - r)^2} \lambda \varepsilon$

$$= (1 + (1 + \beta)) \frac{R^2 - d^2}{d^2 - (d - r)^2} \lambda \varepsilon$$

When $0 < d < r$, that is $i = 1$, for layer 1, it forwards all data coming from outside of layer 1 and also sends data generated from sensor nodes in layer 1. Thus we have

$$E_{r1} = \pi (R^2 - d^2) \rho \beta \lambda \varepsilon$$
\[ E_{r1} = \pi R^3 \rho \lambda \epsilon \]

Then, we have

\[ L_1 = \frac{E_{r1} \text{ / number of nodes in layer 1}}{\pi r^3 \rho} \]

\[ = \frac{\pi (R^2 - d^2) \rho \beta \lambda \epsilon + \pi R^2 \rho \lambda \epsilon}{\pi r^3 \rho} \]

\[ = (1 + \beta \frac{R^2 - r^2}{r^2}) \lambda \epsilon \]

Figure 4.2 depicts the average load vs. \( d \) normalized in units of \( r \) assuming \( R = 10, r = 1, \lambda = 1, \epsilon = 1, \beta = 0.7. \)

![Figure 4.2](image)

**Figure 4.2** Unbalanced load distributions with \( d. \)

As shown in figure 4.2, the average load of a cluster head increases significantly when the distance between the cluster head and the sink node decreases. In [33],
unbalanced load distribution is also studied with different assumptions. That is, the cluster heads closer to the sink node have the higher energy consumption rate than those farther from the sink node. Intuitively, cluster heads in layer 1 have the highest load as they have to forward all the data traffic outside layer 1. When the sensor nodes closest to the sink node drain out their energy, a ring-like “hole” surrounding the sink node is resulted so that the sensor nodes outside the “hole” area are separated from the sink node. As such, the network life time is upper-bounded by the total energy of the sensor nodes within layer 1 for the PMRC-based networks employing the MONL scheme.

4.2 Traffic-similar Sensor Nodes Distribution

To break through the constraint of the aforementioned problem, one possible approach is to use traffic-similar sensor nodes distribution combined with the MONL scheme. The underlying principle is that if the sensor nodes are deployed in the area according to the traffic load distribution (that is, more nodes will be deployed in the range which have higher traffic load), then the traffic load among different layers in the sensor network tends to be balanced.

Figure 4.3 plots the sensor node distribution histogram for traffic-similar distribution and three approximation curves: 1) \( y = d^{-1.5} (d \geq 1), y = 169.3 (0 \leq d \leq 1) \); 2) \( y = d^{-1.0} (d \geq 1), y = 169.3 (0 \leq d \leq 1) \) 3) \( y = d^{-0.5} (d \geq 1), y = 169.3 (0 \leq d \leq 1) \). The reason for using these curves is that the traffic-similar sensor nodes distribution curve can only help balancing initial traffic load among layers in the sensor network. However, the actual traffic load will change while some nodes drain out their residue energy. These simple curves form a series of curves which can be used to approximate an optimal
sensor node distribution which achieves the longest network lifetime by varying the exponential of $d$.

As mentioned earlier, the traffic-similar distribution is static. A more accurate approach is analyzing the dynamic traffic load distribution during the sensor network lifetime.

![Sensor nodes distribution histogram](image)

Figure 4.3 Sensor nodes distribution histogram.

Simulations have been conducted to verify the MONL scheme combined with traffic-similar sensor node distribution. A random experimental outcome with traffic-similar
sensor nodes distribution in which node coordinates are given by MATLAB program is illustrated in Figure 4.4.

Figure 4.4 A random case of traffic-similar distribution.

Comparison of life time is shown in Figure 4.5, between MONL, MONL with uniform sensor nodes distribution, MONL combined with $d^{-x}$ series of curves distribution, and MONL combined with traffic similar distribution.
Figure 4.5 Life time comparisons among MONL cases.
CHAPTER 5

CONCLUSIONS AND FUTURE WORK

In this thesis, we proposed three schemes to solve the bottleneck problem in PMRC-based wireless sensor networks. The first scheme uses overlapped neighbor layers (ONL) to achieve balance among cluster heads at different layers. 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.

The Minimum Overlapping Neighbor Layers (MONL) scheme proposes a new concept of “moving” layers such that the overlapped area between neighbor layers is increased as needed. By this way, the MONL schemes overcomes the limit caused by static network topology control and can adapt to any randomly deployed network as long as the initial topology is connected. Simulation results show that the MONL scheme significantly prolongs network life time and demonstrates steady performance on sensor networks with uniformly distributed sensor nodes.

The third scheme combines the traffic-similar sensor nodes distribution and the MONL scheme to break the constraint in the MONL scheme. The traffic-similar nodes distribution concept can be applied in optimizing sensor network deployment to achieve desired network life time. Such optimized deployment can be performed by plane or
other facilities. For example, hundreds or thousands of sensor nodes can be deployed following a pre-determined distribution by a plane flying over a remote or dangerous area [18].

Future work includes the study of other factors, such as unequal cluster sizes, which may have negative impact for the ONL scheme on prolonging the network life time. A further study on dynamic traffic load distribution during the sensor network life time is needed to provide more accurate node distribution model. Moreover, the interference in physical layer and impact to MAC layer design due to application of the three schemes should be investigated. In addition, theoretical life time limits, behavior of “resigned” sensor nodes, queue length and packet delay of network applied with the three schemes should be studied.
BIBLIOGRAPHY


MATLAB File 1: Traffic-similar sensor nodes distribution

NumberOfNodes = 400;
Dimension = 200;
xFinal = 1:NumberOfNodes;
yFinal = 1:NumberOfNodes;
TransmissionRange = 40;
NumberOfLayers = ceil((Dimension/2)*1.414/TransmissionRange);
Beta = 0.7;

%the following has an error : 169.3->170
DimensionForFilter = ceil((1+Beta)*NumberOfLayers^2-Beta);

i = 1;
while (i <= NumberOfNodes)
    x = randint(1,1,[0,Dimension]);
    y = randint(1,1,[0,Dimension]);
    filter = randint(1,1,[0,DimensionForFilter]);
distance = ((x-(Dimension/2))*(x-(Dimension/2))+(y-(Dimension/2))*(y-(Dimension/2)))^(0.5);

if (distance > TransmissionRange)
  if (filter < (1+(1+Beta)*(NumberOfLayers^2-
  (distance/TransmissionRange)^2)/((distance/TransmissionRange)^2-
  ((distance/TransmissionRange)-1)^2)))
    xFinal(i) = x;
    yFinal(i) = y;
    i = i+1;
  end;
end;
if (distance <= TransmissionRange)
  xFinal(i) = x;
  yFinal(i) = y;
  i = i+1;
end;
end;
plot(xFinal,yFinal,'.);
%x=xFinal';
%y=yFinal';
MATLAB File 2: $d^{-1.5} / d^{-1.0} / d^{-0.5}$ sensor nodes distribution

NumberOfNodes = 400;
Dimension = 200;
xFinal = 1:NumberOfNodes;
yFinal = 1:NumberOfNodes;
TransmissionRange = 40;
NumberOfLayers = ceil((Dimension/2)*1.414/TransmissionRange);
Beta = 0.7;
%the following has an error: 169.3->170
DimensionForFilter = ceil((1+Beta)*NumberOfLayers^2-Beta);
i = 1;
while (i <= NumberOfNodes)
    x = randint(1,1,[0,Dimension]);
    y = randint(1,1,[0,Dimension]);
    filter = randint(1,1,[0,DimensionForFilter]);
    distance = ((x-(Dimension/2))*(x-(Dimension/2))+(y-(Dimension/2))*(y-(Dimension/2)))*((x-(Dimension/2))*(x-(Dimension/2))+(y-(Dimension/2))*(y-(Dimension/2)))^(0.5);
    if (distance > TransmissionRange)
        % the following code is for the $d^{-1.0}$ curve, replace -1 with -1.5 / -0.5, then you will have the code for the $d^{-1.5} / d^{-0.5}$ curve;
        if (filter < DimensionForFilter*((distance/TransmissionRange)^(1)))

55
xFinal(i) = x;

yFinal(i) = y;

i = i+1;

end;
end;

if (distance <= TransmissionRange)

xFinal(i) = x;

yFinal(i) = y;

i = i+1;

end;
end;

plot(xFinal,yFinal,'.');

%x=xFinal';

%y=yFinal';
VITA

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