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Optimizing Sensor Count in Layered Wireless Sensor Networks

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Abstract – Due to severely constrained resources, sensor nodes are subject to frequent failures. Therefore, wireless sensor networks (WSN) are typically designed with a large number of redundancies to achieve fault tolerance and to maintain the desired network lifetime and coverage. This work proposes an equation to determine the optimal number of redundant sensor nodes required in each layer of a WSN with the layered structure. Matlab simulations are used to verify the proposed equation.

Keywords: *fault tolerance, wireless sensor network, layered structure, simulation*

1. Proposed Sensor Count Equation

The minimal (optimal) sensor count, N_n, necessary in Layer n of a layered wireless sensor network while keeping the desired network lifetime and coverage level, is given by:

$$N_n = [cd^2 (\sum_n + 1)\, \tau\, N_{active\_n}\, T_{totalsense}] / (E_{node}\, T), \qquad (1)$$

where c is a proportionality constant; its value mainly depends on the electromagnetic conditions in the atmosphere where the information is transmitted. d is the distance between two adjacent layers. $\sum_n$ is the number of nodes from the outer layers which are connected to a node in Layer n. τ is the transmitting time for a node to transmit its sensed information, i.e., 1 packet. N_{active_n} is the number of active nodes required in Layer n. $T_{totalsense}$ is the total monitoring period, i.e., the desired network lifetime. E_{node} is the total energy available for each node. All the sensor nodes are assumed to have the same initial total energy. T is the time period between two transmissions for the same node. The time division multiple access (TDMA) method is used for sharing the same channel among all active nodes in WSN.

In Equation (1), $cd^2 \tau$ and $cd^2 (\sum_n+1)\, \tau$ indicate the energy spent by a sensor to transmit one packet and all available packets during one transmission cycle, respectively. Thus $cd^2 (\sum_n+1)\, \tau\, N_{active\_n}$ gives the total energy spent by a layer to transmit all available packets during one transmission cycle. Therefore, total energy spent by a layer to transmit all available packets during the total monitoring period is $[cd^2 (\sum_n+1)\, \tau\, N_{active\_n}]*(T_{totalsense}/T)$. The total energy divided by E_{node}, i.e., Equation (1), gives the required number of sensor nodes in the layer.

2. Simulation Setup and Policies

Figure 1 shows an example of WSN with a layered structure as well as its specifications and assumptions used in the Matlab simulations. The four layers in the example are

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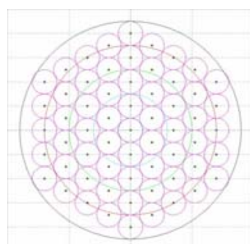
labeled as 1, 2, 3, and 4 from the inner layer to the outer layer and must maintain 6, 12, 18, and 24 active nodes, respectively to achieve the desired coverage level. When any of these nodes fails and has no replacement, the network coverage falls below the desired level and the network is regarded as being failed. Hence, to maintain the desired lifetime of a WSN, some number of redundant nodes must be deployed. The backup nodes are placed at the same position as the dying node because this is the optimal position for backup nodes according to a study in [1].



- $T_{totalsense}$ = 1000 units; T = 1 units; τ = 0.001 units; c = 1.
- E_{node} varies from 1 unit to 2 units with a step of 0.1 unit.
- d is always within the transmission range of a node and d varies from 2 units to 3 units with a step of 0.1 unit.
- A node can send a beacon to indicate that it does not have enough energy and it needs to be replaced.
- A tolerance factor of 5% is taken into consideration for the energy of each node to consider the inefficiency of the supply batteries.

Fig. 1: An Example WSN with Layer Structure and its Specifications.

To verify the proposed equation, we use the above specified values and calculate N_n. We then use the calculated sensor count to run the simulation to see if the real network lifetime is close to the theoretical value used in the calculation. Note that the calculated sensor count is normalized before being used in the simulation such that the numbers are in multiples of 6, 12, 18 and 24 in layers 1, 2, 3, and 4, respectively. We investigate effects of two parameters, E_{node} and d on the sensor count via simulations. We also investigate effects of three policies for defining the minimum/threshold energy required by a node (E_{min}). A node is regarded to have permanent failure when the energy of the node goes below E_{min}.

- **Policy 1**: The shortest distance routing algorithm will be used. E_{min} depends on the traffic of nodes in the innermost Layer 1. Specifically, E_{min} is directly proportional to the product of the average number of packets sent by a node in the innermost layer and the energy required to transmit one packet between two adjacent layers (denoted by E_1). To consider the worst case scenarios we let E_{min} be twice the above product. This policy is simple but can cause some energy waste for nodes in outer layers since less traffic will be involved in outer layers than in inner layers when the base station is in the center.
- **Policy 2**: This policy is similar to Policy 1 except that E_{min} depends on the traffic of the node in its respective layer. In this case, E_{min} is directly proportional to the product of the average number of packets sent by a node in that particular layer and E_1.
- **Policy 3**: E_{min} is equal to E_1. A dynamic routing algorithm will be used; each node checks its upstream neighbors one by one until it finds a neighbor that has sufficient energy to transmit the information. If none of neighbors has enough energy to send the total number of packets, then the first node that was checked will be regarded as being failed and it will be replaced with a backup node.

3. Simulation Results and Analysis

Figure 2(a) depicts the theoretical lifetime (1000 units) used in Equation (1) and the simulated network lifetime as E_{node} varies from 1 unit to 2 units with a step of 0.1 unit. The difference between the simulated lifetime and the theoretical value is less than 10%.

This conclusion applies to all the three policies. Also, we observe that policies 2 and 3 deliver better network performance than Policy 1 as the simulated lifetime in policies 2 and 3 is always greater than the theoretical time. The Policy 3 is the best one in terms of network lifetime, but this policy involves more processing in each node and thus is more costly due to the dynamic routing algorithm used. The fluctuations in the simulated curves are caused by the normalization of calculated sensor counts and the potential bottleneck layer in WSN. A bottleneck layer is the one the uses up all the backup nodes earliest and thus dies first. Figure 2(b) shows the changes of network lifetime as we vary the value of d from 2 to 3 units using a step of 0.1 unit. Similar conclusions may be obtained.

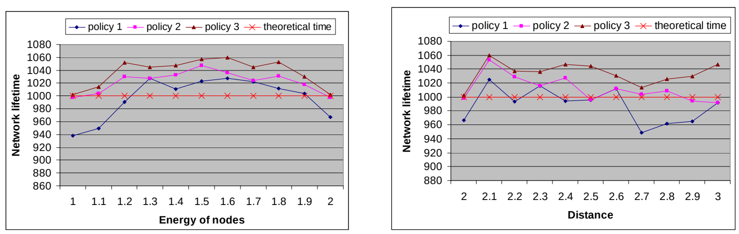
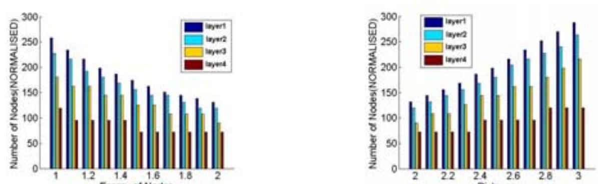


Fig. 2: (a) Network Lifetime vs. E_{node} (b) Network Lifetime vs. d.

Figure 3(a) and (b) shows the effects of E_{node} and d on the (normalized) sensor count, respectively. We observe that as the energy of each node increases or the distance between two adjacent layers decreases, the total number of nodes required for maintaining the same WSN lifetime decreases. Figure 3(b) can be explained that with E_{node} being kept constant, as d increases, the nodes consume more energy to do the data transmission and thus will die faster. Therefore, more replacements will be needed to keep the same lifetime of the network.



(a) Effects of E_{node} (b) Effects of d

Fig. 3: Effects of Two Parameters on the Optimal Sensor Count.

According to Figure 3, we can also see that the inner layers require more redundant nodes than the outer layers. This is because the nodes in inner layers involve more traffic and are used more often to communicate with the base station than the nodes in the outer layers. Therefore, the nodes in the inner layers fail more often than the ones in the outer layers and more redundant nodes are needed.

4. Conclusions

We proposed an equation for determining the optimal number of sensors in each layer of a layered hexagonal WSN. The equation was verified using Matlab simulations. Three different policies for defining the minimum node energy as well as effects of node energy and distance between adjacent layers on the optimal sensor count were also investigated.

References

[1] Kumar, A., *Preservation of Wireless Sensor Network Coverage by Energy Efficient Node Scheduling*, Masters Project Report, Electrical and Computer Engineering Department, University of Massachusetts Dartmouth, 2008.