CHAPTER 3

CAPACITY-PRESERVED, ENERGY-ENHANCED HYBRID TOPOLOGY MANAGEMENT SCHEME

3.1 INTRODUCTION

A sensor node consists of a processing unit, transceiver unit, sensing unit, and a power unit. A wireless sensor network (Akyildiz and Vuran 2010) consists of a large number of sensor nodes densely deployed in the field. These nodes monitor the environment, and detect if any event occurs and send the related information to the sink. In sensor networks, the nodes operate with a battery of limited energy storage capacity. The transceiver unit consumes larger power compared to other units and the sensor nodes can be used efficiently by putting their transceiver unit in an off state. Various topology management schemes have already been proposed (Jardosh and Rajan 2008, Li et al 2008, Santi 2005) to use the transceiver effectively, and improve the network parameters such as lifetime, at the cost of latency and capacity.

Sustainable Physical Activity in Neighborhood (SPAN) (Chen et al 2002) is a topology management scheme, in which a few nodes called as coordinators will be in the active state and form a backbone path, lowering the latency in SPAN. The drawback of SPAN is that it has a lesser lifetime, compared to the Sparse Topology and Energy Management (STEM) scheme. STEM, (Schurgers 2002) is another topology management scheme in which each and every node will have two radios, a data plane radio and a wake up plane radio. Usually, the data plane radio will be in an off state, and if any event occurs, the wake up plane radio will send a wake up message, and
activate the data plane radio of another node. The main advantage of STEM is its longer system lifetime. The drawback of STEM is high latency and smaller capacity. In this chapter, the interaction of STEM and SPAN is analyzed by deploying 80, 90, 100, 110, and 120 nodes in various field sizes, such as 60m*60m, 85m*85m, and 105m*105m (15 scenarios).

Wireless sensor networks (WSN) have wide applications (Birdar et al 2009, Raghavendra et al 2004), such as health, military and environment monitoring for detecting hazards. This growth has led to their widespread popularity in wireless communication, and hence, numerous research works are being carried out in this field. In large-scale wireless sensor networks or in hazardous applications, it is impossible to either recharge or replace the batteries. Hence, energy has to be used efficiently in order to improve the lifetime of the network. This has motivated the researcher to propose a scheme to improve the important network parameters.

The rest of the chapter is organised as follows. An overview of the two schemes, namely, STEM and SPAN are discussed in the next section. In section 3.3, the proposed scheme is elaborated. The results of this scheme are discussed in section 3.4. Section 3.5 gives the summary.

3.2 TOPOLOGY MANAGEMENT SCHEMES USED FOR INTEGRATION

The Sparse Topology and Energy Management scheme, and Sustainable Physical Activity in Neighborhood topology management scheme, are considered for integration, which is described below.

3.2.1 STEM

The main objective of topology schemes (Labrador and Wightman 2009, Jardosh et al 2008, Mo Li et al 2006, Ilyas and Mahgoub 2004) in
wireless sensor networks is to reduce energy consumption and maintain connectivity, in order to efficiently forward data to the sink. In STEM, (Rong Yu et al 2007, Schurgers 2002) the wake up radio is periodically on, for monitoring the environment. Typically, the data radio in the next hop between a node and the sink will be in the off state. To overcome this problem, each node will periodically turn on its radio for a short time to check if any other node wants to communicate with it. In principle, the communication capacity could be reduced to virtually zero, by turning off the radios of all nodes (i.e., putting them in the sleep mode). When a possible event is detected, the main processor is woken up to analyse the data in detail. The radio, which is normally turned off, is woken up if the processor decides that the data needs to be forwarded to the sink. Now, the problem is that, the radio of the next hop to the data sink is still turned off, if it did not detect that same event. As a solution, each node periodically turns on its radio for a short time, to listen if someone wants to communicate with it (Schurgers et al 2002, Sohrabi et al 2000).

In most of the applications, nodes are in the idle state and waiting for an event to happen. STEM reduces the energy consumption of the sensor nodes by switching its radio off when it is idle. STEM, with its wake-up interval of 600 ms, which reduces the energy consumption of the node by a factor of about 2.5. STEM conserves energy at the expense of network capacity and higher latency.

### 3.2.2 SPAN

In the Sustainable Physical Activity in Neighbourhood scheme (Chen et al 2002), only a few nodes will be elected as coordinators. If two neighbours of a node cannot reach each other directly, then that node becomes a coordinator. The coordinators are selected based on this coordinator election rule, that equal chance is given for all the nodes to become a coordinator. The
coordinators will form a definite backbone path in the network, through which data is forwarded from the source to the sink. Since there is a definite backbone path, the latency is less. SPAN preserves network capacity.

3.3 THE PROPOSED SCHEME

In the proposed technique, two different topology management schemes, namely, the Sparse Topology and Energy Management Scheme (STEM) and the Sustainable Physical Activity in Neighborhood (SPAN) scheme are integrated. Each node has two radios, namely, the data radio and the wake up radio. The coordinators are elected using the proposed coordinator eligibility algorithm. The non-coordinator nodes will be put in the sleep state and the coordinator nodes will be turned on. These coordinators will form a definite backbone path through which data is forwarded to the sink. When the sensor node detects an event, it will wake up its radio when it is needed to transmit data to the sink. Here, the problem is that, the radio of the next hop in the path to the data sink is still turned off. To overcome this problem, each node periodically turns on its radio at the same time as shown in Figure 3.7, to check whether any of the other nodes wants to communicate with it. The wake up plane wakes up the data plane radio, and thus, a connection is established between two nodes and thereby data is sent. A node, which wants to communicate with another node, is the initiator node and the node, which is being communicated, is the target node.

The proposed scheme has been tested by deploying various numbers of nodes such as 80, 90, 100, 110, and 120 in different field sizes, such as 60m*60m, 85m*85m, and 105m*105m and, the performance was analyzed. Due to a definite backbone path and dual radio, latency is reduced and more energy is conserved, preserving the capacity of the network. Capacity is the number of packets the network can successfully deliver per unit time. It is inversely proportional to the network’s packet loss rate. The proposed hybrid scheme does not degrade the network capacity, as SPAN does. Hence, the capacity is preserved.
3.3.1 System Model

The following assumptions are made in the proposed model shown in Figure 3.1.

(i) Both uniform and random deployment of nodes
(ii) Fixed transmission radius
(iii) Sensing range is less than transmission range
(iv) Dual radio
(v) Homogeneous network
(vi) Boundary effects are negligible

![Figure 3.1 Proposed System Model](image)

- Sensing range \( r_s \)
- Radio range \( R \geq 2r_s \)
- Non coordinator node
- Coordinator node

Sink node
A wireless sensor node has a battery of limited energy, and therefore, the network lifetime depends on how wisely the energy is used. In critical applications such as chemical plants, forest fires and nuclear reactors, it is often not possible to replace or recharge the battery. The objective was to improve the lifetime and reduce the latency, without scarifying the capacity. This is achieved by integrating the definite backbone of SPAN and the dual radio approach of STEM, to develop the network architecture with low power consumption and low latency.

3.3.2 Uniform Deployment of Nodes

Nodes are deployed uniformly as shown in Figure 3.2. This uniform deployment of nodes will form segments of a hexagon. A uniform deployment of nodes is used for many static applications such as precision agriculture, car parking, and chemical plants (Nirmal Kumar et al 2011, Garcia-Hernandez et al 2007). Nodes are deployed uniformly with the distance between two nodes in the horizontal direction as ‘r’, and the distance between two nodes in the vertical direction as ‘h’. Here, the radio range is R=20metres.

3.3.3 Mathematical Model for Node Deployment

Let, \( L \times L \) be the size of the sensor field

‘N’ be the total number of nodes

‘\( N_x \)’ be the number of nodes in the horizontal direction

‘\( N_y \)’ be the number of nodes in the vertical direction

‘\( D_x \)’ and ‘\( D_y \)’ be the distance between two nodes in the horizontal and the vertical direction respectively

‘r’ be the side of the hexagon

‘h’ be half the height of the hexagon in the vertical direction

‘R’ be the radio range
For uniform deployment, the distance between the nodes in the horizontal direction \((r)\) and the distance between the nodes in the vertical direction \((h)\) are predetermined and deployed accordingly.

The relationship of the distance between the nodes in the vertical direction ‘\(h\)’ and horizontal direction ‘\(r\)’ is given by,

\[
h^2 = \left[ r^2 - \left( \frac{r}{2} \right)^2 \right]
\]

(3.1)

\[
h = \frac{r\sqrt{3}}{2}.
\]

To ensure the connectivity \(r \leq R\)

\[
\text{Figure 3.2 Uniform Deployment of 100 Nodes}
\]

The product of the nodes arranged in the horizontal and vertical directions gives the total number of nodes. So,
The distance between two nodes is arranged as shown in Figure 3.3. that is,

\[ D_x : D_y = 1 : \frac{\sqrt{3}}{2} \]  \hspace{1cm} (3.5)

By using equations 3.2 to 3.5, the following equation is obtained.

\[ 1.155N_x^2 - 0.155N_x - N = 0 \]  \hspace{1cm} (3.6)

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**Figure 3.3 Calculation of the Location of the Nodes in Uniform Deployment**
By solving this, the number of nodes in the horizontal direction is obtained and by substituting this in equation (3.2) the number of nodes in the vertical direction can be determined, and this is given in Algorithm 3.1.

**Step 1** : Compute the number of nodes in the x-direction by solving $N_x$.

$$1.55N_x^2 - 0.155N_x - N = 0$$

**Step 2** : Compute the number of nodes in the y-direction,

$$N_y = \frac{N}{N_x}$$

**Step 3** : Compute the distance between two nodes in the x and y-directions,

$$D_x = \frac{L}{N_x - 1} \text{ and } D_y = \frac{L}{N_y - 1}$$

**Step 4** : If $(D_x > R) \&\& (D_y > R)$ then communication capacity becomes zero, else assign nodes as shown below.

$$\begin{bmatrix}
\frac{D_x}{2}, 0 \\
0, D_x \\
\frac{D_x}{2}, 2D_x \\
\vdots \\
0, (N_y - 1)D_x \\
N_y, D_x \\
\end{bmatrix}$$

**Algorithm 3.1 Node Deployment Algorithm**

3.3.4 Random Deployment of Nodes with Mobility

Here the nodes are deployed randomly in the field as shown in Figure 3.4 using a random waypoint mobility model, which is the most widely
used model (Camp et al 2002). Sensor nodes move randomly in the field and the destination, speed and direction are all chosen randomly.

![Figure 3.4 Random Deployment of Nodes (Random Waypoint Model)](image)

3.3.5 Coordinator Eligibility Rule

For any node to become a coordinator, a new coordinator eligibility algorithm is proposed, and explained further as shown below, and in Figure 3.5.

**Step 1**: Compute the number of neighbors for each node. Given nodes $i$ and $j$ in a wireless sensor network where all the nodes have the same radio range($R$). $D_{ij}$ denotes the Euclidean distance from $i$ to $j$, and $D_{ij} \leq R$. Node $j$ is node $i$’s neighbor.

**Step 2**: Nodes having maximum neighbors wait for the following delay and later announce as a coordinator.

$$Delay = \left[ \left( 1 - \frac{E_s}{E_k} \right) + \left( 1 - \frac{C}{0.5n(n-1)} \right) + R \right] * n * T$$
Remaining nodes are put in the sleep state.

**Step 3**: Let \( N_i, N_k \) be neighbors to \( N_j \) If \( D_{ik} > R \), then \( N_j \) becomes coordinator after the delay in step 2.

**Step 4**: For \( \forall N_c \), checks whether it is within the radio range of any coordinator node \( C \), else that \( N_c \) becomes coordinator \( C \).

**Step 5**: If two or more nodes satisfy step 1 to 4, then each node checks its distance to the sink.

**Step 6**: If \( (D_{is} < D_{js}) \& \& (D_{is} < D_{ks}) \) then \( N_i \) becomes coordinator else if \( (D_{js} < D_{is}) \& \& (D_{js} < D_{ks}) \) then \( N_j \) becomes coordinator else \( N_k \) becomes coordinator

**Algorithm 3.2 Coordinator Election Algorithm**

**3.3.6 Coordinator Withdrawal Rule**

Chen et al (2002) proposed a coordinator withdrawal algorithm, which is mentioned below. The flow of the coordinator withdrawal is explained further in Figure 3.6.

**Step 1**: Each coordinator checks periodically if it should withdraw as coordinator.

**Step 2**: Let \( N_i, N_k \) be neighbors to \( N_j \) if \( D_{ik} \leq R \), then \( N_j \) withdraws its coordinator after the delay

**Step 3**: graceperiod = current time-last withdrawn if(graceperiod \( \geq 2s \)) sleep state

**Algorithm 3.3 Coordinator Withdrawal Algorithm**
3.3.7 Theoretical Analysis

3.3.7.1 Coordinator calculation

In a uniform deployment of nodes, the nodes will be at the vertex of the hexagon (Ren Ping Liu et al 2007). Each hexagon has six vertices. Each node at the vertex is shared by three hexagons. Therefore, each hexagon has two coordinators. In order to find the number of coordinators, the number of hexagons in the given area has to be known, which is given by

$$N_h = \frac{A_f}{A_h} \quad (3.7)$$

Let the number of coordinators be ‘C’ and the non-coordinator be \(N_c\).

$$C = 2 \left[ \frac{A_f}{A_h} \right]$$

$$C = 2 \left[ \frac{L^2}{6\sqrt{3}} \right] \quad (3.8)$$

Thus, the number of coordinators is calculated.

The total number of nodes (N) is

$$N = C + N_c \quad (3.9)$$

For N nodes, the coordinator node ratio is \(\alpha\) and is given by

$$\alpha = \frac{C}{N} \quad (3.10)$$
Figure 3.5 Flowchart for Coordinator Election

The non-coordinator node ratio is given by

\[ \beta = 1 - \frac{C}{N} \quad (3.11) \]

Thus,

\[ C = N(1 - \beta) \quad (3.12) \]
Figure 3.6 Flowchart for Coordinator Withdrawal

Hence \( N(1 - \beta) \) nodes will be in the on state and \( N\beta \) nodes will be in the off state. For a field size of \( L \times L \), the area is \( L^2 \text{ (m}^2) \).
3.3.7.2 Latency calculation

The initiator node will first start to send beacons to the target node and after receiving the beacons, the target node will respond. Once both the nodes turn their data radio on, a link is established between them, and data is transferred. If the transferred data is not meant for this node, then this becomes the initiator node and sends the packet to the node in the next hop towards the destination, and this process is repeated.

For simplicity, a location service is not used in the simulations. A node obtains the location of the destination node from the General Operations Director (GOD) module in NS2 (The NS Manual 2011). The location is required once per flow at the sender. Nevertheless, location services such as Grids Location Service (GLS) (Li et al 2000) can be used with the hybrid scheme. To obviate the problem of interference between the wake up beacon
and the data transmission, the transceiver uses the dual radio and each radio
operates at different frequency bands.

The frequency band $f_w$ (wake up plane radio) is used to transmit
wakeup messages. Once the target node has received a wakeup message, both
the nodes will turn on their radios operating at frequency band $f_d$. The data
packets are transmitted in this frequency band, and they are called the data
plane ($f_d$). The time taken for this process is the set up latency. The
probability of the target node being turned on at the same time as the initiator
node during the time interval ‘T’, as shown in Figure 3.7, is given by,

$$P(T_s = B_{xy}) = \frac{T_b - B_x}{T}$$ (3.13)

If the total time period (T) is greater than the ‘ON’ time duration ($T_b$), of the wake up plane radio, then the average set up Latency per hop is
given by

$$T_s = \frac{T + B_{xy}}{2}$$ (3.14)

If the total time period (T) is equal to the ‘ON’ time duration ($T_b$) of the wake up plane radio, then the average set up latency per hop is given by

$$T_s = B_{xy}$$ (3.15)

The total latency between the source and the sink is given by

$$T_l = T_s \times (C - 1)$$ (3.16)
3.4 PERFORMANCE ANALYSIS

The proposed hybrid topology management scheme is implemented, and the performance parameters, like energy conservation, latency, and capacity are analysed and compared with those of the SPAN and STEM topology management schemes. It is observed that the combined scheme has better performance and overcomes the limitations of both STEM and SPAN.

3.4.1 Simulation Environment

In this work, the Network simulator-2 (NS-2) tool is used, and both uniform and random deployment of nodes are considered individually over the sensor field. Here, the transmission range is fixed as $R = 20$ m, which has the radio characteristics as shown in Table 3.1. The power consumed by the node in the transmit and receive modes is the power required for transmission and reception, respectively. Idle power is the power consumed when the radio is ‘on’ but no data is transferred. Sleeping power corresponds to the power consumed when the node is in the sleep state.

<table>
<thead>
<tr>
<th>Radio Mode</th>
<th>Power Consumption (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit</td>
<td>0.01488</td>
</tr>
<tr>
<td>Receive</td>
<td>0.01250</td>
</tr>
<tr>
<td>Idle</td>
<td>0.01236</td>
</tr>
<tr>
<td>Sleep</td>
<td>0.000016</td>
</tr>
</tbody>
</table>

Table 3.1 Radio Characteristics
In this simulation, traffic loads are generated by the constant bit rate (CBR) flows. Different numbers of nodes such as 80, 90, 100, 110, and 120 are deployed both uniformly and randomly in 60m*60m, 85*85m, and 105m*105m field sizes separately. Here, the simulation time is set as 600 seconds.

3.4.2 Simulation Results

In the uniform deployment of nodes, the location of the nodes is predetermined and deployed. In the random deployment of nodes, nodes are deployed randomly, and a random way point model is used as the mobility model. The proposed scheme is implemented by integrating the STEM and SPAN topology management schemes and coordinators are elected using the proposed coordinator eligibility rule. The number of coordinators is observed in various field sizes (60m*60m, 85m*85m, and 105m*105m) by deploying different numbers of nodes (80, 90, 100, 110, and 120). Figure 3.8 shows the number of coordinators for all these scenarios, and it is inferred that the proposed scheme has almost the same number of coordinators as that of SPAN. Also, it is inferred that as the number of nodes increases, the coordinator will almost remain constant because only a smaller fraction of nodes will become coordinators. As the field size increases, the distance between two nodes will increase, but the radio range remains constant. Since the distance between the nodes increases, the number of neighbors getting benefited will reduce. In order to cover all the nodes in the field, the number of coordinators elected increases for a constant radio range. Similarly the number of coordinators in random deployment is also analyzed.
Figure 3.8 Number of Coordinators in Uniform Deployment

Figure 3.9 Number of Coordinators in Random Deployment
Figure 3.9 shows the number of coordinators in random deployment for various scenarios, as considered in uniform deployment. Unlike the uniform deployment, the number of coordinators keeps varying to cover the entire field, due to mobility.

![Graph showing number of coordinators](image)

**Figure 3.10 Energy Conserved in the Network (Uniform Deployment of Nodes)**

Figure 3.10 shows the total energy conserved in the network for both the combined scheme and the SPAN scheme, for different scenarios in uniform deployment. It is inferred that the total energy conserved in the network increases with the number of nodes. This is due to the fact that as the number of nodes increases, the number of coordinators remains constant, whereas the number of non-coordinators increases. These non-coordinator nodes are put in the sleep state, and thereby more energy is conserved. It is also inferred that the combined scheme conserves more energy compared to the SPAN scheme, because of the low duty cycle radio concept, and the
proposed coordinator eligibility rule. Here, each and every node has an initial energy of 1000J. Hence, the total energy conserved in the network is given as

\[ E_{\text{conserved}} = E_{\text{total}} - E_{\text{consumed}} \]  

(3.17)

\[ x 10^4 \]

\[ 9 \]

\[ 8.5 \]

\[ 8 \]

\[ 7.5 \]

\[ 7 \]

\[ 6.5 \]

\[ 6 \]

\[ 5.5 \]

\[ 5 \]

\[ 80 \]

\[ 85 \]

\[ 90 \]

\[ 95 \]

\[ 100 \]

\[ 105 \]

\[ 110 \]

\[ 115 \]

\[ 120 \]

Number of Nodes

Total Energy conserved in the network (J)

Figure 3.11  Energy Conserved in the Network (Random Deployment of Nodes)

Similarly, the total energy conserved in the network in random deployment for both the SPAN and combined schemes for different scenarios, is shown in Figure 3.11. It is inferred that the energy conserved in random deployment is less compared to that of uniform deployment. In random deployment, the combined scheme conserves more energy compared to the SPAN scheme, as the number of nodes increases, and when the field size is reduced.
Figure 3.12 Lifetime Improvement Factor (Uniform Deployment of Nodes)

Figure 3.12 shows the lifetime improvement factor of the combined scheme and SPAN scheme in uniform deployment. It is observed that the combined scheme extends the network lifetime, compared to SPAN. As the number of nodes increases, the lifetime improvement factor of the network increases for all the field sizes for both the schemes. SPAN improves the lifetime by about 3.3 times when the number of nodes is 120 in the 60m*60m field size. Compared to SPAN, the combined scheme improves lifetime further to approximately 3.8 when the number of nodes is 120 in the 60m*60m field size. It is inferred that as the number of nodes increases for a given field size, the lifetime increases. Also, as the field size is reduced for a given number of nodes, the lifetime increases.
Figure 3.13  Lifetime Improvement Factor (Random Deployment with Mobility)

Figure 3.13 shows the lifetime improvement factor of the combined scheme and SPAN scheme in random deployment. As the number of nodes increases, the lifetime improvement factor of the network increases for all the field sizes for both the schemes. SPAN improves the lifetime by about 3.2 times when the number of nodes is 120 in the 60m*60m field size. Compared to SPAN, the combined scheme improves the lifetime further to approximately 3.6 when the number of nodes is 120 in the 60m*60m field size. It is observed that as the number of nodes increases for a given field size, the lifetime increases. Also, as the field size is reduced for a given number of nodes, the lifetime increases.
Figure 3.14 Capacity in Uniform Deployment Network

SPAN preserves the capacity to a great extent, by exploiting the energy factor. STEM conserves energy, whereas it does not preserve the capacity.

Figure 3.15 Capacity in Random Deployment Network
Thus, the integration of STEM and SPAN, results in capacity preservation and energy conservation. Capacity is the total number of packets delivered successfully per unit time. Here, a graph is plotted between the number of nodes and the capacity by varying the field size as shown in Figure 3.14. The combined scheme the preserves capacity without sacrificing the energy and latency. It is observed that as the number of nodes increases, the capacity is reduced.

Figure 3.15 shows the capacity in the network where a random deployment is employed for eight different scenarios. The combined scheme preserves the capacity as that of SPAN in all the scenarios. Figure 3.16 shows the latency for the STEM and the combined scheme, by deploying nodes uniformly in the field. It is observed that STEM has more latency due to an indefinite backbone path. This increase goes further, as the number of nodes increases in the different fields. Also, the latency increases as the field size increases. The latency decreases for all the scenarios in the combined scheme, due to a definite backbone path formed by the coordinators. The data is forwarded from the source to the sink through this path.

![Figure 3.16 Latency in the Network (Uniform Deployment)](image-url)
Figure 3.17 shows the latency of the combined scheme and the STEM scheme by deploying nodes randomly in the field. It is observed that the combined scheme has less latency compared to the STEM scheme.

![Figure 3.17 Latency in the Network (Random Deployment)](image)

### 3.5 SUMMARY

In this chapter, a novel hybrid topology management scheme was proposed by integrating the STEM and SPAN, and the coordinators were elected using the new coordinator eligibility rule. Here, various parameters such as energy conservation, lifetime, capacity, and latency are analysed by deploying 80, 90, 100, 110, and 120 nodes in various field sizes, such as 60m*60m, 85m*85m, and 105m*105m, using uniform and random deployment of nodes. It is inferred that in both cases, as the number of nodes increases, the total energy conserved in the network increases by keeping the field size constant. Similarly, as the field size is reduced, the total energy conserved in the network is increased for a fixed number of nodes. Thus, it
can be concluded that deploying more nodes (120 nodes) in a small field size (60m*60m) conserves more energy.

It is also inferred that the combined scheme results in larger energy conservation compared to SPAN, which reflects in further improvement in the lifetime factor of about 3.8 compared to SPAN. The combined scheme has less latency compared to STEM, due to a definite backbone path through which the data is forwarded to the sink. These improvements in the network parameters such as energy conservation, lifetime, and latency are achieved, without sacrificing capacity. The critical application requires the data to be forwarded quickly to the sink by conserving more energy without any loss of data. Since the proposed scheme meets all these requirements, it will be well suited for hazardous applications.