GSIS of Ajou University

Research on Energy Efficient Communication Schemes for Wireless Sensor Networks

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To all from whom I have learned
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Saurabh Mehta

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Abstract

Wireless sensor networking is an emerging technology that has a wide range of potential applications including monitoring, medical systems and robotic exploration. Sensor networks normally consist of a large number of densely deployed distributed nodes that organize themselves into multiple-hop wireless networks. As sensor networks become an integral component of future communication services, energy efficiency will be an important design consideration due to limited battery life of sensor nodes. Since the communication component is a significant consumer of energy, considerable research has been devoted to low-power design of the entire networks protocol stack of sensor networks.

This thesis proposed four different energy efficient schemes for sensor networks. First one is topology generation algorithm by using flooding and gossiping methods with some new parameters. In second scheme, we proposed energy efficient algorithm to help routing protocols to increases a network lifetime by fairly distributing the relay load among the nodes with the help of two different operating modes. We proposed an IS-MAC protocol in third scheme that improves the energy efficiency further from S-MAC and T-MAC by redefining the minimum timer period. We also addressed the QoS issues like per-node fairness, channel capacity utilization and latency. Finally IS-MAC based flooding protocol is presented in fourth scheme.

All the performance evaluation for each scheme shows that proposed schemes save the energy consumption over existing schemes in given sensor networks.
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Chapter 1 Introduction

Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power; multifunctional sensor nodes that are small in size and communicate in short distance [1], [2]. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of wireless sensor networks. Wireless sensor networks represent a significant improvement over traditional sensors.

A wireless sensor networks is composed of a large number of sensor nodes that are densely deployed either inside the phenomenon or very close to it. Although many protocols and algorithms have been proposed for traditional wireless ad hoc networks, they are not well suited to the unique features and application requirements of wireless sensor network. The difference between wireless sensor networks and ad hoc networks are [3]-[8]:

- Sensor nodes are densely deployed. The number of sensor nodes in a sensor network can be up to hundreds to thousands, higher than the nodes in an ad hoc network.
- Sensor nodes are prone to failure and the topology of sensor network changes very frequently (it depends on application).
- Sensor nodes mainly use broadcast communication methods whereas most ad hoc networks are based on point-to-point communications.
- Sensor nodes may not have global identification (ID) because of the large amount of overhead and large number of sensors.
- In sensor network multi hop communication is expected to be less power consuming compared to the traditional single hop
communication due to densely deployment.
• Multi hop communication can also effectively overcome some of the signal propagation effects experienced in long distance wireless communication.

In the past few years, many wireless sensor networks have been deployed. We present a short summary of the recent deployed sensor network applications. These applications decide wireless sensor networks (WSNs) architecture design and lead to explore the requirements and constraints for WSNs.

**Smart Spaces**
Smart Spaces are work environments with multi-modal sensors, embedded computers, and information appliances allowing people to perform tasks efficiently by offering unprecedented levels of access to information and assistance. Given the great market potential, this application will surely mark a big milestone in sensor networks. An example application in this category is “Smart Kindergarten” [9].

**Environment Monitoring and Forecasting**
Environment sensor networks such as in plains or deserts or on mountains or ocean surfaces are used to detect, monitor, and forecast environmental changes.

**Surveillance and Security**
Wireless surveillance sensor networks for providing security in a shopping mall, parking garage, or other facility.

**Traffic Monitoring**
Wireless traffic sensor networks are deployed to monitor vehicle traffic on a highway or in a congested part of a city.
Although the basic goals of WSNs generally depend upon the application, but the following requirements are common to many WSNs:

1. Energy Efficiency
2. Scalability
3. Self-configurability
4. Security
5. QoS Support and simplicity

This thesis presents my graduate school work on developing energy efficient schemes for wireless sensor networks. We have developed four energy efficient schemes for wireless sensor networks. In chapter 2, we propose an energy efficient and self-configure topology generation algorithm for sensor networks that is based on flooding and gossiping methods. We proposed the energy efficient algorithm to increase a sensor network lifetime in chapter 3. A node lifetime and numerical analysis show the comparison of the proposed algorithm with existing algorithm to increase a network lifetime. The proposed algorithm increases a critical node lifetime by 38% and enhances a network lifetime.

In chapter 4, we proposed the Improved Sensor (IS) MAC protocol for a wireless sensor network. The proposed protocol algorithm maintains energy efficiency in all traffic conditions as well as QoS issues like per-node fairness, channel capacity utilization and latency. Analytical results show that IS-MAC has significant improvements in energy consumption and QoS parameters compared to the existing
MAC protocols under varying traffic and QoS conditions for sensor networks.

In chapter 5, we proposed the IS-MAC based flooding protocol. Numerical results show the proposed algorithm’s energy efficiency over existing protocol.

Finally in chapter 6, we conclude our works on energy efficient communication schemes for wireless sensor networks.
Chapter 2 Topology Generation Algorithm for Sensor Networks

2.1 Introduction

For ad-hoc networks protocols, like wireless sensor networks, there exist two important phases. The first one is route discovery and the second one is route maintenance. A sensor network has some special requirements like low mobility network, security, energy efficiency, self configuration, scalability and simplicity. As a result, sensor networks encounter some challenges like energy constraint, topology discovery, collaborative signal, information processing and security. In this chapter, we proposed topology generation algorithms for sensor networks. Figure 2-1 shows the application scenario of sensor networks.

![Fig.2-1 Application scenario](image-url)
2.2 Motivation and Related Work

In cluster formation, there are mainly two types of approaches. The first one is flat and the second one is hierarchical type. For our problem, there are many topology algorithms available but after comparing and evaluating different topology algorithms [11]-[16], we proposed our algorithm. Bluetooth technology is another good candidate solution for static or low mobility networks, but it has some disadvantages as it is only good for cluster type of structure. We can not apply it for flat type topology. Even in the cluster approach, Bluetooth can take only maximum 7 nodes as group members. Major flaw is that a master has to synchronize with its all member nodes. It has to transmit signal on a regular interval which is not energy efficient. When any master wants to talk with other cluster master and if its node capacity is full, it can’t communicate with others. Even if any vacant place is available, one master has to change its status from master to slave. This situation changes the topology so this can not be suitable for energy constraint networks [11]. As discussed in [12], we need some position indicating systems to maintain topology which is very complex and needs good precision techniques. That is, a network has to take care of two things: location system and topology. GPS can be a solution for location but, GPS is a non-realistic approach in home networks environment. Randomized leader election protocol is more suitable for ad hoc networks, but not for sensor networks. The approach in [13] also requires the support of GPS system. Similar problem can be found in [14]. Such a method is good for large and open space applications but it is not suitable for home environment.
Garcia in [15] proposed some good algorithms which are cluster based. Cluster based architecture is always complex in nature compared to flat type of architecture. It increases the overhead in networks due to cluster’s ID and individual ID. It imposes extra burden on cluster head for routing data between nodes and sink. Merging of two groups and mobility management is also more complex as well as energy inefficient in some applications. It may also create the problem of latency. In [15], whenever any change occurs in topology, all nodes should be reconfigured. While designing a network, we have to take care of boundary nodes as well. Deb in [16] has offered 3 and 4 colors methods but it is very complex. In addition, the algorithm’s accuracy depends on timer setting and system of distance measurement. The method proposed in [17] is further advancement of color based algorithm system. They have set some parameters to make the algorithm energy efficient but this is also very complex. Furthermore, the same problem of parameter setting in [16] arises. All above proposed algorithms are suitable for ad hoc network but we can not apply them directly to sensor networks. As we mentioned previously, since sensor networks have some special characteristics, we need to improve them and apply some new techniques.

2.3 The Proposed Topology Discovery Algorithm

The proposed algorithm is based on flooding and gossiping methods. We used some simple techniques and introducing some new parameters to improve the flooding method in energy efficient way. It also increases network robustness, reduces latency, abbreviates data
congestion, and suits for dense sensor networks environment. We have taken the reference [10] as our base and proposed an improved technique. In addition, we assume that sensors are uniformly distributed and deployed with static ID. The parameter $K$ is different from the normal cluster ID. It decides the number of children nodes rather than the node’s address.

2.3.1 Algorithm
1. If we want to deploy $X$ number of nodes in a given area, we have to take $(X + C)$ nodes for deploying, where the parameter $C$ stands for extra nodes to increase topology robustness.
2. Each node sets one $K$ value. Value of $K$ decides the number of children nodes that a parent node is going to support.
3. Each node can select just one node as its parent.
4. If a node receives two signals from two different nodes like $X$ and $(X + 1)$, it will select $(X + 1)$ as its parent node and neglect other signals.
5. After selecting any node as a parent node, children nodes can’t accept any more advertise.
6. Children nodes can broadcast Hello signal only after it receives an ACK signal from its parent.
7. After selecting its entire children set (set $K$) a parent node will not broadcast any signals.
8. After discovery phase, network gathers information about all nodes at a regular interval. As a result, whatever changes occur in network, it can configure to accommodate them.
We can understand all above steps from the example shown in figure 2-2. For this example, \( K=3 \) is used and any node can select maximum 3 children nodes. Node 1 is a sink node (basic node). It will send Hello signal. Node 2, 3 and 4 accept node 1’s advertising signal and send their response back to node 1. Therefore, node 1 is a parent node for them and node 2, 3 and 4 can not accept any other advertising signals. The numbers in brackets represent the parent’s ID.

Now node 2, 3 and 4 advertise and node 5 first selects node 4 as its parent as shown in figure 2-2. Here dotted line shows a possible route and we can see node 6 receives advertise from node 4 and 5 but it will select node 5 as per the proposed algorithm’s step No. 4. Because of this condition, the network grows further and tries to cover area very rapidly. After finishing discovery phase, the network is ready for data transmission. This algorithm has 3 phases, namely broadcasting, response, and maintenance. After some predefined time interval, all parents gather information from their children and send it to the root of the network. As the root has all nodes’ ID and route information, whenever any node dies due to power problem, the root can easily reconstruct the topology. For most cases, we don’t need to discover the full network topology.

![Sensor network topology (\( K=3 \))](image)

Fig.2-2 Sensor network topology (\( K=3 \))
2.3.2 Algorithm Signal Flow

The proposed algorithm uses 4 signals for topology discovery. They are as follows.

1. Hello signal: This is a broadcast signal that gives advertisement data of broadcasting node, like ID etc.
2. Request signal: In response to Hello signal children nodes send their request to select parent node.
3. Acknowledgement signal: After receiving request signals from children nodes, the parent node checks its present value of $K$. If it is less than the set value, it will accept the request signals and send back acknowledgement signals. After receiving this acknowledgement signal, children node stops sending request signals and thus saves energy.
4. Hi signal: After discovering full topology, sink node will pass this signal to every node. This signal is only used by sink node. When topology discovery operation finished, there are only children and they broadcast Hello signal on a regular basis which is of no use. To save energy, sink node transmits Hi signal after discovering topology. This signal used to switch off the broadcasting of Hello signal from children nodes as well as from parent node whose $K$ value is smaller than the set $K$ value. Figure 2-3 shows the all four signals.

Fig.2-3 Different signals used for the proposed algorithm
2.4 Performance Metrics

2.4.1 Node degree
This metric represents the number of children that every node has. This is a very important metric because that can directly effect on energy consumption of that particular parent node. Here every node takes data from children and forwards it to upper root (parent node), so for every signal or data, parent node has to use its own energy. If we select low value of $K$, it can reduce energy consumption but it will increase latency in the network and also increase number of hops in the network. For small value of $K$ like $K=1$, it is very difficult to form network topology so we have to choose optimal value of $K$, that the designer can select by proper simulation. From above discussion we can conclude that:

\[ E_{\text{node}} \propto K \]  

(1)

2.4.2 Robustness
Robustness of the network shows the capability of the network to work even after any node gets failed. By providing number of links between neighbor nodes (Mesh Networks), we can increase robustness of the network. Therefore we need to do some modifications in the proposed algorithm’s step no.3. But this approach is not always good as it can also create the problem of more power consumption. Some extra nodes ($C$ factor in the step No. 1) can help in maintaining network topology and robustness. For example, if we take 13 nodes for covering required area and set $K=3$, then there will be 4 parent nodes (considering worst case) in this example. If any of the parent nodes gets affected due to power failure, then there will be disconnection between that parent node and its
children. If we consider the case where all other parents are full with their children capacity, then we have to discover new topology. As a result, we can provide some extra nodes which can take charge of disconnected children(s). For the aforementioned example, we can take the value of $C$ from 1 to 2. Basically that depends on total number of nodes, the value of $K$, and the required quality of service of networks.

2.4.3 Latency
Latency means the delay in time when a node is asked to sense till the sink receives the query response. It depends on the number of hops in networks and factor $K$. If value of $K$ is small then the number of hops and links will increases. This can create a problem in response. So we have to choose all parameters in such a way that, it can give tolerable value of latency as required.

From above discussion, we calculated the numerical results. For our numerical results we consider the 25 sensor nodes. Figure 2-4 shows the average number of node supported by parent nodes whose $K$ value varies from 1 to 5. And figure 2-5 shows the graph of packet arrival rate vs. energy consumption by parent node to supports its children. From figure 2-4 we can observe that as value of $K$ increases average number of node supported by parent node decreases and hence decreases the energy consumption of a parent node. Figure 2-5 shows the same fact with different packet arrival rates.
Fig. 2-4 Different value of $K$

Fig.2-5 Energy consumption of a parent node
2.5 Summary and Future Work

In this chapter, we proposed a simple flooding and gossiping based method with some new parameters. The objectives of the proposed approach are the simplicity and reduced overhead control load. The proposed algorithm improves performance, robustness, and node degree and also reduces the latency. In this chapter we considered all nodes with the same value of $K$. But we can consider an algorithm with different values of $K$. And at the end, we presented our numerical results. This algorithm is simple to implement and also reduces overhead control load. The proposed algorithm is more suitable for the dense sensor networks environments.
Chapter 3 The Energy–Efficient Algorithm for a Sensor Network

3.1 Introduction

The rapid development in small, low-power, low-cost microelectronic and micro-electromechanical (MEMs) sensor technology along with the advances in wireless technology have enabled wireless sensor networks to be deployed in large quantities to form wireless sensor networks for a wide uses. A dense wireless sensor network (WSN) collects environmental data and sends to a sink node. There are multiple scenarios in which such networks find uses, such as environmental monitoring and controlling, automatic manufacturing environments, interactive toys, the smart home providing security, identification, personalization and context awareness, and medical applications.

3.2 Motivation and Related Work

Due to energy constrain, energy efficiency is a critical consideration for designing the sensor networks and its routing protocols. In [18] authors describe upper bound on the lifetime of sensor networks, while in [18] the lifetime of a cluster based sensor that provides periodic data is studied. In a large sensor network all the nodes send their data to sink node for the further processing as shown in figure 3-1, due to this fact the nodes near to sink node consumed their energy more rapidly compared to other sensor nodes. In [19] authors describe the problem of developing an energy efficient operation of
a randomly deployed multi-hop sensor network by extending the lifetime of the critical nodes and as a result the overall network’s operation lifetime, were considered and analyzed but they didn’t propose any solution for the same. In this chapter, we are extending our work further from [19] and proposing algorithm to increase the critical node lifetime and hence a network lifetime. In [20-23] authors suggested power aware multiple paths algorithms to distribute the relay load equally among all the nodes. In a multiple paths algorithm node has to maintain the routing table which requires good memory capacity and periodic update for any new change in topology but this update increases the overhead. Multiple paths also help to distribute loads among the sensor nodes. But for distributing equally or fairly we need to set some metrics. Generally it may be energy, delay or minimum hop count path and etc. All these metrics calculation requires complex algorithm and high computational resources but beside these disadvantages multiple paths structure is very robust and reliable. Especially it is very useful for static applications.

In single path algorithm there is only one path available from source to sink and normally it is a minimum hop path. Due to single path there is always very heavy traffic on the route and also its lifetime is short but we can overcome these disadvantages by implementing the proposed algorithm which distributes the load among the nodes. In multiple paths every node is connected to the number of paths and it is not practical to make them work in just one mode. Further we evaluated the efficiency of each algorithm from mathematical and numerical analysis. In most of the literature [18-23] authors emphasize on energy efficient routing algorithm or physical layer. As
far as our knowledge is concerned all proposed solutions for the sensor networks lifetime are categorized as follows.

- Using an energy efficient routing algorithm.
- Using higher battery capacity relay node or cluster based method.
- Distributing the routing load among the all sensor nodes (Multiple paths approach).
- Using the different working modes for a node.

In this chapter, we concentrated on a link instead of considering the full path for the routing data and proposed the energy efficient algorithm for a node to decide when it should take part in routing and when it should leave the routing. We also compared the performance of existing power aware energy algorithm with our proposed algorithm.

### 3.3 Sensor Networks Model

Here we considered a large network which contains $N$ number of densely deployed sensor nodes with one sink.

![Fig.3-1. Sensor networks](image)
All nodes have to transfer their data to sink that means a common destination address for all the nodes. All nodes in a sensor networks are static, same in size, battery capacity and etc. Every node has a static ID (Not IP) and does the relying and sensing. We make our further assumption from [19] as follows.

- \( E_o \) = Total energy of a node.
- \( e_s \) = The energy needed to sense one bit for \( i^{th} \) node that is \( s_i \). It depends on the power dissipation of the internal circuitry.
- \( e_{ri} \) = The energy needed to receive a bit by \( i^{th} \) node.
- \( e_{ti} \) = The energy required to transmit a bit. It is given by the \( e_{ti} = E_o + ep (d/d_s)^n \), where \( ep \) is the energy consumed to transmit a bit to the reference distance \( d_s \) and \( n \) is the path loss index. \( d \) represents actual distance.
- \( e_p \) = The energy consumed per bit for data processing.
- \( e_{pro} \) = The energy consumed for data processing and aggregation by \( i^{th} \) node. \( e_{pro} = e_p + ed(\gamma) \), where \( ed(\gamma) \) is energy required for data aggregation. It is a function of aggregation ratio \( \gamma \). \( e_{pro} = e_p \), where \( ed(\gamma) = 0 \) when \( \gamma = 1 \).
- \( \lambda_s \) = The number of packets generated per unit time by \( s_i \).
- \( \lambda_r \) = The number of packets relayed per unit time by \( s_i \).
- \( L \) = Length of a data packet.

Figure 3-1 shows a sensor network model’s first quadrant, here we considered only one collector node which is placed at the center of a network. Now based on the above definitions and assumptions, the power dissipation of node \( s_i \) in a sensor network is given by
\[ p_i = \epsilon_s \lambda_{ai} L + \epsilon_s \lambda_{ri} L + [\lambda_{ai} + \lambda_{ri}] \epsilon_{pos} L + [\lambda_{ai} + \lambda_{ri}] \epsilon_{rs} L. \] 

(1)

For simplicity we considered \( \gamma = 1 \) and \( d = d_0 \). Still we can simplify above terms by assuming that \( \epsilon_p = \epsilon_s = \epsilon / 2 \) and \( \epsilon_{rs} = \epsilon_{rs} = \epsilon \) [18].

From all above assumption we can rewrite (1) in the following way

\[ P_i = [2 \epsilon + \epsilon_s f] \lambda_{ai} L + [2.5 \epsilon + \epsilon_s f] \lambda_{ri} L \]

(2)

And let \( E(t_i) \) be \( i \)th node lifetime that we have

\[ E(t_i) = \frac{E_0}{P_i}. \]  

(3)

From (2) we can observe that power consumed by a node is divided into two terms. First term is used only for sensing and transmitting its own data and second term used for the relaying purpose. Figure 3-2 (a) shows the above condition. From (2) we can conclude that 65% of its energy gets used only for the relaying data that is main cause of energy consumption for a node [20].

We can make second term equal to zero only if a node doesn’t need to relay any external data packet. This can be possible only in one case when a sink node is in range of all sensors as shown in figure 3-2 (b). This means we need to create an infrastructure or backbone in a
sensor networks which will carry the node’s relay load but still this will cause a problem of an early disconnection in the networks. Here we proposed our scheme which helps nodes to create an energy efficient routing backbone based on energy consumption metric.

### 3.4 Proposed Scheme

The basic idea of the proposed scheme can be understand from the following steps.

1. All nodes are working under two mode, relay and sense and keep changing their modes as per the scheme’s set condition. Figure 3-3 gives clear idea about these two modes and their transition.
2. At first, sink node will broadcast an advertisement for hop count information and after some delay all nodes will know its hop position.
3. After the hop information, sink node choose random nodes which are one hop apart from each other for carrying relay loads.
4. Let us denote all randomly chosen nodes as Cluster Node (CN). All CN(s) advertise about their status and collects information about their members.
5. All CN(s) will establish connection with just one node which is only one hop apart and has lower hop count than CN and it will be also consider as CN.
6. All CN will operate in relay mode and the rest of the nodes are in sense mode. CN will operate in relay mode until the remaining energy reach to its set energy threshold. Then it will broadcast an advertisement for a mode change. This advertisement contents its ID, upper and lower hop CN ID and its energy level.
7. CN will wait for some random delay. During this delay time some response will come from the near by node and CN will change its mode from relay to sense. Furthermore it will choose new CN for the relay. Due to densely deployment of sensors, backbone connectivity with upstream and down stream neighbors will maintain.  

8. Now old CN will work in sense mode. If any advertisement comes for relay and if that advertisement satisfied all decision condition then it will again enter into the relay mode otherwise remain in a same mode.

![Diagram](image)

(a) Two modes of a node  
(b) A node change its state

**Fig. 3-3. A node’s transition**

- **Proposed Scheme Pseudo Code**

```plaintext
Begin
  If (mode==sense) sense_mode ();
  else relay_mode ();
End

sense_mode ();
Begin
  If (senser_pkt_int==arrived) ++sense;
  --energy; create_data_tx ();
  Begin
    If (energy>adv_energy) change_mode ();
    else cont_sense_mode ();
  End
End

relay_mode ();
Begin
  If (relay_pkt_int==arrived) ++relay;
End
```
--energy; next_hop_tx ();
Begin
Begin
If (energy<limit) energy_adv_tx ();
else cont_relay_mode ();
End
End

Where,

1. create_data_tx () = Procedure for creating data frame and transmitting to near by CN(s).
2. change_mode () = Procedure for changing the operation mode.
3. cont_sensing_mode () = Procedure for continuing the operation in sensing mode.
4. next_hop_tx () = Procedure for transmitting packet to next hop.
5. energy_adv_tx () = Procedure for transmitting an advertisement for changing the mode and change the mode on receiving acknowledgement.

3.5 A Node Lifetime Analysis

As we proposed in the scheme all nodes will work in two modes and their energy consumption will change according to their operating mode. Energy consumed in relay mode is given by

\[ P_{\text{ri}} = (2.5 \varepsilon + e_{rf}) \lambda_n L. \]  \hspace{1cm} (4)

Energy consumed in sense mode is given by

\[ P_{\text{si}} = (2 \varepsilon + e_{sf}) \lambda_n L, \]  \hspace{1cm} (5)

but in our proposed scheme sensor node also need to transmit and receive some overhead signals. We added 0.5 \varepsilon in the above term. So modified equation is as follows.

\[ P_{\text{n}} = (2.5 \varepsilon + e_{rf}) \lambda_n L. \]  \hspace{1cm} (6)

In multiple paths, a node’s energy consumption is given by
In the proposed algorithm nodes change its state according to energy threshold set that is decided by a number of neighbor, so to find lifetime of a node we need to find average power consumption at node during all modes and it is given by

\[ P_i = [\lambda_o + \lambda_n][2.5\epsilon + \epsilon_f]L. \]  

(7)

where \( n \) and \( m \) is a number of time node enter in relay and sense mode, while \( H_t \) and \( H_i \) represents total number of hop count and individual node respectively. To know networks lifetime we need to calculate average lifetime of critical node. Here critical node means a node which connects sink with other sensor nodes. To calculate average lifetime of a node we need to calculate maximum traffic rate arriving at critical node in multiple path as well as single path case.

3.5.1 Multiple Path Analysis

Maximum traffic that can arrive at critical node is given by

\[ \text{Relay packets} + \text{Own generated packets} = \left[ \sum_{i}^{n_p} \lambda_o f(e) + \sum_{i}^{n_c} \lambda_o + \lambda_s \right]. \]  

(9)

Where \( n_p \) is number of path connected to critical node and \( n_p \) means number of critical paths connected to critical node. If we consider that multiple path algorithm is energy aware, \( n_p \) is depends on a function of energy \( f(e) \) and its value varies from 1 to 0. Here critical path means, a path don’t have any other routing path except one connected to critical node. Now from (1), (7) and (9), power consumed at multiple paths node is given by
From (3) and (10) node lifetime is given by

\[ E(t_i) = \frac{E_0}{\left\{ \sum_i^s \lambda_i f(e) + \sum_i^s \lambda_i + \lambda_s \right\} (2.5e + e_f)L}. \]  \tag{11} \]

\[ P_i = \left[ \sum_i^s \lambda_i f(e) + \sum_i^s \lambda_i + \lambda_s \right] \times [2.5e + e_f]L. \tag{10} \]

3.5.2 Single Path Analysis

Maximum traffic that can arrive at node when it is in relay mode is given by

\[ \lambda_{ri} = \sum_{j=H_i+1}^{H} \lambda_{rhi}. \tag{12} \]

Where \( \lambda_{rhi} \) is the number of packets relay by a CN. Maximum traffic at node when it is in sense mode is given by \( \lambda_s \) and average \( P_i \) is given from (8). From (3) and (8) node lifetime is given by

\[ E(t_i) = \frac{E_0(m+n)}{\left\{ \sum_i^s \left[ \sum_{j=H_i+1}^{H} \lambda_{rhi}(2.5e + e_f)L \right] + \sum_i^s \left[ (2.5e + e_f)\lambda_i L \right] \right\}}. \tag{13} \]

To understand our analysis considered the example shown in figure 3-4. As shown in figure 3-4 nodes A is surrounded by four nodes B, C, D and E respectively and located at first hop so all nodes are considered as critical nodes. Node A’s lifetime represents a network lifetime. First, node A selected as CN node and work in relay mode. Rest of the nodes will work in sense mode. Now our proposed scheme will control the topology.
3.6 Numerical Results

In this section, we show numerical results based on the node lifetime analysis introduced in the previous section. All nodes have 6 joule battery capacity which can support 9000 packets of 32 bytes long for receiving and transmitting. In sensor networks relay rate is always higher than the packet generating rate.

![Node A and its neighbors](image)

Fig. 3-4. Node A and its neighbors

From [18], [20], and [23], we assumed some parameter’s values and summarized them in TABLE I.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Assumed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_s$</td>
<td>6 j</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>50 nj</td>
</tr>
<tr>
<td>$\lambda_s$</td>
<td>5 pkt/hr</td>
</tr>
<tr>
<td>$L$</td>
<td>32 byte</td>
</tr>
<tr>
<td>$\epsilon_v$</td>
<td>2.5 $\mu_j$</td>
</tr>
</tbody>
</table>
We divided the total energy into the number of threshold level, as per the proposed scheme node will change its state on every threshold level. As we can see it from figure 3-5, the number of packet arrival rate will also change accordingly. When a node is in a relay mode it has to process on a larger number of packets than in sense mode. This is the key factor of the proposed scheme. Because of two operating modes average arrival rate of packets is low compared to energy aware multiple path algorithm.

Figure 3-6, 3-7 and 3-8 show some important numerical results which are based on a node lifetime analysis and assumptions. Figure 3-6 shows the critical node A’s lifetime. From figure 3-6 we can observe that the proposed algorithm increases the critical node lifetime and hence a networks lifetime. From figure 3-6 we can observe that the arrival rate of packets in multiple paths scheme is depends on a function of energy. As the energy level decreases the number of packet process by a node decreases but the average arrival rate of packet is higher than a single path algorithm. This is the main difference between the two schemes. From figure 3-7 we can observe the lifetime of node B, C, D and E. They change their mode according to proposed scheme. If we take cumulative effect of all nodes (A, B, C, D and E) then it will increase networks life time by 4 times but here we consider only one critical node lifetime as networks lifetime.
Figure 3-5 shows the energy consumed by one packet to reach destination from source. The proposed scheme always creates a minimum hop path from source to destination. But in multiple path algorithm it generally varies from a minimum hop path to maximum as multiple path scheme is depends on a function of energy. For real time application the number of hop required to transmit the data from source to destination is very important because it involves the delay factor in transmission.

Fig. 3-6. Critical node lifetime
Fig. 3-7. Node A, B, C, D and E’s lifetime

Fig. 3-8. Hop path for a node
3.7 Summary

In this chapter, we proposed the scheme to increase a network lifetime and we compared it with multiple energy aware path scheme. The proposed scheme increases a network lifetime by fairly distributing the relay load among the nodes with the help of two different operating modes. So our approach is suitable for a densely deployed sensor networks. Numerical result shows the good improvement in a critical node lifetime. The proposed scheme increase the lifetime by around 38% which looks quite promising and the proposed scheme generate a minimum hop path which is very important result for the real time data applications.
Chapter 4 Improved Sensor MAC Protocol for a Sensor Network

4.1 Introduction

Wireless sensor networking is an emerging technology that has a wide range of potential applications including monitoring, medical systems and robotic exploration. Sensor networks normally consists of a large number of densely deployed distributed nodes that organize themselves into a multi-hop wireless networks.

4.2 Motivation and Related Works

Communication in wireless sensor networks is divided into several layers. One of those is the Medium Access Control (MAC) layer. MAC is an important technique that enables the successful operation of the network. MAC protocol tries to avoid collisions so that two interfering nodes do not transmit at the same time. There are some MAC protocols that have been developed for wireless sensor networks. Typical examples include S-MAC and T-MAC [24], [25]. The main design goal of a typical MAC protocols is to provide high throughput and QoS. On the other hand, wireless sensor MAC protocol gives higher priority to minimize energy consumption than QoS requirements [24], [25]. Energy gets wasted in traditional MAC layer protocols due to idle listening, collision, protocol overhead, and over-hearing [25].

Idle listening is the most prominent reasons for the energy waste among all the above mentioned reasons. In many MAC protocols
such as IEEE 802.11 ad hoc mode or CSMA nodes have to listen to the channel to receive possible traffic. Simulation results from [26] and Wireless LAN module (IEEE 802.11) specification [27] show that the energy consumption ratio between idle-mode, receive-mode and send-mode is 1:1.05:1.4 and 1:2:2.5 respectively. IEEE 802.11 MAC protocol uses contention-based CSMA and has power saving characteristics. However, all nodes need to be located in the same network and thus communication is limited to one hop. Hence, it is not suitable for sensor networks which require multi-hop communication [24]. In [28] authors used wake up signal for waking up nodes and thus no additional data processing is necessary. Although, the protocol is highly energy efficient, additional devices need to be implemented on nodes and a separate frequency needed to be allocated for the signal.

S-MAC and T-MAC protocols are proposed to improve energy efficiency in wireless sensor networks [24], [25]. S-MAC is a contention based MAC protocol that uses a single frequency. In S-MAC time is divided into frames that consist of active and sleep periods as shown in figure 4-1(a). During the sleep period, radio is turned off and data is not transmitted but stored in buffer. During the active period the stored data is communicated with neighboring node. S-MAC uses fixed duty cycles that is fixed according to high traffic condition. Hence, it is not suitable for varying traffic conditions that cause the energy waste. T-MAC is modified form of S-MAC protocol that uses a timer to switch to sleep mode after a certain period of time when it detects that there is no data to send and receive.
(a) One complete cycle of sensor network’s MAC protocol

(b) Sub part of active time

Fig. 4-1 Main and subpart of sensor network’s one complete cycle.

This timer improves the energy efficiency of protocol. T-MAC gives better performance than S-MAC especially for low traffic rate. Figure 4-2 represents one complete cycle of T-MAC.

Fig. 4-2 T-MAC completes cycle with different time frame.

Most of the proposed MAC-protocol focused on energy efficiency rather than higher throughput and QoS issues. In this chapter, we proposed Improved Sensor-MAC (IS-MAC) protocol that improves the energy efficiency further from S-MAC and T-MAC by redefining the minimum timer period. We also focused to achieve better energy efficiency with good throughput and QoS issues like per-node fairness, channel capacity utilization and latency in all varying traffic
conditions. The proposed IS-MAC protocol works in two different modes to get better energy efficiency and QoS.

The contributions of this chapter are as follows.

- We defined minimum timer period to switch to sleep mode that improves the energy-efficiency of the MAC protocol.
- We divided the data buffer into three threshold levels and set priority according to specific threshold levels to improve energy efficiency and fairness per-node.
- We redefined bakeoff timer according to threshold levels to improve the fairness per-node.
- We defined the two working mode of IS-MAC

4.3 IS-MAC Protocol

IS-MAC uses a fixed sized buffer to store the data which are generated during the sleeping time. Here, we defined three threshold levels HIGH, MEDIUM and LOW as shown in figure 4-3. Theses threshold values solve two problems and used for IS-MAC. First, threshold value reduces the unfairness problem of IEEE 802.11 by changing the back-off timer. Second, it optimizes energy efficiency in varying traffic conditions. Threshold values depend on the buffer length. Data is transferred if the buffered data exceed lower threshold value. Otherwise, the timer is set to a smaller value than in T-MAC. The protocol switches to sleep mode when node does not transmit Request-to-Send (RTS) control packet or data packet during the timer period. $q_{\alpha}$ is the accumulated data packets size in a buffer, $q_t$ is the total buffer size of the sensor node, and $\alpha$ is the threshold weight. $Th_l$, $Th_m$, and $Th_h$ represents LOW, MEDIUM, and HIGH threshold value
respectively, where $0 < \alpha_l < 0.25$ for $Th_l$, $0.25 < \alpha_m < 0.5$ for $Th_m$, and $0.5 < \alpha_h < 0.75$ for $Th_h$. The threshold values are expressed as follows.

$$Th_k = \alpha_k \times q_k.$$  

(1)

Where, $k= l, m, \text{and } h$ is low, medium, and high respectively.

![Fig.4-3 Buffer with threshold values](image_url)

In IS-MAC protocol, sensor nodes check the value of the accumulated data packets size ($Q_{size}$) in their buffers and transfer data only if the condition $Q_{size} \geq Th_l$ is met. Future RTS (F-RTS) is used to reserve multi-hop data transfer within the same frame. This feature significantly improves the data transmission delay along with the energy efficiency. We need to limit F-RTS to certain hop to trade off between channel utilization efficiency and delay. We explored this issue under performance analysis section.

IS-MAC works under 2 modes.

1. Buffered mode with future reservation
2. Buffered mode without future reservation.

1 **Buffered mode with future reservation:** In this mode, IS-MAC protocol transfer the maximum $N_{is-mac}$ data packets until 3 hops within one cycle time using F-RTS signal (Assuming fixed active period). For the optimal performance analysis we considered the $Q_{size} = Th_l = N_{is-mac}$ condition. This mode helps sensor node to take the
advantage of pipeline operation of IS-MAC. Pipeline operation is very useful when a source node have more than $N_{is-mac}$ data packets in its buffer to transmit. For pipeline operation a node should satisfy lower threshold condition in every cycle and set the piggyback massage in the last data packet for maintaining the channel access in following cycles. (We explored this pipeline concept under the buffer’s optimization section.) We considered only this mode for our analysis.

2 Buffered mode without future reservation: In this mode, IS-MAC uses the lower threshold condition for data transfer but limited to 1 hop within one cycle. This mode is similar to S-MAC protocol. Due to lower threshold condition we can maintain fairness per node and priority setting advantage of IS-MAC. In this chapter, we didn’t consider this mode for our performance analysis. This mode is similar to S-MAC but still gives the better energy efficiency and fairness per node.

4.3.1 Back-off Time
Because of back-off time algorithm nodes have very heavy competition among them to access free channel. On every unsuccessful trial window size gets doubles till its maximum value and increases back-off time. Some times a node with few data packets gets priority over node having large number of data packets because of the fact that permission to access channel do not depends on the number of data packets. For Ad-hoc networks this characteristics of MAC may not be so important but for sensor networks it’s very important. For the same reason we modified IS-MAC back off time that gives higher priority to node with large
number of packets and also reduces unnecessary competition among sensor nodes. In IEEE 802.11 specification [27] back-off time is defined as follows

\[ bt(r) = \left\lceil W(r) + \left\lfloor RAN(\cdot) \times W(r) \right\rfloor \right\rceil \times \Delta. \]  

(2)

The back-off time \(bt\) is a function of a retrial number \(r\). Let \(W(r)\) be the back-off window frame and its given by \(W(r) = 2^{2r}\). Where, \(RAN()\) denotes a random value between 0 and 1 and \(\Delta\) is duration of each time slot. \([\ast]\) define the largest integer value which is equal to \(\ast\).

Based on equation (2) we proposed a modification in back-off time for IS-MAC. Here, back-off time \(bt\) is a function of priority level \(p_{bt}\) and a retrial number \(r\). \(p_{bt}\) depends on \([1 - \alpha]\), where \(\alpha = [\alpha_i, \alpha_m, \alpha_s]\). We can fix the maximum number of retrial and duration of each time slot for a fixed contention time frame. For each priority level, the back-off time is determined as follows.

\[ bt(p_{bt}, r) = \left\lfloor p_{bt} \times \left\lceil W(r) + \left\lfloor RAN(\cdot) \times W(r) \right\rfloor \right\rfloor \right\rceil \times \Delta. \]  

(3)

In IS-MAC protocol, each node has one of the different priority levels: HIGH, MEDIUM, and LOW. These priorities are given to node according to buffer length. Back-off timer also depends on these priorities and helps protocol to increase fairness per node.

### 4.3.2 Optimization for buffer’s minimum threshold level

As we mentioned earlier in this chapter IS-MAC can only transmits the data when \(Q_{size} \geq T_{th}\) condition gets satisfied. Now it is very important to optimize the buffer’s threshold value that controls the network delay performance. Sensor networks is an application based networks and applications requirement gives the upper bound on the network delay. Threshold levels in IS-MAC reduce the competition
among the nodes and gives higher priority to a node with large amount of data. The only disadvantage of threshold is that it increases the delay in transmission but we can control it within the maximum bound. In this chapter, we assumed the fix active time. This active time gives the bound on the maximum number of packet that node can transmit in one cycle. And as we know IS-MAC supports 3 hop communications, so ideally the maximum data packet transmission rate reduces to 1/3 for 1 hop communication. But the biggest advantage we get is that first node and node no.4 as shown in figure 4-9 can transfer the data simultaneously after the first cycle; provided the node 4 will get access to channel after first cycle. Because of this pipeline concept node can transfer the data to sink node in just few cycles than S-MAC and T-MAC. This concept solves the problem of latency with the protocol’s maximum energy efficiency. In any case IS-MAC latency performance will be same or better than S-MAC and T-MAC. If we set the threshold value equal to 1/3 of the maximum packet will give the best solution for delay and cycle to packet delivery value. Figure 4-4 shows the number of cycle required for source node to start the transmission for different threshold values. For analysis we considered the fix buffer size of 100 and varied the threshold level from 5% to 15 % of the total buffer size. We calculated the number of cycles required by source to satisfy $Q_{size} \geq Th_i$ condition. For further analysis, we choose the buffer limit to 5% that satisfy the $Q_{size} = Th_i = N_{u-max}$ condition.
4.4.3 Operation of IS-MAC Protocol

Figure 4-5 shows flow diagram of IS-MAC protocol. In IS-MAC protocol, sensor nodes check the value of the accumulated data packets size ($Q_{size}$) in their buffers and transfer data only if the condition $Q_{size} \geq Th$ is met. Figure 4-6 shows the control and data packets flow of IS-MAC. As we mentioned earlier IS-MAC redefine the minimum timeout timer. T-MAC uses a timer defined in (5) to switch to sleep mode. This minimum timer period reduces unnecessary idle listening time when there is no data to be received [25].

$$T_o > T_{cont} + T_{RTS} + T_{SIFS}.$$  \hspace{1cm} (4)

Where, $T_{cont}$ is contention interval, $T_{RTS}$ is RTS time interval, and $T_{SIFS}$ is very short time interval between RTS and Clear-to-Send (CTS). Similarly, in IS-MAC minimum timer can be defined in (5) to switch to sleep mode.
\[ T_{IS} > T_{RTS} + T_{CTS} + T_{F-RTS} \]  \hspace{1cm} (5)

Where, \( T_{F-RTS} \) is future RTS time interval. IS-MAC can transfer the data packet up to 3 hops within the same frame. In IS-MAC, timer operates after contention period. Since IS-MAC timer is shorter than of T-MAC protocol therefore, IS-MAC can reduce a waste of energy according to idle listening. Figure 4-7 shows the active timer of T-MAC and IS-MAC

Fig.4-5 Flow diagram of IS-MAC
Fig. 4-6 Control and data packets flow of IS-MAC

(a) Active timer of T-MAC

(a) Active timer of IS-MAC

Fig. 4-7 T-MAC and IS-MAC’s active timer.
As we mentioned earlier S-MAC, T-MAC, and IS-MAC used fixed duty cycle. Fixed duty cycle set according to maximum traffic condition. With this duty cycle we can achieve the high energy efficiency. One complete cycle of sensor MAC is given by

\[ C = C_{active} + C_{sleep} . \] (6)

And duty cycle is defined as

\[ \text{DutyCycle} = \frac{C_{active}}{C_{sleep}} . \] (7)

From equation (6) and (7) we can define the energy saving for fixed duty cycle as

\[ E_s = 1 - \frac{C_{active}}{C_{sleep}} . \] (8)

Figure 4-8 shows the percentage of energy saving with fixed listening time. For analysis we considered the listen time of 120ms with duty cycle of 10%. These values save around 90% of energy.

![Figure 4-8 Energy saving vs. frame time for the listen time of 120ms and 60ms.](image)

**Pseudo code:**

```
Pseudo Code
Begin
    Radio On ();
End
```
if (mode== BMWF); BMWF ( );
else BMF ( );
End

Buffered mode with future reservation
BMWF ( );
Begin
if (control signal== Receive Control Signal ( ));
else Threshold ( );
End

Receive Control Signal( );
Begin
if (receive signal == rts );
Send CTS ();
Data receive ( ) ;
else if ( receive signal== cts);
Send F-RTS ( );
Data receive ( ) ;
else ( receive signal == f-rts );
Data receive ( ) ;
End

Threshold ( );
Begin
if ( qsize => lower threshold);
Send RTS ( );
Data Send ( );
else Timer ( );
End

Timer ( );
Begin
if (Timer ( )== finished);
Radio Off ();
else if (control signal== Receive Control Signal ( ));
Receive Control signal ( );
else
Timer expire ( );
Radio Off ( );
End

Where,
1. *Radio On ( )* = Procedure to turn on transceiver of a node.
2. *BMWF ( )* = Procedure to execute buffer mode with future reservation signal.
3. *BMF ( )* = Procedure to execute buffer mode without future reservation signal.
4. *Receive Control signal ( )* = Procedure to receive control signal from a sender node.
5. *Send RTS ( )* = Procedure to send RTS frame.
6. *Send CTS ( )* = Procedure to send CTS frame.
7. **Send ACK ()** = Procedure to send ACK frame.
8. **Threshold ()** = Procedure to check the lower threshold condition.
9. **Send F-RTS ()** = Procedure to create and transmit F-RTS frame.
10. **Data Send ()** = Procedure to create and transmit Data-frames
11. **Data receive ()** = Procedure to receive data frames from a sender node.
12. **Timer ()** = Procedure to set timer value.
13. **Radio Off ()** = Procedure to turn off transceiver of a node.

### 4.4 Performance Analysis

We compared the performance of existing sensor networks MAC protocols with IS-MAC with the help of mathematical analysis. Generally for source to sink scenario data flows in single path and that we represented by 10 hop liner topology as shown in figure 4-9, where all nodes know its position and node number. We compared the performance analysis on the given liner topology. For analysis we considered the fixed duty cycle of 10% with listen time of 120ms for S-MAC, T-MAC and IS-MAC.

![10 hop liner topology with one source and sink](image)

**Fig.4-9** Ten hop liner topology

**Parameter Description**

- $T_{total}$ Total radio ON time in active mode
- $t_{cont}$ Contention time
- $t_{IS-cont}$ IS-MAC contention time
- $t_c$ Control packet transmission time
\( t_r \) Data packet receiving time  
\( t_t \) Data packet transmission time  
\( t_{ack} \) Acknowledgement packet transmitting and receiving time  
\( T_a \) Active time  
\( T_0 \) Timeout interval in T-MAC  
\( T_{IS} \) Timeout interval in IS-MAC  
\( T_{on} \) Starting time of active period  
\( T_{off} \) Ending time of active period  
\( T_l \) Time length for packets to transmit/receive  
\( E_t \) Energy consumed for a packet transmission \([\mu J / \mu s]\)  
\( E_r \) Energy consumed for a packet reception \([\mu J / \mu s]\)  
\( E_{id} \) Energy consumption for idle listening \([\mu J / \mu s]\)  
\( p_{T-mac} \) Probability for T-MAC to transmit no data during active time  
\( q_{T-mac} \) Probability for T-MAC to transmit data during active time  
\( P_{IS-no} \) Probability for IS-MAC to receive no RTS, when \( Q_{size} \leq \) \( Th_i \)  
\( P_{IS-data} \) Probability for IS-MAC to transmit data packet, when \( Q_{size} \geq \) \( Th_i \)  
\( N_{r_d} \) Number of hops reserved for 2 hops transmission (Idle case)  
\( N_{r_c} \) Number of hops reserved for scheme under consideration  
\( N \) Number of data packets  
\( D \) Data transmission delay

### 4.4.1 Transmission time

S-MAC, T-MAC, and IS-MAC are single-frequency contention based protocols. Their working is almost similar to IEEE 802.11 MAC protocol but these protocols time is divided into main two parts; an active part and a sleeping part. We can also fix active cycle according to maximum traffic expected in the networks. Data transmission can only take part during the active time so for analysis we only considered the fixed active period (Duty cycle) while sleep period remains as constant. For all three protocols we considered the
same active time and cycle time. S-MAC can transmit to only next hop while T-MAC and IS-MAC can transmit till 3 hops in one cycle (within same active period). The number of maximum data packets that S-MAC can transmit to next hop in a given active time is determined from the following equation.

\[ N = \frac{T_s}{t_{\text{cont}} + t_{\text{rs}} + t_{\text{cs}} + n(t_{\text{data}} + t_{\text{ack}})} \]  

(9)

Where, \( n \) is the fixed size data packet count between 1 hop nodes. From this equation we can define the cycle and active time for S-MAC as follows

\[ C = C_{\text{active}} + C_{\text{sleep}} \]
\[ C_{\text{active(\text{s-mac})}} = t_{\text{cont}} + 2t_s + Nt_s + Nt_{\text{ack}} \]  

(10)

\[ C_{\text{sleep}} = t_{\text{sleep}} \]

In T-MAC protocol, the data can travel to maximum 3 hops in one frame by using F-RTS signal [25]. As we mentioned earlier the active time remains same as S-MAC for T-MAC so the total data packets that can be transferred till 3 hops for the same active period reduces. We can define the active time (for 3 hops) for T-MAC as follows

\[ C_{\text{active(\text{t-mac})}} = 3T_s + 3Nt_s + 3t_{\text{ack}} \]  

(11)

Where, \( N_{t_{\text{mac}}} \) represents the number of maximum data packets that T-MAC can transmit to next hop. The maximum data packets of T-MAC are nearly \( N \geq 3N_{t_{\text{mac}}} \) while comparing with S-MAC. Similarly, we can define the active time (for 3 hops) for IS-MAC as follows

\[ C_{\text{active(\text{i-mac})}} = t_{\text{is-\text{cont}}} + 3T_is + 3N_{is-mac}t_is + 3t_{\text{ack}} \]  

(12)

Where, \( N_{is-mac} \) represents the number of maximum data packets that IS-MAC can transmit to next hop. And the maximum data packets of IS-MAC are \( N = 3N_{is-mac} \) while comparing with S-MAC. From the above analysis we can find out the number of cycles required for each
protocol to transfer the number of maximum data packets until \(n\)-hops communication. Here we also assumed that communication is continues. From the following formulas we can calculate the lower bound on delay time required by a source node to destination node via \(n\)-hops communication.

In S-MAC, \(N\) or less than \(N\) data packet transmission time for \(n\) hops is given by

\[
D_{s-mac} = \sum_{i} D_i = n(t_{cont} + 2t_c + Nt_t + t_{ack} + t_{sleep}) = nC
\]

\(C = t_{cont} + 2t_c + Nt_t + t_{ack} + t_{sleep}\).

\(C_{active} = t_{cont} + 2t_c + Nt_t + t_{ack}\).

Where, \(C\) is a cycle time that is divided into active and sleeping time.

\(N_{s-mac}\) data packets transmission time for T-MAC for \(n\)-hops \((D_{t-mac})\) is given by

\[
D_{t-mac} = \sum_{i} (N_{s-mac} \times t_i + N_{s-mac} \times t_{ack} + T_v) = [n(C/3)].
\]

Where, \([*]\) define the largest integer value which is equal to \(*\). From equation (10) and (12), \(N_{t-mac}\) data packets transmission time for IS-MAC for \(n\)-hops \((D_{is-mac})\) is given by

\[
D_{is-mac} = \sum_{i} (t_{is-cont} + T_{is} + N_{is-mac}t_i + t_{ack}) = [n(C/3)]
\]

where, \(t_{is-cont} = bt(p_{i,k}, r)\).

Above mentioned assumptions and transmission time analysis helps to calculate certain numerical results. Figure 4-10 shows the graph of number of packet generated per cycle vs. number of cycle required to
send data packets to sink node over 10 hop liner topology. For analysis we assumed that IS-MAC satisfy minimum threshold condition and continuous transmission for all data rate. Figure 4-11 and 4-12 represents the latency performance for different traffic conditions of sensor networks. Here, we considered 15 packets and 4 packets generated per cycle as heavy and light traffic respectively. From the graph we can observe that IS-MAC gives better performance in all traffic condition. Figure 4-10, 4-11, and 4-12 gives the minimum bound on delay performance of all three sensor networks MAC protocols.

4.4.2 Active time

In sensor networks protocols, major part of energy is only consumed during the active period. In this sub-section, we compared active time of S-MAC, T-MAC, and IS-MAC protocols for which node’s radio remains on ideally. Figure 4-13 shows accumulated active time of S-MAC, T-MAC, and IS-MAC when equal numbers of packets transmitted by a node until one hop distance.

\[
T_{\text{total}} = \sum_{i=1}^{n} T_{A} = \sum_{i=1}^{n} (T_i - n_i \times t_i).
\]  

(16)

Where, \(n\) is number of data packets. T-MAC protocol is classified into two states. The probability that there is no data to be transmitted is \(p_{\text{t-mac}}\)

\[
T_{A_{\text{p-mac}}} = p_{\text{t-mac}} \times T_u.
\]  

(17)

The probability that there is data to be transmitted is \(q_{\text{t-mac}}\)

\[
T_{A_{\text{q-mac}}} = q_{\text{t-mac}} \times (T_i - n_i \times t_i) + T_u.
\]  

(18)

The total active time in T-MAC protocol is therefore given by (where, \(p_{\text{t-mac}} + q_{\text{t-mac}} = 1\)
In IS-MAC protocol, active time is classified into three states. If \(0 \leq Q_{\text{size}} \leq T_h\), the probability that RTS packet is not received is \(\rho_{\text{IS}}\), then
\[
T_{A_{\text{is-no}}} = p_{\text{IS-no}} \times (T_{\text{IS}} + t_{\text{is-cont}}).
\]
(20)

If \(Q_{\text{size}} \geq T_h\) then the probability is \(P_{\text{IS}}\) and active time is given by
\[
T_{A_{\text{is-data}}} = p_{\text{IS-data}} \times [(T_i - n \times t_i) + (T_{\text{IS}} + t_{\text{is-cont}})].
\]
(21)

If F-RTS/RTS packet is received and data packets are also received, the probability that data are transmitted to a neighbor node or not is \(1 - P_{\text{IS-no}} - P_{\text{IS-data}}\). Then active time is given by
\[
T_{A_{\text{is-no-RTS-no}}} = (1 - P_{\text{IS-no}} - P_{\text{IS-data}}) \times [(T_i - n \times t_i) + (T_{\text{IS}} + t_{\text{is-cont}})].
\]
(22)

The total active time in IS-MAC protocol is given by
\[
T_{\text{total}} = p_{\text{IS-no}} \sum T_{\text{IS}} + t_{\text{is-cont}} + p_{\text{IS-data}} \sum (T_i - n_i \times t_i) + (T_{\text{IS}} + t_{\text{is-cont}}) + (1 - P_{\text{IS-no}} - P_{\text{IS-data}}) \sum (T_j - n_j \times t_j) + T_{\text{IS}}.
\]
(23)

Figure 4-13 shows accumulated active time of S-MAC, T-MAC, and IS-MAC when equal numbers of data packets are transmitted. From the figure we can compare the total active time for which node’s radio remains on ideally for each protocol and hence energy consumption. Here, we assumed the continuous transmission and for each packet IS-MAC’s transmission condition get satisfied.
Fig. 4-10 Networks latency performance

Fig. 4-11 Networks latency performance under heavy traffic condition
Fig. 4-12 Networks latency performance under light traffic condition

Fig. 4-13 Total accumulated active time
4.4.3 Control Packet Overhead

Control packet overhead is one of main factors of energy consumption in wireless sensor networks. As we mentioned above all three protocols uses same active time for transferring the data packets. S-MAC can transfer the data packets to just next hop but T-MAC and IS-MAC transfers till 3-hops. All three protocols have different maximum number of data packets limit that they can transfer within one cycle. So all protocol uses different number of acknowledge packet according to maximum data packets limit. For control packet we only considered the signal packets required for accessing the channel. In S-MAC, two control packets are needed to transmit data packets at each hop. Therefore, Control Packet Overhead (CPO) for \( n \)-hops transmission is given by

\[
CPO = \sum_{i=1}^{\lfloor n/2 \rfloor} 2i. 
\]  

(24)

In T-MAC, we can send the data till 3 hops using F-RTS signal. The total CPO for \( n \)-hops transmission for T-MAC is given by (assuming that transmission is for 3 hops)

\[
CPO = \sum_{i} k_i t_i, \quad k_i = \begin{cases} 3, & i = 1,4,7,10,\ldots \\ 2, & i = 2,5,8,11,\ldots \quad (n \geq 3) \\ 1, & i = \text{otherwise} \end{cases}
\]  

(25)

In IS-MAC, multi-hop communication is reserved by using F-RTS and except for first hop, only one control packet is used for next 1 hop. Therefore, control packet overhead can be reduced in IS-MAC. Control packets for \( n \)-hops transmission are given by

\[
CPO = \sum_{i} k_i t_i, \quad k_i = \begin{cases} 3, & i = 1,4,7,10,\ldots \\ 1, & i = 2,5,8,11,\ldots \quad (n \geq 3) \\ 0, & i = \text{otherwise} \end{cases}
\]  

(26)
Figure 4-14 shows control packet overhead occurred according to the number of hops. From figure 4-14 we can see the reduction of control packets in IS-MAC compared to T-MAC and S-MAC. Reduction in control packets results into energy efficiency.

### 4.4.4 Energy Consumption

In S-MAC protocol, $N$ data packets can be transmitted to next hop node within one cycle. The energy consumption ($E_{s-mac}$) for $n$-hops transmission is given by

$$
E_{s-mac}(n) = \sum_{i=1}^{n} \left[ t_{cont} E_{id} + t_c (E_i + E_r) + N \times t_i (E_i + E_r) + N \times t_{ack} (E_r + E_c) \right] + E_{id} \left[ T_d - n(t_i + t_{ack}) \right]
$$

(27)

![Fig.4-14 Control packets overhead](image_url)
In T-MAC protocol, $N_{t-mac}$ data can be transmitted until 3-hops within one cycle. Energy consumption ($E_{t-mac}$) for $n$-hops transmission is given by

$$E_{t-mac}(n) = \sum_{i}^{n} \left[ k_{i} t_{c}(E_{i} + E_{r}) + N_{t-mac} t_{a} (E_{i} + E_{r}) + t_{ack}(E_{i} + E_{r}) + T_{a} E_{id} \right]$$

\[k_{i} = \begin{cases} 3, & i = 1, 4, 7, 10, \cdots \\ 2, & i = 2, 5, 8, 11, \cdots \\ 1, & i \text{ otherwise} \end{cases} \quad (n \geq 3) \]  

In IS-MAC protocol, data packets can be transmitted until 3-hops for fixed active period. In case of 1-hop transmission at each cycle, three cases of probability exist. The data packets are transmitted only when the buffer is equal or greater than the threshold value. For the first case if the probability that the nodes do not receive RTS packet from neighboring nodes is $P_{IS-no}$, then

$$E_{IS-mac} = P_{IS-no}(t_{IS-cont} E_{id} + T_{IS} E_{id}).$$  

Here we are assuming that transmission is going to be continuing till 3 hops and we formulate the formula according to that assumption. Now for second case If the probability that $Q_{size} \geq Th$ is $P_{IS-data}$, then the energy consumption ($E_{IS-mac}$) is given by

$$E_{IS-mac} = P_{IS-data} \left[ t_{IS-cont} E_{id} + 3t_{c}(E_{i} + E_{r}) + N_{IS-mac} t_{a} (E_{i} + E_{r}) + t_{ack}(E_{i} + E_{r}) + T_{IS} E_{id} \right].$$  

For third case, if $0 \leq Q_{size} \leq Th$, the probability is $1 - P_{IS-no} - P_{IS-data}$, then

$$E_{IS-mac} = (1 - P_{IS-no} - P_{IS-data}) \left[ t_{IS-cont} E_{id} + 3t_{c}(E_{i} + E_{r}) + N_{IS-mac} t_{a} (E_{i} + E_{r}) + t_{ack}(E_{i} + E_{r}) + T_{IS} E_{id} \right].$$  

In IS-MAC protocol, data can be transmitted until 3-hops within one cycle period. Energy consumption for IS-MAC for $n$-hops is given by (assuming continues transmission)
\[ E_{\text{w-max}}(n) = \sum_{i} k_{t_i}(E_i + E_r) + N_{\text{w-max}} \times t_r(E_r + E_r) + t_{\text{ack}}(E_r + E_r) \]

\[ + n[t_{\text{conf}}E_d + T_rE_d] \]

\[ k_i = \begin{cases} 
3, & i = 1, 4, 7, 10, \ldots \\
1, & i = 2, 5, 8, 11, \ldots \\
0, & \text{otherwise} 
\end{cases} \quad (n \geq 3). \]

Figure 4-15 shows energy consumption of all three protocols for their maximum packets transmission limits. As we mentioned above all protocols have different maximum packet transmission limits for a fixed active time. So we can not get the clear idea about the energy efficiency of each protocol till we compare them on common variable so for that we selected the different packets value and calculated the number of cycles required to transmit different packets value over 10 hop liner topology. From figure 4-16 we can observe that IS-MAC consumes more energy compared to T-MAC for low data rate; because IS-MAC always transmits minimum threshold limit packets together. IS-MAC is independent of packet generation rate below minimum threshold value. From this we can conclude that IS-MAC can give better performance during low packet rate.
4.4.5 Channel Utilization Efficiency

In densely deployed sensor networks the competition to reserve a free channel is very high hence; channel utilization should be at its maximum. In F-RTS scheme channel is reserved for more than 2 hops. When one hop node’s communication is going on next hop node can’t communicate due to RTS/CTS signal. The F-RTS scheme makes consecutive node idle so there is always a trade-off between
Fig. 4-16 Energy consumption of 10 hop sensor networks

delay and channel utilization. Figure 4-17 shows the channel utilization efficiency values versus the number of hops reserved by F-RTS scheme. We fixed the IS-MAC reservation maximum value to 3 hops.

Fig. 4-17 Channel utilization capacity
Channel utilization efficiency is given by

\[ E_{\text{chn}} = \left( \frac{N_{r_{id}}}{N_{r_{c}}} \right) \times 100 \]  

(33)

Where, \( N_{r_{id}} \) and \( N_{r_{c}} \) are number of hops reserved for idle case (2 hops) and the scheme under consideration respectively.

### 4.5 Comparison between S-MAC and IS-MAC

From the above numerical results and discussion we can conclude that for low traffic T-MAC gives considerably good results but for the heavy traffic condition it gives higher latency. For large amount of data transfer it is no point to consider T-MAC. For the same reason we only considered S-MAC and IS-MAC for comparison during higher data transfer rate. Figure 4-18 shows the graph of number of segments vs. number of cycles required to transfer the data to sink node over given ten hop liner topology. Figure 4-19 represents the average number of packets delivered by per cycle vs. number of segment. From the figure 4-19 shows that IS-MAC achieves the highest ratio due to its pipeline operation. Figure 4-20 shows the cycle-segment cost for 10 hop liner topology and from the graph we can observe that IS-MAC gives the better performance.
Fig. 4-18 Latency performance of sensor networks under heavy data packet transfer

Fig. 4-19 Average number of packets gets transferred within a cycle
4.6 Summary

In this chapter, we proposed an IS-MAC protocol that uses timeout timer to reduce the idle listening problem in sensor networks. We also introduced threshold values in buffers of sensor nodes to improve energy efficiency and per-node fairness. We restrict maximum hops (of continuous transmission) to 3 for IS-MAC that maintains a good channel utilization efficiency and data rate. IS-MAC achieved the prime goal of energy efficiency as well as QoS issues like per-node fairness, channel capacity utilization and latency. Analytical results show the significance of IS-MAC over existing sensor networks MAC protocols in varying traffic conditions.
Chapter 5 IS-MAC based flooding Protocol for Sensor Networks

5.1 Introduction

In this chapter, we introduced IS-MAC based flooding protocol (ISF) for wireless sensor networks. Most of the previous works on flooding protocols are focused on building optimal flooding tree in the networks. Existing flooding protocols are based on IEEE 802.11 MAC layer that gives ideal listing problem for the sensor network. Ideal listening is the most prominent cause for energy waste in sensor networks. Most of the flooding protocol can divided into two categories; table driven and on-demand routing protocols. Table driven protocols consumes good amount of resources in terms of energy and memory capacity for mobile and static networks environment. In contrast to that, on-demand based protocols are good for mobile environment. As we mentioned earlier, most of the protocols are based on IEEE 802.11 MAC layer which is very heavy for wireless sensor networks in terms of energy consumption. In this chapter, we proposed ISF routing protocol that gives energy efficient data delivery mechanism for wireless sensor networks. Special features of IS-MAC makes the ISF most promising candidate for the routing protocols for wireless sensor networks. ISF protocol uses hop count/location information to achieve energy efficiency for the data delivery mechanism. The proposed protocol can lead the flooded packets to flow towards their destination, hence eliminating unnecessary packets in forwarding and reducing the total energy
consumption. Our simulation results show the reduced energy consumption of ISF over existing flooding protocols.

5.2 Motivation and Related Works

Wireless sensor networks are of increasing interest in different application areas. Such as remote monitoring and surveillance, inventory control, assembly line monitoring, and networks of biosensors for health monitoring. Sensor nodes are typically characterized by small form factor, limited battery power, and a small amount of memory. Sensor networks enable distributed collection and processing of sensed data. These networks are usually connected to the outside world with a base station or sink node through which a user can retrieve the sensed data for further action or processing. For wireless sensor networks, there has been recently lots of attention on routing protocols.

Most of the routing protocols in wireless sensor networks are based on variations of “flooding” even though they use some optimizations. Flooding is clearly a straightforward and simple solution, but it is very costly in general. Furthermore, most protocols are based on IEEE 802.11 MAC protocol. This MAC protocol could cause serious problems of contention, collision, and redundant broadcasts can be referred as the broadcast storm problem [29]. And above all this gives the ideal listening and data overhearing problems that waste lots of energy of sensor nodes [chapter 4]. We proposed IS-MAC protocol that gives energy efficiency as well as addressed QoS issues like channel capacity utilization, per node fairness and latency. There have also been a number of recent works on efficient data
delivery in wireless sensor networks. Theses schemes also use routing cost to determine whether to forward or not. However, such schemes typically require full neighbor information, thus necessitating initial set-up time when the nodes get to know their neighbors. In case of dynamic environment, these protocols require periodic monitoring of neighbor’s information and it causes many overhead in the aspect of number of packets, energy consumption, and delay.

In this chapter, we proposed the flooding protocol that is based on the IS-MAC protocol. For delivering the packets to destination node IS-MAC uses RTS, CTS, and F-RTS signals. To generate RTS, CTS and F-RTS signals frame needs destination or next hop ID hence, routing table on each node. Periodic advertisement to maintain the routing table is energy consuming procedure. The proposed ISF falls into on-demand protocol category for which node doesn’t need to maintain any routing table. Hence node doesn’t use RTS, CTS and F-RTS signal for communication. Without these handshaking signals it is very difficult to overcome ideal listening and data overhearing problems. To solve these problems we used filter signal that uses hop count information or location based information. In the later section we will discuss more about this signal in details. Thus, by utilizing hop counting, location or any other matrices information, we attempt to reduce the number of nodes unnecessarily involved in the flooding process. In [30] authors proposed directional flooding but it is based on the IEEE 802.11 MAC. Authors minimized the number of node for flooding using directional information but the basic question of ideal listening and data overhearing remains unsolved. The proposed ISF’s simulation results shows the superiority over directional
flooding and direct flooding. As far as our knowledge is concerned it’s the first time to represent the flooding protocol based on sensor network’s MAC protocol especially for sensor networks.

5.3 The Proposed IS-MAC based Flooding (ISF) Protocol

In this subsection, we described The ISF algorithm. For forwarding the data packet to next hop we need to consider hop counting, location or any other matrices information. But here we used only hop counting information for forwarding the data packets and also assumed that data packets flow from sensor nodes to sink. Sink node periodically transmits its location information and all nodes know its location information.

5.3.1 IS-MAC Background

![Fig. 5-1 Active and Timer frame](image)

We described the IS-MAC protocol’s basic operation and mechanism in chapter 4. We briefly discussed about IS-MAC to give clear
understanding of ISF. For flooding IS-MAC will work in buffered mode without future mode and IS timer will defined as follows

\[ T_{IS} > F_{filter} + Ack. \]  

(1)

Where, \( F_{filter} \) frame is for filter signal, and \( Ack \) for acknowledge signal. And this timer runs only after contention period. Figure 5-1 shows the Active and Timer time frame. Active time will be fixed as per maximum traffic conditions available in the sensor networks. As IS-MAC is worked in buffered mode without future reservation it can pass data to only one hop distance within one cycle. So its latency performance will be similar to S-MAC but with better energy efficiency. For further details reader can refer chapter 4.

In ISF protocol used hop counting information for flooding. We define new filter frame for the protocol in which nodes keeps the hop count value after calculating its own distance from sink node, own id and etc information. In response to filter frame addressed node will send acknowledge frame. In this way \( F_{filter} \) and \( Ack \) frame will act like RTS and CTS frame and gives the same advantage of handshaking method of MAC without even maintaining routing table information.

5.3.2 ISF working

Figure 5-2 shows the self explanatory flow diagram of ISF protocol. Figure 5-3 shows the flow of different control packets between two sensor nodes.
Fig. 5-2 Flow diagram of ISF

Fig. 5-3 Control and data packets flow between two sensor nodes.
(a) Sensor networks with one source and sink node

(b) Node D transmits F-Filter Frame

(c) Node E transmits $ACK$ Frame
5.3.3 ISF Algorithm

- Initially sink node transmits its location information periodically. All nodes can listen to this information and calculate the number of hops required by them to send data to sink node.
- When any node satisfies the buffer condition [chapter 4] will send filter packet.
- All nearby nodes will listen to this frame and compare its own hop count with the frame. Node will send Ack frame to sender.
node if its value is lower than the value loaded in filter frame. These two frames will create the same effect like RTS and CTS signals.

- Data transfer will take place until the active time is on.

**Working:** Figure 5-4 provides an illustration for more detailed operations of the proposed ISF algorithm. Figure 5-4 (a) shows the initial topology of sensor networks with one source and sink node. Node D first satisfies the lower threshold condition and gets a chance to access the channel. It transmits the F-Filter frame with the hop count information for our example hop count value is 3. Node A, B, C, E, and F listen to F-Filter frame and compare their hop count value with Node D’s value as shown in the figure 5-4(b). Only Node C and E satisfied the condition: hop count > current hop count. As shown in figure 5-4 (c) and 5-4 (d) Node E sends the acknowledge frame to node D and be ready for data transmission. Nodes C will go back to sleep after listening to acknowledgement frame and save the energy from unnecessary overhearing of the data. Similar operation carried out by the nodes E and G till data packets reaches to the Sink node as shown in the figure 5-4 (e).

**Pseudo code:**

```plaintext
Proposed scheme Pseudo Code

Begin
Radio On ();
Receive Control Signal ();
Threshold ();
End

Receive Control Signal ();
Begin
if (control signal == f-filter);
Send ACK ();
else Threshold ();
```

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End

Threshold ( );

Begin
    if ( qsize >= lower threshold);
        Send F-Filter ( );
        Data Send ( );
    else Timer ( );
End

Timer ( );

Begin
    if ( control signal == ack);
        Data receive ( );
    else Timer expire ( );
        Radio Off ( );
End

Where,
1. *Radio On (*) = Procedure to turn on transceiver of a node.*
2. *Receive Control signal (*) = Procedure to receive control signal from a sender node.*
3. *Send ACK (*) = Procedure to send ACK frame.*
4. *Threshold (*) = Procedure to check the lower threshold condition.*
5. *Send F-Filter (*) = Procedure to create and transmit F-frame.*
6. *Data Send (*) = Procedure to create and transmit Data-frames*
7. *Data receive (*) = Procedure to receive data frames from a sender node.*
8. *Timer (*) = Procedure to set timer value.*
5.4 Performance Evaluation

In this subsection, we evaluated the performance of ISF and compared with the directional and direct flooding. For our evaluation we consider basically two matrices; average energy consumed by a node and total number of packet transmitted in the networks. ISF reduces both the matrices values hence, increases networks lifetime. For our performance evaluation we modified the CMU wireless extended version of ns-2. All nodes are randomly distributed in confined space of $200 \times 200 \, m^2$. Transmission range of each node is 30 meters and each packet size is fixed to 64 bytes. We used Berkly motes physical layer specification [29] for calculation. We run the simulation for 300 sec time. As we mentioned earlier, we considered only one way communication scenario that is nodes to sink. Figure 5-5 shows the performance of the ISF when we vary the number of nodes. We considered the data arrival rate/event generating rate of 5 sec and just one source node. As the number of nodes increases, both the matrices value start increasing for all protocols but ISF performance remains almost constant. Figure 5-6 shows the performance of the ISF under varying the source nodes. For this analysis we considered the 125 sensor nodes with data arrival rate of 5 sec. From the graph we can observe the superiority of ISF especially for higher number of source nodes. Figure 5-7 shows the performance of the ISF under varying the data arrival rate. For this result we considered the one source node and 125 nodes. As the data arrival time begins to increase, total generated traffic reduces and hence both the matrices value for all protocols. From all given graphs we can conclude that ISF performs better than direction flooding. Because ISF minimize the number of nodes for delivering the data.
and also removes the ideal listening and data overhearing problems for nearby node hence, reduce the average energy per node.

![Graph](image1)

(a) Average energy consumption per node

![Graph](image2)

(b) Total number of transmitted packets

Fig. 5-5 Performance of the ISF by varying the number of nodes
Fig. 5-6 Performance of the ISF by varying the number of source nodes

(a) Average energy consumption per node

(b) Total number of transmitted packets
Fig. 5-7 Performance of the ISF by varying data arrival rate
5.5 Summary

In this chapter, we presented an ISF routing protocol for wireless sensor networks. ISF uses the hop information to deliver data towards sink node. ISF optimized the number of sensor node for flooding the data as well as solves the problem of ideal listening. Our performance evaluation shows the superiority of ISF over the direct and directional flooding.
Chapter 6 Conclusions

This thesis has addressed the importance of energy efficiency in wireless sensor networks and also proposed four energy efficient schemes. The main contributions of this thesis are as follows.

- In chapter 2, we proposed the topology generation algorithm for densely deployed sensor networks. The proposed algorithm is based on flooding and gossiping method with some new parameters. The proposed algorithm helps the sensor networks to self configured in energy efficient manner as well as reduces the latency.

- In chapter 3, we proposed the energy efficient algorithm that helps routing protocols to increases a network lifetime by fairly distributing the relay load among the nodes with the help of two different operating modes. The proposed scheme increase the lifetime of a critical node by around 38% which looks quite promising and the proposed scheme generate a minimum hop path which is very important result for the real time data applications.

- In chapter 4, we proposed an IS-MAC protocol that maintains energy efficiency in all traffic conditions as well as QoS issues like per-node fairness, channel capacity utilization and latency. Analytical results show that IS-MAC has significant improvements in energy consumption and QoS parameters
compared to the existing MAC protocols under varying traffic and QoS conditions for sensor networks.

- In chapter 5, we proposed an IS-MAC based flooding protocol and compare its performance with Direct and Directional flooding protocols. The proposed protocol is not only energy efficient but also suitable for mobile sensor nodes scenario.

Finally, we can conclude that all the performance evaluation for each scheme shows that proposed schemes save the energy consumption over existing schemes in given sensor networks.
References


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