Chapter 2

Literature Review
Chapter 2

Literature Review

2.1 Introduction

Due to lack of the infrastructure, the nodes in wireless ad hoc networks communicate with each other either single hop communication or through multihop communication. These nodes are typically empowered with limited energy supply. When a node runs out its battery, it becomes non-functional. Thus, energy efficiency is important to minimize the energy consumption of network.

Since routing is one of the core functions in ad hoc networks, a lot of researches have been made to design routing protocols in such networks. A lot of survey work considers different aspects of routing is analysed in the literature. In [11], authors make a comprehensive survey on routing protocols for mobile wireless networks. In [12], a survey on the routing protocols for wireless sensor networks (WSNs) is presented. It classifies the routing protocols into three categories: flat, hierarchical and location based routing protocols. Furthermore, these routing protocols can be classified into multipath, negotiation based etc. The surveys in [8] and [10] addressed several energy efficient strategies for ad hoc and sensor networks. However, the surveys were not devoted to the routing only. The survey in [5] discusses several lifetime maximizing energy efficient routing protocols for ad hoc wireless networks. Moreover, in [9], the authors present a family of energy efficient routing strategies for multimedia based WSNs. However this survey work discusses various energy efficient routing techniques, it is mostly based on routing protocols combining QoS in multimedia sensor networks.
Although, a large number of routing protocols are available in the literature, this chapter presents a literature survey emphasizing on energy efficient routing protocols in order to support efficient data transmission in wireless ad hoc networks. Energy efficient routing can addressed from two perspectives: either to maximize network lifetime or to minimize total energy consumption of the network. In order to evaluate energy consumption of node, it is important to study energy model and wireless communication model. Thus, in this chapter, definition of network lifetime, wireless communication model and energy model are given for completeness.

The chapter is organized as follows. Section 2.2 presents various definition of network lifetime. Energy consumption model and wireless communication model are stated in Section 2.3 and Section 2.4 respectively. Section 2.5 highlights different reasons of energy consumption in the network. Next, a detailed classification of energy efficient routing protocol is given in Section 2.6. Routing protocols with energy-related metrics are described in Subsection 2.6.1. In Subsections 2.6.2 and 2.6.3, energy aware - QoS based routing protocols and energy efficient multipath routing protocols are discussed respectively. Hierarchical routing algorithms are addressed in Subsection 2.6.4. Finally, Section 2.7 concludes the chapter.

## 2.2 Definition of Network Lifetime

Energy efficiency in wireless ad hoc networks is measured by the lifetime of the network. However in the literature, there is no commonly agreed definition of the network lifetime. Several definitions of the network lifetime exist (c.f. [26]), the most frequently used ones are:

**Definition 2.1**

**First Node Die:** Time elapsed until the first node in network depletes its energy.

**Definition 2.2**

**Last Node Die:** Time elapsed until the last node in network depletes its energy.
Definition 2.3

**Percentage of Node Die:** Time when certain percentage of nodes will run out their energy.

### 2.3 Energy Model

First order radio model [18] is used to calculate the energy consumption of a wireless node. According to this model, energy consumption for transmitting a \( l \)-bit packet to a distance \( d \) is given by

\[
E_{tx}(l, d) = \begin{cases} 
    lE_{etc} + lE_{amp}d^2, & \text{if } d < d_0 \\
    lE_{etc} + lE_{amp}d^4, & \text{if } d \geq d_0 
\end{cases}
\]  
(2.1)

where \( E_{etc} \) is energy/bit consumed by transmitter/receiver electronics, \( E_{amp} \) is energy dissipation for transmitter amplifier and \( d_0 \) is threshold distance. Both the free space (\( d^2 \) power loss) and multipath fading (\( d^4 \) power loss) channel models are considered depending on the distance between sender and receiver. In this energy model, \( E_{amp} \) is written as \( \epsilon_{fs} \) for free space model and to \( \epsilon_{mp} \) for multipath model. The energy spent for receiving a \( l \)-bit packet is

\[
E_{rx}(l) = lE_{etc} 
\]  
(2.2)

If a node spends energy \( E_{a} \) to aggregate one bit, then the energy used to aggregate \( l \)-bit packet is

\[
E_{DA} = lE_{a} 
\]  
(2.3)

### 2.4 Wireless Communication Model

According to the most popular model used for power attenuation wireless communication [158], the signal power attenuates at a rate which is proportional to \( d^{-\alpha} \) where \( d \) is the Euclidian distance between sender and receiver and \( \alpha \) is the path loss constant whose value ranges between 2 to 4 depending upon the characteristics of medium of propagation [18]. Under this model, transmitter node \( u \) can successfully send a signal to receiver node \( v \), at a distance \( d \) with the transmission power given as
2. Literature Review

\[ P_{t,u} = P_{r,\text{threshold}} d^\alpha \]  \hspace{1cm} (2.4)

where \( P_{r,\text{threshold}} \) is the minimum receiving threshold at node \( v \).

According to this model, the transmission range of any node \( u \) can be expressed as

\[ T_R = \left( \frac{P_{t,u}}{P_{r,\text{threshold}}} \right)^{\frac{1}{\alpha}} \]  \hspace{1cm} (2.5)

2.5 Reason for Energy Consumption

In wireless ad hoc networks, a lion’s share of energy consumption of a node is due to transmission and reception of packets. In addition to this energy, a significant amount of energy is also consumed by a node due to following reasons.

1. **Overhearing**: If a packet is sent by a node, all nodes in the transmission range receive this packet even it is not addressed to them. This is called overhearing and energy is wasted due this overhearing.

2. **Interference**: Each node located between transmission range and interference range receives a packet but cannot decode it. This is called interference. Due to this interference, a node can drain out its energy.

3. **Collisions**: When a collision occurs at a node, energy dissipation for the transmission as well as reception is increased.

2.6 Classification of Energy Efficient Routing Protocols

Generally, energy efficient ad hoc routing protocols can be classified into following categories:

- **Routing Protocols with Energy Related Metrics**: These protocols use energy-related metrics such as transmission power, residual energy, interference and a combination of other network parameters for calculating energy efficient paths. The main objectives of these protocols are to decrease the overall energy consumption of the network and/or maximize the network lifetime. The aim of these protocols is to minimize the energy consumption of nodes, to avoid interference and to prolong the network lifetime. Several routing protocols with energy aware metrics can be found in Section 2.6.1.
2. Literature Review

- **Energy Aware - Quality of Service (QoS) based Routing Protocols**: The objective of these protocols is to provide QoS in an energy efficient manner. QoS parameters are delay, reliability, throughout etc. However, it is difficult to provide QoS because of the dynamic nature of the network. Various energy aware and QoS based routing protocols are discussed in Section 2.6.2.

- **Energy Efficient Multipath Routing Protocols**: These protocols maintain multiple paths from the source to the destination. Multipath routing scheme selects multiple paths for forwarding the packets or a set of paths from all possible paths for relaying the packets to the intended destination. These routing protocols improve reliability, fault tolerance and energy efficiency of the network. Multipath routing protocols are briefly described in Section 2.6.3.

- **Hierarchical Routing Protocols**: Hierarchical routing is typically used by cluster based routing protocols. In these protocols, nodes are grouped into different clusters. The main objective of these protocols is to improve the scalability and bandwidth of the network. Cluster based routing is also an efficient way to lower the energy consumption of nodes and to prolong the network lifetime. Various hierarchical routing protocols are presented in Section 2.6.4.

The following sections present each of the four classes of energy efficient routing protocols in details.

### 2.6.1 Routing Protocols with Energy Related Metrics

Several energy aware routing protocols have been presented in the literature, which use energy aware metrics such as residual energy, transmission power, and interference for finding energy efficient paths in the network. Objective of these metrics is to maximize the network lifetime or to minimize the energy consumption of nodes. Singh et al. [76] proposed different metrics that can be used to classify power aware routing algorithms for mobile ad hoc networks. This section describes some of the energy aware routing algorithms, which use energy related metrics.
2. Literature Review

2.6.1.1 Transmission Power and Residual Energy based Protocols

- **Minimum Total Energy (MTE)**

Minimum Total Energy (MTE) [70] routing scheme selects the path that uses the least amount of energy to transfer the data packet from the source to the destination. Assuming that, the energy consumption is directly proportional to the squared distance between two nodes, the intermediate nodes that act as the forwarders are chosen for minimizing the sum of squared distance over the path.

For example, let, a network is formed by three nodes \( u, v \) and \( w \). The distance between \( u \) and \( v \) is given by \( d_{uv} \), the distance between \( u \) and \( w \) is \( d_{uw} \) and the distance between \( w \) and \( v \) is \( d_{vw} \). In MTE, it was assumed that \( d_{uw} < d_{uw} \). The source node \( u \) intends to send the data to the destination node \( v \). It has two options for forwarding the data packets to node \( v \). Node \( u \) can directly send the data to node \( v \). On the other hand, \( u \) can send the data to node \( v \) via node \( w \). If the angle \( \angle uwv \) is obtuse, the node \( w \) can participate to the route if \( d_{uv}^2 > d_{uw}^2 + d_{vw}^2 \) is satisfied.

- **Minimum Transmission Power Routing (MTPR)**

The objective of MTPR protocol [106] is to find the route that minimizes total energy consumption for forwarding a unit of information from the source to the destination. In MTPR, transmission power \( P_{t,uv} \) between two adjacent nodes \( u \) and \( v \) is used as routing metric to find the energy efficient route. Thus, the total transmission power \( P_{t,p} \) for any route \( p \) has been expressed as

\[
P_{t,p} = \sum_{i=0}^{[V]-1} P_{t,v_{i+1}}
\]

where \( v_0 \) and \( v_{[V]} \) are source and destination respectively. Now, for a given source - destination pair, if there exits more than one routing path, the desired route \( p^* \) is one for which \( P_{t,p} \) is minimum and it can be given by

\[
p^* = \min \{P_{t,p} | p \in P\}
\]

where \( P \) is set of all possible paths from the source to the destination. Well-known shortest path algorithms like Bellman-Ford’s algorithm were applied to solve this
2. Literature Review

One of the drawbacks of MTPR is that it tends to choose the paths with large number of hops and thus increases end to end delays. To address this problem, a simple modification was suggested in [106]. While selecting a route, both reception power and transmission power were considered in the cost metric design. This modified scheme can find the routes with fewer hops than MTPR algorithm, since reception power is considered to be independent of distance and also identical for all the nodes. The main disadvantage of these algorithms is that they do not consider the residual energy of nodes and may quickly exhaust the batteries of nodes along the energy efficient path.

- **Battery Capacity Aware Routing**

In MTPR [106], nodes near to the sink act as relays for forwarding the packets of others. Thus, nodes close to the sink tend to be overused and die soon which may lead to partition of the network. The Minimum Battery Cost Routing (MBCR) [76] algorithm uses a cost function to maximize the lifetime of the network. In MBCR, battery cost function was designed for each node. This cost function is inversely proportional to the remaining battery capacity of that node and reflects the fitness of any node to participate in forwarding task. The battery cost function in MBCR has given as

\[ f_v(RE_v) = \frac{1}{RE_v} \]

where \( RE_v \) is the remaining battery capacity of any node \( v \). Therefore, the battery cost \( C_{path}(p) \) of the route \( p \) is sum of cost function of the nodes constitute the route and it is expressed as

\[ C_{path}(p) = \sum_{v=0}^{\text{|P|}} f_v(RE_v) \]

MBCR attempts to find the path which has minimum battery cost i.e., it selects the path \( p^* \) such that

\[ p^* = \min\{C_{path}(p) \mid p \in P\} \]

However, the route metric developed in MBCR has some drawbacks. Since MBCR uses the summation based cost function, it can still select a route containing nodes with low remaining battery capacity.
To overcome this problem, Min-Max Battery Capacity Routing (MMBCR) was proposed in [76]. MMBCR is an extension of MBCR, which uses min max route selection. It chooses the path for which the minimum of the residual energy of the nodes on the path is maximum i.e.,

\[ p^* = \max_{p \in P} \min \{ f_v(RE_v) \mid v \in p \} \]

Since MMBCR tries to avoid routes with least battery energy, the depletion of battery power of nodes is more evenly as compared to previous schemes [70, 76, 106]. Unlike MTE, MBCR and MTPR, MMBCR never tries to minimize the total transmission energy along a path and increases overall energy consumption in a network.

- **Conditional Max-Min Battery Capacity Routing (CMMBCR)**

To maximize the network lifetime, it is important to balance between energy usage and network lifetime. A conditional variant of MMBR, called Conditional Max-Min Battery Capacity Routing (CMMBR), was proposed in [2] to achieve this goal. In CMMBR, the battery capacity of a route is defined as the minimum of remaining battery capacity among all the nodes in the route. CMMBR finds a minimum energy path from the source to the destination in which no node has residual energy below some threshold value. If none of the routes satisfies the condition, then route with maximum battery capacity is selected. If one or more paths fall below the threshold then CMMBR switches to MMBR. Simulations results showed that the value of the threshold factor has great impact for minimizing total energy consumption and maximizing the network lifetime as well. Furthermore, one of the advantages of CMMBR is that it may select shorter routes.

- **Flow Augmentation Algorithm**

In [114], the authors addressed the problem of routing in static ad hoc networks. The objective is to maximize the network lifetime. They proved that the maximum lifetime routing is max flow problem and used linear programming to formulate the problem under the flow reservation constraint at each node in a network. In order to solve this problem, Flow Augmentation algorithm (FA) using Bellman-Ford’s shortest path algorithm was proposed. FA problem is a minimum cost path routing
2. Literature Review

problem in which the link cost is defined as the function of transmission and reception energy and residual energy level of transmitting and receiving node. FA algorithm has received considerable attention because it can achieve a lifetime that is very close to the optimal network lifetime which can be obtained by solving linear programming problem. However, no analytical performance evaluation was presented for FA algorithm. In [3], the authors considered maximum lifetime routing problem and proposed a distributed algorithm to reach to near optimal solution in relatively small error. Moreover, they considered multi-commodity and different power consumption model to reach to the solution.

- **Power Efficient Data Gathering and Aggregation Protocols**

It is believed that the lifetime of the network can be maximized if the total energy consumption of the network is minimized - this is not true in realistic situations. Two minimum spanning tree based routing algorithms, namely PEDAP (Power Efficient Data Gathering and Aggregation Protocol) and PEDAP-PA (Power Efficient Data Gathering and Aggregation Protocol with Power Aware) were proposed in [109] to maximize the network lifetime. PEDAP maximizes the network lifetime by finding minimum energy path from source to the sink, while PEDAP/PA prolongs the lifetime by balancing energy consumption among the nodes. In PEDAP, the link cost function is sum of transmission energy cost and receiving energy cost. On the other hand, in PEDAP/PA, link cost function is asymmetric and it is defined by dividing PEDAP link cost by the transmitter residual energy. Though both the protocols reduce energy consumption of wireless sensor networks, the network lifetime is shortened as well. This is because PEDAP does not consider residual energy of nodes in route selection and usually places heavy burden on nodes near to the sink. Another disadvantage of PEDAP is that it always chooses the minimum energy efficient path and uses the path continuously until the first node dies. This may also shorten the lifetime of the network. Moreover, after failure of a path, a new routing path is set up by the sink node using global routing information and thus overall routing overhead is increased. PEDAP/PA also has some drawbacks. It only considers residual energy of transmitter in link cost and does not perform well in dense network where residual
energy of receiver plays a vital role for minimizing energy dissipation of the network.

- **Energy Aware Routing Algorithm for Low Energy Networks**

The objective of Energy Aware Routing algorithm (EAR) [120], a destination initiated reactive routing protocol, is to improve the lifetime of the low energy wireless networks. In EAR, suboptimal paths are used to improve the path reliability and energy efficiency. It is different from other reactive protocols in the sense that it keeps a set of multiple paths and uses one of them with a certain probability. Choosing suboptimal paths improves the operational lifetime of node along the path and thereby improves the lifetime of the network. EAR finds multiple paths between the source and the sink. Then the paths are assigned certain probability depending on the energy consumption of that path. When the data packets need to be transmitted from the source to the sink, one of the multiple paths is chosen depending on the probability of that path.

EAR mainly consists of three phases: (i) setup phase, (ii) data transmission phase and (iii) route maintenance phase. In setup phase, localized flooding occurs to create the routes between the source and the sink and their cost. In data transmission phase, one of the paths is selected with certain probability which is calculated using energy metric. In route maintenance phase, localized flooding is performed infrequently to keep all the paths alive. However EAR improves the network lifetime, still this alternative path routing incurs high cost. This happens because nodes exchange their routing information frequently in the network to get precise information of routing metric.

- **Energy Balanced Routing Algorithms**

A Distributed Energy Balanced Routing (DEBR) protocol was proposed in [122]. The main idea is to balance two conflicting goals in wireless sensor networks, namely, choosing a path with maximum residual energy and minimum energy consumption. DEBR is a decentralized routing protocol where each node locally decides its best next hop node based on the local neighborhood routing information. In DEBR, the link cost is defined as function of residual energy of transmitter and transmission energy consumption and it has written as
Moreover, DEBR uses the total energy cost (TEC) associated with each neighbor node $v$. Thus, $TEC_{uv}$ for each link $(u,v)$ is written as

$$TEC(u,v) = C_L(u,v) + C_L(v,BS)$$

The best next hop node of each node $u$ is

$$w = \arg\min_{v \in N_u \cup \{u\}} TEC(u,v)$$

where $N_u$ is set of 1-hop neighbors of node $u$. The authors of [122] claimed that DEBR can achieve energy sufficiency as well energy efficiency. However DEBR has some major drawbacks. First, only the transmission energy cost was taken into consideration in link cost computation, while energy consumption due to reception and overhearing were ignored. Second, the cost function is the ratio between the transmission energy cost to the residual energy and its value becomes low in the case when transmission energy cost is low and residual energy is high.

Authors in [123] investigated a Uniform Balancing Energy Routing Protocol (UBERP) for wireless sensor networks. UBERP is centralized energy efficient routing algorithms where the path selection for multihop transmission is done using the minimum energy transmission method. The key idea is to balance the transmission energy consumption over the entire network in order to avoid energy depletion of the nodes along the shortest routes. In UBERP, the node, whose remaining energy level is greater than some threshold, can only participate in multihop communication. This threshold value is equal to the average residual energy of the network. Like other centralizes routing algorithms, UBERP excludes the nodes with lower remaining energy and edges with higher energy consumption for finding minimum energy path and then uses a shortest path routing algorithm to calculate the optimal energy efficiency. Since global information is required to exclude such energy in efficient nodes and edges, UBERP increases the overall routing overhead, which may limit the extensibility of the protocol.

The objective of Energy Efficient Routing Algorithm to Prolong Lifetime (ERAPL) [124] was to prolong the lifetime of WSNs. ERAPL uses data sequence.
to eliminate the mutual transmission as well as the loop transmission among the nodes. In ERAPL, each node can proportionally forward the traffic to the neighbor node in data sequence. A mathematical model was formulated to optimize the network lifetime. The model considered both the minimal residual energy of nodes and total energy consumption. Moreover, a genetic algorithm was proposed to find the optimal solution of the programming problem.

In [125], Das et al. presented an Energy Balanced Routing Protocol (EBRP) for low energy networks. In EBRP, the data traffic is forwarded to the sink through the dense energy area so that the nodes having lower residual energy can be protected from early run out. Three independent virtual potential fields such as depth, energy density and residual energy were constructed for maximizing energy efficiency. The depth field is required for establishing basic routing paradigm for forwarding the traffic towards the sink. The energy density is used for passing the data packets through the high energy area whereas the residual energy field is required to protect low energy nodes. In EBRP, these three fields are combined together for obtaining final routing decision.

Authors in [133] proposed a single path based static routing algorithm for maximizing the operational lifetime of the network. This algorithm basically works in centralized fashion. In their routing algorithm, the authors first obtained an optimal multipath solution and then applied an approximation algorithm to the result in order to obtain the energy optimized path. They also claimed that theoretically their solution can achieve a constant factor approximate of the optimal solution. However, use of same routing path all the times may deplete the battery of some nodes on the paths more quickly than other nodes. As a result, the network may become partitioned.

Authors in [159] proposed an on-demand routing algorithm for multi-radio multihop wireless networks to minimize the total energy consumption in a network and maximize the network lifetime. They considered the energy consumption of nodes as well as link to define a utility function to make a trade-off between these conflicting metrics. The drawback of this algorithm is that it has higher hardware cost.
• **Aggregation based Energy Aware Routing Algorithms**

Aggregation / compression are one of the effective techniques for increasing the survivability of the network. The main aim of aggregation is to minimize the energy consumption at node during transmission. Authors in [130] proposed a Least time, Energy efficient, One level data aggregation protocol (LEO) for maximizing the lifetime of wireless sensor networks. LEO is proactive routing protocol. Each node in LEO maintains a database and keeps records of residual energy of neighboring nodes and the absolute time required to reach to the base station from that neighboring node in its database. Data aggregation is done only at a node just immediate to the source node along the routing paths instead of all the nodes along the route or at a particular node. LEO selects the path based on the residual energy of nodes and uses the path until all the nodes along the route drain out their energy completely.

Another data aggregation based routing protocol was proposed in [131]. The objective was to maximize the lifetime of shortest path based data aggregation trees. In this aggregation based protocol, delay was considered as an important parameter in routing process (especially in time critical application) and a tree protocol was proposed to minimize the routing delay and network lifetime. Authors of [131] showed that when it is restricted to shortest path trees the problem is polynomial time solvable. The problem can be further converted into semi matching problem and solved by min cost max flow approach which is in polynomial time. The main disadvantage of this protocol is that transmission cost and reception cost were considered as constant and residual energy of neighboring nodes were not taken into consideration in next hop selection process.

**2.6.1.2 Interference based Approach**

Interference is one of the main concerns when building wireless networks. There is no unified definition for interference in the literature. To be precise, interference at a node is a combination of received signal strength from different transmitting nodes simultaneously. If the total of interference signals is smaller than some threshold value, then valid signal will be received correctly and interference can be ignored; otherwise, the signal is distorted and interference occurs. Interference
increases retransmission, delay and energy consumption at nodes. Reducing interference is a challenging issue in wireless ad hoc networking. Many routing protocols have been proposed in literature to decrease the effect of interference in the network. This section studies some of the interference aware routing algorithms for ad hoc networks.

- **Interference Aware Routing Algorithms**

Heijenk and Liu proposed Balanced Interference Routing Algorithm (BIRA) [77] for multihop CDMA type wireless networks. In BIRA, the link cost is calculated based on the interference level of each node and a fixed value. Based on the link cost, Dijkstra’s algorithm is used to compute the routes. BIRA finds the interference minimized routes and interference level at a node is calculated using the protocol interference model. Moreover, BIRA does not consider interference associated power consumption in route construction process and thus is less energy efficient.

In [83], the authors proposed an interference aware routing algorithm that calculates the aggregate interference costs for all the paths between the source and the destination and chooses the one with the least cost. The algorithm developed in [86] takes similar approach as well, except it uses the energy costs of the path along with the interference costs. Though the algorithms proposed in [83, 86] are efficient for sparse networks, they do not scale well with increased number of nodes.

Wei and Lee [87] investigated an interference aware routing protocol, which trade-offs between the energy and security. This protocol was specially designed for Wi-Fi based multihop wireless networks where security is one of the prime considerations. The routing scheme integrates Interference Aware Minimum Energy Path (IA-MEP) [86] and the Security Protocol for Reliable Data Delivery (SPREAD) [73] to compute the routes. IA-MEP and SPREAD consider energy and security issue independently, while, in [87], these parameter are integrated together to provide minimum energy and reliable data transmission.

In [78, 81], the authors introduced the probabilistic solution to model the interference at node and proposed routing algorithms to find interference aware
routing paths. In [78], the protocol interference model was used to capture the interference, while in [81], both the protocol model and physical model were used to model the interference at a node. Moreover, the protocol in [81] was implemented through a cross layer design method.

Several routing metrics [79-80] have been developed in the literature for reducing the impact of interference in the network. Interference Aware Routing metric (IAR) [79], uses the MAC-level information to measure the interference on a link. This information includes the back-off time, waiting time and number of retransmission due to interference. IAR always selects least interference links in route construction process. Though it uses the links that experience least interference, it has not considered the energy loss due to interference in their metric design.

In [80], the authors proposed Interferer Neighbor Count (INX), which takes into account interference through the number of links that can interfere on a link. INX performs better only in low traffic load conditions since no load balancing mechanism is incorporated in the routing metric. As a result, it faces quick performance degradation with increase in network load. Moreover, it uses probing technique to measure the interference parameters of the link in a static way. This adds overhead and also fails to predict the true quality of the link.

- **Energy Efficient Interference based Routing Algorithms**

Poor and Comaniciu [82] developed a joint power control and routing based protocol for finding energy efficient paths in wireless ad hoc networks. They assumed that all the links interfere with each other and the links must meet the signal to interference plus noise ratio (SINR) in routing paths. The main drawback of [82] is that it did not consider the load balancing issue and is not useful in networks with higher traffic condition. In [85], the authors proposed a maximally node disjoint protocol based on power control. Unlike [82], they assumed that all the links do not interfere with each other and claimed that their algorithm has achieved more than 300% substantial gain over [82]. Though the algorithm in [85] finds multiple disjoint paths, it allows the data to be sent along the primary path at a time. Hence, load balancing issue is not attained completely.
Optimal SINR routing (OptSINR) [84] is energy efficient interference based routing algorithm that aims to find the optimal routes in terms of energy consumption over the entire network. It is basically a class of link scheduling scheme, which takes into account the interference created by existing flows in the network and exploits both the SINR (physical layer information) and power control (MAC layer information). In OptSINR, after assigning a link cost to each of the corresponding links, a shortest path algorithm, e.g., Dijkstra’s algorithm is applied to find the minimum cost path. Finally, that the minimum cost path is used to serve the incoming flow. Though OptSINR minimizes energy consumption, associated complexity for route formulation is high.

In [88], Mahmood et al. developed an interference aware energy efficient routing protocol specially targeted to CDMA based ad hoc sensor networks. They proposed two algorithms in order to maximize the throughput and minimize the energy consumption in the network. The first algorithm is based on the minimum energy routing and the potential interference levels, while the second algorithm is based on joint minimum energy and near far effect. Both the algorithms tried to mitigate the near-far effect at network layer by making appropriate selection of next hop node. Moreover, several additive and multiplicative metrics were developed to improve the energy efficiency. In [89], the authors analysed the joint effect of power control and routing and proposed routing strategies to maximize the network lifetime. In this protocol, interference and geographic distance were taken into consideration while selecting relay. The main drawback of these protocols is that they are mainly confined in single path routing.

### 2.6.2 Energy Aware - Quality of Service (QoS) based Routing

In ad hoc networks, there is a fundamental trade-off between energy and delay, since optimization of energy efficiency is obtained inevitably at the expense of increasing delay. However, low delay is an important requirement in many applications where the data transmission needs to be performed in time. Therefore, while energy efficient operation is important for the longevity of network, balancing this with an effort to certain delay requirement is sometimes required. Moreover, in addition to low delay, other QoS requirement may be required as
In this section, several energy efficient and QoS aware routing protocols are briefly described.

- **Energy Aware Routing Algorithms for Cluster based Ad Hoc Networks**

In [47], the authors addressed the problem of clustering in WSNs subject to the upper bound on the maximum delay, energy consumption and cluster size. Their proposed approach focused on the optimal placement of gateways to access the remote central clusters subject to delay and energy consumption constraint. In [47], the network is divided into number of disjoint clusters and they are formed using minimum dominating set (MDS) so that all the nodes in the network can be covered. In each cluster, a gateway is selected and a spanning tree rooted at gateway is used to aggregate the data packets and to forward the aggregated packet to the remote cluster.

Energy Efficient and QoS aware Routing (EEQR) protocol for clustered WSNs was proposed in [48]. To improve the energy efficiency and to minimize the delay, a combination of static sink and mobile sink is used for forwarding the data packets form the sources. Further, to increase the network lifetime, high priority or delay sensitive data traffic is forwarded through the static sink and delay tolerant or low priority data packets are forwarded through the mobile sink. Although EEQR is energy efficient and delay sensitive, it is compute intensive and extra overhead for placing the multiple sinks and also for the prioritization of data based on the message type and content.

- **Delay Minimum Routing Algorithms for Real Time Communication**

In [135], the authors proposed a stateless routing protocol, called SPEED to support soft real-time communication for sensor networks. In SPEED, three types of services are provided, namely, real-time unicast, real-time area-multicast, and real-time area-anycast. In this protocol, sensor nodes are location aware and maintain location information about their neighbors to make localized routing decisions. Moreover, SPEED maintains a desired delivery speed across a sensor network in order to provide soft QoS. This protocol assumes that the end-to-end delay depends on not only single hop delay but also distance between the source
and the sink. In SPEED, sensor nodes estimate their packet delay based on the speed of the packet and the distance to the sink.

In [149], Delay minimum Energy aware Routing Protocol (DERP) was proposed to provide real time communication service. DERP is based on the depth first search tree where the maximal hop number from each sensor node to the sink was minimized. The main drawback of DERP is that it does not include energy consumption of link (or nodes) while selecting the next hop node in route selection process. Another disadvantage of DERP is that hop count is used to measure the delay of the network which is not applicable in many realistic situations.

- **Delay Minimized Multipath Routing Algorithms**

Multipath Multispeed Protocol (MMSPEED) [143] extends SPEED [135] by introducing multiple speed layers in a single network to provide QoS in terms of reliability and timeliness. In MMSPEED, for $M$ virtual speed layers, there is $M$ set of speeds. Moreover, First-Come-First-Serve (FCFS) queuing model is used to serve the buffered packets. MMSPEED supports the timeliness of packet delivery using cross layer interaction and establishes multiple disjoint paths to satisfy the reliability requirement of packet forwarding. However, the major drawback of MMSPEED is that usage of geographic routing with greedy forwarding may not improve the performance of the network always. Further, data transmission over longer links increases the transmission energy cost at nodes and thus this protocol cannot be used in energy constraint wireless networks.

Sohrabi et al. [145] proposed a Sequential Assignment Routing (SAR) protocol in which sensor nodes select a path among multiple ones for forwarding the packets to the sink. It is a table driven routing protocol which utilizes energy resources, QoS and the priority level of a packet for selecting routing path. Using multiple trees, SAR creates multiple paths from each node to the sink where each tree is rooted from 1-hop neighbors of the sink. SAR has gained better performance in QoS provisioning such as energy efficiency. However, this protocol leads to higher overhead cost due to the need of maintaining tables and multiple trees.
2. Literature Review

- Energy-Aware QoS Routing Protocols

Authors in [146] suggested an energy aware routing protocol for satisfying bounded delay requirement for data transmission in wireless networks. This routing algorithm takes into consideration several parameters such as transmission power, residual energy, error rate and some other communication parameters for calculating link cost and then employs $k$-shortest path algorithm to find a set of candidate routes. For each of the routes, end to end delay constraint is checked and the path that satisfies this delay requirement is selected for data transmission.

To achieve the on-time delivery of real-time data, Weighted Fair Queuing (WFQ) packet scheduling technique along with leaky bucket was employed in [146]. In addition, this routing mechanism was extended to provide uninterrupted message delivery for a mobile gateway. The algorithm behaves well both in energy and delay bounded metrics, but has high overhead because of the distributed Dijkstra procedure for computing $k$-shortest path and number of iterations. In addition, in order to calculate the link cost, each node requires global knowledge of all the nodes in the network, which limits scalability of in large networking paradigm.

Reliability is also an important QoS metric in energy constraint multihop wireless networks. To improve the reliability and energy efficiency, a Delay bounded Energy constraint Adaptive multipath Routing (DEAR) was addressed in [154]. DEAR computes multiple paths to provide fault tolerance against link failures and thus continues the flow of the packets through other paths. It considers various factors such as transmission energy, differential delay and reliability for designing delay bounded energy aware paths. The main objective of DEAR is to make a balance between the differential delays among different paths through a polynomial time algorithm. This algorithm was developed for a special case of DEAR where edge delay and differential delay bounds are assumed to have integer values. The main drawback is that the energy saving is not worth considering and the network performance in terms of network latency decreases substantially.
2. Literature Review

- **Energy Efficient Routing with Delay Guarantee**

Monaco et al. [134] analysed the impact of different network design strategies for data gathering. Several optimization problems have been proposed in energy-latency domain. To design the optimization problem, authors considered quasi ideal network condition by implementing a time schedule that avoids collisions at media access layer and assumes negligible transmission errors as well as ideal data correlation. For different network design strategies, they developed DA-trees that satisfy some optimization constraints. Two optimizations viz., latency oriented and energy oriented were proposed in [134]. In energy oriented optimization, the solution tries to optimize the network lifetime and overall energy consumption. Instead of static routing, the authors showed that dynamic re-routing and scheduling can balance the energy consumption in time and maximize the network lifetime while maintaining low latency. Further, they proposed two algorithms for optimal re-routing. These are re-routing latency oriented and re-routing energy oriented. In former case, the primary objective is to minimize the latency, while the secondary objective is to balance the energy consumption among the nodes. In later case, the primary objective is to minimize the energy consumption among the nodes, while the secondary objective is to minimize the latency.

In [147], Energy Aware Routing with Real Time (EAR-RT) guaranteed delivery protocol was proposed for wireless sensor networks. In EAR-RT, residual energy and energy drain rate are used together for routing the data packets and these are updated periodically in order to achieve energy awareness. The information is obtained through overhearing. When two nodes are within the transmission range of each other, the neighboring node can overhear the packet being transmitted. Overhearing enables each node to obtain the energy information of neighboring nodes and to update the routing table. In EAR-RT, real time packets must be arrived before the deadline. It also protects any route from being selected all the times, preventing energy depletion.

Delay constraint Least Energy Consumption (DLEC) [148] routing protocol sends the data packets within a bounded time. DLEC constructs subset of paths that meet the delay bound and picks the path having minimum energy cost from this subset. In DLEC, delay is measured in terms of hop count and this hop count can be
2. Literature Review

replaced by queuing delay, transmission delay and also other delays in the network. In [148], DLEC is further extended to DLEC-E. DLEC-E uses only local information and dynamic programing strategy to select the delay bound least energy path.

- **Minimum Delay Maximum Lifetime Routing Algorithms**

In [150], the authors presented a data dissemination protocol in wireless sensor networks has been presented to achieve a trade-off between network lifetime and delay. They decomposed the transmission range of sensors into Concentric Circular Bands (CCBs) and classify them as well. The set of CCBs can be classified into three categories: the first subset favours energy consumption minimization; the second subset favours delay minimization and the third subset minimizes both energy consumption and delay simultaneously. In [150], source is enabled to specify its Degree of Interest (DoI) in minimizing energy consumption and/or delay. A particular CCB is used to express a DoI. Each of the first two subsets of CCBs could be further classified depending on how DoI is given. Authors also claimed that choosing sources, that lie on or closely to the direct path between source and sink as proxy forwarders, leads to maximum energy saving and minimum delay. Regardless of DoI specified by the source, the protocol selects the sensor with maximum remaining energy and located close to the shortest path between source and sink as proxy forwarder.

Topology control is one of the effective mechanisms for optimizing the energy consumption with delay. In [152], authors investigated a Topology control problem for Delay Constraint Data Collection (TDDC) and then formalized it into linear integer programming problem. Because of NP-Hardness of the problem, they designed a heuristic solution, called load aware power increased topology control algorithm, to solve TDDC. They also claimed that theoretically TDDC can reach $O(1)$ approximation for linear graph. The impact of delay constraint on worse case for the planar graph has also been analysed in [152]. Moreover, two heuristic solutions, known as SDEL and DDEL, were designed which are based on the area division for TDDC problem. One of the drawbacks of TDDC is that delay is measured in terms of number of hops which is very restricted in real lifetime application. Furthermore, only transmission cost is used for measuring the energy
consumption at a node while the other sources of energy wastage were not taken in consideration.

In [153], the authors developed anycast packet forwarding scheme to reduce the event reporting delay and to maximize the lifetime of wireless sensor networks by employing an asynchronous wake-up scheduling. To reduce the delay and to maximize the lifetime of a network, two optimization problems have been introduced: (i) delay minimization problem and (ii) lifetime maximization problem. In delay minimization problem, the authors showed that given the wake-up rates of sensor nodes, how to choose the any cast forwarding policy optimally so that the end to end delay in network is minimized. In this problem, the wake up time of sensor nodes follows Poisson process. In lifetime maximization problem, given a constraint on the expected end to end delay, they addressed optimization the lifetime of network by jointly controlling wake-up rates of nodes and packet forwarding policy.

Authors in [155] highlighted two issues i.e. reducing end to end packet delivery delay and increasing the lifetime of network through the use of cooperative communication. They proposed a Delay and Energy aware Cooperative Media Access Control (DEC-MAC) policy, which trades-off the packet delay and node’s energy consumption while selecting suitable cooperative relay node. To balance between the energy consumption of nodes and delay, DEC-MAC considered both the residual energy and delay in next hop node selection. The selection algorithm uses complementary cumulative distribution function for selecting most optimal relay within a shortest time period. Authors in [155] claimed that DEC-MAC protocol is able to determine the optimal relay in more than three mini slots. Though DEC-MAC maintains balanced energy consumption among the nodes and reduces the transmission delay, use of cooperative technique requires special hardware support to the node with increase in hardware cost.

- Energy-Delay Trade-off using Multi Objective Optimization

Multi objective optimization for maximum lifetime and minimum delay was proposed in [151]. A data forwarding protocol was proposed that trades-off between energy with delay (TED) and then this problem is formulated as multi objective optimization problem which can be solved by weighted scale uniform
2. Literature Review

unit sum (WES) approach. Same as in [150], the algorithm is based on the slicing of communication range of sensor nodes in order to optimize the two conflicting goals, namely minimum energy consumption and minimum delay. The communication range of each node is divided into number of concentric circle bands and each band is used to represent the requirement of applications in terms of energy consumption, delay and energy depletion. In TED, the author derived an upper bound on energy consumption, delay and the size of the proxy server which is used to select best next hop node in order to make a trade-off between energy and delay.

2.6.3 Energy Efficient Multipath Routing

Multipath routing protocols select multiple paths to deliver the data packets from the source to the destination. It can largely address the reliability, robustness, fault tolerance and load balancing issues of single path routing protocols. Many multipath routing protocols have been addressed in wireless networking paradigm. Existing multipath routing protocols can be classified into three categories: (i) fault tolerant multipath routing, (ii) multipath routing for concurrent transmission, and (iii) energy aware multipath routing. This section presents a detailed review of multipath routing protocols of each category.

- Fault Tolerant Multipath Routing Algorithms

Multipath routing can be node disjoint or link disjoint or braided routing [90-92]. The general idea behind this classification is to provide reliable data transmission and fault tolerance against node failure or link failure. Various metrics (e.g. residual energy of node, hop count, energy cost of node) can be used to find different disjoint paths. Two paths are said to be node disjoint if there is no common nodes or links between the paths. Therefore, any node or link failure in a set of node disjoints paths may affect only the path which contains the failed node or link. Determining the set of node disjoint paths in a network is not easy to perform. Unlike the node disjoint routing, link disjoint paths may contain common nodes-there is no common links between the paths. Finally, braided paths can contain a set of nodes and links which are common between the two or more than two paths. Though braided paths are easily discovered, they are not fault tolerant.
Suurballe [90] proposed a minimum weight $k$-disjoint paths algorithm from the source to the destination in a non-negatively weighted directed graph. This method runs iteratively until there are $k$ node disjoint paths. During each iteration, the algorithm uses Dijkstra’s method to find the shortest path, and then modifies the weights of links in the graph and then runs Dijkstra’s algorithm a second time. The weight modification preserves the non-negativity while allowing the Dijkstra’s algorithm to find the correct path.

In [91], the authors proposed two variants of minimum energy multipath routing schemes viz., multipath with disjoint links and multipath with disjoint nodes to improve the network lifetime and reliability against node or link failures. They also claimed that the link disjoint path routing is more energy efficient, while the node disjoint path routing is more reliable for the packet transmission.

Braided multipath routing [92] was designed to provide robustness and fault tolerance in wireless sensor networks. In this routing scheme, several partially disjoint paths are constructed between the source and the destination. Two types of path reinforcement message were used to construct the primary path and alternative paths: (i) primary path reinforcement message and (ii) alternative path reinforcement message. Primary path is constructed by sending a primary path reinforcement message by the sink to its most preferred neighbor node towards the source node. When an intermediate node receives this message, it forwards this to its preferred next hop neighbor node and this process is repeated until the message is reached at the source node.

In addition, all the nodes along the primary path also construct an alternative path around their next hop neighbor nodes. To do this, the sink sends alternative path reinforcement to its next preferred neighbor. All the nodes including the source generate this alternative message and sends to their next preferred next hop. In this way, nodes along the path construct alternative routes towards the sink. In addition, when a node, not the members of the primary path, receives this message, it forwards this to its most preferred next hop neighbor node. This process terminates when a node along the primary path receives the message. In this way, a set of alternative paths are maintained by each intermediate node and whenever the primary path fails to forward the data packets, one of the constructed alternative paths can be utilized to avoid the data transmission failure.
The advantage of the braided multipath routing is that it has lower overhead and provides a better resilience against failure than disjoint path routing. However, usage of the same path depletes the energy of nodes more quickly and causes early death of nodes on the paths.

In [94], the author proposed a set of routing algorithms to compare the performance of node disjoint, link disjoint and zone disjoint multipath routing with minimum hop. Simulation results showed that the number of link disjoint paths is significantly higher than that of node disjoint and zone disjoint paths in a network. Nevertheless, the node disjoint routes have smaller hop count than link disjoint paths. The main drawback of [94] is that it is based on Remove and Find method (RF method). Although RF method is simple, it may give false alarms about the non-existence of paths when such paths actually exist.

- **Multipath Routing for Concurrent Transmissions**

The use of concurrent multiple paths has obtained a significant attention to support reliable data transmission over an unreliable transmission medium by introducing data redundancy at the time of data transmission. A large set of routing protocols fall in this category. This section provides a study of these protocols.

Wenjing [95] proposed an efficient $N$ to 1 protocol, which discovers multiple node disjoint paths from each node in one route discovery process. This is basically a one-time computation process. For the route discovery, the sink node broadcasts the route update message. On receiving the message, each node, for the first time, sets the sender node as its parent node and propagates the message. If an intermediate node overhears the update message from the neighbor node that has node disjoint path towards the sink, it adds this path to its routing table. This process continues until all the nodes find their primary paths. The approach forms a breadth first spanning tree with the sink node as the root of the tree. Although the protocol improves the path reliability by discovering multiple paths, use of simple flooding technique do not result in constructing high quality paths with less interference. This is because the discovered paths are located nearby and concurrent transmissions over these paths increase the effect of interference on the nodes.
In [96], Huang and Fang presented Multi Constraint QoS Multipath Protocol (MCMP) to provide soft QoS guarantee in wireless sensor networks. It utilizes the braided multiple paths for providing QoS in terms of reliability and delay. In MCMP, the end to end soft QoS problem is formulated as an optimization problem and a linear integer programming based algorithm was proposed to solve the optimization problem. Nevertheless, while choosing the paths having minimum hop count to decrease the path delay; MCMP increases the energy consumption at nodes. Another problem of MCMP is data redundancy. Since the partially disjoint paths are located close to each other, high volume data transmission from nearby nodes may cause high amount of interference and thus the data transmission rate gets affected.

To overcome the problems of MCMP, Bagula et al. proposed Energy Constraint Multipath Protocol (ECMP) [97]. ECMP extends MCMP protocol by formulating the QoS routing problem as an energy optimization problem that is constrained by reliability, delay and geo-spatial energy consumption. The main motivation of ECMP was to support multi constraint QoS in energy efficient manner. MCMP chooses the next hop nodes arbitrarily without considering the energy consumption at nodes, while ECMP transmits the data towards least energy consuming links. Both MCMP and ECMP improve the delay of the formulated path, however ECMP has lower energy consumption than MCMP. One of the disadvantages of ECMP is that all the constructed paths are located in the physical proximity of each other and therefore, interference from the nearby transmissions increases the overall energy consumption of the network.

Effects of interference can be quantified using graph-theoretic approaches (i.e. contention graph / conflict graph) [98-99]. In [98], authors developed an Interference Minimized Multipath Routing protocol (I2MR), which aims to provide high data rate streaming in low power wireless sensor networks. I2MR tries to construct zone disjoint paths considering the effects of the wireless interference and distributes the traffic over the discovered paths using minimal localization support. In I2MR, the source node discovers a set of paths: one is the primary path and others are the backup paths; the secondary paths are used to control the congestion. The main disadvantage of I2MR is that it does not focus on the issues of power...
consumption and interference associated power consumption in link cost design. Thus, it is not energy efficient at all.

In [102], the authors proposed a node disjoint Interference Aware Multipath OLSR (IA-MPOLSR) routing protocol for mobile ad hoc networks. In IA-MPOLSR, they developed weighted node interference metric for calculating the interference of a link. Interference of a node depends on the distance from the node to other nodes within its interference range. To calculate the interference, the interference region of a node is divided into smaller regions and each region is assigned an interference weight. Though IA-MPOLSR finds the interference minimized paths, these paths are not energy efficient. Moreover, in IA-MPOLSR, protocol interference model is used to calculate the interference at node, which may not be realistic in many practical scenarios.

- **Energy Aware Multipath Routing Algorithms**

Energy aware multipath routing protocols are mostly heuristic protocols that basically pick up the next hop node primarily based on the residual energy of neighboring nodes. The main objective of this kind of routing is to balance the traffic load at nodes.

Robust and Energy Efficient multipath Routing protocol (REER) [100] takes into account the residual energy, node’s buffer size and interference at node in order to locate next hop node of routing paths. In REER, two different approaches were proposed for traffic allocation. The first approach uses the single path among the set of discovered paths for forwarding the data packets. When the cost of this path falls below a certain value, the next path is selected. In second approach, message is split into number of segments and REER uses multiple paths with XOR based error correction codes. The multiple paths are constructed by broadcasting a 'HELLO' message. Each node maintains a neighbor table to store the list of the capable neighboring nodes. Based on the information of the neighboring nodes, REER chooses the best next hop node to forward the data. While REER improves the end to end delay and reliability, physical interference model to measure the interference level at link was not taken into consideration. Moreover, the flooding technique used in REER during neighbor discovery process also increases the routing overhead in the network.
Energy Efficient and Collision Aware multipath routing protocol (EECA) [101] is an on demand multipath routing protocol, which uses location information of the nodes to establish multiple collision free paths. The main objective of EECA is to reduce the effect of wireless interference through constructing two paths in both sides of direct line between the source-sink pair. In EECA, the distance between these two paths should be more than the transmission range of nodes. In order to transmit a packet to the sink node, the each node broadcasts a route discovery message to the neighbor nodes. Each node then transmits this route discovery message and data, using the power level required, to the next hop node. When the source has packets to send, it finds its neighbor nodes and the selects the two groups of nodes that satisfy the following three conditions: first, nodes should be closer to the sink node; secondly, a group of nodes at one side of source-sink line should lie opposite to other group of nodes and finally, distance between two nodes more than the transmission range of the node.

Although EECA tries to design collision free paths, it needs the nodes to be GPS assisted and relies on the localized information. This increases the cost of network deployment and communication overhead. Moreover, transmitting the data packets over minimum delay paths (though theoretically it reduces the end to end delay), in low power wireless networks increases probability of packet loss.

In [103], Radi et al. proposed a Low Interference Energy efficient Multipath Routing protocol (LIEMRO) for wireless sensor networks that improves the performance of event driven sensor networks through the generation of adequate number of interference minimized paths. It utilized an iterative approach to set up a sufficient number of node disjoint paths with minimum interference from each event area towards the sink. LIEMRO uses link cost function for selecting the suitable next hop node, where the link cost is a weighted combination of residual energy of node, accumulated ETX (expected transmission count) value and the interference level at a node. In LIEMRO, physical interference model is used to measure the interference level at a node.

LIEMRO balances the traffic load of the network through distributing the data packets over high quality paths with minimum interference, but it assumes that the node uses the maximal transmission power to communicate with the next hop node.
Moreover, the buffer capacity of the participating nodes was not taken into consideration to adjust the traffic over the paths.

Li et al. [104] designed a multipath energy efficient routing protocol for wireless sensor networks considering wireless interference between the paths. Their proposed method searches for the shortest paths with least interference and nodes in the interference zone of the discovered path are marked and not allowed to take part in subsequent routing process. In this way, two paths with least interference are discovered and the data packets are distributed over multiple paths instead of a single path. The drawback of this routing protocol is that the number of paths is always two and the physical interference model was not taken into consideration in order to capture the interference experienced from the adjacent transmissions.

In [105], the authors proposed a multipath routing protocol, called QEMPR (QoS and Energy aware Multipath Routing) for real time application with the minimum energy. In this protocol, each node in the network is assigned with a unique ID and the node has capability of calculating the packet receiving and packet sending probability using the link quality information. Moreover, each node maintains a neighbor table for storing different information about the neighbors. QEMPR performs path discovery to discover multiple paths using residual energy, packet receiving probability, sending probability and interference. After constructing the paths, the packets will be transmitted based on the sequence number and number of hops it is away from the sink. This means that the packet with lowest sequence number will be transmitted through the path that has the lowest hop number. Then, the sequence number and hop go higher and higher. This process will be repeated until the sink receives all the packets. QEMPR helps to distribute the traffic over multiple paths, thus improves the network lifetime and QoS. However, the employed paths cannot be always the interference minimized paths.

2.6.4 Hierarchical Routing

Hierarchical routing or cluster based routing was proposed in the literature to improve the scalability and energy efficiency of wireless networks. In cluster based network topology, nodes are organized into different clusters, where the roles and functions of nodes are different at various levels of hierarchy. Clusters are arranged
based on certain parameters [67] and nodes belonging to same cluster are interconnected with a clusterhead (CH), which is a special node dedicated in maintaining the communication between the members nodes of the cluster. There can be multiple clusterheads in a cluster and a member node can belong to the multiple clusters. The number of clusterheads is directly proportional to the number of nodes in the network, while the number of nodes in a cluster is independent on the network size. There are numerous clustering algorithms in the literature. The surveys in [15-17, 64] present various clustering algorithms for wireless ad hoc and sensor networks. This section presents some of the existing clustering algorithms for ad hoc and sensor networks.

- **Heuristic Clustering Algorithms**

Parekh [57] proposed a degree based heuristic, called Highest Connectivity Clustering (HCC) protocol for mobile ad hoc networks. In HCC, the node with the highest degree (i.e. maximum number of neighbor nodes) is selected as clusterhead and, other neighbor nodes whose status are not yet decided, become the member nodes and do not participate in election process. A higher degree of connectivity ensures the better network performance by minimizing the number of clusters in the network. The network performance includes low delay, less number of orphan nodes and better connectivity. HCC has some drawbacks. First, it does not put any restriction on the upper bound for number of nodes in any cluster, which increases energy consumption at nodes in the cluster. Second, the clusterhead changes frequently due to the host mobility.

An identifier based clustering protocol, called Lowest ID (LID) protocol was designed in [54]. In LID, every node is assigned with a unique non-negative identifier and node having lowest identifier is selected as clusterhead. The ordinary member node which is in the transmission range of multiple clusterheads joins the cluster with lowest cluster ID. LID does not allow two clusterheads to be neighbors, so the gateway nodes are used for routing between the clusters. Time division multiple access (TDMA) based probing message is exchanges among the nodes to ensure a contention free communication. The main objective of LID is to achieve a connected network topology. LID was used as a benchmark for producing stable clusters as discussed by authors in [55-56]. The major drawback
of LID based heuristic is that nodes with smaller identifier tend to be selected as clusterheads repeatedly which may lead to the drainage of battery of certain nodes. In addition, LID has fewer clusterhead changes than degree based algorithm because the connectivity of a node changes more frequently - that necessities clusterhead re-election.

- **Mobility Aware Clustering Algorithms**

Mobility aware clustering algorithms utilize the mobility of nodes for clusterhead selection and cluster formation process. In [58], the authors proposed mobility based clustering protocol for mobile networks. Each node is assumed to be equipped with Global Positioning System (GPS). Moreover, each node is aware about the mobility of its local neighborhood and the clusters are formed around the node which is more stationary in a neighborhood.

MOBIC [59] uses mobility information of nodes for cluster formation, especially clusterhead selection. In MOBIC, clusterhead election is done locally based on the mobility information of the neighbors and node itself. MOBIC uses an aggregate local mobility to elect the clusterhead such that the node with the least mobility has more chance to become head of the cluster. It gives better network performance where nodes move in group and it is easy to find the relative mobility of a node with respect to its neighbors. However if a node moves randomly and changes its position time to time, the performance of MOBIC may be degraded. In [61], McDonald investigated a distributed clustering algorithm for mobile ad hoc networks. It ensures that the probability of mutual reachability between any two nodes in a cluster is bounded over time.

- **Mobility and Energy Efficient Clustering Algorithms**

Mobility and energy efficient clustering protocols [50, 63, 68] consider multiple parameters, viz., mobility, residual energy and node degree in cluster formation process. In [60], the authors proposed a Weighted Clustering Algorithm (WCA) for mobile ad hoc networks, where the re-election of clusterhead takes place on demand. WCA considers several system parameters such as node degree, residual energy, transmission power, mobility in clusterhead selection. Moreover, these parameters are given different weights depending on the application requirement.
In WCA, the node with the smallest weight is selected as clusterhead and its one hop neighbors become the members of the corresponding cluster. WCA has several disadvantages. First, a large number of messages are exchanged among the nodes to find the smallest weight and this becomes worse with increase in the network size. The second drawback of WCA is that it does not perform re-clustering for the smallest weight member node when it enters into a cluster.

Another weight based clustering algorithm, called WBCA was proposed in [62]. In WBCA, a combined weight is associated with each node in the network. The weight is calculated on the basis of mean degree of connectivity and residual energy. Unlike [54] and [57], WBCA gives more stable clustered topology. However, the calculation of mean connectivity degree for a node is computationally hard, especially in a dynamic network where the mobility of nodes frequently changes its degree of connectivity. To address this problem, several mobility prediction based clustering algorithms [65, 66] were proposed. These algorithms predict the node’s mobility and use this information to build the stable clusters in the network.

- **LEACH: Low Energy Adaptive Clustering Hierarchy**

In [18], Heinzelman et al. introduced an energy aware hierarchical protocol for wireless sensor networks, called LEACH (Low Energy Adaptive Clustering Hierarchy). LEACH is a self-organizing clustering protocol, which includes distributed cluster formation. Local clusters are created with one or more nodes. In a cluster, all the data processing is performed at the clusterhead. In LEACH, clusterhead receives the data packets from the nodes of its own clusters and then compresses the data and sends the aggregated data packets to the sink. It selects the clusterhead randomly with certain probability and rotates this role evenly to the nodes for balancing the energy consumption among them. Data gathering cycle is known as round. LEACH has four phases in each round: steady setup, clusterhead selection, cluster formation and data transmission. Each node decides whether it will be the clusterhead in current round or not based on some threshold and random number. Each elected clusterhead broadcasts an advertisement message to all the nodes in the network. Each non-clusterhead node receives the message and chooses the cluster that they want to join based on the received signal strength. Moreover,
each clusterhead creates a TDMA schedule and assigns each node a slot in which it can transmit.

LEACH has several advantages. First, it is simple and fast. Second, if a node has just been elected as a clusterhead, it is eligible to make its next self-election only after some time period. Therefore, other nodes which have not been elected as clusterheads will have a higher likelihood to be selected as clusterheads. By rotating the role of clusterhead among the nodes, LEACH achieves balanced energy consumption of the network. Although LEACH improves the network lifetime, still it has some drawbacks. First, residual energy of nodes was not taken into consideration in head selection probability. Second, clusterhead selection probability function was based on the assumption that all the nodes have same initial energy which is not true for the heterogeneous network. Third, since the clusterhead selection is performed in terms of probability, it is hard to determine clusterheads to be uniformly distributed throughout the network. Finally, LEACH leads to imbalance energy dissipation among the nodes because energy of nodes which are located far away from their clusterheads (or sink) can be easily used up for the data transmission to their clusterheads (or sink).

- Several Variants of LEACH

Several variants of LEACH were proposed to maximize the network lifetime. A centralized version of LEACH, called LEACH-C was proposed in [19]. LEACH-C uses the sink as the central controller to form the clusters. During each round, each node sends its current residual energy and location information to the sink. Based on this information, the sink computes the average node energy and chooses those nodes whose energy level is above this average value as candidate clusterheads. For minimizing the total sum of squared distances between all the non-clusterheads and the closest clusterhead, LEACH-C uses simulated annealing to find the optimal clusters.

In [20], the authors proposed another variant of LEACH, called Two Level hierarchy for LEACH (TL-LEACH). TL-LEACH is extension of LEACH, which utilizes two levels of clusterheads (primary, secondary) in addition to the other nodes. In TL-LEACH, the primary clusterheads communicate with the secondaries,
and the corresponding secondaries communicate with other nodes within their sub cluster. It uses a probability function same as LEACH for choosing the clusterheads and rotates the role clusterheads among the nodes to balance the energy consumption of the network. TL-LEACH has some advantages and disadvantages. The main advantage of TL-LEACH is that it can minimize the inter-cluster energy consumption cost at nodes because of its two level of hierarchy and thus improves the network lifetime. However, randomized election of clusterhead still causes imbalanced energy dissipation among the nodes.

In [21], vice-CH (VLEACH) was proposed where sensor node will become a clusterhead if the current clusterhead uses up its energy. In this method, several substitute clusterheads are chosen within a cluster for continuing the data transmission in the network. VLEACH reduces the clustering overhead by minimizing the chances of re-clustering and thus improves the network lifetime. Moreover, it ensures that the sensed data will always be reached to the sink. However, it is unnecessary to elect the substitute clusterhead taking the role of clusterhead which dies during the operation.

A Multihop Routing with Low Energy Adaptive Clustering Hierarchy (MR-LEACH) protocol, which uses multihop routing for forwarding the data from sources to the sink was designed in [22]. The clusterhead election in MR-LEACH is based on the available energy, and it partitions the network into different layers of clusters. Clusterhead in each layer is responsible for relaying the data for the clusterheads at lower layers in order to transmit it to the sink. Thus, MR-LEACH allows multihop communication to forward the data to the sink and thus conserves the energy. However in multihop routing, nodes near to the sink may be over utilized and it results rapid battery drainage and network partitioning.

- Residual Energy based Hierarchical Clustering Algorithms

Two hierarchical routing protocols TEEN (Threshold sensitive Energy Efficient sensor Network protocol) and APTEEN (Adaptive Periodic Threshold sensitive Energy Efficient sensor Network protocol) were designed in [23] and [24] respectively for the time critical operations. In TEEN, the data transmission is done less frequently. It uses clustering strategy of LEACH to select the clusterhead. In TEEN, the network uses two level clusterheads to improve the energy efficiency in
the network. The first level clusterheads are formed away from the sink and second level clusterheads are formed near to the sink. The main drawback of this scheme is that if the thresholds are not received timely, the nodes will never communicate and nodes will not get any data from the other nodes in the network. On the other hand, in APTEEN, threshold value changes periodically over the time. Simulation results showed that the performance of TEEN and APTEEN is better than LEACH. However, APTEEN lies between TEEN and LEACH in network lifetime and total energy consumption. The main drawback of these protocols are the complexity and routing overhead for maintaining clusters at different levels and calculation of threshold value for data forwarding.

Power Efficient data Gathering in Sensor Information Systems (PEGASIS) [25] is an enhanced clustering protocol over LEACH. The main objective of PEGASIS was to improve the lifetime of the network by balancing the load among nodes. In PEGASIS, the nodes form a chain and one node in a chain is used to transmit the data packets to the sink instead of multiple nodes. PEGASIS assumes that the locations of nodes are random and node can perform multiple operations such as aggregation, sensing and transmission. It also maintains a database for storing location information of nodes. PEGASIS has several advantages and disadvantages. The main advantage of PEGASIS is that it distributes the energy load among the nodes in a network. However, the major drawback of this technique is that the communication suffers excessive delay because of the chaining method. In PEGASIS, there is high probability for any node to become a bottleneck node. In addition, it is difficult task for a node to maintain the details of all the other nodes in network and even the network is not very scalable as nodes need to keep the global knowledge of network.

Hybrid Energy Efficient Distributed clustering (HEED) [26] is a distributed clustering protocol in which clusterheads are selected based on the residual energy and node degree/ connectivity of nodes. Unlike LEACH, HEED chooses the clusterhead which has higher residual energy and lower intra-cluster communication cost. HEED minimizes the overhead of re-clustering by keeping the CH for a fixed number of iteration. Non-clusterheads join to the cluster for which lowest intra-cluster communication cost is minimized. HEED is fast and improves uniform clusterhead distribution across the network than LEACH.
Although HEED creates distributed clusters without the size and the density of network being known, the cluster topology fails to achieve minimum energy consumption in terms of intra-cluster communication [46]. Furthermore, only the residual energy of nodes are taken into consideration during the CH election process whereas the other factors such as link quality or topological importance of node that could influence the network performance, have not been taken into consideration in election probability metric.

Another energy aware hierarchical clustering approach, called Energy Residue Aware (ERA) was proposed in [27]. ERA is more improved than LEACH since it includes the residual energy of nodes, the inter cluster communication cost and intra cluster communication cost in cluster formation phase. Like LEACH, ERA selects the clusterheads randomly. Although it improves efficiency of network, random election of clusterhead and irregular distribution of CHs make the algorithm energy efficient.

Thein et al. [32] extended LEACH’s stochastic clusterhead selection algorithm by modifying the probability of a node to become clusterhead based on the remaining energy of nodes. Since the head selection metric includes the residual energy of nodes, this algorithm minimizes the energy consumption of nodes. In order to balance the energy consumption, the role of clusterhead is rotated among the nodes periodically. Simulation results showed that Thein’s algorithm improves the network lifetime than LEACH. This clustering algorithm however has some disadvantages. First, it does not consider parameters like node degree or energy cost in clusterhead selection. Second, in this algorithm, non-clusterhead nodes choose their clusters based on the received signal strength between the nodes, which can cause uneven energy depletion among the clusterheads. Third, the performance with heterogeneous network is satisfactory.

The objective of Energy Based Selective Clusterhead Rotation (EBSCR) [33] was to minimize the routing overhead due to re-clustering and re-election of clusterhead. EBSCR rotates the role of clusterhead among the nodes to balance the energy consumption at nodes and thus prolongs the network lifetime. EBSCR follows the same routing process as designed in PEGASIS [25]. However, in EBSCR, the clusterhead are changed based on the current energy level of nodes.
In [34], authors developed a clusterhead selection process using $K$-Means clustering algorithm with an objective of minimizing the energy spent in communication. Initial clustering is done using $K$-Means clustering algorithm and a node, for which the sum of Euclidean distance between the CH and member nodes is minimum is selected as clusterhead. Re-election of clusterhead occurs only when the energy level of current node is lower than some threshold value. In order to balance the energy consumption, the role of clusterhead is periodically rotated among the nodes in a cluster. In [34], rotation of clusterhead was done using the unique IDs of nodes. This protocol is simple and does not require a large communication overhead. However, its performance in heterogeneous networks is not well, since it elects the clusterhead without considering the residual energy of nodes.

- **Multi Weight based Energy Aware Clustering Algorithms**

The clustering scheme proposed in [28] uses probability to elect the clusterhead. In every round, each node decides whether it will be the clusterhead in that round, on the basis of the threshold value. This threshold value is calculated in terms of the residual energy and number of alive neighbor nodes by using a combined weighted approach. If a randomly generated number between 0 and 1 is smaller than the threshold value, the node elects itself as clusterhead. Though the algorithm improves network lifetime, it still has some drawbacks. First, every non clusterhead nodes choose the clusters that they want to join without considering the residual energy of the corresponding clusterhead. Second, although the algorithm creates distributed clusters, yet the clustering process fails to minimize total energy consumption of the network.

MWBC [29] is a multi-weight based clustering algorithm for maximizing the lifetime of sensor networks. It takes into account many factors such as the node degree, link quality, residual energy, transmission power and relatively position of nodes for electing clusterheads. Routing messages are exchanged among the nodes in order to obtain the information regarding the different parameters of MWBC. Further, these parameters are combined together using a weight based metric. Nodes use this weight based metric to compete for the clusterhead selection. Simulation results showed that MWBC achieves good clusterhead distribution and
better load balancing feature. However, the weight of each parameter is determined using to trial and error method, which results routing overhead and will influence the overall performance of MWBC.

Another weight based clustering algorithm, called Weighted Self-Organized Head Selection (SOHS) was proposed in [30]. SOHS uses local information such as node connectivity and residual energy for calculating the fitness function of each node and incorporates that fitness for head selection technique. Although SOHS is simple and improves network lifetime, unbalanced energy consumption among the clusterheads still exists because a non-clusterhead chooses a clusterhead that is closest to it.

- **Location based Clustering Algorithms**

Total energy consumption of a cluster is related to the location of clusterhead in the cluster. Selecting the node near to the centroid as a clusterhead may reduce the intra-cluster energy consumption cost of nodes. The clustering algorithm addressed in [35] considers several parameters such as residual energy, position of node and energy cost in order to select the clusterhead. These parameters are combined through the weighted average approach. In [36], a distributed clustering algorithm was proposed for maximal lifetime wireless sensor network design, which takes into consideration two factors such as residual energy and topological features of nodes. This clustering algorithm chooses the central node as clusterhead and thus minimizes the energy consumption in the network.

In [37], the authors studied the algorithms for finding best locations of clusterheads in wireless sensor networks in order to minimize the overall energy consumption. They proposed three algorithms for finding the best location of clusterhead in a single cluster; the best formation of a given number of clusters where each cluster communicates with the sink directly and the best formation of a given number of clusters when the clusterhead communicates to the sink in ad hoc manner. In each case, two different models, namely free space and multipath were considered. Though these algorithms minimize the overall energy consumption of the network, they are not energy efficient since the clusterheads are chosen without considering the residual energy of nodes.
2. Literature Review

• Balanced Clustering Algorithms

Rotating the role of clusterhead balances the power consumption among the nodes. Power consumption can be further minimized if the clusters have equal size. Several algorithms [39, 40, 69] have been proposed for achieving load balanced clustering in wireless sensor networks. Nam et al. [42] showed that energy balanced clusters can be achieved by balancing the load in terms of power consumption. The rationale is that the local cluster knows the optimal cluster size and uses this information for adjusting the position of clusterhead in the cluster. They considered optimizing cluster formation by calculating the distance between clusterhead and member nodes.

Another load balanced clustering algorithm, called Equalized Cluster Head Election Routing Protocol (ECHERP) was proposed in [43]. ECHERP uses Gaussian elimination method to calculate the combination of nodes that can be chosen as the clusterheads. It only considers energy consumption of nodes for selecting the clusterheads of the network. To balance the intra-cluster energy consumption, the authors [45] investigated multihop transmissions within a cluster. In this case, the transmission range of all the nodes was assumed to be same. Though the algorithm improves the energy efficiency of the network, it increases delay as well.

Distributed Weight based Energy Efficient Hierarchical Clustering (DWEEHC) [46] was designed to achieve load balanced clusters. It is similar to HEED [36]. In DEEHC, every sensor node computes its score function using residual energy and number of neighbors. In a neighborhood, sensor with the largest score is elected as clusterhead and all the neighborhood members are attached to it using multihop fashion. In DWEEHC, the number of levels in the hierarchy depends on the cluster range and TDMA schedule is used for data transmission. In [69], the authors proposed a distributed clustering algorithm for sensor networks, which optimizes the communication workload, network lifetime and node degree. In this technique, balanced clusters are produced over a diverse set of random scenarios.
2. Literature Review

• Unequal Clustering Algorithms

Several unequal clustering algorithms have been investigated in literature to improve the balanced energy consumption in the network. In [38], the authors proposed a distributed Energy Efficient Clustering Scheme (EECS) for sensor networks. In EECS, nodes with higher residual energy are elected as clusterhead to cover the network. It is based on LEACH [18] protocol. In EECS, each clusterhead directly sends the data packets to the sink. Moreover, the cluster range of each node is set according to the distance between node and sink. In EECS, the node farther away from the sink forms a smaller cluster, while the node nearer to the sink constructs larger cluster.

Unequal Cluster based Routing (UCR) [41] is another distributed algorithm that performs single level and multilevel clustering. In UCR, the clusterheads are elected using localized competition. This decision is based on the residual energy of nodes. In UCR, two types of clusters are constructed. The cluster range of node decreases as its distance from the sink increases. Clusters near to the sink have smaller size than the clusters farther away from the sink. In [44], the authors proposed a Sink Oriented Layered Clustering (SOLC), which forms the clusters of unequal sizes. In SOLC, concentric circles are formed and a cluster consists of only the nodes located at same ring. A cluster in a ring closer to the sink has smaller size. SOLC elects the clusterheads based on the residual energy of nodes. Even though, EECS, UCR and SOLC prolong network lifetime, still uneven energy distribution still exists at nodes because of multihop communication.

• Non-Uniform Clustering Algorithms

Several clustering methods have been proposed for heterogeneous networks. In [49, 51], the authors presented energy efficient heterogeneous clustered algorithms for wireless sensor networks. In [52], the authors proposed clusterhead election techniques for the network with non-uniform node distribution. This algorithm focuses on coverage preservation, but involves higher energy consumption and lesser network lifetime as well. Considering non uniform node distribution, authors in [53] proposed a hierarchical structure of sensor network with energy aware cluster formation and cluster based routing algorithm. They used competition range
to construct the clusters of even sizes. The routing algorithm increases the network lifetime by forcing clusterheads to choose the nodes with higher residual energy and fewer member nodes as their next hops and achieves load balancing among clusterheads.

2.7 Conclusion

This chapter has given an overview of existing routing protocols for wireless ad hoc networks, and existing energy efficient routing algorithms used for such networks. These algorithms are classified into four classes: (i) Routing protocols using energy-related metrics, (ii) Energy aware - QoS based routing, (iii) Energy efficient multipath routing, and (iv) Hierarchical routing. For each class, routing algorithms have been presented and briefly described.

Although energy efficient routing algorithms are often helpful to increase the lifetime of the network, most of them do not take into account the energy spent by the nodes due to overhearing of nearby transmissions which are not intended for them. Therefore, energy cost for the overhearing transmission is considered to be an area of further research. Most of the energy efficient routing algorithms achieve QoS with increased routing overhead. In this thesis, the above mentioned problem has been identified and addressed.

Recent studies on multipath routing investigate that the energy efficiency of the nodes can be improved by establishing multiple paths. However, the main drawback of multipath routing is increased hop count and interference from adjacent transmissions. On the other hand, several protocols use the power control mechanism to minimize interference at node. In this thesis, these two approaches are combined together for minimizing the network energy consumption and at the same time providing QoS in energy efficient manner.

It is clear from above discussion that cluster based routing is effective to minimize the energy consumption of nodes. Most of the clustering algorithms focus on the energy consumption of node to prolong the network lifetime. In this thesis, cluster based routing will be considered for balancing the energy dissipation of nodes to maximize the network lifetime.