2. Theoretical Background

2.1. Introduction

This chapter describes the work done in the field of Wireless Sensor Network (WSN) and also specifies why this topic was chosen by the author for his research work. Section 2.1 deals with clustering. The section 2.2 and 2.3 deals with Routing and the different routing protocols proposed by different researchers respectively. The section 2.4 discusses the design parameters of WSN. The next section deals with the coverage issues and the ways to handle these issues in WSN. The section 2.6 deals with connectivity issues and their solutions in WSN. The subsequent section introduces the concept of having multiple sinks. With multiple sinks, the network becomes many to many in contrast with traditional many to one scenario. The section 2.8 introduces the radio model. Finally, the last section summarizes the work proposed in different chapters of the thesis based on the critical literature review mentioned in sections 2.2 to 2.8.

2.2. Routing in WSN

WSN normally consists of a large number of sensing nodes deployed in a region to sense any physical quantity like temperature, pressure, humidity etc[1]. Such sensing nodes are capable of sensing, processing and transmitting the data to a base station or a sink. If the sink is within the transmission range of the node, it transfers the data in single hop. But if the sink is far off, the node sends the data in multiple hops. Sensor nodes have a limited transmission range as well as limited processing and storage capabilities. When the nodes have to send the data in multiple hops, a routing path must be established between the node and the sink. The routing path is determined by a routing protocol. The routing protocols have to ensure reliable multi-hop communication under the limited resources of a WSN. The design space for routing algorithms for WSNs is quite large and we can classify the routing algorithms [22] for WSNs in many different ways. Different routing protocols are depicted in the Figure 2.1. They are discussed in detail in the subsequent section.
2. Theoretical Background

Routing Protocols
- Location Based
- Data Centric
- Hierarchical Clustering
- Mobility Based
- Multipath Based
- Heterogeneity Based
- QoS Based

Figure 2.1.: Routing protocols
2.3. Routing Protocols

Many routing algorithms were developed for wireless networks in general. Many researchers have written survey papers comparing the different routing protocols [23, 24, 25, 26, 27]. All major routing protocols proposed for WSNs may be divided into seven categories [28] as depicted in Table 2.1. They will be described in the subsequent sub sections.

### 2.3. Location Based Protocols

In location based protocols, the sensing nodes are addressed with the help of their locations. Such protocols are equipped with a hardware to determine the location of the node like a GPS unit or a localization system [37]. Geographic Adaptive Fidelity (GAF): GAF [29] is an energy-aware routing protocol primarily proposed for MANETs, but can also be used for WSNs because it favors energy conservation. Geographic and Energy-Aware Routing (GEAR) [30] is an energy-efficient routing protocol proposed for routing queries to target regions in a sensor field. Span [31] is a routing protocol which is motivated by the fact that the wireless network interface of a device is often the largest consumer of power. Hence, it’s better to turn the radio off during idle time. TBF [32] is a routing protocol which on the basis of the location information of its neighbors, has a forwarding sensor which makes a greedy decision to determine the next hop that is closest to the trajectory fixed by the source sensor.

Bounded Voronoi Greedy Forwarding (BVGF) [33] uses the concept of Voronoi diagram [6]. The sensors eligible for being the next hops are the ones whose Voronoi regions are traversed by the segment line joining the source and the destination. Geographic Random Forwarding (GeRaF) was proposed by Zorzi and Rao [34]. In this protocol, there is no
2. Theoretical Background

guarantee that a sender will always be able to forward the message toward the sink. This is the reason why GeRaF is also called best-effort forwarding.

Minimum Energy Communication Network (MECN)[35] is a self-reconfiguring protocol which maintains the network connectivity, even though the sensors are mobile. Small Minimum-Energy Communication Network (SMECN)[36] is an improvement over MECN. The sensors discover its immediate neighbors by broadcasting a message using some initial power that is updated incrementally. Such protocols have costly sensing nodes due to the installed GPS unit.

2.3.2. Data Centric Protocols

In data centric protocols, the sensors send their data to the sink in multiple hops. The intermediate sensors perform some form of data aggregation on the data coming from multiple sending nodes and send the aggregated data to the sink. A lot of energy is wasted in transmission of data. Thus the process of data aggregation results in energy savings. Sensor Protocols for Information via Negotiation (SPIN)[38, 39] solves the problem of implosion and overlap. The SPIN protocols are based on two key mechanisms namely negotiation and resource adaptation. The sensors negotiate with each other before any data transmission to avoid injecting non-useful and redundant information in the network. SPIN uses meta-data as the descriptors of the data that the sensors want to transmit. The meta-data avoids the occurrence of overlap as the sensors can name the interesting portion of the data they want to get.

Directed diffusion [40] is used for sensor query dissemination and processing. The main elements of this protocol are data naming, interests and gradients, data propagation, and reinforcement. Rumor Routing: Rumor routing is a logical compromise between query flooding and event flooding app schemes [41]. The Cougar protocol[42] has a query layer which allows the user to query the data from the WSN. The user need not know which of the sensors has processed its query. The protocol also uses in-network processing which in turn helps in reducing the energy consumption.

Active Query Forwarding in Sensor Networks (ACQUIRE)[43] provides query optimization which enables the sensors to answer complex queries through simple several answers. Each sub query is answered through a database stored in the relevant sensors. Energy-Aware Data-Centric Routing (EAD)[44] provides high level of in-network processing and traffic relaying.

2.3.3. Hierarchical Protocols

Considering the constraints of a WSN, energy-aware routing and data gathering protocols should be developed [45]. Grouping of sensors in clusters offers the said objectives. The
2.3. Routing Protocols

Figure 2.2.: Cluster creation in WSN

Table 2.2.: Comparison of different LEACH protocols

<table>
<thead>
<tr>
<th>Routing Protocol</th>
<th>Mobility</th>
<th>Scalability</th>
<th>Self Organisation</th>
<th>Distributed</th>
<th>Hop Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEACH</td>
<td>Fixed BS</td>
<td>Limited</td>
<td>Yes</td>
<td>Yes</td>
<td>Single</td>
</tr>
<tr>
<td>LEACH-S</td>
<td>Fixed BS</td>
<td>Good</td>
<td>Yes</td>
<td>Yes</td>
<td>Single</td>
</tr>
<tr>
<td>Multi-hop LEACH</td>
<td>Fixed BS</td>
<td>Very Good</td>
<td>Yes</td>
<td>Yes</td>
<td>Multi</td>
</tr>
<tr>
<td>LEACH-M</td>
<td>Mobile BS</td>
<td>Very Good</td>
<td>Yes</td>
<td>Yes</td>
<td>Single</td>
</tr>
<tr>
<td>LEACH-A</td>
<td>Fixed BS</td>
<td>Good</td>
<td>Yes</td>
<td>Yes</td>
<td>Single</td>
</tr>
<tr>
<td>LEACH-C</td>
<td>Fixed BS</td>
<td>Good</td>
<td>Yes</td>
<td>No</td>
<td>Single</td>
</tr>
<tr>
<td>LEACH-B</td>
<td>Fixed BS</td>
<td>Good</td>
<td>Yes</td>
<td>Yes</td>
<td>Single</td>
</tr>
<tr>
<td>LEACH-F</td>
<td>Fixed BS</td>
<td>Limited</td>
<td>No</td>
<td>No</td>
<td>Single</td>
</tr>
<tr>
<td>LEACH-L</td>
<td>Fixed BS</td>
<td>Very Good</td>
<td>Yes</td>
<td>Yes</td>
<td>Multi</td>
</tr>
<tr>
<td>LEACH-E</td>
<td>Fixed BS</td>
<td>Very Good</td>
<td>Yes</td>
<td>Yes</td>
<td>Single</td>
</tr>
</tbody>
</table>

clusters have a Cluster Head (CH) which performs special task of data aggregation and fusion. The research in clustering in WSN deals with the identification of CHs or finding the optimal routing path ensuring minimal energy consumption. A simple illustration of cluster formation in a region to be sensed is depicted in the Figure 2.2.

Some of the clustering protocols are explained here in brief. Low-energy adaptive clustering hierarchy (LEACH) is the first and most popular energy-efficient hierarchical clustering algorithm for WSNs [3]. In this protocol the CHs send the data directly to the sink in single hop. The CHs perform data aggregation. The CH is selected randomly among the nodes in the cluster. The comparison of different Leach protocols Leach-S[46], Multi hop Leach[47], Leach-M[48], Leach-A[49], Leach-B[50], Leach-C[51], Leach-E[52], Leach-F[53] and Leach-L[54] is shown in the Tables 2.2 and 2.3.

All the mentioned LEACH protocol variations are hierarchical routing protocols with randomized cluster head selection and they use data aggregation techniques. These protocols were designed by different researchers having one or the other benefit depending upon the
Table 2.3.: Comparison of different LEACH protocols II

<table>
<thead>
<tr>
<th>Routing Protocol</th>
<th>Centralised</th>
<th>Energy Efficient</th>
<th>Homogeneous</th>
<th>Use of location information</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEACH</td>
<td>No</td>
<td>High</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>LEACH-S</td>
<td>Yes</td>
<td>V. High</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Multi-hop LEACH</td>
<td>No</td>
<td>V. High</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LEACH-M</td>
<td>No</td>
<td>V. High</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LEACH-A</td>
<td>No</td>
<td>V. High</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>LEACH-C</td>
<td>Yes</td>
<td>V. High</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LEACH-B</td>
<td>No</td>
<td>V. High</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LEACH-F</td>
<td>Yes</td>
<td>V. High</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LEACH-L</td>
<td>No</td>
<td>V. High</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LEACH-E</td>
<td>No</td>
<td>V. High</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

application for which it was used. In one type of LEACH one parameter was better than the other LEACH variation and in other protocol some other parameter was made better. There is always a trade off between the different design parameters of WSN which solely depends upon the application for which the network is going to be used.

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [55] forms chains of sensors and only one node in that chain transmits the data to the sink. The sensors transmit the data to its neighbors instead of sending it to the CH. Instead of selecting the CH at random as in Leach, Hybrid, Energy-Efficient Distributed Clustering (HEED) [56] protocol selects a CH on the basis of residual energy.

Threshold Sensitive Energy Efficient Sensor Network Protocol (TEEN) [57]. The closer nodes form clusters and this process goes on the second level until the sink is reached. TEEN is not suitable for applications where periodic reports are required since the user may not get any data at all if the thresholds are not reached. Adaptive Periodic Threshold Sensitive Energy Efficient Sensor Network Protocol (APTEEN) [58] is an advanced TEEN protocol which senses critical as well as periodic data. It removes the drawbacks of TEEN. Hierarchical clustering is explained in detail later.

2.3.4. Mobility Based Protocols

In such protocols, the sinks are mobile. The routing protocols should be able to transmit the data to the mobile sink. In the case of static sinks, the CHs or the nodes which are close to the sink and highly loaded and get energy depleted faster as compared to other sensing nodes. To avoid this problem, the sinks are made mobile so that the nodes close to the sink are always changing and thus the chances of nodes getting die out decreases. As a result the overall network lifetime increases. Joint Mobility and Routing Protocol [59] considers
2.3. Routing Protocols

mobile trajectory to be concentric circles or annuli. Data MULES Based Protocol proposes to address the need of guaranteeing cost-effective connectivity in a sparse network [60].

Scalable Energy-Efficient Asynchronous Dissemination (SEAD) is a self-organizing protocol consists of three main components namely dissemination tree (d-tree) construction, data dissemination, and maintaining linkages to mobile sinks. Dynamic Proxy Tree-Based Data Dissemination [61] form a tree between the source sensor and the multiple sinks which wish to receive the data. Each source is represented by a stationary source proxy and each sink is represented by a stationary sink proxy. But, in such protocols, extra energy is consumed in finding out the location of the nodes and the sink every time the sensing node needs to send the data.

2.3.5. Multipath Based Protocols

The routing of data from the sensing nodes to the sink is single path or multi path. In the case of single path, the node finds out the shortest path to the sink and sends the data through that path. In the case of multi path, the nodes finds ‘k’ shortest paths to the sink and then the node distributes its load evenly on those multiple paths. Thus the data reaches the sink on many paths as a result of which the energy consumption reduces whereby increasing the network lifetime. Sensor-disjoint multipath routing[62] protocol helps in finding a small number of alternate paths that have no sensor in common with each other or with the primary path. The primary path is the best route where as the alternate paths are less desirable because of their longer latency. Braided multipath[63] first forms the first primary path. Then for every node on the primary path, the alternate paths are constructed from those nodes to the sink. These paths are called idealized braided multipaths. N-to-1 Multipath Discovery [64] is based on the simple flooding originated from the sink. It is composed of two phases, branch aware flooding and multipath extension of flooding.

2.3.6. Heterogeneity Based Protocols

In heterogeneous WSNs, there are two types of sensors namely line-powered sensors and battery powered sensors. The line powered ones have no energy constraint, and the second ones have limited lifetime. The routing protocols should be chosen such that their available energy is efficiently managed among the two types of nodes. Information-Driven Sensor Query (IDSQ)[64] has a subset of sensors active when there are interesting events to report to the sink in some parts of the network. Cluster-Head Relay Routing (CHR)[65] uses two types of sensors to form a heterogeneous network. It has a large number of low-end sensors, denoted by L-sensors, and a small number of powerful high-end sensors, denoted by H-sensors. Both the H and L sensors are static and know their locations.
2. Theoretical Background

Table 2.4.: Design Factors for Protocol

<table>
<thead>
<tr>
<th>Design Factor</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data delivery model</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Data aggregation</td>
<td>Possible</td>
</tr>
<tr>
<td>Power usage</td>
<td>Low</td>
</tr>
<tr>
<td>Mobility</td>
<td>Possible</td>
</tr>
<tr>
<td>Scalability</td>
<td>Good</td>
</tr>
<tr>
<td>Security</td>
<td>Possible</td>
</tr>
<tr>
<td>Topology</td>
<td>Self organizing and random</td>
</tr>
</tbody>
</table>

2.3.7. QoS Based Protocols

Apart from minimization of energy consumption, it is also important to consider the requirements for quality of service (QoS) with respect to reliability, delay and fault tolerance in WSNs. These protocols find a balance between energy consumption and the QoS requirements. Sequential Assignment Routing (SAR)[66] is a table-driven multi-path approach which tries to achieve energy efficiency and fault tolerance. The routing decision is dependent on factors like QoS on each path, energy resources and priority level of packet. SPEED [67] is another QoS routing protocol which provides soft realtime end-to-end guarantees. In this protocol, each node maintains its neighbor information and uses geographic forwarding to find the routing paths. SPEED ensures a certain speed for each packet to be sent to the sink. When compared to Dynamic Source Routing (DSR) [68] and Ad-hoc on-demand vector routing (AODV)[69], SPEED performs better with respect to end-to-end delay and miss ratio. In Energy-Aware QoS Routing Protocol, realtime traffic is generated by imaging sensors [70]. It finds a least cost and energy efficient path that meets certain end-to-end delay.

2.4. Design Parameters of a WSN

After comparing the existing routing protocols with the consideration of several design factors like Scalability, Power Usage, Mobility, Over-heads, Query-based, Data Aggregation and Localization, the parameters to be included in designing a new routing protocol are listed in Table 2.4. Ideally the new proposed routing protocol should follow the parameters listed in the Table 2.4, but due to the inter dependency of parameters, it is not possible to achieve all the ideal characteristics in a routing protocol.
2.5. Coverage in WSN

Coverage in WSN is defined as how much and for how long the sensors are able to sense the physical phenomenon in the region they are deployed to be sensed. The issues and the approaches for solving the problem of coverage is discussed in the subsequent sub sections.

2.5.1. Issues with Coverage in WSN

There are several issues while considering the coverage in WSN. Some of them are listed in Table 2.5:

**Coverage types**

Depending upon the application either there is a need to monitor the entire region called full coverage [71], or track only a certain area of the network or sense only some set of targets. Full or blanket coverage means that each and every point of the area is covered by at least one sensor. The research paper [72] focuses on the problem of finding the minimum number of sensors that maintain full coverage. Given a region R containing sensors, if each crossing point in R is covered by at least one other sensor in R, then R is said to be completely covered. A crossing point is an intersection point of the two sensing disks of two neighboring sensors, or that of a sensing disk and the boundary of region R. The paper [73] takes one step further and proves that if all the crossing points in the region R are k-covered, then R is k-covered. It also proves that if all the crossing points inside the sensing range are at least k-covered, then a node can be in the sleep mode or inactive. Thus there are two coverage problems:

1. Given the sensing range R of sensors, how to place the sensors so that the number of sensors N needed for full coverage minimized
2. Theoretical Background

2. Given the number of available sensors $N$, how to place the sensors so that the sensing range $R$ needed for full coverage is minimized

The current research work concentrates on clustering so as to have maximum coverage. Target coverage observes a fixed number of targets[74, 75].

Deployment

The sensors are either deployed at pre-decided position in the network i.e. deterministic [76], or they are randomly deployed[77]. The first case is generally used with costly motes and the major problem is that of placement, determining the exact locations of the sensing nodes so that the coverage is maximum. The second case covers inexpensive small motes and the most important problem in this case is that of density control. The deployment of sensors in WSN can be dense or sparse. The dense deployment is usage of large number of sensors and is used in critical application when all the events need to be tracked. Sparse deployment is the organization of less sensors. After deployment the sensors may be static or mobile. All these factors depend upon the application for which the WSN is employed. In the paper[78], the lifetime of a WSN is defined as the period starting from the deployment time until the WSN fails to satisfy its requirements (including coverage, connectivity and success transmission rate). The author produces a deployment model which affects the coverage. The current research work deals with random deployment and the nodes are static after placement.

Node types

The sensor nodes selected for the WSN are homogeneous or heterogeneous as shown in the Figure 2.3. Homogeneous nodes WSN have all the nodes of the same type with similar properties like sensing range, transmission range and energy. M.Gupta deals with the coverage of a homogeneous WSN[79]. Heterogeneous nodes WSN have nodes of different types with different properties. Guan Zhi-yan researches on coverage for such WSN[80].

Constraints

The most important constraint in designing a WSN is that of energy. The nodes are small with limited source of energy. The lifetime of a network is directly proportional to the residual energy of the node. Cardei and Wu, in their research paper have presented a summary of different approaches to energy efficient coverage problems[81]. The author has proposed algorithms to keep the energy consumption of the network as low as possible.
Figure 2.3.: Homogeneous and Heterogeneous Network

**Dimensional coverage**

WSN is employed in either two dimensional or three dimensional space. It is much easier to formulate protocols for two dimension as compared to three dimensional space. The paper [82] was one of the first to describe 3-D space. The authors assume that the sensor’s coverage ranges are in the form of a sphere.

Sensing coverage and network connectivity are two of the most fundamental problems in WSNs. Finding an optimal node deployment strategy that would reduce computation and communication overhead, minimize cost, be resilient to node failures, and provide a high degree of coverage with network connectivity is extremely challenging.

### 2.5.2. Approaches to Coverage in WSN

**Art Gallery problem**

The Art Gallery problem in computational geometry says that a point \( x \) is visible by another point \( y \) (guard) if the entire straight line from \( x \) to \( y \) is within the polygon (area) [83]. Applied to coverage in WSN, a guard represents a sensor and the polygon depicts the area to be sensed. If the entire polygon is seen by any guard then it is said to be covered. Howard et al[84] state that the art gallery problem can be used as a base for a coverage algorithm only when the shape of the area to be sensed is known before deployment. It would usually only be used with the deterministic placement of the sensor nodes in WSN.

**Voronoi diagram and Delaunay triangulation**

The Voronoi diagram for a WSN is a diagram of boundaries around each sensor such that every point within a sensor’s boundary is closer to that sensor than any other sensor in the
2. Theoretical Background

Figure 2.4.: Voronoi Diagram and Delaunay triangulation

network. A formal definition of the Voronoi diagram [83] is

Let \( P = \{p_1, p_2, ..., p_n\} \) be a set of points in a plane

A Voronoi region \( V(p_i) \) is the set of points that are as close to \( p_i \) as any other point as mentioned in the equation 2.1

\[
V(p_i) = \{x: |p_i - x| \leq |p_j - x| \text{ for all } j \neq i\}
\] (2.1)

The authors[85] have solved two coverage problems using Voronoi diagrams. The Delaunay triangulation is the triangulation of an area such that there are no points in any triangle which are located within the circumscribed circle of any other triangle in the area. It can be built from a Voronoi diagram by drawing edges that connect the sensors which border one another. The Delaunay triangulation is used to find the nodes which are at the shortest distance. Neither the Delaunay triangulation nor the Voronoi diagram can be constructed with localized algorithms [86]. Figure 2.4 shows the two diagrams.

The authors[81] tackles the coverage problem by using Voronoi diagrams generated with delaunay triangulation.

**Disjoint sets**

When the nodes are densely randomly deployed, it may happen that many nodes are placed in one single region which are not actually needed for the required coverage of that particular region. In such cases, the unneeded sensors can be put to sleep, thus conserving the overall energy of the network. One way to accomplish this goal is to divide the sensors into groups or sets. Each set should be able to cover the area to be sensed. The disjoint set cover is a subset of the sensors that is capable enough of covering the entire area by itself [87]. Each set cover is activated and put to sleep in turn so as to conserve the overall energy of the network. Zhao et al[88] discuss the shut off and turn on of sensors in the network.
2.6. Connectivity in WSN

In addition to coverage it is important for a WSN to maintain the connectivity. Connectivity is defined as the ability of the sensor nodes to reach the sink. If there is no route available from a sensor node to the sink then the data collected by that node can not be processed by the sink. Each sensing node has two types of ranges i.e. sensing range and transmission range. The area which the sensor is capable to sense is called as the sensing range. The transmission range is the area up to which the node can transmit the data to other node or to the sink. The subsequent sub sections discuss the network connectivity issues and some proposed solutions to connectivity problems in WSN.

2.6.1. Connectivity Issues in WSN

The node sends the data to another node or the sink within its transmission range. The connectivity of a network is maximum when there is a path between all the nodes of the WSN to the sink. This path can be direct or through multiple hops. If the link between the two nodes or between the node and the sink breaks, then the connectivity of the network is broken. There are many reasons a link between nodes can fail, like sparse amount of nodes, physical damage to nodes, Energy depletion of nodes, Security threat/denial of service, Environmental changes and Mobility of nodes.

Sparse amount of nodes

When the nodes are randomly deployed, there may be very few nodes in a region of the area to be sensed. In such regions, due to limited transmission energy of the nodes, the connectivity of the network is effected and leaves the network with communication holes[89].

Physical damage to nodes

There can be a physical damage to the sensor nodes either due to environmental conditions or through can be crushed by an animal, enemy soldiers etc. Depending upon the region where the nodes are deployed, the nodes can be damaged by different ways. Once any node gets damaged, its link is broken with the rest of the network. It may also be a part of a multi hop route of one node to the sink, thus affecting the connectivity of the entire network.

Network security threat

The nodes are always susceptible to security threats, specially when the WSN is used in highly confidential regions like military areas etc. In such cases, when any nodes gets hacked, the connectivity of the entire network is affected [90, 91].
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Energy depletion of nodes

The sensor nodes have limited source of energy. Generally the WSN are employed in regions where the nodes are unattended for very long duration. Thus, there are no options of recharging the battery of the sensor nodes. A lot of energy is consumed in transmitting the data to other nodes or the sink. The energy of the nodes get depleted fast. Various algorithms have been proposed by the researchers for energy efficient transmission [92, 93, 94]. But when the nodes get die out due to energy depletion, the connectivity of the network is seriously affected.

Environmental changes

The environment in which WSNs operate may change due to certain circumstances. Radio connection is very sensitive to rain and growing plants, which consequently changes the network topology [95]. When the WSN is employed in some cultivation fields or in forest, the plants grow up after some time and prevent the nodes to connect to each other leading to in-connectivity in the network.

Mobile nodes

Nodes may be mobile as required by the application or may be displaced by human and animals. It may also be floating with running water if deployed in the sea. Mobility of nodes causes a great impact on the network connectivity [96]. When a node selects a routing path and the nodes in the routing path change their locations, it will change the connectivity between source and destination. In another case, if a data packet is long and due to mobility the node changes its current location, part of the data may be lost at the receiving node.

Coverage and connectivity together can be treated as a measure of quality of service in a sensor network; it tells us how well each point in the region is covered and how accurate is the information gathered by the nodes. Therefore, maximizing coverage as well as maintaining network connectivity using the resource constrained nodes is a non-trivial problem.

2.6.2. Solution to Connectivity in WSN

A solution to maintain or to re-establish network connectivity is to remove the nodes which are creating connectivity problems and deploy more nodes in the sensor field. But generally the WSN are employed in regions where it’s not possible to replace a node or deploy more nodes to maintain the connectivity. Thus efficient routing protocols and WSN algorithms should be used to curb down the issues of connectivity.
2.7. Multiple Sinks

Graph models

A WSN is often represented by a graph in which vertices represent the sensors and a directed edge corresponds to the communication link between one node to another. The communication link signifies that one node can transfer the data to the other. Since it’s a directed graph, a directed edge between node A and node B means that node A can send the data to node B but the vice versa may not be true. But if all nodes have equal transmission ranges as in a homogeneous network, then the graph becomes undirected. A network is called connected if this associated graph is connected[97, 98] . It is sometimes useful to consider stronger forms of connectivity, like k-connectivity, in which the network remains connected even if $k−1$ nodes are removed. A k-connected network ($k > 2$) has better fault-tolerance than 1-connected[99]. Random graphs may also be applied to model communication networks to highlight their randomness. Mathematically, a random graph is generated by a stochastic process [100].

2.7. Multiple Sinks

The issues of coverage and connectivity in WSN have already been discussed. Some of the above mentioned issues are resolved by the use of multiple sinks. In a WSN, the fundamental question is to have the data routed over single hop or multiple hops. This question is answered by considering the answer to the question that the data needs to be sent over a longer or a shorter hop. Short-hop routing leads to reduced energy consumption and higher signal-to-interference ratios[101]. The less but longer hops lead to more energy consumption but less Signal to Interference Ratio (SIR). Research paper [102] it’s proved that single-hop transmission is more efficient, when power consumption of real wireless sensor node’s transceivers are taken into account. So, this leads to four types of networks:-

1. Single hop single sink routing (SH-SS)
2. Single hop multiple sink routing (SH - MS)
3. Multiple hops single sink routing (MH – SS)
4. Multiple hops multiple sink routing (MH – MS)

The first scenario is the most elementary one with direct transmission. The LEACH protocol which is better than the direct transmission, deals with single hop single sink clustering protocol [3].

A lot of research is done for the third scenario [47, 103, 104]. The modification of LEACH protocol having multiple hops instead of single hops[47]. In [103] compares the single and multiple hop routing.
2. Theoretical Background

Table 2.6.: Related work in multiple sinks in WSN

<table>
<thead>
<tr>
<th>Research Paper</th>
<th>Hops</th>
<th>Sinks</th>
<th>Mobility of the Sink</th>
<th>Sink Positioning</th>
<th>Network Restructuring</th>
</tr>
</thead>
<tbody>
<tr>
<td>[110]</td>
<td>Multiple</td>
<td>Multiple</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>[109]</td>
<td>Multiple</td>
<td>Multiple</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>[19]</td>
<td>Single</td>
<td>Multiple</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>[111]</td>
<td>Single</td>
<td>Multiple</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>[4]</td>
<td>Multiple</td>
<td>Single</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>[3]</td>
<td>Single</td>
<td>Single</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>[47, 103, 104, 106]</td>
<td>Multiple</td>
<td>Single</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>[16]</td>
<td>Multiple</td>
<td>Multiple</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

In [16], a multi hop protocol spends most of its energy for relaying data packets so the concept of multi hop multi sink WSN is discussed. The concept of particle swarm optimization is used.

The current research work deals with the second scenario i.e. Single hop multiple sink. The biggest disadvantage of single sink is that certain sensors near the sink or on critical paths consume energy much faster than other nodes [105]. Thus the current work uses the advantage of having multiple sinks. Multiple sinks ensure shorter hops and thus the 18 advantages as discussed in the paper [101] are also achieved. Multiple hops are generally used to reduce the hop distance [106]. But if multiple sinks are used, the hop distance automatically reduces. Thus, the research deals with single hop and thus avoiding the drawbacks of having multiple hops.

Network lifetime (NL) is a critical metric in the design of energy-constrained WSN[107]. The basic aim of the researchers is to minimize the energy consumption and at the same time increase the network lifetime. The authors in the paper [108, 109] deal with mobile multiple sinks. Data dissemination to multiple mobile sinks consumes a lot of energy [110]. Many papers [108, 16] have concentrated on positioning of the sink to have optimal energy consumption. The current research work talk about the random deployment of the sink thus saving power in determining the position of the sink. Then the network is re-structured to have balanced energy consumption amongst all the sinks. Table 2.6 summarizes the related work done in the field of single/ multiple hops, single/multiple sinks and moving/stationary nodes.

Depending upon the requirements of the application where the WSN is going to be used, the factors mentioned in the Table 2.6 are chosen. If the network is very large and cost effective then single sink multiple hop network is used. If the cost can be increased to make the network lifetime better, then multiple sinks can be used. The mobile sinks increase the network lifetime to a great extent [110] but finding out the location of the sink makes the network computationally complex[112]. The authors in the research paper [111] talk
about lexicographically optimal commodity lifetime (LOCL) routing problem to position the multiple sinks at optimal positions in order to increase the network lifetime. Network restructuring is changing the neighbor nodes connected to a sink depending upon the energy consumption by that sink. In the current research work the number of sensors connected to any sink is changed if the energy consumption by the sink is more than the threshold. To have balanced energy consumption amongst all the nodes, the entire network is re-structured.

2.7.1. Multiple Sinks Placement

Oymen et al [113] proposed an algorithm for finding the position of sinks using k-means clustering. The cluster centroids are chosen as the optimal position of sinks. The sink placement problem is NP-complete [114], and finding the best position of sink is very hard. The authors in the research paper [115] introduce some sink placement strategies and also discuss their pros and cons. The Geographic Sink Placement (GSP) [116] strategy places the sinks at center of sector of a circle. In Intelligent Sink Placement (ISP), the possible sink locations are determined by sampling all possible regions. All combinations of these candidate locations are found out, depending on the number of sinks. Then the optimal location of the sink is calculated. ISP is found to be optimal buts it is computationally expensive. Another algorithm, called Genetic Algorithm-based sink placement (GASP) [117] provides a good heuristic based on Genetic Algorithm for optimal sink placement. In [118] the authors have proposed an algorithm for sink placement using linear programming. The problem of finding the optimal number and the position of the sink nodes resembles some classical problems like problem of plant location [119], problem of warehouse location [120], and the concentrator location problem (CLP) [121]. But, there are many differences between these problems and the multiple sink location problems as stated in paper [113]. First of all the sinks can be placed anywhere in the network and secondly the transmission are done in multi hops as compared to direct in the traditional problems.

2.8. Radio Model

In a wireless channel, the electromagnetic wave propagation can be modeled as falling off as a power law function of the distance between the transmitter and receiver. In addition, if there is no direct, line-of-sight path between the transmitter and the receiver, the electromagnetic wave will bounce off objects in the environment and arrive at the receiver from different paths at different times. This causes multipath fading, which again can be roughly modeled as a power law function of the distance between the transmitter and receiver. No matter which model is used (direct line-of-sight or multipath fading), the received power decreases as the distance between the transmitter and receiver increases [18].
2. Theoretical Background

For the simulation performed in this thesis, both the free space model and the multipath fading model were used, depending on the distance between the transmitter and receiver, as defined by the channel propagation model in [18]. If the distance between the transmitter and receiver is less than a certain transmission range \((d_0)\), the Friis free space model is used \((d^2\text{ attenuation})\), and if the distance is greater than transmission range \((d_0)\), the two-ray ground propagation model is used \((d^4\text{ attenuation})\). The transmission range is depends upon the different wireless technologies such as Bluetooth [122], Zigbee [123], and GSM [124] etc. In most of the cases sensor network uses Zigbee technologies because low power requirement, easy protocol stack and long distance transmission. The transmission range point is defined as follows in Eqn: 2.2

\[
d_0 = \frac{4\pi\sqrt{L}h_t h_r}{\lambda}
\]  

(2.2)

where

- \(L \geq 1\) is the system loss factor not related to propagation,
- \(h_r\) is the height of the receiving antenna above ground,
- \(h_t\) is the height of the transmitting antenna above ground,
- \(\lambda\) is the wavelength of the carrier signal, and
- \(d_0\) or \(R_t\) is the transmission range.

A great deal of work is going on energy consumption of radio models in Figure 2.5 and eq. 2.3 to 2.8. Different assumptions made in radio models have different advantages. In our work, we consider a simple model where radio dissipates \(E_{elec} = 50nJ/\text{bit}\) to run transceiver circuitry and \(\epsilon_{fs} = 100pJ/\text{bit}/m^2\) for transmitter amplifier, so as to achieve acceptable SNR ratio[3].

To transmit information as given in eq. 2.5 transmitter expends:

\[
E_{Tx}(k, d_{ij}) = E_{Tx-elec}(k) + E_{Tx-fs}(k, d_{ij})
\]  

(2.3)

\[
E_{Tx}(k, d_{ij}) = E_{elec} * k + \epsilon_{amp} * k * (d_{ij})^n
\]  

(2.4)
2.9. Summary

\[ E_{Tx}(k, d_{ij}) = E_{elec} \times k + \varepsilon_{fs} \times k \times (d_{ij})^2; d_{ij} < d_0 \] (2.5)

\[ E_{Tx}(k, d_{ij}) = E_{elec} \times k + \varepsilon_{mp} \times k \times (d_{ij})^4; d_{ij} > d_0 \] (2.6)

\[ E_{Rx}(k) = E_{Rx-elec}(k) \] (2.7)

\[ E_{Rx}(k) = E_{elec} \times k \] (2.8)

Where

- \( E_{elec} \) is the energy dissipation in electronic circuitry in Transmitter and Receiver,
- \( k \) is the number of bits,
- \( d_{ij} \) is the distance between \( i^{th} \) node to \( j^{th} \) node,
- \( n \) is the path loss exponent,
- \( \varepsilon_{amp} \) is a proportionality constant,
- \( \varepsilon_{fs} \) is a proportionality constant in free space,
- \( \varepsilon_{mp} \) is a proportionality constant in multi path, and
- \( d_0 \) is the transmission range.

Using these parameters, receiving a message is not a low cost operation. So protocols used in the network should try to minimize not only the distance between two nodes but should also minimize the number of transmissions and receptions for each message. Path loss exponent \( (n) \) depends upon different environments [125] and are shown in Table 2.7.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path loss exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>2.7 to 3.5</td>
</tr>
<tr>
<td>Shadowed urban cellular radio</td>
<td>3 to 5</td>
</tr>
<tr>
<td>In building line-of-sight</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstructed in building</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Obstructed in factories</td>
<td>2 to 3</td>
</tr>
</tbody>
</table>

2.9. Summary

Having discussed the different types of routing protocols, design parameters of WSN, Coverage issues and the approaches to coverage, connectivity issues in WSN and their solutions, and finally multiple sink, the author proposes his work in different chapters of the thesis.
2. Theoretical Background

The main objective is to minimize the energy consumption, maximize the coverage and connectivity and the optimization of the network lifetime. The next chapter deals with a novel algorithm which employs clustering in a single sink WSN so as to have the minimal energy consumption. If the energy consumption is minimized the network lifetime is automatically increased. A WSN is designed to be deployed to sense multiple physical attributes in an environment and produce an alarm if any unexpected condition is predicted.