CHAPTER 1

INTRODUCTION

Wireless Sensor Networks (WSN) are essential for gathering information from many sources, particularly publicly accessible ones and effectively transferring it across various nodes.Even when each nodes power and transmission capabilities are constrained, the fewer data that must be transferred when a WSNs sensor nodes cooperate to send their observed data to the sink or to do some local coordination for data aggregation.It has three tasks that the sensor node can carry out: sensing, processing,and communication. Among these,communication requires more energy than other operations in most of the applications and to extend the life time of the sensor nodes, it must preserve battery power using energy-saving techniques, such as those suggested in research studies.

1.1 WSN ARCHITECTURE

WSN is essentially a network of small sensor nodes that gather data and send it to a central node or sink or base station using a multi-hop communication paradigm or intermediate nodes. The architecture of WSN (Kaur et.al., 2014)is given in Figure1.1.

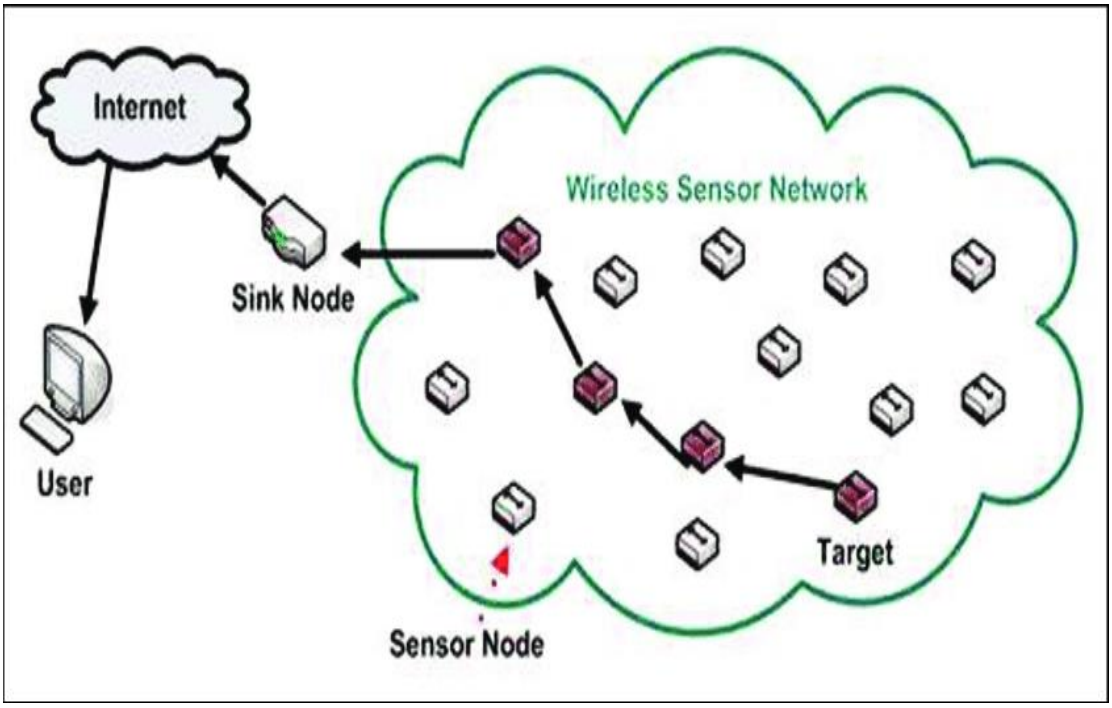

Figure 1.1 Architecture of WSN

In a WSN, there are three basic parts in each sensor node:

Sensing - It is used to measure the physical environment,including temperature, pressure, humidity and so on.

Processing – it is utilized for local processing and data aggregation to limit the amount of data transmission.

Transceiver or Radio – It is the medium by which data travels from the originators to the final recipients.

The Communication requires the most effort in almost all situations and it can have any topology used in the sensor nodes and organize themselves in the sensor network.

1.2 ELEMENTS OF A WSN SENSOR NODE

There are many electronic components inside a WSN node (BenSaleh et al., 2020), including the microcontroller, analog circuit, radio, battery and sensor interface as given in Figure 1.2. More radio activity or data rates result in greater power consumption for battery-operated equipment. Nowadays,WSN systems are based on ZigBee because of its low-power consumption, which results in good battery life, and power management technologies.

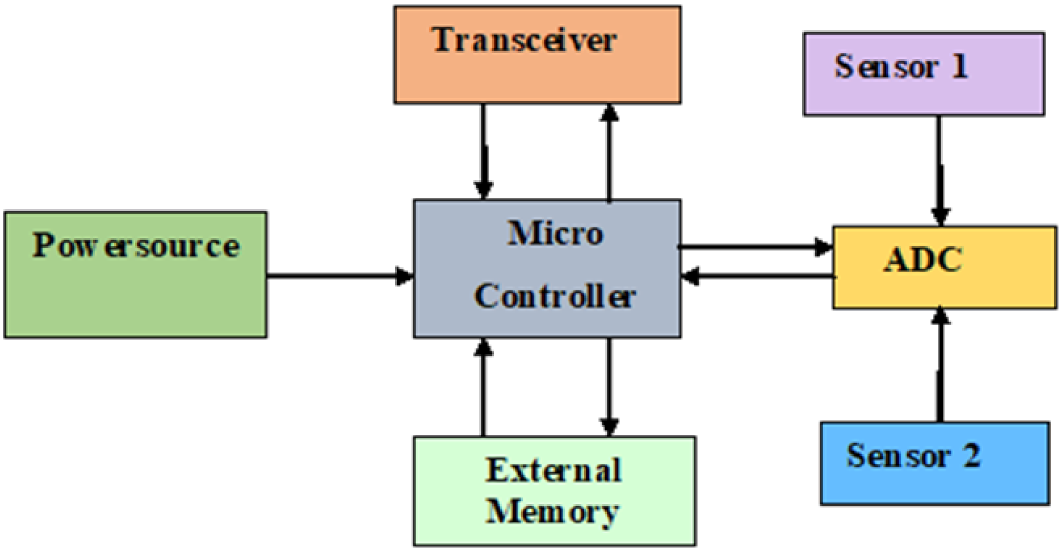

Figure 1.2 Internal Components of Sensor Node

The WSN system is the technological factor to think about not only battery life but also the availability of batteries, their size and weight and the international regulations regarding the transport of batteries. Carbon,zinc and alkaline batteries are popular due to their in expensive price and a wide availability.

A WSN node saves electricity by cycling on and off its radio to send and receive data at regular intervals.WSN require radio technology that can both deliver a signal efficiently and then put the system into a power-saving sleep state. This necessitates a processor that can effectively enter and exit sleep mode (Gulati,Ket.al., 2022). With WSN, the latest microprocessor developments are lowering power consumption without losing performance. When choosing a processor for WSNs, the trade-off between power consumption and processing speed is just as important as it is when picking a radio.

1.3 IMPORTANCE OF WSN

To collect and communicate information about the physical properties of the surroundings, sensors in a WSN are placed in various locations. The following are few examples of its significance (Shaikh & Pathan., 2012):

- Remote Monitoring: Without the need for human intervention, WSNs allow for the real-time monitoring of physical environments in hazardous or remote areas, including temperature, humidity and air quality, as well as the health of infrastructure like pipelines and bridges and natural phenomena like earthquakes and forest fires.
- Energy Efficiency:Many WSN protocols and algorithms are designed to optimize energy consumption, prolonging the network lifetime. This is particularly important for battery-operated sensor nodes deployed in remote or harsh environments where replacing batteries is challenging.
- Scalability:WSNs can be easily scaled by adding or removing sensor nodes as per the requirements of the application. This scalability makes them suitable for applications ranging from small-scale deployments to large-scale sensor networks covering vast geographical areas.
- Healthcare and Wellness Applications:In healthcare, WSNs are employed for remote patient monitoring, fall detection for the elderly and tracking vital signs, promoting early detection of health issues and enabling timely medical interventions.

1.4 APPLICATIONS OF WSN

WSN is widely used to data transfer, security, quality-of-service etc. The few of its applications are:

- Environmental Monitoring (temperature, humidity and air pressure)
- Military Based Applications
- Industrial Monitoring and Control
- Intelligent Buildings
- Logistics
- Internet of Things (IoT)
- Medical applications
- Agriculture
- Traffic Monitoring and Prediction

1.5 CHALLENGES FACED BY WSN

Some of the difficulties faced by WSN process are:

- ✓ **Energy Efficiency**

Each sensor node relies on its own finite battery capacity to carry out its three primary responsibilities:data collection, data processing and data communication (including network construction) (Krishna et al., 2018). Energy consumption is determined by factors like event sensing, data transmission rates and disparities between nodes which may reduce the lifespan of the network. For this reason, the WSN should be designed with energy efficient activities (Tarannum., 2010).

- ✓ **Node Deployment**

During the initialization, the sensor nodes are deployed either by placing directly in its position or releasing in the sensing field. Expiry of node happens because of energy consumption by different activities of the node or battery damage during deployment. Battery damage also provides wrong sensor readings which cannot complete the task of the node and the sensor nodes may not be spatially distributed properly.Network congestion may occur due to multiple transmissions simultaneously.The primary challenge in WSN is the lack of available data in the deployment. Auto configuration of sensor networks is required for random deployed nodes (Ringwald & Romer., 2007). Reconfiguration of network happens automatically during node failure and additional node deployment.

- ✓ **Topology Control**

WSN uses various types oftopology like bus, tree, mesh and star and so on for the communication. The effective topology control provides selection at an optimal distance, loss of messages, and interference minimization which leads to reduced waiting for sensors data communication. Topology, which is employed to lower energy consumption, also affects data aggregation.

- ✓ **Localization**

Localization is the process of determining each sensor nodes exact ambient position. It is a crucial component of many network sensor applications (Zhenjie&Changjia, 2006). Then the applications like tracking or event detection, location of the information is most important. Location information will not be configured during deployment.

- ✓ **Synchronization**

WSN share a common time reference but its individual nodes are free to make their own decisions and operate in isolation. Synchronization (Blum, P et al., 2004) is required for localization algorithms which use ranging techniques and for setting up a Time Division Multiple Access schedule (TDMA). But the applications like event detection and tracking nodes should be synchronized to get higher accuracy.

- ✓ **Quality of Service (QoS)**

The system service must be compatible with the necessary infrastructure and software. The network requirements are bandwidth, jitter, cost, probability of packet loss and so on. Similarly, the measurement, deployment, coverage, energy and number of active sensor nodes are Quality of Service (QoS) factors in all applications:Bandwidth constraints, removel of redundant nodes, energy and latency trade-offs, numerous data rate requirements, topology changes and scalability are the difficulties in maintaining QoS in WSN.

- **Security**

Security is the prime requirement of WSN especially in military and the other home basedapplications. Some security requirements of WSN are data integrity,confidentiallyauthentication,data freshness, availability, tradeoffbetween security and quality of service.

1.6 ENERGY CONSERVATION

Energy conservation is crucial in WSN due to the limited power available to sensor nodes. In WSNs, there are many methods whichaids in energy consumption. Wireless sensors are used to monitor a variety of parameters includingvibrations, seismic activity,temperature, humidity and more.The compact device known as a sensor node is equipped with three subsystems: a wireless communication subsystem for data transfer, a sensing subsystem for obtaining information about the physical environment and a processor subsystem for local data processing and storage.

The device gets power from a power source to perform the predefined tasks. Mostly, the power comes from a battery that have only limited energy. It may also be difficult or inconvenient to routinely recharge the battery if nodes are positioned in hazardous or unusable locations. However, lifetime energy is required for the sensor network to fulfill the requirements of the application.

1.6.1 Need for Energy Conservation

Many sensor nodes in a WSN will have finite amounts of memory, computing power and battery life. Most of its deployments are in outlying areas, from any civilization that can dispatch a technician to replace a dead sensor node battery or ensure its continued operation. The battery life, network strength and other factors that affect the nodes viability are the primary factors in its overall life time. After a WSN has been deployed, the network has run its full operations and maintain the battery life.

Based on the application, the energy required doing the operations like sensing, data processing and data transfer would be varied. In most of the applications, data communication consumes higher energy and the sensor nodes use a wide variety of methods to reduce power consumption at every step of operation. Longevity can be enhanced by incorporating both energy harvesting and energy conservation measures.

Energy conservation is achieved by reducing the amount of samples taken in sensing operation which also leads to reduced data communication. Radio frequency can operate in three states: idle, active, and sleep. The total number of power or energy used during the active mode is more than required during the sleep mode. Power is also used when a device is switched from an active to a sleep state and back again. The longer sleep state requires higher energy and time to wake and frequent state change results in more power consumption than retains in active mode.

1.7 CONGESTION IN WSN

In WSN, congestion is a prevalent issue. It happens when the capacity of the network is exceeded by the number of demand placed on it (Flora, D., 2011). Recently, rapid advances have taken place in WSN, broadening the borders of its applications from academics to healthcare and from home to industry.These applications result in generationof huge number of data leading to congestion.Congestion in WSN is a common problem which occurs when the demand placed on the network exceeds the capacity of the system (Flora, D., 2011). Recently, rapid advances have taken placein WSN, broadening the borders of its applications from academics to healthcare and from home to industry.These applications result in generation of huge number of data leading to congestion. Congestion in WSN depends on the number of deployed nodes and resource constraint specification (Ghaffari., 2015).

There are two distinct kinds of congestion: those that occur at individual nodes and individual links. A node is overloaded when itsin bound packet rate exceed sits out bound packet rate. Congestion arises due to the inevitable interference between traffic flows when several sensor nodes uses the same communication channel.There are various causes behind congestion occurrence in the network (Stais&Xylomenos., 2019; Ghaffari., 2015; Flora, D., 2011).

- ✓ **Buffer Occupancy**

A sensor node can only process a tiny subset of incoming packets before forwarding them because to its limited buffer space.Sensor nodes uses a buffer to temporarily hold packets before they are added to the queue (Raiesh et al., 2017; Ghaffari., 2015) as a node buffer fills up, packet loss begins. As long as the servicing rate of the node is greater than or equal to the incoming packet rate, the node will process all incoming packets. When the number of data in a buffer increases above certain point, it indicates the presence of congestion.

- **Channel Contention**

When multiple nodes are competing for access to a single transmission channel, it is known as channel contention which leads to collisions and interference. Contention also increases Round Trip Time (RTT), packet loss, packet retransmissions and network load (Maity et al., 2017). Carrier Sense Multiple Access (CSMA) / Collision Avoidance (CA)is a contention strategy which was used in WSNs at the MAC layer.Wireless communication faces two types of interferences

✓ **Co-channel interference**

Co-channel interference takes place when radio waves from different sensor nodes travel through same frequency band in the same area. Main cause behind co-channel interference is shared access of sensor nodes to the communication medium (Hu et al., 2017).

✓ **Adjacent channel interference**

When transmissions from several applications using neighboring frequency bands interfere with one another, it creates a secondary wave that either cancels out or reinforces displacement. This phenomenon is known as adjacent channel interference (Hu et al., 2017).Interference can be avoided by efficient channel planning. Medium Access Control layer uses Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and CollosionDivision Multiple Access (CDMA) to prevent interference and collisions (Akyildiz &Vuran., 2010).

- **Collisions**

Collision is a challenge in statistically multiplexed wireless sensor network. Simultaneous or overlapping access of transmission medium by several sensor nodes result in collision. Communication in WSN is half-duplex, hence Medium Access Control (MAC) layer exploits collision avoidance techniques rather than detection techniques (Khandish et al., 2018; Kumar & Tiwari., 2018). The MAC layer employs an exponential back off CSMA/CA schemeto prevent collisions, this method makes use of a series of brief packets known as Request to Send and Clear to Send.

- **Many-to-one data transmission nature**

Several sensor nodes are scattered across the sensing environment, with one or more serving as a central processing unit, or sink. Physical and environmental characteristics are sensed by sensor nodes, processed, and sent to the sink. There can be two types of communications (Wang et al., 2007):

- ✓ **Downstream traffic**: Downstream traffic of Wireless Sensor Networks (WSNs) refers the data flowinthe sink node (also known as base station or gateway) to the sensor nodes.
- ✓ **Upstream traffic**: It is sent by sensor nodes to sink also known as many-to-one communication. Upstream traffic increases probability of congestion occurrence near sink due to its convergent nature,impairing QoS in WSN.

- **Unfair utilization of resources**

Unfair utilization of resources in sensor networks lead to congestion (Bachir et al., 2010). When multiple sources and destinations use the same optimal route to transmit packets, for instance, the quantity of packets on that route exceeds the carrying capacity of the transmission medium, which has two main effects on the network resources.First is high utilization of resources such as bandwidth and energy in the selected route. Second effect is under utilization of resources in other routes.Over utilization makes forwarding nodes run out of energy, creating holes in the networks which is causing the packets loss. It increases number of retransmissions thus increasing traffic load on the network and it is creating congestion.

- **Bit Error Rate (BER)**

Wireless communication channel is unreliable (Mohammadi &Jadidoleslamy, 2011) increasing possibility of introducing errors in the transmitted data.The term biterror refers to the number of times data bits were corrupted during transmission as a result of factors such background noise, interference, distortion, phase jitter, attenuation, multipath fading and bit synchronization error.

The ratio of bits received in error to all bits transmitted on a communication channel is known as the Bit Error Rate (BER) in a Wireless Sensor Network (WSN).BER can be calculated usingthe equation (1.1).

$$\text{BER} = \frac{\text{Number of incorrect bits received}}{Total\ no\ of\ received\ bits} \quad (1.1)$$

BER is a fundamental parameter to measure the link quality and Packet Delivery Ratio (PDR). Low BER gives the link quality and more PDR. BER is function of Signal-to-Noise Ratio (SNR) (Singla M et al., 1994). BER is low when SINR is high and vice versa. When link quality is poor, BER is high and more number of incorrect bits are received by receiver. Error correction techniques are used when bits are less affected, otherwise the data needs to be retransmitted which is used to increase network load and create the congestion.It also wastes energy and transmission resources and reduces the accuracy of sink-based event detection.Congestion in networks can be attributed to a few main factors:

- **Buffer Overflow:** It occurs when packets are received at a rate that is too high for the networks buffers to handle and packet rate is reduced and increased data transmission delay. All incoming packets will be lost and critical service metrics, such as packet loss ratio, end-to-end delay, and mean energy consumption, will deteriorate when the accumulating buffer overflows.
- **Channel Quality:** Time varying channel quality degrades the link capacity which causes congestion and leads to packet drop.
- **Loss Rate:** When an event occurs, the packet loss rate increases because more data packets are sent across the network but never arrive at the sink. The most common symptom of network congestion is a rise in packet loss or drop.It is measured as a proportion of lost data to total data transmitted.
- **Increased Delay**: Congestion level significantly affects queuing delay in WSN which in turn affects data transmission delay.
- **Utilization of Energy:**Packet retransmission leads to more energy consumption in WSN.

1.8 CONGESTION TYPES

Wireless Sensor Networks (WSNs), congestion can manifest in various forms, each affecting the network's performance and reliability. Here are the main types of congestion typically observed in WSN.The type of Congestion in WSN is given in Figure 1.3 (Sergiou et al., 2014).

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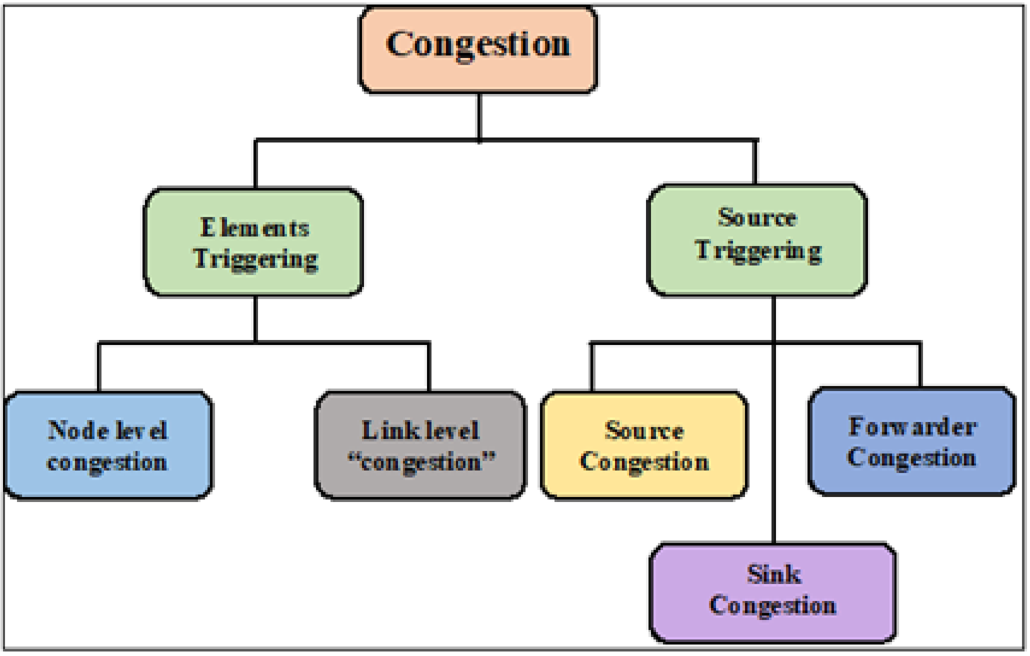

Figure 1.3 Congestion Types in WSN

- **Elements Triggering**

There are two types of elements triggering in a network: link-level congestion and node-level congestion.

- **Node Level Congestion**

Packets drop may occur when a node is receiving data at a faster rate than the sending capacity. Packet drops are due to buffer overflow and collision of packets in the medium. Congestion at the node level occurs when the rate at which packets arrive is greater than the rate at which they can be serviced. It occurs most frequently at sensor nodes near the sink since these nodes have the most upstream traffic. As a result, more energy is used in the form of retransmission. When the queue length rises above a pre determined threshold, this phenomenon can be monitored proactively (Samiullah et al., 2012).

- **Link Level Congestion**

Packet loss rises when multiple nearby sensor nodes attempt to use the channel simultaneously, leading to collisions. At the link level, congestion happens.Because it takes longer to process a packet, link-level congestion reduces throughput and utilization (Wang et al., 2007).Transitory congestion can be alleviated with explicit local synchronization between neighboring nodes. Congestion at the nodes and at its link reduces energy efficiency. Thus, effective management of congestions is essential. Congestion at the node and link levels is shown in Figure.1.4.

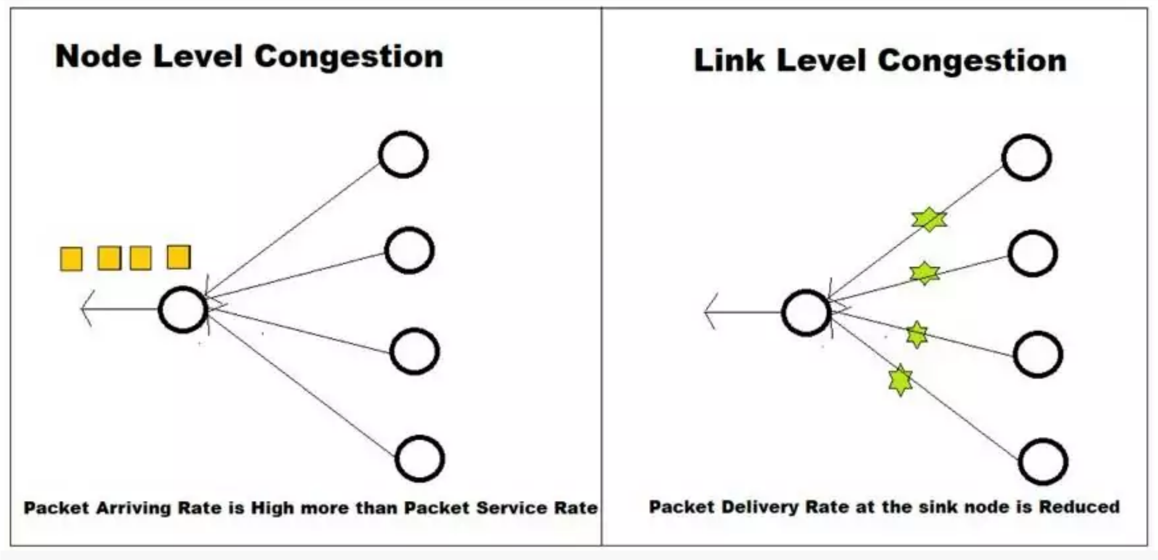

Figure 1.4 Node and Link level Congestion

- **Source Triggering**

The source triggering congestion is a type of traffic jams which includes source jams, sink jams and forwarder jams (Sergiou et al., 2014).

- **Source Congestion**

In densely deployed environment, on occurrence of any event, the nodes within that area detect the source congestion. These nodes become a source to transmit the packet and a hot spot zone develops around the sources when a large number of source nodes begin transmitting packets simultaneously. A significant amount of data will be lost in this dead zone. Source congestion describes this form of traffic jams. Either a traffic management strategy or a resource management strategy can help reduce the problem.

- **Sink Congestion**

On frequent occurrence of any event, the volume of traffic around the sink becomes high. A hotspot around the sink is created. The packets get dropped near the sink. This is termed as sink congestion. The energy lost by the nodes around the sink is huge and they get worn out. This makes rest of the nodes inaccessible to the sink. Deploying several sinks that are uniformly distributed across the node. The sensing field is an effective method of avoiding sink congestion.

- **Forwarder Congestion**

The source node uses forwarding nodes to send packets to the sink when it detects an event.The network has multiple paths which interconnect with one another. This creates an intersection which possibly becomes a hotspot. It is called forwarder congestion.

1.9 CONGESTION CONTROL IN WSN

Congestion management works to improve network performance by lowering congestion rates and maximizing throughput in congested areas. Congestion control strategies are more challenging to implement in WSN because of limited resources. In addition, the limited memory, power and capacity of sensors makes it even more challenging to introduce innovative algorithms to reduce congestion. The four stages of a congestion management mechanism operation are:

- **Congestion Prevention**

It is the goal of congestion avoidance research to find ways to keep network loads in the network capacity and hence prevent from congestion occurring (Sangeetha et al., 2018). When the strain placed on a network exceeds its capacity, congestion occurs (Shah et al., 2017).

- **Congestion Detection**

When a networks nodes or communication channels can handle more data packets than they can handle, congestion arises.

This leads to packet loss, increased latency and poor network performance (Jin et al., 2004). Whenever there is congestion at a node, packets are lost more frequently at the drop on the buffer.

- **Channel Load**

It is a tool for gauging the wireless channel packet load. The activity ratio of a channel is the percentage of time during transmissions or collisions occurred which is expressed as a fraction.

- **Time of Packet Service**

The time required to send a packet from the source node to the destination node, including all necessary processing and communication overhead, is referred to as packet service time. It is a critical metric in assessing the performance and efficiency of the network.

- **Packet Loss**

In WSN, the packet loss occurs when data packets sent between sensor nodes are unsuccessful in reaching their intended recipients.Packet loss can occur due to various factors such as interference, signal attenuation, limited battery power, node failure and network congestion.

- **Delay**

The time it takes for data packets to travel from a source node to a destination node is known as the delay. WSN delay reduction is essential for real-time applications like surveillance, healthcare and environmental monitoring.Then, to reduce latency and enhance network performance in WSNs, a variety of strategies are employed, including data aggregation, energy-efficient communication protocols and effective routing algorithms.

- **Notification of Congestion in WSN**

If the congestion is identified, the source or upstream node is informed of the congestion situation and to regulate its traffic rate. congestion notification may be explicit or be implicit in the network(Zheng &Jamalipour 2009).

- **Explicit Congestion Notification (ECN)**

It employs supplementary control messages to report congestion details. The intermediate nodes alert sources of congestion by setting bits on congested packets, but they do not specify how much slowing down will occur.

- **Implicit Congestion Notification (ICN)**

It is a mechanism that incorporates congestion data into already transmitted packets of data. A node can learn about congestion if it gets or overhears one of these data packets. The lost packet act as an implicit signal for congestion control. In ICN, use of an additional control packet is avoided and is known as congestion mitigation.

- **Congestion Control**

Congestion develops when there is a demand for network resources greater than available capacity. This results in packet loss, delays, and subpar performance.Congestion has the consequence of increasing energy consumption in WSN. Congestion detection, on the other hand, entails locating and identifying instances of congestion within a system, network, or region. Congestion control enhance efficient communication and ensuring reliable data delivery.Congestion notification is reached, then apply either resource or traffic control approach to control congestion. A resource-based approach would either increase the capacity of the current network without enough power, nodes will quickly die and disrupt the networks continuity or create a new channel for the transfer of additional data packets from the sensor nodes to the sink.

To address these problems, numerous traffic congestion control algorithms have been proposed. The adoption of traffic control systems that either reduce traffic at the source or intermediate nodes or seek for an alternate route helps to alleviate congestion. This lowers the nodes overall bandwidth requirements. Traffic management systems employs either end-to-end or hop-by-hop control, or a hybrid of the two node. End-to-end control describes a scenario where the sink controls the source node to precisely change the rate. The implications of end-to-end monitoring and management are:

- Sources node caches the packet.
- The design process is simplified at the intermediate nodes.
- It is a slow-response issue.
- High Round Trip Time(RTT).

Rates are adjusted at intermediate nodes using hop-by-hop control,which might cause the network to fragment.The importance of hop-by-hop regulation is given below:

- Intermediate node caches the packet.
- A quicker turnaround time for responses.
- Packet forwarding rate is hard to tune at intermediate nodes.

- **Virtual Queue**

A virtual queue is one concept for managing communication between sensor nodes and a central base station, also known as a sink node. In a Wireless Sensor Network (WSN),sensor nodes usually have restricted resources, which affects their processing capacity, communication range and battery life.Therefore,efficient communication management is crucial to prolong the networks lifespan and maximize its performance.The virtual queue works in a WSN as follows:

- ✓ **Data gathering**- Collect data from their environment based on their sensing capabilities.

- ✓ **Data Aggregation**- Sensor nodes may locally aggregate or summarise their data rather than transmitting raw data to the base station, which could result in excessive energy usage and network congestion.
- ✓ **Queue Management-** Each sensor node maintains a virtual queue to store the aggregated data or packets that are waiting to be transmitted to the base station. This queue helps in managing the flow of data and scheduling transmissions to avoid collisions and optimize energy consumption.
- ✓ **Transmission Scheduling-**Transmission scheduling in the virtual queue of a WSN involves determining the order and timing of transmissions among sensor nodes. This is crucial for efficient utilization of network resources, minimizing collisions and conserving energy.
- ✓ **Energy efficiency-**One of the primary goals of virtual queue management in WSNs is to maximize energy efficiency. This involves minimizing the number of transmissions, reducing idle listening time and employing techniques like duty cycling to put nodes into low-power sleep modes when they are not actively transmitting or receiving data.
- **QoS Support-**Depending on the application requirements, the virtual queue management system may also prioritize certain types of data or guarantee a certain level of Quality of Service (QoS). For example, critical data packets might be given higher priority to ensure timely delivery, while non-critical data could be buffered or aggregated for more efficient transmission.

Virtual queues are used in WSNs to increase network longevity, lower energy consumption, and enhance performance. This makes WSNs ideal for a variety of applications, including smart infrastructure, industrial automationand environmental monitoring.

- **Bandwidth Allocationin WSN**

WSNs often operate under resource constraints, including limited bandwidth. Efficient bandwidth allocation is crucial for ensuring the proper functioning and performance of the network.

Some common techniques and considerations for bandwidth allocation in WSN are:

- ✓ **Traffic Management:**Understand the types of traffic in the network. Differentiate between critical data, such as event alerts, and non-critical data, such as periodic sensor readings. Allocate more bandwidth to critical traffic to ensure timely delivery.
- ✓ **Quality of Service (QoS):** Determine the QoS requirements of different applications and prioritize bandwidth allocation accordingly. Some applications may require low latency, while others may prioritize reliability or throughput.
- ✓ **Dynamic Bandwidth Allocation:**Implement dynamic bandwidth allocation algorithms that adjust bandwidth allocation based on network conditions, traffic patterns and application requirements.
- ✓ **Compression and Aggregation:**Both compression and aggregation help in reducing the communication overhead in WSNs, leading to longer network lifetime, improved scalability and enhanced reliability. However, it is essential to strike a balance between data compression ratios, aggregation strategies, and the accuracy of information required for the intended application.
- ✓ **Energy-Bandwidth Tradeoff:**Be mindful of the tradeoff between energy consumption and bandwidth utilization.

- **Bandwidth Utility Function**

The phrase bandwidth utility function in Wireless Sensor Networks (WSNs) is a mathematical model or function that is used to measure the effectiveness or utility of available bandwidth resources inside the network.A bandwidth utility function typically takes into allows various factors such as:

- ✓ **Throughput:** The number of data that can be transmitted per unit time.
- ✓ **Latency:** The delay experienced by packets traveling through the network.
- ✓ **Reliability:** The probability of successful packet delivery.
- ✓ **Energy Consumption**: The energy required for transmitting and receiving data.

The utility function can be used in various ways within the context of WSNs, including:

- ✓ **Routing Protocol Optimization:**Selecting routes that maximize the overall utility of available bandwidth while minimizing energy consumption and latency.
- ✓ **Resource Allocation:** Dynamically allocating bandwidth resources among competing nodes or applications to optimize network performance.

- ✓ **Adaptive Transmission Control:**Adjusting transmission parameters such as modulation schemes, transmission power and packet sizes based on the estimated utility of available bandwidth.
- ✓ **Congestion Control:**Managing congestion by dynamically adjusting data transmission rates are given by the perceived utility of available bandwidth.

- **Data Aggregation**

In Wireless Sensor Networks the data aggregation method is a methodology used to decrease the amount of data transmitted in the network, resulting in decreased latency, energy conservation, and increased network scalability.Typically, WSNs are made up of a large number of sensor nodes that are placed around a region in order to monitor and gather environmental data.These nodes often have limited energy, computation, and memory resources. Data aggregation is the process of gathering and compiling information from several sensor nodes and sending it to the base station or sink node.

- **Compressive Sensing:**With compressive sensing techniques, a sparse signal can be reconstructed from a little amount of data.
  - ✓ Sensor nodes can use compressive sensing to directly transmit compressed data to the sink node, reducing a amount of a data transmitted.
  - ✓ Data Fusion: Data fusion involves combining data from multiple sources to obtain a more accurate calculate of a underlying phenomenon. Sensor nodes can fuse data locally before transmitting it to the sink node, reducing the amount of redundant information.
  - ✓ **Quality-Aware Aggregation:**Nodes can consider the quality of data, such as the precision or dependability of sensor readings, rather than just aggregating it mindlessly. This ensures that only high-quality data is transmitted to the sink node.

- **Power Management:**

Wireless Sensor Networks (WSNs) depends heavily on power management to function well and last a long time. Since sensor nodes are typically powered by batteries and are often deployed in remote or hard-to-reach locations, conserving energy is essential to prolong network lifetime and reduce maintenance costs.

Some key strategies for power management in WSN are:

- ✓ **Low-Power Hardware Design:**Using energy-efficient hardware components, such as low-power microcontrollers, transceivers, and sensors, can significantly reduce power consumption in WSN nodes. Hardware optimizations such as sleep modes and duty cycling help minimize energy usage during idle periods.

- ✓ **Energy-Efficient Protocols:**In WSNs, choosing or designing energy-efficient communication protocols is essential. Data aggregation, route optimization and sleep scheduling are some of the strategies used by protocols like Zigbee and Low-Energy Adaptive Clustering Hierarchy (LEACH) to reduce communication overhead and increase network lifetime.
- ✓ **Data Aggregation and Compression:**Aggregating and compressing sensor data at the node level before transmission can reduce the amount of data sent over the network, thereby lowering energy consumption. Techniques like spatial and temporal correlation-based data aggregation help in minimizing redundant transmissions
- ✓ **Adaptive Transmission Power Control:**Energy can be saved by varying transmission power in response to node distance and communication link quality. By using lower transmission power levels when nodes are in close proximity or the channel conditions are favorable, nodes can conserve energy without sacrificing communication reliability.

1.10 CLASSIFICATION OF CONGESTION CONTROL IN WSN

Methods for reducing congestion are chosen on an individual application basis. The requirements for moving data between events can vary greatly. As a result, it is in appropriate to use the same congestion control approach across many applications; doing so will severely impact the underlying applications throughput and network life time. For instance, phase shifting methods perform better than traffic-based congestion control strategies at the originating node in event-based applications due to the low rate of communication. Data packets are continuously sensed and have a fixed amount of time to transmit from source to sink in continuous-based real-time applications. As a result, alternatives to traffic-based congestion control, such as those balanced on managing available resources.

1.10.1 Traffic-Based Congestion Control in WSN

One approach to traffic-based congestion management is to restrict the rate at which incoming packets are sent to their final destination. Due to congestion, the speed limit may be reduced at certain points. Congestion management based on traffic flows can be divided into two categories like sequentially and comprehensively.

- **Hop-By-HopTraffic Control**

Each relay node along the path keeps track of a packets relevant data in its buffer as part of hop-by-hop traffic control. By minimizing the amount of distance data must be retransmitted, this technique helps conserve the energy of a node. Also, the high feedback delays (Lee, J. H., & Jung, I. B., 2010), the approach drastically decreases the necessary buffer size. The buffer overflow is monitored at each intermediate node. As a result, unlike with an end-to-end system, congestion can be promptly and easily notice all intermediary nodes between the source and destination area whenever congestion arises in the network.

Each source node in an end-to-end packet recovery system keeps a copy of the packet data and is responsible for re-sending it,if it is lost. When the last node repeatedly receives the same acknowledgment message or a timeout occurs, it indicates congestion (base station)status in the network. i.e, the importance of reliability and timeliness to the underlying application will determine whether a hop-by-hop or end-to-end approach is used.

1.10.2 Resource Based Congestion Control in WSN

When the traffic rate management measures do not changethe traffic rate and the resource-based methods step in to help. For instance, real-time multimedia WSNs, which reply heavily on network up timeare one type of application that requires a very high level of dependability. Resourcecontrol utilizes the networks slack capacity to equalize data transmission rates. As aresult, idle nodes receive more traffic than they otherwise would, maximizing available bandwidth.

The activation of in active nodes or the choice of alternate routes during periods of peak traffic can alleviate congestion (Jain, S., &Usturge, S.I., 2011). Data packets now have a higher chance of returning to the base station as a result. But every possible solution has trade-offs that need to be allowed.

1.10.3 Hybrid Congestion Control in WSN

- **Hybrid Rate-Based Congestion Control (HRTC)**

The best elements of resource-based and traffic-based approaches of congestion management are combined into a single primary strategy that is adhered to by all of the protocols in a hybrid congestion control system. These protocols often use an adaptive congestion control scheme based on the type of data being delivered and implementing the resource-based congestion control option is the best solution when the previously indicated technique is not practical.

- **Hybrid Optical and Copper Access (HOCA)**

It detects the congestion by the Active Queue Mechanism at the relay nodes and send the congestion notification by the method of explicit and control the congestion in the hybrid method and reducing end-to-end latency and maximizing network lifespan depends on energy efficiency and fairness.Here, currently there is no method for avoiding Congestion on non-critical data is taking as a strength and the Connectivity Endurance, Average remaining energy, End-to-End delay and equity is a weakness of the protocol.

- **Hierarchical Tree-based Cooperative Communication with Forwarding and Link Quality(HTCCFL)**

It detects the congestion by the Packet Service Ratio and Buffer Occupancy by the method of Explicit and control the congestion in the hybrid method and Enhanced Packet Delivery Success Rate, Reduced Packet Loss, Lower Power Usage. These are the strengths ofthe protocol and the Power Consumption, The rate of Packet Drop, Packet Delivery Rate, and latencyis the evaluation parameters.

1.11 METRICS USED FOR CONGESTION DETECTION

To demonstrate the effectiveness of congestion control, the metrics such as energy efficiency, throughput, average delay and packet loss are used.

1.11.1 Energy Efficiency Analysis

In WSNs,the transport layer protocols are designed to tackle the congestion and improve the energy efficiency. It can decrease packet loss and delay and improve the lifespan of WSNs.In WSNs, energy efficiency analysis entails assessing how much energy is used by different network functions and components in order to maximize energy use and extend network lifespan.

While sending data, protocols that regulate resources always begin with the quickest path. All these protocols reply on some form of topology management to increase the number of possible connections between nodes (Angadi et al., 2016). When the network traffic is intense, energy consumption can be balanced across number of different channels. Since the nodes discharge their energy consistently, peak lifespan is attained.

In contrast, hybrid congestion control methods initially attempt to manage congestion by determining whether the impacted nodes buffers are full or not. Instead of rejecting packets or slowing down data in the traffic flow, these protocols can reroute the traffic away from a crowded node and back towards the base station whenever the buffer at that node reaches a certain threshold value. The negative of these protocols is the extra overhead introduced by control packets.

Overall, energy efficiency analysis in WSNs is crucial for maximizing the lifetime of network, minimizing operational costs and ensuring sustainable operation in resource-constrained environments.

1.11.2. Throughput

The fastest path from source to destination is usually taken by traffic-based control methodsin order to maximize throughput, however exhausts available network resources.By lowering source node data rates, which leads to poor throughput, an increase in packet loss, and slower base station speeds, these techniques avoid congestion.

In order to deliver data down alternative channels, resource-based control protocols make use of the network’s idle resources. These strategies prevent dropped packets and provide consistent network energy consumption, leading to increased throughput. Yet, these protocols introduce a new layer of complexity due to the necessity of sending control messages over the network.

When it comes to mission-critical, real-time transmission, higher reliability and increased throughput, hybrid congestion management approaches are the way to go for continuous event-based applications. Congestion control methods offer significantly higher throughput than resource-based and traffic-based alternatives while consuming roughly the same level of energy on all nodes.

1.11.3 Average End-To-End Delay Analysis

In Wireless Sensor Network (WSN), the average end-to-end delay is a critical performance metric that refers to the average time it takes for a data packet to travel from a source node to a destination node across the network. Analyzing and optimizing this delay is crucial for applications requiring timely data delivery, such as real-time monitoring and control systems.

Designing a congestion control plan should take delay into parameter.There are several mission critical applications that could fail catastrophically if packets arrive late. A protocols ability to quickly alleviate or avoid congestion is shown by the End to End delay. As the delay was reduced, performance is improved and vice versa.

Time lag is more prevalent in protocols that manage scarce resources as opposed to those that prioritize data delivery. This is because there are more hops along the way before the packet reaches its destination. Moreover, the retransmissions that take place in the crowded hotspots, i.e., Building a path via a series of hops from the source to the base station, with option to switch to a new path whenever congestion is detected, is wasteful and slow. The use of back pressure messages to switch from traffic-based management to resource control causes delays in hybrid systems to either grow or remain constant.

1.12 MOTIVATION OF THIS RESEARCH WORK

WSN offer a low-cost option with regards to maintenance and installation, their use and deployment are likely to increase over the coming decades. Each sensor node contains hardware and software required to send and receive data packets.When there are many nodes in close proximity to one another or when the data flowrate is high, packet congestion occurs, which causes data loss, in efficiency and unfairness. Congestion has been the primary cause of transmission loss in WSNs since their infancy, spanning multiple decades. As a result, detecting and managing congestion is essential for maximizing data transmission efficiency across a network.The Weighted Priority Differential Rate Control (WPDDRC) method addresses this problem by combining the Weighted Priority (WP) of a traffic class with the Difference of Differential Rate (DDR) of a single node.Here, the DDR with WP does not take congestion into reason when allowing for queue size and buffer occupancy. If the queue length exceeds the buffer occupancy, this could lead to significant packet loss and delay. The introduction of a robust congestion control strategy inspired this investigation. Theprimaryobjective of this study isto find ways to reduce network congestion, maximize energy efficiency and lengthen the lifespan of WSN.

1.13 RESEARCH GAP

There are no proper rate control algorithms to control congestion in Wireless Sensor Networks with the combination of queue management and power management of each node along with fair allocation of bandwidth and more over it is still a challenging issue due to limited resources and bandwidth.

1.14 PROBLEM STATEMENT

Queue overflow is one of the constraints which is responsible for the packet loss in the network. The rate control at a given sensor node with the combination of priority assignment of traffic class, fair distribution of bandwidth is not sufficient to control the congestion under all circumstances and hence effective queue management is essential for an energy efficient rate control scheme.

1.15 OBJECTIVE OF THE THESIS

The objectives of this research work are as follows:

- To reduce the packet loss by virtual queue management.
- To maximize the bandwidth utility function in WSN.
- To predict the nodes and control the packet retransmission by using the data aggregation technique.
- To evaluate the QoS standards in terms of data transmission rate adjustment, reduce energy consumption of the nodes and increase network life time.

1.16 CONTRIBUTION OF THE THESIS

The contribution of the research work are given as:

- Congestion in WSNs is regulated in the initial stage of the research process by proposing a WPDDRC with a single physical queue(virtual queue) called the Proficiency Rate Control (PRC) algorithm.

- A PRC with Fair Bandwidth Allocation (PRC-FBA) technique is developed in this study to balance traffic type priority and bandwidth fairness.
- To maximize equitable battery utilization among all involved nodes, a PRC with Data Aggregation and FBA (PRCDA-FBA) method was proposed.
- To satisfy Quality of Service requirements for faster data transfers, less energy usage by energy-hungry nodes and better network performance, enhanced PRCDA-FBA (EPRCDA-FBA) is being developed.

1.17 ORGANIZATION OF THE THESIS

The thesis contents are organised as follows:

Chapter 1 discusses about the overview of WSN, its characteristics, congestionand the congestion control mechanism in WSN.

Chapter 2 a brief review of the congestion control technique in wireless sensor network is done. From the study, the key challenges are identified.

Chapter 3 explains the first objective of PRC algorithm and its derivation towards the congestion avoidance in WSN.

Chapter 4describes the second goal of the study, PRC-FBA, and how it is used to address the bandwidth allocation issue.

Chapter 5describes the third objective of the study, PRCDA-FBA, and the implementation module that is used to improve the power of each node.

Chapter 6describes the fourth objective of the research EPRCDA-FBA and its description for preventing the degradation of network performance.

Chapter 7concludes with the results and discusses for the future improvements thatcould be done