A Review on Energy and Latency Efficient Routing Protocol Design for Wireless Sensor Networks

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Abstract: Wireless sensor networks (WSNs) have been utilized by various industries, such as disaster management, the chemical and heavy industries, marine research, and space exploration. One of the primary challenges faced by wireless sensor networks is their limited network lifetime. Several techniques have been devised to extend the duration of network operation. This proposed method introduces a threshold-based algorithm to minimize the amount of data that needs to be transferred. In this approach, the selection of cluster heads and their sizes is not fixed. Instead, they are dynamically determined at the beginning of each iteration. The design of routing algorithms for wireless sensor networks faces three main challenges: lowering the rate at which the average node energy declines, minimizing the number of dead nodes, and eventually prolonging the network's lifetime. This paper provides a thorough examination of efficient routing protocols for wireless sensor networks with the goal of improving network longevity.

Keywords: Efficient Routing, WSN Clustering, Network Latency, Network Lifetime.

I. INTRODUCTION

The Wireless Sensor Network (WSN) has a substantial number of sensor nodes that are responsible for detecting various physical conditions [1] . The functionality of miniature sensors is expanding in terms of data sensing, processing, and communication, allowing for the deployment of Wireless Sensor Networks (WSNs) that rely on the collective contribution of several small sensor nodes [2]. Wireless Sensor Networks (WSNs) offer a diverse variety of applications. As WSNs continue to evolve, they will become an essential component of our everyday lives. To fully exploit the potential uses of WSNs, it is necessary to have efficient and advanced wireless data transfer protocols. Wireless sensor networks (WSNs) consist of a significant number of sensor nodes that are responsible for detecting and monitoring various physical or environmental conditions. To ensure accurate observation and informed decision-making, it is imperative that sensor nodes correctly detect and measure physical events or environmental conditions[3]. The sensor nodes should have the ability to process the raw data they sense and transmit only the processed data, as they generate a large volume of raw data. The protocols should possess self-organizing characteristics in order to enable the efficient utilization of the network. The architecture of the WSN comprises of the following attributes:

Sensor Nodes: At the core of any WSN are the sensor nodes. These nodes are equipped with sensors to detect physical or environmental conditions such as temperature, humidity, or motion. Each sensor node typically consists of a sensing unit, a processing unit, a transceiver unit, and a power unit. The sensing unit captures data, the processing unit manages data processing and storage, the transceiver unit handles communication with other nodes, and the power unit, often a battery, supplies the necessary energy. The design of sensor nodes aims for minimal energy consumption to prolong the network's operational lifespan [4].

Communication Architecture: The communication architecture in a WSN is crucial for data transmission between sensor nodes and the base station. Nodes communicate wirelessly, often forming a multi-hop network where data is relayed through intermediate nodes to reach the base station [5]. The communication protocols must ensure reliable data transmission while conserving energy. Common protocols include Zigbee, Bluetooth Low Energy (BLE), and Wi-Fi, each chosen based on specific application requirements regarding range, power consumption, and data rate [6].

Network Topologies: WSNs can be organized in various topologies, including star, mesh, and cluster tree topologies [7]. In a star topology, each sensor node communicates directly with a central base station, suitable for small-scale networks. Mesh topology allows for multiple pathways between nodes, enhancing reliability and fault tolerance, ideal for larger networks. Cluster tree topology combines elements of both, organizing nodes into clusters managed by cluster heads that communicate with the base station, balancing energy efficiency and scalability [8].

Data Aggregation and Processing: Data aggregation is a vital aspect of WSN architecture to reduce the amount of data transmitted and, consequently, the energy consumed. Nodes often perform preliminary data processing and aggregation, combining data from multiple sensors before sending it to the base station [9]. This process can involve data fusion techniques to enhance data quality and reduce redundancy. Efficient data aggregation protocols are essential to maintain the network's energy efficiency and prolong its operational life.

Power Management: Power management is a critical consideration in WSN design due to the limited energy resources of sensor nodes. Techniques such as duty cycling, where nodes alternate between active and sleep states, are employed to conserve energy. Additionally, energy-efficient routing protocols ensure that data packets take the least energy-consuming paths [10]. Harvesting energy from environmental sources like solar or vibration energy is another strategy to extend the network's operational duration.

Security Considerations: Ensuring the security of WSNs is paramount, given their often-deployed environments, which can be prone to physical tampering and eavesdropping. Security measures include encryption, authentication, and secure routing protocols to protect data integrity and confidentiality [11]. Lightweight security algorithms are essential to accommodate the limited computational resources of sensor nodes.

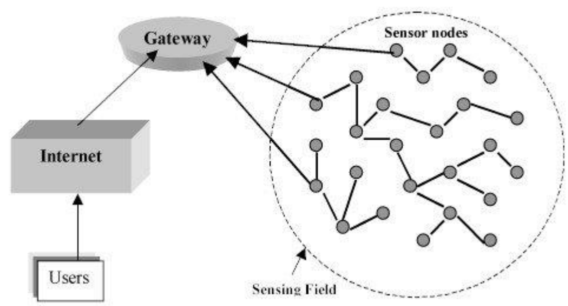

Fig.1 A Typical WSN structure

The basic components of WSN nodes are [12]:

1) Sensing unit,
2) Processing unit,
3) Transceiver unit
4) Power unit.
5) Mobilizer and Location Finding Unit

The sensing module is basically an amalgamation of the analog sensor which senses the analog data such as temperature, pressure etc. However, there is a need to convert the data into digital format which needs the analog to digital converter. The ADC processes the data and converts the data to be compatible with digital formats [13]. There also exists a processor which processes the data and has a storage capacity in the memory. The data may be needed to be help for a while prior to transmission [14]

The transceiver is of fundamental importance which is responsible for the transmission and reception of data packets. The power unit is generally operated via batteries since it's not feasible to operate a line wired power source to the sensing module. The battery operated sensing module imposes the limitation of the power consumption and the network lifetime. This puts a fundamental necessity on the system of attaining a high network lifetime [15].

The mobilizer and position finding system are optional modules in the WSN. It may be needed to locate the sensing module at times and change its position. The position finding system does the work of finding the position of the sensing module and relaying the information to the control station. Typically, servo motors etc. are used as mobilizers. This however may be optional in WSNs [16].

II. ENERGY CONSUMPTION AND LATENCY IN WSNs

If we consider an ideal situation, then all the nodes in the network can be assumed to be distributed uniformly. They would however have different individual lifetimes. Thus average energy for round k can be given by $\bar{E}(r)$ of rth round is as follow:

$$\bar{E}(k) = \frac{1}{L} E_{Tot}\left(1 - \frac{k}{R}\right) \quad (1)$$

Here,
R is an indicative of the aggregate rounds of the lifetime of the WSN.
M is the total number of transmissions
L is the number of nodes.

The latency in the Network is given by:

$$L = \frac{1}{n}\sum_{i=1}^{n} T_i^S - T_i^r \quad (2)$$

Here,
L is the average latency
n is the number of nodes
T_i^S represents the time at which data is sensed by node i
T_i^r represents the time at which node i's data is received by data sink

It is always desirable to reduce the latency and the average energy of the WSN so as to improve the performance and the network lifetime.

III. RELATED WORK

The following section summarizes some of the prominent work in the field of WSNs in a chronological order. It can pave the path for further improvements in the field.

Gamal et al. proposed that the lifetime of WSNs must be prolonged to increase their use for various applications. One of the most effective methods for improving the network's lifetime is clustering with the optimal cluster head (CH). This study proposes a fuzzy Logic (FL) low-energy adaptive clustering hierarchy (LEACH) technique-based particle swarm optimization (PSO). It employs hybrid PSO and a K-means clustering algorithm for cluster formation. It selects the primary CH (PCH) and secondary CH (SCH) using FL

Huang et al. proposed a a communication scheme named first relay node selection based on fast response and multihop relay transmission with variable duty cycle (FRAVD) is proposed. The scheme can effectively reduce the network delay by combining first relay node selection with node duty cycles setting. In FRAVD scheme, first, for the first relay node selection, we propose a strategy based on fast response, that is, select the first relay node from adjacent nodes in the communication range within the shortest response time, and guarantee that the remaining energy and the distance from sink of the node are better than the average.

Cen et al. presented the idea of LANET: which stands for visible light mobile ad-hoc networks. The data transfer in this case was in the form of visible frequencies. It was shown by dint of the experimental set-up that the proposed system was capable of increasing the network lifetime as the power consumption compared to conventional techniques was lesser in the proposed case.

Liu et al. proposed the QTSAT model. This was primarily used for the delay minimization in wireless sensor networks. The system was basically developed using the MAC protocol for the WSNs. Power consumption was not the primary focus of the paper and throughput enhancement was targeted.

Quing Liu et al. proposed a technique for the implementation of unicast-broadcast mechanism for WSNs. It was shown that often, unicast mechanisms in a broadcast network can provide more energy saving compared to conventional techniques. The evaluation of the system was based on the energy required per transmission.

Mathews et al. proposed a technique for software defined radio (SDR) concept for wireless sensor networks. It was a new approach for the design of Software Defined (SD) based WSNs. The information leveraged in this case was the channel information of the WSN for increasing the network lifetime.

Zhan et al. presented the concept of UAV enabled data collection in wireless sensor networks. The idea was to increase the lifetime and decrease the delay latency of the network by switching to the UAV technology of the network. The evaluation parameters were the network lifetime and average delay.

Yuxin Liu et al. proposed a technique for secure and trustworthy techniques for data routing in WSNs. The approach evaluated the chances of data theft in Wireless Sensor Networks in the absence of strong encryption algorithms which may not be practically possible in real life situations due to the limitations of the sensor module.

Ren et al. evaluated the lifetime and energy holes in Wireless Sensor Networks. The technique tried to evaluate the free spectrum and term it as a hole to avoid data congestion in the WSN. Lesser congestion would lead to lesser delays.

Dong et al. presented a concept to increase the lifetime and also decrease the delay in wireless sensor networks. The approach was tested under the constraints of reliability constraints of the WSN architecture. This approach was practical in the sense that WSNs are seldom highly reliable.

Khan et al. presented a VDGRA based approach in which a virtual grid based approach was used. The evaluation of the system was done based on network lifetime. It was shown that the proposed approach could attain a network lifetime of around 800 rounds of data transfer for a node count of 400.

Luo et al. put forth opportunistic algorithm approach for wireless sensor networks. It was shown that ss the network lifetime is of a key importance for the performance of the wireless sensor network, improvement and its enhancement can be very beneficial. This could be done using optimization based approaches.

Yao et al. presented a WSN architecture for delay minimization and lifetime enhancement in heterogeneous networks. It was shown that with Link heterogeneity one can get huge information transmission range easily. As it is more bound towards the link and connectivity framework it yields better and reliable links and connection paths for routing. It gives a good transreceiver which is greater in size and length.

Guo et al. presented an opportunistic flooding in WSNs. It was proposed that the routing and information exchange must be designed diligently such that the entire functions consume minimum power. Also the power consumption parameter hugely impacts the overall network functioning effectiveness and power of the sensor node.

Yang et al. proposed a Complete Targets coverage in Energy Harvesting based approach for WSNs. It was shown that the connectivity metric is of enormous use as it decides the protocol of the information transmission. Strong data exchange connectivity amidst the cluster heads and sensor nodes shall impact the time period of the sending and receiving of the data.

Butun et al. presented an intrusion detection mechanism for wireless sensor networks. The approach was targeted at detecting the chances of possible attacks in WSNs. The need for the study arose due to the fact that node modules are not sophisticated enough to implement complex encryption algorithms to thwart off security threats in WSNs

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Ranjan Rout et al. presented a method for the increasing network lifetime using the duty cycle approach and network coding. It was shown that the technique of network coding could indeed increase the network lifetime. It was also shown that strong data exchange connectivity amidst the cluster heads and sensor nodes shall impact the time period of the sending and receiving of the data.

Yao et al. presented an approach in which it was shown that with Link heterogeneity one can get huge information transmission range easily. As it is more bound towards the link and connectivity framework it yields better and reliable links and connection paths for routing. It gives a good transreceiver which is greater in size and length.

Tyagi et al. proposed a survey on the LEACH algorithm used for clustering techniques. It was shown that clustering is of high importance in this context. The objective here has to be minimum energy consumption by the nodes. The sensor node is operated by battery hence the network lifetime then becomes dependent on the lifetime of the battery. So the routing and information exchange must be designed diligently such that the entire functions consume minimum power.

Ehsan et al. proposed a survey on routing protocols with the Quality of Service or QoS as the primary metric. The proposed system explained the need for the connectivity must all matter when the base station and control station interact with the sensor nodes and the user for the target data. So, proper connection between all the network nodes and units must exist for a robust WSN design. The Qos was responsible for rendering reliability to the WSN data transfer.

Aziz et al. presented a survey on different techniques on distributed control topologies for the increase in network lifetime of WSNs. The target was the increase in network lifetime for battery powered wireless sensor networks. It was shown that the adaptive routing algorithms could enhance network lifetime.

The approaches renders insight into the common approaches employed to increase the network lifetime and reduce the latency.

IV. EVALUATION PARAMETERS

The evaluation parameters for the performance evaluation of the WSN are [17]-[18]:

Energy Consumption

The energy consumption also depends on the duty cycle which is given by:

$$DC = \frac{1}{K} \tag{3}$$

Here,

DC represents the duty cycle.

K is the number of nodes among which a CH is selected.

It can be clearly inferred that as the value of K increases (duty cycle decreases), the number of nodes for which one CH is chosen also increases. This clearly decreases the energy consumption i.e. the energy consumption decreases with decrease in duty cycle and increases with the increase in the duty cycle i.e.

$$Energy\ Consumption = f\ (DC) \tag{4}$$

One Hop Delay

Moreover, as the cluster size increases, i.e. K increases (DC decreases), the one hop delay of the system increases which is nothing but the delay the data packet takes for a single hop transmission. Thus decrease in DC increases one hop delay and increase in DC decreases the one hop delay.

Network Delay

The network delay is often computed w.r.t. the distance from the sink. Clearly, as the distance from the sink increases, the time required for the data to reach the base station also increases i.e.

$$ND = f(d_{sink}) \tag{5}$$

ND is the network delay
f stands for a function of
d_{sink} is the distance of the nodes from the sink

Energy Consumption and Residual Energy of nodes w.r.t. distance from sink

In case the node is far away from the sink, its chances for a long distance transmission reduces, hence it would transmit to a nearby node, thereby reducing the energy consumption. This would in-turn increase the residual energy of the nodes.

Thus as the distance from sink increases, the energy consumption decreases and the residual energy increases. Thus,

$$E_C = f(d_{sink}) \tag{6}$$

$$E_{Residual} = f(d_{sink}) \tag{7}$$

Thus two important considerations have been seen which are conserving the energy of the system so as to increase the network lifetime and moreover increasing the efficacy with which the packets are transmitted and received by the transmitting end and the receiving end. This would in turn increase the latency performance of the system by reducing the da=delay of the system. The formulations above give the relation among various variables for the computation of the same.

V. CONCLUSION

Wireless Sensor Networks (WSNs) are a notable technological progress in the realm of sensing and data gathering. Consisting of multiple compact, battery-operated sensors, Wireless Sensor Networks (WSNs) enable the gathering and transfer of data in diverse settings without the requirement of substantial infrastructure. These networks play a crucial role in a wide range of applications, including environmental monitoring, healthcare, industrial automation, and smart cities. The previous talks have led to the conclusion that minimizing latency and energy consumption in wireless sensor networks is crucial. The significance of this lies in the fact that a poor network lifetime leads to reduced operational efficiency of Wireless Sensor Networks (WSNs) due to frequent system shutdowns. Furthermore, another crucial factor is the delay or latency, which must also be minimized. The study provides a thorough examination of the current methods in the field in order to gain a better understanding of future concepts.

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