Quality-of-Service Prediction Techniques for Wireless Sensor Networks

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Abstract. The rapid development of smart sensor nodes generates great interest in Wireless Sensor Network (WSN). The distinct applications of these networks have evolved in the field of border surveillance, Internet of Things, agriculture, healthcare, and disaster monitoring. It is a complex task to satisfy the need for Quality-of-Service (QoS) in a real-world environment, due to the size and dynamic nature of the mobile sensor nodes. This paper addresses the QoS metric based on the layered architecture of WSN. There are two types of layered architectures, namely classic-layered architecture and cross-layered architecture. In a classic-layered architecture, QoS is achieved based on the individual layer. Due to the interconnected nature of these layers, it is difficult to achieve the overall QoS in a classic-layered architecture. This challenge is resolved with the help of cross-layered architecture. Further, the proposed statistical analysis illustrated the fact that the QoS metric enhances the performance of the network in terms of latency, throughput, energy, and reliability. Finally, the machine learning approaches are discussed in the light of QoS metrics to enhance the overall performance of the network.

Keywords. Quality-of-Service, Wireless Sensor Network, Machine Learning, Classic-layered architecture, Cross-layered architecture

1. Introduction

Wireless Sensor Network (WSN) comprises numerous small sensor nodes that are randomly deployed in the area to be monitored. The versatile applications of WSN include health monitoring, traffic monitoring, industrial automation, disaster prediction, and many other distinct fields of routing, Quality-of-Service (QoS), localization, energy efficiency. Energy is an important constraint in WSN due to the limited resources of the sensor node. Sensor node consists of low energy and it is required to maintain the energy efficiency across the network while transmitting the data from sender to receiver [3].

The life-cycle of WSN is categorized into three parts namely, start-up phase, life phase, and death phase. The start-up phase comprises the initial organization, optimization, and configuration of the network and is also known as the birth phase of WSN. This phase utilizes a great amount of energy, so there is a requirement to develop protocols that consume minimum energy. This phase is application-oriented and at least one sensor node should communicate with a data collecting unit. The communication structure should be fully connected in the entire network. The actual communication in WSN takes place in the Life Phase. The main function of sensing the information in the field of interest and forwarding this knowledgeable information to the base station is carried out in this phase. It also performs data transmission, error reporting, and threat detection across the network. The main aim of this phase is to achieve the best QoS and retain the predefined QoS. The Death Phase comprises energy...
drainage, malicious attacks, and sensor node failures. This is also an application-oriented phase. WSN is categorized as Terrestrial WSN, Mobile WSN, Multimedia WSN, Underground WSN, and Underwater WSN based on the environment in which it is deployed. The various categories are described below [23]:

Terrestrial WSN: In terrestrial WSN, sensor nodes are deployed in a pre-planned manner, or ad-hoc manner. In a pre-planned manner, the sensor nodes are placed at a specific position but in an ad-hoc manner, the sensor nodes are distributed randomly within the target area. The efficiency of communication in terrestrial WSN is very effective as compared to other types of WSN deployments [24].

Mobile WSN: In mobile WSN, sensor nodes are dynamic and can organize themselves across the network. This dynamic nature leads to a high degree of connectivity and coverage throughout the network. Data delivery to a specific destination is an important challenge in mobile WSN because the dynamic nodes will consume more energy as compared to static nodes [25].

Multimedia WSN: The cameras and microphones are embedded with sensor nodes and deployed in a structured fashion in Multimedia WSN. Multimedia content comprises video, audio, and images. It requires a high bandwidth because multimedia data is transmitted from source to destination. QoS provisioning is very important in the streaming of multimedia content across the network. Multimedia content consumes a large amount of energy throughout the network.

Underground WSN: The sensor nodes equipped with batteries are deployed underground in the mines and caves for Underground WSN. It is costly as compared to terrestrial WSN. It requires careful pre-planning during the deployment of sensor nodes underground. The hidden nodes observe the behaviour or condition of the underground environment and forward information to the base station. A high degree of attenuation occurs in this type of network [26].

Underwater WSN (UWSN): In UWSN, the sensors are deployed underwater and have a limited non-rechargeable battery. Energy consumption in UWSN is more than the terrestrial WSN [26] due to the unique feature of an acoustic communication channel.

QoS is important for various types of WSN. Traditionally, QoS was not considered a crucial parameter by various researchers as it was more focused on individual attributes and followed the classic individual layered design. But now QoS is an important part of the WSN because it is significant for various real-world applications and also follows the cross-layered design for overall network optimization. In real-world applications assurance is required for optimal performance. The performance of WSN is dependent on the QoS metrics such as throughput, latency, energy efficiency, packet loss ratio, and reliability [2]. Earlier researchers focused mainly on the trade-off between throughput and delay which are inversely proportional to each other. WSN is entirely different from traditional networks because it comprises of small sensor nodes and has limited resources. There is a need for considering other metrics of QoS which provide good performance in WSN such as reliability, latency, throughput, and energy.

Machine Learning (ML) improves the efficiency of the network with the help of prior learning experiences. It can be classified into three categories namely supervised, unsupervised, and reinforcement learning. Supervised learning deals with labeled input data. The examples of supervised learning classifier are Decision tree and Support Vector Machine (SVM). On the other hand, unsupervised learning deals with unlabeled data. K-means is an example of unsupervised learning. Reinforcement learning uses the rewards scheme. Rewards can be positive and negative. Q-learning is an example of reinforcement learning [5].

The rest of the paper is organized as: Section 2 describes the role of QoS in WSN and provides discussion about the requirement of QoS; Section 3 elaborates on the QoS metrics for various WSN layers; Section 4 presents the statistical analysis of ML for QoS parameter; open issues are discussed in Section 5. Finally, the discussion concludes with various research issues in Section 6.
2. Quality-of-Service in Wireless Sensor Network

The main goal of the WSN is to achieve QoS for users and applications. Due to the presence of mobile sensors in WSN, the topology of a network changes dynamically. It is difficult to access the performance of a network in terms of the QoS parameter. These issues are resolved by using the ML approaches. ML solves the complex problems of WSN with greater efficiency and is more adaptable to the frequent topological changes.

2.1. QoS support in traditional network

QoS can be determined in traditional networks using traffic engineering, network over-provisioning, and differential treatment of packets inside routers. Traffic engineering requires the information of available resources and estimated traffic in the different communication paths of the network. In traffic engineering, routes are designed to enable maximum packet flow using the available network resources. Network over-provisioning deals with the inclusion of a large count of resources in the network which is limited to the capacity of the router and bandwidth. This scenario is quite expensive for WSN. In the differential treatment of packets inside the router, QoS is achieved using classification, queuing, and scheduling of packets. WSN is entirely different from the traditional networks because it comprises tiny sensor nodes having resource constraints. There is a need for more adaptability for emerging requirements of QoS defined according to the dynamic and complex nature of WSN.

2.2. Requirement of QoS in WSN

The QoS requirements can be divided into two categories namely functional and non-functional parameters. The measurable parameters are known as functional parameters and non-measurable parameters are called non-functional parameters. This work considers the core functional parameters such as throughput, energy efficiency, reliability, and latency [8]:

2.2.1. Throughput:

Throughput is a significant parameter and has a great impact on the performance of the network. Throughput is the total data transferred from sender to receiver per unit time and is measured in bits/sec. The formula of throughput is given as:

\[ \text{Throughput} = \text{Efficiency} \times \text{Bandwidth} \]  \hspace{1cm} (1)

The range of the throughput is based on different multiple access networks which are given below as:

Time Division Multiple Access (TDMA) per slot =1 \hspace{1cm} (2)

For slotted ALOHA = \frac{1}{e} \hspace{1cm} (3)

2.2.2. Energy Efficiency:

Energy is a critical issue of QoS due to the small size of sensor nodes. It is the total bits transmitted from the source node to the target node measured as a unit of power usage. The unit of energy is bits/joule. The formula of energy consumption at the physical layer is given as:

\[ \text{Energy} = \left( \frac{P_{\text{send}}}{\eta} + P_{\text{amplifier}} + P_{\text{sc}} + P_{\text{rc}} \right) \times T_{\text{all}} \]  \hspace{1cm} (4)

where Energy denotes energy consumed, \( P_{\text{send}} \) is the sending power of source sensor node, \( \eta \) represents amplification efficiency of signal amplifier at the sender end, \( P_{\text{amplifier}} \) indicates energy consumed in the power amplifier (\( P_{\text{amplifier}} = \omega P_{\text{send}} \)), \( P_{\text{sc}} \) = Power consumption at the transmitting end, \( P_{\text{rc}} \) = Power consumed at the receiving end and \( T_{\text{all}} \) = Total time consumed to send the data.
2.2.3 Reliability:
Reliability states that the system can perform well without any failure for a given specific time. The formula of reliability is given as:

\[ R(t) = e^{- \int_0^t z(t) dt} \]  

(5)

where \( R(t) \) indicates a reliability function and \( z(t) \) represents failure rate function. The range of reliability lies between 0 to 1. If the reliability is greater than 0.8 then it indicates good reliability. But if it is less than 0.53, it is considered as poor reliability [28]. Battery level reliability is calculated as:

\[ \text{Reliability}_{\text{battery}}(\text{Level}) = \begin{cases} 
1 & \text{if Level ranges from 100\% to 81.81\%} \\
\frac{\text{Level-Min}}{\text{Max-Min}} & \text{if Level ranges from 81.81\% to 53.94\%} \\
0 & \text{if Level is below 53.94\%}
\end{cases} \]  

(6)

2.2.4 Latency:
Latency is the total time consumed by data transmission from sender to receiver across the network. It is inversely proportional to the performance of the network. The increases in latency will diminish the performance of the network. The unit of latency is milliseconds and its formula is given as:

\[ \text{Network Latency} = \text{Propagation Delay} + \text{Serialization Delay} \]  

(7)

where Propagation Delay = \( \frac{\text{Distance}}{\text{Speed}} \) and

\[ \text{Serialization Delay} = \frac{\text{Packet Size (bits)}}{\text{Transmission Rate (bps)}} \]

The range of latency is dependent on the type of application. In gaming, the acceptable range is 100ms, for optimal solutions latency value lies between 20-40 ms and in wireless communication such as 5G, the range lies between 1 to 10 ms [30].

3. QoS parameters based on WSN Layers
QoS is defined as it is the agglomeration of services provided by the network when data is transmitted from source node to target node. It can be determined in the terms of throughput, latency, reliability and energy. The two approaches of QoS provisioning are classic-layered architecture and cross-layered architecture [27].

3.1. Classic-Layered Architecture:
The classic-layered architecture consists of five layers physical, Media Access Control (MAC) layer, network, transport and application. QoS parameters are assigned according to the individual layer of WSN shown in Figure 1.

3.2. Physical Layer:
Physical Layer is a first layer of WSN and deals with hardware components, transmission medium and topology of the network. The physical layer comprises of sensor, processor and communication component. The main functions of this layer are:

- Data Flow: It includes the direction of data flow from sender to receiver. It can be simplex, half-duplex and full-duplex mode.
Topology: Topology is defined as a geometrical representation of devices, and how these devices are arranged. Bus, star, tree, mesh, ring, grid and circular are the examples of topology used in WSN.

Data Rate: It provides information of transmission rate and is expressed in the form of bits per second.

![WSN Layered Architecture](image)

**Figure 1.** QoS Parameters in WSN Layered Architecture

### 3.2.1. MAC Layer:
MAC layer is the second layer of WSN which is considered as the lower layer of the data link layer. The performance of upper layer is based on the components used in this layer. On the other hand, MAC protocols provide reliable communication in the network. In this layer, medium access delay is reduced, reliability is enhanced, collisions are minimized, adaptability enhanced and the energy consumption is reduced. This layer deals with the communication range, energy efficiency and throughput metric of QoS. The functions performed by the MAC layer are [22]:

- **Error Control:** MAC layer is responsible for error control and enhances the reliability. It provides a fast delivery mechanism to send the data and reduce energy consumption.
- **Clustering:** MAC layer simplifies coordination and synchronization within neighboring nodes of the group.
- **Power Control:** MAC layer adjusts sending power of the node. It reduces power consumption for successful transmission of data.

### 3.2.2. Network Layer:
Network Layer is a significant layer of WSN where data is transmitted in the form of packets. This layer is responsible for route maintenance and energy efficiency of the network. QoS mechanism is performed at the network layer which enables:

- **Multipath Routing:** It includes multiple copies of data being sent from sender to receiver using multiple paths. It provides data reliability to achieve QoS entire the network.
- **Energy-Aware Routing:** The minimum distance path with energy efficient communication is determined to transmit data from source node to the target node.
- **Low-Cost Forwarding:** The minimum cost path is identified in the network layer to reduce cost in large-scale WSN.
Maintaining minimum routing control overhead: Routing control overhead is minimized by reducing transmission of unnecessary control packets.

3.2.3. Transport Layer:
The transport layer is responsible for process-to-process delivery. QoS used in the transport layer to enhance the end-to-end reliability, bandwidth fairness, minimum congestion probability and minimum latency. QoS functions performed at the transport layer are as follows:

- Congestion Control: It includes congestion notification, detection, avoidance and prevention mechanisms.
- Flow Control: It ensures that the transmission flow of data cannot exceed the reception flow of data.
- Loss Recovery: It includes two phases: notification, identification of loss and the second phase is retransmission recovery.
- Source Prioritization: Sensed information can be prioritized according to the importance of information.

3.2.4. Application Layer:
Application layer is the user-level layer of WSN. Response time, data reliability and system lifetime are the metrics of QoS used in the application-specific layer. Data reliability is a significant feature of QoS because it deals with the sensitive and concise data and it can be maintained by using encryption mechanism. The functions performed at the application layer are as follows:

- Measurement Errors: Error can be identified by the measurement precision of sensor nodes.
- Coverage: Coverage is depending on the specific requirements of QoS at the time of deployment of sensors.
- Exposure: It includes how well the object can be monitored in a specific time.

3.3. Cross-Layered Architecture:
The different metrics of QoS are assigned for different layer of WSN. All layers are interconnected and are dependent on each other for communication. Network Layer cannot work without the support of MAC layer. Similarly, application layer performance is dependent on the network-specific layer. It is difficult to achieve QoS based on a specific layer such as throughput and delay cannot trade-off within a single layer. It can be achieved throughout all layers of WSN and can be implemented by using cross-layered approach [29]. The parameters of QoS which can be achieved by using a cross-layered approach are as follows:

- Energy: Energy consumption is considered at sensor node level as well as network level. Sensor nodes reside in the physical layer of the WSN. It is a complex task to achieve energy harvesting at a specific layer. Cross-layered architecture helps to determine energy consumption across the network.
- Network lifetime: Network lifetime is directly related to network energy. Cross-layered approach improved the energy harvesting and network lifetime.
- Throughput: Cross-layered approach improves the throughput at MAC layer as well as the network layer. It calculates the throughput for the entire network and maintains trade-off between latency-throughput to provide the optimized performance.
- Latency: The different types of delays are delay at the packet level, delay at transmission-level and delay at process level across the network. All delay lies in the different layer of the network. The classic-layered approach determines layer-based delay but cross-layered approach estimates the overall delay occurs in the network.
Reliability: Reliability can be divided into two categories: data reliability and network reliability. Network reliability is determined at the network level and data reliability determined at the application layer. Cross-layered approach improves the overall reliability of the network.

4. Statistical Analysis
The statistical analysis of ML technique in QoS metrics is shown as in Figure 2. Four parameters of QoS are considered in the analysis: throughput, energy efficiency, latency and reliability. The analysis is based on the Table 1 which represents the ML and soft computing techniques for QoS.

| Techniques         | QoS Parameter | Throughput | Energy Efficiency | Latency | Reliability |
|--------------------|---------------|------------|-------------------|---------|-------------|
| Machine Learning   |               |            |                   |         |             |
| DT                 |               | [21]       |                   |         |             |
| SVM                |               | [18][20]   | [18][20]          |         |             |
| KNN                |               | [21]       |                   |         |             |
| K- means           |               | [6][7][17] | [7]               | [6][7]  |             |
| RL                 |               | [8]        | [4][8][13]        | [8][16] | [8][16]     |
| Regression         |               |            |                   | [18]    | [18]        |
| RF                 |               | [9]        |                   | [9]     |             |
| ANN                |               |            |                   | [10]    |             |
| DL                 |               | [1][2]     | [1][20]           | [1][2]  | [20]        |
| Soft Computing     |               |            |                   |         |             |
| Fuzzy              |               | [3][5][15] | [3]               | [10]    |             |
| GA                 |               | [19]       | [11][14][15][19]  | [11]    |             |

Figure 2 shows that researchers emphasize on four main QoS functional parameters: energy efficiency, latency, reliability and throughput across the network. According to the literature, much work has been conducted for the energy efficiency parameter. Genetic Algorithm helps to reduce energy consumption across the network. Similarly, throughput is the least considered parameter although it is an important parameter which enhances performance of the network. Several deep learning approaches are used to increase the network efficiency. With increase in throughput, the energy consumption of the network is also enhanced. So, both the parameters throughput and energy consumption must be considered for an efficient working of the network.
Figure 2. Statistical Analysis of QoS Parameter with ML

5. QoS Challenges and Open Issues

QoS provisioning plays a vital role in the field of WSN. There are diverse challenges when addressing the QoS requirement such as node deployment, scalability, limited resource constraints, application domains, dynamic topology, types of traffic, wireless unreliability and data duplicity. A lot of work has been carried out by the researchers but still, there are certain open issues in these areas discussed below:

5.1. Dynamic Topology:

Due to the mobile nature of sensor nodes, topology of network changes dynamically in the deployed environment. It affects the performance of the network and can sometimes cause packet drop [25]. QoS mechanisms must be applied adapt to dynamic topology changes.

5.2. Limited resource constraints:

WSN has limited resources due to the size of the sensor node. QoS should be aware of limited resources and provide the best QoS with minimized energy consumption [3].

5.3. Scalability:

Scalability deals with the addition and removal of sensor nodes in the wireless network. Sometimes, adding sensor nodes to a network degrades the performance of that network. Researchers should provide QoS mechanisms in the network which can adapt to the concept of scalability. SASC mechanism [7] improves the scalability issue in WSN. But this mechanism lacks the security and robustness concept and doesn’t provide an optimized solution for scalability.

5.4. Wireless unreliable link:

Due to external environmental issues, link failure can occur in the network. Also, some links can be unreliable in the network. Shorter links are more preferable than longer links because there is a low chance of failure and hence provides reliable communication. There is a mechanism which resolves the issue of unreliable link [9]. But the main drawback is real-time implementation of this approach. This issue can be explored in the light of reinforcement learning.
5.5. **Multi-source to the multi-sink system:**
When data is transmitted from multi-source sender to multi-sink receiver then various challenges need to be addressed such as security, congestion, heterogeneity and resource self-management [31].

5.6. **Distinct types of applications:**
QoS metric need to be assured for multimedia and real-time communication. In multimedia applications, audio and video streaming are challenging task and it requires high throughput, high bandwidth, low latency and low data duplicity. Real-time WSN is a critical application, divided into two parts: hard real-time and soft real-time. It requires high bandwidth, delivery time and minimum delay. The hard-real time system needs deterministic bounded delay during data delivery. The packet should be delivered within a deadline mentioned across the network. If the packet is received later than the allotted time, it will be discarded. It is very difficult to achieve QoS within a hard real-time system [32]. Landslide monitoring and fire detection are examples of hard real-time network. On the other hand, it is easy to achieve QoS in soft real-time network. These systems can tolerate delay across the network and require probabilistic guarantee of latency.

5.7. **Data Duplicity:**
Redundant data affects the consistency and acquires more space in the system which diminishes performance of entire network. Sometimes, the duplicity of data interferes with the reliability. It can be minimized using data agglomeration methods and plays a significant role in multimedia WSN [33].

5.8. **Types of Traffic:**
Sensor node is responsible to generate different type of traffic across the network. It can be the peak level and low level. When traffic is at peak level, QoS provisioning is minimized due to congestion created in the communication channel. Sometimes packet collides with each other and degrades performance of the network [34]. There is a need to develop new QoS mechanisms which provide effective results in both of these cases.

5.9. **Node Deployment:**
Node deployment in a structured network is more costly as compared to unstructured network [35]. Neighbour and route discovery problems are resolved by deterministic deployment. It is a challenging task to provide geographically accurate information of the sensor nodes thereby enhancing the QoS.

6. **Conclusion**
Due to the development of various wireless communication devices, the working capability of Wireless Sensor Network (WSN) has considerably enhanced. It is used in different areas such as habitat monitoring, disaster prediction, health science and industrial monitoring. Quality-of-Service (QoS) metric is represented based on the WSN layered architecture. It consists of five layers: physical layer, Medium Access Control (MAC) layer, network layer, transport layer and application layer. Several QoS metrics are used in different layer such as throughput in MAC layer, energy efficiency at network layer and latency at transport layer. All layers in the network are connected with each other. Due to this, lower layer affects the performance of upper layer and it is difficult to determine layer-wise QoS. This issue is resolved by using cross-layered architecture. In this approach, these metrics are not limited to a specific layer and determines QoS of the entire network in terms of latency, throughput, energy efficiency and reliability. Distinct machine learning (ML) techniques are used for enhancing the QoS metric. Statistical analysis shows the significance of ML mechanisms such as deep learning and reinforcement learning minimize latency across the network. Genetic algorithm and fuzzy are the soft computing approaches which are also responsible for improvement of QoS of the entire network.
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