OPTIMAL ROUTING PROTOCOL IN MULTIMEDIA WIRELESS SENSOR NETWORKS

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OPTIMAL ROUTING PROTOCOL IN WIRELESS MULTIMEDIA SENSOR NETWORKS

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ABSTRACT

Wireless Sensor Networks (WSNs) have attracted research interest in recent years due to the significance of the field of applications and the advances in sensor technology. In areas where catastrophic events occur such as environmental disasters and battle fields, the network infrastructure is lost and there is an urgent need to build a network in order to monitor the area and to help in rescue operations or troops deployment. An easy and fast way is to scatter scalar and video sensor nodes in an ad-hoc manner in the area of interest in order to establish a multimedia wireless sensor network (MWSN). Video sensor nodes provide better coverage of the area and enhance the interpretation of the monitored phenomenon.

Two main challenges faced in MWSNs are quality of service (QoS) constraints in addition to energy constraints. Many routing protocols with various routing metrics have been developed for WSNs. However, limited research has been done on MWSN routing protocols and there is room for improvement in this area. Moreover, these routing protocols assume structured network architecture where deployment of nodes is pre-planned. Limited research has been done on routing protocol for MWSN deployed in ad-hoc manner that meets QoS requirements and at
the same time considers energy efficiency for the purpose of prolonging the lifetime of the network.

In this thesis, an optimal routing protocol is developed for MWSN that is energy-aware and QoS-aware. This routing protocol uses ant colony optimization to find the optimal routing path that maximizes the end-to-end path quality and reliability as well as the network lifetime. End-to-end delay is a constraint set depending on the application used. Each metric used in the path cost can be attributed an importance that varies depending on the application requirements.

A simulation model is developed to implement the proposed ant colony optimization algorithm in MWSN. A detailed analysis of various parameters used in ant colony optimization is performed. The proposed algorithm is analyzed and its performance is evaluated. The proposed routing protocol not only provides an optimal path in terms of the QoS and energy metrics but it also has the flexibility to be used in various applications by adjusting the weights for the optimal path metrics based on their importance to the application.
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CHAPTER 1

INTRODUCTION

Wireless Sensor Networks (WSNs) have attracted interest of researchers in recent years because of the significance of its applications in addition to the development and advances in sensor technology. WSN consists of a large number of sensor nodes that are densely deployed and are working together in order to detect or monitor a phenomenon.

Many routing protocols with various routing metrics have been developed for WSNs. However, limited research has been done on multimedia wireless sensor networks (MWSNs) routing protocols and there is lots of room for improvement in this area. Moreover, these few routing protocols in MWSN assume structured WSN where deployment of nodes is pre-planned. Limited research has been done on a routing protocol for MWSN deployed in ad-hoc manner that meets quality of service (QoS) parameters and at the same time considers energy efficiency and prolonging the lifetime of the network.

1.1 PROBLEM STATEMENT

In this thesis, an optimal routing protocol is developed for MWSN that is energy-aware and QoS-aware. This routing protocol finds the optimal path that maximizes link quality, link reliability, and network lifetime in addition to minimizing energy consumption. The optimal routing path is the one that has the minimum cost. The path cost is defined in terms of energy consumption, link quality, and link reliability. End-to-end delay is a constraint set depending on the application used.
1.2 SIGNIFICANCE OF THE RESEARCH

The importance of this research project stems from the significance of its applications. In areas where catastrophic events occur such as environmental disasters and battle fields, the network infrastructure is lost and it is crucial to establish communication for emergency or rescue operations in addition to monitoring a particular area.

A quick way to monitor this incident is to implement a MWSN by scattering scalar and video sensor nodes that are either fixed or mobile in an ad-hoc manner. The use of video sensor nodes in addition to scalar nodes is very useful because it will help in providing a better coverage of the phenomenon and at the same time enhances the interpretation of the situation. In catastrophic events where infrastructure is lost, rescue teams rely on body area network (BAN) with camera sensors to communicate critical information about victims. Moreover, in a battle field scenario, MWSN is used for rescue operations of injured soldiers, dynamic strategic decision taking, or real-time feedback from BAN to system on tanks, unmanned air vehicles (UAVs), etc.

1.3 RESEARCH METHODS AND MATERIALS

Computer simulation programs are developed using C++ language in order to test and evaluate the proposed ant colony optimization algorithm and to simulate an optimal routing protocol based on ant colony optimization in MWSNs.

A comprehensive study of the ant colony algorithm is performed where the effect of various parameters of the algorithm are investigated taking into account computation time. The frequency of running this algorithm is a network designer choice. This algorithm can be run offline periodically to have the optimal paths ready to be used anytime or it can be run online to reactively discover the optimal path. A case study of offline and online routing using ant colony algorithm is performed.

Another comprehensive study of various network parameters such as events arrival rate $\lambda$, transmission bit rate $R_b$, and video frames encoding rate $F_p$ is explored.
The performance of the network is evaluated based on average queuing delay per sensor node, end to end delay per packet, delay jitter, packet loss percentage per event, and total packet loss percentage in the network. To prolong the lifetime of the network, a study of the impact of increasing the importance of remaining energy metric in the path cost is performed.

The rest of the thesis is organized as follows:

Chapter 2: This chapter provides background about wireless sensor networks, multimedia wireless sensor networks, and ant colony optimization. Detailed literature review of the various routing protocols in WSNs and MWSNs is explored.

Chapter 3: This chapter explains the proposed ant colony optimization algorithm in details in addition to multimedia wireless sensor network simulation algorithm.

Chapter 4: This chapter includes analyses of the proposed ant colony optimization algorithm including studying the parameters’ effects and the performance of the algorithm. Moreover, it analyzes the simulation of MWSNs and studies the effect of transmission bit rate, event generation rate, and frame encoding rate on the following: average queuing delay per node, energy level per node, loss percentage per event, total loss percentage, end-to-end delay per packet, and delay jitter. Another study is performed to present the impact of quality of video and transmission bit rate and it is evaluated based on average queuing delay, end-to-end delay, and packet loss percentage. The network lifetime and the frequency of running the ant colony algorithm studies are explored.

Chapter 5: This chapter concludes the research findings and results. Moreover, it highlights future research work.
CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

This chapter provides a background about wireless sensor networks (WSNs) and multimedia wireless sensor networks (MWSNs) in addition to a discussion of the applications and challenges of each network. Moreover, an overview about ant colony optimization is introduced. In each subsection, a comprehensive literature review of the topic is explored highlighting the various types of routing protocols.

2.1 WIRELESS SENSOR NETWORKS

WSNs have captured attention of many researchers especially with the various development and advances in sensor technology. WSN consists of a large number of sensor nodes that are densely deployed and are working together in order to detect or monitor a phenomenon. Sensor nodes can collaboratively monitor physical or environmental conditions such as temperature, humidity, vibration, motion, pressure, sound, and many more [1][2]. In addition, sensor nodes communicate with each other to transmit the sensed data to the user. With the advances in sensor technology, digital electronics, and wireless communication, the development of sensor nodes has improved significantly. Therefore, sensor nodes are nowadays small-sized, low power, and low cost sensors. In addition, they are multifunctional sensor nodes that communicate with each other over short distances.

Sensor nodes have the following main components: a sensing unit, a processing unit, a transceiver unit, and a power unit [1]. Additional units are added to the sensor node depending on the application such as a location finding system, a power generator, and a mobilizer. Traditional sensor nodes are operated mainly by one-way battery (irreplaceable battery) and when the battery runs out, these sensor nodes are discarded.
WSNs can be designed to be structured or unstructured. In unstructured WSN also known as infrastructureless, there is a dense collection of sensor nodes deployed in an ad-hoc manner and left unattended to monitor a particular coverage area. Due to the large number of sensor nodes, network maintenance including managing connectivity and detecting failures is considered a difficult task. While in structured WSN, sensor nodes are deployed in a pre-planned manner. Therefore, fewer nodes can be deployed at specific locations for better coverage. In addition, with fewer nodes, the maintenance and management costs are reduced [2].

There are many challenges and constraints in WSN such as power consumption, network lifetime, short communication range, limited processing and storage, and quality of Service (QoS) provisioning [1][2]. A detailed discussion of QoS support in WSN is introduced in [3] where the authors clarify that supporting QoS in WSNs is different than supporting QoS in traditional networks because of the different characteristics and applications of each network. Reference [3] classifies WSN applications based on data delivery methods into event-driven, query-driven, continuous, and hybrid delivery methods and analyzes each delivery method in terms of end-to-end requirement, interactivity, criticality, and delay tolerance. Unlike traditional network applications, most WSN applications are considered mission-critical and non-end-to-end applications. Non-end-to-end applications mean that one end of the application is the sink and the other end is not a single sensor node but it is a group of sensor nodes. In addition, packet loss can be tolerated to certain extent due to the existence of data redundancy in the network. All traditional data networks have common QoS requirements and same end-to-end parameters while WSN has to consider and handle new QoS requirements.

There is a wide range of important applications for WSNs. In [1], WSNs applications are categorized into military, environmental, health, home, and other commercial applications. In [2], WSN applications are classified into two main categories: Tracking and Monitoring. Figure 2.1 exemplifies the various applications of WSNs in monitoring and tracking which are employed in the following areas: military, business, habitat, public/industrial, health, and environment.
Figure 2.1 Overview of Wireless Sensor Network Applications [2]
Depending on the application characteristics and requirements, WSNs face different constraints and challenges and therefore, WSNs are classified into different types. There are five types of sensor networks: Terrestrial WSN, Underground WSN, Underwater WSN, Multimedia WSN, and Mobile WSN. In [2], the different types of WSNs are discussed and compared with each other. A summary of the comparison in terms of definition, challenges, and applications is found in [2].

### 2.1.1 Wireless Sensor Network Routing Protocols

Reference [4]-[15] explains and discusses various routing protocols used in WSNs. In [4], a detailed discussion of various WSN routing protocols is explored where routing protocols are classified into data-centric, hierarchical, and location-based routing. Some of data-centric protocols are Flooding and Gossiping [6], SPIN [7], Directed Diffusion [8], and Shah and Rabaey [9]. Some of hierarchical protocols are LEACH [10], TEEN [11], APTEEN [12]. Some of location-based protocols are MECN and SMECN [13], GAF [14], GEAR [15].

Table 2.1 taken from [4] presents a comparison between various WSN routing protocols based on their classification and their consideration of QoS, Network flow, and data aggregation.

<table>
<thead>
<tr>
<th>Routing protocol</th>
<th>Data-centric</th>
<th>Hierarchical</th>
<th>Location-based</th>
<th>QoS</th>
<th>Network-flow</th>
<th>Data aggregation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIN</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Directed Diffusion</td>
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<td></td>
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<tr>
<td>Rumor routing</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Shah and Rabaey</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GBR</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>CADR</td>
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<tr>
<td>COUGAR</td>
<td></td>
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<tr>
<td>ACQUIRE</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fe et al.</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>LEACH</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TEEN and APTEEN</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>PEGASIS</td>
<td></td>
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</tr>
<tr>
<td>Younis et al.</td>
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<tr>
<td>Subramanian and Katz</td>
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<tr>
<td>MECN and SMECN</td>
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<td>GAF</td>
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<td></td>
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<tr>
<td>GEAR</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Chang and Tassiulas</td>
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<tr>
<td>Kalpakis et al.</td>
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<tr>
<td>Akkaya et al.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SAR</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SPEED</td>
<td></td>
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</tbody>
</table>

In [5], many WSN routing techniques are discussed in details and are classified into categories based on the network structure and based on protocol
operation. The first category of WSN routing protocols is classified based on the structure of the network into three main groups: flat, hierarchical, and location-based routing. In Flat architecture, all nodes have the same responsibilities and tasks to perform. While in hierarchical architecture, nodes are clustered and clustered nodes do some processing, aggregation, and reduction of data in order to reduce power consumption. Location-based protocol depends on the position of nodes when relaying data to specific nodes rather than all network nodes. The second category used is classified based on the operation of the network into the following groups: multipath-based, query-based, negotiation-based, QoS-based, and coherent-based. In Table 2.2 [5], a summary of WSN routing protocols are compared with each other in terms of their classification and many other metrics. Looking at Table 2.3, it is evident that QoS-based routing protocols do not take into consideration power usage and energy aware routing protocols do not take into consideration QoS parameters.

Based on Table 2.1 and 2.2, [4] and [5] conclude that there are few WSN routing protocols that considered ensuring Quality of Service for multimedia and real-time applications in terms of delay or bandwidth constraints as well as finding energy efficient paths and reducing energy consumption. In other words, research is needed in finding efficient energy-aware QoS routing protocols. Moreover, most of WSN routing protocols considered only stationary source and sink nodes and very limited research is done considering mobile nodes.
Table 2.2. WSN protocols classification and comparison [5]

<table>
<thead>
<tr>
<th>Classification</th>
<th>Mobility</th>
<th>Position Awareness</th>
<th>Power Usage</th>
<th>Negotiation based</th>
<th>Data Aggregation</th>
<th>Localization</th>
<th>QoS</th>
<th>State Complexity</th>
<th>Scalability</th>
<th>Multipath</th>
<th>Query based</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIN</td>
<td>Flat</td>
<td>Possible</td>
<td>No</td>
<td>Limited</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Limited</td>
<td>Yes</td>
</tr>
<tr>
<td>Directed Diffusion</td>
<td>Flat</td>
<td>Limited</td>
<td>No</td>
<td>Limited</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Low</td>
<td>Limited</td>
<td>Yes</td>
</tr>
<tr>
<td>Rumor Routing</td>
<td>Flat</td>
<td>Very Limited</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Good</td>
<td>No</td>
</tr>
<tr>
<td>GBR</td>
<td>Flat</td>
<td>Limited</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Limited</td>
<td>No</td>
</tr>
<tr>
<td>MCFA</td>
<td>Flat</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Good</td>
<td>No</td>
</tr>
<tr>
<td>CADR</td>
<td>Flat</td>
<td>No</td>
<td>No</td>
<td>Limited</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Limited</td>
<td>No</td>
</tr>
<tr>
<td>COUGAR</td>
<td>Flat</td>
<td>No</td>
<td>No</td>
<td>Limited</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Limited</td>
<td>No</td>
</tr>
<tr>
<td>ACQUIRE</td>
<td>Flat</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Limited</td>
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<td>Yes</td>
<td>Yes</td>
<td>No</td>
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</tr>
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<td>Fixed BS</td>
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<td>Maximum</td>
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<td>Yes</td>
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<td>Low</td>
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</tr>
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<td>No</td>
<td>Low</td>
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<tr>
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<td>No</td>
<td>No</td>
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<td>Low</td>
<td>Limited</td>
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<tr>
<td>GOAFAFR</td>
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<td>No</td>
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<td>No</td>
<td>Low</td>
<td>Good</td>
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</tr>
<tr>
<td>SAR</td>
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<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
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</tr>
<tr>
<td>SPEED</td>
<td>QoS</td>
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<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Low</td>
<td>Good</td>
<td>No</td>
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</tbody>
</table>
2.2 MULTIMEDIA WIRELESS SENSOR NETWORKS

MWSN consists of wirelessly connected sensor nodes that are capable of storing, processing and retrieving different types of data such as video, audio, scalar data, and still images [16]. These sensor nodes are equipped with cameras and microphones to retrieve video and audio information from the area of interest.

The availability of low cost hardware such as CMOS cameras and microphones has fostered research and development of MWSNs in the last few years. The use of MWSN not only enhances existing WSN applications such as tracking and monitoring but it also enables new applications such as military, civil, and health applications.

MWSN is considered one of the newest research areas and it has lots of room for improvement due to the various theoretical and practical challenges that it introduces. Some of these challenges are high bandwidth requirements, high energy consumption, data processing and compressing techniques, variable channel capacity, multimedia in-networking processing, and cross-layer design[16].

One of the major challenges in MWSN is QoS provisioning where delivery of multimedia content, such as video and audio, requires certain level of quality with stringent time and reliability requirements. In[16], multimedia traffic classes are classified based on application and QoS requirements taking into consideration the type of data, sensitivity to delay, and loss. The following classes are considered:

- Real-time, loss-tolerant, multimedia streams
- Delay-tolerant, loss-tolerant, multimedia streams
- Real-time, loss-tolerant, data
- Real-time, loss-intolerant, data
- Delay-tolerant, loss-intolerant, data
- Delay-tolerant, loss-tolerant, data
Figure 2.2 illustrates three different architectures of MWSNs[16]. The first architecture shown in Figure 2.2.a illustrates a single-tier network consisting of homogeneous video sensors. Some of these sensors have higher processing capability and they are called processing hubs. Processing of multimedia data is distributed among these processing hubs. After processing multimedia content, it is sent to a wireless gateway which is connected to a storage hub and a sink. The storage hub stores multimedia content for later retrieval and the sink is responsible for querying and tasking in the network. The second architecture shown in Figure 2.2.b illustrates a single-tier clustered architecture of heterogeneous sensors such as video, audio, and scalar sensors. Multimedia content and data is relayed to a central cluster head. The cluster head is responsible for executing intensive multimedia processing on the data. Afterwards, the multimedia content is sent by the cluster head to the wireless gateway and storage hub. The last architecture shown in Figure 2.2.c illustrates a multi-tier architecture of heterogeneous sensors. Each tier is responsible for part of the network functionality. In this architecture, data storage and data processing are distributed.
The following is a combination of the various challenges in WSNs and MWSNs [3]:

- **Severe resource constraints**: Energy, bandwidth, memory, buffer size, processing capabilities, achievable data rates, and limited transmission power.

- **Unbalanced traffic**: Traffic is directed mainly in WSN from a large number of sensor nodes to a small number of sink nodes.

- **Data redundancy**: One of the main characteristic of WSN is redundancy which is helpful in achieving reliability/robustness requirement. However, it also results in unnecessary power consumption and waste of bandwidth and data rate.

- **Network dynamics**: due to node failures, wireless link failures, and node mobility. This necessitates dynamic routing where the routing algorithm dynamically checks the routes either periodically or on demand before transmission.

- **Energy balance**: Balancing energy load between different nodes to prolong the life of the network.

- **Power consumption**: due to transmission, multimedia compression, packet processing, and mobility.

- **Scalability**: Scaling up or down the network by changing the number of nodes should not affect the performance and the required QoS of the network.

- **Multiple sinks**: Having multiple sinks results in having different network requirements.

- **Multiple traffic types**: This would introduce different QoS requirements such as delay and reliability requirements.

- **Packet criticality**: Different packets have different criticality and priority and should be treated differently. For example, type of video frame (I frame).

- **Time constraints**: Multimedia content have certain time constraints and delivery multimedia content after a certain deadline would be very critical.
2.2.1 Multimedia Wireless Sensor Network Routing Protocols

In [16], routing protocols are classified into the following classes: QoS routing based on network conditions, QoS routing based on traffic classes, and routing with support for streaming. The metrics used by each class are shown in Figure 2.3. The majority of WSN routing protocols discussed in the previous references focuses on energy efficiency and assumes data traffic with no constraints on its delivery requirements. However, MWSN requires certain quality of service from the routing protocols in terms of delay, bandwidth, and reliability in addition to energy efficiency.

![Routing Layer Diagram](image)

**Figure 2.3 MWSN Routing protocols classification and metrics [16]**

In [5][16][17], a novel QoS-aware routing mechanism for MWSN is proposed. This protocol uses multichannel multipath approach and ensures meeting bandwidth and end-to-end delay requirements for real time data and maximizing non-real time data throughput. Simulation result demonstrates significant performance improvement in terms of average delay, average lifetime, and network throughput.
In [18], WSN routing protocols are analyzed in terms of their applicability and suitability for MWSNs. The following routing protocol classes are analyzed: data-centric flat-architecture, hierarchical/clustered-based, and QoS-based.

2.2.2 QoS Routing Protocols in Wireless Sensor Networks

The QoS-based class is found to be the most suitable for MWSN. However, lots of improvement is needed in this class of protocols in order to meet the multimedia requirements and constraints. A survey of the main QoS-based routing protocols in WSN is presented in [19]. We are going to discuss the following QoS-based routing protocols: sequential assignment routing (SAR), SPEED, multi-path multi-SPEED, and energy-aware QoS routing protocols.

- **Sequential Assignment Routing (SAR)**

Sequential Assignment Routing (SAR) is a WSN routing protocol that considers QoS in addition to energy efficiency, and packet priority when making a routing decision [4][5][18]-[21]. The routing decision is based on energy resources, QoS for each path, and the priority level of traffic. SAR uses a table-driven multipath approach in order to achieve energy efficiency and fault tolerance. SAR protocol creates trees of the nodes and many paths from sink to sensor nodes are produced from these created trees. Any failure in any of the links can be repaired using an automatic path restoration procedure. The advantages of this protocol are power efficiency, fault-tolerance, and easy recovery. However, the main disadvantage, especially when there is a large number of nodes, is the huge overhead caused by maintaining tables at each sensor node[4][5][18]-[21].
Stateless Protocol for Real-Time Communication Protocol (SPEED)

SPEED is a QoS routing protocol for WSNs that provides soft real-time end-to-end guarantees introduced in [22]. SPEED provides the following real-time services: real-time unicast, real-time area-multicast, and real-time area-anycast. It strives to guarantee a certain speed for each packet in the network. Admission of packet at the network layer is based on the required speed. SPEED uses a routing module called Stateless Geographic Non-Deterministic forwarding (SNFG) and works with the following modules: Beacon Exchange, Backpressure Rerouting, Neighborhood Feedback loop, and Delay Estimation. For more details on these modules, see [4] and [22]. Each node maintains information about its neighbors and paths are found using geographic forwarding. Delay is estimated at each node by calculating the elapsed time when the node receives an ACK from a neighbor. Based on these delay values, SNFG selects the node that meets the required speed and if it fails, the node relay ratio is checked and fed back to the SNFG module.

Comparing SPEED performance with other protocols such as dynamic source routing (DSR) and ad-hoc on-demand vector routing, it has better end-to-end delay and miss ratio. It also provides congestion avoidance if the network is congested. Since SPEED control packet overhead is less and the load is evenly distributed through the SNFG, the total transmission energy is also less. However, there is not any energy metric considered in SPEED and it is not been compared with energy-aware routing protocols.

Multi-Path and Multi-SPEED routing protocol (MMSPEED)

Multi-Path and Multi-SPEED routing protocol is an extension to SPEED protocol and it is proposed in [23]. MMSPEED is a novel cross-layer routing protocol that provides services to packets based on the packet priority and uses multi-path approach to achieve a reliable transmission besides QoS provisioning. Packets are
differentiated based on two QoS domains: timeliness and reliability. Based on the packet’s reliability and timeliness requirement, packet will be serviced with a certain QoS level and certain delivery speed[6][19][20][23][24]

MMSPEED is the only protocol that achieves all of the following:

- Service differentiation and guarantee for both timeliness and reliability domains.
- Localized packet delivery without knowledge of the network topology.
- Overcoming less-reliable and unbounded transmissions over wireless links.

An enhancement to 802.11e MAC protocol is required in order to implement MMSPEED QoS mechanism such as prioritization mechanism based on Differentiated Inter-Frame Spacing (DIFS). Based on the speed value, packet will be mapped to a certain MAC priority class.

MMSPEED has many advantages as it provides QoS differentiation in both reliability and timeliness domains. However, it does not handle the tradeoff between energy and delay and it does not handle network layer aggregation.

- Energy-aware QoS Routing

Reference [25] proposes an energy-aware and QoS-based protocol that finds a least cost and energy efficient path and guarantees certain end-to-end delay. As shown in Figure 2.4, the classifier differentiates traffic into real-time and best effort queues. This protocol supports both types of traffic using a queuing model that permit service sharing between both types of traffic. The scheduler ensures that best-effort traffic should not reduce resources that are required for real-time traffic. This routing protocol is based on a multi-path approach that uses extended version of Dijkstra’s algorithm to find a list of least cost paths and chooses the path that meets end-to-end requirement [4][25].
Energy-aware QoS routing protocol has an excellent performance in terms of QoS and energy metrics. However, it only considers one real-time priority class which is only appropriate for a single real-time application and it is not suitable for multiple applications because it requires several priority classes for different real-time traffic [4][19][20][25].

![Figure 2.4 Queuing model in Energy-aware QoS routing protocol [4]](image)

2.3 ANT COLONY OPTIMIZATION

Ant colony optimization is a metaheuristic method used to solve difficult combinatorial optimization problems. Ant colony optimization is inspired by the behavior of real ants seeking the path from their colony to the food source. Real ant colonies explore the possible paths between food source and their colony while depositing pheromones through the explored path. The deposited pheromone is a communication medium to lead to the shortest path. Ants afterwards find the shortest path by following the path with the highest pheromone trails which would be the shortest path.

Inspired by ant behavior, artificial ants are used to solve many combinatorial problems by using artificial pheromone trails. Based on the amount of pheromone trails, artificial ants construct their solution to the problem to be solved
probabilistically. Moreover, artificial ants adapt their new solutions based on their previous research experience.

Ant colony optimization is used to solve many combinatorial optimization problems like the travelling salesman problem (TSP), quadratic assignment problem (QAP), vehicle routing, car sequencing problem, and network routing problem. There are several variations and extensions to the original Ant System (AS) algorithm used by Marco Dorigo that solve various computational problems based on a probabilistic approach. Some of these variants are Elitist Ant System, Rank-Based Ant System, Max-Min Ant System, and Ant Colony System (ACS) [26].

2.3.1 Ant Colony Based Routing Protocols in Wireless Sensor Networks

Ant colony based routing protocols use ant colony optimization to find the optimal routing path that has the minimum cost and it has been evident that ant colony optimization performs well in WSN. In [27], the authors propose an ant-based routing protocol called energy-efficient ant-based routing (EEABR) that finds optimal routing paths in terms of distance and energy between source nodes and sink nodes. This algorithm results in reduction in communication loads and saves energy which leads to extending the network lifetime. In [28], the authors propose a dynamic and reliable routing protocol using ant colony optimization algorithm. This protocol uses multipath data transmission to increase reliability while maximizing network lifetime. This protocol has a higher energy saving than EEABR. In [29], the authors present a self-optimized multipath routing protocol that considers energy level, delay, and velocity constraints. It also uses multipath approach to avoid congestions and in turns maximizes throughput and minimizes data loss. In [30], the authors propose an improved adaptive routing (IAR) algorithm that optimizes energy consumption, latency, throughput, and packet survival rate. However, these ant colony based routing protocols mentioned above do not consider multimedia QoS requirements such as stringent delay, delay jitter, loss rate, link quality, and link reliability in addition to minimizing energy consumption.
The authors in [31] propose an extension to IAR called multimedia-enabled improved adaptive routing (M-IAR) that targets multimedia applications in WSN. M-IAR optimizes end-to-end delay and jitter in addition to minimizing energy consumption. However, this protocol minimizes energy consumption by choosing the path that includes the least number of hops and has the shortest distance. It does not take into consideration the remaining energy levels of the sensor nodes and therefore the lifetime of the network.

Table 2.3 shows a comparison of various WSN QoS routing protocols in terms of optimization, energy efficiency, and QoS parameters. In conclusion, combining finding an optimal routing path that optimizes various QoS parameters in addition to energy efficiency is yet not well explored and implemented. In this thesis, an optimal routing protocol is developed combining QoS-based and Energy-aware routing for MWSNs using ant colony optimization.

<table>
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<td>Delay, reliability</td>
</tr>
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<td>-</td>
</tr>
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<td>Reference [28]</td>
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</tr>
<tr>
<td>IAR [30]</td>
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<td>Does not consider sensor nodes’ remaining energy level</td>
<td>Delay, packet success rate</td>
</tr>
<tr>
<td>M-IAR [31]</td>
<td>YES</td>
<td>Does not consider sensor nodes’ remaining energy level</td>
<td>Delay, delay jitter, packet success rate</td>
</tr>
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</table>
CHAPTER 3

OPTIMAL ROUTING IN MULTIMEDIA WIRELESS SENSOR NETWORKS

While many routing protocols have been developed for WSNs, there are many challenges and constraints that need to be tackled in WSNs. In this thesis, an optimal routing algorithm is proposed for WSNs that is based on ant colony optimization. This routing algorithm finds the optimal routing path while taking into consideration energy consumption, link quality, and link reliability. These parameters may be accorded varying degrees of importance depending on the application and the type of traffic along with the end-to-end delay as set by the application.

3.1 PROPOSED ANT COLONY OPTIMIZATION ALGORITHM

The proposed algorithm is an ant colony based system that finds the optimal path in WSNs. The optimal path is the one with the minimum cost in terms of energy consumption, link quality and reliability. The end-to-end delay is set as a constraint when choosing the optimal path depending on the application requirements and the type of traffic transmitted.

In ant colony optimization, each ant attempts to find the optimal path. In their journey from source node to destination node, ants move from node i to a neighbouring node j with a transition probability $P_{ij}$, defined as:

$$P_{ij}[k] = \frac{\tau_i^\alpha \eta_{ij}^\beta}{\sum_{l \in N_i[k]} \tau_l^\alpha \eta_{il}^\beta}, j \in N_i[k]$$

(3.1)
where $P_{ij}(k)$ is the probability of ant $k$ to move from node $i$ to node $j$, $\tau_{ij}$ is the pheromone value deposited on the link between node $i$ and node $j$, $\eta_{ij}$ is the heuristic value of the link between node $i$ and node $j$, $\alpha$ and $\beta$ are weights used to control the importance given to the pheromone value and the heuristic value, and $N_i[k]$ is the list of node $i$'s neighbors for ant $k$.

The pheromone value on the links depends on the likelihood that the ants pass by the link while constructing the solutions. The heuristic value depends on the calculated cost of the link.

The initial pheromone value is set to be the same for all links. The heuristic value of the link between node $i$ and node $j$ is calculated as follows:

$$\eta_{ij} = \frac{1}{C_{ij}},$$

where $C_{ij}$ is the link cost between node $i$ and node $j$ and computed as follows:

$$C_{ij} = w_1 \cdot E_{ij} + w_2 \cdot \log(Q_{ij}) + w_3 \cdot \log(R_{ij}),$$

$$E_{ij} = E_{\text{Comm}} + E_{\text{Tran}} + E_{\text{Level}}$$

$$E_{ij} = k \cdot L^n + E_{\text{bit}} \cdot N_{\text{bit}} + (I - E_j)$$

$$R_{ij} = 1 - r_{ij}$$

$E_{ij}$ is the energy cost of the link $ij$, $Q_{ij}$ is the link quality, $R_{ij}$ is the link reliability, and $w_1, w_2, w_3$ are weights the values of which are typically application-dependent. As the link quality and link reliability are multiplicative and the energy cost is additive, the log is used to make the link cost additive. The values of $E_{ij}$, $\log(Q_{ij})$, and $\log(R_{ij})$ are normalized using the following equation: $\frac{x - x_{\min}}{x_{\max} - x_{\min}}$ where $x$ is $E_{ij}, \log(Q_{ij})$, or $\log(R_{ij})$.

The energy consumption metric $E_{ij}$ is the summation of the communication energy which is defined as $E_{\text{Comm}} = k \cdot L^n$, the transmission energy which is defined as $E_{\text{Tran}} = E_{\text{bit}} \cdot N_{\text{bit}}$, and the receiver node energy level which is defined as $E_{\text{Level}} = I - E_j$. 


The communication energy cost $E_{\text{Comm}}$ is proportional to link $ij$’s distance $L$ with exponent $n$ which is the path loss exponent that varies depending on the type of clutter and obstacles faced by the communication signal during propagation. It ranges from 2 in free space model and 4 in cluttered urban environment [32][33]. $k$ is a proportionality constant. The energy transmission cost $E_{\text{trans}}$ is the packet size in bits $N_{ba}$ multiplied by Nano joule energy consumed per bit $E_{ba}$. The energy level $E_{\text{Level}}$ is determined to be the difference between the initial energy $I$ and the current energy of the receiver node $E_j$. Therefore, the node with the lower energy level has a higher cost and thus a lower probability to be chosen.

This energy consumption metric $E_{ij}$ contains different energy consumption costs. Based on the above equations, the optimal path with the minimum cost would be the one with the shortest distance which reduces communication energy cost in addition to reducing delay. Moreover, taking into account the receiver node’s energy level would result in prolonging the life time of the network. Each component of the energy consumption metric can be given different degrees of importance to achieve a finer degree of granularity.

The link quality $Q_{ij}$ is defined as the bit error rate on link $ij$. $r_{ij}$ is the percentage of time that link $ij$ is up and functioning properly. To maximize the link reliability $R_{ij}$, $r_{ij}$ is subtracted from 1 to give the link with low reliability a higher cost and the link with high reliability a lower cost.

After all ants construct their solutions, the amount of pheromone value is updated only on the links of the paths found by all ants as follows:

$$\tau_{ij} = \tau_{ij} + \sum_{k=1}^{m} \Delta \tau_{ij}[k], \forall (i, j) \in \text{Path}[k],$$

(3.7)

where $\text{Path}[k]$ is the path found by ant $k$, and $\Delta \tau_{ij}[k]$ is the amount of pheromone update on link $ij$ deposited by ant $k$ and can be computed as:

$$\Delta \tau_{ij}[k] = \frac{1}{C_{sd}[k]}, \forall (i, j) \in \text{Path}[k].$$

(3.8)
The total cost of a path is the summation of the cost of the intermediate links between a source s and a destination d. It is:

\[
C_{sd}[k] = \sum_s^d C_{ij}
\]

(3.9)

\[
= \sum \left[ w_i \cdot E_{ij} + w_2 \cdot \log(Q_{ij}) + w_3 \cdot \log(R_{ij}) \right]
\]

(3.10)

It’s important to note that the pheromone value evaporates at a rate \(\rho\) on all links in the paths constructed by all ants as follows:

\[
\tau_{ij} = \tau_{ij}(1 - \rho), \forall (i, j) \in Path[k]
\]

(3.11)

Table 3.1 represents a summary of pseudo code for ant colony optimization algorithm.

<table>
<thead>
<tr>
<th>Table 3.1. Ant Colony Optimization Pseudo code</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEGIN</td>
</tr>
<tr>
<td>Input (m, \alpha, \beta, \rho)</td>
</tr>
<tr>
<td>Set ant colony configuration</td>
</tr>
<tr>
<td>Set initial pheromone value and heuristic value</td>
</tr>
<tr>
<td>Get ant colony optimization system based on the calculated cost matrix</td>
</tr>
<tr>
<td>FOR i=1 to Pathn STEP 1 DO</td>
</tr>
<tr>
<td>FOR r=0 to iterations STEP 1 DO</td>
</tr>
<tr>
<td>Reset ants</td>
</tr>
<tr>
<td>Construct ants’ solutions</td>
</tr>
<tr>
<td>Apply local search</td>
</tr>
<tr>
<td>Update best path for (i)</td>
</tr>
<tr>
<td>Update pheromones</td>
</tr>
<tr>
<td>ENDFOR</td>
</tr>
<tr>
<td>Choose best path for (i)</td>
</tr>
<tr>
<td>ENDFOR</td>
</tr>
<tr>
<td>END</td>
</tr>
</tbody>
</table>

3.2 OPTIMAL ROUTING IN MULTIMEDIA WIRELESS SENSOR NETWORKS

Consider a WSN with \(N_S\) sensor nodes and \(S\) sink nodes. These sensor nodes are scattered in an ad-hoc manner to cover an area of interest.
$L$ kilometers by $W$ kilometers to monitor a military event and help in rescue operations. All sensor nodes know their exact physical location (e.g. GPS-aware) and they broadcast it periodically to other sensor nodes using small control packets. Sink nodes have higher processing capabilities, transmission range, transmission bit rate, and energy level than other sensor nodes.

There are two data delivery models used in WSNs: query-driven and event-driven. In a query-driven data delivery model, data is pulled by the sink from specific sensor nodes. While in an event-driven data delivery model, data is pushed to the sink from a group of nodes in the area where an event has occurred.

In MWSNs, multimedia data delivery is constrained with certain QoS such as high bandwidth, low error rate, and delay. Using a single hop communication would result in using low bandwidth and high error rate links. Moreover, the capabilities of sensor nodes in WSNs are limited in terms of transmission range. Therefore, a multi-hop communication is used to transmit data from a source node $N_a$ to a sink node $N_b$. Using a multi-hop communication results in increasing latency due to queuing delay introduced at each hop. This problem can be solved by choosing more efficient routing paths with a delay constraint set by the application used. In the proposed ant colony optimization algorithm, optimal routing paths are found between sensor nodes optimizing energy consumption, link quality, and link reliability in addition to setting delay as a constraint.

Figure 3.1 illustrates event-driven data delivery model in WSN with sensor nodes and sink nodes and Figure 3.2 illustrates a query-driven data delivery model in WSN.
Figure 3.1 Query-driven Data Delivery Model in WSNs

Figure 3.2 Event-driven Data Delivery Model in WSNs
The optimal path is found using the ant colony optimization algorithm and it is the one that has the minimum cost in terms of energy consumption, link quality, and link reliability based on the calculations explained in the previous section.

The end to end delay $T_{\text{total}}$ for an optimal path with $n$ nodes is calculated as follows:

$$T_{\text{total}} = \sum_{i=1}^{n-1} (T_p + T_t + T_q),$$

(3.12)

where $n$ is the number of nodes in the path, $T_p$ is the propagation delay, $T_t$ is the transmission delay, and $T_q$ is the queuing delay at node $x$.

$$T_p = \frac{L_{ab}}{P_s}$$

(3.13)

where $L_{ab}$ is the distance between $N_a$ and $N_b$ and $P_s$ is the propagation speed.

$$T_t = \frac{N_{\text{bit}}}{R_b}$$

(3.14)

where $N_{\text{bit}}$ is the packet size in bits and $R_b$ is the transmission bit rate.

Every sensor node has initial energy set to $I$. For every packet transmitted, energy of the transmitted node is reduced by:

$$\Delta E_{ij} = N_{\text{bit}}(E_{\text{bit}} + \epsilon \cdot L_{ij})$$

(3.15)

where $N_{\text{bit}}$ is the packet size, $E_{\text{bit}}$ is equal to electronics energy in nJ/bit, $\epsilon$ is transmitter amplifier in nJ/bit/m$^\gamma$, $\gamma \in [2, 4]$, and $L_{ij}$ is the distance between node $i$ and node $j$ in meters [32][33].

In MWSN simulation, events are generated randomly from random sensor nodes at an arrival rate $\lambda$. For every event, video frames are generated from the source node at a rate $F_p$ and they are packetized based on the packet size. Deadlines are set for every video frame and optimal paths are found using the proposed ant colony optimization algorithm. If a video frame arrives after the deadline, it would miss its scheduled playout time at the receiver node and it will be of no use and thus discarded. This would result in unnecessary usage of network resources and unnecessary queuing delay. To avoid transmitting packets which would be discarded
later on, a calculation of the possibility for this packet to meet the deadline is performed by the transmitting sensor node before transmitting any packets. Every node keeps track of its average queuing delay and the packet remaining delay is calculated based on the remaining propagation, remaining transmission, and total average queuing delay in the path. If the packet will not meet the deadline based on calculating the remaining delay, the packet is dropped. Due to the importance of meeting deadlines and to reduce packet loss, transmission of packets at each sensor node’s queue is set to be based on earliest deadline first as shown in Figure 3.3.

At the end of the simulation, statistics are collected which include: node’s average queuing delay, node’s remaining energy, loss percentage per event, total loss percentage, packet end to end delay, and delay jitter.

Table 3.2 represents a simplified version of simulated MWSN in pseudo code:
BEGIN
Input $R_b, \lambda, F_p, \text{sim\_time}, N_s$
$s=0$
FOR $i=1$ to $N_s$ STEP 1 DO
  Input node $i$'s $x_i$ and $y_i$ coordinates
ENDFOR
FOR $i=1$ to $N_s$ STEP 1 DO
  FOR $j=i+1$ to $N_s$ STEP 1 DO
    Calculate distance $L$ between node $i$ and node $j$
  ENDFOR
ENDFOR
WHILE $s<\text{sim\_time}$ DO
  Generate event $e$ randomly at rate $\lambda$ using poisson distribution
  Choose source node $n$ randomly using uniform distribution
  Generate video frames at a rate $F_p$ and set deadlines
  Get optimal paths using ant colony optimization algorithm
  FOR $i=1$ to $N_s$ STEP 1 DO
    Reorder packets in node $i$'s queue based on earliest deadline first
    Get first packet in node $i$'s queue $P_0$
    Calculate $P_0$'s possibility of meeting its deadline
    IF packet can meet its deadline THEN
      update $P_0$ delay
      update average queuing delay of node $i$
      depart $P_0$ from node $i$'s queue
      deduct energy at node $i$
      IF node $i$ is not the last node in $P_0$'s routing path DO
        add $P_0$ to the queue of the next node in $P_0$ routing path
      ENDIF
    ELSE
      drop $P_0$ from node $i$'s queue
      increment number of dropped packets per event by 1
      increment number of dropped packet through simulation by 1
    ENDIF
  ENDIF
ENDFOR
ENDFOR
update s
ENDWHILE

Collect statistics
Nodes’ Average Queuing Delay
Nodes’ Remaining Energy
Loss Percentage per event
Loss Percentage for the network
Packet End-to-End Delay
Calculate Delay Jitter per event

END
CHAPTER 4

SIMULATION AND RESULTS ANALYSIS

4.1 PROPOSED ANT COLONY OPTIMIZATION ALGORITHM

Using the proposed routing algorithm, the optimal path with the minimum cost in terms of energy saving, link quality, and link reliability is found. There are many parameters involved in ant colony optimization such as number of ants $m$, the weights of $\alpha$ and $\beta$, and evaporation rate $\rho$. In what follows, a study of the impact of these parameters on the time it takes to find the optimal path is explored. To do so, the program is run with different number of nodes. In each study, three iterations are executed for each run and the program is run 100 times which satisfies a 95% confidence interval.

4.1.1 Number of Ants $m$

Depending on the number of nodes in the WSN, the number of ants is set. Based on the results of the program runs, it is found that increasing the number of ants gives better results as it would ensure getting the optimal path instead of a sub-optimal one. Increasing the number of ants results in an increase in the probability of finding the optimal path from the 1st iteration. In addition, it results in a decrease in the probability of getting a sub-optimal path. However, increasing the number of ants results in an increase in the time to find the optimal solution.

As shown in Figure 4.1 and Figure 4.2, doubling the number of ants results in doubling the time needed to find the optimal solution. Moreover, the probability of finding optimal solution in the 1st iteration increased from 75% to 93% and the probability of getting a sub-optimal solution decreased from 11% to 0%.
Figure 4.1 The Effect of increasing number of ants on Optimal Path Percentage per iteration

Figure 4.2 The Effect of increasing number of ants on computation time per iteration
4.1.2 $\alpha$ parameter

Increasing $\alpha$ results in getting unsatisfactory results as the solutions found may not be optimal ones. The reason behind this is the fact that increasing $\alpha$ means increasing the importance of following the pheromone trails very early on more than the heuristic value which is the real cost of the paths. Therefore, the probability of transition to a neighboring node will be more influenced by the pheromone value than by the heuristic value. To find the optimal path, the heuristic value should be given a higher importance than pheromone value.

4.1.3 $\beta$ parameter

In this section, the effect of increasing $\beta$ on a graph with 4 nodes and on a graph with 20 nodes is tested and analyzed. In addition, the effect of increasing the evaporation rate $\rho$ is tested in each case.

First, a test of increasing $\beta$ on a graph with 4 nodes where alpha is 1 and evaporation rate is 0.2 is performed. As shown in Figure 4.3, increasing $\beta$ from 1 to 2 results in slight decrease in the probability of finding the optimal path in the first iteration but had no effect on the probability of finding a sub-optimal path. However, increasing $\beta$ to 5 results in a significant increase in the probability of finding the sub-optimal path and decreases the probability of finding the optimal path in the first iteration.

Figure 4.4 shows the effect of increasing $\beta$ on a graph with 4-nodes where $\alpha$ is 1 and evaporation rate $\rho$ is 0.5. There is a slight decrease in the probability of finding the optimal path in the first iteration when $\beta$ is increased from 1 to 2 and a slight increase in the probability of finding the sub-optimal path. On the other hand, the change is significant when $\beta$ is increased to 5.
Figure 4.3 The effect of increasing $\beta$ with $\rho=0.2$ in 4-node graph

Figure 4.4 The effect of increasing $\beta$ with $\rho=0.5$ in 4-node graph
Figure 4.5 shows the effect of increasing $\beta$ on a graph with 20 nodes where $\alpha$ is 1 and the evaporation rate $\rho$ is 0.2. In a 20-vertices graph, increasing $\beta$ from 1 to 2 results in an increase in the probability of finding the optimal path in the first iteration from 45% to 76%. Moreover, it results in a decrease in the probability of finding the sub-optimal path from 18% to 13%. In Figure 4.6, a further analysis is represented for the effect of increasing $\beta$ on a graph with 20 nodes where $\alpha$ is 1 and evaporation rate $\rho$ is 0.5. Looking at Figure 4.6, the best $\beta$ value is 2 as it has the highest probability of finding optimal path in the first iteration and has the least probability of finding sub-optimal path. While increasing $\beta$ to 5 results in reaching stagnation very fast and it is evident because there are no optimal paths found in the second or third iterations. It only finds the optimal path in the first iteration with a very low probability or finds a sub-optimal path.

![Figure 4.5 The effect of increasing $\beta$ with $\rho=0.2$ in 20-node graph](image_url)
4.1.4 $\rho$ parameter

Figure 4.7 and 4.8 represent the effect of increasing the evaporation rate $\rho$ in 4-nodes graph where $\beta$ is 1 in Figure 4.7 and $\beta$ is 2 in Figure 4.8. Increasing $\rho$ (0.2 to 0.5) results in decreasing the probability of finding the optimal path in the first iteration. Moreover, it results in an increase in the probability of finding the sub-optimal paths. However, the effect is minimal when $\beta$ is 2.

Figure 4.9 and Figure 4.10 show the effect of increasing the evaporation rate $\rho$ in 20-nodes graph where $\beta$ is 1 in Figure 4.9 and $\beta$ is 2 in Figure 4.10. Increasing evaporation rate $\rho$ would follow the same pattern mentioned in 4-nodes graph which is a decrease in the probability of finding the optimal path in the first iteration and an increase in sub-optimal probability. However, increasing sub-optimal probability has less effect in 20-nodes graph compared to 4-nodes graph. Moreover, as shown in Figure 4.10, the effect of increasing the evaporation rate $\rho$ when $\beta$ is 2 is much less when compared to 4-vertices graph.
Figure 4.7 ρ effect when α=1 and β=1

Figure 4.8 ρ effect when α=1 and β=2
Figure 4.9 $\rho$ effect when $\alpha=1$ and $\beta=1$

Figure 4.10 $\rho$ effect when $\alpha=1$ and $\beta=2$
4.2 SIMULATION AND RESULTS OF OPTIMAL ROUTING IN MWSNs

In the simulation of MWSN, it is assumed that there are $N_s$ sensor nodes and all sensor nodes have same capabilities except the sink node which has a higher processing capability and a higher energy level. In addition, all sensor nodes are location-aware (e.g. GPS, localization methods, etc.) and their exact $x$ and $y$ coordinates are known. Events are generated in a Poisson distribution at an arrival rate $\lambda$ and for every event, the source node is determined based on a uniform random distribution. For every event, video frames are generated from the source node at a rate $F_p$. The proposed ant colony algorithm is executed by the sink node to find the optimal paths for all packets.

It is assumed that the type of traffic is video and every packet is equal to one video frame. For simplicity, retransmission of packets is not considered and a strong forward error correction is assumed. Packet delay is calculated based on transmission delay and queuing delay. Propagation delay is too small and it is negligible compared to transmission delay. Figure 4.11 illustrates MWSN simulation environment.
Various simulation studies are performed to analyze the effect of various parameters such as transmission bit rate $R_b$, event generation rate $\lambda$, and video frame encoding rate $F_p$ on sensor nodes’ average queuing delay, loss percentage per event, total loss percentage, packet end-to-end delay, and delay jitter. In each simulation study, MWSN is observed for $s$ seconds and for every event, video frames are generated at $F_p$ in order to transmit $v$ seconds long video from the event source to the sink.
4.2.1 Effect of Transmission Bit Rate $R_b$

In this study, all simulation parameters are fixed and the effect of increasing transmission bit rate $R_b$ is evaluated. Event generation rate $\lambda$ is set to be equal to one event per second and video frame encoding rate $F_v$ is set to be equal to 10 frames per second.

Figure 4.12 represents the effect of increasing transmission bit rate on average queuing delay per node and it is clear that by increasing $R_b$, the average queuing delay is reduced significantly. Subsequently, the loss percentage per event will decrease as shown in Figure 4.13.
Figure 4.14 shows the end-to-end delay per video frame and as $R_b$ increases, the end-to-end delay decreases. This is due to the fact that the transmission delay is inversely proportional to $R_b$ and thus when $R_b$ increases, transmission delay decreases. In addition, the average queuing delay per sensor node also decreases due to faster transmission of packets as shown in Figure 4.12.

Figure 4.15 shows the delay jitter decreases as $R_b$ increases. In addition, the variation in delay jitter between frames is reduced when $R_b$ increases.
4.2.2 Effect of Event Generation Rate $\lambda$

In this study, all simulation parameters are fixed and the effect of increasing event generation rate $\lambda$ is evaluated. Transmission bit rate $R_t$ is set to be equal to 0.5 Mbps and video frame encoding rate $F_v$ is set to be equal to 10 frames per second.

As shown in Figure 4.16, increasing event generation rate $\lambda$ results in increasing average queuing delay. This leads to delaying many packets beyond the deadline set and results in increasing loss percentage per event as shown in Figure 4.17.

![Figure 4.16 Effect of $\lambda$ on average queuing delay per sensor node](image)

![Figure 4.17 Effect of $\lambda$ on loss percentage per event](image)
Figure 4.18 shows the end-to-end delay per packet where the end-to-end delay per packet increases as $\lambda$ increases due to the increase in queuing delay and the variation in delay jitter increases as shown in Figure 4.19.

![Figure 4.18 Effect of $\lambda$ on end-to-end delay per packet](image)

![Figure 4.19 Effect of $\lambda$ on delay jitter per packet](image)

4.2.3 Effect of Video Frame Encoding Rate $F_p$

In this study, all simulation parameters are fixed and the effect of increasing video frame encoding rate $F_p$ is evaluated. Event generation rate $\lambda$ is set to be equal to 1 event per second and transmission bit rate $R_b$ is set to be equal to 0.5 Mbps.
In Figure 4.20, the average queuing delay increases with the increase of video frame encoding rate in most of the nodes. While in other nodes, the average queuing delay decreases or stays the same and this is because after reaching certain average queuing delay during simulation, the sensor node would drop packets which are expected to miss the deadline based on the estimation of remaining queuing and transmission delay in the path. When the loss percentage per event increases, the nodes’ average queuing delay decreases or stays the same. Figure 4.21 shows the large loss percentage increase while increasing frame encoding rate.
Figure 4.22 shows the end-to-end delay per packet and Figure 4.23 shows the delay jitter. It is noticeable that the end-to-end delay decreased when $F_p=30$. However, this decrease is the result of the large loss percentage which results in either transmitting packets with very low queuing delay or dropping packets. The end-to-end delay when $F_p=30$ is equal to transmission delay for most of the packets and there are only few packets experienced a queuing delay as shown in Figure 4.22. At a transmission bit rate equal to 0.5 Mbps, generating 30 frames per second results in high loss and therefore is not acceptable. In order to generate at 30 frames per second, the transmission bit rate should be higher than 0.5 Mbps.
4.2.4 Impact of Frame Encoding Rate and Transmission Bit Rate

In order to improve the quality of the video transmitted, frame encoding rate should be high. However, as explained earlier, increasing frame encoding rate would result in increasing average queuing delay and loss percentage. In this section, a study of increasing transmission bit rate from 0.5 Mbps to 1 Mbps for a frame encoding rate equal to 20 frames per second is performed.

Figure 4.24 shows the improvement in average queuing delay per node and Figure 4.25 shows the improvement in loss percentage per event. It is evident that increasing transmission bit rate would result in a significant decrease in average queuing delay at all nodes in addition to a decrease in loss percentage per event. Figure 4.26 and Figure 4.27 shows that end-to-end delay and delay jitter decreases when transmission bit rate increases.

![Figure 4.24 Effect of $R_b$ on average queuing delay per sensor node for $F_r=20$](image)

Figure 4.24 Effect of $R_b$ on average queuing delay per sensor node for $F_r=20$
Figure 4.25 Effect of $R_s$ on loss percentage per event for $F_r = 20$

Figure 4.26 Effect of $R_s$ on end-to-end delay for $F_r = 20$

Figure 4.27 Effect of $R_s$ on delay jitter for $F_r = 20$
In summary, the effects of transmission bit rate, event generation rate, and frame encoding rate on the total loss percentage, average queuing delay, and average end-to-end delay are summarized in Table 4.1.

<table>
<thead>
<tr>
<th>Study Parameters</th>
<th>Average Queuing Delay</th>
<th>Total Loss %</th>
<th>Average End-to-End Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R_b Effect</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_b=0.5 Mbps</td>
<td>1.138</td>
<td>8%</td>
<td>38.094</td>
</tr>
<tr>
<td>R_b=1 Mbps</td>
<td>0.349</td>
<td>0%</td>
<td>18.616</td>
</tr>
<tr>
<td>R_b=1.5 Mbps</td>
<td>0.137</td>
<td>0%</td>
<td>11.704</td>
</tr>
<tr>
<td><strong>λ Effect</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>λ=1</td>
<td>1.138</td>
<td>8%</td>
<td>38.094</td>
</tr>
<tr>
<td>λ=2</td>
<td>2.507</td>
<td>23%</td>
<td>42.485</td>
</tr>
<tr>
<td>λ=4</td>
<td>4.716</td>
<td>28%</td>
<td>50.163</td>
</tr>
<tr>
<td><strong>F_p Effect</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F_p=10</td>
<td>1.138</td>
<td>8%</td>
<td>38.094</td>
</tr>
<tr>
<td>F_p=20</td>
<td>1.993</td>
<td>38%</td>
<td>37.114</td>
</tr>
<tr>
<td>F_p=30</td>
<td>1.830</td>
<td>63%</td>
<td>32.061</td>
</tr>
</tbody>
</table>
4.3 NETWORK LIFETIME

One of the challenges in MWSN is balancing energy consumption among sensor nodes in the network to avoid coverage holes and thus prolonging the network lifetime. As previously mentioned, the energy level of sensor nodes is one of the metrics used in finding the optimal path in the proposed ant colony algorithm and it is important for prolonging the network lifetime. In this section, a study is performed on the effect of increasing the importance of $E_{\text{Level}}$ on MWSN simulation. When the weight of $E_{\text{Level}}$ metric changes, the link cost changes and subsequently the optimal paths differ during MWSN simulation.

Table 4.2 shows the loss percentage per event and Table 4.3 shows the average queuing delay and remaining energy per node. Table 4.4 summarizes total loss, average end-to-end delay, and average queuing delay.

Table 4.2. Loss Percentage

<table>
<thead>
<tr>
<th>Events</th>
<th>$w_1$</th>
<th>$w_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E0</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E1</td>
<td>2.07%</td>
<td>2.08%</td>
</tr>
<tr>
<td>E2</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E3</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E4</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E5</td>
<td>0.36%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E6</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E7</td>
<td>0.00%</td>
<td>0.44%</td>
</tr>
<tr>
<td>E8</td>
<td>26.85%</td>
<td>23.15%</td>
</tr>
<tr>
<td>E9</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E10</td>
<td>0.52%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E11</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>E12</td>
<td>7.58%</td>
<td>4.55%</td>
</tr>
<tr>
<td>E13</td>
<td>0.79%</td>
<td>0.79%</td>
</tr>
<tr>
<td>E14</td>
<td>8.26%</td>
<td>5.56%</td>
</tr>
<tr>
<td>E15</td>
<td>3.96%</td>
<td>10.00%</td>
</tr>
</tbody>
</table>
### Table 4.3. Average queuing and remaining energy per sensor node

<table>
<thead>
<tr>
<th>Sensor Node</th>
<th>Average Queuing Delay (msec)</th>
<th>Remaining Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w₁</td>
<td>w₂</td>
</tr>
<tr>
<td>N₀</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N₁</td>
<td>8.23821</td>
<td>7.91058</td>
</tr>
<tr>
<td>N₂</td>
<td>0.178919</td>
<td>0.31594</td>
</tr>
<tr>
<td>N₃</td>
<td>2.81341</td>
<td>2.84357</td>
</tr>
<tr>
<td>N₄</td>
<td>0</td>
<td>0.179328</td>
</tr>
<tr>
<td>N₅</td>
<td>1.99102</td>
<td>2.90574</td>
</tr>
<tr>
<td>N₆</td>
<td>4.7831</td>
<td>4.47812</td>
</tr>
<tr>
<td>N₇</td>
<td>0.350433</td>
<td>0.455635</td>
</tr>
<tr>
<td>N₈</td>
<td>0.5273</td>
<td>0.934937</td>
</tr>
<tr>
<td>N₉</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N₁₀</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N₁₁</td>
<td>0.62035</td>
<td>0.62035</td>
</tr>
</tbody>
</table>
When the weight of $E_{\text{Level}}$ increases and the weight of $E_{\text{Tran}}$ and $E_{\text{Comm}}$ decrease, the proposed ant colony algorithm will favor paths that include sensor nodes with high energy level and it may even be longer paths. Transmitting packets through other paths involving more nodes would result in balancing energy consumption in the network and prolonging the life time of the network. However, it results in higher energy consumption if the paths chosen are longer ones. In addition, the average queuing delays per node increases as many packets will pass through more nodes. Average packet end-to-end delay increases due to the increase in transmission delay and in queuing delay.

### 4.4 CASE STUDY

The proposed ant colony optimization algorithm can be run offline periodically to have the optimal paths ready to be used anytime or it can be run online before every event to reactively discover the optimal path. A study of offline and online approaches using ant colony algorithm is performed.
In this case study, ant colony algorithm is run after every event to find the optimal paths for the packets to be transmitted in MWSN simulation. Running ant colony after every event would result in updating the path costs and finding a new optimal path. In this simulation, transmission bit rate is set to be equal to 0.5 Mbps and event generation rate to be equal to 1 event per second.

This simulation is run for $F_p=10$ and $F_p=20$ and the results are shown in Table 4.5 and Table 4.6. This case study’s results show that the total loss percentage decreased in comparison with periodic running of ant colony algorithm. In periodic run with $F_p=10$, the total loss is 8.11% while running ant colony per event results in a total loss equal to 2.80%. In periodic run with $F_p=20$, the total loss is 37.45% while running ant colony per event results in a total loss equal to 23.86%. Moreover, in this case study, the total network remaining energy is higher than periodic run of ant colony case and thus longer lifetime of the network.

Although running the proposed ant colony algorithm for every event results in a decrease in loss percentage and increase in network lifetime, it is at the expense of extra computation time.

<table>
<thead>
<tr>
<th>Events</th>
<th>Loss Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>E0</td>
<td>0.00% 19.20%</td>
</tr>
<tr>
<td>E1</td>
<td>2.07% 14.41%</td>
</tr>
<tr>
<td>E2</td>
<td>0.00% 6.06%</td>
</tr>
<tr>
<td>E3</td>
<td>0.00% 15.15%</td>
</tr>
<tr>
<td>E4</td>
<td>0.00% 10.69%</td>
</tr>
<tr>
<td>E5</td>
<td>0.36% 9.82%</td>
</tr>
<tr>
<td>E6</td>
<td>0.00% 15.14%</td>
</tr>
<tr>
<td>E7</td>
<td>0.00% 10.40%</td>
</tr>
<tr>
<td>E8</td>
<td>13.00% 16.01%</td>
</tr>
<tr>
<td>E9</td>
<td>0.00% 15.75%</td>
</tr>
<tr>
<td>E10</td>
<td>0.52% 28.84%</td>
</tr>
<tr>
<td>E11</td>
<td>0.00% 15.63%</td>
</tr>
<tr>
<td>E12</td>
<td>7.58% 29.57%</td>
</tr>
<tr>
<td>E13</td>
<td>0.79% 28.11%</td>
</tr>
<tr>
<td>E14</td>
<td>8.26% 30.33%</td>
</tr>
<tr>
<td>E15</td>
<td>3.96% 21.61%</td>
</tr>
</tbody>
</table>
Table 4.6. Average queuing and remaining energy

<table>
<thead>
<tr>
<th>Sensor Node</th>
<th>Average Queuing Delay (msec)</th>
<th>Remaining Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fp=10</td>
<td>Fp=20</td>
</tr>
<tr>
<td>N0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N1</td>
<td>8.23821</td>
<td>2.08185</td>
</tr>
<tr>
<td>N2</td>
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<td>3.22622</td>
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<tr>
<td>N3</td>
<td>2.81341</td>
<td>3.01922</td>
</tr>
<tr>
<td>N4</td>
<td>0</td>
<td>3.18176</td>
</tr>
<tr>
<td>N5</td>
<td>1.99102</td>
<td>0.689308</td>
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<tr>
<td>N6</td>
<td>4.7831</td>
<td>3.19749</td>
</tr>
<tr>
<td>N7</td>
<td>0.350433</td>
<td>4.10955</td>
</tr>
<tr>
<td>N8</td>
<td>0.5273</td>
<td>0.287074</td>
</tr>
<tr>
<td>N9</td>
<td>0</td>
<td>0.530125</td>
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<tr>
<td>N10</td>
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<tr>
<td>N11</td>
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<td>5.39805</td>
</tr>
<tr>
<td>N12</td>
<td>5.41681</td>
<td>4.90342</td>
</tr>
<tr>
<td>N13</td>
<td>3.68349</td>
<td>2.24373</td>
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<tr>
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<td>N15</td>
<td>1.84199</td>
<td>0.496682</td>
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<td>N16</td>
<td>1.27169</td>
<td>3.79442</td>
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<tr>
<td>N18</td>
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<td>1.68344</td>
</tr>
<tr>
<td>N19</td>
<td>0</td>
<td>4.2237</td>
</tr>
</tbody>
</table>
CHAPTER 5

CONCLUSIONS

An optimal routing protocol that is energy and QoS-aware is developed for MWSN. This routing protocol uses ant colony optimization to find the optimal routing path between sensor nodes and the sink node. Ant colony optimization algorithm minimizes energy consumption and maximizes link quality, link reliability, and network lifetime. The energy consumption used considers communication energy cost, transmission energy cost, and the sensor node’s energy level. This results in choosing the optimal path that minimizes energy consumption and prolongs the lifetime of the network. Moreover, the optimal path has a high link quality and reliability. Depending on the application and traffic type, different weights may be given to energy, link quality, and link reliability metrics.

A study of this algorithm is performed on different network sizes and this algorithm is further analyzed for the effect of changing the number of ants $m$, pheromone value importance $\alpha$, the heuristic value importance $\beta$, and the evaporation rate $\rho$ on the probability of finding the optimal path and the time taken to find the optimal path.

Increasing the number of ants $m$ increases the probability of finding the optimal path but results in increasing the computation time. Increasing $\alpha$ means increasing the importance of following pheromone trails and would result in unsatisfactory path. Increasing $\beta$ means increasing the importance of the heuristic value which is the real cost of the path. Increasing $\beta$ to 2 increases the probability of finding the optimal path in the first iteration. Increasing $\beta$ to 5 results in stagnation which is a stage where no more paths are explored and in this case, the probability of finding the optimal path decreases. Increasing $\rho$ would result in faster evaporation of pheromone trails and decreases the probability of finding the optimal path.
A simulation of MWSN that use the proposed ant colony optimization in finding the optimal path is performed. An evaluation of the effect of transmission bit rate, event generation rate, and frame encoding rate on various performance metrics is examined and analyzed.

Increasing the transmission bit rate would result in decreasing the average queuing delay per node, the loss percentage, the end-to-end delay and the delay jitter. Increasing the event generation rate would result in increasing the queuing delay per node, the loss percentage, the end-to-end delay, and the delay jitter. Increasing frame encoding rate is required for good quality video and increasing the frame encoding rate results in an increase in loss percentage. Therefore, at high frame encoding rates, a high transmission bit rate is required to decrease the loss percentage.

Increasing the importance attributed to sensor nodes’ remaining energy levels results in balancing energy consumption among sensor nodes in the network to avoid coverage holes and thus prolonging the network lifetime. However, it may result in choosing longer paths and thus higher energy consumption and longer queuing delay. Moreover, running the ant colony algorithm more often results in increasing the network lifetime and decreasing the frame loss percentage. However, it is at the expense of extra computation time.

Future work directions include studying optimal routing in MWSN where sensor nodes are mobile and their location can change at any time in addition to studying MWSN where all sensor nodes have different capabilities in terms of transmission range, energy level, and computation capabilities.
REFERENCES


VITA

Hiba Al-Zurba, a married lady with two daughters, was born on November 23rd, 1985 in Kuwait. In 2003, she graduated from Halifax West High School (Halifax, NS, Canada). Subsequently, she obtained a Bachelor of Computer Science (B.CSc) from Dalhousie University (Halifax, NS, Canada) in 2006. Afterwards, she obtained a Master of Education (M.Ed.) in Curriculum Studies with concentration in Educational Technology from Mount Saint Vincent University (Halifax, NS, Canada) in 2007. She received several undergraduate scholarships and awards (e.g. Dalhousie University Entrance Scholarship, In-course Scholarship, Sexton Scholarship).

Hiba Al-Zurba taught at Sharjah University as a teaching assistant for one year (2007-2008). In September 2008, she joined the Master of Science in Computer Engineering program at the American University of Sharjah (AUS). Meanwhile, she worked as a teaching assistant at AUS and as an adjunct faculty member at Dubai Mens’ College (Higher Colleges of Technology).