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Congestion Free Routing Mechanism for IoT-enabled Wireless Sensor Networks for Smart Healthcare Applications

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***Abstract*—Recently, the Internet of Things (IoT) topology has used to collect physical, physiological, vital signs of patients in consumer-centric e-health or consumer' wellness care services. In such healthcare systems, varieties of medical sensors are attached to the patients to collect vital signs from those who are under observation. The data gathering process in IoT-enabled Wireless Sensor Network (WSN) suffers from the congestion problem. The effect of this translates on missing packets, a decrease of reliability and throughput degradation in IoT-enabled WSN. This paper proposes a distributed congestion control algorithm for IoT-enabled WSNs to effectively resolve the congestion for healthcare applications. The proposed scheme alleviates congestion by a priority-based data routing strategy. Furthermore, this paper presents a priority queue based scheduling scheme for better reliability. We analyze the properties of the proposed congestion control mechanism mathematically and validate its performance through extensive simulation and real-life experiments. The application of this work can be used to an early warning system in detecting abnormal heart rate, blood pressure, ECG, EMG in the hospital/home care environment to the state-of-art diagnosis.**

***Index Terms*— Healthcare system, Internet of Things (IoT), Wireless Sensor Network (WSN), Congestion Control.**

I. Introduction

RECENT advances in microelectronics fabrication and Very Large-Scale Integrated (VLSI) circuit technologies allowed the development of smart electronics devices with the capability of sensing, processing, and transmission [1]-[5]. These electronic devices are combined to form a network that achieves some shared objectives. They interact with the physical world pervasively with the aid of enhanced communication protocols and distributed intelligence, which constitute a novel paradigm called the Internet of Things (IoT). The IoT is possible through the integration of several heterogeneous network infrastructures such as Radio Frequency Identification (RFID) systems, Machine-to-Machine (M2M) communication systems, Wireless Sensor Networks (WSNs) and much more. WSNs are used for tracking the status of the real-world object. All these different network infrastructures together compose the backbone network infrastructure for IoT. WSN has a lot of unique challenges and constraints such as self-management, energy limitation, congested packet transmissions, ad hoc deployment, unattended operation, etc. This unique infrastructure nature of WSN demands a protocol designed that should fit for its specialties, especially for the consumer-centric e-health or consumer' wellness care services.

In the field of consumer electronics, several features in the IoT-based Healthcare aware Wireless Sensor Networks (HWSNs) implementation are considered, such as (1) Quality of Service (QoS) (2) low cost, (3) low power consumption, (4) easy integration, and (5) low complexity [6], [7]. The primary challenge of HWSNs is congestion control during physiological data routing that helps to provide a high QoS. Congestion control in HWSNs is much more complicated compared to the congestion control in other traditional networks. In HWSNs, different types of congestion may occur at different points and locations of the networks. In a sensor network, deployed sensor nodes have limited resources for computing, bandwidth, memory storage, energy supply, and communication [8-10]. The event-driven character of the network channels to an unpredictable communication load within the network. In healthcare applications, the network stocks low traffic load when there are no special events but the happening of medical emergencies may generate burst traffic which leads to congestion in the network [11], [12]. Therefore, overloaded nodes exhaust more energy than other sensor nodes. Furthermore, they are subject to premature death because of heavy traffic. Once the nodes with heavy load die, some other sensor nodes should relay data to the gateway node originally forwarded by these dead nodes. It leads to dynamical changes in the routing paths, as well as creates congestion within the other sensor nodes. As a result, doctors and nurses cannot receive update information from patients under observation [13], [14]. On the other hand, in healthcare applications, sensors attached to the patient's body sense and transmit vital signs (such as the heart rate and breathing condition) very frequently and simultaneously to the gateway node. Due to dynamical changes of routing paths, huge data loads can quickly generate congestion within the network. Congestion creates considerable delays within the network. Therefore, data packets are likely to be lost due to congestion and a high amount of energy is consumed in forwarding packet toward the gateway node. A lot of research has been conducted to enhance the performance of the HWSNs. A congestion avoidance scheme known as Relaxation Theory

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with Max-Min Fairness (RT-MMF) is presented to avoid congestion in the wireless body sensor network [15]. A congestion avoidance scheme called Adaptive Duty-cycle Based Congestion Control (ADCC) has proposed to handle congestion in home automation networks which use both the resource control and traffic control mechanize to mitigate packet loss [16]. However, existing congestion control mechanize does not perform well in the health care application because they are unable to reduced transmission delay during vital signs transmission from the monitoring patients to medical staff. Also, existing approaches used huge message overhead to control burst traffic within the network that significantly reduces network lifetime. Moreover, many approaches are already available in the literature on congestion control routing for WSNs. However, the consumer-centric IoT environment includes heterogeneous sensor devices. Hence, the traditional congestion control approaches for WSNs must be enhanced to suit the WSNs in the consumer-centric IoT environment. Thus, congestion control is one of the most critical problems in the designing and implementation of WSNs, especially for the consumers-centric e-health or consumer' wellness care services where a vital event may occur any time and on arbitrary nodes within the network.

To address these issues, this paper proposes a distributed traffic-aware congestion control scheme for IoT-enabled WSNs. In the proposed scheme, deployed sensor nodes are divided into different levels and transmit their sensing information through the congestion-free path. The proposed algorithm minimizes the total energy consumption of the network and improves the Quality of Services (QoS). For efficient and reliable communication in IoT networks, we aim to frame a cross-layer design that spans different layers, i.e., stable congestion-free routing in the network layer, effective access control and transmission power control in MAC sub-layer, reliable and light-weight transmission control at the transport layer, and a middle-ware technique to integrate the wireless personal area network application subnet with the Internet backbone. In this paper, we propose a congestion-free data forwarding method at the network layer.

The rest of the paper is organized as follows. Section II introduces related works. Section III presents the network model and problem formulation. Section IV gives an analytical description of the proposed congestion control mechanism. Theoretical analysis has presented in Section V. Section VI presents experimental results and analysis and Section VII finally concludes this paper highlighting the main conclusions of the study.

II. Related Works

Congestion control is a primary objective in several multi-hop WSNs especially in healthcare applications where deployed sensor nodes continually sense data from the monitoring patients and forward this information to the Base Station (BS) to satisfy certain requirements of the medical staff. This section provides an overview of the most recent existing research works related to congestion control in WSNs.

A Fairness-Aware Congestion control scheme (FACC) [7] was proposed by Huang et al. where a rate-based fairness aware congestion control was reported. This approach divides all intermediate sensor nodes into near-source and near sink nodes. It detects congestion according to the packet loss rate at the sink node. Kang et al. [8] proposed a Topology Aware Resource Adaptation (TARA) scheme to alleviate congestion in WSNs. This approach focuses on the adaptation of the extra resources to control congestion within the network. This approach activates a particular sensor node whose mode is sleeping to form a new topology. A new topology of the network can control the increased traffic of the network. It puts a large overhead for the large scale WSNs. On the other hand, Sergiou et al. [17] proposed a Hierarchical Tree Alternative path (HTAP) algorithm for congestion control in WSN. It builds a source-based tree to find all possible routes to the sink. HTAP selects the least buffer node to forward the excess packets. This algorithm also suffers from large message overhead and a huge time delay. Misra et al. [11] proposed a Reliable and Energy Efficient Protocol (REEP) for reliable and energy-efficient data routing in WSNs. It is a data-centric and on-demand routing protocol where the routing phase selects based on local communication. This approach puts huge message overhead on the network. It also includes high transmission costs.

Sharma et al. [18] presented a congestion control protocol for the WSNs called Bidirectional Reliable and Congestion Control Transport Protocol (BRCCTP). In this approach, a rate adjustment based scheme is used to manage congestion within the network. It provides bidirectional reliability during data transmission. The proportion of average packet service time over average packet inter-arrival time is used to detect the congestion level in the nodes. In this approach, all data sources are assigned by an equal priority index that helps to mitigate congestion. In this approach, if congestion is detected within the network then it significantly increases data transmission latency.

Zhuang et al. [19] proposed a congestion control mechanize for data gathering in sensor network called Congestion-Adaptive Data Collection scheme (CADC). In this paper, an adaptive lossy compression based mechanism is developed to mitigate congestion. Furthermore, a weighted CADC scheme is applied to manage cyber-physical applications congestion. In CADC, data items are defined by the different priorities. However, CADC does not focus on the energy consumption of the deployed sensor nodes. Therefore, this approach suffers from a poor network lifetime.

It has been seen from the literature that the existing congestion control method leads to a large number of message exchanges over the network for data and status exchange. It increases data transmission delay within the network and energy consumption of the deployed sensor nodes. Also, the quality of services (QoS) of the existing approaches is very poor. Due to poor performance and high transmission delay of the existing set of approaches, it is very challenging to implement in IoT-based healthcare applications. In this paper, a distributed level based congestion control mechanism has been proposed for effectively classifying the data packets which help in congestion avoidance. Furthermore, a level-based data routing scheme is used for making a more suitable decision to implement an optimal value in the route identification process. The existing congestion control routing protocols which were proposed for routing in WSNs are not able to provide optimal energy consumption solution. Therefore, the proposed model considered the sensors present in the IoT scenario. Hence, the proposed congestion control data routing scheme provides optimal results by reducing the energy consumption and delay. The proposed scheme is increasing the packet delivery ratio by avoiding congestion in the network. This is achieved by the effective monitoring of different queues. It helps to avoid packet drops occurring due to congestion. Finally, it is noted that the proposed scheme gives optimal results in terms of QoS in IoT-based healthcare applications.

III. Network Model and Problem Formulation

A. Network Model

We consider an IoT-based healthcare network consisting of N numbers of static sensor nodes arbitrarily located in the hospital environment. In the initial network topology, each node has transmission range R_{max} and deployed network topology is represented with an undirected weighted graph $G=(V, E)$, where $V=\{v_1,v_2,....,v_N\}$ is the set of nodes and $E=\{(v_i,v_j)\big| dis(v_i,v_j)<R_{\max}\}$ is the set of edges, where $dis(v_i,v_j)$ shows the distance between nodes v_i and v_j. The data transmission links between any two nodes do not have the same capacity and edge $(v_i,v_j)\in E$ is expected to have a stipulated capacity C_{v_i,v_j} to transmit packets from node v_i to node v_j. Each deployed node $(v_i \in V)$ periodically sends the sensed data to the BS through multi-hop communication. The first order radio model is used for energy consumption [20-22]. So the energy consumed while transmitting a β-bit message to a receiver node located d distance apart can be formulated as the equation,

$$E_t=\begin{cases}\beta E_{elec}+\beta\varepsilon_{fs}d^2 & d\le d_o\\ \beta E_{elec}+\beta\varepsilon_{amp}d^2 & d>d_o\end{cases} \tag{1}$$

where E_{elec} denotes transmitting circuit loss and d_0 is the threshold distance. ε_{fs} and ε_{amp} denote the energy for power amplification in the models, respectively. The energy consumption for receiving an β –bit message depends on the dissipation in the circuit. Therefore,

$$E_r=\beta E_{elec} \tag{2}$$

For idle listening, the energy consumption rate of the sensor nodes is denoted by E_{idle}.

B. Problem Formulation

Let x_i is the packet sending rate of v_i and if x_i is detected as zero then v_i is out of work. Therefore, $G_x=(V, E, X)$ graph simulate a topology of sensor-based IoT network, in which $X=(x_1, x_2, ..., x_n)^T$. X presents the sending rate of all deployed nodes, which varies with time. In the IoT network, when traffic demand exceeds the network's bandwidth, data packets will accumulate in the cache of nodes, which will cause congestion. This means that when node v_i sends data to v_j, if $x_i > x_j$, then the queue length of cache in the node v_j will gradually increase, the network congestion occurs. Q_H, Q_L, and Q_C are the specific queues used for storing different types of medical data in relay nodes.

The congestion index helps in identifying the level of congestion in the IoT network and is given by the following equation:

$$C_i=\textstyle\sum_{i,j\in n,v_{i,j}\in V}(x_j-x_i)+Q_i \tag{3}$$

Where,

$$Q_i=\begin{cases}1 & \text{Length (Q)} \ge \text{threshold}\\ 0 & \text{Length (Q)} < \text{threshold}\end{cases}$$

The objective of this paper is to estimate the congestion during data gathering process, energy consumption and routing delay for an IoT-based healthcare network, to provide an important guideline for network optimization, such as routing design and network lifetime. The entire network lifetime is divided into $p+1$ stages $[S_0,S_1,S_2,....,S_{p-1},S_p]$, where S_i represents the i^{th} network stage, e.g. the first sensor node of the IoT network dies at the end of stage S_0 and the network is totally out of work at the stage S_p. The duration at each stage, namely the number of data phases at each stage S_i, is denoted by $[a_0,a_1,a_2,.....a_{p-1},a_p]$. Thus, $a^{(0)}$ is the IoT network lifetime from network initialization until the first node dies. The average traffic load of node v_i in a data round of each stage is denoted by $[t_i^{(0)},t_i^{(1)},t_i^{(2)},......t_i^{(p-1)},t_i^{p}]$. Specifically, we present our objectives as follows.

1. For an IoT based healthcare network, each deployed sensor node effectively estimates congestion, energy consumption and routing delay according to C_i and selects an energy-efficient query processing/data gathering path.
2. The average traffic load and energy consumption of the deployed sensor nodes at each stage, i.e., for each $0<i\le n$, $t_i^{(j)},e_i^{(j)}$ should be minimum. Then, we can mitigate energy consumption problems in high traffic congestion.

The average duration vector of the network stages $[a_0,a_1,a_2,......a_{p-1},a_p]$ should be minimum based on C_i. Then, we can reduce packet loss in high traffic congestion.

IV. Proposed Congestion Control Mechanism

The main objective of the proposed scheme is to control congestion in IoT-based healthcare aware WSNs which can potentially increase the network's lifetime. The proposed scheme also considers the fairer delivery of sensing information to the gateway. To achieve these objectives, the proposed scheme considers two main parameters energy and delay. Furthermore, it considers two types of traffic: sensitive and non-sensitive. Sensitive traffic is designed to transfer high priority data and non-sensitive traffic is designed to transfer normal data.

The proposed congestion control scheme consists of three phases: 1) setup phase, 2) request distribution phase and 3) data routing and event occurrence report phase. In healthcare applications, due to different stages of vital signs and different priorities of several IoT based medical devices, the proposed scheme forwards sensed information to the gateway node with different priorities. Before packets transmission, the source node sets a priority according to the importance of the data. Intermediate nodes route these packets according to the priority of the data packets.

A. Setup Phase

The setup phase runs only once, during the initialization of the network. In this phase, after deployment each node detects its single-hop neighbor nodes and deployed nodes are also divided into different levels. For level detection, initially gateway sets its level value once i.e. *L(Gateway)=1* and sends a request message *LEVEL* to the sensor nodes in the range R_{max}.

Algorithm 1: Level Detection Algorithm

Input: Deployed sensor nodes
Output: A level value has allotted to all sensor nodes

```
Initialize: L(Gateway)=1;// L(Gateway) initialized to one
Gateway broadcasts a LEVEL msg. in the range R_max.
for each sensor node v_i
    if (D(Gateway,v_i) ≤ 2R_max) then
        L (s)= L(Gateway)+1;
        PN(v_i)=Gateway;
    end if
end for
Similarly, node v_i broadcasts a MOD_LEVEL msg. in the range 2R_max
if (node v_j receives the msg. and L(v_j)>L(v_i)) then
    L(v_j)=L(v_i)+1;
    PN(v_j)=v_i
    CN(v_j) =v_i.
else
    Discord the msg.
end if
for each sensor node v_i
    v_i sends its current level value, energy condition, ID, Location
    information;
end for
```

The message contains its *ID*, level (*L*) and location information. When a sensor node v_i receives the *LEVEL* message then v_i sets its level value to one higher than the gateway, i.e. $L(v_i)= L(Gateway)+1$ and also sets the gateway as its parent node (*PN*) i.e. $PN(v_i)=Gateway$. Similarly, all sensor nodes within the *range* $2R_{max}$ to the gateway node increase their level value to one higher than the gateway node and set the gateway as their parent node. Recursively, node v_i broadcasts a *MOD_LEVEL* message to the deployed sensor nodes in the range $2R_{max}$. The message contains its *ID*, $L(v_1)$, current energy condition ($E_{current}$), and location information. If a sensor node v_j receives the *MOD_LEVEL* message and its level is less than the level value of the node v_i, it sets as one of the child nodes i.e. $CN(v_j)=v_i$. Otherwise, it updates its level to one more than the level value of the node v_i and sets it as one of the parent nodes, i.e., $PN(v_j)= v_i$. In the setup phase, all deployed nodes detect their single hop parent node-set and their current energy condition. Recursively, all deployed sensor nodes also identify their single-hop child nodes and their current energy condition. After level detection, all sensor nodes transmit their update level value, *ID*, location information and current energy condition to gateway node through their intermediate parent nodes. Due to mobility, sensor nodes may change their current locations. If the sensor node moves from one level to another level, the mobile node updates its current level value with the help of neighbor nodes. The detailed description of the process is summarized in algorithm 1.

B. Query Distribution Phase

In this phase, when the gateway node receives a query from the medical staff (doctor/nurse), the gateway node distributes received requirements among deployed nodes to fulfill the need of the medical staff. In healthcare applications, the type of data is very important during the data gathering process. In some situations, health parameters may include highly sensitive information. During the query distribution phase, gateway identifies level and location information of the sensor node from the earlier record and calculates the lifetime of a query packet within the network. The lifetime of the query packet can potentially increase the reliability of data transmission and reduces message overhead within the network. The lifetime of the query packet is calculated as follows

$$L_{Life\_Packet} = \sum_{1}^{d(level)} (T_T + T_R) * P_t \qquad (4)$$

where *d(level)* is the level value of the destination node. T_T is the transmission delay and T_R is the receiving delay. P_t is the processing delay.

Then the gateway broadcasts an *RREQ* message within the level one sensor nodes. The message contains a query for radio links capacity, *ID* of the destination node, level (*L*) value of the destination node, lifetime of the request (L_{Life_Packet}), and location of the destination node. To obtain an estimation of these capacities, every node, v_i, assesses radio link related it to its parent, v_p $(v_p \in PN(v_i))$, by sending a burst of packets during a determined amount of time, *T*. Every packet is sent after the reception of the previous packet's acknowledgment or after a time-out from the former submission. The link capacity, C_{v_i,v_p}, is then approximated by the total number of acknowledged packets divided by the period *T*. When a node v_i receives *RREQ* message, it checks destination node *ID*. If request node *ID* is the same with v_i, v_i sends its update information to the gateway through the highest capacity link. Otherwise, it checks the level value of the destination nodes and lifetime of the request packet. If the level of the node v_i is equal or less than the level of the destination node and lifetime of the request packet is expired, it simply discards the message. Otherwise, it forwards the *RREQ* message within the child nodes. In healthcare applications, the gateway may receive multiple requests at the same time for the same or multiple IoT based medical devices. If gateway executes these requests at the same time then congestion may occur within

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the network.

Algorithm 2: Request Distribution Algorithm

Input: Query from the doctors and nurses
Output: Respond of the query

```
Gateway receives a query from the doctors and nurses
Start answering process according to request priority
if required data is not available then
   Gateway identifies level and node ID of the v_j node
   Calculated L_Life_Packet using eqn. 1
   Set life time of the query packet
   Broadcast RREQ msg. within the single-hop one node
for each node v_i
   if node ID(v_i) = ID(v_j) then
      Send requested data to the gateway
   end if
   if L(v_i) ≠ L(v_j) then
Node v_i forwards RREQ msg. within the child nodes
   end if
if L_Life_Packrt=0 and L(v_i) < L(v_j) then
     Discord the message
  end if
  end for
```

Therefore, the proposed scheme identifies the priority of the query according to the priority of the patient. The proposed scheme also considers the request time to specify the execution of the query for a part node. For example, in healthcare applications, vital signs related to sensitive information (such as the heart rate, breathing condition, and blood sugar) have high priority; therefore this type of request is assigned a high priority. Also proposed scheme can consider other types of traffics for data related to non-sensitive (such as legs sensors) which has a lower priority. In the proposed scheme, when the gateway node receives a query from the medical staff, gateway sets query dissemination time concerning the current time. On the other hand, each sensor node attached to the patient's body should report to the gateway when it detects vital signs out of the normal range. In that situation, the source node sets high priority during the vital sign transmission. The detail description of the query distribution process is summarized in the algorithm 2.

C. Data Routing and Event Report Phase

After the request dissemination phase, the destination node sends its update information to the BS/gateway node through the energy-efficient highest capacity link. Similarly, if a node senses a medical emergency based on its duty, it will report to the gateway according to the specifications. The reports must have the required parameter values so that the gateway can show the proper reaction and sends a medical emergency report to the doctor/nurse.

In this phase, the information related to the occurring medical emergency is sent to the gateway. For this purpose, the node creates a packet containing the information related to the sensed event and sends it to the nearest parent node through the highest capacity link. According to the setup phase, a sensor node may have multiple parent nodes and multiple paths to the gateway. Let $\{v_1, v_2, v_3, \ldots, v_p\}$ are the set of nodes belonging to set $PN(v_k)$. For sending a medical emergency packet or a normal data packet, node v_k calculates the average residual energy of the parent sensor nodes, using the formula

$$\delta(v_k) = \sum_{i=1}^{p} E_{Current}(v_i) \Big/ p \tag{5}$$

where p is the number of nodes in the $PN(v_k)$ and $E_{current}$ is current energy condition. Let $S=\{s_1, s_2, \ldots, s_p\}$ be the parent nodes that residual energy is greater than or equal to $\delta(v_k)$. Then v_k sends all data packets to the parent node concerning the buffer status of the parent sensor node (which is specified by congestion index C_i) and distance of the parent sensor node. If the buffer status of the nearest parent node is overflow, v_k selects the next nearest parent from S. The pseudo-code of the routing algorithm is described as follows.

Algorithm 3: Event Distribution Algorithm

Input: Event identifies by the sensor node
Output: Event report receive at BS/Gateway

```
for each sensor node v_k
     for each sensor v_i belongs to PN(v_k)
          sum=sum + E_current (v_i)
     end for
     δ(v_k) = sum / |PN(v_k)|
     for each sensor node v_i belongs to PN(v_k)
          if (E_current (v_i) ≥ δ(v_k) )
             S=union (S,v_1)
          end if
  end for
  for each sensor node v_l belongs to S
       if (MAX> E_current (v_k) && min D(v_l,v_k) then
          MAX=E_current(v_k)
          Node v_l selects data routing.
       end if
end for
```

D. Congestion Control Mechanism

The main objective of this work is to provide a routing and congestion management mechanism for IoT-based healthcare network. In this work, deployed nodes select their data routing path in such a way that the congestion occurrence probability will be reduced. The congestion control phase is executed with the data routing algorithm.

The proposed congestion control scheme uses a classifier to classify different types of data and route them into different queues. All data packets are classified into three categories: a) high priority data packets, b) low priority data packets, and c) control data packets. Each data packet contains its type in the packet header. Classifier classifies received data packets and sends them into different queues concerning their class. The proposed scheme uses a priority queue based scheduler to transmit different data. If class 1 data is found within the queue, scheduler stop class 2, class 3 data transmission and start class 1 data transmission. After transmission of all class 1 data packets, the scheduler starts class 2 and class 3 data packets transmission.

If the data transmission rate Tx_{max} is less than the data receiving rate $\sum_{i=1}^{c} Rx_i$, the buffer of a node will overflow after some interval time. In this situation, the node does not receive

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any data from its child node and the network suffers from the packet loss problem. To solve this problem, the proposed scheme selects an alternative path when the buffer level reaches the threshold value (which is identified by C_i). When a node receives a data packet from the child node then it sends buffer status with the *ACK* message. If a node v_1 detects that class 1 queue has reached the threshold value, it sends *H_AlterPath* message to all child nodes so that the high priority data is sent to another immediate energy-efficient shortest path. When a node v_k receives an alternative path selection message from the parent node then v_k selects the next nearest energy level node from the parent node set $PN(v_k)$ and sends all high priority data from this parent node. Similarly, when node v_k detects it is class 2 queue and class 3 queue have overflows then it sends *L_AlterPath* and *C_AlterPath* message to all child nodes. Child nodes also select an alternative path for class 2 and class 3 data packet transmission. The threshold value for the alternative path selection process depends on the number of child nodes hold by a parent node and receives the data rate of the node. In this work, when a parent node detects that its queue is 95% full by received data packets, then it sends an alternative path selection request to the child nodes. After some time when node v_k again senses that its buffer is less than the threshold value then also it sends *REQ 1*, *REQ 2*, and *REQ 3* message to all child nodes for resending class 1, class 2, and class 3 data packets.

V. Theoretical Analysis of Proposed Congestion Control mechanism

This section examines the complexity of the proposed congestion control algorithm to provide a theoretical analysis of whether the proposed solutions are applicable in real-world healthcare practice.

Theorem 1: The message complexity of the proposed congestion control algorithm in *O (N)* where *N* is the number deployed IoT-enabled sensor nodes.

Proof: The total number of messages exchanged by the deployed IoT based sensor nodes over the network for executing the proposed congestion control scheme is known as message complexity. In the setup phase, the proposed congestion control scheme needs one message exchange over the network that means each node v_i broadcast a single message to their neighbors. Based on the received data each sensor node v_i calculates its level value and parent node. Therefore, the proposed congestion control algorithm needs maximum O (*N*) message exchange over the network.

Theorem 1: Assume that v_i is in the small region of A_d with the width of σ. Denote *d* as the distance between A_d and the base station. If each node receives one query packet per round, the average data sent by v_i in a round at S_0 is

$$t_{i_D}^{(0)} = \begin{cases} (z_1+1)+\dfrac{z_1(1+z_1)r}{2d}, & if \quad d \ge \sigma \\ \dfrac{1}{2}(z_2+2)\sigma^2\theta\rho+\dfrac{1}{2}z_2(z_1+1)r\sigma\theta\rho, & otherwise \end{cases} \quad (6)$$

where $z_1 = \lfloor (R-r) \rfloor / r$ and $z_2 = \lfloor (R-\sigma) \rfloor / r$

Proof: Since node v_i is the small region of A_d, its traffic load can be calculated as the average traffic load in A_d according to our analytic model. Therefore, we first calculate the average traffic load in A_d. σ is the width of A_d and σ denote the angle formed by A_d and the sink/base station; thus, we can obtain the number of nodes in A_d. The number of nodes in A_d is

$$N_{A_d} = \begin{cases} d\sigma\theta\rho, & if \quad d > \sigma \\ \theta\sigma^2\rho, & otherwise \end{cases} \quad (7)$$

As these nodes receive and forward the data from the lower level regions, the number of nodes in the upper level A_{d+ir}, is

$$N_{Ad+ir} = \begin{cases} (d+ir)\sigma\theta\rho \mid 0 < i < z_1, & if \quad d > \sigma \\ (\sigma/2+ir)\sigma\rho\theta \mid 0 < i < z_2, & otherwise \end{cases} \quad (8)$$

where $z_1 = \lfloor (R-r) \rfloor / r$ and $z_2 = \lfloor (R-\sigma) \rfloor / r$

Since each node only generates a data packet per round with respect to one query, the number of data packets equals to the number of the involved nodes. Thus, the number of data packets sent by A_d is

$$D_{A_d} = N_{A_d} + N_{A_{d+r}} + \ldots + N_{A_{d+zr}} \quad (9)$$

Based on the above equation, we have the average traffic load of A_d as D_{A_d}/N_{A_d}. Since the traffic load of the node v_i approximately equals the average traffic load of the sensor nodes in A_d for data packet transmission, the traffic load of the node v_i at S_0 should be $t_i^{(0)} = D_{A_d}/N_{A_d}$. With some simple calculation, we have $t_i^{(0)}$ as (6).

Theorem 2: Assume that v_i is in the small region of A_d with the width of σ. Denote b_0 as the distance between A_d and the boundary node. If the sink node forwards one query packet for each node per round, the average query sent by v_i in a round at S_0 is

$$t_{i_q}^{(0)} = \begin{cases} (z_1+1)+\dfrac{z_1(1+z_1)r}{2b_0} & if \quad b_0 \ge \sigma \\ \dfrac{1}{2}(z_2+2)\sigma^2\theta\rho+\dfrac{1}{2}z_2(z_1+1)r\sigma\theta\rho & otherwise \end{cases} \quad (10)$$

where $z_1 = \lfloor (R-r) \rfloor / r$ and $z_2 = \lfloor (R-\sigma) \rfloor / r$

Proof: Similar to the proof of Theorem 1.

The average traffic load of node v_i due to query distribution and data gathering in a data round of each stage is $t_i^{(0)} = (t_{i_d}^{(0)} + t_{i_q}^{(0)})$.

Theorem 3: Denote μ_r as the time period for one query processing round i.e. query transmission and data gathering round. Node v_i is in the region A_d, where *d* is the distance between A_d and the sink. If the data transmission rate of the sensor node is *G* bits/s, in a data round, the average energy consumption e_i^0 of v_i is $e_i^0 = e_{i,r}^{(0)} + e_{i,t}^{(0)} + e_{i,j}^{(0)} + e_{i,q}^{(0)}$, where

$$\begin{cases} e_{i,q}^{(0)} = t_d^{(0)}\tau E_{elec} + (t_d^{(0)}-1)(E_{elec}+\varepsilon_k k^{\alpha})\tau \\ e_{i,r}^{(0)} = (t_d^{(0)}-1)\tau E_{elec} \\ e_{i,t}^{(0)} = t_d^{(0)}\tau(E_{elec}+\varepsilon_k k^{\alpha}) \\ e_{i,j}^{(0)} = E_{idle} m_{d,j}^{(0)} = E_{idle}(m_{\alpha} - \dfrac{2t_d^{(0)}\tau}{B} + \dfrac{\tau}{B}) \end{cases}$$

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And if $d > r$, $k = r$; otherwise, $k = d$, and if $k \le k_0$, $\varepsilon_k = \varepsilon_{fs}$ and $\alpha=2$; otherwise, $\varepsilon_k = \varepsilon_{amp}$ and $\alpha=4$.

Proof: In a data round, the energy consumption of node v_i consists of the following four parts.

1) Energy consumption for query distribution: Since node v_i in the region A_d, the received queries in a round is $t_j^{(0)}$ and send queries $(t_i^{(0)} - 1)$. Thus, the energy consumption for query distribution is
$e_{i,q}^{(0)} = t_d^{(0)} \tau E_{elec} + (t_d^{(0)} - 1)(E_{elec} + \varepsilon_k k^{\alpha})\tau$.
2) Energy consumption for data receiving: Since node v_i is in the region A_d, the received data amount in a round is $(t_i^{(0)} - 1)$, according to theorem 1. Thus, the energy consumption for receiving is $e_{i,r}^{(0)} = (t_j^{(0)} - 1)\tau E_{elec}$.
3) Energy consumption for data transmitting: Since the data amount sent by v_i in a round is $t_j^{(0)}$, the energy consumption for data transmitting is
$$\begin{cases} e_{i,t}^{(0)} = t_i^{(0)} \tau (E_{elec} + \varepsilon_{fs} k^2), & k \le k_0 \\ e_{i,t}^{(0)} = t_i^{(0)} \tau (E_{elec} + \varepsilon_{amp} k^4), & otherwise \end{cases}$$
If $d > r, k = r$; otherwise $k=d$. That is because the transmission distance is r if $d \ge r$; otherwise, it is d.
4) Energy consumption for idle listening: According to the network model, the duty cycle is γ. Thus, the active time per round is $b_a = B_r \gamma$. The energy consumption for idle listening is the multiplication of E_{idle} and the duration in idle listening. Since the duration in idle listening, denoted by $b_{i,j}^{(0)}$, is the active time excluding the time for data transmitting and receiving, we have $b_{i,j}^{(0)} = b_a - \frac{(t_i^{(0)} - 1)\tau}{G} - t_i^{(0)} \tau / G$. Therefore, we derive the energy consumption for idle listening as $e_{i,j}^{(0)} = E_{idle} b_{i,j}^{(0)} = E_{idle}(b_a - \frac{2t_d^{(0)}\tau}{G} + \frac{\tau}{G}$. To summarize, in a round, the energy consumption $e_j^{(0)}$ of node v_i is $e_i^{(0)} = e_{i,r}^{(0)} + e_{i,t}^{(0)} + e_{i,q}^{(0)} + e_{i,j}^{(0)}$.

Theorem 4: For each network stage S_i, the reaming energy of any node v_k after S_i is $\phi_k^i = E_0 - \sum_{c=0}^{i}(e_k^{(i)}.t^{(i)})$, and the remaining energy of the network after S_i is $\phi_k^i = n(E_0 - \sum_{c=0}^{i}(e_k^{(i)}.t^{(i)}))$.

Proof: Since $e_k^{(i)}$ is the average energy consumption of node v_k in a data round (combination of query distribution and data collection) at S_i and $t^{(i)}$ is the duration of S_i, we can determine the energy consumption of node v_k during S_i as $E_{k,i} = e_k^{(i)}.t^{(i)}$. From S_0 to S_i, the total energy consumption of node v_k is $E_{use}^{i,k} = \sum_{c=0}^{i} E_{i,k}$ and the total energy consumption of the network is $E_{use}^{i} = \sum_{c=0}^{i}\sum_{k=0}^{n} E_{i,k}$. As the initial energy of the network in nE_0, after S_i, the remaining energy of node v_k is $\phi_k^i = E_0 - E_{use}^{i,k} = E_0 - \sum_{c=0}^{i}(e_k^{(i)}.t^{(i)})$ and the remaining energy of the network is $\phi^{(i)} = nE_0 - E_{use}^{i} = nE_0 - \sum_{c=0}^{i}\sum_{k=0}^{n}(e_k^{(i)}.t^{(i)})$.

Theorem 5: The estimated Query Processing Delay (QPD_i) for sensor node v_i is $2 \times dist(v_i - v_j)/c + 2\tau_i$ where, τ_i is the processing time.

Proof: Estimated query processing delay is the approximate time required by a sensor node v_i to transmit its query as well as data to all its surrounding neighboring nodes which are coming under its transmission range r. The estimated query processing delay QPD_i can be defined as

$$QPD_i = \{2 \times \max(QPD_{i,j} + \tau_i), \quad \forall v_i \in Neg_i\}$$

Where $QPD_{i,j}$ i.e. estimated transmission time between the sensor v_i and v_j and τ_i is the processing delay of v_i. The $QPD_{i,j}$ can be calculated as given in

$$QPD_{i,j} = dist(v_i, v_j)/c$$

where c is the speed of light.

We define the estimation error E_k at node v_i equals the accumulated errors from each of its children $v_1, v_2, \ldots, v_k, \ldots, v_{N_{A_D}}$:

$$E_v = \sum_{i=1}^{N_{AD}} (\chi_i^v - \chi_i)^2 = \sum_{i=v_1} (\chi_i^v - \chi_i)^2 + \ldots\ldots + \sum_{i=v_{N_{AD}}} (\chi_i^v - \chi_i)^2$$

where χ_i denotes the data measured by node i and χ_i^v denotes the value of χ_i received by node v_i. For theorem 1 we can easily calculate the number of nodes in A_d is N_{A_D}. The estimated error E_v at node v_i equals the accumulated errors from each of its children. We define the error contribution of v_i's child node v_k as

$$C_{v_k} = \sum_{i=1}^{N_{AD}} (\chi_i^v - \chi_i) = \sum_{i=1}^{N_{AD}} ((\chi_i^v - \chi_i^{v_k}) + (\chi_i^{v_k} - \chi_i))^2$$

$$= \sum_{i=1}^{N_{AD}} (\chi_i^v - \chi_i^{v_k})^2 + \sum_{i=1}^{N_{AD}} (\chi_i^{v_k} - \chi_i)^2 + 2\sum_{i=1}^{N_{AD}} (\chi_i^v - \chi_i^{v_k})(\chi_i^{v_k} - \chi_i)$$

$$\le \sum_{i=1}^{N_{AD}} (\chi_i^v - \chi_i^{v_k})^2 + \sum_{i=1}^{N_{AD}} (\chi_i^{v_k} - \chi_i)^2$$

$$+ 2\sqrt{\sum_{i=1}^{N_{AD}} (\chi_i^u - \chi_i^{v_k})^2 . \sum_{i=1}^{N_{AD}} (\chi_i^{v_k} - \chi_i)^2} = D_{v_k} + E_{v_k} + 2\sqrt{D_{v_k} . E_{v_k}}$$

where E_{v_k} is the estimation error at child v_k and D_{v_k} is data distortion due to data compression of v_k.

VI. Results and Discussion

A. Simulation Environments and Simulation Results

We performed extensive experiments on the proposed scheme using NS-2 [23]. The medical sensor nodes are randomly distributed in 2D space. An IoT-enabled gateway/BS was used for data gathering and queries processing. The proposed congestion control mechanism for

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IoT-based healthcare aware network is evaluated and compared with the existing well-known TARA [8], REEP [11], HTAP [17], BRCCTP [18], and CADC [19] schemes in the literature in terms of percentage of the successfully received packet, average throughput, average hop-by-hop delay. Furthermore, the energy-saving performance of the proposed algorithm and the network lifetime was evaluated where the initial energy of each sensor node is E_0=0.5 [Joules]. All the simulations are based on collision-free MAC protocol. Simulation parameters are listed in Table 1.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Deployment area	100×100 m^2
Number of nodes	20-100
Data packet size	500 bits
Initial energy of each node (E_0)	0.5 Joules
$\boldsymbol{E_{elec}}$	50nJ/bit
$\boldsymbol{\varepsilon_{mp}}$	0.0013 pJ/bit/m^4
$\boldsymbol{\varepsilon_{fs}}$	10pJ/bit/m^2
Control message size	100 bits
Duty cycle	10%
Duration of a data period	10s
Energy consumption rate for ideal listening	0.88 mJ/s
Data transmission rate	512 Kb/s
Sensing radius	20m
Antenna type	Omni Antenna
Max packet in queue	50

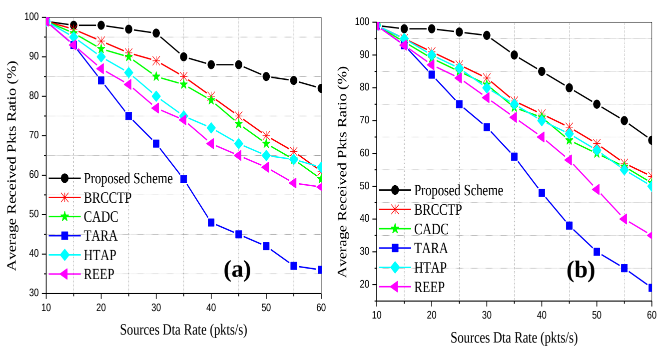

Fig.1. Percentage of successfully received packets. a) 20 nodes, b) 100 nodes.

Fig. 1a and 1b present the percentage of successfully received packets of the proposed scheme. This is measured with the number of data packets received at the gateway. Fig. 1a shows that the percentage of successfully received packets of the proposed scheme is more by 37% as compared with BRCCTP, 39.4% as compared with CADC, 41.3% as compared with the REEP scheme, 42.5% as compared with the HTAP scheme, and 57% as compared with the TARA algorithm. Also, Fig. 1b indicates that the proposed scheme increases the percentage of successfully received packets up to 38% comparing with BRCCTP, up to 42% comparing with CADC, up to 44 % comparing with REEP, up to 45.7% comparing with HTAP and up to 59% comparing with TARA. This causes due to the level-wise elimination of data congestion during the data routing process and priority-based congestion control mechanism.

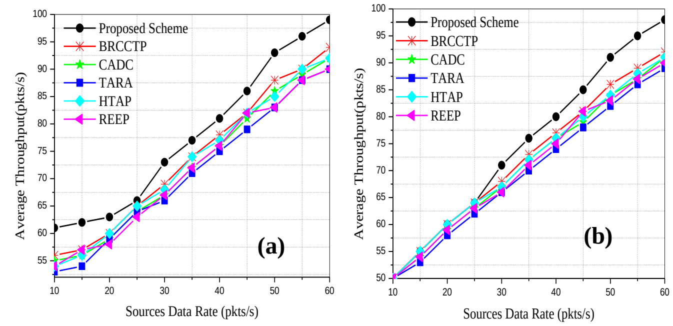

Fig.2. Comparison of average throughput. a) 20 nodes, b) 100 nodes.

Fig. 2a and 2b present the throughput of the proposed scheme using different percentages of sensor nodes in the network. This is measured with the rate of data that reaches the gateway node. Fig. 2a indicates that the proposed scheme improves throughput up to 29% comparing with BRCCTP, up to 31% comparing with CADC, up to 33% comparing with REEP, up to 34.33% comparing with TARA and up to 36% comparing with HTAP. Fig. 2b shows that the proposed scheme improves throughput up to up to 26.5% comparing with BRCCTP, up to 29% comparing with CADC, up to 31.21% comparing with REEP, up to 32% comparing with TARA and up to 33.45 % comparing with HTAP. It is due to the level-based congestion control mechanism where data transmission congestion is controlled through the effective alternative data routing path selection process.

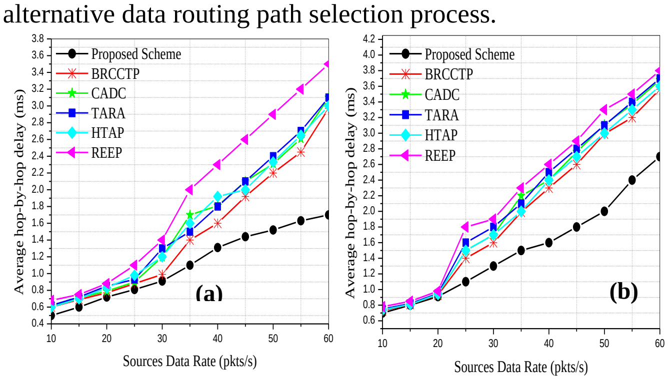

Fig.3. Distribution of average hop-by-hop delay according to the sources data rate. a) 20 nodes, and b) 100 nodes.

Fig. 3a and 3b present average hop-by-hop delay results using the tested algorithms in scenario 1 (20 nodes) and scenario 2 (100 nodes). This performance metric is important for how the proposed scheme controls inter-path interferences, link-layer retransmissions, and overhead introduced by control packet exchanges. In Fig. 3a, it is seen that the proposed scheme has a less average hop-by-hop delay of 31% as compared to BRCCTP, 33.6% as compared to CADC, 35.4% as compared to REEP, 38.5 % as compared with HTAP, and 41% as compared with TARA algorithm. Fig. 3b indicates that the proposed scheme reduces average hop-by-hop delay up to 28% comparing with BRCCTP, up to 31.3% comparing with CADC, up to 32% comparing with REEP, up to 35% comparing with HTAP, and up to 37% comparing with TARA algorithm. It is since the proposed scheme efficiently selects the data routing path with the minimum number of control packet exchanges. Therefore, the average data transmission delay is less in the proposed scheme.

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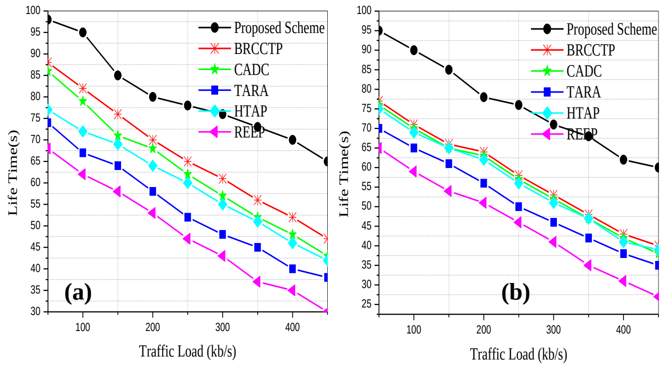

Fig.4. Comparison of Lifetime over traffic load. a) 20 nodes and b) 100 nodes.

In Fig.4a and 4b, the energy performance of the proposed scheme is measured compared with BRCCTP, CADC, TARA, HTAP, and REEP scheme from the view of traffic load. In Fig. 8a, it is seen that the proposed scheme has more network lifetime of 37% as compared to BRCCTP, 40% as compared to CADC, 43% as compared to TARA, 42.3% as compared to HTAP, and 45 % as compared to REEP. Also, Fig. 4b indicates that the proposed scheme increases network lifetime up to 38.5% comparing with BRCCTP, up to 42% comparing with CADC, 44.91% comparing with TARA, up to 43.78% comparing with HTAP, and up to 48% comparing with REEP. The lifetime of the network is measured with the first dead node. The lifetime of the proposed scheme is more since it energy efficient as compared to BRCCTP, CADC, TARA, HTAP, REEP scheme.

TABLE II

PARAMETERS VALUES USED IN THE INDOOR TESTED EXPERIMENT

Parameter	Value
Number of sensor nodes	20
Deployment area	15×15 m^2
Base Station/Gateway	1
Sending rate	1 packet/s
Packet size	500 bits
Initial voltage of battery	1.6.0V

B. System Implementation and Testing

A testbed of the proposed congestion control scheme has been created for demonstration where twenty medical sensor nodes are used for data collection. In this experimental setup, we used a blood pressure sensor, pulse oximetry sensor, ECG sensor, EMG sensor for data collection. The testbed consists of a gateway for query processing and data collection from the deployed medical sensor nodes. Twenty medical sensors are deployed into two different laboratory rooms where each person is monitored by four medical sensors. The detailed parameters and corresponding values in real experiments are reviewed in Table 2.

Fig. 5a shows that the result of the practical test is almost similar to that of the simulation case in Fig. 1. As predicted by the theoretical case in Fig.1, it can be seen that the percentage of successfully received packets of the proposed scheme was decreased when sources data rate increased. From these results, it can be observed that our proposed scheme shows improved performance compared to the existing congestion control approaches in the real IoT-based healthcare experiments.

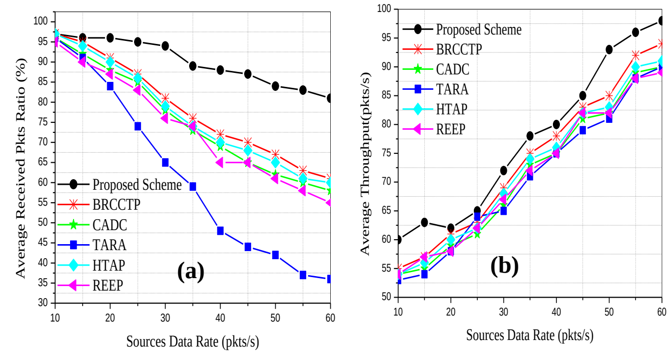

Fig.5. Comparison of real testbed results. a) Percentage of successfully received packets and b) Average throughput in different data rate.

Fig. 5b illustrates that our proposed scheme has an increased average throughput compared to BRCCTP, CADC, TARA, HTAP, REEP schemes, verifying the theoretical case in Fig. 2. From the figures, it is clear that the proposed scheme demonstrates desirable performance for the congestion control mechanism in an IoT-based healthcare system.

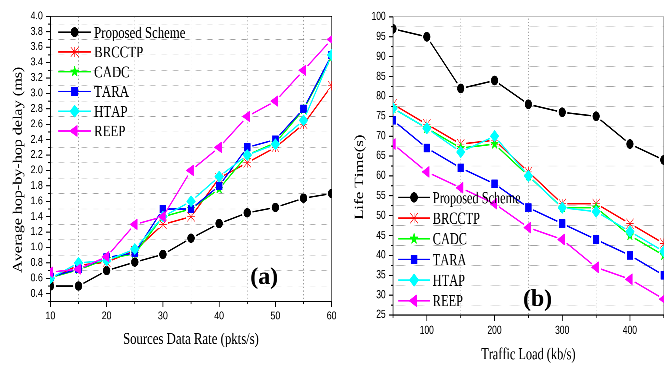

Fig.6. Comparison of real testbed results. a) Average hop-by-hop delay and b) Lifetime over traffic load.

Fig. 6a shows the average hop-by-hop delay in the practical test. It can be seen that the average hop-by-hop delay has been reduced compared to BRCCTP, CADC, TARA, HTAP, and REEP schemes. As described in the theoretical case, our proposed scheme shows an improved result because of the class-based congestion management mechanism.

Fig. 6b shows the lifetime over traffic load. As predicted by the simulation tests, it can be seen that the lifetime of the proposed scheme was increased when the traffic load was increased within the network. From this result, it can be observed that our proposed scheme shows improved performance in an IoT-based healthcare system compared to the state-of-the-art congestion control approaches such as BRCCTP, CADC, TARA, HTAP, and REEP in the real hardware experiments.

VII. CONCLUSION

This paper proposed a congestion control mechanism for wireless sensor networks applied in IoT-based healthcare scenarios. The proposed scheme used a priority-based data routing strategy to control congestion within the network. It classifies data packets into three different categories according to the priority of the data packets. Furthermore, the proposed scheme used a priority queue based scheduler to transmit