A Data Transmission Protocol for Wireless Sensor Networks: A Priority Approach

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***Abstract*—Recent development in the field of a wireless sensor network has shown the significant improvement and has emerged as a new energy efficient wireless technology for low data rate applications. Handling different types of event data altogether is a crucial task in the sensor networks. This paper presents the solution to the problem of heterogeneous data transmission of long distance prioritised nodes in low data rate wireless sensor networks (LR-WSNs). The solution comprises three main algorithms, namely data reporting, traffic scheduling, and centralised reporting rate mechanism. The data reporting algorithm reports the demanded data in each specified decision window size with variable reporting rate. The traffic aware packet scheduling algorithm performs the packet reprioritisation and scheduling. The priority assignment is designed based on the data priority and hop count. It serves transient traffic against newly sensed packets, or less hop distance travelled packets. As a result, it minimises the chances of dying earlier than its deadline. The third algorithm presents the flexible data gathering approach based on the level of the buffer either sensed by its own or recently received information from hop node. It uses a decision interval window for managing the frequency of data delivery. This centralised decision approach makes the sink node more adaptive for data gathering and controlling the active source nodes. This multi-tier framework functions over CSMA/CA due to its unique feature of energy saving, especially for LR-WSNs. The reported work is simulated and examined over various scenarios in the multi-hop wireless sensor networks. Moreover, the performance of the scheduler proves better data transmission rate for priority-based traffic over regular traffic flows; approximately 7% over First-Come-First-Served (FCFS) and 5% against Precedence Control Scheme (PCS) mechanism using theoretical analysis and computer simulations.**

***Index Terms*—Buffer Management; Priority; Transport; Packet Scheduling; Wireless Sensor Networks; Reporting Rate.**

I. INTRODUCTION

Nowadays, the scope of the battery powered low rate wireless sensor networks (LR-WSNs) [1]-[5] is not limited for which it was invented particularly - military surveillance. It is continually covering almost all low data rate requirement applications of every sector of the industry. Therefore, the challenges in such resource constraint sensor networks vary according to their application types such as for homogeneous traffics or heterogeneous traffic with or without delay constraints needs. For this reason, a ZigBee technology is beneficial for low data rate transmission with the utilisation of minimum resources. However, for high data rate (up to 1300 Mbps, IEEE 802.11ac) – Wi-Fi technology (IEEE 820.11 family) [1, 6] is useful for mobile devices, home network, corporate and campus management over a longer distance where energy is not a severe problem. Low data rate (up to 2mbps) – Bluetooth supports mobile and laptop devices for exchanging the multimedia data over a short distance, and the lowest data rate (up to 250kbps) – ZigBee (IEEE 802.15.4 family) is used for delivering a small amount of data.

IEEE 802.15.4 [5, 7] networks are mainly designed for controlling and monitoring remote location data gathering where internet connectivity is unavailable or where automation is required for managing the operations remotely and automatically without human interference. Nowadays, it is not only limited to industrial automation processes but also are widely used in home automation, smart city, and in electronics appliance, for instance, fridge, TV, remote, and much more. Each node has a life up to 10 years of using AA batteries. Conversely, handling multiple tasks simultaneously increases the complexity of data transmission mechanisms, and their overheads reduce the life of the network.

Currently, small-scale industries [2] have also started automation for increasing the productivity and capability of managing the jobs remotely using small size short-range devices. Periodic scheduling [2, 3] is commonly used to manage and preserve power; if not scheduled, waiting time to get the required resources will shorten the life of the network. Therefore, developing a priority-based data gathering transmission protocol is an essential step to handle a vast heterogeneous data. This specific need has gained the attention of many active researchers in heterogeneous WSNs.

In addition, to develop an application specific data scheduler over the MAC protocol [5] is also a non-trivial requirement. However, at another end sometimes regular events occur far away from the sink node. Usually, such sensing devices always experience delay irrespective of dynamic routing topology. The static distance remains the same and only routing path changes. In particular, less attention is given to address the delay in such applications. Sometimes for delay sensitive applications where packet delivery is 100%, data becomes useless if it is not delivered in time. Therefore, to resolve this problem, a priority approach can be applied to data packets (application specific) or packets with the hop count (distance specific) [8] in order to serve them in time. In this paper, the second type of priority, i.e. based on hop count is taken into account for designing the Data Transmission Protocol using Priority Approach (DTP-PA) for IEEE 802.15.4 networks. The data priority and hop count are two essential attributes for developing the priority aware scheduler approach for multi-event sensor networks. Handling the event priority and its distance to a base station are a necessity when delay sensitive protocol is designed.

In the multi-hop wireless topology, packets are routed through various paths with respect to the design considerations of routing protocols or sometimes are designed particularly for the identified networks concerning the need of applications. Typically, source node (also called as reduced function devices-RFDs) senses the information and delivers to its upstream node which has the capability of receiving, transmitting, sensing, and processing the packets; such nodes are called as full function devices (FFDs) [4] [5]. They perform the non-trivial job in a sensor network. Though they are designed for routing the packets for extending the network path or acting as range extender for the source nodes; they can be utilized for processing some jobs of base station to reduce the load to some extent which will not solve only the bottleneck problem but will also reduce the propagation delay increasing the network life. This distributed approach brings the new aspect of handling the heterogeneous data simultaneously into low data rate IEEE 802.15.4 networks. This type of approach is truly essential for LR-WSNs due to its rapid growth to a variety of industries.

Moreover, every industry comprises a set of events' data gathering requirements. This is not only limited to data gathering but also need a focus on delay tolerance level of each contributing application and their distance from the base station. However, the delay tolerance level of each traffic flow is out of the scope of this paper. The priority to packets is defined based on the hops it has passed through. In particular, it generates the non-trivial need for the development of data-aware information gathering mechanism according to their transmission levels. However, considering the scope of this paper, the reported work focuses on multi-event packet transmission scheduler at intermediate nodes. The design scope of packet scheduler includes two types of data packets, namely long distance travelled packets and newly sensed packets by the hop node.

To sum up, our contributions are briefed as follows.

- The data reporting algorithm presents the data delivery with variable reporting rate in decision interval specified by the sink node
- It presents two methods, viz. networked traffic first, and packet scheduling based on their data priority and hop count. First, it serves the high priority traffic over regular newly sensed traffic by the hop node. The notification mechanism is sent on the buffer overflow event.
- The adaptive rate control mechanism is core operation for achieving the high reliability for different traffic flows using decision interval window. It uses the buffer occupancy for updating the rate.
- Finally, the proposed priority scheduler is validated in various intensive cases to check the correctness of the queuing operations for priority-based traffic.

The residual segments of this paper are structured as follows. Section-2 describes reference work particularly, the priority-based scheduling approaches. Section-3 represents the proposed network assumptions, mathematical model, and operational flow of three algorithms. The performance evaluation is put forth in Section-4. Lastly, the work is concluded and put forth the further scope in Section-5.

II. RELATED WORK

The study focuses on priority-based buffer management and scheduling approaches for multi-event wireless sensor networks. The scheduling algorithms [9] are applied for reducing the problem of traffic conditions in urban areas. The intersection points of the roads are different in each location. These presented algorithms have considered variable lanes while validating the results in order to test in the various situations as per claimed made in the performance analysis part. Furthermore, the efficiency of the Earliest Deadline First (EDF) algorithm is better over a fixed priority (FP) algorithm. As a result, the network remains into the uncongested state due to deadline aware scheduling approach for different intensity levels of traffics. For example, in high-intensity traffic, the EDF has shown 21% reduction of mean trip time, at another side, FP has shown by 16% reduction. The mean trip time, a number of stops and delay parameters are evaluated. In the end, the reported work shows that traffic congestion is reduced noteworthy by following the deadlines with the rate of mean speed. The proposed approach works well over some lanes. The buffers [8] are managed using two different traffic flows such as transient traffic and local traffic. The weighted dual buffer and flexible scheduler solve the problem congestion using three different steps, namely congestion notification, detection, and control. The packet priority is updated at every intermediate state. Based on the level of buffer the packets are accepted, filtered, or rejected. At every instance, the weighted changing rate is computed to ensure the reasonable processing rate. It is simulated over tree-based topology and highlights the improvements over the CODA protocol to a great extent. However, this protocol talks about notification of reporting rate on fixed decision interval in order to reduce the extra data travelling rate in the network.

Table 1
Summary of Motivations & Differences

Research Focus	ECODA [4]	ESRT [23]	PCS[28]	DTP-PA (proposed work)
Type of delivery	Rate-based	Rate-based	Rate based	Rate-based
Traffic flows	Homogeneous traffic	Heterogeneous traffic	Heterogeneous traffic	Heterogeneous traffic
Decision window	Not addressed	Window-based	Not addressed	Window-based
Priority	Hop-count based	Not addressed	Hop-count	Hop-count & Data priority
Buffer Management	Dual buffer	Single buffer	Single buffer	Single buffer

The PRIN [10] MAC protocol presents information prioritisation using buffer management over one-hop network topology. The nodes are defined with static priority. It has been implemented over CSMA protocol and priorities are assigned to nodes according to the distance. Apart from that model also decides according to their inter-arrival time. It is compared with results of S-MAC and T-MAC protocols to ensure effectiveness for data transmission specifically for high priority packets. Observations state that source-nodes near to base station have greater network load as compared to long distance node. In [11], the presented approaches focused on the congestion problem and prioritised information delivery in a real-time environment. The patient information example is taken for minimising delay overheads of high priority data packets in wireless biosensor networks.

Furthermore, the congestion control scheme is equipped with parent node where generally traffic is more. The nodes sensing the patient information, immediately report to the sink node for getting high bandwidth (for child nodes). The service differentiation is used based on the level of abnormality of the patient. It is essential to have this kind of approach in multi-event wireless sensor networks. The purpose of assigning the highest priority to the child nodes with high bandwidth is to serve in time otherwise; it may be harmful if the decision exceeds the required time. Three levels are considered, namely - normal, urgent, and critical. The high priority level denotes the severity of patient state. However, in the case of congestion, the low bandwidth is allocated even if traffic is a high priority to avoid the overflow.

A RushNet [12] protocol describes the ways to prioritise the information for delay tolerant and delay sensitive applications. To achieve the desired throughput, a token passing mechanism is proposed for decreasing the contention and blockages. While at another end, the multi-hop approach is designed to cut down the propagation delays. The power variation method is used for high and low precedence, 5dBm, and <3dBm, respectively. The purpose is to attend the high priority packets first with good RSSI value. The performance reports describe that it works smoothly in the saturated sensor network with the pre-emptive scheme.

CSMA/SF [13] presents the optimal solution for common “energy hole problem” around the sink node. Two methods are proposed to address this problem, namely length detection, and anti-starvation mechanism. In length detection, nodes are selected as a high priority those who are holding the small data frames. However, large data frame holding nodes are selected to be low priority nodes. But in the worst case, if low priority nodes are not getting a chance to access media for a long time, then backoff counter sets to default low value with an intention to get media as early as possible. The reserved field of frame length is used for the size of PHY payload. The listening node checks the data frame length of transmitting node randomly. So this reduces the overheads to reports to each sensing device separately. The GTSs are used to dedicated nodes for transmitting the required data using the CSMA/CA MAC protocol. The EDF scheme is used and shown remarkable enhancements over standard CSMA/CA. In [5] [14]-[17], energy hole problem is discussed. In [14] and [16], the prototype is presented to address issues of energy hole.

In [18], the starvation and throughput inequality problems are addressed in the multi-hop sensor network. In [19], signal collision problem of CSMA compared to CSMA/CA is studied thoroughly in multi-hop LR-WSNs. The problems of priority challenges are investigated in [20]-[22]. In [23], the author describes the outcomes of MAC in the 2D Poisson distribution mesh based sensor networks. In protocols [24]-[26, 30], many nodes are taken whereas our study focuses the reasonable amount of nodes. The motivational protocols and differences compared to presented work in this paper, is as described in table 1.

III. DESIGN & MATHEMATICAL MODEL

A. *Network Model & Assumptions*

Let the $\mathrm{n_i} = \{1,2,3,\ldots,\mathrm{m}\}$ be the number of source nodes, $\mathrm{h_j} = \{1,2,3,\ldots,\mathrm{n}\}$ be the hop nodes, and S be the sink node. A multi-hop network comprises of source nodes and hops; having the sensing and transmitting capabilities.

The network communication model is shown in Figure 1.

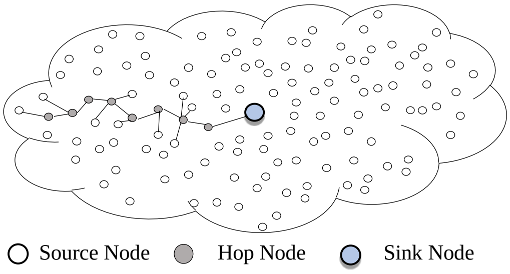


Figure 1: DTP-PA multi-hop topology for priority-based data transmission in heterogeneous traffic flows

The intelligence of packet scheduling mechanism is incorporated in the hops. This distributed approach basically filters each incoming packet and schedules its transmission based on its distance history. The more distance travelled count; the more priority is given to that particular packet. This makes the approach distance aware for packet scheduling of each traffic flow. The purpose is to reduce the delay of longest distance travelled packets over newly sensed packet by the hop or short distance source nodes. This approach adds knowledge to each range extender node of the topology. The mesh topology is practically used, and nowadays the varieties of hardware have come up with mesh-based protocol, for instance, JN5168, nRF24L01, and much more. These ICs are equipped with software lower layer stack includes self-configurable, self-healing, self-joining, and self-sensing based on periodic interval features. Furthermore, the work is also tested over three hops and five hops distance on the nRF24L01 controller with the Arduino nano development compatible board. The hop-by-hop decision approach brings down delay and load of the sink node.

Generally, a sink node takes the decision based on some periodic interval in the star topology instead of multi-hop topology. However, the proposed DTP-PA has tried to incorporate this approach of decision interval in the multi-hop sensor network. Nevertheless, the work has been distributed among hop and the sink. The hop performs a job of classification and scheduling of data packets to the sink node. In addition to that, if it detects the buffer overflow, then it forwards the congestion notification message in the first slot of the cooling window to the sink node after the termination of the current decision interval.

For that reason, the cooling window size is designed to double. The second window slot is purposefully made available because in some worst cases the control packets get delayed, and congestion occurs. Therefore, in addition to routing packets, the capability of hop nodes is increased without putting additional overheads on the network. Additional hardware resources are not required in this approach. Routing information is handy to identify hops at any moment of time. The routing agent is developed for every hop node wherein this scheduling approach is incorporated for prioritising the information based on the hop count. Additionally, data level priority is considered.

B. *DTP-PA Mathematical Model*

This section describes the implementation workflow of the proposed DTP-PA algorithms. A description of mathematical terms is defined in Table 2.

Table 2
Glossary of Mathematical Terms

Term	Definition
h_j	j^{th} hop node
L_j	load on j^{th} hop
P_{type}	packet type
b	buffer
λ_j^{in}	the average incoming rate at hop j
μ_j^{out}	the average outgoing rate at hop j
$p_{r,p}^{in}$	incoming packets types of regular & priority
$p_{r,p}^{out}$	outgoing packets types of regular & priority
x	number of regular packets
y	number of priority packets
P_{pend}	pending packets
P_j	probability at j^{th} hop
U_c	channel utilisation
h_c	hop count
c_t	cooling window time
f_l	Frequency level
DI	Decision interval
α_1, α_2	tuning parameters ($\alpha_1 = 0.5, \alpha_2 = 0.8$)

It includes two parts, namely classification of information and scheduling the packets. To do this, the single queuing system is designed to handle different traffic flows of the networks. A single buffer holds the priority and regular packets with their hop count. The filtered data packets are scheduled based on the hop count and priority bit. Let b be the buffer. For the type of packets, let p_r be the regular packets from different sources (e.g. humidity) and p_p be the priority packets (e.g. fire) from different priority nodes. For the simplicity purpose only, two types of applications are considered which are humidity and fire.

The total applications load at any given time over hop node h_j is as shown in Equation (1).

$$L_j(hop) = \sum_{type=reg,pri} (P_{type}, b) \tag{1}$$

Let P_{type} be the type of traffic either regular or priority-based. The average rate of incoming flow into the buffer is expressed in Equation (2).

$$\lambda_j^{in} = \sum_{\substack{1\le r\le x \\ 1\le p\le y}} (p_{r,p}^{in}) \tag{2}$$

The average outgoing traffic flow of a hop node is expressed in Equation (3).

$$\mu_j^{out} = \sum_{\substack{1\le r\le x \\ 1\le p\le y}} (p_{r,p}^{out}) \tag{3}$$

The pending packet at any given time at a particular hop is:

$$P_{pend} = \lambda_j^{in} - \mu_j^{out} \tag{4}$$

The probability of any particular hop, P_j , is described as:

$$P_j = \frac{\mu_j^{out}}{\lambda_j^{in}} \le 1 \tag{5}$$

The average probability of hops of the network, P_{hops} , is:

$$P_{hops} = \frac{\sum_{j=1}^{m} (\frac{\mu_j^{out}}{\lambda_j^{in}})}{h_j} \le 1 \tag{6}$$

The goal of the proposed DTP-PA algorithm achieves the maximum delivery ratio of prioritised traffic over regular traffic flow. For this reason, the queuing model is designed in order to handle the traffic flow rate and scheduling decision after each time interval. Let p_{pdr} be the packet delivery ratio.

For the effective channel utilisation, CSMA/CA MAC protocol is used, and the theoretical throughput is computed as expressed in Equation (7) [29].

$$U_c \approx \frac{1}{(1+2\sqrt{\omega})} (\text{for } \omega \ll 1) \tag{7}$$
$$\text{where}, \omega = \frac{\tau C}{L}$$

However, the performance CSMA/CA protocol is dependent on the attribute value of ω, which indicates the network delay and carrier idle identification time. τ denotes time (s), C indicates the channel bit rate, L denotes packet bits. The CSMA/CA protocol performs well for the small value of ω with the variable offered load.

C. Algorithm Operations

This section presents three basic algorithms particularly designed for priority-based traffic flows in the multi-hop wireless sensor network. The Algorithm-1 shows the communication flow operation based on the decision interval time window. The Sink initiates the communication establishment request to all source nodes by broadcasting the control message. In response to that, all source nodes send the join request to a sink node. Afterwards, a sink node sets and broadcast the default reporting rate based on the traffic load using attributes like buffer size, the rate of transfer, and number path available. According to the newly received reporting rate, source nodes begin the data transmission in each decision window. In every window, source node gets the new updated reported rate. In each interval, it waits for the new reporting rate. This process continues until event time expires.

Algorithm (1): Data Reporting Mechanism

```
Input: sense info
Output: Transmit actual data packets
Prerequisites: control message from sink
Begin
do
Listen(contrl_pkt);
Send (Res_pkt); // joining interest
for(DI) do
  Update reporting rate;
  Transmit (data packets);
Listen(); // signal from S
end For
while(!DI==0)
end of do-while
End
```

The Algorithm-2 describes the operational flow of traffic aware scheduling approach which runs over each hop node. It stores all incoming packets into the buffer and scans for identifying the type of packets. The screening of packets is based on their priority bit and hop count. The scheduler chooses the packet which has higher priority bit (i.e. 1 for low priority or 2 for high priority) and higher hop count. In particular, hop node increments its hop count by 1 when it schedules for the transmission. This process continues until it reaches the sink node. The buffer management module mainly designed to give the preference to higher priority traffic flows and notification message to a sink node for further decision in the subsequent decision interval window.

Algorithm (3): A Centralized Reporting Rate Mechanism

```
Input: recent decision interval history
Output: new reporting rate
Begin
    Broadcast (event interest packet);
    Set (rate); // based on traffic interest
    Comp_dist (hop); //
    foreach (DI)
      Broadcast(rate);
      Receive(pkts);
      Wait(CW);
      Update(rate) based on following conditions
        Case1: Alert Situation
          $(l > b_{max})$ {drop $(p_r) \leftarrow b$; Schedule $(p_p) \leftarrow b$}
          $f_{l+1} \leftarrow \left\lfloor \frac{f_l}{\eta} \alpha_1 \right\rfloor$ // Multiplicative decrease
        Case2: optimal Situation
          $(b_T < l \le b_{max})$ {Schedule $(p_p) \leftarrow b$}
          $f_{l+1} \leftarrow f_l$ // maintain the reporting rate
        Case3: Under Control Situation
          $(l \le b_T)$ {Schedule $(p_{type}) \leftarrow b$}
          $f_{l+1} \leftarrow \left\lfloor \frac{f_l}{(\eta/\alpha_2)} \right\rfloor$ //aggressively increases rate
    end of for each
End
```

The work of [27] inspires this model, and their model equations are modified according to the buffer level occupancy for the presented work in this paper. However, they have considered star topology with observed reliability factor for updating the reporting rate at each interval whereas this work focuses on buffer occupancy level at different hops for updating the reporting rate.

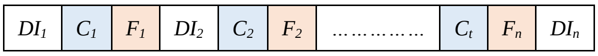
The Algorithm 3 presents the centralised reporting rate mechanism for source nodes those are farthest from the base station. It begins with the communication establishment phase and sends the default reporting rate based on parameters like some source nodes and their reporting rate. After each decision interval, the sink receives the buffer level information from various hops and its own buffer level, based on that the new reporting rate is computed and updated. The updated new reporting rate is broadcasted to all source nodes. The buffer level (η) is used for the additive increase and multiplicative decrease the value of reporting frequency based on the current status of the buffer, as expressed in Equation (8).

$$\eta = \frac{(l - q_{min})}{(q_{size} - q_{min})} \tag{8}$$

In order to prevent the congestion during the transmission of real data packets with the control packets, the propagation period is measured according to the packet history of longest sources. Nodes that are farthest from sink generally have the longest propagation delay. Therefore, it has been considered as a parameter for the cooling window after the expiry of each decision interval. Also, the cooling parameter is used to extend the window size to prevent the signal collision in a worst case. The cooling window period (c_t) is as expressed in Equation (9).

$$c_t = c_t * 2 \tag{9}$$

After expiry of the cooling period, the base station sends the new reporting rate to all source nodes through multiple hops. For this reason, each source node updates their old reporting frequency to newly received rate and starts delivering the packets once the next decision interval starts, as shown in Figure 2. However, in some cases, if the base station does not receive control packets, then it continues with the old frequency reporting rate.



DI_1	C_1	F_1	DI_2	C_2	F_2	……………	C_t	F_n	DI_n

Figure 2: Decision Interval window of distributed DTP-PA algorithm

The proposed mathematical mechanism is designed uniquely to function for achieving the desired reliability in a multi-event situation as compared with existing systems [28] in this context.

IV. RESULTS AND DISCUSSION

A. Simulation Experiment Setup and Analysis

This section presents the evaluation of DTP-PA scheduler for heterogeneous traffic flows. It works in three stages, namely source to an intermediate node, intermediate to sink and sink to source nodes via intermediate nodes. This distributed strategy is applied to increase the packet delivery ratio with minimum energy consumption and delay. In addition, it also reduces the load on the base station. DTP-PA is evaluated over 2, 3 and 4 hops with a varied number of traffic nodes. However, the evaluation is shown for 35, 61, 76, 81, and 101 nodes. The levels of the buffer are defined as shown in Equation (10). A runtime experimentation view is depicted in Figure 3 which is implemented in ns2 [30].

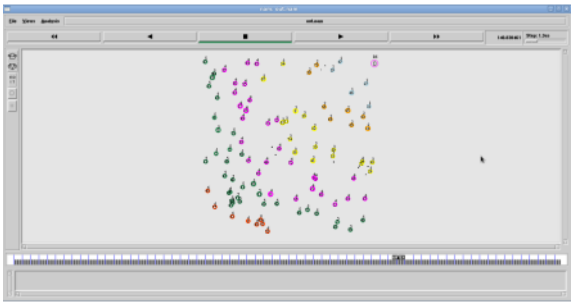


Figure 3: Screenshot of the simulation environment setup for DTP-PA protocol evaluation

$$b_{max} = \left\lceil \frac{2.3}{3} b_{size} \right\rceil ; b_T = \left\lceil \frac{1.8}{3} b_{size} \right\rceil \tag{10}$$

The tuning parameter α_2 achieves the optimal rate by keeping average 16 packets in the buffer in order to make the processing faster. Network parameters are defined in Table 3.

Table 3
ns2 Simulator Setup

Attributes	Values
Sensing filed area	1000x1000m^2
No. of source nodes	31,41,61,76,81
Transmission range	70m
IF queue size	20 packets
Payload length	36 bytes
Transmit Power	0.660w
Receive Power	0.395w

In the simulation setup, the source nodes are placed in 1000x1000m2 area in such a way that they are at least 2, 3, and 4 hops away from the base station.

The different types of source nodes are joined to each hop node in order to generate heterogeneous traffic scheduling. Considering the transmission range, source nodes are placed so that they will join at a different location to different hop nodes. The length of the buffer is carefully chosen from an operational point of view. In order to make data transmission collision-free, the CSMA/CA MAC protocol is chosen for effective data transmission. Due to page limitation, the analysis section covers only important demonstration.

The decision interval period and cooling window size are set in view of propagation delay. The simulation ran five times and put forth the average of them in each analysis part. In the below discussion the performance analysis of 35 nodes are taken into account, and at the end, the packet delivery ratio of 35, 61, 76, 81, and 101 is demonstrated. However, except buffer management, the other underlying protocols like routing efficiency, MAC support for delay constraint or collision scheduling, and PHY frame reserve length provision or power management are not taken into account for this reported work. It may be taken up for further enhancement of this proposed work considering the application specific needs and time bounds.

Figure 4 shows the aggregate throughput of DTP-PA; it is presented over five experiments of each time period mentioned. The comparison is shown with existing protocols, namely PCS and FCFS mechanism. Here, two types of flow are considered, viz. regular (temperature) and priority (oximeter-O2 saturation level). The graph illustrates that the proposed DTP-PA scheduler presents throughput improvement approximately 5%-7% against PCS and 7%-9% against FCFS mechanism, respectively.

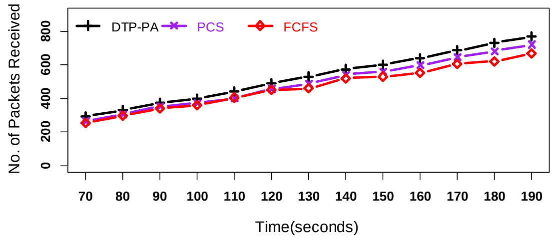


Figure 4: Throughput comparisons over variable period

The adjusted buffer level is based on the traffic load and flexible reporting rate to optimise the network utilisation efficiency by using each decision interval. This dynamic reporting rate based on the level of the buffer takes the decision of increasing or decreasing the traffic flow which results in low congestion and high throughput of the overall network. Besides, it also shows the significant improvement in regular traffic rate when the proportion of regular traffic and priority traffic is the same.

The throughput performance of priority flow and regular flow of priority scheduler is demonstrated in Figure 5 for small size network. The scheduler scans the buffer concerning priority bit and hops number; selects the packet which has high priority bit, i.e. 2 and highest hop count among them. Afterwards, its hop count is incremented by 1 and forwarded to next hop. This strategy of data scheduling has shown significant improvement for priority-based traffic for those who were occurred at long distance, and they will always get served first at each intermediate node. This strategy brings less delay experience to the leaf nodes.

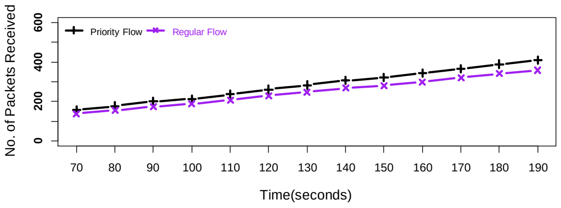


Figure 5: Traffic based throughput comparison

The graph illustrates that the scheduler transmits high priority first and because of that, the specific throughput of high priority packets over the regular traffic is comparatively more. However, in small size network though noticeable differences are not highlighted, but after putting the scheduler into dense network setup, it has shown the more significant difference of improvements over the regular traffic flows.

Figure 6 shows the packet delivery ratio, is examined for 35, 61, 76, 81, and 101. However, the PDR is purposefully shown for more number of node simulations in order to put its test results. However, other assessments of performance metrics are shown for 35 nodes. The graph illustrates ratio little down with the increase in hops and displays little steady from node volume 81 nodes. However, DTP-PA using EDF manages to keep the PDR ratio above 76% compared to 72% and 65% against PCS and FCFS scheduling, respectively of size 101 nodes.

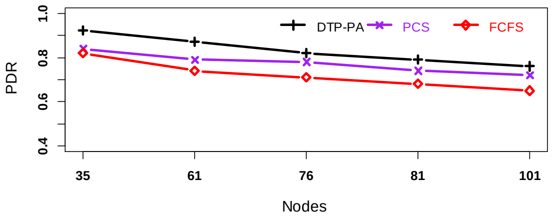


Figure 6: Packet delivery ratio comparisons

The close analysis shows that the buffer level management helps to keep the delivery ratio at higher end compared to traditional approaches. Though the delivery difference is less but it makes the good impact on long-distance priority traffics or for delay bound applications (if it will be applied).

The DTP-PA approach has experienced less delay comparative to PCS and FCFS due to efficient time-based reporting rate mechanism after every specific interval, as demonstrated in Figure 7.

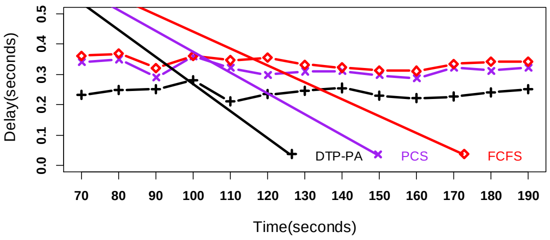


Figure 7: Delay comparisons over different time

The second reason is that the buffer level-based operations help to prevent the occurrence of congestion. For that reason, packet drop ratio and unnecessary retransmission of packet delivery decrease significantly. Sometimes, the set of control packet increases the level of congestion. Therefore, to avoid it, the decision interval is used to avoid the signal interference by taking the cooling window large in size. This aspect significantly showed the less delay with minimum power consumption. However, the analysis of delay constraints to each traffic flow is out of scope for the analysis. The variance in average delay consumption is shown on average 70ms-150ms; and 80ms-180ms against PCS and FCFS mechanisms in underlying topology configuration.

Figure 8 shows the waiting time in a buffer is reduced for priority-based flows over regular. Network delay of high priority is reduced around 20ms-37ms over five hops multi-hop topology as compared with regular traffic. However, it has shown the significant improvement in the delay when hop count goes over 10. However, the waiting time of data packets in the buffer hampers the overall network delay. Therefore, our approach is useful for delay sensitive applications wherein the small time period is also measurable for taking action in time or measuring some parameter based on the time limit. Specifically, when it targets the healthcare application; however, hard time constraints are not in the scope of DTP-PA.

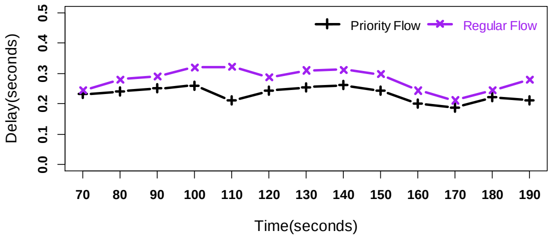


Figure 8 Traffic based delay comparison over different time

B. *TestBed Setup and Result Analysis*

The TestBed includes 2.4GHz nRF 24L01 Nordic, and Arduino Nano ATmega328 microcontroller for processing the data packets at various routing devices called as repeater devices. The nodes are placed randomly in the garden area during the experimentation in such a way that they will join each other and form multi-hop topology automatically. The node physical view is shown in Figure 9.

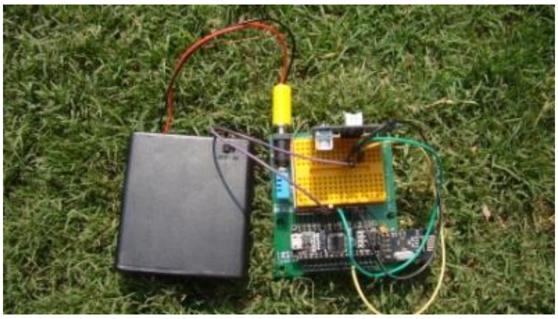


Figure 9: Top views of 2.4GHz RF with ATmega328 microcontroller node used for experimentation

The TestBed setup is depicted in Figure 10. A TestBed consists of 6 +1 nodes (six nodes are slave, and one is master). Each node has a range around 70m as per specification. During experimentation, purposefully they are placed out of range of base station so that they can join to the nearest another device for routing the sensed data.

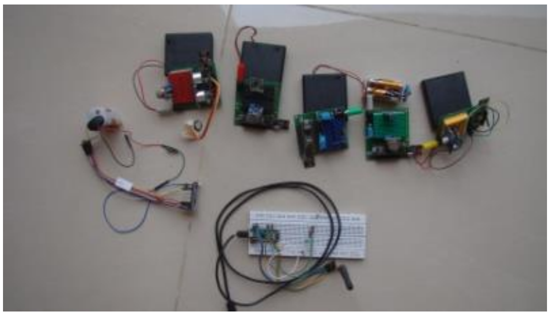


Figure 10: TestBed Setup (6+1) nodes for evaluation of DTP-PA protocol

Furthermore, self-joining and self-routing are the core features of each sensor node. Each sensor node is equipped with four sensing devices, namely temperature, humidity, water level sensor, and air quality. The data rate is set to 250kbps, and all are battery powered. The packet inter-departure time is set to 0.1second. Figure 11 shows an outcome of DTP-PA protocol regarding the delay, i.e. propagation. Observations state that repeater node performs data classification and scheduling efficiently. Each repeater node checks the type of packet and schedules accordingly. A packet which is travelled from the long distance with having high priority is scheduled first over the regular packet.

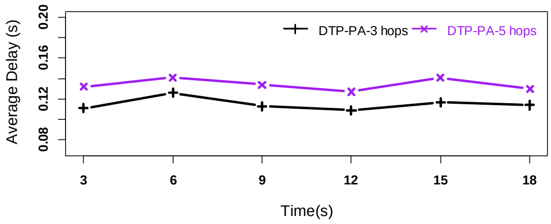


Figure 11: Analysis of delay with variable time period over the 3 hop and 5 hops mesh topology

It is observed that a high priority event experiences less delay comparatively with other events. The average delay is shown around 0.12 seconds over the 3 and 5 hops topology.

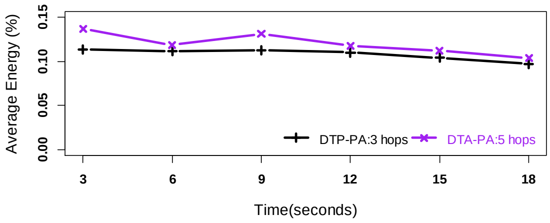


Figure 12: shows the average energy consumption in 3 and 5 hops topology

Figure 12 plots the average energy consumption over the variable hops in the mesh routing topology. The very minimal difference is noted in-between the 3 and 5 hop topology. It can be noted that the processing overheads are put on each repeater node. It reduces the load on the base station. The purpose of the distributed approach is to recover the lost data immediately and classify and schedule the high priority first. It is useful for delay sensitive applications. The average energy consumption in terms of percentage is noted at approximately around 1.2%.

Figure 13 illustrates the packet delivery ratio of DTP-PA protocol in a mesh topology. It is tested by varying the number of hops. The DTP-PA protocol shows the packet delivery ratio above 98% and the average PDR goes around 99% and above. Therefore, it can be noted that the distributed data processing approach works better over the centralised approach in the heterogeneous wireless sensor networks.

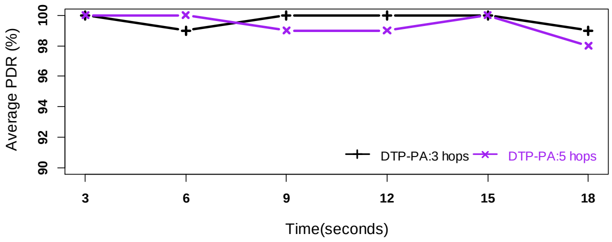


Figure 13: Analysis of Packet Delivery Ratio with variable experimentation time period

The auto retransmission mechanism improves the packet delivery ratio over multiple hops. However, DTP-PA has shown 94% PDR ratio in absenteeism of auto retransmission mechanism. Figure 14 describes the network throughput of DTP-PA protocol. DTP-PA protocol shows the excellent throughput by incorporating the distributed data packet processing approach. DTP-PA has shown approximately 38229bps using 3 hop topology and 37930bps using five hop topology per second with 0.1 seconds inter-packet departure time with three sensing devices.

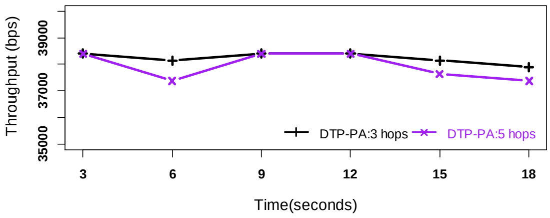


Figure 14: Comparison of network throughput of DTP-PA over 3 and 5 hops topology with different experimentation time.

The auto retransmission mechanism with priority approach has shown remarkable performance regarding network throughput. It can be noted that all successfully received packets are error-free. Therefore, the DTP-PA can be used for delay sensitive applications.

V. CONCLUSION

The stated work in this paper gives the optimum solution to address the problem of unfairness treatment to the long distance travelled packets. The flexible scheduler using EDF approach is presented to transport the high priority packets in the multi-hop sensor network, and its scalability is tested using various discrete scenarios. The DTP-PA scheme outperforms against a traditional FCFS mechanism for priority-based traffic flows. The mathematical model is designed and validated for priority flow traffics. Moreover, the outcome of DTP-PA is examined against the FCFS approach and PCS scheduling scheme, particularly using metrics like throughput, packet delivery ratio, energy consumption, and delay. The analysis reports show that the proposed DTP-PA illustrates 7% and 5% better performance over traditional FCFS approach and PCS scheduling mechanism, respectively in the presented underlying network setup. Moreover, over the TestBed, it has shown a 99% PDR ratio with minimal delay. Furthermore, this approach can be extended to time constraints applications. Besides, priority-based scheduling approach would be incorporated into beacon-enabled network using flexible backoff counter for prioritised traffic flows over no-priority traffic flows.

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