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Performance Evaluation and Optimization of Key Performance Indicators of WSN Metrics

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Abstract— ***This research seeks to address the problem of congestion in WSNs by identifying the metrics that strictly relate with the philosophy and design of WSNs. From various study on WSN, the focus on experimental Key Performance Indices is yet to be adequately addressed considering periodic event sensing. Consequently this work proposes a congestion management scheme that will detect and overcome the congestion prior to its instantaneous occurrence called Priority Early Detection Congestion Avoidance Mechanism (PEDCAM). The main feature of the proposed algorithm is priority early detection of the congestion pre-occurrence, control optimization and buffer scheduling. With PEDCAM, a comprehensive trace file validation environment based on C/C++ OPNET Modeller was developed. Using this environment, two other similar schemes viz: CODA and CONSEQ which also performs distributed rate adjustment of the FIFO queues on the sensor nodes were compared with PEDCAM. The results from the performance evaluation and optimization of the WSNs KPI metrics were obtained. It was observed that the normalized throughput for CONSEQ = 33.55%, CODA = 33.22% and PEDCAM = 33.23% respectively. Similarly, the packet service rate was 33.33% for all the three schemes. The latency for the three schemes offered 44.74%, 36.84%, and 18.4% respectively, while the queuing length variations gave CONSEQ = 29.41%, CODA = 31.29% and PEDCAM = 39.30%. It was therefore concluded that PEDCAM demonstrates a reliable congestion technique on the basis of the studied KPIs. This analysis can enables experts examine the behavior of sensor nodes vis-à-vis queuing optimization, their impact to congestion in WSNs before making actual deployment with PEDCAM scheme.***

Index Terms—**Congestion management, PEDCAM, WSNs, queuing, data transmission.**

I. INTRODUCTION

Due to advances in wireless communications and electronics over the last few years, the development of networks of low-cost, low-power, multifunctional sensors has received increasing attention. These sensors are small in size and able to sense, process data, and communicate with each other, typically over an RF (radio frequency) channel. A sensor network is designed to detect events or phenomena, collect and process data, and transmit sensed information to interested users. Basic features of sensor networks are [1]:

i. Self-organizing capabilities
ii. Short-range broadcast communication and multihop routing
iii. Dense deployment and cooperative effort of sensor nodes
iv. Frequently changing topology due to fading and node failures
v. Limitations in energy, transmit power, memory, and computing power

These characteristics, particularly the last three, make sensor networks different from other wireless ad hoc or mesh networks. By combining small sensors, these low-power devices can offer an innovative platform that has numerous important uses and applications [1]. Some of the applications and technical challenges are discussed next.

A. Applications of WSN

i. General Engineering

These are found in Automotive telematics, Fingertip accelerometer virtual keyboards, Sensing and maintenance in industrial plants, Complex industrial robots, Aircraft drag reduction, Smart office spaces, Tracking of goods in retail stores, Tracking of containers and boxes, Study of human interaction and social behavior, Commercial and residential security.

ii. Agriculture and Environmental Monitoring

These are found in precision agriculture, planetary exploration, geophysical monitoring, monitoring of freshwater quality, Habitat monitoring, Disaster detection and Contaminant transport.

iii. Civil Engineering

Such as in monitoring of structures, Urban planning, and Disaster recovery

iv. Military Applications

These are found in (i) Asset monitoring and management, (ii) Surveillance and battle-space monitoring, (iii), Urban warfare, (iv) Protection of Sensitive objects such as atomic plants, bridges, retaining walls, oil and gas pipelines, communication towers, ammunition depots, and military headquarters can be protected by intelligent sensor fields able to discriminate between different classes of intruders (v), Self-healing minefields and (vi) Health Monitoring and Surgery as found in Medical sensing and Micro-surgery

B. Technical Challenges of WSN

Addressing issues like traffic congestion in populated networks of sensors requires a fundamental understanding of techniques for connecting and managing sensor nodes with a communication network in scalable and resource-efficient ways. Clearly, sensor networks belong to the class of ad hoc networks, but they have specific characteristics that are not present in general wireless networks. Ad hoc and sensor networks share a number of challenges such as energy constraints and routing. On the other hand, general ad hoc networks most likely induce traffic patterns different from sensor networks, have other lifetime requirements. Network

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nodes are equipped with wireless transmitters and receivers using antennas that may be omnidirectional (isotropic radiation), highly directional (point-to-point), possibly steerable, or some combination thereof. At a given point in time, depending on the nodes' positions and their transmitter and receiver coverage patterns, transmission power levels, and co-channel interference levels, a wireless connectivity exists in the form of a random, multihop graph between the nodes. This ad hoc topology may change with time as the nodes move or adjust their transmission and reception parameters. Because the most challenging issue in sensor networks is limited and unrechargeable energy provision, many research efforts aim at improving the energy efficiency from different perspectives. In sensor networks, energy is consumed mainly for three purposes: data transmission, signal processing, and hardware operation [2]. It is desirable to develop Congestion scheme that is energy-efficient and who's processing techniques improves KPI requirements across all levels of the protocol stack and, at the same time, minimize message passing for network control and coordination. The various metrics for WSN is presented below.

C. Performance Metrics of WSN

To discuss the issues raised above in more detail, it is necessary to examine a list of metrics that determine the performance of a sensor network:

i. Energy efficiency/system lifetime: The sensors are battery operated, rendering energy a very scarce resource that must be wisely managed in order to extend the lifetime of the network [3],[4].

ii.. Latency: Many sensor applications require delay-guaranteed service. Protocols must ensure that sensed data will be delivered to the user within a certain delay. Prominent examples in this class of networks are certainly the sensor-actuator networks.

iii. Accuracy: Obtaining accurate information is the primary objective; accuracy can be improved through joint detection and estimation. Rate distortion theory is a possible tool to assess accuracy.

iv. Fault tolerance: Robustness to sensor and link failures must be achieved through redundancy and collaborative processing and communication. The queuing length plays a very vital in this regard.

v. Scalability: Because a sensor network may contain thousands of nodes, scalability is a critical factor that guarantees that the network performance does not significantly degrade as the network size (or node density) increases.

vi. Transport capacity/throughput: Because most sensor data must be delivered to a single base station or fusion center, a critical area in the sensor network exists, whose sensor nodes must relay the data generated by virtually all nodes in the network. Thus, the traffic load in WSNs has a paramount influence on system lifetime, packet end-to-end delay, and scalability. Because of the interdependence of energy consumption, delay, and throughput, all these issues and metrics are tightly coupled. Thus, the design of a WSN necessarily consists of the resolution of numerous trade-offs, which also reflects in the network protocol stack, in which a cross-layer approach is needed instead of the traditional layer-by-layer protocol design.

II. LITERATURE REVIEW

Various works on WSN have been carried out in the areas of congestion management schemes. In [5], explained that various optimization methods are used to decrease power consumption and improve performance of wireless sensor networks. A cross-layer approach for improving performance and energy preservation in wireless sensor networks was reviewed and state of the art is presented. The paper developed a benchmark methodology and performance evaluation model of various optimization methods for wireless sensor networks. In [6] and [7], a linear dependent WSN topology was proposed for a pipeline structure. Their work was based on the LRRCC scheme must leveraged on Resource Reservation Protocol module (RSVP) which was achieved through the cooperation of three processes: the RSVP Application interface process, the RSVP process, and the traffic control process for the system architecture. There are several congestion detection and avoidance protocols that have been developed. One of the popular congestion avoidance schemes is Congestion Detection and Avoidance (CODA) (Chieh-Yih et al, 2004) [8], which is an upstream congestion mitigation strategy where the congestion detection mechanism is based on queue length at the intermediate nodes and channel load. Another popular protocol Event to Sink Reliable Transport (ESRT) (T.Sankarasubramaniam et al 2003) [9], provides event-level reliability from sensors to sink by controlling the congestion in the network. Compared to these end-to-end congestion control protocols, there are also several hop-by-hop congestion control protocols (Kim, Sankar, and Lee, 2007) [10], (B.Scheuermann, et al , 2007) [11], (Yi and Shakkottai, 2007) [12] and (J.Helonde et al. 2010) [13] where congestion is controlled at each hop level of the network instead of the base station, and these protocols show improvement in performance and faster congestion control. I.F Akyildiz,et al (2006) [14] used various parameters like received signal-to-noise ratio, relay traffic, buffer length, and energy level of the nodes to determine if it can participate in the communication or not. C.Basaran et al (2010) [15] proposed Control of Sensor Queue (CONSEQ) as a cross-layered congestion control mechanism where congestion is estimated based on queue length and the channel conditions at a one-hop neighborhood with no optimization analysis. X.R et al (2008) [16] proposed Real Time Communication System (RCS) which employs prioritized queuing to provide service differentiated, soft, real-time guarantees where there are multiple queues maintained at the nodes for service differentiated applications. H.J and Balakrishman (2004) [17] presented a locality driven congestion control solution which is based on common demands on the behavior of sensor networks as well as a multi-event Congestion Control Protocol scheme by Hussain, F.B et al (2008) [18]. Many other works by various authors were fully captured by

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A.N.Uzoamaka, 2015 [19]. No work has discussed optimization control before priority scheduling. This paper observes some limitations of the existing schemes to include the following:

1. Most of the schemes require huge experimental set up to investigate on queuing optimization.
2. Formal mathematical models make for complexity in most congestion control proposals.
3. Most of the proposals lack in-depth contributions in quality of service metrics such as throughput effects, packet service rate, buffer variation effects etc.
4. Congestion mitigation is still lacking in mission critical testbeds as a result of queuing effects.
5. The scarcity of an efficient congestion control protocol for handling diverse data within a single node is a major shortcoming of existing schemes leading to the development of the proposed PEDCAM.

In this work, the PEDCAM protocol uses an effective early congestion detection mechanism which addresses both node and link level congestions. The KPI and its optimization validation will be presented.

III. SYSTEM DESIGNS AND ANALYSIS

For the purposes of the KPI analysis, a queuing model for a typical WSN is developed and shown in Figure 1. Each node is given a label using IP addresses for tagging and identification. In deploying the wireless sensor nodes, a novel queuing model with PEDCAM Deterministic Queuing Resolution (DQR) was used in the buffer algorithm of the sensor nodes as shown in Figure 2.

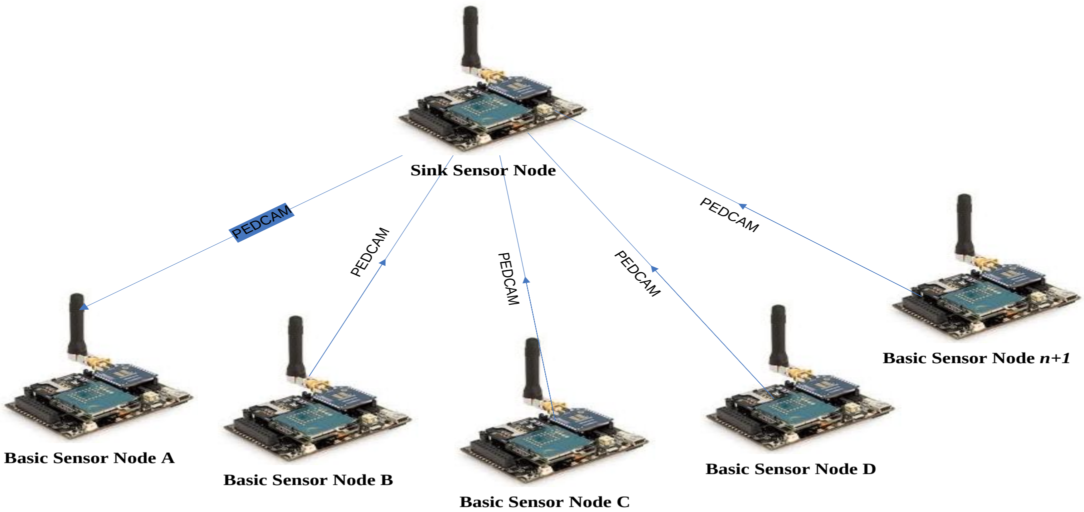

Fig 1: Proposed PEDCAM System Architecture

In the model shown in Figure 1, the efficiency of DQR was derived from the architectural layer of the node which accounts for its robustness during a sensing operation depicted in Figure 2. The sensed queuing parameters were captured in terms of Humidity Queues (HQ), Link Indicator Queues (LIQ), Receive Signal Strength Queues (RSSQ), and battery voltage Queues. Figure 2 shows the derived queuing model in a typical WSN architecture, where **N=** number of connected TelosB base stations. $\mathbf{G_{A=}}$ general arrival process. $\mathbf{G_{T=}}$ general transmission process. **λ=** arrival rate. **I** = index of node number

In a populated scenario, the service time per transmission is given as:

$$T = T_T + T_D(X) + T_{ACK} \qquad (1)$$

Where,

T_T = transmission time, $T_D(X)$ = random transmission delay, T_{ACK} = acknowledgement time

The generalized throughput of the queuing model given as:

$$S = \frac{\sum_{i=1}^{M} \pi_i iT}{\sum_{i=0}^{M} \pi_i \left(iX + Y\right)} \qquad (2)$$

Where, S = the expected throughput

π_i = stationary distribution

T = packet length

$X = T + t_o + t_p$ = transmission period

$Y[2\tau / X]X + X$ = time that channel become idle between rounds

The expected delay of a packet in the transmission sequence is given by

$$\text{D}=\frac{\text{M}}{\text{S}}-\frac{1}{\lambda} \qquad (3)$$

Where,

M = number of nodes

S = Throughput

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$\frac{1}{\lambda}$ = mean of exponential distribution

λ = arrival rate

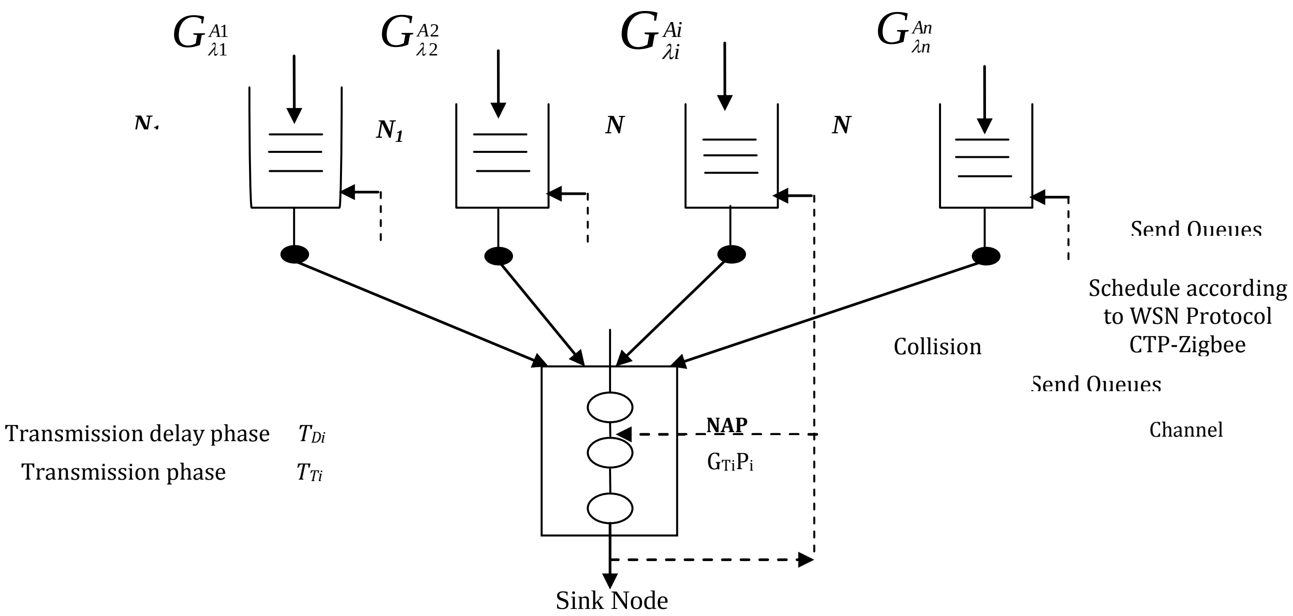

Fig 2: A Queuing Model for TelosB WSN

The WSN delay is obtained by dividing the number of data packet sent by the overall duration of transmission (T_{Di}). This now gives

$$N_d = {}^{N_P}/_{T_T} \quad (4)$$

At the buffer level, the queuing length if given by Q_L

This work proposes a number of packet metrics to evaluate the performance of WSN under congestion. The metrics considered includes: Priority Normalized Throughput, Packet Service Rate, Latency Variations and Queuing Length Variations. Since congestion degrades channel quality, increases energy consumption, and leads to node starvation or saturation in a worst case scenario, to mitigate congestion effects, the proposed PEDCAM algorithm seeks to achieve these goals viz:

I. Increase network efficiency to reduce consumption and improve channel quality.

ii. Avoid starvation to improve the per node end –to-end throughput distribution and WSN efficiency.

A. Simulation Test bed Procedure

In this research, the proposed PEDCAM algorithm for sensor node efficiency was deployed in a validation testbed in Fig.3, using OPNET Modeller 9.1. The simulation settings for evaluating the proposed algorithm is as follows: 8 sensors were randomly deployed in 100 ×100 m^2 sensor field. The transmission range of each sensor was set to 30*m*. Maximum communication channel bit rate was set to 250*kbps*. Each packet size was set to 128bytes. The control packet size (RTS, CTS, and ACK) was set to 3 bytes. The maximum receive lifetime was set to 0.5J and the weight used in the weighted moving average distribution set to 0.1. In the setup, the sensor nodes emulated the MAC layer protocol while sensing and sending the traffic parameters to the sink. For optimal simulation response, the node buffer size was varied in consonance with the data rates from 10 to 250kbps. Each queue size was set to hold maximum of 15000 packets. The total queue length for the node was set to 10000 packets. Throughout the simulation, this work used a fixed workload that consists of 7 sources and 1 sink. The initial originating rate was 4pps (packets per second) and maximum originating rate was limited to 16 pps.

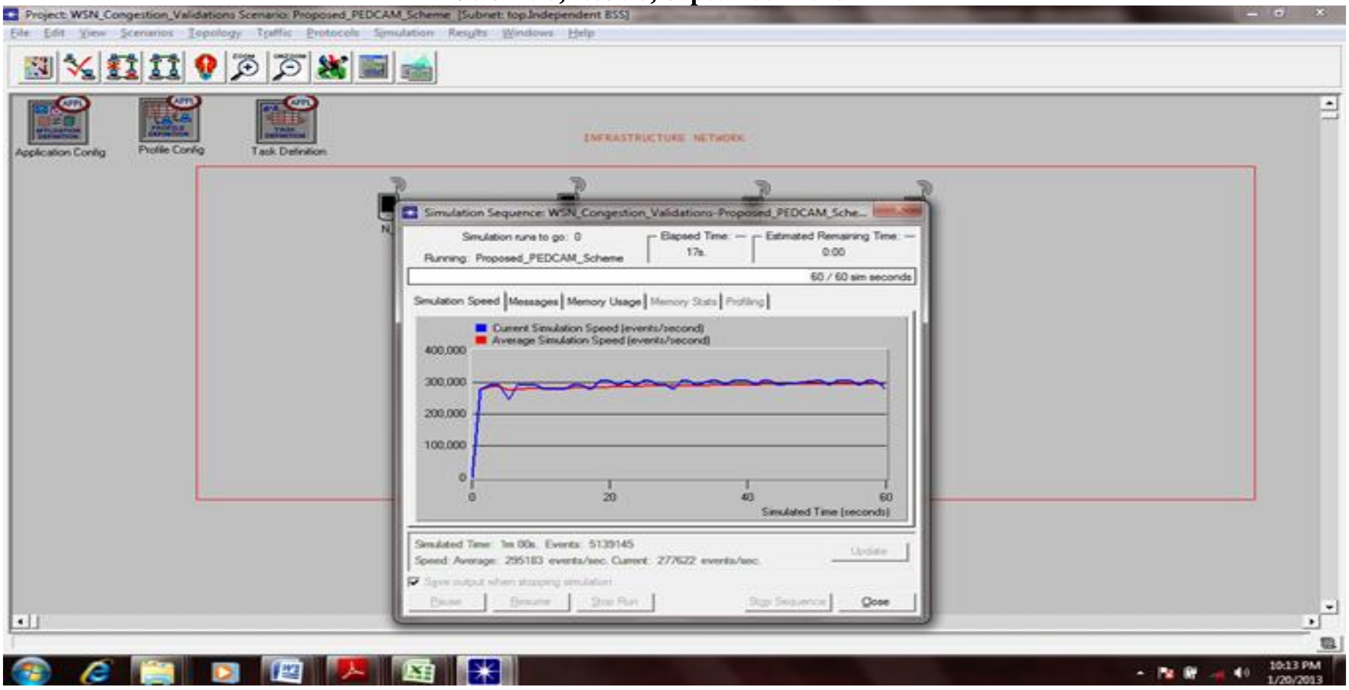

Fig 4: A validation simulation scenario for the proposed PEDCAM algorithms

The procedure on how the simulation is carried out is as follows:

i. OPNET tool was used in carrying out a composite validation simulation using its event script imported from the developed MATLAB algorithm.

ii. The simulation trace file is created and the trace events (discrete events) are configured to remain compatible with C based environments like MATLAB, MIDE, Catastelia, OMNET++, NS2-PT++ and stored in the Opnet_model logs.

iii. Next the object palette tool was used to generate the WSN block sets and imported into the work area environment mapped with 100x100m^2 sensor field.

iv. The simulation design involving the use of application configuration tabs, objects, tools are used to configure all the parameters.

v. The workflow is then enabled i.e characterizing traffic mix in the trace file event (importing the algorithms).

vi. The traffic mix is configured which involves the background traffic flows based on the configured scenario algorithms of PEDCAM, CODA and CONSEQ.

vii. Configure the discrete event parameters viz the simulation time, parameters, logs etc.

viii. Enable the event statistics, animation and results window.

IV. RESULTS AND DISCUSSION

A. Verification of PEDCAM

This work has compared the proposed PEDCAM algorithm with CODA [8] and CONSEQ [16] as they both perform the distributed rate adjustment of the FIFO queues on the sensor nodes but not scheduling of the FIFO queues.

ix. Run discrete event simulations and collect results.

Generation of datasets and validation plots was obtained from the above procedure. In this work, the term buffer and queue were interchangeably used to express the traffic conditions on the nodes. The three schemes and their algorithms were setup in concurrent scenario event which lasted for 120secs

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So in order to quantify the performance of the proposed PEDCAM scheme, an experimental validation procedure was set up in the OPNET simulation environment taking cognizance of the common metrics for the three scenarios. In the new environment involving a production testbed, signal measurement tools or software could be used to carry out a validation study which will definitely not have much

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discrepancy with the study in a simulation context. The essence of a simulation analysis is to enable this work to have good basis for its justifications. In this work, an extensive simulation verification to evaluate the performance of proposed PEDCAM algorithm is now presented.

B. Performance Evaluation

i. Throughput Periodic Workload

The periodic workload represents a typical monitoring sensor network in which the sensor nodes generate readings at varying time intervals down to the sink. In the scenarios, each node sources traffic at the rate specified and forwards same to the sink. From Fig.5, the normalized throughput behavior is depicted in the plot. The CONSEQ offered 33.55%, CODA yielded 33.22% while the proposed PEDCAM yielded 33.23% aggregate throughput received at the sink. This is evaluated regardless of the node that delivers the data. As shown in Fig. 5, as the offered load increases, the throughput response with time follows a transition from the initial low point to higher values for all the algorithms (CODA, CONSEQ, and proposed PEDCAM).

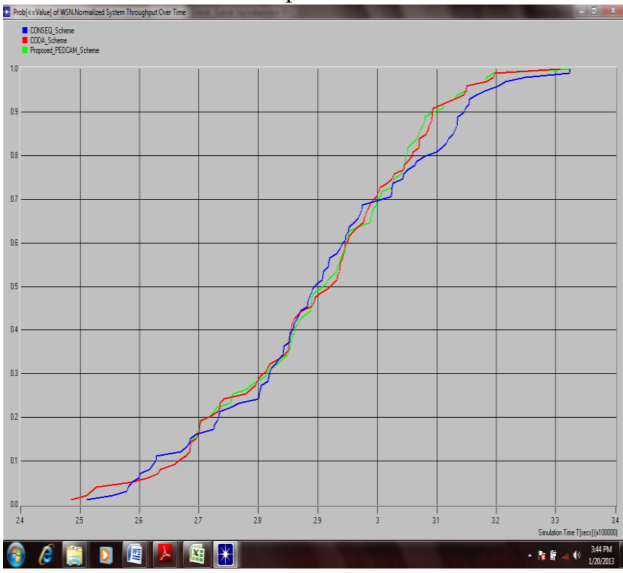

Fig 5: Normalized Throughput Effect

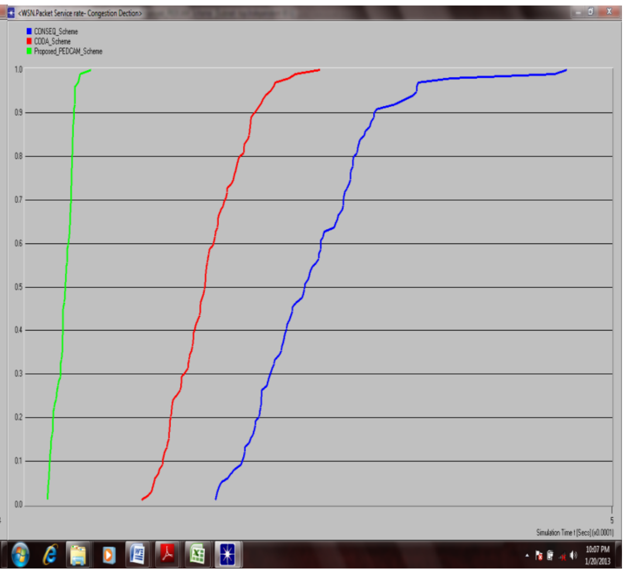

Fig 6: Packet Service Rate Response

Essentially, a similarity response plot was observed for the CODA, CONSEQ and proposed PEDCAM schemes as shown in Fig 5. The classifier optimization controller and scheduler with feedback loop played a major role in the proposed PEDCAM scheme making the throughput to scale gracefully with others with optimal value of 1kbps. Again, the rate limiting feedback loop reduces the transmission rates of the nodes to reach the sink thereby affecting the trends in throughput. Without congestion control, about 62% of the nodes deliver less than one packet reliably every 1sec, making the network to have poor performance. The throughput trend was observed to be a very important primary metric because a poor throughput depicts an inefficient WSN and consequently affecting the overall efficiency.

ii. Congestion Detection/Avoidance Effect with Packet Service Rate

Fig. 6 shows the early congestion detection response plot with a similarity traffic pattern of not more than 33.33% for each of CONSEQ, CODA and proposed PEDCAM. Using the packet service ratio to ascertain or detect congestion for the number of active sources in the network, it is shown that with an increased number of active sources after an initial period of restlessness, the proposed algorithm hardly varies. The other algorithms also show a progressive increase in congestion detection for the number of active nodes in the network. If no congestion control or avoidance is used, the delivery ratio suffers due to the increase on the total number of packets generated. As observed in Fig. 6, an interesting characteristic of the proposed PEDCAM scheme was observed. It is expected that with an increase in the active sources in the network, this would result in a greater number of packet drops without an optimized rate regulation. However, a forward decision index makes full use of the available queues in the nodes by monitoring queue sizes of neighboring downstream nodes before taking a forwarding decision. As a result, packets are transmitted only if they can be accommodated by candidate downstream nodes and not dropped due to congestion. Ideally, the congestion avoidance algorithm cannot absolutely guarantee the complete exclusion of packet drops due to congestion rather it can pre-detect and regulate the thresholds. The packet service rate is dependent on the volume of sensed data/event.

iii. Latency Variations in Periodic Workload

Fig. 8 shows how in the presence of the offered load, the latency response of the three independent algorithms varies. This work measured the latency from the application-level transmit time on the originating node to the time at which the sink receives the packet. Since this work only measures the latency of packets received at the sink, this metric must be viewed with fairness. The primary source of latency in the WSN is the transmission, delay, the queuing delay and the

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feedback loop which reduce the rate of packets a node sends. Latency decreases with increasing offered load. In this work under very light loads, the latency response of the proposed PEDCAM scheme is much lower by 18.42%. However under a very high traffic load, the CODA and CONSEQ schemes scale better as the nodes' packets get through the core of the network closer to the sink. Also CONSEQ has 44.74% while CODA has 36.84% of the network latency. Since the PEDCAM strategy is optimized from inception and the offered load increases, a greater proportion of the packets is received but in a very low fashion as a result of its lower latency response compared with CODA and CONSEQ.

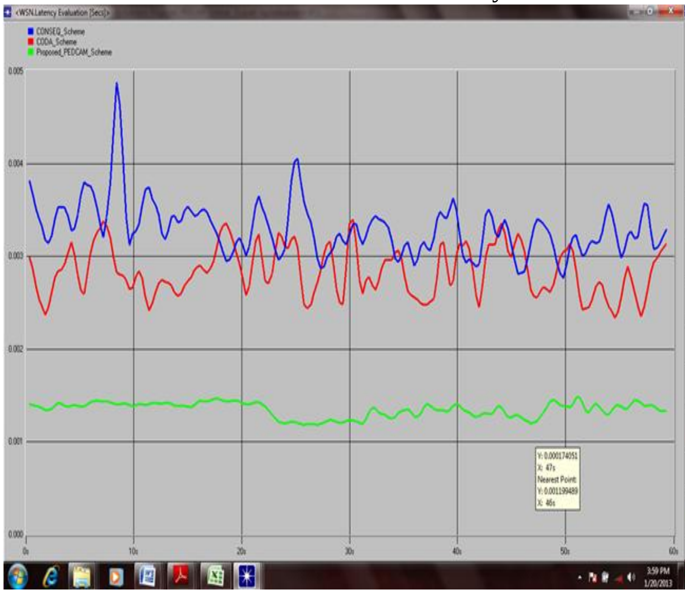

Fig 8: A Plot of Latency Variations

Fig 9: A Plot of Queuing length variations

iv.Queuing Length Variations

Fig 9 shows the queuing length variations with time *t*. Due to the node queue sizes being of paramount importance in the working of the proposed scheme, it was desired to monitor both the instantaneous and the average queue sizes of the sensor nodes in the network with varying number of active sources. It is evident from the plot that the proposed scheme makes greater use of the available FIFO queues in the network with about 39.30% higher compared with CODA(31.29%) and CONSEQ(29.41%) schemes. This result also explains that the buffer occupancy remains relatively higher with an increase in number of active sources. The other schemes show a gradual increase in the average queue occupancy but the proposed mechanism consistently uses the extra available resources to minimize the packet drops due to congestion. For a mission critical real – time network, a consistently high queue occupancy rate is desirable provided that the rate regulation schemes result in zero packet drops. From Fig 9, it can be observed that the proposed PEDCAM buffering scheme also uses large parts of its available queue length for its packet transmission. Again due to the queuing length optimization, the proposed scheme has a better overall memory usage since the packets are forwarded based on the neighbour FIFO queue characteristics. This makes load balancing in such a scenario more effective with increased number of nodes in the WSN. Use either SI (MKS) or CGS as primary units. (SI units are strongly encouraged.) English units may be used as secondary units (in parentheses). **This applies to papers in data storage.** For example, write "15 Gb/cm^2 (100 Gb/in^2)." An exception is when English units are used as identifiers in trade, such as "3½ in disk drive." Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation. The SI unit for magnetic field strength *H* is A/m. However, if you wish to use units of T, either refer to magnetic flux density *B* or magnetic field strength symbolized as $\mu_0 H$. Use the center dot to separate compound units, e.g., "A·m^2."

V. CONCLUSION

This work has presented an improved and a feasible congestion management scheme which was compared with other schemes in the context of normalized throughput, packet losses, buffer occupancy, queuing delay, packet service ratio (μ), etc. The system model was developed while observing that the proposed protocol maintains a moderate queue *Q* to avoid buffer overflow. The congestion detection and avoidance optimizations guarantee energy efficiency of WSN deployments in general. In this paper, the use of low power sensor nodes to collect simulation event data shows that regardless of the congestion status, the KPIs are affected by the environmental conditions and as such, sensor node deployments must be carefully done to sense data accurately. Higher packet delivery ratio owing to energy efficiency achieved via optimized feedback control or rate regulation, scheduling, and better FIFO queue management will in turn account for better buffer utilization for the proposed algorithm in comparison with the conventional mechanisms. In this work, congestion control algorithms were conducted on a high-fidelity, robust WSN test bed based on generic sensor node. Validation approach for congestion metrics used queuing studies while establishing a comparative analysis between CODA, CONSEQ and PEDCAM. The contribution in context is that PEDCAM scheme offers a better contribution to quality of service for WSN deployment leveraging threshold adjustment, buffer occupancy in sensor nodes thereby mitigating congestion effects. With effectiveness and efficiency of any congestion management algorithm, packet error control, faster convergence, lower latency and overall throughput can easily be realized. WSN networks when consolidated can be used with other control systems technologies to achieve long lasting applications.

The recommendations in this research include:

1. The PEDCAM scheme should be integrated in WSN while liaising with industry vendors for such integrations.
2. Complete electronic development automation software could be used for modeling the WSN using FPGA/CPLDS and compared with conventional controllers to observe their performance characteristics.
3. A complete WSN test bed which is scalable and can be upgraded to accommodate various network interfaces should be developed as this will facilitate this research area.

Future research will focus on developing new software architecture for WSN nodes as well as integrating a real time WSN with PEDCAM scheme. Such a WSN facility will consist of a global wired network with programmable and virtualized network elements along with edge wireless access deployments intended to support experimentation with mobile computing devices, embedded sensors, etc.

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[19] Improving Queuing In Wireless Sensor Network Using Pedcam Congestion Management Scheme

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