ADAPTIVE CONGESTION CONTROL PROTOCOL (ACCP) FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

In Wireless Sensor Networks (WSN) when an event is detected there is an increase in data traffic that might lead to packets being transmitted through the network close to the packet handling capacity of the WSN. The WSN experiences a decrease in network performance due to packet loss, long delays, and reduction in throughput. In this paper we developed an adaptive congestion control algorithm that monitors network utilization and adjust traffic levels and/or increases network resources to improve throughput and conserve energy. The traffic congestion control protocol DelStatic is developed by introducing backpressure mechanism into NOAH. We analyzed various routing protocols and established that DSR has a higher resource congestion control capability. The proposed protocol, ACCP uses a sink switching algorithm to trigger DelStatic or DSR feedback to a congested node based on its Node Rank. From the simulation results, ACCP protocol does not only improve throughput but also conserves energy which is critical to sensor application survivability on the field. Our Adaptive Congestion control achieved reliability, high throughput and energy efficiency.

KEYWORDS

Energy Efficient Congestion Control, Event Detection, Traffic Control, Resource Control, Wireless Sensor Network.

1. INTRODUCTION

The emerging field of wireless sensor network (WSN) has potential benefits for real-time system monitoring. A wireless sensor network consists of remotely deployed wireless sensor nodes in a physical phenomenon. The embedded sensors continuously monitor the physical process and transmit information in a multi-hop fashion to a special node called the sink. WSN therefore has three basic characteristics: centralized data collection, multi-hop data transmission, and many-to-one traffic patterns. It means that the nodes closer to the base stations need to send more data packets and their traffic burden will be more severe. This leads to severe packet collisions, network congestion, and packet loss. In most severe cases it even results in congestion collapse.Within the framework of (WSNs), there are many application areas where sensor networks are deployed: for environmental monitoring, battlefield surveillance, health and industrial monitoring control. We use the recent oil find in Ghana and its associated environmental impact as example of one application and describe congestion problem in WSNs in this context. Residents of oil and gas field communities often report incidents of: asthma, respiratory and cardiovascular illnesses, autoimmune diseases, liver failure, cancer and other ailments such as headaches, nausea, and sleeplessness. These health effects could be the result of air contaminant such as Volatile Organic Compounds (VOCs). We envisage the use of wireless sensor network in Ghana to monitor the quality of air in oil and gas field communities. One of the main problems to the success of the monitoring scheme might be congestion in the wireless sensor network.

A typical WSN deployment scenario is illustrated in figure 1. The VOC measurement in the oil and gas field is done by sensors deployed in the field. Information gathered from the sensor nodes is transmitted in a multi-hop fashion to the sink node and then to the gateway computer as shown in Figure1.

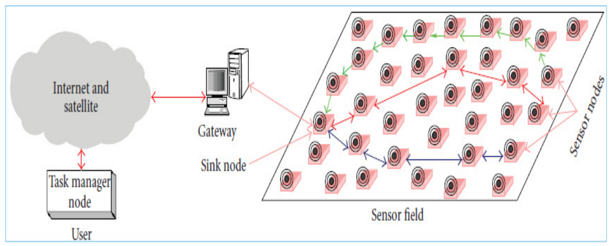

Figure 1: WSN deployment scenario

The traffic in the network is low under light load conditions. When an event is detected, the load increases and transmission of traffic through network approaches the packet handling capacity of the network. Congestion is a state in a network when the total sum of demands on network resources is more than its available capacity. Mathematically:

$$\sum \text{Demand} > \text{Available Resources} \quad (1)$$

In WSNs, congestion happens due to contention caused by concurrent transmission, buffer overflows and dynamic time varying wireless channel condition [1][2][3].

At low levels of VOC pollution when the load is light, throughput and hence the wireless sensor network utilization increases as the load increases thus before point *A* in figure 2a.

As the load increases, a point *A* in Figure 2a is reached beyond which the wireless network utilization (throughput) increases at a rate lower than the rate the load is increased and the wireless sensor network enters into moderate congestion state. As the load continues to increase and the queue lengths of the various nodes continue to grow, a point *B* is reached beyond which the throughput drops with increased load.

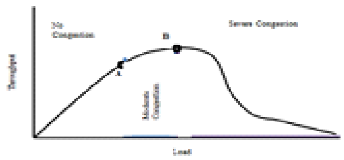

Figure 2a: Levels of Congestion

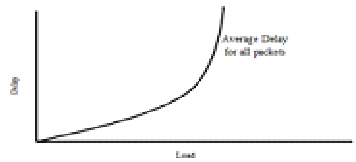

Figure 2b: Effect of Congestion

As seen in figure 2a, the sharp decline of throughput from point *B* is a state where wireless sensor network is rendered inefficient since critical network resource such as energy and bandwidth are wasted. This is a state where bandwidth and buffer overflow have reached a threshold value that any further packet arrival leads to severe network performance degradation. In terms of VOCs monitoring from the oil field, the gateway computer will receive and report data that is *misleading* due to the severe congestion. It is therefore imperative to control congestion in the WSN.

Existing congestion control protocols solve the severe congestion problem using unilateral congestion control approach [4][5][6]. That is the use of either traffic control or resource control strategy. There exists, for instance, an inverse relationship between energy and throughput in these approaches.

$$E = \frac{1}{TP}, E = energy, TP = Throughput \qquad (2)$$

A good energy and throughput performance cannot be achieved through this unilateral approach. In this paper, we proposed the development of ACCP a protocol that uses a switch algorithm to trigger DelStatic (traffic) or DSR (resource) protocol that results in both good energy and throughput performance in WSNs.

The remainder of the paper is organized as follows: Section II provides review on literature, Section III on ACCP Design, Section IV on ACCP NR and Feedback Calculation and the final section on Simulation and Results.

2. LITERATURE REVIEW

A number of previous works have addressed the issue of congestion control in Wireless Sensor Networks [7]. In these works congestion alleviation is either by traffic control or resource control approach.

2.1. Traffic Control

Congestion at a node happens when the incoming traffic volume exceeds the amount of resources available to the node. To alleviate congestion, the incoming data is throttled (referred to as traffic control) mostly using hop-by-hop backpressure. Congestion Detection and Avoidance (CODA) uses Buffer size and Channel condition to detect congestion and then reduces the rate of incoming traffic into the network[8]. The algorithm used to adjust traffic rate works in a way like additive increase multiplicative decrease (AIMD).

The reduction in traffic affects the accuracy level when congestion is transient. In such transient congestion condition, increasing resources such as hop-by-hop bandwidth or additional data path may be a better option to cope with congestion. In addition CODA used Closed Loop end-to-end upstream approach to control congestion. This approach generally has a longer response time when congestion occurs, and in-turn results in dropping of lots of segments [9]. The drop of segments results in the waste of limited energy resources.

Event-to-Sink Reliable Transport (ESRT) is traffic congestion scheme that provides reliability from sensors to sink in addition to congestion control [10]. It jointly uses average local packet service time and average local packet inter-arrival time in order to estimate current local congestion degree in each intermediate node. The use of hop-by-hop feedback control removes congestion quickly.

Priority based congestion control protocol (PCCP) [11] defines a new variable, congestion degree as a ratio of average packet service time over average packet interval arrival time at each sensor node. PCCP uses a hop-by-hop rate adjustment technique called priority-based rate adjustment (PRA) to adjust scheduling rate and the source rate of each sensor node in a single-path routing WSN. The idea is to allow data flow generated by a source node to pass through the nodes and links along with single routing path. With PCCP control, it is easy for sensor nodes to learn the number of upstream data sources in the sub tree roots and measure the maximum downstream forwarding rate. This helps the congested nodes to calculate the per-source rate based on priority index of each source node.

Dynamic Predictive Congestion Control (DPCC) [12] predicts congestion in a node and broadcasts traffic on the entire network fairly and dynamically. To achieve a high throughput value, DPCC uses three rate adjustment techniques: backward and forward node selection (BFS), predict congestion detection (PCD) and dynamic priority-based rate adjustment (DPRA), which are introduced with responsibility for precise congestion discovery and weighted fair congestion control.

In a hop by hop mitigation congestion control protocol [13], congestion detection is based on the following parameters: buffer size, hop count and MAC overhead. When congestion is detected at a node, each downstream node is set with a congestion bit using Node Rank threshold policy. With hop by hop traffic control mitigation strategy, each source node will adjust their transmission rate dynamically based on the RAF feedback from a congested node.

2.2. Resource Control

In resource congestion control schemes when data traffic at a node increases beyond the resources available at that node, the resources to the node are increased to enable the node cope with the excess traffic. In [14] a resource congestion control scheme is developed where large numbers of sensor nodes are turned off during normal traffic. When congestion is detected some nodes are woken up to form one or more additional routing paths called multiplexing paths. The congestion is taken care of by distributing the incoming traffic over the original path and the multiplexing paths. The challenge is that precise network resource adjustment is needed to avoid over- or under- provision of resources. The paper established that when congestion is transient, increasing resources by creating multiple paths around the hotspot effectively increases the number of delivered packets (accuracy level), and saves a lot of energy by avoiding collisions and retransmissions.

3. ACCP DESIGN

Sensitive wireless sensor applications such as medical and hazardous environmental monitoring are loss-intolerant. In such applications it is required to have accurate data (high fidelity) from the source nodes to the sink node for reliable analysis. The use of traffic congestion control in particular during transient congestion may result in the reduction in the accuracy level of data reaching the sink. ACCP uses a sink switching algorithm to switch between traffic congestion control logic (DelStatic) and resource congestion control logic (DSR). DelStatic is developed by introducing backpressure mechanism into NO Ad-Hoc Routing Agent (NOAH). We analyzed various routing protocols and established that DSR has a higher resource congestion control capability.

As shown in Figure 3, an intermediate node receives data traffic from multiple source nodes. The many-to-one modelposes threat to the resources available to the intermediate nodes. If bandwidth and buffer occupancy usage of the node exceeds a threshold, congestion sets in. It is important to control congestion at the intermediate node to guarantee reliable transmission of data generated by the source nodes to the sink node (base station)

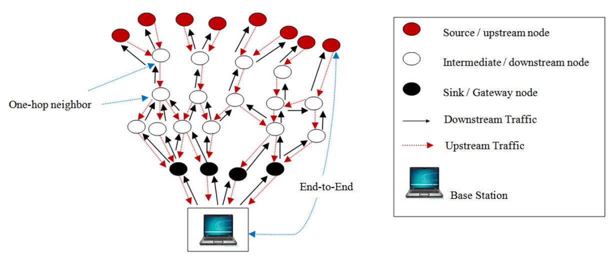

Figure 3: Wireless Sensor Network and data transmission

ACCP is thus based on two mechanisms:

1) Detect congestion at a node using Buffer Occupancy & Channel Utilization Strategy
2) Control the detected congestion by initializing ACCP protocol

3.1. Congestion Detection

To effectively detect congestion, we implement in ACCP a double congestion detection mechanism: channel utilization strategy and buffer occupancy.

3.3.1. Buffer Occupancy

In ACCP the instantaneous buffer occupancy of intermediate nodes is compared to a threshold value. If the threshold value is reached, then congestion may be about to set in. This kind of detection is also seen in [15][16]. In order to avoid late buffer threshold detection, the buffer growth rate is also monitored. An exponentially weighted moving average of the instantaneous queue length is used as a measure of congestion [17]:

$$AVG_q = (1 - w_q) * AVG_q + w_q * inst_q \qquad (3)$$

Where: 1) $AVG_q = averagequeuelengthofnode$

2) w_q = weighted queue length of node

3) $in\, st_q = queuelenghtofnodeatthecurrentinstant$

The average queue length is updated whenever a packet is inserted into the queue. Thus, if AVG_q exceeds a certain upper threshold U, the node is said to be congested. The node remains in a congestion state until AVG_q falls below a lower threshold L. In practice, a single threshold is too coarse-grained to effectively react to congestion. Buffer occupancy alone is not a reliable congestion indicator because packets can be lost in the channel due to collision or hidden terminal situations and have no chance to reach a buffer [18]. ACCP implements both Channel Utilization Strategy and buffer occupancy for effective congestion detection.

3.3.2. Channel Utilisation and Detection Strategy

Channel Utilization is the fraction of time the channel is busy due to transmission of frames. High channel utilization is used as an indication of congestion. When a sensor node has a packet to be sent, it samples the state of the channel at regular interval. Based on the number of times the channel is found to be busy, the node calculates a utilization factor which when above a certain level indicates congestion.

Channel Utilization technique uses Carrier Sensing Multiple Access (CSMA) algorithm to listen to the communication medium before data is transmitted. This is accomplished with the help of the MAC Protocol. In ACCP we used IEEE 802.11 MAC with collision avoidance. The channel occupation due to MAC contention is computed as:

$$C_{occ}=t_{RTS}+t_{CTS}+3t_{SIFS} \quad (4)$$

where

t_{RTS} and t_{CTS} are the time spent on *RTS* and *CTS*, exchanges and t_{SIFS} is the SIFS period.

Then the *MAC* overhead is represented as

$$OH_{MAC} = C_{occ}+t_{acc} \quad (5)$$

where t_{acc} is the time taken due to access contention. That is,
OH_{MAC} is strongly related to the congestion around a given node.

The channel busy ratio is another factor used in ACCP

$$CHBR = \frac{Blnt}{Ttot} \quad (6)$$

Where $Blnt$ represents the time interval that the channel is busy due to successful transmission or collision, and $Ttot$ represents the total time.

To maximize channel utilization detection strategy, the channel detection delay of wireless medium is of essence [19].

$$S_{max} \approx \frac{1}{\left(1+2\sqrt{\beta}\right)}\left(for\beta = \frac{\tau C}{L} \ll 1\right)$$

1) S_{max} = CSMA maximum theoretical throughput approximation
2) β = the measure of radio propagation delay and channel detection delay
3) τ = the sum of both radio propagation delay and channel idle detection delay in seconds
4)C = the raw channel bit rate
5)L = the expected number of bits in a data packet

In achieving a high S_{max}value for good performance, we lowered the β value, which determines how quickly a node can detect idle periods. CSMA efficiency is highly dependent on the β value.

3.2. ACCP Algorithm

To effectively detect congestion, we implement in ACCP a double congestion detection mechanism: channel utilization strategy and buffer occupancy.

The NS2 modular implementation of ACCP is based on DSR and DelStatic protocols. The Dynamic Source Routing (DSR) is an on-demand routing protocol that is based on the concept of source routing where the sender of a packet determines the complete sequence of nodes through which, the packets are forwarded.

Our DSR logic has the capability to reduce the sleeping interval of backup nodes near the congested node so that they become active. One's they become active, they can communicate with each other using DSR Route Discovery and Route Maintenance algorithm to trace the sink node. The goal of DRS is:

- To increase resource provisioning as soon congestion occurs*;*
- To reduce the resource budget as soon as congestion subsides

The DelStatic logic has a backpressure mechanism that allowsa sensor node that has its channel utilization level and buffer occupancy above a threshold broadcasts a suppression message to upstream nodes. It uses an open-loop hop-by-hop data flow strategy until the message reaches the source nodes. Each node reacts to the suppression message by throttling its sending rate or drop packets using packet drop and Additive Increase Multiple Decrease (AIMD) policy. The DelStatic traffic reduction scenario is as shown in Figure 4.

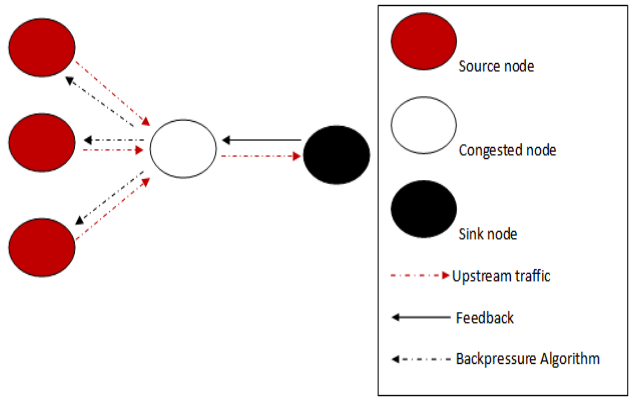

Figure 4: DelStatic Traffic Reduction Scenario

The goal of this work is to allow DelStatic and DSR congestion control protocols to work in one framework by implementing a switching mechanism that is controlled by the sink node. From the framework diagram in Figure 5, congestion detection is done at the node level with a feed sent to the sink to report congestion in the network.

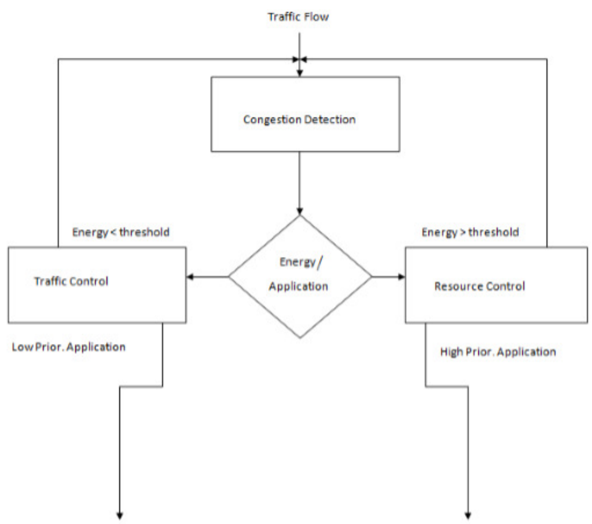

Figure 5: Framework for Adaptive Protocol

The sink uses two important parameters, Energy Remaining (*ER*) and Sensor Application Priority (*SP*) to determine the control to the sending node. Either Traffic Control (DelStatic) or Resource Control (DSR) is triggered by the sink depending on the algorithm below:

Switch (congestion control){
Case 0:
If (Energy > threshold){resource control}
Case1:
If (Energy > threshold){traffic control}
Case2:
If (High- fidelity/priority application){resource control}
Case3:
If (Low- fidelity/priority application){traffic control}
default: congestion control not triggered}

3.3. ACCP NR and Feedback Calculation

With adaptive control, each node calculates its node rank (NR) based on its Buffer level and Channel Utilization Ratio. Here the channel busy ratio represents the interference level and is defined as the ratio of time intervals when the channel is busy due to successful transmission or collision to the total time. After estimating its rank, a node forwards this to its downstream node. When NR crosses a threshold T, then the node will set the congestion bit (CB) in every packet it forwards. On receiving this node rank, the downstream node will first check for the congestion bit. If it is not set, it will simply compute its node rank and adds it to the rank obtained from its previous node and passes on to the next node. On the other hand, if the congestion bit is set, the node sends a feed to the sink node to confirm whether to trigger DelStatic or DSR control. Depending on the energy remaining to the network and the sensor application priority, the sink will send a feedback control to the sending node. This node will in-turn based on the information received from the sink set Rate Adjustment Feedback (RAF) either triggers an alternate path (DSR Control) or transmit it towards the source as a feedback. On receiving the feedback, the source nodes will adjust their transmission rate (DelStatic).

Each node calculates its node rank NR based on the following parameters *BSize, HC, CBHR* and OH_{MAC}, where *BSize*is the buffer size of the node and *HC* is the hop count value.

$$NR = \alpha 1. BSize_{n1} + \alpha 2. H + \alpha 3. CHBR + \alpha 4\, OH_{MAC} \qquad (8)$$

Here $\alpha 1, \alpha 2, \alpha 3$ and $\alpha 4$ are constant weight factors whose values between 0 and 1

Each data packet has a congestion bit (CB) in its header. Every sensor node maintains a threshold T. When NR crosses the value of T the node will set its CB in every packet it forwards.

In Figure 6, for example nodes n1, n2, n3 estimates their rank NR1, NR2, NR3 and forwards this to its downstream node n4 along with data packets. On receiving NR1, NR2 and NR3, n4 will first check their CB value. If it is not set, it will simply compute its node rank NR4 and adds it to the rank obtained from nodes n1, n2, and n3 and passes it to the next node or sink. On the other hand, if the CB is set at n1, n2 and n3, the node n4 will send a feed to the sink about the congestionscenario. The sink node uses energy remaining (*ER*) to the network and priority of sensor application (*SP*) to determine which control to use for feedback

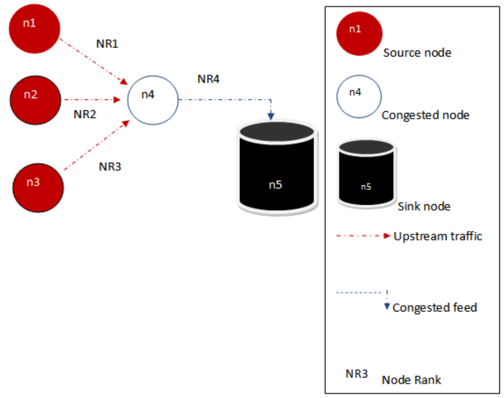

Figure 6: Node Rank (NR) Propagation

The sending node receives either *N1* (DSR Control) or *N0* (DelStatic Control) from the sink as a feedback signal. The sink operates the feedback with request from directed diffusion protocol to disseminate *N1* and *N0* information to the congested nodes.

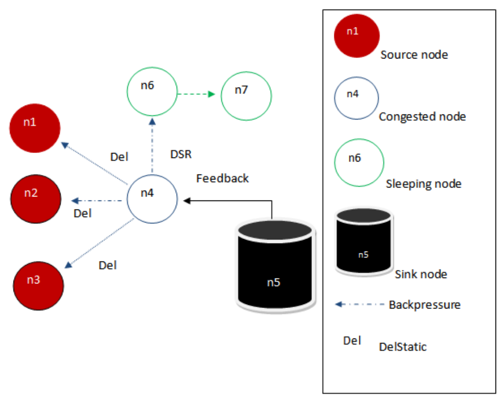

Figure 7: Feedback Propagation

The sending node based on the *N1* or *N0* feedback information from sink calculates its Rate Adjustment Feedback (*RAF*) based on the rank as:

$$RAF = \left(\frac{Arate}{HC}\right) - \sum {}^{OH}/_{MACi} - \sum CBHRi \qquad (9)$$

Where $Arate$ is the arrival rate of packets at node *n* which is given as:

$$Arate = \frac{NP}{t} \qquad (10)$$

Here NP – is the number of packets received and t is the time of interval for the packet transmission.

When feedback (N1) is received, the RAF is propagated to a neighboring node by waking up a sleeping node (DSR Control) as shown in figure 7. On receiving the feedback packet, a neighboring node n6 is signaled to continue data transmission.

When feedback (N0) is received, backpressure algorithm is initiated to the upstream nodes n1, n2, n3 to adjust their transmission rate by dropping packet or triggering a delay in milliseconds. To adjust the rate dynamically, DelStatic protocol uses formulae on node

$$Nrate = Nrate - RAF \tag{11}$$

Thus the traffic rate is adaptively adjusted according to the MAC contention and buffer size. The procedures are repeated for all the hops towards the sinks which are congested.

4. SIMULATION RESULTS

We use ns2 to simulate ACCP protocol. For the purpose of achieving our objective, we modified the routing agent class of NOAH to ‘start-DelStatic’. The ACCP agent interface linkage to MAC component is also modified to enable fix routing in DelStatic Control.

In testing ACCP protocol, sensor nodes of sizes 25, 64 and 150 nodes were deployed using grid and random topology for 10 seconds of simulation time. We set all nodes to have transmission range of 250 meters, interference range of 550 meters and maximum packet in queue of 50. The simulated traffic source is Constant Bit Rate. The performance of DelStatic compared with NOAH protocol using the metrics of throughput and energy consumption.

The result of the simulations is an output trace file that can be used to do data processing and to visualize the simulation with a program called Network Animator (NAM). For this project, NS version 2.34 is used.

4.1. Simulation Parameters

Table 1: Simulation Parameters

No. of nodes	Transmission Range	Interference Range	Mac Protocol	Maximum packet in Queue	Source Agent	Sink Agent
25	250	550	Mac/802_11	50	UDP	null

Simulation Time (seconds)	Source Traffic
10	CBR

Ad-hoc Protocol	Interface Queue Type
AODV	Queue/DropTail/PriQueue
DSDV	Queue/DropTail/PriQueue
DSR	CMUPriQueue
TORA	Queue/DropTail/PriQueue

4.2. Energy Parameters

Set opt(initialenergy) 900 ;# Initial energy in Joules
-rxPower 0.3 \ ;# power consumption in state (watt)
-txPower 0.6 \ ;# power consumption in sleep state (watt)

4.3. Part 1: TADD Protocols

Simulation is conducted on Ad hoc On-demand Vector Protocol (AODV), Destination-Sequenced Distance Vector (DSDV), Dynamic Source Routing (DSR) and Temporarily Ordered Routing Algorithm (TORA) which forms the TADD protocols. The aim is to compare these routing protocols and their performance in terms of traffic bytes generated, end to end delay and throughput. The protocol with a higher metric value, DSR is used for the resource controlling part of ACCP.

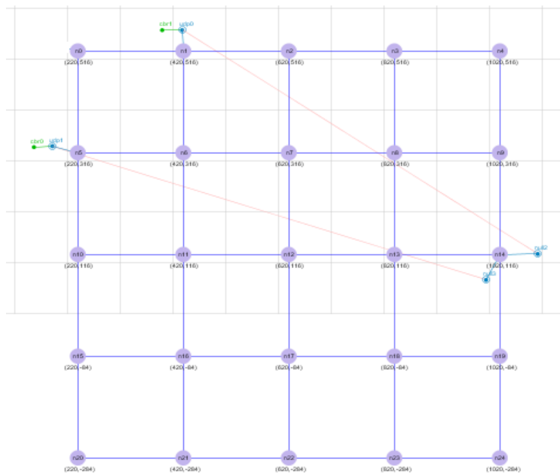

Figure 8: Grid Topology 25 nodes [2 Source / 1 Sink]

In Figure 9, the average end to end delay has a maximum value at '5.5' and a minimum at '0.0'. This is a positive result from DSR protocol. Though 5.5 seconds is on the high side, it is an indication that CBR source data is transmitted over a significant period. Congestion is effectively dealt with during the transmission process.

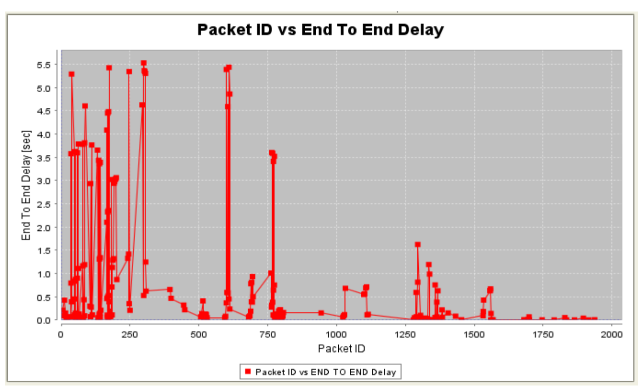

Figure 9: End to End Delay of DSR

4.4. Part 2: NoAH and DelStatic

Our proposed traffic control (DelStatic) protocol is compared with NOAH protocol using metrics of end to end delay and throughput. The generated graph shows a significant throughput increase in DelStatic protocol over a NOAH protocol.

It is observed in Figure 10 that the delay performance of DelStatic is better than that of NOAH. The better delay performance is due to the backpressure algorithm we introduced in DelStatic. The backpressure algorithm is significant in controlling congestion during data packet transmission from source nodes to the sink node.

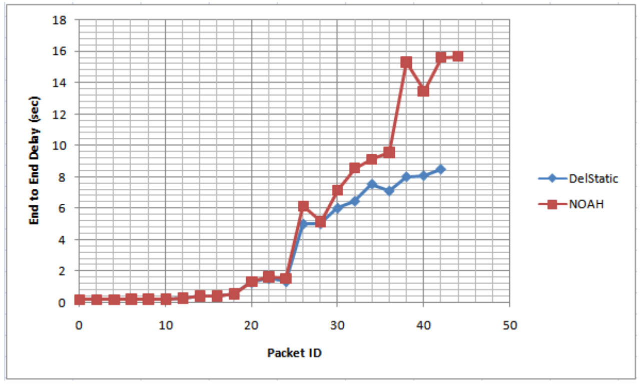

Figure 10: End to End Delay of DelStatic and NOAH

Throughput is the average rate of successful packet delivered to the sink over a sensor network. As seen in Figure 11, the throughput performance of DelStatic is better than that of NOAH during congestion. An average throughput value of 8 is recorded during the initial stages of simulation as compared to 7 of NOAH protocol.

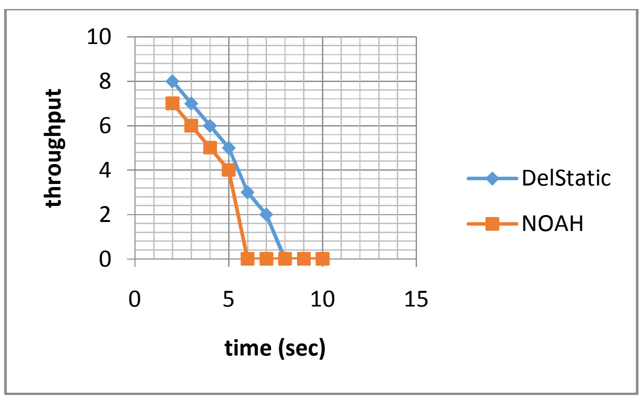

Figure 11: Throughput, DelStatic and NoAH

4.5. Part 3: ACCP

The proposed adaptive congestion control seeks the gains of DSR and DelStatic protocol when used in sensor networks. The metrics of essence are the energy remaining and throughput value which are essential for a successful data delivery and prolonged sensor life deployment.

We first examine the energy performance of DSR and DelStatic. The energy threshold was set at 500 Joules and the simulation runned for 10 seconds. It was noted as seen in figure 12 that, DelStatic after controlling congestion had 600J of energy remaining. This is above the set threshold value. DSR after congestion control had only 100J of energy left.

The sink node of an application using ACCP will use the switching algorithm to trigger DelStatic anytime energy consumption is below a constant threshold. ACCP protocol is energy efficient.

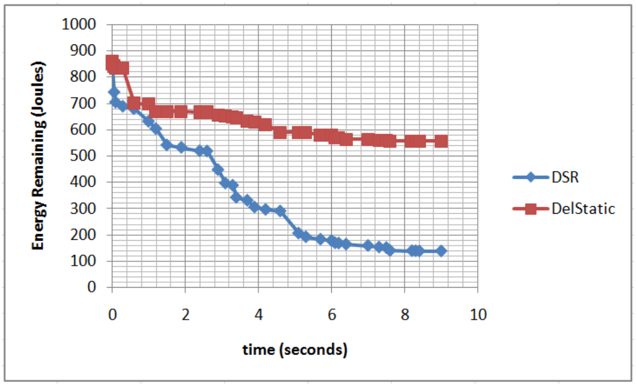

Figure 12: Energy Remaining, ACCP

Figure 13 shows the throughput performance of ACCP. As expected, the figure shows a higher throughput value for DSR as compared to DelStatic.

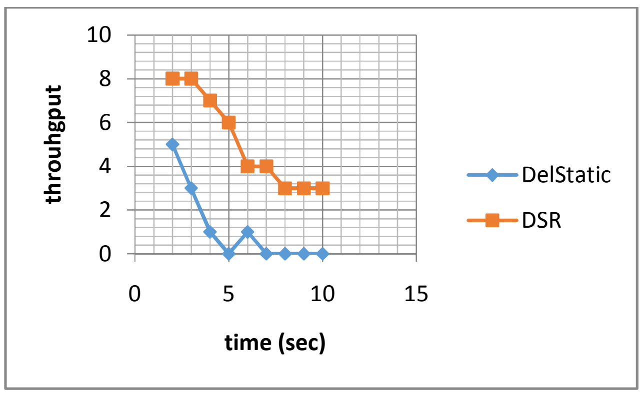

Figure 13: Throughput, ACCP

ACCP protocol is recommended for a wireless sensor network application that requires high data accuracy level and energy efficiency.

5. CONCLUSION

In this paper, we proposed Adaptive Congestion Control protocol which switches between DSR and DelStatic to control congestion in WSNs based on the nodes remaining energy and priority of the application. We developed DelStatic by introducing backpressure mechanisms into NOAH. We chose DSR after our analysis of various on-demand routing protocols showed that DSR has the highest resource congestion control capability. The simulated results show that ACCP is both energy and throughput more efficient than existing traffic only or resource only protocols.

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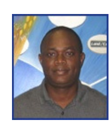

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