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Abstract
There is need for a wireless sensor network (WSN) linear congestion control protocol that can fit into a typical linear topology of a pipeline infrastructure. In such a topology, congestion management must capture congestion detection, feedback signaling with rate Regulator, etc. This work presents LRRCCP in the context linear congestion management for wireless sensor deployment. Three major algorithms were presented with relevant problem formulations to comprehensively address congestion issues in WSN deployments. A conceptual framework for the topology design was presented while addressing the shortcomings of the existing congestion control schemes. To leverage LRRCCP, there must be a comparison with existing congestion control schemes based on selected QoS metrics such as throughput, packet loss ratio, efficiency and traffic flow fairness degree in linear topology wireless sensor network. This work finally outlines the implications of the proposed LRRCCP.

Keywords: Wireless Sensor Network, Congestion, QoS Metrics, Network Topology, Efficiency

1. Introduction

1.1. Background Study
There are so many environmental monitoring wireless sensor network applications. In these applications, a sink gathers data from battery-operated sensors which are deployed on a linear topology. This kind of networks are called “linear wireless sensor networks (LWSNs)”[1]. It has been shown that LWSNs are used in a number of specific application scenarios such as monitoring bridges [2], gas or oil pipelines [3] and roadside or highways (e.g accident detection on highways) [4].
The LWSN can be applied in railroad/subway operation and monitoring where the long freight train themselves have a linear structure by nature and sensor modules with external sensors can be deployed near or on the wheels where failures most commonly occur [5]. For instance, acoustic sensors might be used to detect cracked or flat wheels, while a thermocouple might be used to detect overheated wheel bearings. The sensor modules relay sensor data and alert the base station, which is deployed on the locomotive [5],[6],[7],[8]. A miner monitoring system, deployed in the confined environment of a coal mine can be used to keep track of the situation in the mine and the activities of the miners. It is an example of an ultra sparse network with linear topology [9],[10]. According to [5], underwater pipelines extend for hundreds of kilometers at depths reaching hundreds of meters and are subjected to high pressure. At such depths, it is really difficult to perform maintenance activities. As such, LWSNs can be used for monitoring underwater pipelines [11],[12],[13]. In greenhouse agriculture, LWSNs can be very useful to monitor crop’s growing environment. After measuring and transmitting crop’s environmental parameters to farmers, they can make decisions based on the data to improve yields and quality [14]. Another LWSN application example is the case of a speleologist going deep down into the bowels of the Earth, who can deploy the wireless network in order to maintain a communication channel with the outside world[15].
In [16], a lightweight lap time measurement system based on wireless sensor nodes that are linearly deployed for Alphine skiing is presented. Another application example of LWSNs is Parking Sensor Network (PSN) which is a special form of WSN. It is rapidly attracting attention around the world and is regarded as one of the first implemented urban services in smart cities [17]. Among the numerous applications of sensor networks, monitoring systems for electric cable, boats in a watercourse, smart grids, borders and production line are other examples of linear wireless sensor networks [18],[19],[20],[21].
These tiny sensor nodes are low cost, low power, easily deployed, and self-organizing. They are usually capable of local processing. Each sensor node is capable of only a limited amount of processing, but when coordinated with the information from a large number of other nodes, they
have the ability to measure a given physical environment in great detail.
Research in the field of Wireless Sensor Networks is relatively active and involves a number of issues that are being investigated. These issues are congestion management, efficient routing protocols [22], QoS support [23][24], security [25], and middleware [26]. Most of these issues were investigated under the assumption that the network used for sensors does not have a predetermined infrastructure [27][28][29][30]. Fortunately, the wireless sensor network needed for monitoring linear infrastructures such as pipeline or tunnel is usually a structured network in which all sensor nodes are distributed in a linear topology. This characteristic can be utilized for enhancing the communication quality and reliability in this kind of networks. A wireless sensor network is also constrained by memory space, computation capacity, communication bandwidth, and energy supply. It is obvious that the number of applications requiring LWSN is continuously increasing. That is why a growing number of researchers are turning to investigating the specifics of these networks and proposing new, more tailored solutions for increasing their efficiency and performance. Consequently, the capacity of sensors is limited which can lead to congestion. Congestion occurs when the traffic load being offered exceeds the available capacity of sensor nodes. In most applications, every sensor node will send the event it has sensed to a sink node. This operation makes the sensors closer to the sink, resulting in congestion. Congestion may cause packets loss, lower network throughput and sensor energy waste. To address this challenge, this paper proposes a congestion control approach that mitigates congestion and allocates appropriate feedback signal from a sink node to a basic sensor node. In this paper, a Linear Resource Reservation Congestion Control Protocol (LRRCCP) which detects local congestion at proper node placements and sinks, and delivers the congestion information to upstream nodes by exploiting the transmission of Request-To-Send (RTS) and Clear-To-Send (CTS) frames. Meanwhile, it adapts to the channel access priorities and data transmission rates of sensor nodes. Thus, it can adaptively adjust the allocation of channel resource among sensor nodes.

The proposed protocol considers not only the packets delivery rate, but also retains the buffer size of each node as well as avoiding packets drop due to traffic congestion. In its active state, a Resource Reservation Algorithm (RRA) at the sinks allows the sinks to reserve resources for unicast and multicast data flows of the captured events. This scheme can offer better than the previous congestion management schemes.

1.2. Research Motivations
In most cases, conventional congestion control schemes simply reduce the transmission rate at transport layer to relieve network congestion. As a consequence, they cannot maintain stable network throughput and other critical QoS parameters. In a linear resource-constrained WSN, the following are pertinent questions that must be addressed:
   i. In an energy-constrained linear distributed wireless sensor node, how will energy or network life time be conserved at the event of congestion?
   ii. Since the retransmission of dropped data packets will cause significantly large energy consumption, thus reducing the network life cycle, how will convergence be realized?
   iii. How will the RRA for reservation of network resources for unicast and multicast data flows improve deployment lifecycle?

From the foregoing, this work proposes a framework for data congestion management in a linear topology based wireless sensor network using a Linear Resource Reservation Congestion Control Protocol (LRRCCP) scheme. In the proposed LRRCCP, resource reservation protocol at the sink can assist in handling buffer occupancy issues. For the linear topology, the LRRCCP will share with a contention-based MAC protocol at the MAC-layer to study channel information including buffer occupancy ratio and congestion degree of local node. This work shows that with LRRCCP, the sensor nodes dynamically adjusts channel access priority in MAC layer and data transmission rate of the node to tackle the problem of congestion. This scheme will specifically address congestion issues in a linear topology.

2. Related Works
This section presents a review of some related congestion management schemes in WSN literature. In [5], the authors addressed a group of WSNs that require linear or chain topology, called Linear WSN (LWSN). The work observed that linear topology creates additional problems like increased delays, uneven load distribution between the nodes (relay burden problem), but also provides unique possibilities to address the issues of delay control and energy efficiency at the media access (MAC) layer.
In [31] a discussion on the various parameters (root causes of congestion), which can help to avoid and control
the congestion in the wireless sensor network was presented. The parameters considered the paper include: input/output flow rate, node density, non-linear or unbalanced distribution of load, processing/service time of node and reliability of network. The work explained that congestion occurs in WSN occurs due to i) Radio channel interference, ii) Addition and removal of sensor nodes, iii) Lastly sensed event cause bursts of messages. In [32], Congestion Detection and Avoidance (CODA) which is an energy efficient congestion control scheme were presented. It performs three mechanisms: Congestion detection, Open-loop hop by hop backpressure mechanism and a close loop multi-source regulation mechanism. CODA attempts to detect congestion by monitoring current buffer occupancy and wireless channel load. In an open-loop hop-by-hop back pressure if buffer occupancy or wireless channel load exceeds a threshold, it means that congestion has occurred. The node that has detected congestion will then notify its upstream neighbor to reduce its rate. Using AIMD method the upstream neighbor nodes trigger reduction of their output rate. CODA regulates a multisource rate through a closed-loop end-to-end approach.

In [32] an event-to-sink reliable transport protocol (ESRT) provides support for congestion control. ESRT regulates the reporting rate of sensors in response to congestion detected in the network. ESRT monitors the local buffer level of sensor nodes and sets a congestion notification bit in the packets it forwards to sinks if the buffer overflows. If a sink receives a packet with the congestion notification, a bit set infers congestion and broadcasts a control signal informing all source nodes to reduce their common reporting frequency according to some function. To address issues of packet losses, throughput degradation and energy waste, the authors in [33] developed, formulated and analyzed an enhanced rate based scheme called Rate Feedback Early Detection Congestion Avoidance scheme (RF-EDCAS) that addresses congestion issues in Wireless Sensor Networks. In [34], a cross-layer active predictive congestion control scheme (CL-APCC) for improving the performance of networks is proposed. The work applied queuing theory in the CL-APCC to analyze data flows of a single-node according to its memory status, combined with the analysis of the average occupied memory size of local networks.

Similarly, in [35] Early Detection Congestion Avoidance Mechanism (EDCAM) scheme for Wireless Sensor Network was proposed. The scheme is used in detecting and addressing the congestion. The main feature of proposed algorithm is early detection of the congestion. Rather than taking corrective action, preventive action is taken to prevent congestion occurrence. In [36], a Hybrid Congestion Control Protocol was proposed for a distributed algorithm that mitigates congestion and allocates appropriate source rate to a sink node for sensor networks. The protocol was perceived to avoid packets drop due to traffic congestion and improve the network throughput. In [37], a proposal on a new bidirectional wireless communication scheme based on the high-level data link control (HDLC) standard, for devices with short range transmission capabilities for linear sensor topology was presented. By applying for the first time a standard data layer along with a time division multiple access (TDMA)-based medium access control (MAC) and time synchronization technique specifically designed for the linear topology, the work addressed the interoperability problem with guaranteed energy efficiency and data link performance in linear sensor topology. The proposed Wireless HDLC supports half-duplex communication, point to point (peer to peer), and multipoint networking. Since congestion schemes may be classified into priority based, rate-based, and buffer-based schemes [35], a LRRCCP that satisfies the above classification while improving stability and lifetime of networks under either channel collision or buffer congestion is highly recommended. Resource reservation is a key advantage of the proposed scheme. This is lacking in most works. Besides, this is basically cost effective in deployment contexts.

3. Proposed Architecture

3.1. Characterization Environment

This section describes the characterization scenario where the procedure and performance metrics are studied. After several consultations and search for complete set of infrastructure for carrying out real life study for LRRCC, this research then used an experimental testbed called NeddiNet, a wireless sensor network system. It is sensor deployment area which was in an out-door environment where sensor nodes were placed on a pipeline to form a linear structure, in order to develop the simulation testbed for accurate performance analysis in the context of congestion control for the linear topology. NeddiNet tested works in a manual approach of placing the sensor nodes along the pipe or the straight linear object in an open outdoor environment to measure temperature and humidity of the area the experiment was conducted as seen in Fig 1. This will be used for future experimental data analysis.
A composite linear topology was contextualized in Fig 1. An assumption that each link is symmetric with each sensor node $S_{n,n}$ having two neighbor nodes: one is a group of upstream neighbors and another is a series of downstream ones was made. Let $S_{n,2}$ be the next upstream neighbor to node $s_{n,1}$, which pass through the Data Relay Node (DRN) sink and forward sensed data to the Network Collection Center (NCC) for status report. It is assumed that each sensor node has a counter that can calculate the data rate from upstream neighbors and decode the data rate to downstream neighbors for congestion alerts. An upstream neighbor is of higher priority while the downstream neighbor is of lower priority. The priority allocation is set for each scenario run and buffer sizes are monitored. This is represented by $RB_{i}$ and the net flow size of $S_{n,n}$ is represented by $NS_{n,n}$. Again, it is assumed that the packet length is fixed and each sensor node $s_{n,i}$ has a congestion state $C_{si}$, which is the index of congestion level.

According to the congestion degree, this work now classifies the current traffic load of each node into light-load state and heavy load state (see rate regulator section). Sensor nodes have a neighbor table to record the congestion degree and traffic information of neighbors. The deployment scenario this work assumes that the spatial topology of pipelines must be known, including the pipe length, the pipes diameter. Besides, the pipeline scenario is assumed to interconnect a set of vertical and horizontal pipes, starting with a sensor node_1 to sensor node_n. In the absence of automatic sensor node deployment in the deployable subnets, manual effort is required to place the sensor nodes at least one every 7meters for indoor but this work is done outside and the sensor node is place 20meters apart. Sensor node measures 10mm in diameter, which can fit on all pipes, tunnels and roads in the linear topology.

The current sensor node used in this work uses a 2.4 GHz radio (CC2420) to send/receive messages. Considering water scenario, high frequency radio is not the ideal choice in water, as water absorbs radio waves and limits its transmission range. The proposed system method (as shown in fig 1) involves the following four steps, viz:

1. **Preparation Step**: The pipeline or tunnel spatial topology must be measured in appropriate as a manual placement of the sensor nodes. The distance from each sensor must be measured and sensor nodes ready to be placed on the pipeline in the linear topology. This preparation step constitutes an onetime manual effort at the start of deployment.

2. **Sensor Deployment Step**: Prior to the sensor node deployment, inspection algorithm must be computed for its deployment position. Figure 3.1 describe the sensor deployment environment. The simulation system at run time, sends the release event message including the deployment position for the BSN and sink as well as dispatch queue for 10meters Distance sensor measurement and 20meters Distance sensor measurement.

3. **Sensor Latching Step**: The sensor node location and measurement is taken as it is placed along the pipeline. The sensor node then reports latch completion to the NCC sink. Thus, the deployment of sensor nodes continues until all the possible flow paths in the pipeline or tunnel is covered. This work used few sensor nodes up to six for the congestion study and is split into three scenario seen in Fig.3

4. **Sensor Replacement Step**: Sensor nodes consume battery power during the data collection phase. At some point, some sensor node may report low-battery to the NCC system.

5. **NCC Status report**: All BSN and sinks have update report from the NCC site. The reports include the congestion state, link information, rates, priority, and buffer information.
NeddiNet. This testbed gave a clear and accurate scenario for the congestion study in a typical linear topology. This testbed (Fig 1) connects 6 transparent pipe tubes and 2 water valves and forms a pipeline network that starts with one vertical path, followed by a horizontal path, and forks into two paths in the middle of horizontal path. These 6 transparent pipe tubes, each measuring 5cm in diameter. The two valves at the end of each horizontal path is meant to control the volumetric flow rate on each flow path. A sensor node was connected to a laptop computer used as the sink node where the data were collected.

Under multi hop connection, the congestion measurement device used is a 10 pieces zigbee transceiver which can sense some physical parameters that was measured like Temperature, Humidity, Signal Strength, Count-rate and Link Quality. In this experiment, it was observed that for a mission critical application (real-time), congestion effect can adversely affect such system, and for a non-mission critical application, congestion effect is less significant. The real life data obtained from the RF Zigbee (CC2420) wireless sensor nodes calibrated was calibrated in Fig 1. Fig 2 lists the lengths of each pipe tube segment in the testbed while Fig 3 shows the dynamic real node deployment which will form the basis the system for simulations. In relation to the congestion study, the LRRCC mechanism is discussed next.

Now, considering Fig 3, suppose that sensor node A (Sn_1), node B (Sn_2) and node N (Sn_n) are arbitrary intermediate nodes in a WSN, all of which perform the congestion control algorithm. All of them compute their own local congestion information while sending their data to the sinks. Based on the priority weight of the sensor nodes, sensor node N (Sn_n) feeds back its congestion information to its upstream node B (Sn_2). After receiving the feedback signal, node B will add its own congestion information into the feedback signal from node N, and then relay the new feedback signal to its upstream node (Sn_1). Node B also carries out local congestion processing and feedback signal processing to relieve the congestion within the downstream node N and itself. Node A (Sn_1) processes the feedback signal in the same manner with node B(Sn_2), and the feedback signal will be sent to the source node (Sn_1) on a hop-by-hop basis. Finally the source node will adjust its data transmission rate to relieve congestion via a feedback messaging.

The major components in the LRRCC scheme will be presented in details while elaborating on the congestion detection method, feedback signal generation and transmission sending method, feedback signal and local congestion processing methods. It is worth noting that frequent hop-by-hop transmission of feedback signals would consume significant amount of the node’s energy, which is not conducive to prolong network lifetime. To avoid this problem, the LRRCC algorithm adopts implicit notification mechanism. The feedback signal is attached in the RTS/CTS control frame of MAC protocol. The MAC layer manages the radio channel and sends the congestion signal to the source node hop-by-hop, which can avoid energy waste caused by broadcast unicast.
4.1. Description of LRRCC MAC/Physical Layer

As shown in Fig 3, the BSN MAC sub-layer provides two services: the MAC data service and the MAC management service interfacing to the MAC sub-layer management entity (MLME) service access point (SAP) (MLMESAP). The MAC data service enables the transmission and reception of MAC protocol data units (MPDU) across the PHY data service. The features of MAC sub-layer are beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association and disassociation. Now, the Personal Area Network for the WSN allows the optional use of a superframe structure defined by the coordinator sink. The beacon frame is sent in the first slot of each superframe (16 slots size). If a coordinator does not want to use the superframe structure, it may turn off the beacon transmissions. The beacons are used to synchronize the attached devices, to identify the PAN and to describe the structure of superframes. The superframe can have an active and an inactive portion. During the inactive portion, the coordinator will not interact with its PAN and may enter a low-power mode. The active portion consists of Contention Access Period (CAP) and Contention Free Period (CFP). Any device wishing to communicate during the CAP shall compete with other devices using a slotted CSMA-CA mechanism. On the other hand, the CFP contains Guaranteed Time Slots (GTSs). The GTSs always appear at the end of the active superframe starting at a slot boundary immediately following the CAP. The PAN coordinator may allocate up to seven of these GTSs and a GTS can occupy more than one slot period. Fig 4 depicts a superframe structure.
The length of the CFP is determined by the total length of all of the combined GTSs. No transmissions within the CFP shall use a CSMA-CA mechanism. A device transmitting in the CFP will ensure that its transmissions are complete one IFS period before the end of its GTS. IFS time is the amount of time necessary to process the received packet by the PHY. Transmitted frames shall be followed by an IFS period. The length of IFS depends on the size of the frame that has just been transmitted. In this kind of network, a coordinator shall not transmit any beacons, all transmissions except the acknowledgement frame shall use unslotted CSMA-CA to access channel, GTSs shall not be permitted.

4.2. Congestion Detection Model

In order to satisfy the accuracy and low-cost requirements of network congestion detection, LRRCCP used a detection mechanism of observing the buffer occupancy to understand its state. For the linear topology, this work defines two parameters: congestion state \( C_s \) and buffer occupancy ratio \( B_r \). Congestion state indicates the changing tendency of buffer queue. Table 1 shows the congestion detection phase of the LRRCCP algorithm.

4.3. Feedback Signal Generation and Update Transmission

The second phase of LRRCC is to generate feedback signal for upstream node and process local congestion based on the state of the rate regulator. There are three issues that need to be addressed in this phase:

i. When to transmit the feedback signal in the linear topology?

ii. How to transmit the feedback signal topology?

iii. How to process the congestion locally in the linear topology?

In general, a sensor node may have three modes: transmitting mode, receiving mode and sleeping or inactive mode. Since a sensor node can only execute the congestion control algorithm when it is not in sleeping state, there are two mechanisms to generate congestion feedback signal viz:

one is to generate feedback signal before the node transmits data packets, and the other is to generate feedback signal before the node receives data packets. With the first mechanism when the local node is ready to transmit data packets, LRRCC performs local congestion detection, and adjusts channel access priority according to the congestion condition.

<table>
<thead>
<tr>
<th>Table 1: Algorithm 1: Congestion Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input:</strong> Node’s buffer occupancy ratio ( B_r ) and congestion state ( C_s ).</td>
</tr>
<tr>
<td><strong>Result:</strong> Node state change</td>
</tr>
<tr>
<td>1: Initialize node information;</td>
</tr>
<tr>
<td>2: Compute ( B_r ) and ( C_s );</td>
</tr>
<tr>
<td>3: if ( C_s &gt; 1 ) &amp;&amp; ( B_r &gt; B_{max} ) then</td>
</tr>
<tr>
<td>4: Set the node state to congestion state and perform local congestion processing mechanism;</td>
</tr>
<tr>
<td>5: Send congestion information (i.e. feedback signal) to upstream node and examine the feedback signal from downstream node;</td>
</tr>
<tr>
<td>6: end if</td>
</tr>
<tr>
<td>7: if ( C_s &gt; 1 ) &amp;&amp; ( B_r &lt; B_{max} ) then</td>
</tr>
<tr>
<td>8: Adjust local data transmission rate;</td>
</tr>
<tr>
<td>9: end if</td>
</tr>
<tr>
<td>10: if ( C_s &lt; 1 ) &amp;&amp; ( B_r &lt; B_{max} ) then</td>
</tr>
<tr>
<td>11: Set local node state to non-congestion and send node state information to upstream node;</td>
</tr>
<tr>
<td>12: End</td>
</tr>
</tbody>
</table>
The node then sends the congestion information attached in RTS (Request to Send) packet to the upstream node. The upstream node adjusts its channel access priority according to the received congestion information when it begins to transmit a new data packet in next time slot. This work will now outline the relevant algorithms for the LRRCC scheme.

4.4. LRRCC Feedback Signalling
Considering Fig 5, if the sensed data does not contain rate regulator tag in the downstream to upstream sensor node. Table 2 shows the algorithm used for sending feedback to upstream sink.

Table 2: Algorithm II: LRRCC for Feedback Conditions (Process Algorithm)

<table>
<thead>
<tr>
<th>Input: Set Buffer Occupancy, Set Rate regulator status ri, Qeq, Qs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output: LRRCC message sent</td>
</tr>
<tr>
<td>If (q(t) &lt; Qo) { LRRCC message sent};</td>
</tr>
<tr>
<td>If (Qo &lt; q(t) ≤ Qs) {Normal LRRCC message sent};</td>
</tr>
<tr>
<td>Return;</td>
</tr>
<tr>
<td>If (q(t) &gt; Qs) { LRRCC message sent};</td>
</tr>
<tr>
<td>Return;</td>
</tr>
<tr>
<td>If the sensed data does not contain rate regulator tag</td>
</tr>
<tr>
<td>If (q(t) &lt; Qo) &amp;&amp; (CPid = Sn CPid) {No LRRCC message sent};</td>
</tr>
<tr>
<td>Return;</td>
</tr>
<tr>
<td>Return;</td>
</tr>
</tbody>
</table>

4.5. Buffer Occupancy and Rate Regulator Model
Fig 5 shows the unit block diagram of Fig 3 used for the congestion scenario of the linear topology previously discussed.

![Figure 5: LRRCC Model for Buffer Occupancy and Rate regulator](image)

From Fig 5, the LRRCC scheme is modelled as a rate-based closed-loop feedback control into the upstream sensor node as depicted in Fig 3. This work assumes that sensor nodes are equipped with rate regulator (RR) which sharpens traffic (packet/frames) update to the upstream neighbour’s. Traffic control at the BSN congestion point (CP), is a function of monitoring the length of output queues and making traffic control decision. If traffic poll at the sending of packets is high leading to congestion, the RR advertises signals to source BSN using feedback message Fbm. The Fbm messages contain details for the BSN source to adjust their flow rates. The sources can reset to the received Fbm and updates the rate of its regulator status. A threshold is set to indicate tolerable congestion levels on the BSN RR given by Qsmax. The counter basically counts the number of arrivals (A) and departure packets (d) and samples the incoming packets with a steady state probability Ps. When the sensed data is sampled, the buffer occupancy and RR is checked to determine the congestion level on the sensor node and may send the Fbm message to the source terminal of the sampled data. If the traffic congestion is extreme, the sensor may send a Stop Fbm message. The key details of the Fbm message are the source traffic type and link congestion measure, as well as destination congestion point and capacity of the link C. Now the traffic-type tells the sensor node and possibly the sources about the Fbm. The congestion point id CPid is the id for link congestion (MAC type interface). e_s is the buffer link congestion measure fed back to the source. From Fig 3.5, the key measure of congestion on a link is e_s which consists of a weighted sum of the instantaneous queue offset and queue variation over the last sampling interval. This is given by the equation;

\[ e_l = \frac{q_{off}(t) - W(q_{dema})}{q_{dema}} \]

Where \( q_{dema} \) = queue weight given by \( W(q_d - q_a) \) and \( q_{off}(t) = \) instantaneous queue offset given by \( q_{off}(t) = q_{q}(t) - q_{bm} \)

\[ Hence e_l = \frac{(q_{q}(t) - q_{bm}) - W(q_d - q_a)}{q_{dema}} \]  

\( q_{dema} \) is the queue variation over the last sampling interval and is defined as the difference in the number of sensed data that arrived \( q_d \) and the number of packets that were served \( q_a \) since the last sampling event. A heuristic algorithm showing traffic control Equilibrium Level \( Q_{eq} \) possible event in scenario subnets is presented in Algorithm III. The first line in the algorithm is the case where the queue length is short and the sources can increase their rates. Line 2 is the case where even though the queue length is small, it is increasing, and as the traffic congestion is building up, the sources are signalled to decrease their sending rates. In line 3, the large queue indicates that the links are congested, and the sources are signalled to decrease their rates.
Table 3 shows the traffic control equilibrium level for the LRRCC.

Table 3: Algorithm III: LRRCC Traffic Control for Equilibrium Level (Qeq).

<table>
<thead>
<tr>
<th>Input:</th>
<th>Set Buffer Occupancy, Set Rate regulator status ri, (F_{eq}, Q_{eq}, q_{i} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output:</td>
<td>(c_{i} )</td>
</tr>
</tbody>
</table>

/*Traffic control decision at Qeq*/

\[\text{If} \ (q(t) < Q_{eq}) \ & \ \& \ (q_{i} = q_{d}), \ [ei > 0] \ \text{return;}\]

\[\text{If} \ (q(t) < Q_{eq}) \ & \ \& \ (q_{d} > q_{i}), \ [ei < 0] \ \text{return;}\]

\[\text{If} \ (q(t) > Q_{eq}) \ & \ \& \ (q_{i} = q_{d}), \ [ei < 0] \ \text{return;}\]

\[\text{If} \ (q(t) > Q_{eq}) \ & \ \& \ (q_{d} < q_{i}), \ [ei > 0] \ \text{return;}\]

End;

Recall that from Fig 3, the downstream and upstream sensor nodes adjust their rates using an enhanced Additive increase and Multiplicative Decrease (AIMD) algorithm which has been proven to be sufficient, efficient and shows fairness under certain common conditions shown in equation (3a/b). Hence, the LRRCC for traffic control rate using the AIMD algorithm is modelled as follows:

\[\text{LRRCC} \ r_{i} = r_{i} + G_{e}e_{i}R_{u} \ \text{if} \ e_{i} > 0 \quad (3a)\]

\[\text{LRRCC}r_{i}=r_{i}+G_{e}e_{i}R_{u}, \text{if} \ e_{i} < 0 \quad (3b)\]

Where \(G_{e}\) is the additive increase gain parameter, \(R_{u}\) is the increase rate unit parameter, and \(G_{d}\) is the multiplicative decrease gain parameter. Under certain conditions \(r_{i}\) can give good performance metrics. Furthermore, The algorithm for LRRCC for feedback conditions described in table 3 explains that if the arriving sensed data are sampled with a steady state probability \(P_{s}\), for each sampled packet, the LRRCC \(F_{bm}\) shows an optimal response.

4.6. Feedback Signal and Local Congestion Processing

The rate adjusting strategy could affect network communication performance significantly, especially network throughput and transmission fairness. When the upstream processes the feedback signals from the downstream node, it as well considers its own congestion condition. Assuming that the upstream node receives congestion signal successfully, the feedback signal and local congestion processing method used in LRRCC will maximize size of channel contention window in the MAC protocol. Besides, the LRRCC exploits the AIMD strategy for transmission rate adjustment. The major purpose of using this strategy is to relieve local congestion as soon as possible while keeping stable network throughput.

4.7. LRRCC CSMA-CA

Considering Fig. 3 by using the superframe structure for the BSN in PAN is shown in Fig. 4 where the slotted LRRCC CSMA-CA will be used. If beacons are not being used in the PAN or a beacon cannot be located in a beacon-enabled network, unslotted CSMA-CA algorithm is used. In both cases, the algorithm is implemented using units of time called backoff periods, which is equal to a UnitBackoffPeriod symbols. In slotted LRRCC CSMA-CA channel access mechanism, the backoff period boundaries of every device in the PAN are aligned with the superframe slot boundaries of the PAN coordinator. In this case, each time a device wishes to transmit data frames during the CAP, it shall locate the boundary of the next backoff period. In unslotted CSMA-CA, the backoff periods of one device do not need to be synchronized to the backoff periods of another device. Each device has 3 variables: NB, CW and BE as part of the LRRCC boundary variables. NB is the number of times the CSMA-CA algorithm was required to backoff while attempting the current transmission. It is initialized to 0 before every new transmission. CW is the Contention Window length, which defines the number of backoff periods that need to be clear of activity before the transmission can start. It is initialized to 2 before each transmission attempt and reset to 2 each time the channel is assessed to be busy. CW is only used for slotted CSMA-CA. BE is the backoff exponent, which is related to how many backoff periods a device shall wait before attempting to assess the channel. Although the receiver of the device is enabled during the channel assessment portion of this algorithm, the device shall discard any frames received during this time.

In slotted LRRCC CSMA-CA, NB, CW and BE are initialized and the boundary of the next backoff period is located. In unslotted CSMA-CA, NB and BE are initialized (step1). The MAC layer will delay for a random number of complete backoff periods in the range of 0 to \(2^{BE} - 1\) (step 2), and then request that PHY performs a Clear Channel Assessment (CCA) (step 3). The MAC sublayer shall then proceed if the remaining LRRCC CSMA-CA algorithm steps, the frame transmission, and any acknowledgement can be completed before the end of the CAP. If the MAC sublayer cannot proceed, it shall wait until the start of the CAP in the next superframe and repeat the evaluation. If the channel is assessed to be busy (step 4), the MAC sublayer shall increment both NB and BE by one, ensuring that BE shall be no more than \(aMaxBE\).

In slotted LRRCC CSMA-CA, CW can also be reset to 2. If the value of NB is less than or equal to maxMaxCSMABackoffs, the CSMA-CA returns to step 2, else the CSMA-CA shall terminate with a Channel Access Failure status. If the channel is assessed to be idle (step 5), in a slotted CSMA-CA, the MAC sublayer shall ensure that contention window is expired before starting transmission. For this, the MAC sublayer first decrements
CW by one. If CW is not equal to 0, go to step 3 else start transmission on the boundary of the next backoff period. In the unslotted CSMA-CA, the MAC sublayer starts transmission immediately if the channel is assessed to be idle. The whole CSMA-CA algorithm is shown in figure 6b.

4.8. Data Transfer Model
The mechanism for each of these transfers depends on whether the network supports the transmission of beacons. When a device wishes to transfer data in a non-beacon-enabled network, it simply transmits its data frame, using the unslotted CSMA-CA, to the coordinator. When a device wishes to transfer data to a coordinator in a beacon-enabled network, it first listens for the network beacon. When the beacon is found, it synchronizes to the superframe structure. At the right time, it transmits its data frame, using slotted LRRCC CSMA-CA, to the coordinator. As shown in Fig.6a, after define system boundaries: Q_{avg}, Q_{NB}, CW and BE, etc, the PAN BSN \((i),\) DRN \((j),\) and DDN \((k)\) are enabled. Using a rate counter, the model verifies if the constituents of the BSN \((i),\) DRN \((j),\) and DDN \((k)\) are present. The next step is to check for effective congestion areas so as to send a slotted LRRCC CSMA-CA feedback message for priority signaling, rate and buffer regulations. But if the sink experiencing intense congestion, then the slotted LRRCC CSMA-CA procedure in Fig. 6b is evoked thereby mitigating any network congestion effects.

From Fig 7, the filter entity is built upon the MAC filter core of the IEEE 802.11 to reflect a practical scenario. Because intermediate nodes know the reverse path by the RRA, the feedback packets don’t need to go through the underlying routing procedures of LRRCC.

5. Research Implications
The linear topology for typical pipeline deployments requires linear placement of the WSN nodes. In its active operation, the LRRCC scheme must leveraged on Resource Reservation Protocol module (RSVP) and is achieved through the cooperation of three processes: the RSVP-Application interface process, the RSVP process, and the traffic control process for the system architecture. Again, for the sensor nodes and the sinks, RSVP is enabled to minimize the data drop in the unicast flows to the upstream sinks. Every sensor node sends messages to the sinks where the event are sensed. Because all sensors nodes (downstream and upstream) are data sources, all of them relays their data from their upstream neighbors toward the DRN and then via the DDN to the NCC. Each sensor cannot move after deployment. The sensors are controlled by the LRRCC algorithm implemented on the existence MAC layer and network layer. The congestion control techniques previously discussed must be well integrated into the implementation scenario for optimal results. To assess the performance of the proposed schemes, three congestion control schemes including LRRCC, CODA, and ESRT will be simulated while carrying out the analysis of the performance these mechanisms in terms of packet loss ratio, network throughput, average source transmission rate (i.e. average transmission rate of source nodes), energy efficiency and fairness evaluation. This forms the basis for a future research.

6. Conclusion
This paper has presented the behavioral descriptions of a Linear Resource Reservation Congestion Control Protocol for a linear pipeline infrastructure. The LRRCC mitigates congestion and allocates appropriate resources to the sensor nodes and sink node in the linear sensor network model. LRRCC comprises of these phases: congestion detection phase based on priority assignment, data rate adjustment phase and buffer size occupancy phases. It maintains the global flow information from the sources (BSN) to the sinks. The proposed scheme is expected to mitigate congestion at a very high efficiency compared to other schemes. Each node in the network individually allocates or reduces the data rate of upstream or downstream neighbors to avoid the congestion as shown in Fig 3. The parameters for variations and analysis will be presented in future studies.

7. Appendix
Figs 6a, 6b and 7 represent the functional flowcharts of the LRRCC scheme discussed above.

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References


Start

Define System Boundaries: $Q_{avg}$, $Q_{th}$, $Q_{c}$, NB, CW and BE

Define & Set PAN [BSN (i), DRN(j), DDN(k)]

Define Scenario (3)-Enable RRA, MAC-Parameters

Increment B

Rate Counter $R_c = 0$

Generate $F_{\text{mm}}$

Is Buffer Occupancy High > 1 [Congested]

Is Sink Congested ?

Is BSN (i), RR Ready?

Is DRN (j), RR Ready?

Is DDN (k), RR Ready?

$K_1$

Figure 6a: LRRCC Flowchart on Traffic initialization
**LRRCC Algorithm Superframe**

1. **Slotted?**
   - Yes
   - **NB=0, Cw=2**
   - **Energy life Extension**
     - Yes
     - **BE=Max, Min BE**
     - **BE≥2MacMinBE**
     - **Locate backoff Period boundary**
     - **Delay for Random (2^BE-1) Unit Backoff Period**
     - **Perform CCA on backoff Period boundary**
     - **Channel Idle?**
       - Yes
       - **Cw=Cw+1**
       - **Failure**
       - **NB>MacMax CSMA backoff**
         - Yes
         - **Cw = 0?**
           - Yes
           - **Success**
           - **Measure Avg.Aggr.Input rate rin**
           - **Measure Max.Number of Data in the Output Queue Q**
           - **End**
           - **Failure**
         - No
         - **Failure**
       - No
       - **Cw=Cw+1**
       - **NB+1, BE=Min(BE+1, MaxBE)**
     - No
     - **Cw=2, NB=NB+1, BE=MinBE+1, MaxBE**
     - **Measure Avg.rate of data sent from Sn_out**
   - No
   - **Delay for Random (2^BE-1) Unit Backoff Period**
   - **Perform CCA**
   - **Channel Idle?**
     - Yes
     - **NB=macCSMA Backoff?**
       - Yes
       - **Failure**
       - **Success**
       - **Measure Avg.Aggr.Input rate rin**
       - **Measure Max.Number of Data in the Output Queue Q**
       - **End**
     - No
     - **Measure Avg.rate of data sent from Sn_out**

**Figure 6b: LRRCC Flowchart with CSMA-CA**

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Start

Set the Application layer
Mac layer Process

Set $Q_{avg}$, $Q_{th}$, $Q_c$: (Initialize)

Count = 0

Receives an Interested Packet

Is this a Data Packet?

$Q_{avg} \geq Q_{th}$

Y

Increment $Q_c$ by 1

Counter = Counter +1

N

$Q_c > 0$?

Y

Pass the packet to Next filter

N

Counter = Counter +1

Feedback Packet

Pass to Upstream Node

$Q_{avg} < Q_{th}$

Y

Congestion is Occurring in an Upstream

Counter = Counter +1

N

Set $Q_c = 0$

Schedule feedback ()
Priority Signaling ()
Buffer Management ()

End

Fig 7: Filter Entity in DRN Sink for Congestion Packet