Multi-Layer and Distributed Congestion Control for Wireless Sensor Networks

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***Abstract*—Congestion in Wireless Sensor Networks (WSN) may cause non-desirables behaviors like low energy efficiency, high delay in the communication, inefficient use of network resources, high probability of service degradation, high risk of packet loss, etc. With the projections of increasing Internet traffic in next years and the adoption of the IoT in people's daily lives, it is necessary to investigate and develop congestion control methods that detect, notify and mitigate congestion in a WSN. To meet this challenge, a method that considers a distributed and multi-layer congestion control called MLDC (Multi-Layer and Distributed Congestion Control) is proposed. It considers the layers a) Priority access to the channel, b) Buffer management, c) Routing algorithm to avoid and mitigate congestion and d) MLDC-based application. A novel comparative evaluation of different Congestion control methods in three network topologies is carried out. MLDC works properly in all the topologies evaluated, improving the behavior of the network and reaching and optimizing the proposed congestion control metrics.**

***Index Terms*—WSN, Congestion Control, Distributed, Multi-Layer, Buffer Administration, Prioritized Channel Access, Routing, Traffic, Congestion mitigation, network topology, performance, QoS metrics.**

I. INTRODUCTION

During the last years, different kind of researches have been developed to enable the Internet of Things (IoT) technologies spanning from MEMS (Micro-Electro-Mechanical Systems), develop of physical intelligent objects, embedded systems and wireless communications [1]. One of the most common type of wireless communication in IoT is the Wireless Sensor Networks (WSN) which are ad-hoc networks composed by devices with low capabilities distributed in a bounded geographic area in order to perform some kind of monitoring activities [2]. The communication channel is wireless and the recollected information from the embedded sensors in nodes is send to a base station usually called Sink node. This type of networks are considered self-healing and self-configurable in terms of its topology construction, routing algorithms, cluster generation, failure control, among others [3].

Nowadays, WSNs are under constant research and develop by the science community and industry [4], it has allowed the application of this type of networks in different applications like military, environmental, logistics, Human Activity Recognition (HAR), smart cities, agriculture, etc. Rashid et al. in [5] present a detailed study of WSN application in urban areas, it can be shown that this networks could significantly vary due coverage area, types of nodes (usually called motes), fault tolerance, expected life time and application. For this reason a design of a WSN must consider an exhaustive analysis of network topology to be used, routing protocols, congestion control methods, self-healing algorithms among others.

Due to the intrinsic characteristics of the WSN and nodes, the congestion phenomenon could appear which is related with the motes capabilities and the amount of generated and transported traffic through the network. The amount of transported traffic in Internet is growing every year, Cisco has projected a Zettabyte era in Internet because the traffic will reach 3.3 ZB per year in 2021 [6]. About the 50% of this traffic will be because of M2M (Machine-to-Machine) communication which is the most common in IoT and WSN. This projection in the increase in traffic makes it important to carry out researches in the field of congestion control because it becomes increasingly necessary to detect, prevent and mitigate congestion in devices limited in capacity and energy as in the nodes in a WSN.

In this paper, we propose the definition of metrics that evaluate the performance of a WSN from a congestion point of view: *fairness, sink received throughput, average packet delay, energy consumption and percentage of packet loss*. It is also done a novel evaluation of different congestion control methods in different network topologies and finally the formulation, simulation and evaluation of a new distributed method which acts in multiple layers in WSN nodes.

MLDC (Multi-Layer and Distributed Congestion Control) considers four techniques in three layers that detect, notify and mitigate the congestion in WSNs. The first technique es *MLDC Prioritized MAC* in which congested nodes can access to the channel in prioritized manner. The second technique is *MLDC Buffer Management* that performs a queue scheduler and buffer management. The third technique is *MLDC Router* which describes all the activities to be performed by the network layer in the WSN node and the last technique is *MLDC-based Application* that presents recommendations for the application layer to avoid congestion in the network. This method is consider as an integration of different types of congestion control algorithms available during the formulation of MLDC.

The rest of the paper is organized as follows: Section II presents a detailed analysis of the congestion control issue in WSN and the classification of congestion control methods based of the mitigation phase, in Section III we present the related work on the subject, in Section IV the MLDC method is presented, in Section V the proposed metrics for congestion evaluation are detailed explained, in Section VI the simulation results and its analysis is presented, finally the paper is concluded in Section VII with the conclusions of the research and suggested future works.

II. Congestion control in WSN

Due to high the high traffic that an application could generate, congestion can happen in different nodes of the WSN. Suppose λ represents the arrivals rate of packets at a certain point in the network (link or node), μ the service rate of packets in the point and ρ the utilization; the congestion in the WSN is presented when the arrival rate is greater than the service rate as shown in the Equation 1.

$$\rho = \frac{\lambda}{\mu} > 1 \tag{1}$$

The congestion in WSNs could generate:

- High risk of lost or blocked packets.
- Higher probabilities of service degradation.
- Use of more resources in case of retransmissions.
- Delays in communication.
- Discontinuation of the channel connection.
- Low quality of service.
- Significant energy losses.
- Obsolete information in the network due to high delays in the transmission processes.

For these reasons is necessary to implement congestion control mechanisms in order to decrease the presence of unwanted behaviors in the network or that mitigate the consequences if the congestion is happening.

In different paper [7] [8] [9], authors classify congestion based on the place that is presented:

- Node level congestion: It is described in the Equation 1 when the node utilization is greater than 1. This type of congestion usually happens in nodes near to Sink.
- Link level congestion: It is produced when nodes must enter in a competing state with their neighbors to access the shared medium to transmit their data, collisions could happen and it could be presented errors in transmission due interference.

Congestion control methods include the next three phases to handle with congestion issues:

1) Detection: It is the process in which nodes detect congestion in some point of the network. Usually it is perform measuring the occupancy size of the buffer, channel load, packet service time or a combination of the previous.
2) Notification: When congestion is detected, it is necessary to inform neighbors about the presence of it in the network. This notification could be perform using the next techniques:
    - Implicit: Headers in routing packets are use to inform the state of congestion.
    - Explicit: New packets are created to inform the congestion event. This technique is not desired because it uses additional control packets that could generate more load in the network.
3) Control: It refers to reactive actions when congestion occurs. The methods can be classified into: Traffic control and resources control.

Methods that use traffic control aim to reduce the transmission rate in congested nodes (by reducing the package arrival rate λ) informing transmitting nodes about the congestion event. A well-know technique is AIMD (Additive Increase / Multiplicative Decrease) used by TCP which controls congestion using the Equation 2 performing a linear increase in transmission rate when no congestion happens, otherwise an exponential reduction when it is presented.

$$f(t+1) = \begin{cases} f(t) + a & \text{if } c = 0 \\ f(t) * b & \text{if } c = 1 \end{cases} \quad a > 0,\ 0 < b < 1 \tag{2}$$

In the other hand, resources control methods uses alternatives nodes or new paths in the network through changes in the original network topology.

III. Related work

The authors in [7] [8] [9] present different studies and comparatives analysis between congestion control methods, enumerate their strengths and weaknesses and give recommendations for future research in congestion control algorithms. They recommend the use and implementation of methods like the proposed in [10], [11], [12], [13], [14], [15], [16]. After a exhaustive analysis of them, we choose ECODA, DAlPaS and FUSION to evaluate and implement through a WSN simulator.

Enhanced Congestion Detection and Avoidance (ECODA) [10] is a traffic control algorithm which compromises three mechanism, the first is related with the congestion detection using dual buffer thresholds and weighted buffer difference. It defines three states in the buffer: *accept state*, *filter state* y *reject state* in which some packets are accepted or dropped depending on static and dynamic priority. The second one uses a Flexible Queue Scheduler for packets based on priority and source traffic and the third mechanism adjust the nodes sending rate based on bottleneck-node detection.

Hull et al. in [16] present the FUSION congestion control method that acts as a union or three techniques. The hop-by-hop flow control technique make use of channel load information and buffer occupancy to detect congestion in a specific node, if this mote is congested, a bit in all the outgoing packets is set to inform the neighbors about the congestion event and them stop sending packets to the congested node in order to let it drain the buffer. In the rate limiting technique, each node monitors traffic in transit to determine the sending rate of the parent node, based on this information is calculated

N, the total number of routes by the father. Specifically, the *Token Bucket Scheme* is used to regulate the sending rate of each node. The node transmits when the token account is greater than zero. The prioritized MAC layer technique uses the CSMA (Carrier Sense Multiple Access) to mitigate the congestion in the node. It uses the *backoff window* to perform transmission contention when the node is not congested, it means that if a node is congested its *backoff window* is smaller than other in order to get higher priority to access to the channel.

DAlPas (Dynamic Alternative Path Selection) [11] it is a congestion control algorithm that uses resource control through alternative paths to mitigate congestion. In general DALPaS consists of 4 stages:

1) Setup: It only runs once, all nodes discover each other and update their routing tables with the neighbor node ID, buffer occupation, remaining energy, network level and a flag which indicates the availability of the node.
2) Topology Control Scheme: Uses the information of the neighbor table created in the previous phase to transmit the data, each node reviews this table and sends the information to the neighbor node with the lowest level. When a node has more than one node with the same level in the neighbor table, it chooses the next hop based on the Round-Robin method.
3) Soft Stage Scheme: This phase occurs when a node receives more than one flow, in this case, the congested node informs one of the nodes that it prefers to stop receiving flows from that node. The node that receives this message is programmed to verify alternative paths.
4) Hard Stage Scheme: If in the previous step the node did not change its routing, and it is necessary to reactively react to the congestion, it is necessary to go to this phase. The purpose is to change the value of the flag of the neighbor table from True to False to inform that the node is unavailable.

IV. MLDC Protocol Design

To mitigate congestion in a wireless network of sensors, there are different methods that act on different communication layers in the nodes. In [17] the author presents a classification of the congestion control mechanisms based on the layer that exercises the control, it is analyzed that the techniques that are based on more than one layer give greater reliability to the network since there is more points and variables to control. Most of the congestion control methods investigated operate at two levels maximum, however, they focused mainly on one of them. In this paper, the MLDC (*Multi-Layer and Distributed Congestion Control*) method is proposed, it implements actions in the MAC layer, Network layer, Buffer management layer and Application layer to detect, notify and mitigate the effects when congestion is presented in the network.

In addition to the multi-layer characteristics, it is considered a distributed control over all the nodes of the network (source, sink and intermediaries). This type of methods have greater advantages with respect to those centralized in a WSN because preventive and corrective actions can be taken hop-by-hop [18], they are more tolerant to failures at the expense of more processing in the node and latency [19].

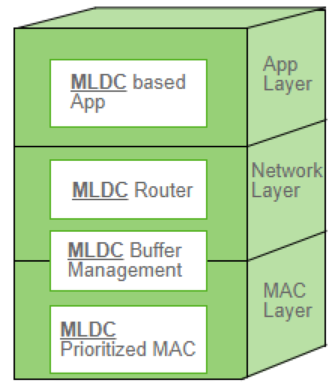

Fig. 1. MLDC Modules

The Figure 1 presents the designed modules in MLDC and their respective layer where they carry out their actions to avoid and mitigate congestion.

A. Prioritized Channel Access

Traditional congestion control methods in WSN can not always react to sudden changes in traffic and congestion status because they are network-based [16]. M. Zawodniok et al. in [20] justifies that the use of lower communication layers in congestion control techniques present better results because traditional schemes give results with a high percentage of lost packets, unfair scenarios, low throughput and a significant waste of energy due to re-transmissions. In MLDC, the use of proposed priority access is based on [16].

In IEEE 802.15.4-based networks, the media access is perform by the CSMA/CA algorithm. This technique uses BEB (Binary Exponential Back-off) to control the nodes media access through a random interval. When a node is congested, the MAC layer is notified in order to modify the Back-off window size to be reduced in comparison with non-congested nodes. It is suggested to set the window size to 25% of the original due on average a node will gain access to the channel only after half of its neighboring nodes have been transmitted [16].

This Back-off size modification can be applied to networks with CSMA/CA like IEEE 802.11 and IEEE 802.15.4 networks in the Super frame (Beacon Mode) and Non-Beacon Mode. When Beacon Mode is used, this technique works when the media access control is in CAP (Contention Access Period).

This prioritized channel access technique allows a congested node to drain quickly the packets that are enqueued in the buffer. In addition, the latency of the packets decreases when congestion occurs.

B. Buffer Administration

Due to the limited resources of the nodes in a WSN, it is necessary to use them as efficiently as possible. The buffer in a node is one of the resources that should be exploited in an optimal way because when it reaches its maximum use, the node inevitably enters a congestion state and it is necessary to drop packets.

The efficient use of the buffer resources in the node has been extensively researched by the scientific community. Different works such as [21], [22] and [23] have proposed interesting methods of buffer management for WSN. The ECODA method proposed in [10] suggest to manage a dual buffer, one for local generated traffic and the other one for transient traffic as shown in Figure 2. Also, the author suggest to implement a buffer Scheduler in order to organize the packers in the queue based on priorities.

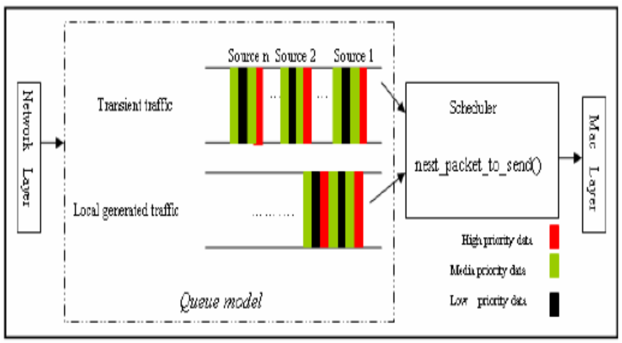

Fig. 2. ECODA queue model. Taken from [10].

MLDC adopts the ECODA buffer management technique because it takes into account the expense of node resources to transport packages in a multi-hop network, giving higher priority to transient traffic. This method allows to give greater reliability to the nodes away from the sink so that they can transmit their information to the central node and that their packages will not be lost in the multiple hops that have to be presented.

In addition, MLDC suggests that the static priorities of the generated packages are as presented in Table IV-B and that the maximum dynamic priority in the network is Five, that is, any package that reaches this threshold will always be located in the head of the queue and it will be the first packet to be served by the node.

Packet type	Priority
Routing Information	3
Information Traffic	2
Other	1

Table I
MLDC PACKETS PRIORITY

The use of the static and dynamic priority shown in the Equation IV-B with α=0.5 and β=0.02, allow the routing algorithm presented in the Section IV-C to propagate their updates quickly through the network, to have convergence of routing information in all neighboring nodes.

$$DP = \frac{\alpha \cdot hop + SP}{1 + \beta \cdot delay} \quad (3)$$

In addition, MLDC suggest to the manage the buffer states as follows:

- If the buffer occupancy is less than 60%, the buffer is in Accept state and all packets are enqueue.
- If the buffer occupancy is is less than 80% and greater than 60%, the buffer is in Filter state and some packets with low dynamic priority are dropped.
- If the buffer occupancy is greater than 80%, the buffer is in Reject state and son packets with high dynamic priority are dropped.

C. Routing Algorithm

In [24] a study of routing protocols designed for WSN is presented, many of them are designed to be fault tolerant, self-configurable, with conservative energy consumption, creation of clusters, among others; however, like well-known protocols such as AODV (ZigBee) and DSDV, they do not offer routing changes when there is congestion in the network.

In [25] and [26], the authors present routing protocols which were designed to update the routing tables depending on the congestion in the nodes. These carry out the mitigation of the congestion by limiting node's transmission rates. However, MLDC considers a routing method based on the presented in [11], performing the route selection based on information from the neighbors as occupation of buffer, remaining energy and availability. MLDC implements the steps 1, 2 and 4 of DAlPas method described in Section III.

MLDC does not use the *Connect* and *ACK* packages since those packets increase the load on the network at the time of the initial creation of the topology. In the Setup stage, the sink node begins the transmission of a broadcast type packet (DAlPaS Hello Package) so that it propagates through the network in order that each node constructs its neighbor table as presented in the Figure 3

Node ID	Buffer occupancy	Remaining power	Level	Flag
2	0.84	0.91 J	1	True
3	0.90	0.95 J	1	True
7	0.92	0.96 J	2	True

Fig. 3. MLDC routing table. Taken from [11].

In the same way of DAlPaS, MLDC implements the topology control scheme by exchanging small packages that indicate when there is a change in some of the variables of interest for congestion. When a node has two or more parents with the same characteristics, it balances the load between them using round robin in order to avoid congesting a route.

MLDC does not implement the *Soft Stage Scheme* it because the proposed node buffer management can maintain different traffic flows fairly, and because this technique considerably increases the load on the network without performing a effective congestion control.

This routing algorithm is designed for WSN with *Many-to-One* communication and nodes with the same characteristics do not exchange application information, this causes a tree network topology creation and the neighbor tables are smaller compared to those suggested in ZigBee or DSDV.

D. MLDC Application Layer

The MAC, buffer management and network layers can control and mitigate congestion efficiently, however to have a network where congestion be a sporadic phenomenon, the application layer must be aware of the node state in order not generate information and packages that could be discarded. For this, MLDC suggests the application can review the state of the node in order to decrease or increase its packet rate generation based on the information provided by its lower layers. The application must generate packets at a equal rate or lower than the service rate so that the utilization never exceeds 1 as presented in the Equation 1.

V. Congestion Control Metrics

To perform the quantitative evaluation of the behavior of the congestion control methods with respect to the traffic generated and the topology used, it is necessary to define the quality of service metrics and define a clear procedure for its measurement. The following QoS metrics are proposed:

- Indicates the average transmission rate of the packets in the network. The measurement must be carried out in the Sink node sensing the data transport rates of all the packets arriving at the node without errors in a specific period of time.
- *Fairness* This metric is used to determine if multiple users (in WSN: nodes), are receiving equitable resources among them. The index *Jain's Fairness* qualifies the justice in a network based on the throughput of the packets arriving at the sink [27]. To calculate this metric, the Equation 4 was used.

$$J(X) = \frac{(\sum_{i=1}^{N} Xi)^2}{N \cdot \sum_{i=1}^{N} Xi^2} \tag{4}$$

- *Average packet delay* This metric indicates how the algorithms can handle interferences in the network, processing and transmission times from the packet generation to the reception at the Coordinator node of the network. To perform the measurement, the delay of each arriving packet at the Sink is estimated, then the average of these data is calculated.
- *Network life time* The lifetime is measured as the total remaining energy of the network at different times.
- *Packet loss percentage* This metric indicates the relationship between the number of lost packets and all packets generated by the network.

The described metrics was chosen because they describe the behavior of the WSN in different aspects, for instance, it is desirable to have fairnes in the network due it is more important to hear equitable transmission rates from a lot of sensors in a region than high rates from few sensors [16]. Throughput indirectly indicates the amount of information that reaches the sink node, Energy consumption is critical for a WSN because it is desired that it be minimal so that the maintenance of the network is not carried out frequently, a low packet loss percentage gives reliability to the network, and low and stable average packet delay indicates that the network could transport the data in a real-time manner. Congestion can significantly damage these metrics, which would cause service degradation for the network and a bad performance for the application

VI. Simulation and Analysis

For this paper we make use of NS-2 (Network Simulator Version 2) which is an open source event-based simulator that has gained popularity in the scientific community since 1989 due to its flexibility and modular nature.

The evaluation of the congestion control algorithms in NS-2 is done using the parameters:

- *Channel*: Wireless channel.
- *Propagation*: Considers path loss, shadowing and fading models.
- *Media Access Control*: IEEE 802.15.4.
- *Antenna*: Omni-directional.
- *Buffer Size*: 20 Packets.
- *Traffic Type*: On-Off traffic. ON time was configured in 8ms in which packets of 70 bytes were transmitted at a rate of 250 Kbps.
- *Energy Model*: The NS2 energy model model specifies the transmission, sensing, reception power and initial energy.
- *Nodes*: 101 nodes. One Sink (in the center of the region) and the others are sensing nodes.
- *Nodes Distribution*: Random in a 150m x 150m geographic region.
- *Network Topologies*: Mesh, tree and star.

A total of 1500 simulations were carried out to evaluate the behavior of the network without congestion control, using ECODA, DAlPaS, Fusion and MLDC in the three network topologies. In the Figure 4 the metrics evaluation results are shown. The graph corresponds to the average values obtained during the tests (each bar is an average of 100 simulations).

A. Fairness

This metric measures how fair was the distribution of the throughput between the nodes that generate information in the network. The topology that gives more justice to the network is the star, followed on average by the tree topology and finally the mesh. This behavior indicates that the nodes communicated with rates similar to the sink. However, this metric must be analyzed in conjunction with the Throughput as presented in Section VI-F.

Fig. 4. Simulation results.

B. Percentage of packet loss

This metric measures the total number of packets discarded or lost due to communication problems. Having a low percentage of lost packets gives the network greater reliability in that the generated packets will be transmitted and received properly in the Sink.

The topology with the best behavior in this metric is the star, followed by the tree and finally the mesh. These results are presented because the star does not consider hops in the packets, therefore the points of failure in the network decreases with respect to the other two topologies evaluated.

C. Average Packet Delay

The average packet delay is measured as the time since the packet was transmitted by the originating node until the moment in which the Sink node received it correctly. A packet should not remain in transit for a long time on the network because if it carriers events or alarms information, the congestion control algorithms must act fast for transmission.

Due to the intrinsic characteristics of the star topology in which there are no multi-hops, this has the best behavior followed by the tree and the star.

D. Throughput

This metric measures on average, the amount of information that correctly arrives at the sink per time unit (measured in Kbps). In a WSN, this parameter have to be as highest as possible since it indicates that the network is collecting much information from the sensors.

However, in networks that have many traffic generating nodes, it is advisable to analyze this metric in conjunction with the fairness in the distribution of resources in the network since it is desired that the WSN have high Throughput with a high Fairness.

The topology that obtained better results is the tree, followed by the mesh and finally the star. In the section VI-F an analysis between the Fairness and the Throughput of all the simulations is presented.

E. Energy consumption

This parameter is very important in a WSN because it must usually work without maintenance during a long time, specifically in terms of battery charge or battery change.

The consumption of energy in the processing, transmission and reception process affects directly the life time of the network. For this reason, this metric is measured by analyzing the amount of energy of all the nodes at different times in the network.

Due in the star topology there are no multi-hop, the power consumption in processing at the nodes is lower. The second method of congestion control in energy saving is the tree followed by the mesh.

F. Fairness - Throughput relationship

It is necessary to analyze these two metrics together due to the fact that in networks with several users the results can be misinterpreted, for example, having a high Fairness but a low Throughput means that very few nodes were attended and they access to network resources leaving others without service.

The ideal scenario is to achieve a high Fairness with high Throughput too, which implies that many nodes obtained a equally transmission rate.

The Figure 5 presents a scatter graph of the average values obtained in the simulations carried out in the three topologies evaluated and in each congestion control method. The topologies with the best Throughput are the tree followed by the mesh. Regarding the Fairness metric, the best result is the star followed by the tree and finally the mesh. However, this result

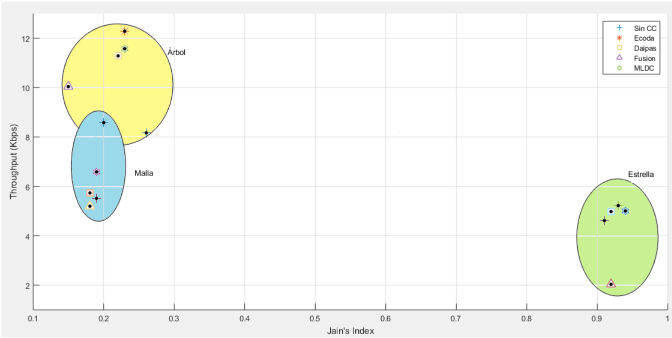

Fig. 5. Fairness - Throughput relationship.

in ”justice in the network” is not desired in a WSN because it means that very few nodes were treated equally and the rest transmitted at 0 Kbps.

VII. Conclusions and Future Work

The tests and simulations carried out in the simulations justify the importance of having a congestion control in a WSN because they improve the behavior of the network under the selected metrics and mitigate the effects produced when there is high traffic in the network. The process of selecting the congestion control method must be done in a rigorous way, under an analysis of the implications that implementation may have on nodes.

Another important factor in the WSN design is the network topology. Topologies due to their intrinsic properties, directly affect the communication and the state of congestion in different points of the network. Tree and Mesh type topologies allow distributing the nodes in broader terrains in comparison to the Star. For this reason, the selection of the network topology should be analyzed depending on the requirements of the application and solution that the WSN will provide.

When using multi-hop topologies, it is necessary to implement an adequate management and administration strategy for the nodes’ resources, especially the buffer, since it was demonstrated that the congestion control methods that have buffer management algorithms have better results.

A Wireless Sensor Network has different restrictions and differences with traditional wired and wireless networks, for this reason specific metrics must be defined to describe the behavior of the network under these restrictions. The proposed WSN congestion metrics describe the behavior of a WSN from a network traffic point of view; The design of algorithms for congestion control, routing, self-healing, etc., should seek to optimize these metrics.

Fairness and Throughput must be analyzed together due to the fact that the results obtained in some analysis of a WSN can be misinterpreted.

MLDC method works properly in the three topologies evaluated, improving in all cases different congestion control metrics and the general behavior of the network, so its use and implementation is highly recommended.

As future work it is suggested to perform the evaluation of congestion control methods in real environments, to look for alternative window back-off size programming for the media access control, to evaluate different algorithms of buffer administration in the nodes, to evaluate other network topologies such as tree-cluster and implement a cluster heads selection method based on congestion information.

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