WSN Simulation Model with a Complex Systems Approach

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Abstract

We present a new simulation analysis, with a complex systems perspective, in order to study WSN operations. We have built different scenarios on which we evaluate the congestion control and the routing mechanisms. An agent-directed simulation has been developed, where data packets are regarded as active entities, i.e., agents. With this approach, it is possible to analyze the system behavior, either from a microscopic or macroscopic view. The simulation model proposed fosters the development of solutions for routing and congestion control.

1. INTRODUCTION

WSN is an emerging technology offering a wide range of possibilities. It is also known that there are open issues that limit the practical adoption of WSN [1]. These limitations come from the fact that each individual wireless node in the WSN has reduced processing capabilities, as well as, modest energy budget. The potential of WSN stands on the possibility of building a cooperative solution where each individual device works on behalf of a collective entity, i.e., each node works for the overall network. Devices do not only produce information, but they also forward and route data packets to an appointed sink node. The major challenge consists in programming each autonomous node to make decisions based only on its local conditions, having in mind that each decision impacts on the overall network behavior. Indeed, this is the complex systems perspective applied to the WSN considered in our model.

Simulation tools are the best suited resources when analytic methods are unable to provide accurate solutions, or when direct experiments are not feasible. Both conditions can be met in WSN. Due to the amount of interacting wireless nodes, analytic tools can hardly assess the parameters that feature the system's performance. On the other side, deploying an experimental settlement can be very expensive and the obtained results are difficult to be taken into consideration for a more general framework. Therefore, specialists on WSN prefer simulation tools to study network operations such as communication protocols.

In this work we present a new model that incorporates a complex systems perspective where M. Mitchell [2] describes complex systems as: -"*These are made up from a massive network of interacting components, without a central control, that follow a simple set of operational rules and are able to achieve an elaborated collective behavior, thanks to sophisticated information processing techniques and adaptation, based on learning or evolution"*-. It is clear to us that WSN do perfectly fit with the definition of a Complex System: there is a massive number of interconnected entities which have local interactions based on simple algorithms and, therefore, a proper programming can lead to an emerging behavior which should be able to tolerate alterations in the WSN, such as the failure of a component or congestion.

We built different WSN arrangements to test congestion control proposals. From our approach, inspired from agent-directed simulations [3], data packets are regarded as the active entities whose interactions shape the overall system behavior. Our tool supports the study of individual agents, also shows the network aggregated data transfer. This means that the simulation can zoom in, to a microscopic level, or zoom out to a macroscopic level on the network's traffic view, with the complex systems approach.

2. RELATED WORK

Networks simulation tools are used to develop and optimize communication protocols. The most used simulators are: NS-2, OMNet++, Prowler, OPNET and TOSSIM [4]. All they have important features for development of routing protocols and control congestion schemes, such as scalability to large networks (except NS-2); support for dynamic topology change; standard routing support; standard energy modeling; and they also implemented radio models. However, these simulators need extensions for a proper work on WSN. For example: Prowler does not consider node energy, TOSSIM does not support dynamic network topology change, NS-2 does not have good scalability for large sensor networks, OPNET causes scalability problems, etc. [4-5]

It's not possible to say which simulator is the best adapted for a given application, since most of them follow different approaches to investigate different problems.

We present a simulation model oriented to test and evaluate various control congestion schemes and routing options. The proposal is based on analyzing the global behavior of network traffic, from the interaction between data packets, for which the analysis is conducted from a perspective borrowed from complex systems. To the best of our knowledge, this is a new approach that we have barely found in a small set of related proposals, such as: [6] where authors propose using the complex system theory to deal with WSN; a more comprehensive proposal is presented in [7], which proposes an agent-bases simulated framework, this work focuses in a environment model more than a WSN model; finally from an agent-based approach, an improvement on directed diffusion routing protocol is presented in [8].

It is very important to underline that we present a model that can be implemented using any type of discrete events simulation tool. The value of our proposal stands on the fact that we incorporate the key aspects that define, from our perspective, a WSN environment, such as: wireless losses, energy consumption and dynamic topology changes. The order of the underlying graph, i.e., the number of nodes that can be studied, it is an implementation issue that depends on the hardware and software in charge of the simulation.

3. WSN ANALYSIS FROM THE COMPLEX SYSTEMS PERSPECTIVE

3.1. Traffic and Congestion in WSN

Since one of the focus of our proposal is to test various control congestion schemes, we must know: how does congestion occur?

We considered that the network congestion arises when the traffic density reaches a condition where most of the exchanged packets experience delays or are lost. Therefore, the overall system's performance is degraded and may collapse. To avoid this condition, congestion control techniques are design to carry as many packets as possible and minimizing the elapsed time, from source to destination. Additionally, in WSN, congestion mechanisms should consider the side effects of wireless transmissions, such as interference and power loss. Thus, our simulation model comprises wireless effects and scenarios with network congestion.

Congestion occurs when the system is close to its carrying capacity and, an increase on the incoming traffic, or even a burst, may overload the packet buffers with a potential domino effect that may turn into a disaster. On these conditions, and unless a control mechanism is turn on, the number of packet arrivals to their final end falls abruptly. In contrast, a network under control keeps close to an ideal response. This is, the outgoing traffic equals the carrying capacity.

Besides the common congestion sources, in this work we study the bottlenecks that arise when all packets are routed to a single sink node.

3.2. Conceptual Framework

We present a list of concepts from a complex systems approach that is based on [8], these concepts reinforce our view and allows us to find similarities between WSN and Complex Systems, accordingly.

Preliminary, we state that:

- A Complex System is made up from agents
- Each agent is an entity that interacts with its environment
- Agents have goals and an individual behavior oriented to achieve these goals
- The behavior of an agent affects in positive, negative or neutral way the possibilities of the others to achieve their own goals. Therefore, there is a relationship among agents
- Each agent's satisfaction is assessed with a variable $\sigma \epsilon [0,1]$
- The overall system satisfaction depends on each agent

$$\sigma_{sys} = f(\sigma_1, \sigma_2, \ldots, \sigma_n, \omega_0, \omega_1, \omega_2, \ldots, \omega_n) \quad (1)$$

  Where ω_0 represents a trend from the system, while the rest of the weights show the importance given to each σ_i
- Friction happens when the increase on an agent's satisfaction causes a decrease on some others' satisfaction and the magnitude of the increase is less than the magnitude of the decrease. Individually, it can be measured according to

$$\phi_i = \frac{-\Delta\sigma_i - \Delta\sigma_{sys}(n-1)}{n} \quad (2)$$

3.3. Agent-Directed Simulation

Agent-directed simulation is the use of agent technology to generate model behavior or generation of model behavior monitoring [3]. The key premise that guides the construction in [9], is that "reducing friction between agents pays back benefits on the system satisfaction, which means, a better performance evaluation". Therefore, maximizing σ_{sys} can be accomplished by limiting the action of those agents that reduce others $\sigma_i's$, while preserving functionalities and fostering synergy, i.e. positive interference, among them.

Table 1. Components, goals and its equivalences for the WSN proposed model

Concept	WSN equivalent
Agent	Data packet
Goal	Arrive to the sink with minimum delay
Satisfaction *	0 if data packet does not arrive to the sink, 1 if it arrives to the sink within minimum time
Behavior	Packets travel across the network to the sink
Friction	An increase on the incoming traffic (throughput), reduces the outgoing traffic (goodput)
System's satisfaction	Can be evaluated from the outgoing traffic
Mediators	Nodes
Mediator's role	To execute a (distributed) algorithm that prevents congestion and maximizes the outgoing traffic

As agents may present conflicting goals, their behavior is limited or regulated by means of mediators. These entities are charged to minimize conflicts, interferences and frictions, in order to maximize cooperation and synergy.

Table 1 shows the correspondence between WSN concepts and the concepts from complex systems that we have introduced. These ideas are the departing point for the construction of the proposed simulation.

4. A WSN MODEL

The model devised comprises the following set of modules.

- Network settings
- Packets generation
- Routing
- Congestion control
- Wireless effects
- Energy consumption
- Performance evaluation

4.1. Network Settings

This module fixes the space and time properties of the supported WSN model.

* Notice that satisfaction and friction are user-defined measures and they can change if required.

4.1.1. Space Scale

It describes the extension of the area, spanned by the WSN, as well as, its shape, e.g. square, circle or irregular.

4.1.2. Time Scale

It settles the total simulation time, as well as, the length of the window that measures $\Delta\sigma_{sys}$. It is known, that many control mechanisms strongly depend on the time scale chosen to introduce adaptive decisions, but also the effectiveness of these mechanisms becomes evident depending on the time scale chosen to evaluate the system's performance: "an apparently bad decision in the short term may turn into a good decision in the long term".

4.1.3. Type of Nodes

In our model we consider 3 types of nodes:

- *Sink:* It is the final destination of the packets carried by the network. Therefore, the outgoing traffic, i.e. throughput, is measured considering the number of packets delivered at this point
- *Source:* These nodes generate the incoming traffic, i.e., the packets that are carried by the network towards the sink. If necessary, these nodes may also develop forwarding operations
- *Forwarding:* These nodes are charged to route the packets on their way to the sink

The number of deployed nodes is defined by the user, who also defines the number of source nodes. The sink has a random location, as the rest of the nodes deployed.

4.1.4. Average Node Degree

This parameter defines the average number of connections each node has. In WSN, nodes' degree can be featured as a random variable that follows a probability distribution function (PDF). In this particular case, we generate a random number using a normal distribution and then we round it to the closest integer. According to this characteristic, each node is connected with those nodes within its propagation radio. The global effect of these local connections is the resulting graph that models the underlying communications network**.**

4.1.5. Coverage

Due to the fact that coverage directly depends on the transmission power, coverage also affects the nodes' lifetime. A wider coverage area means that the corresponding node is running out of its energy more rapidly. Coverage is also considered a random variable that follows a normal distribution.

4.1.6. Reception Buffer Size

It is known that, in packet switching networks, congestion occurs when data packets cannot be temporarily accommodated on the forwarding nodes. This is a direct consequence of the number of packets that each node is able to accommodate; which depends on the buffer size. In our case, this variable takes the values, 0, 2, 4, 8, 16, 32, 64 and infinite following a normal random distribution, in the same way that the average node degree.

4.1.7. Other Parameters

- Transmission rate and packet size
- Supported error rate
- End-to-end delay can be selected
- Energy consumption per packet, which depends on coverage

4.2. Packet generator

The traffic scenarios are simulated by traffic generated at the source nodes. This has the possibility of issuing a given number of packets per unit time, according to any of the following options

- Generating a random number using a normal PDF and then it is rounded to the closest integer
- Generating a random number using a Poisson PDF
- A continuos generation rate
- An augmenting rate that grows 'x' packets per unit time, every fixed step time

4.3. Routing

The routes from all sources to the sink node are settled once at the beginning of each simulation, using a well-known distributed algorithm [10], called "Propagation of Information" (PI). This initialization step produces a spanning tree with root at the sink. The routing strategy that a given node follows is very simple: it just forwards a packet to its father node or, alternatively, to any node of level less or equal to that of its father. It is very important to remark that, due to our modular design, a different settlement can be introduced to test alternative strategies.

4.4. Control Congestion

The module in charge of the control congestion is one of the key issues of our work. This module includes the following features.

- A self-organized and self- configurable distributed algorithm
- It works like a semaphore that controls the transit of packets on their way to the sink. Either let the packets to go forward, or it stops the packets at the buffers
- The "green" and "red" lights depend on a function that intends to maximize the overall system satisfaction

As an example we propose a very simple settlement, we define the satisfaction of a packet σ_i as a function that depends on its delivery delay.

$$\sigma_i = \begin{cases} 0 & if\ delay > 9 \\ 1 - \frac{delay}{10} & if\ delay \leq 9 \end{cases} \qquad (3)$$

This means that the packet satisfaction decreases with its delay up to the point when its attention is worthless. Now, we define the overall satisfaction as the average of all individuals $\sigma_i's$

$$\sigma_{WSN} = \sum_{i=1}^{n} \frac{\sigma_i}{n} \qquad (4)$$

In turn, we propose that the friction of packet *i*, is defined according to the following expression

$$\varphi_i = \sigma_x - \sigma_i \qquad (5)$$

Where σ_x is the average satisfaction of all packets sharing the same route with packet *i*.

Each packet knows its satisfaction as show in Equation (3), and each node calculates the friction of the forwarded packets. This is the information assessed from a microscopic point of view of the traffic behavior of the network. We can deduce from Equations (3) and (5) that, a) the packet does not produce friction, when its satisfaction equals to σ_x; b) packet causes a positive friction, when its satisfaction is less than σ_x; and c) it causes a negative friction, i.e., interference, when its satisfaction is greater than σ_x. Using this information, each node can make decisions that maximize network satisfaction, see Equation 4, i.e. nodes help to improve the macroscopic behavior of the network traffic.

A possible congestion control mechanism should take into account these measurements, in order to keep the overall system under control. For instance, it could forward more rapidly those packets with φ_i less than -3, another option is drop them. As congestion is strongly correlated with routing mechanisms, we also consider the option of testing alternatives.

The simulation model presented in Section 5 allows the user to build and evaluate their own control congestion algorithms.

4.5. Wireless Effects Simulation

Our design considers the free space loss model, the effects of thermal noise and interferences. We calculate the normalized signal to noise ratio and, for the binary phase-shift keying modulation (BPSK), we assess the bit error rate (BER). We determine the error probability per packet according to a fixed error tolerance. With this probability we are able to simulate packet losses due to wireless effects.

The simulations of wireless effects are considered and in the final statistics, it can be distinguished between packet losses due to wireless effects from those due to routing congestion.

The equation to calculate the signal power is:

$$P_r = \frac{P_t \lambda^2}{(4\pi d)^2} \tag{6}$$

Where: P_r is the received signal power [w]
P_t is the power of transmitted signal [w]
λ is the wavelength [m]
d is the distance between transmitter and receiver [m]

Wireless simulation also includes the effects of thermal noise and interference in transmission of each node. We can calculated the maximum capacity of the channel (C) using the Shannon capacity for 8 kHz bandwidth (B).

Using Equation 7 we found the normalized signal to noise ratio (*Eb/No*).

$$\frac{E_b}{N_0} = \frac{B}{C}\left(2^{C/B} - 1\right) \tag{7}$$

We choose BPSK because requires less *Eb/No* than other traditional modulation techniques.

From a table of BER for BPSK, BER is obtained, and considering the application requirements, specifically the bit error tolerance, the packet error rate (PER) is estimated, as follows.

$$PER = 1 - \sum_{i=0}^{t} \binom{p}{i} [BER^i (1 - BER)^{p-i}] \tag{8}$$

Where: t is the number of bit errors tolerated by the application
p is packet size [bits]

The packet losses due to wireless effects are estimated by the PER.

4.6. Power Consumption Simulation

The WSN topology changes are represented using the power consumption simulation, due to the loss of connectivity caused by nodes that have depleted their battery energy. This effect is simulated by setting a percentage of consumed power in the data transmission. The consumption of energy due to processing capabilities is no considered in the simulation.

Packet losses resulting from the effects described in the previous paragraph are considered losses by routing. It is clear that as the network topology changes, it is required an adapting and self-configurable routing protocol.

4.7. Performance Evaluation

This module performs the recording of different parameters of the network, such as packet losses, offered traffic, throughput and goodput. Different performance metrics are also calculated with the information obtained, for example, buffering time, lifetime of the network. Additionally, the user can propose other performance metrics, which can be drawn from the measurement of ϕ_i and σ_{sys}.

5. SIMULATION USING THE COMPLEX SYSTEMS PERSPECTIVE

The simulator used is based on a discrete event simulation (DES), in order to characterize the asynchronous packet exchange in the WSN.

5.1. Discrete Events Simulation

A Discrete Events Simulation (DES) generates a representation of the system's history and, as a consequence, it is required to organize all the events within the simulation. These events order must characterize the cause-effect relationships that take place in a real system. It is also required to know the status of the simulated system at anytime. In our proposal, the communication channels are supported using FIFO queues that link each couple of nodes involved in a packet exchange. Thus, we model a WSN as a queueing network. The WSN status is affected by the state of each buffer's node and, by the exchange of packets in the WSN, which in turn, changes the buffers conditions. The simulation has two types of events, packet transmission and packet arrival.

5.2. Architecture

The simulation model was developed under the object oriented programming (OOP) paradigm. This section provides the general details for this simulation implementation in any OOP language.

The programming classes included in the proposal are:

- *Simulation:* During the execution this class is responsible for, initializing the network from the parameters set defined by the user, updating the clock, assigning and dispatching events, calculating and displaying, the performance statistics of the network at running time.
- *Scheduler*: schedules events and it returns the next event to be attended.
- *Event:* Each event has the following attributes: type (it can be: packet-send, packet-arrival and update-stats), time of execution, associated package or payload, and the immediate target node identifier.
- *Network:* The network attributes are related to the transmission and the fault tolerance of the WSN modeled. At the initialization process the following activities are performed: nodes are randomly scattered over a given area, each node is randomly linked to those nodes within its area of coverage, nodes execute the routing algorithm and get prepared to run the congestion control algorithm.
- *Link:* Two nodes are assigned to each link. To initialize the link, the BER is calculated and according to this probability it is determined if the link transmits a packet or loses it.
- *Node*: A node consists of a buffer and a given number of incoming and outgoing links. Nodes dispatch two types of calendar events: packet-send and packet-arrival. The control packets fields are defined by the user with the routing mechanism and congestion control. When a node sends a packet, it uses both, the routing and control congestion modules.
- *Buffer:* Each buffer acts as a FIFO queue, the buffer size is set according to a normal distribution.
- *Packet:* Each packet has the following fields, source node ID, target node ID, next destination identifier, time to live (TTL), type which it may be data or control type. The control packets fields are defined by the user within the context of the routing and congestion control mechanisms.

5.3. NetLogo Simulation

We have developed our scenarios using NetLogo [11], which is a complex systems simulator. The simulator works with a scheme of object-oriented programming and its programming language is a Logo dialect extended to support agents. This simulation implements the modules described in Section 4.

The settings interface and the WSN view are showed in figures 1 and 2, respectively.

In Figure 2 we can see the following features:

- The nodes random deployment
- The sink node is represented by 2 concentric circles; source nodes are represented by a triangle; and dead nodes are represented by an 'x'.
- Packets are represented by a gray box.
- The node color (in gray scale) changes with the battery charge. Nodes with full battery are darker than nodes with less battery.
- The node size increases according to the number of packets that the node has allocated at the buffer.
- Solid lines represent links which have been used at least once.
- Simulation provides a spatial scale of 1 ha.

Figure 3 shows the results. In Figure 3a, we can see when the number of transported packets increases, the arriving packets delay increases. This can be observed in the second half of the simulation, where the amount of buffered packets increases, due to the fact that nodes are busier and packets must be stay into the buffer for more time.

Figure 3b shows that in the last part of the simulation, routing losses increased considerably, due to ten nodes that have consumed their entire battery, so the connectivity of the network has been affected. In the other hand, congestion losses increase as a function of the number of sent packets.

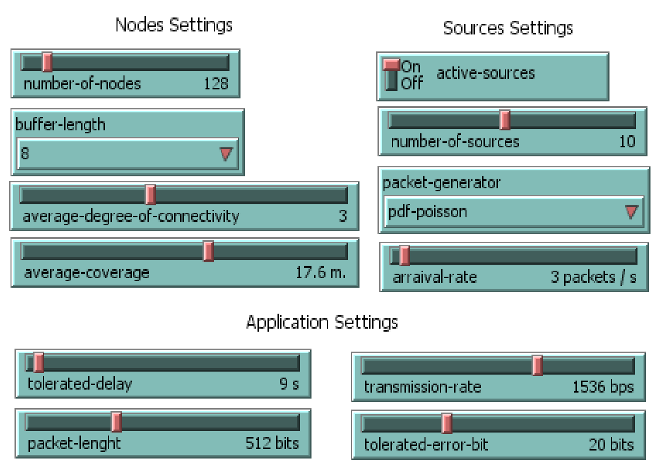
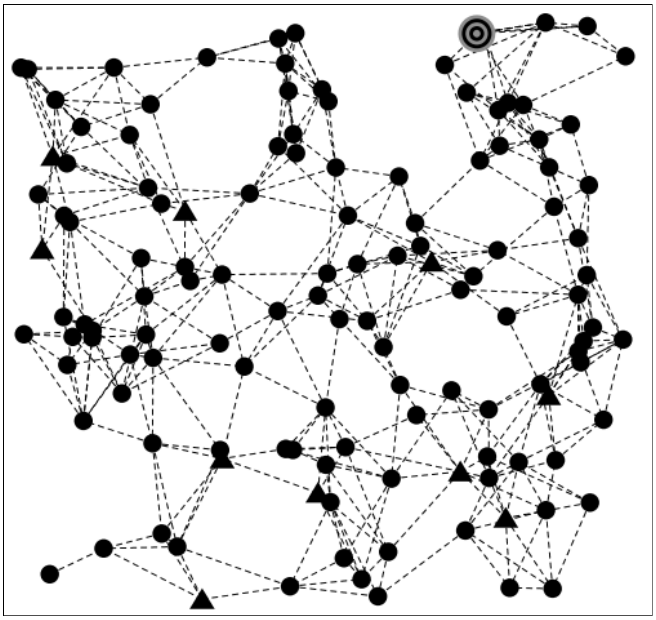
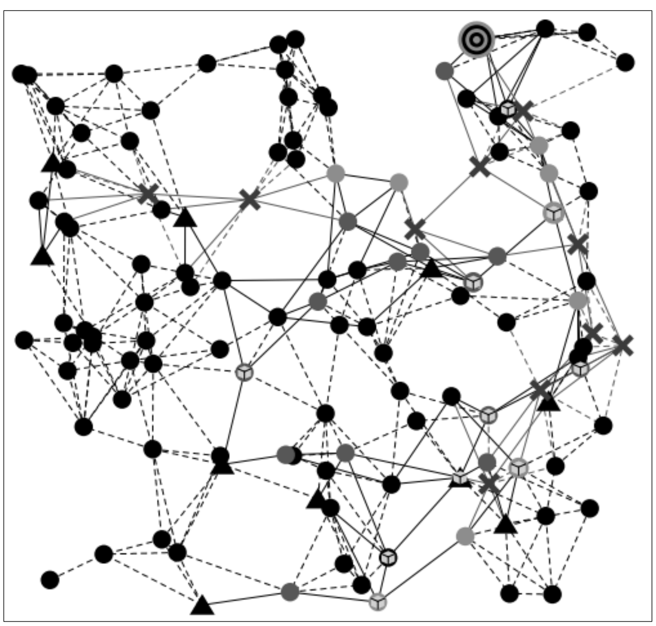


Figure 1. Settings interface

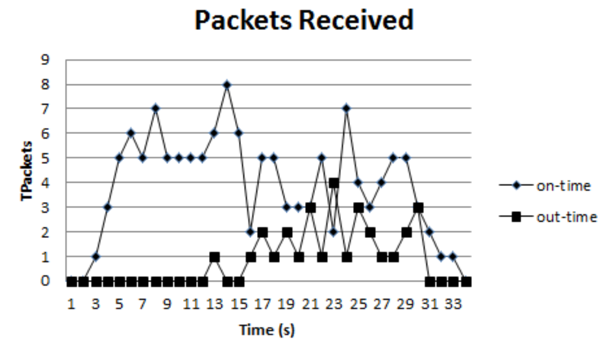


(a)

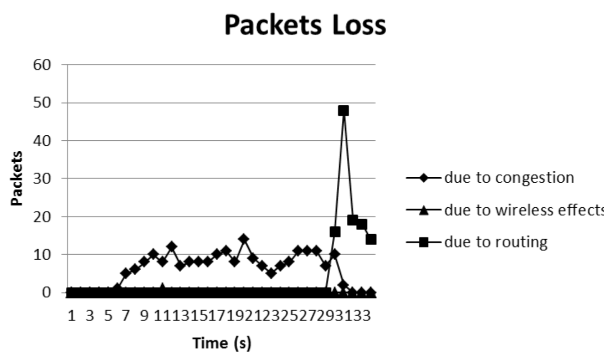


(b)

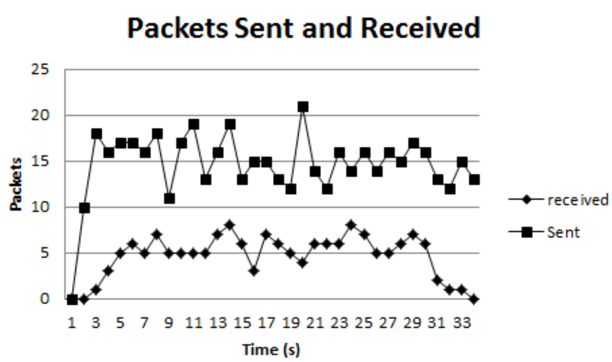
Figure 2. WSN view (a) before of the simulation execution and (b) after the simulation execution of 14 seconds.



(a)



(b)



(c)

Figure 3. Performance charts

6. CONCLUSIONS & FUTURE WORK

We have developed a simulation model, to study congestion control operations in WSN, from the perspective of complex systems. We consider that this viewpoint provides with alternative ways to understand the undergoing processes that take place in wireless sensor deployments. Data packets are regarded as the active entities or agents, which travel across the network to reach an appointed node called "sink". In time, nodes are perceived as mediators that are intended to reduce friction among packets and maximize the overall system satisfaction. This performance parameter can be compared with a traditional network parameter such as throughput.

From our approach, we distinguish two different causes that contribute to packet losses, i.e., due to wireless effects and congestion. We tested the control mechanisms under dynamic conditions, in order to evaluate their ability to reinforce steady conditions. For this purpose, we include arbitrary topology changes.

In complex systems it is a common practice to study a phenomenon under different space and time scales (from microscopic to macroscopic views). We decided to introduce this property in our model in order to zoom in or out for a particular aspect of the system under study.

Finally, we consider that our proposal can be extended to study other telecommunications systems, such as wired networks.

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Biography

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