Performance Analysis of a Multi-Mode AdHoc Wireless Network via Hybrid Simulation

J.R. Emiliano Leite, Edson L. Ursini, and Paulo S. Martins

Abstract— **The growing application of sensors, devices and computers in communication networks has created opportunities to both increase and exploit the real-time data and information available. We propose a flexible, multi-mode AdHoc Network model and show through a hybrid discrete-event and Random-Way-Point simulation that its behavior can be analyzed for a set of performance parameters, including mean queueing time and CPU utilization. The introduction of modes of operation to the model, both with emergency nodes to increase security and with links to balance the Internet traffic, and especially the joint use of a discrete-event together with a mobility simulation model, are the major contributions of this work. We depart from a simple network case study and evolve to a more complex hybrid simulation model.**

Keywords— **Mobile AdHoc Networks (MANET), Wireless Sensor Networks (WSN), Emergency Services, Multi-mode**

I. Introduction

The increasing utilization of sensors, devices and computers in communication networks has created opportunities to exploit the growing availability of real-time data and information [1]. On the other hand, the evolution of the IoT technology brings several challenges in relation to reliability and traffic performance. We can classify IoT networks in networks formed by RFID networks, Wireless Sensor Networks (WSNs) and AdHoc networks. All these types of network generate traffic that converge to an IoT Mediator, which needs to be carefully designed. This paper aims to approach in more detail the AdHoc network as a significant part of IoT traffic.

A wireless AdHoc network is a computer network requiring relatively minimal configuration and quick deployment, which makes it suitable for emergency situations like natural disasters or military conflicts [1]. Wireless AdHoc networks are decentralized and can be used for a variety of applications where central nodes cannot be relied upon. They also improve the scalability of networks compared to other traditional networks.

In emergency situations, the flexibility of wireless communication networks and their overall timing (delay) performance are an essential requirement to be addressed [2]. To study AdHoc network characteristics and performance, we propose a multi-mode network model that can be instantiated and adapted for a number of scenarios. To illustrate the concept, we adopted a set of modes of operation, where in each mode the network reconfigure one or more of its resources (links and nodes) according to the surrounding environment, in an attempt to sustain or even increase its performance in the presence of an abnormal event.

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Network performance (i.e. mean queueing time and CPU utilization) is evaluated for a set of scenarios through a number of case studies. Each case is built in increasing order of complexity, using a distributed environment, where packets are forwarded through network links from one node to the next in the proposed AdHoc network model. Each node receives packets at the input link and forwards them to one of the depart links using UDP over IP (Datagram). Since the arrival of requests for the AdHoc network can be modeled as a Poisson process, the traffic volume of each individual node can be extended to the traffic volume of a cluster by the simple sum of the rates of Poissonian arrivals. Furthermore, the Random Way Point model also plays an essential role in assessing the probability of packet loss, depending on the characteristics of the signal (e.g. transmission frequency, power, antenna gain), thus allowing the model to be closer to the physical characteristics of a real network.

The remainder of this paper is organized as follows: Section II addresses related work. Section III describes the proposed model. Section IV introduces four case studies using the simulation model. Section V presents the results and a discussion, and Section VI addresses the conclusions.

II. Background and Review of Earlier Work

The use of dynamic and adaptive routing protocols enables AdHoc networks to be quickly formed. Wireless AdHoc networks can be classified by their application: Mobile AdHoc Networks (MANET), Vehicular AdHoc Networks (VANETs), Smart Phone AdHoc Networks (SPANs), Internet based Mobile AdHoc Networks (iMANETs) and Military / Tactical MANETs [1].

The AdHoc protocol has the following highlights: 1) International Standard IEEE 802.15.4; 2) used in Mobile AdHoc Networks (MANET), Wireless Sensor Networks(WSN), Catastrophe and Emergency Networks; 3) base of ZIGBEE Architecture, BLUETOOTH Architecture, IoT Access; 4) it will increment the future D2D Protocol of 5G Architecture and CRAN (Cognitive Radio AdHoc Networks)). These features are used to guide the formulation of the simulation model and the performance evaluation of the AdHoc network in the remainder of this paper.

Suh *et al* [1] address an AdHoc Distributed Simulation for Transportation System Monitoring. Their approach employs a dynamic collection of autonomous simulations interacting with each other and with real-time data. The authors used a real-time distributed simulation environment and tested their approach on a transportation network. The geographical distributions of client locations and traffic demands are all distinct.

Hiromoto *et al* [2] show a Mobile AdHoc Wireless Network for pre and post-emergency situations in Nuclear Power Plants (NPPs). They proposed to integrate MANET and Bluetooth-like technologies, to create an indoor and outdoor communication for the NPP. Boutin [3] uses MATLAB with Random Waypoint Mobility Model (RWP) as the main software tool to study the characteristics and performance analysis of a communication network regarding mobility. Within the realm of defense communications, and specifically modeling and simulation of complex systems such as mobile AdHoc networks (MANETs), Yoginath *et al* [4] propose a time-synchronized virtual machine framework that accurately lifts the network communications and the devices to a virtual time plane while retaining full fidelity.

Despite the existence of a body of work on AdHoc networks, none of the studies cited and surveyed in the literature tackle the features of the AdHoc under consideration in our work, i.e. the issue of modes of operation to increase network robustness (emergency mode) and traffic balancing. Furthermore, they do not address a more comprehensive simulation model for traffic performance evaluation, with the adoption of discrete event simulation using Arena and Matlab and the extension of traffic analysis allowing the inclusion of clusters.

III. Network Model

Figure 1 shows the full network model with the possible inputs (packets) and outputs (also packets) to each node. The network has 11 nodes, i.e. 7 user nodes and 4 gateway nodes, as well as 7 sensor inputs and 3 Internet outputs.

The entities are the packets and the resources are the nodes. An TCP/IP packet is modeled as an entity that arrives in the system and crosses several internal queues in a node, before it leaves the system (i.e. is consumed by an application). Inherent to each queue is the waiting delay, before a packet can be processed by a server. Clearly, both queueing time and processing time are subject to statistical distributions. A network node has a number of internal queues (each one associated to an outbound link). Each queue is in turn associated to a CPU. Thus, each node may have multiple CPUs allowing multiple parallel connections.

The upper part of Fig. 2 illustrates a cluster as a set of 10 nodes, and the lower part shows the simulation components of an individual node, which is described as follows:

- *Enter block*: the enter block simulates the arrival of a packet in a node. It accounts for the number of packets entering the node.
- *Chance* is an Arena DECIDE type of block, and it distributes the packets across a set of outgoing lines, where each line is associated with an outgoing queue. The probability of packet loss (which was obtained in case 4) is also accounted for in this block. The probability of a packet being forwarded to an outgoing link is arbitrarily set and shown in Fig. 1 for each link, e.g. 1/4 from node 1 (i.e. ND_1) to node 2 , and 3/4 from node 1 to node 5.
- *Output Queue* represents the queueing time in the outgoing line, and
- *Output node* simulates the output (i.e. forwarding) of packets from the node. It is also responsible for accounting for the number of packets leaving the node.

Four modes of operation are included: *Regular, Balanced, Emergency* and *Mobility* modes. The *Regular mode* of operation, as the name implies, models normal operating conditions of the network. *Balanced mode* is the mode that attempts to balance out the volume of inelastic and the elastic traffic. This is accomplished by the addition of new links between nodes where the traffic is high and needs added capacity. The *Emergency mode* models abnormal operating conditions. In our example, we use the amount of traffic as the indicator of such abnormal behavior. Therefore, an excessive traffic volume may trigger the need for transition of the network to an emergency mode, whereby new nodes are added to compensate and normalize the network. Clearly, other variables may be used as a mode-change trigger.

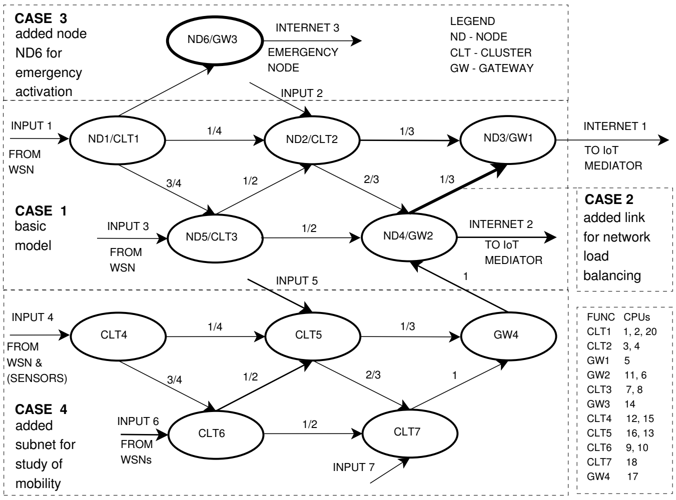

Fig. 1: Proposed AdHoc network model

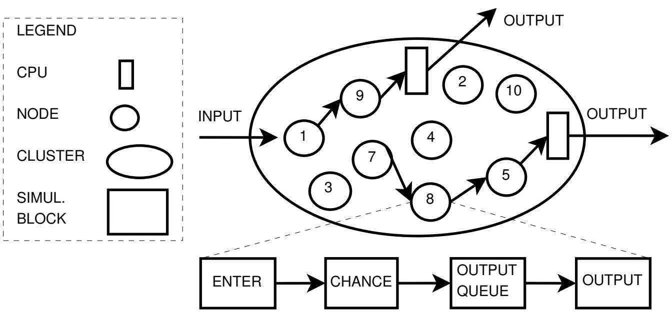

Fig. 2: Cluster organization model (Case 4)

IV. Case Studies

In this section, we present four cases in an incremental way to finally arrive at the complete traffic model (Table I).

A. CASE 1: Basic network: regular and unbalanced mode

The simulation model uses five AdHoc nodes (Fig. 1) that communicate by means of standard RF (Radio Frequencies).

TABLE I: Case studies and parameters under consideration

	Case Study			
Variable #	1	2	3	4
# modes	1	2	3	4
mode name	regular	balanced	emergency	mobility
mode action	basic	new link	new node	added mobil.
balanced traffic	✗	✓	✓	✓
emergency mode	✗	✗	✓	✓
# user nodes	3	3	3	70
# gateway nodes	2	2	3	4
total # nodes	5	5	6	74
# clusters	0	0	0	7
mobility	✗	✗	✗	✓
performance parameter	CPU utilization queue time	utilization queue time	utilization queue time	util, queue time + netw. connectivity
goal: to study the impact of:	reference network	added link	added gateway 3	connectivity due to mobil.
arrival rate (packets/s)	0.5	0.5	5	1.67
service rate (packets/s)	3	3	3	10

The topology adopted is a multi-hop, i.e. nodes receive and forward packets to other nodes until the packets reach their final destination. The model analyzes the flow of packets in the network with respect to mean queueing time and CPU utilization. After execution, it is noted that the system is unbalanced, e.g. there are 343 packets received in node 3 and 1202 packets in node 4.

B. CASE 2: Net. capacity extension: balanced mode

This application contemplates the possibility of using stream or inelastic (sensitive to delay and jitter) and elastic (sensitive to packet losses) services. Stream service provides an almost constant flow of bits and elastic services provides an intermittent flow. Aiming at a balanced Internet traffic between the two flows, a new mode of operation is added whereby a new data link is added between nodes 3 and 4. Note that CPU 11 had to be added to node 4 as well. This CPU was required to process incoming packets from the new (added) link from nodes 4 to 3. Also, although the IoT stream traffic is not comparable in size and volume to other stream traffic, for example, to the VoIP (the latter being much larger), this case study is important since it will help us in future work assess the total traffic that arrives in an IoT mediator.

C. CASE 3: Net. topological expansion: emergency mode

In the Emergency Mode, one new node (node 6, ND_6) is added to the network to forward the traffic of packets to the Internet in the situation of an Emergency with high traffic. It is fundamental to know (or define) what triggers the Emergency mode. What triggers a mode change from any mode to the Emergency mode is the size of the queues, considering the spare capacity for congestion or fault. The simulation model dynamic and automatically switches network operation to the Emergency mode whenever the node's output to the Internet surpasses a threshold number of packets N, which is a configurable parameter. Likewise, if the number of packets decreases below N, the network returns to regular mode of operation.

Figure 3 presents the mean queueing waiting time and the mean CPU utilization for the four cases. In the Basic Model (case 1) the CPU utilization in node 4 (CPU 6) is larger than in

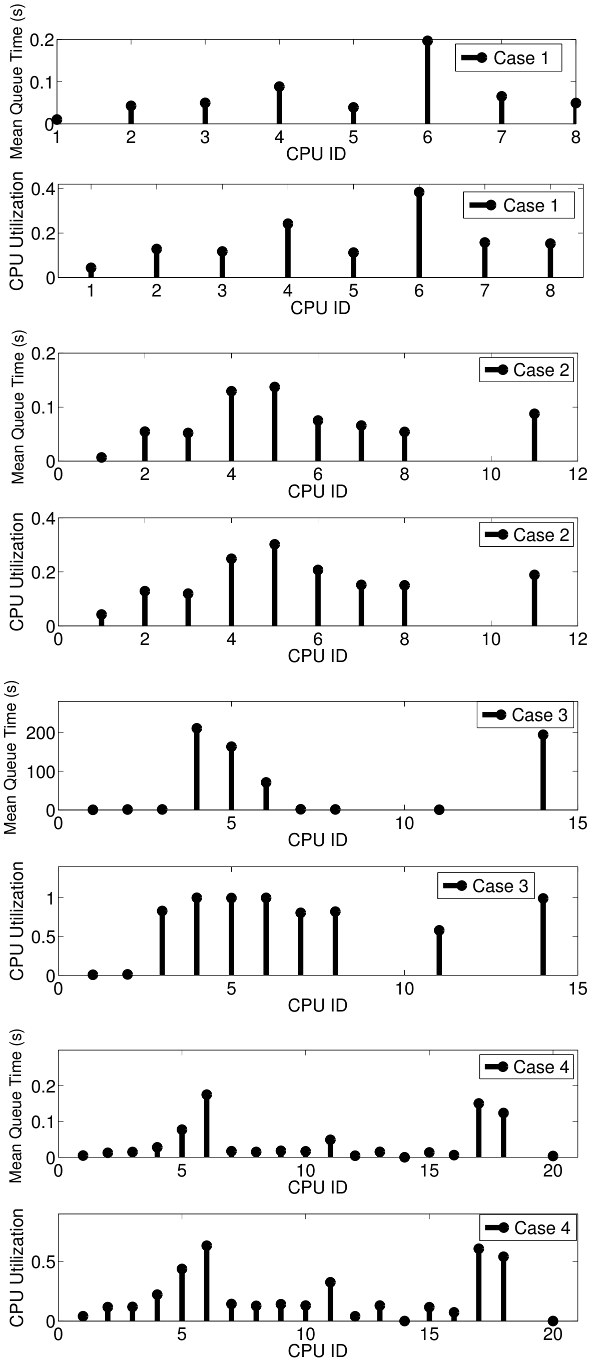

Fig. 3: Mean queue waiting time and mean CPU utilization for cases 1-4.

node 3 (CPU 5). In the Balanced Mode (case 2), the system is more balanced (no CPU utilization is greater than 20%). The graph for case 3 shows an extremely high mean queueing time, thus justifying the activation of the Emergency mode. Case 3 shows that the CPU utilization is no longer too large as in the preceding case due to the activation of the Emergency node; in consequence, the utilization of node 2 decreases because the flow goes to Emergency node.

We forced the emergency condition on purpose to exercise the activation of the emergency node. Upon activation, this node shared traffic with node ND_1 (specifically with its internal CPU 20), increasing the service rate and thus relieving (but not yet stabilizing) node 1, the Internet outputs and the overall network.

D. CASE 4: Complete AdHoc Networks Considering Mobility

The goal of this case study is to analyze different ways of enhancing connectivity for different and varying parameters. It includes a more complete traffic model with node mobility. Moreover, due to Poisson characteristics for input traffic, it is possible to sum the rates of each individual node and then consider a cluster formed by ten nodes. Assuming that the mean inter-arrival time in a single node is 6 secs, the individual cluster mean arrival time becomes 0.6 sec/packet EXPO (i.e. 6/10). Thus, the arrival rate is 1/0.6 = 1.67 packets/sec. The mean service time is 0.1 sec/packet and the service rate (1/0.1) = 10 packets/sec. It is possible to adequately locate each node as in Amis *et al* [5]. However, in this paper we are more interested in the issue of traffic volume.

Thus, we expanded the network by considering seven clusters of ten nodes each, and introduced node mobility via the *Distributed Dynamic Routing* (DDR) algorithm for mobile AdHoc networks [3].

Figure 1 shows one upper subnetwork with three clusters (CLT_1, CLT_2, and CLT_3) and three Internet nodes (GW_1, GW_2, and GW_3, the latter is the emergency node) and a lower subnetwork with four clusters (CLT_4, CLT_5, CLT_6, and CLT_7) and one gateway node (GW_4, used for interconnection).

To evaluate each node independently, a Matlab routine generates random positions for the ten nodes within the cluster, every one sec (in our case). Table II shows the input parameters for the Matlab algorithm. This case used the Random Waypoint Mobility Model (RWP) to simulate the performance of the network.

By changing different parameters such as the number of user nodes, number of gateway nodes (interconnection), simulation time and simulation area, we can either increase or decrease the connectivity. We can increment the connectivity by either increasing 1) the number of user nodes, or 2) the number of gateway nodes, or 3) simulation time or else by decreasing the simulation area. Mobility determines the location of each node that selects a random destination, and travels towards it in a straight line at a randomly chosen uniform speed.

The distance to connect nodes lies within the 200-500 meter range. We used a 1000 x 1000 m^2 area. The adopted mobility model is the one presented by Boutin [3].

Two basic propagation models (FS = Free Space and TR = Two-Ray ground propagation model) were considered, which are described by the following equations:

$$d_{TR} = \left(\frac{P_t G_t G_r h_t^2 h_r^2}{P_{t,FS} L}\right)^{1/4}, \quad d_{FS} = \sqrt{\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 P_{t,FS} L}} \quad (1)$$

where d is the minimum distance (in meters) required for connection between a pair of nodes. Using values from Table II, we obtain d_{FS} = 582 m and d_{TR} = 564. Depending on the scenario (indoor, free space) it is possible to switch from one

TABLE II: Case 4: Matlab input parameters

Input Parameters	Values
Receiver Threshold	-88 dBm
Area size	1000 x 1000 m
Antenna type	Omnidirectional
Antenna height (ht, hr)	1.5 m
Antenna gain (G_t, G_r)	1.0
System Loss Coefficient (L)	1.0
# Mobile nodes in a Cluster	10
Mobility model	Random Waypoint
Speed interval	[0.2 - 2.2] m/s
Pause interval	[0-1] s
Walk interval (walk time)	[2-6] s
Direction interval	[-180 + 180] degrees
Transmission frequency	5.8 GHz
Transmission power (Pt)	15 dBm
Simulation time	306 s

propagation model to another. Since both values obtained are close, we adopted the value of 500 m. By running the model (Matlab simulation) 20 times, we observed distances greater than 500 m, and the number of nodes that remained connected per observation (i.e. simulation run) is shown in Fig. 4.

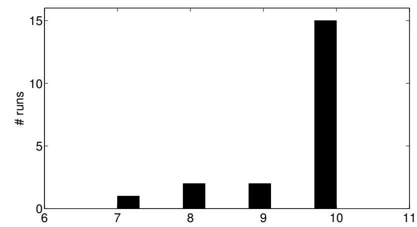

Fig. 4: Case 4: Number of active nodes in a cluster per simulation runs.

According to Fig. 4, for 15 simulation runs we had 10 nodes connected, and 2 runs had 9 nodes, for example, in a total of 20 runs. The probability of no connection P_f is given by:

$$P_f = 1 - \frac{15 \cdot 10 + 2 \cdot 9 + 2 \cdot 8 + 1 \cdot 7}{200} = 1 - \frac{191}{200} = 4,5\%. \quad (2)$$

Thus, we had 191 transmissions with success and 9 without success within 200 possible transmissions (20 · 10 nodes). The P_f value is used in the Arena Chance Block to represent the probability of a node being in the “DISCONNECTED-STATE”.

Figure 5 shows two examples of situations with different positions for the nodes. The second example shows that three nodes have distance higher than 500 meters and they are disconnected. The importance of these parameters is such that it justifies the use of both Arena and Matlab simulators. If we use 250 m (or less) as the minimum distance d for connectivity instead of 500 m, the blocking probability (or no connection) could be less than 50%.

V. Summary, Results and Discussion

Case 1 is simpler and represents an AdHoc Network with no operating modes and no mode changes. The distribution

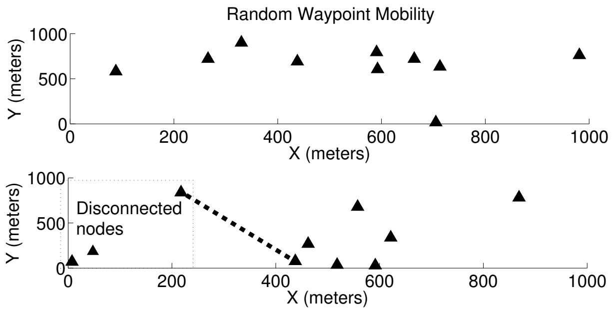

Fig. 5: Case 4: Different positions of nodes.

of packets shows that one Internet link is more used than the other, i.e. the network is unbalanced. Specifically, we observed that the volume of data traffic in the Internet links in node 3 is very different from node 4.

In Case 2 the AdHoc topology is incremented with new critical resources at the bottleneck (i.e. connection between nodes 3 and 4) allowing a more balanced traffic to the Internet. Specifically, this case was supplemented with both a new CPU and a new link from node 3 to node 4. Furthermore, we added two types of service: Elastic (Burst Flow, e.g. data files) and Inelastic (Constant Flow, streaming), with quite different features.

Case 3 is incremented with an Emergency mode, that adds and emergency node, which represents a decrease of delay and an increase of the network throughput. Additionally, the robustness and fault-tolerance aspects of the network are also ameliorated. Clearly, the addition of one node is for the sake of illustration and the system can be mostly improved if we augmented the network with a larger number of new nodes in emergency scenarios.

Finally, Case 4 presents a more complete traffic model using the Distributed Dynamic Routing (DDR) algorithm for mobile AdHoc networks, employing seven clusters with ten nodes each. The Random Waypoint Mobility Output (Matlab Software) feeds the Discrete Event simulation Arena Software. This case has new CPUs now modeling the clusters with ten nodes each. Regarding the Random Waypoint Mobility Model, it is possible to increment network connectivity by adding either more user nodes, or gateway nodes (to provide interconnection), or simulation time, length and width of simulation area, or a combination of these factors.

Since the initial simulation model has both exponential arrival and service distributions, it may be validated against Jackson's open queueing network model [6]. The solution is obtained from a Markov chain. The packet arrival rate is 1/0.6 = 1.67 packets/sec. The first seven arrivals, each generated by a cluster (gateways do not generate traffic), yield 1.67 packets/sec (the remaining four are gateway inputs), therefore: γ = [1.67, 1.67, 1.67, 1.67, 1.67, 1.67, 1.67, 0, 0, 0, 0]. We also need the matrix that describes the probabilities shown in Fig. 1 , which results in a 11 x 11 matrix R. The total arrival rates in each cluster or gateway is given by the vector: $\Lambda = \gamma\ [I - R]^{-1}$, Λ = [1.67, 3.54, 2.92, 1.67, 3.54, 2.92, 5.49, 4.68, 10.49, 0, 6.67]. From the rates obtained, it is possible to calculate the delays for each CPU (W_i, [i=1....20]) by means of the equation for the delay in an M/M/1 queue:

$$W_i = \frac{\lambda_i/\mu_i}{\mu_i - \lambda_i}, \qquad \mu_i = \frac{1}{0.1} = 10 \tag{3}$$

packets/s, where λ_i and μ_i are the rates for each CPU. Since all the delay values obtained from the simulation model matched the ones from the analytical model, the simulation model may be deemed validated. This validation is a crucial step since it allows further extensions to this model, i.e. the inclusion of other model features such as new types of distributions.

VI. Conclusion

The main objective of this work was to provide a simulation model that allows the evaluation of several key aspects of an AdHoc network, including robustness in the event of an emergency, traffic volume and node connectivity. It is part of a wider goal that attempts to dimension the traffic that goes through the so-called mediator function within an IoT context.

The use of operating modes in an AdHoc network with emergency nodes and balancing links to maintain or even increase network performance (including traffic flow and robustness) under abnormal conditions, and especially the joint use of a discrete event simulation model using the Arena software with the Matlab mobility simulation model, are the major novelties of this work. Another relevant issue considered was node connectivity within the AdHoc mobile environment - under two different types of traffic - the inelastic and the elastic traffic, which turned the model more realistic through the inclusion of packet loss. Through the case studies, the simulation model has shown indications that it may provide an efficient tool for analyzing a number of scenarios, specially the ones that may compromise network service and can be remedied through network reconfiguration via modes of operation and their transitions.

Future work will focus on a number of features, including topological features such as increased number of emergency nodes, increased number of fault-tolerant nodes and clusters, variations in traffic volume (specially the traffic through an IoT mediator), and dynamic mode changes across all operating modes. These features will augment the resilience capabilities of the network as well as its overall traffic performance.

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