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Hybrid Model For Making Decision Methods In Wireless Sensor Networks Through Neuro-Fuzzy Inference System

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HYBRID MODEL FOR MAKING DECISION METHODS IN WIRELESS SENSOR NETWORKS THROUGH NEURO-FUZZY INFERENCE SYSTEM

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Dedication

To my Husband and Family in Colombia. Thanks for loving and supporting me during this long trip.

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by

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Abstract

Considering the complexity and multiple alternatives for technology decisions in Wireless Sensor Networks (WSNs), a multicriteria selection method (MCDM) is an appropriate approach for choosing the best option in technical projects. Purely quantitative decision-making procedures have currently been created based on client requirements and recommendations from industry professionals in many domains. In this context, implementation and operational costs could be increasing due to technical problems and additional processes. In order to prevent future difficulties and obtain a more accurate technology selection, a new method was being developed to involve qualitative and quantitative parameters taken from real scenarios and technical literature review and optimized with a Neuro-Fuzzy Inference Systems using Mamdani Approach (NFIS) design. This dissertation provides a detailed description of the Multicriteria Decision methods as AHP, ANP, Vikor, and others. In addition, the process to generate data for NFIS systems, and the Hybrid methodology designed, including the economic analysis, are explained.

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Chapter 1: Introduction

1.1 Problem Definition

The demand of wireless sensor network (WSN) technology is expanding across all industries due to new services and applications for the operational requirements into the companies. For example, temperature, humidity, and presence readings have been requesting for oil and gas, health, food, and geology sectors. Several types of technologies could be applied for taking the measurements, but some factors need to be evaluated for selecting the appropriate technology, such as location, infrastructure, economic, technical, regulatory, and social aspects[1]. Table 1. Describes the parameters involved in each criterion for the evaluation.

Table 1. Criteria for Technology Evaluation[2], [3]

Factors	**Parameters involved**
Environmental/Geographical aspects	Type of location (plain, mountainous), Geometric form of the locality, weather parameters, Variety of flora and fauna
Technical	Channel capacity, reliability, percentage of packet lost, flexibility, scalability, bandwidth, data rate, type of data.
Infrastructure	Presence of electricity, buildings, cellular and microwave reception.
Social	Solvency and social structure of communities, size of population
Regulatory	Rights of way, licensing, spectrum availability
Economic	Investment, operational costs, ROI (return of investment)

Decision models, called Multicriteria Decision Making methods (MCDM), have been used to obtain the best technical solution for different applications based on theoretical parameters, technical standards, and expert opinions becoming the solution in a pure qualitative decision. Some

MCDM adopted for wireless sensor networks decision process are AHP [4], ANP[5], Vikor [6], parametric model [3], and others will be explained in detailed on chapter 2.

Therefore, some problems could be raised in the implementation and operation process such as high costs or low communication quality because real scenarios and parameters are not taking under consideration during the decision process. To avoid this situation, an exhaustive quantitative and risk study is needed to obtain the best result in the technology selection guaranteeing high quality and performance for different applications.

1.2 Research Question

Due to the lack of a quantitative study because there is not a simulation method for real cases where input parameters are combined to generate an exhaustive analysis of the technology factors, the question for this project is: Can a multi-criteria decision model provide an effective and reliable solution about the technology to be used in a given application, including real and specific parameters corresponding to technical, economic, social, regulatory, environmental factors, and risk evaluation?

1.3 Proposed Work

In this research, we are proposing a novel multicriteria decision method to provide an effective and reliable solution about the technology to be used in a given application, including real and specific parameters corresponding to technical, economic, social, regulatory, and environmental aspects and risk evaluation is designed, simulated and compared with AHP methodology.

The new methodology, called Hybrid Decision Model for Selecting Wireless Sensor Networks Technologies, is divided in two sections according to Figure 1. On the first stage, customer requirements are collected, and real scenario is simulated via Netsim® (Network simulator) to generate data for stage 2. Also, an Analytic Hierarchy Process (AHP) model is executed to make the comparison between the two models. For the second stage, a Neuro-Fuzzy inference system based on Mamdani approach is developed to optimize the Multicriteria decision method proposed. Data generated in stage 1 is used to train the inference system and economic and environmental risk analysis is running to obtain the final result using decision trees.

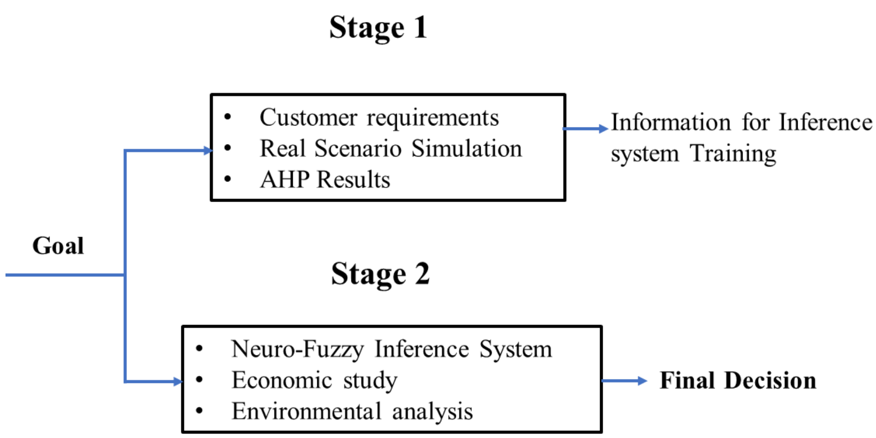


Figure 1. Methodology Hybrid Decision Model for selecting Wireless Sensor Networks Technologies

The dissertation is organized as follows:

Chapter 2 introduces the concept of Multicriteria decision methods. This is followed by the description of present decision methods used on wireless sensor networks and wireless communications, AHP, ANP, Vikor, Parametric model, Hub structure model and Business Canvas model for decision process. Chapter 3 describes the stage 1 of the model, includes the characterization of scenarios, parametric model features and results from the NetSim simulations.

Chapter 4 explains the stage 2 of the multicriteria decision model, Neuro-Fuzzy inference system with Mandami approach, economic decision tree and risk evaluation. Chapter 5 analyses the scenarios results for stage 2 and the comparison with AHP. Chapter 6 includes the conclusions related to the results and future work.

Chapter 2. Literature Review: Multicriteria Decision Methods and WSN

2.1 Multicriteria Decision Methods

Multiple criteria decision making (MCDM) refers to all methods for helping people or processes to make decisions in the presence of multiple conflicting factors. Decision problems are frequently in real life and different contexts [7]. For example, to buy a house involves different parameters such as price, location, neighborhood, years of built, materials, and others. A young woman can choose her life partner based on intelligence, studies, money, looks, etc. Those situations are classified in personal or familiar context. For business situations, A human resource person can characterize the employees by studies, years of experience, salaries, area of experience, etc. In academic situations, the annual budget can be assigned to each department according to number of enrolled undergraduate/graduate students, number of faculty and staff, research projects and others. For our specific case, we are using the MCDM methodology to obtain the appropriate technology in wireless sensor network according to the application and customer requirements. Some multicriteria methods used for selecting wireless sensor networks technologies will be explained in the next section. Those methods are Analytic Hierarchy Processes (AHP), Analytic Network Process (ANP), Vikor, Parametric Model and Business canvas model addressed for technology selection.

2.1.1 Classification of MCDM Models

The literature review indicates that considerable studies have been conducted by academics in the telecommunication fields to create the optimum communication selection model for every scenario where parameterized and organized criteria such as geographic, technical, and socioeconomic elements are taken under consideration. These models can be classified as comparison models and weighted models [1].

2.2.1.1 Weighted Models

Figure 2 illustrates a basic procedure for weighted strategies. The first step is to establish the objective in accordance with customer specifications. Then, based on the expert opinions and theoretical concepts, evaluation elements are established and examined. In the third step, numerical weights are given to each parameter depending on the evaluation of the client's benefits, and a mathematical model is employed to determine the final decision. The Analytic Hierarchy Process (AHP), the Analytic Network Process (ANP), the Parametric Model, and the Vikor Process are weighted model types, [8] , [9].

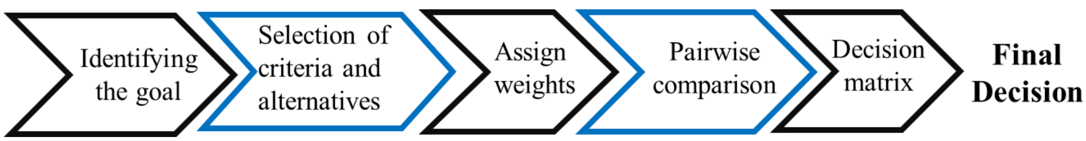


Figure 2. Basic Process for Weighted Methods

2.2.1.1.1 Analytic Hierarchy Process (AHP)

The objective of the AHP, developed by Saaty in 1980 [4], is to build a hierarchy process in which a collection of assessment parameters and alternatives are considered. Figure 3 shows the process. The first step is to clearly define the goal according to the requirements of the study. The second level is selecting the criterion parameters to satisfy the goal demands [10], and the third level involves the determination of the possible alternative results based on the criteria in level 2.

The processing level is the sub-level between the second and third level. In this sub-level, the result of the evaluation of criteria is a weight in accordance with the "Saaty decision score table" presented in [9],[10].

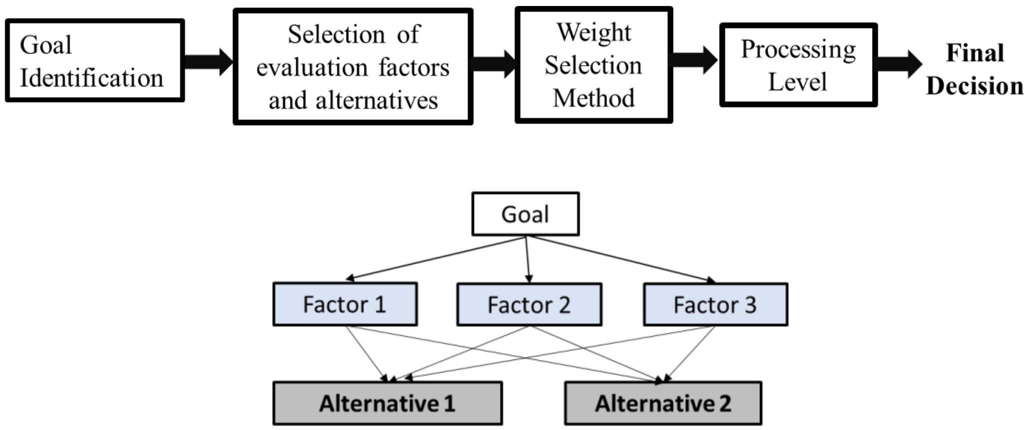


Figure 3. Analytic Hierarchy Process (AHP) [1]

The processing level is the sub-level between the second and third level. In this sub-level, the result of the evaluation of criteria is a weight in accordance with the "Saaty decision score table" presented in [9],[10]. This level involves two steps. The comparison between two evaluation parameters and alternatives to generate the dominance coefficient result (a_{ij}) and a square matrix n x n (pairwise comparisons) refer to the first step [11]. This is an estimate of the first element's ((*i*) predominance over the second element (*j*). Table 2. is used to choose the coefficients (a_{ij}). In the second step of processing level, all the dominance coefficients and matrices from level 1 are synthesized, and the final decision is taken according to the higher weight. In conclusion, the optimal choice is the one that accomplishes the best value between several criteria [4].

AHP is frequently used in many industries such as communications, transportation, administration, and medical to make difficult decisions. For example, in Hong Kong, for vendor selection of telecommunication system, in Nigerian Mobile Telecommunication for subscriber retention, in addressing consumers' preferences in Telecommunication Operators in Bangladesh, and so on [9], [12], [13].

Table 2. Saaty Decision Score table [4]

Scale	**Numerical Rating**	**Reciprocal**
Equal importance	1	1
Equal to moderate importance	2	1/2
Moderate importance	3	1/3
Moderate to strong importance	4	1/4
Strong importance	5	1/5
Strong to very strong importance	6	1/6
Very strong importance	7	1/7
Very strong importance to the extreme importance	8	1/8
Extreme importance	9	1/9

2.2.1.1.2 Analytic Network Process (ANP)

The analytic network process (ANP) is defined in [5] as an extension of the AHP approach in which networks are used instead of hierarchies to show the parameters dependence and the interaction between the alternatives and criteria. The ANP model consist of two parts. In the first part, factors are identified and grouped into the clusters with similar characteristics' parameters groups or clusters. The second part consists on the feedback of the clusters' influence concerning to each other. Also, the presence of feedback, as seen in Figure 4, denotes the reciprocal outer dependency of the criteria in two distinct groups. Similar to the AHP, the ANP process is built on the expertise and experience of specialists, reasoning, and soliciting management inputs in order to get organized communication and structure, while also considering qualitative decision considerations [14]. In addition, the ANP methodology is analogous to AHP, Figure 5 shows the process.

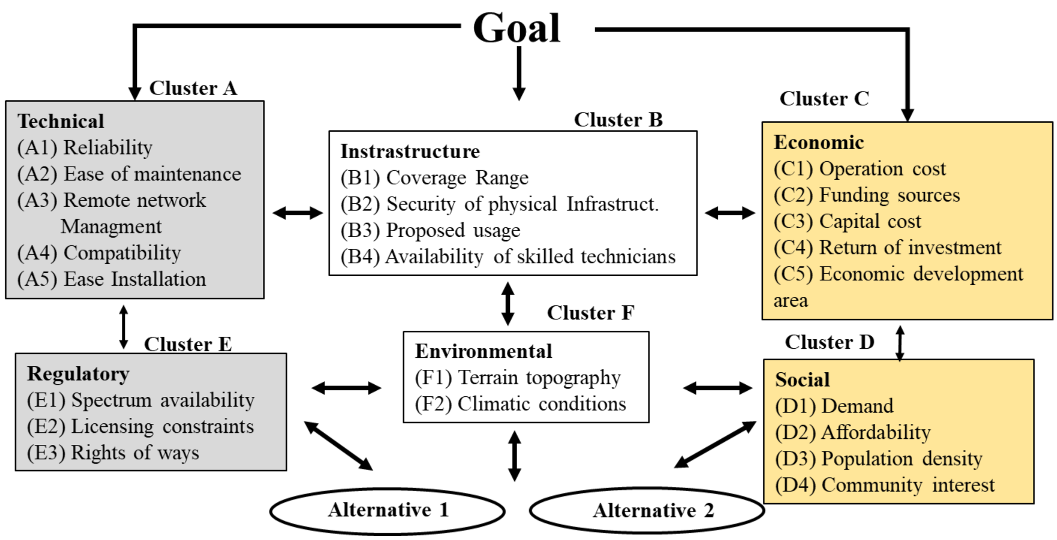


Figure 4. ANP Cluster example

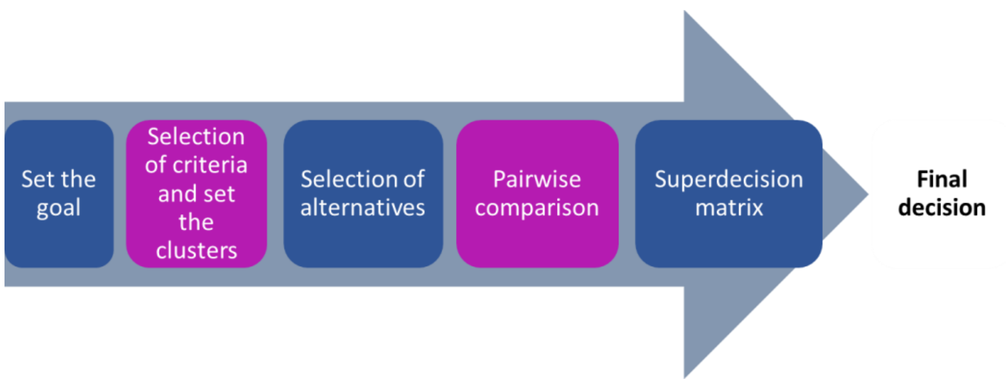


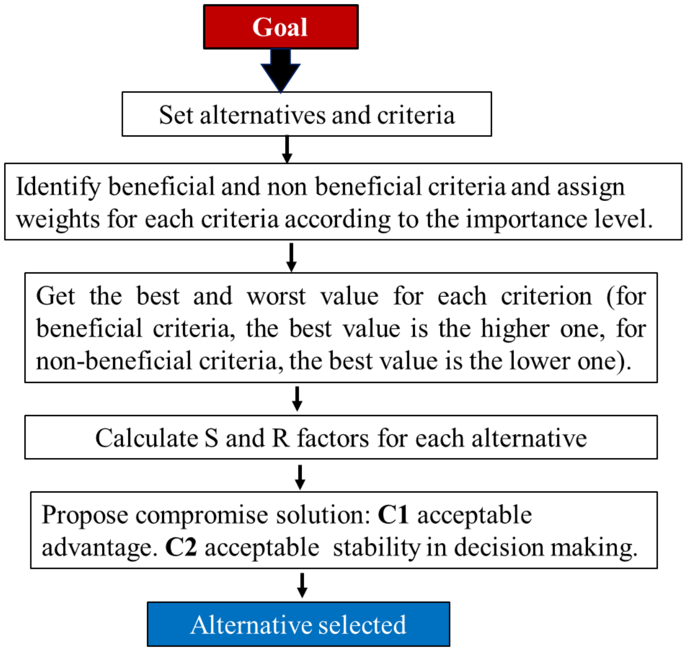
Figure 5. ANP Process

In order to choose a communication technology, the first step of the ANP process is a comprehensive literature review of previous research on comparable difficulties and conversations with telecommunication experts to generate a consolidated list of criteria that includes the most essential variables for the study, [5], [14]. After structuring the problem, the following stage is to examine the influence between criteria. Survey questionnaires are developed to detect the relationships between factors and clusters in order to obtain the objective. Finally, an unweighted matrix containing priority and cluster comparisons is constructed.

As a result, a value of zero ("0") is given when there is no association and a value of "1" when there is a link between two criteria. Then, Table 2 is utilized to complete the super-decision matrix and pair comparison, and the final selection is made in accordance with AHP process [15],[16]. The ANP had been used in the telecommunications industry for the evaluation of the Iran mobile communication operator, the service supply chain of Indian Telecommunication, the evaluation of Turkish mobile communication operators, the utilization of ICT (Information and Communication Technology) in Central European enterprises, the selection of rural telecommunications infrastructure technology, and other applications [14].

2.2.1.1.3 Vikor

Vikor (Vlse Kriterijumska Optimizacija Kompromisno Resenje, Serbian name) is an optimized multicriteria selection method with a compromise solution that permits simultaneous evaluation of the proximity to ideal and non-ideal alternative because of basic calculation processes [6],[17]. The fundamental analysis of the Vikor method is presented in Figure 6. The difference between beneficial and non-beneficial elements, as well as the independence of each element, is a critical characteristic of this methodology, [18]. Because Vikor method combines opportunity loss with the minimax regret, this technique is being utilized for prioritizing methods based on decision-making under uncertainty approach.



Note: S is the maximum group utility and R minimum individual regret of the "opponent"

Figure 6. Vikor Model

This model, as AHP, implies specific or conceptual values available for both new and existing projects, such as vendor selection process (VSP), assessing mobile services, evaluating quality service, and others. In certain circumstances, unfortunately, this assumption leads to unrealistic system outputs, [17], [18], [19], [20].

2.2.1.1.4 Parametric Model of a locality

The main purpose of the Parametric model of a locality, presented in [3], is to expand the services already installed to additional regions using the general and administrative factors previously established. This decision model is divided into two levels. The first level, called general parameters level, contains the parameters that describe the entire locality such as weather, location, type of population and others. The administrative parameters level is the second level in which the parameters for the specific area, city or building are included. Each level consists of dynamic classes, according to Figure 7, where groups of parameters can be added depending on the project requirements.

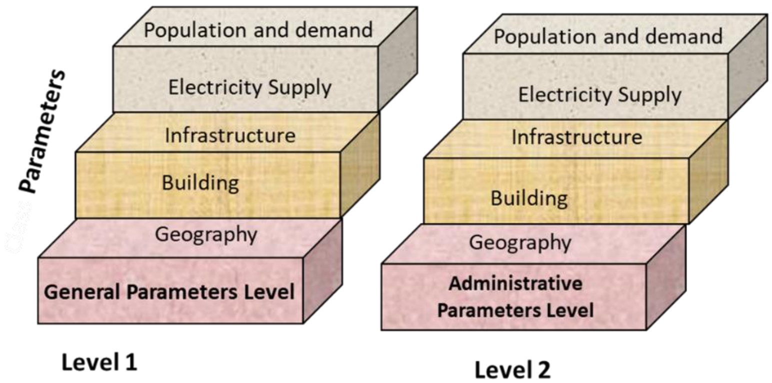


Figure 7. Parametric Model of Locality, levels and classes of parameters.

The functionality of the parametric model of a locality is focused on the imitation of the network construction and operating processes. The objective is to evaluate the implementation and operation costs, and revenues as well as the length of the network construction. Two steps are included in the model functionality according to Figure 8. The first step is the comparison between client demands, locality parameters, and technology considered for the implementation. The second step is the cost calculation and final decision where the "net cash flow indicator" concept identifies the most appropriate technology for the application required. This approach is extensively used by the largest Ukrainian telecommunications provider to build plans for access networks in rural and urban areas, [3].

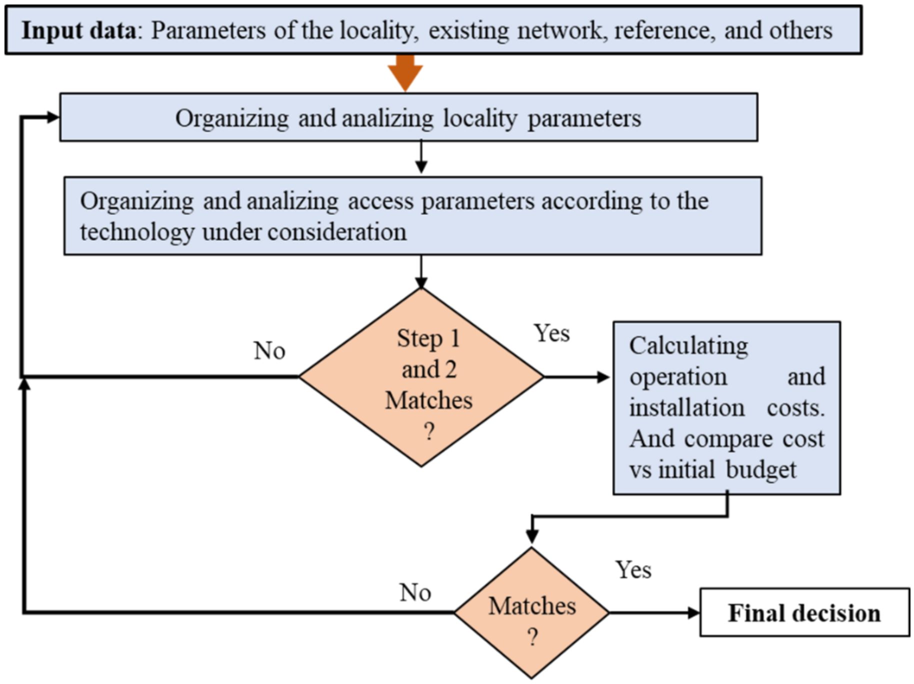


Figure 8. General functionality for the parametric model of locality

2.2.1.2 Comparison Models

For this categorization, the application purpose and problem are specified in the first stage, then, the evaluation factors are defined according to the technology, infrastructure, installed in site previously, carriers, large cities near to small villages o rural places in order to minimize the costs and investments, [8]. Notice that comparison matrices for taking the final decision are built without weighting process, only focused on the community demands. Figure 9 presents the basic strategy for Comparison models.

2.2.1.2.1 Business Canvas as a Selection Model

Business Canvas is a visual chart used to describe company plan's value proposition, infrastructure, clients, and financing for building start-ups business plan. For the selection model, the business canvas is divided in two essential parts: value proposition, where community requirements, profit and potential consumers are taken under consideration, and key partners in which the appropriate resources and cost structure are determined, [21].

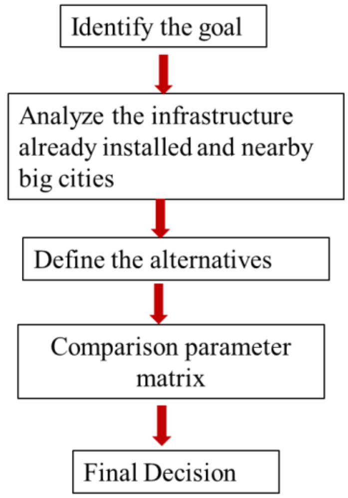


Figure 9. Basic strategy for Comparison models.

For a specific region, the selection of a telecommunication operator depends on the local carriers' availability, data rate, bandwidth, channel capacity, standards and other. However, for remote areas with low population and no service provider a private network can be the best option. Figure 10 shows the business canvas and the decision tree model.

According to [21], this strategy is implemented in remote locations that require telecommunications infrastructure, such as Amazon region in South America, an American Indian reservation, and Western New Guinea, Africa, and others.

2.2.1.2.2 Hub structure Model

The main idea of the hub structure model is to decrease the costs associated with infrastructure such as devices, licensing, operation, and implementation, [22]. Several cities with robust communication infrastructure serve as the centers for surrounding areas in this model, with a 30- to 50-mile radius. The study is focused on improving the current communication technology to provide an optimal service for rural and urban areas. As a result, the selection of the appropriate communication technology is supplied by the best set of hub cities via AHP decision model, [22].

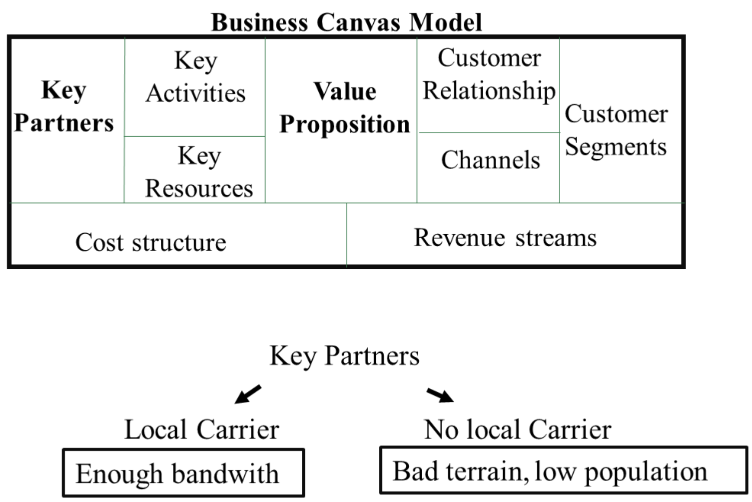


Figure 10. Business Canvas model and Key partners decision tree

2.2 Wireless Sensor Networks (WSNs)

A wireless sensor network (WSN) can be defined as a collection of tiny embedded devices, called sensors, equipped with wireless radios to allow wireless communication and deployed in a specific location with an ad hoc configuration [23]. A sensor node is a unit that transforms a physical characteristic (such as humidity or temperature) into a user-comprehensible representation. These nodes include a power source module, sensing module, communication module and memory [24]. Data is acquired and sent to a central location (which manages and controls the network) using different wireless technologies such as Zigbee, WIFI, LTE, and so on.

Zigbee is a low cost, low power, low data rate (250Kbps) wireless technology with connectivity standard IEEE 802.15.4 [25] working in 2.4GHz, 900MHz and 868MHz unlicensed frequencies. Currently applications include IoT networks, domotic, industrial control systems and others, [25], [26]. For detailed information and characteristics review [27]-[29].

WIFI (Wireless Fidelity) is a wireless technology based on standard IEEE 802.11[30] using 2.4GHz and 5GHz. There are some versions of standard 802.11 that include 802.11a, b, g, n, ac, ax, and others. We used 802.11n (100Mbps) because is one of the most used versions in the global market. Some applications include internet connection, wireless sensor networks, automotive application, industrial sensing applications, and others, [31]-[34]. LTE (Long term evolution) is the standard for the wireless mobile communication, currently called 4G or 4Generation. Data rates include 100 Mbps in downlink and 50 Mbps in uplink. It is used for video transmission and mobile communication, [35]-[37] .

Some application areas for WSN include vehicle tracking, telemetry, precision agriculture, oil and gas exploration and exploitation, animal tracking, surveillance, motion, health care monitoring, environmental and industrial monitoring, and others. Figure 11 presents a basic configuration of WSN.

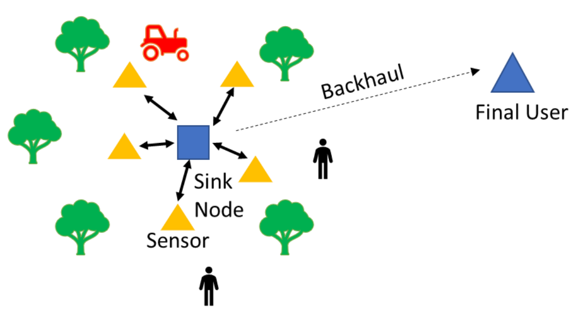


Figure 11. Basic configuration for WSN

Chapter 3. Hybrid Model for making Decision Methods in WSN

One of the most difficult areas in wireless sensor network communications is choosing the optimum technology for urban or remote areas. This technological selection is currently determined using a variety of techniques, some of them described in Chapter 2, focused only on qualitative considerations ignoring quantitative factors. Due to network congestion, lack of coverage, poor quality, difficulty in accessing, and natural factors, among others, this deficit may raise the costs of implementation and operation. Based on these factors, an initial decision model was suggested on [38], lowering the risky aspects, preventing unnecessary expenditures, and giving specific project characteristics for the election. Figure 12 shows the initial model proposed in [2].

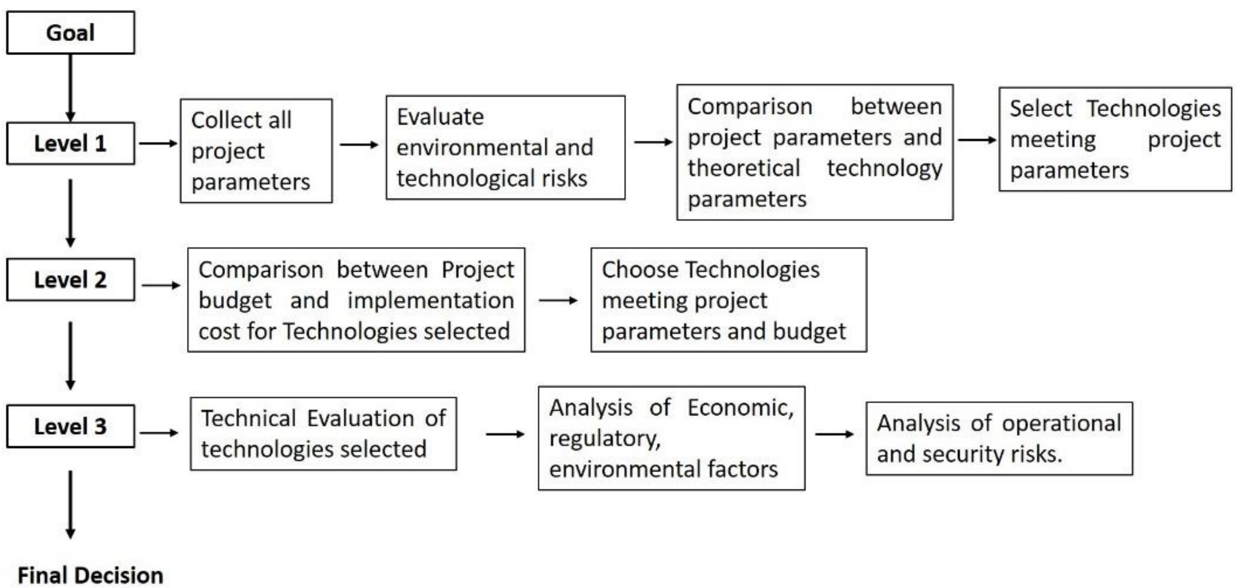


Figure 12. Initial Hybrid model proposed on [2]

As stated in Figure 12, the hybrid model is composed of three levels. The project definition and the objective are established at the first level and integrated in a hierarchical structure focused on the components and deciding parameters. Then, project parameters are collected, and technical and environmental risk evaluation are executed by comparison of the customer requirements and theoretical information from literature review and standards. Let's x_i the project parameter and x_j the technology specification, then the result must be 1 if the technology specification meets the customer requirement, if not, the response should be 0 according to Eq. 1.

$$x_{i,j} = \begin{cases} 1 & \text{if } x_i \ meets \ x_j \\ 0 & \text{if } x_i \ not \ meets \ x_j \end{cases} \qquad (1)$$

Later, the weight factor (W_1) is calculated for each technology, based on Eq. 2, to generate the initial technology list.

$$W_1 = \sum x_{i,j} \qquad (2)$$

The technologies that do not fulfill the first customer criteria are discarded using a threshold (α), then, $W_1 < \alpha$.

At the second level, the budget is the fundamental factor in determining if it is appropriate to include the technologies in the output list or not. A comparison between the budget proposed by the client and the technological cost is made. Eq. 3 shows the process for level 2.

$$y_{i,j} = \begin{cases} 1 & \text{if } y_i \ meets \ y_j \\ 0 & \text{if } y_i \ not \ meets \ y_j \end{cases} \qquad (3)$$

In which y_i is the customer budget and y_j is the technology cost. Then, weight factor (W_2) is computed by Eq. 4, for each technology from level 1 list.

$$W_2 = \sum y_{i,j} \qquad (4)$$

If the level 2 threshold value ((β) is met, then the technology advances to level 3, $W_2 \geq \beta$.

Technical assessment is conducted at the third stage to determine crucial variables such as insufficient coverage, low quality, network congestion, and others by using network and traffic simulators such as Netsim®. Also, in order to prevent budget increases, a thorough economic, regulatory, operational and environmental risk study must be done employing Neural networks methodology and an analysis of sensitive points and tradeoffs. [38], [39].

The evaluator follows scenarios through the architecture, identifying the important components and connections involved in the current scenario, to find sensitivity, risk, and tradeoff points. Following then, the assessors ask explicit questions on the system answer. Lastly, the goal of this risk analysis is to validate the information obtained from each level and improve the communication system to prevent failures [38].

The final response of the model is the last step of level 3, where the weight factor (W_3) is calculated for all technologies, based on Eq. 5 and 6.

$$z_{i,j} = \begin{cases} 1 & \text{if } z_i \; meets \; z_j \\ 0 & \text{if } z_i \; not \; meets \; z_j \end{cases} \qquad (5)$$

where z_i is the technology and z_j is the parameter obtained from simulations and risk analysis. Then, the weight factor (W_3) is computed for the technologies in the output list of level 2, according to Eq. 6.

Then,

$$W_{3=} \sum z_{i,j} \qquad (6)$$

A threshold value (μ) for level 3 is assigned and compared with W_3, if $W_3 \leq \mu$, then, a final list is generated and possible technologies to be use for the project will be found. However, a new model was developed because of the poor input and output parameters for the neural network in the technical study considered for the final decision.

3.1 Cycle 1– Manual Process

The hybrid model consists of two cycles: dataset generation and model optimization. In the optimization cycle, a fuzzy inference system is used as a data classifier to obtain the scenario outputs such as delay, percentage of packet loss, and throughput. Then, data for the model training must be generated on the first cycle based on the scenarios information and AHP model previously discussed. According to Figure 13, this part includes three stages: At level 1, project requirements are collected and compared with theoretical information as the initial model, and a weight is assigned to the comparison based on Table 2. Therefore, Eq. 7 is rewritten as

$$W_{i,j} = \begin{cases} > 0 & if\ x_j\ meets\ x_i\ requirements \\ 0 & if\ x_j\ does\ not\ meet\ x_i\ requirements \end{cases} \tag{7}$$

where, x_i is the customer requirement and x_j is the technical specification, and $W_{i,j}$ is the comparison result.

$$W_T = \sum_{i,j}^{n,m} W_{i,j} \tag{8}$$

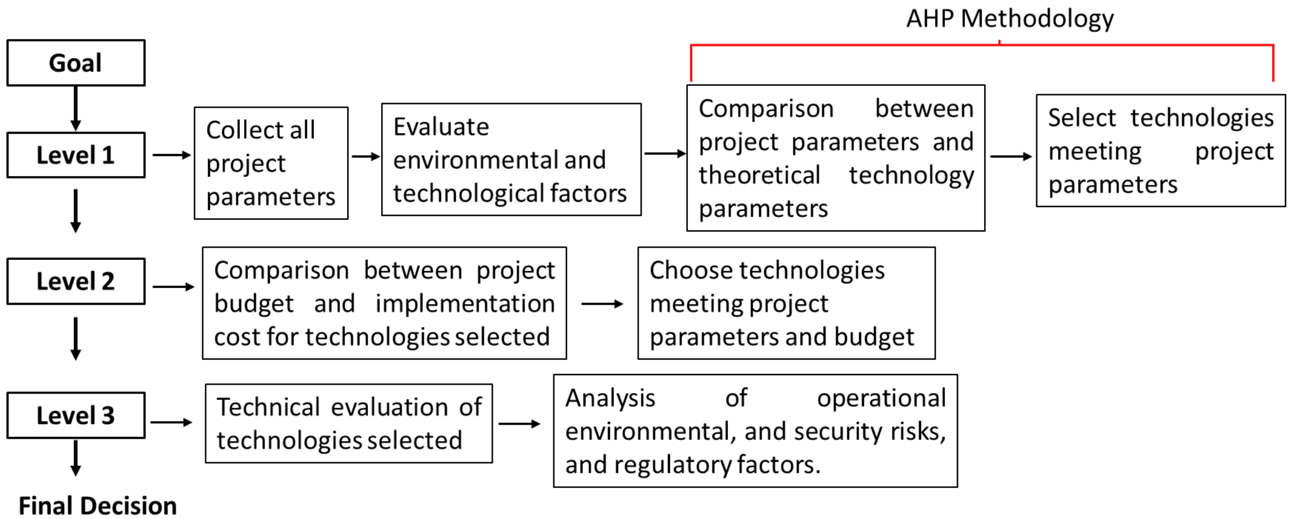


Figure 13. Optimized Hybrid Multicriteria Decision Method [40]

The normalized matrix is created and a mathematical approach described in [10] is utilized to generate the level 1 final decision list. Level 2 includes a budget analysis taking the results from level 1, implementation, and operation activities into account. The technologies that do not fit the customer's expected budget requirements are rejected using a threshold (β).

Let y_i is the budget required for the project and y_j is the budget calculated, then, a weight of 1 is assigned if y_j meets y_i, otherwise, a zero value is assigned, according to Eq. 9.

$$L_2 = \begin{cases} 1 & \text{if } y_i \ meets\ \beta \\ 0 & \text{if } y_i\ \ not\ \ meets\ \beta \end{cases} \quad (9)$$

Where L_2 is the component of the final list for level 2.

On level 3, a technical evaluation is performed to determine key features such as a percentage of lost packets, throughput, and delay. For this step, the project area is divided into small portions of $150m\ x\ 150m$, in order to create a parametric model. The sensor deployment starts at coordinate (25,25), to avoid low connectivity and poor communication quality (blind point), in numbers of 4, 9, 16, 25, and 36 in random and orthogonal topologies, section 3.1.1 describes the parametric model design. A network simulator must be used to recreate the scenario required for the client. On this research project, we are using Netsim® (Standard version 13.0.29) simulator to conduct the technical simulation and examination. NetSim® is a continuous-time, discrete-event network simulator that lets users create a virtual network with different technologies, devices, links, applications, etc., and then analyze the system's performance and behavior. Therefore, using Netsim® tool, the event must be created to obtain the output required to evaluate the technology.

Even though, there are different technologies such as Bluetooth, WIMAX, and LORA only Zigbee, Wifi and LTE wireless technologies are assessed in this study because of the popularity in the global market. For Bluetooth, the distance range is low, less than 10m, for the application proposed. WIMAX components are not easy to get in the retail market and network simulators do not include the simulation library. LORA is a low range wireless technology; few vendors provide the components for the networks and simulators do not include the libraries needed.

However, to recreate the customer scenario with the combination of traffic parameters, technologies and different numbers of nodes will require too much time, probably weeks to obtain the event results, then, a classifier tool based on Neuro Fuzzy inference system with Mandami approach was designed to obtain the results instantaneously in cycle 2. Section 3.1.2 explains the classifier tool configuration.

3.1.1 Parametric Model for Hybrid Multicriteria Decision methodology in WSN

In order to have homogeneous scenarios a parametric model was developed based on coverage area and quality of the communication technologies. The total coverage area is divided into small portion of 150m x 150m, as Figure 14 is showing. In addition, according to communication quality is reduced when real coverage area is 70% of the theoretical value (100m), so the distances between gateways and sensors must be equal or less than 70m. Euclidean distance equation is used to calculate the value. Eq. 10 shows the example to calculate the distance between gateway 1 (G1) and sensor 1 (S1) from Figure 14.

$$d_{G1,S1} = \sqrt{(Y_{G1} - Y_{S1})^2 + (X_{G1} - X_{S1})^2} \qquad (10)$$

$$d_{G1,S1} = \sqrt{75 - 25\,)^2 + (75 - 25)^2} \cong 70m$$

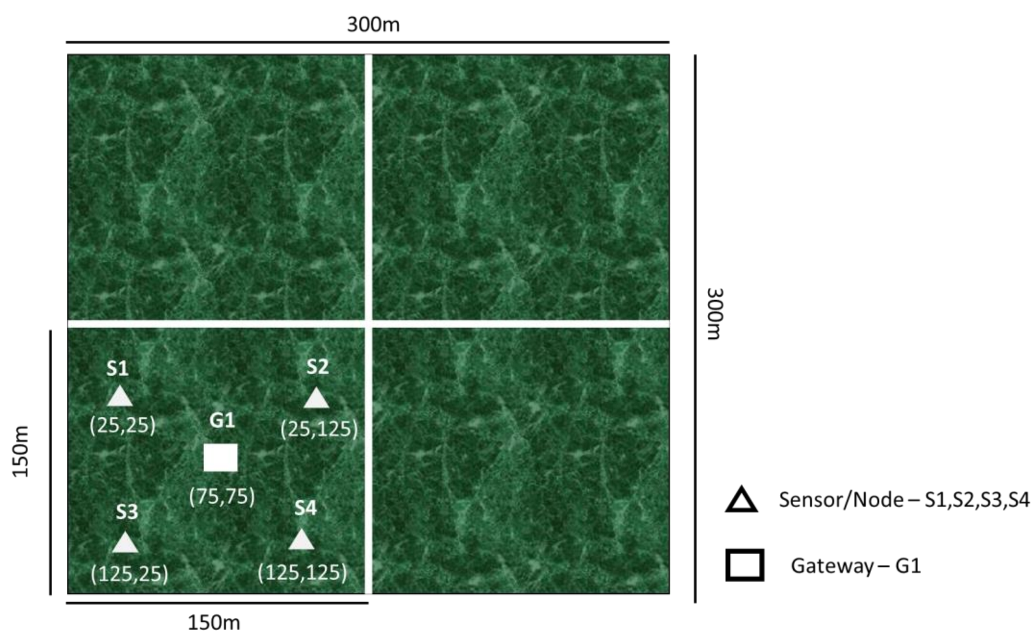


Figure 14. Parametric model example with 4 nodes.

3.1.2 Scenarios in Netsim®

Some scenarios were running in Netsim in order to generate the data for training the Neuro Fuzzy inference system. Taking the parametric model under consideration, parameters involved into the traffic metrics were combined to obtain the outputs considered for the technology election.

The number of nodes was changed between 4 to 36 taking numbers with entire square root; packet size was varying from low values as 50 bytes to high values as 1460 bytes. Inter-arrival time between packets was exchanged between 1000 µs to 1000000 µs. Also, probabilistic distribution for packet size and interarrival time was varying between constant (CBR) and exponential (VBR). Table 3. presents all the possible combinations and Figures 15, 16 and 17 shows some features of Netsim® tool.

Table 3. Netsim® Scenarios

VBR			
No. of nodes	**Packet size (Bytes)**	**Inter-arrival time (µs)**	**Technology**
4,9,16,25,36	30,50,75,100,500,1000,1460	1000,3000,5000,10000, 50000,100000,500000,1000000	WIFI, LTE
4,9,16,25,36	30,50,75,100	1000,3000,5000,10000, 50000,100000,500000,1000000	Zigbee

Figure 15. Netsim® logo

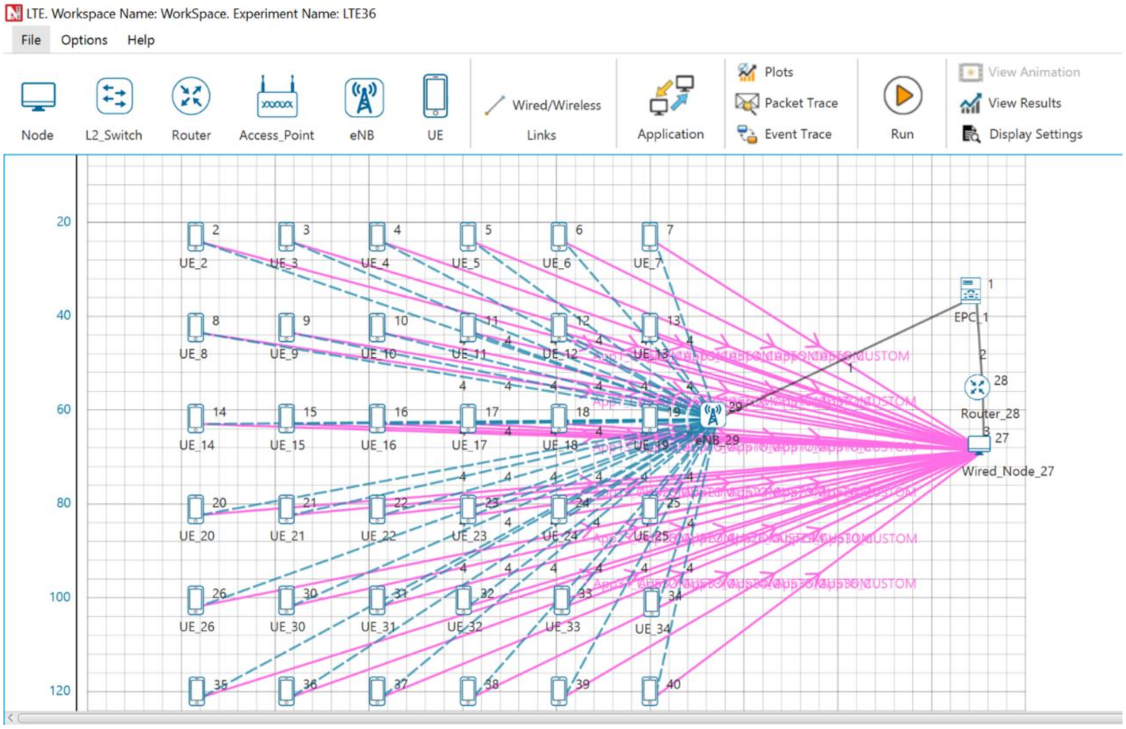


Figure 16. Sensor deployment for LTE – 36 Nodes

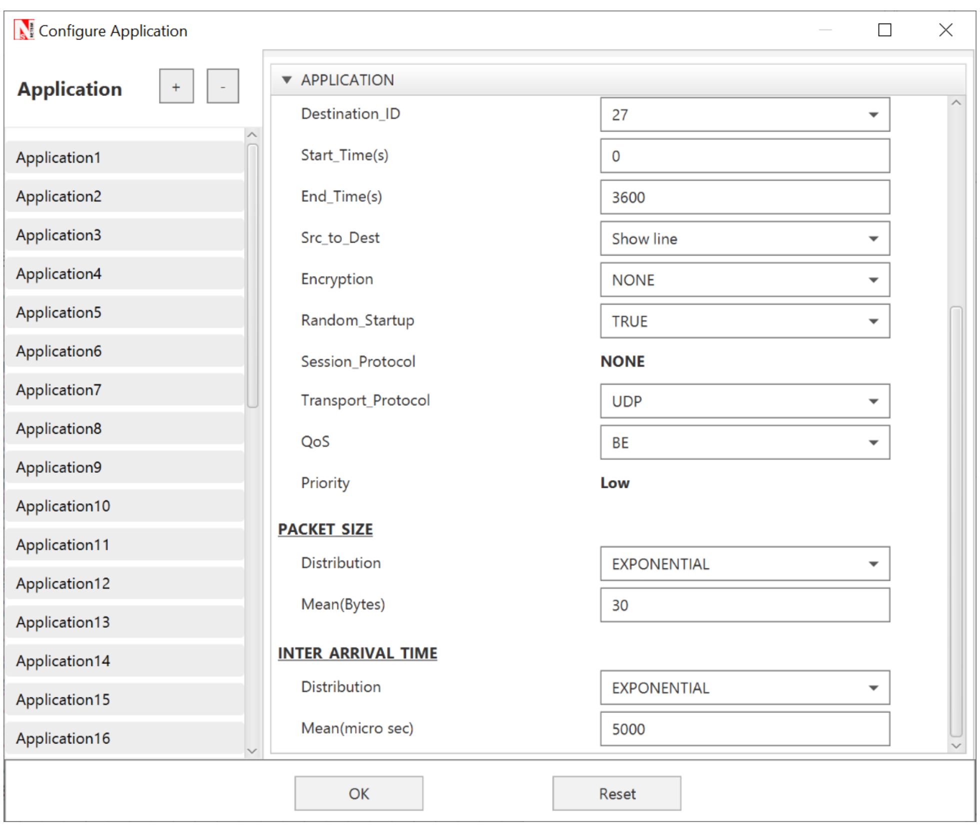


Figure 17. Traffic configuration

3.2 Cycle 2 - Optimized Model through NFIS systems.

On cycle 2, a Neuro Fuzzy inference system (NFIS) was created in order to optimize the simulation and decision processes. The NFIS combines fuzzy inference systems, which include human knowledge and execute inference and decision-making, with neural networks (NNs), to identify patterns and trends and adapt themselves to changing conditions, [41], [42].

3.2.1 Concepts

Neural Network (NN) is a group of neurons connected to each other and learn from the application or information obtained from their environment to find important linear and nonlinear tendencies in complex data. Neural nets can be used to predict what will happen in new situations, classify, cluster, and others, [43], [44]. The fundamental computing units of the NNs that process the local information inside the networks are called neurons [45].

In the other hand, Fuzzy logic provides a valuable flexibility in reasoning other than Boolean logic, 0 or 1, for imprecise or vague data sets (called fuzzy sets). Linguistic labels and membership functions are assigned for inputs and outputs, and numerical operation is performed according to if-then rules designated in each application. These rules are the essential component of the FIS for human knowledge in a particular application, [41].

Neuro-Fuzzy Inference is composed for both processes: Neural Networks and Fuzzy Logic. The steps following by NFIS are [42]:

1. Identify input and output variables.
2. Assign Linguistic Variables for each input and output variables
3. Define Membership functions for the inputs and outputs

4. Fuzzification for inputs
5. Form a rule base
6. Rules evaluation
7. Defuzzification

Universal set: is a group of all potential components that can be used in an experiment.

Crisp sets: is a collection of elements grouped according to any classification and derived from universal set. For example,

Let X the universal set for men age.

$$X = \{1,2,3,4,5,6, \dots \dots ..100\}$$

Then,

A= Set of child age-less than 12 years ={1,2,3,…,10}

B= Set the teenager age - between 11 to 16 ={ 11,…..,16}

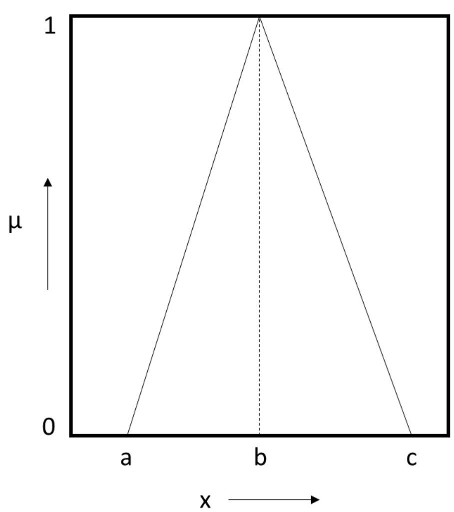
C = Set the young age - between 17 to 25 ={ 17,…..,25}

Therefore, A, B and C are the crisp sets obtained from the universal set X.

Linguistic variables: regularly numerical values are taking to complete mathematical processes, however in fuzzy systems non-numerical values (such as words or sentences) have been employed to facilitate rules expression. For example, *distance* is a linguistic variable if its values are words or sentences instead of numbers, i.e., very near, near, medium near, far, very far, remotely, [44].

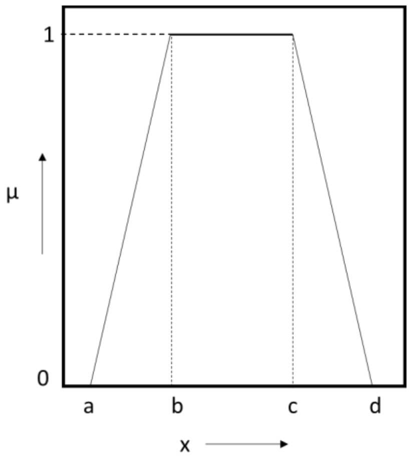
Membership function: the input data or crisp set data is not a fuzzy set by itself, then a fuzzification process must be performed using a membership function. The main idea is to transform the crisp inputs into values between 0 and 1 according to the type of the membership function. The value obtained from fuzzification process is called membership value or degree of membership and is denoted by μ(x), [42]

There are different types of membership functions such as Sigmoid, Gaussian, Bell, Singleton, Triangular, Trapezoidal and others. In this study we used Triangular and Trapezoidal membership functions. Figures 19 and 20 present those membership functions and Eq. 11 and 12 represent the μ values for each membership functions, [42]



$$\mu_{triangle} = max\left(min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \quad (11)$$

Figure 18. Triangular Membership Function



$$\mu_{trapezoidal} = max\left(min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right) \quad (12)$$

Figure 19. Trapezoidal Membership Function

Rule Base: To correlate the inputs and outputs, variables must be represented in a rule base form. Then, inputs are the antecedents and outputs are the consequent and IF-THEN rule are constructed using different operator for the evaluation such as AND, OR, NOT. Table 4. Show the operator evaluation rule. Let, I_1 and I_2 the inputs and O_1 the output for the system an example of a rule base is IF I_1 is Low **AND** I_2 is High THEN O_1 is Medium, [44]

Table 4. Operator for Rule Base form in Fuzzy Logic

Operator	**Evaluation**
AND	$min\{\mu_A(x), \mu_B(x)\}$
OR	$max\{\mu_A(x), \mu_B(x)\}$
NOT	Additive complement

Defuzzification: is the reverse process of the Fuzzification, where, fuzzy results are converted to crisp results. Different methods are used for this operations: Center of sum methods, Centroid method, Mean of Maxima method, First of Maxima (FOM), Mean of maxima (MOM), Last of Maxima, and others, [42], [44]. In this model, we are using the centroid method where crisp value is delivered based on the fuzzy set's center of gravity. The membership function distribution used to depict the combined action is separated into several sub-areas and each of these small areas value is calculated as well as the centroid (center of gravity). Finally, a summation is executed according to Eq. 13.

$$x^* = \frac{\sum_{i=1}^{N} A_i f_i}{\sum_{i=1}^{N} A_i} \qquad (13)$$

Where, N is the number of sub-areas, A_i is the area values and f_i represents the center of the area.

To summarize, for this research a Mamdani approach were used to optimize the decision methodology. Therefore, the steps followed for the Mamdani approach are shown on Figure 20. Layer 1 corresponds to the Fuzzification process, layer 2 is related to the rule form base, layer 3 is correlated to the rule evaluation (rule inference) and Layer 4 corresponds to the Defuzzification Process, [42].

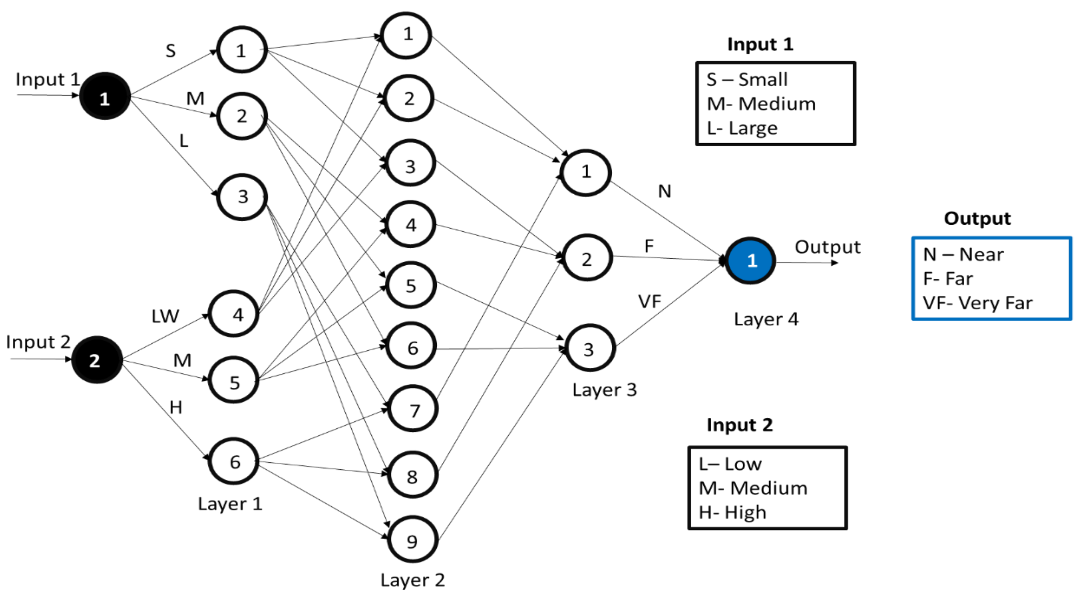


Figure. 20 Mamdani approach for Multicriteria Decision Methods in WSNs.

3.2.2 Methodology description

With the help of the technical data obtained during cycle 1 for training the Neuro-fuzzy system, the purpose of the level 1 from cycle 2 is to get an initial technology list based on the customer and location requirements. Figure 21 shows the methodology for cycle 2. For this project we are considering three technologies Zigbee, WIFI and LTE for sensor stage and Satellite, LTE and Wire for the Backhaul.

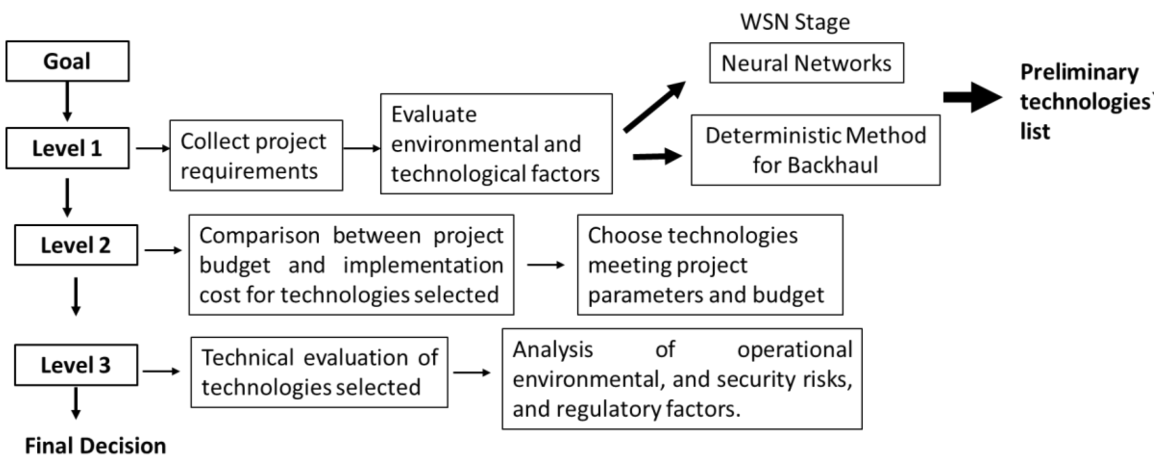


Figure 21. Second Cycle for Hybrid model proposed

The backhaul is the system where information collected for the sensors is delivered to the end-user via LTE, Wire or Satellite depending on the scenario's specification. A deterministic method was developed to determine the technology used for the backhaul. Figure 22 shows the basic process. For instance, cellular or wired communication is required if an end user is established close to a WSN deployment. In the other hand, cellular or satellite system is required if the end user is located far from the WSN area.

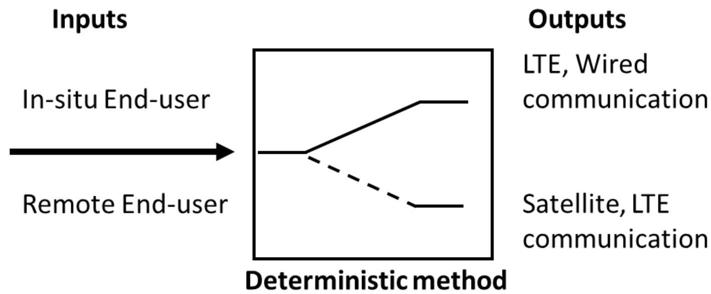


Figure 22. Backhaul selection process cycle 2

Figure 23 presents the inputs and outputs for the inference system. The inputs for the NFIS are coverage area, which is correlated to the number of the repeated parametric model useful for the costs analysis, distance between nodes is associated with the number of nodes in the parametric model and the type of data is related to data rate, CBR is used for video streaming, pictures and VBR is utilized for data. Outputs obtained from the NFIS process are throughput, delay and percentage (%) of packet loss.

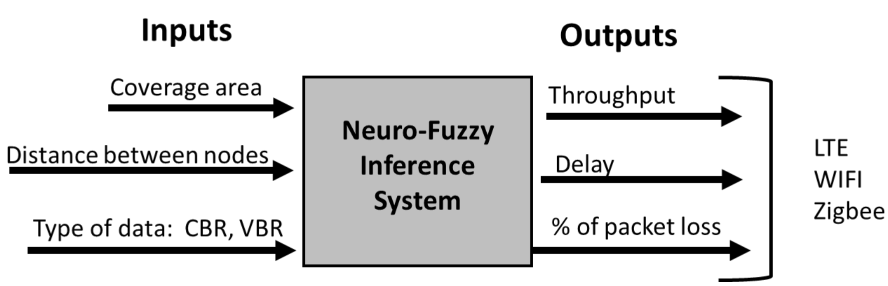


Figure 23. NFIS basic structure for sensor network , cycle 2

For level 2, an economic study is performed according to the level 1 technology decision results. Implementation, components (sensors, cable, connectors), technical and non-technical services, operational costs, transportation, and others, are taking under consideration according to the current market costs in USA.

On level 3, final decision is taken based on regulatory and environmental considerations for each particular scenario. For example, if any particular region does not allow the use of LTE technology, then, Zigbee or WIFI must be used.

Chapter 4. Scenarios and Results

4.1. Network Performance Parameters Database by Netsim®

To generate the database for training the NFIS system, several scenarios were executed to obtain a considerable amount of data for the NFIS system and provide quality for the methodology proposed. Inputs used for the system are No. of nodes placed on the parametric model, packet size and interarrival time between packets. Those parameters were varying according to the values showed in Table 3 to generate different traffic values and outputs.

The outputs considered in this study to assure the quality and feasibility of the projects are throughput, delay and percentage of packet loss. In addition, technologies used for the simulations were Zigbee, WIFI and LTE and were selected because of distance range between nodes, market availability, capacity, data rate, and cost. Table 5 presents some technologies features. In addition, Scenarios created for each technology are presented in Table 6.

Figures 24, 25, 26 and 27 present some Netsim® scenarios for Zigbee, WIFI, and LTE, respectively, and Figure 28 shows the results provided by the simulator for each iteration.

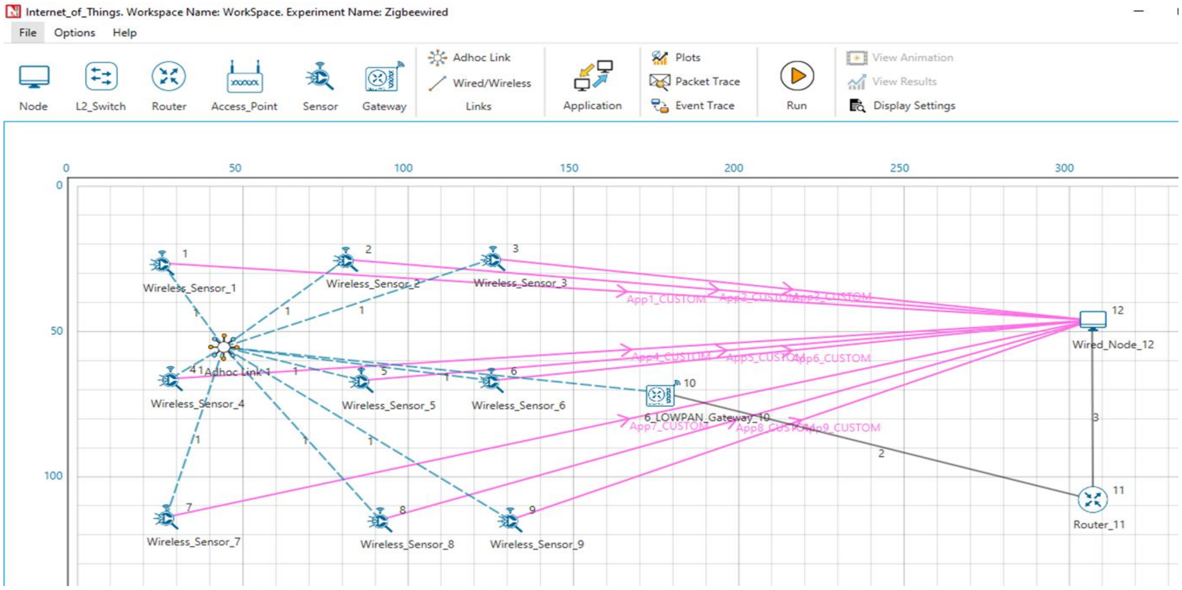


Figure 24. Zigbee Netsim® example

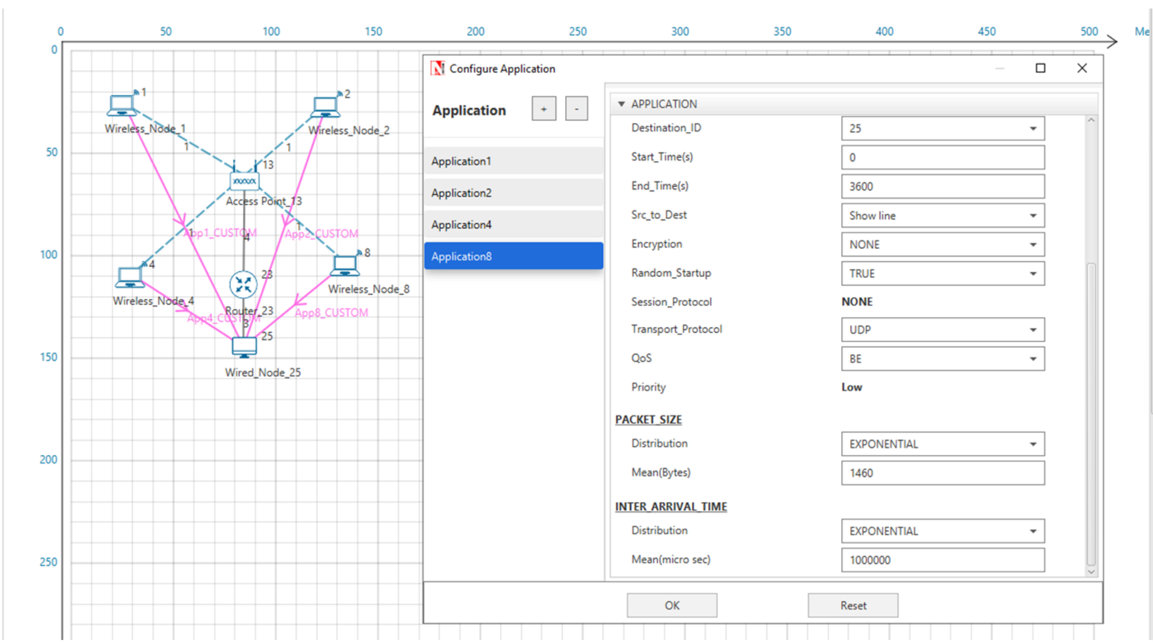


Figure 25. WIFI Netsim® example with application window

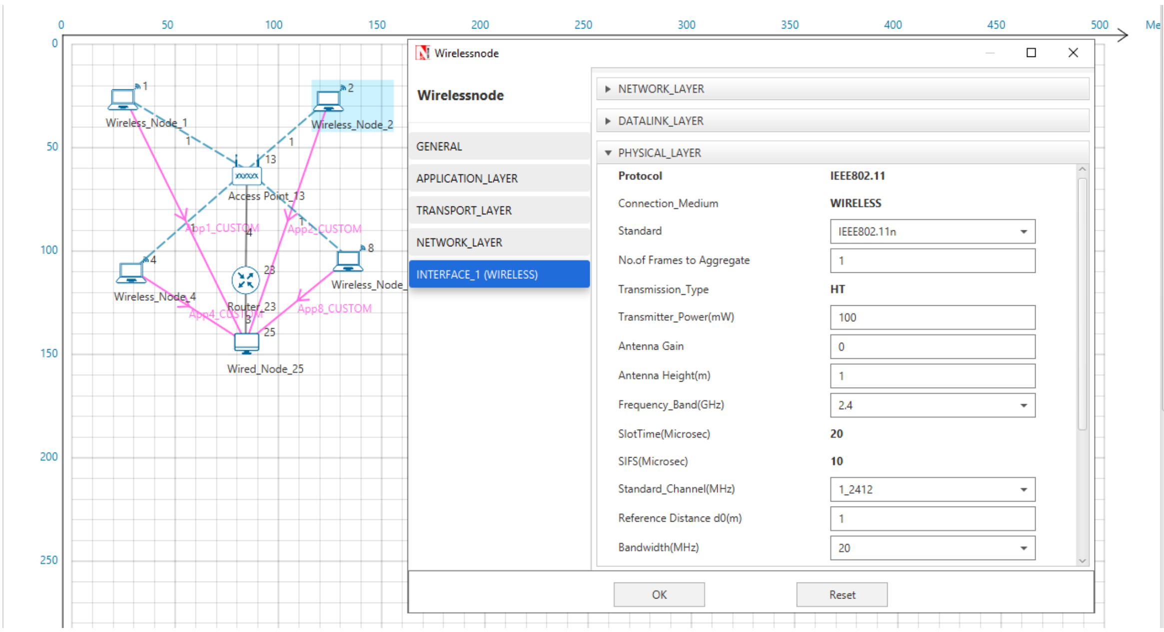


Figure 26. WIFI Netsim® example with Wireless node parameters window

Table 5. Technologies used in the Hybrid Multicriteria Decision Method.

Technology	Standard	Coverage area	Bandwidth	Frequency	Data rate	Radio Technology
Zigbee	802.15.4	0-20m indoor 300m outdoor	1Mhz	2.4Ghz, 868Mhz, 915Mhz	250Kbps	
WIFI	802.11	20m - indoor 100m-outdoor	20Mhz	2.4Ghz	1-2Mbps	CSMA/CA
	802.11a	35m - indoor 120m-outdoor	20Mhz	3.7 - 5Ghz	Max 54Mbps	OFDM
	802.11b	35m - indoor 140m-outdoor	20Mhz	2.4Ghz	Max 11Mbps	DSSS/CSMA
	802.11g	38m - indoor 140m-outdoor	20Mhz	2.4Ghz	Max 54Mbps	OFDM
	802.11n	70m - indoor 250m-outdoor	20-40Mhz	2.4/5Ghz	150Mbps -SISO Max 600Mbps - MIMO	OFDM/MIMO/SISO
	802.11ac	35m - indoor 140m-outdoor	20/40/60/80/ 160 Mhz	5Ghz	72Mbps-1.3Gbps	OFDM/MIMO
	802.11ad	60m - indoor 100m-outdoor	2160Mhz	60Ghz	7Gbps	OFDM/MU MIMO/SC
	802.11ah	1Km	1Mhz	0.9Ghz	150Kbps	
	802.11ax	35m - indoor 140m-outdoor	160MHZ	2.4/5Ghz	9GbpS	OFDMA/QAM/MIMO
	802.11ay	60m - indoor 1000m-outdoor	8Ghz	60Ghz	20-40Gbps	MIMO/QAM
LTE-4G	LTE Basic	2Km/3Km	20Mhz	700/1500/1700/2100/ 2600/3700MHz	20Mbps	TDD/FDD

Table 6. Traffic generator scenarios

Parameter	**Zigbee**	**WIFI**	**LTE**
Protocol	802.15.4	802.11n	4G-3GPP 36 Series
Antenna	1x1	1x1	2x2
Frequency Range	2.4Ghz	2412MHz	FR1 3550 – 3700 MHz
Channel Bandwidth	2Mhz	20Mhz	20Mhz
Type of data	VBR	VBR/CBR	VBR/CBR
Transport Protocol	UDP		
Packet Size	30-100 Bytes	30 – 1460 Bytes	30 – 1460 Bytes
Distribution	Exponential/Constant		
Interarrival-time (IAT)	1000µs to 1000000µs		
Topology	Orthogonal		
Start time	Random (0 to IAT)		
End Time	3600s		

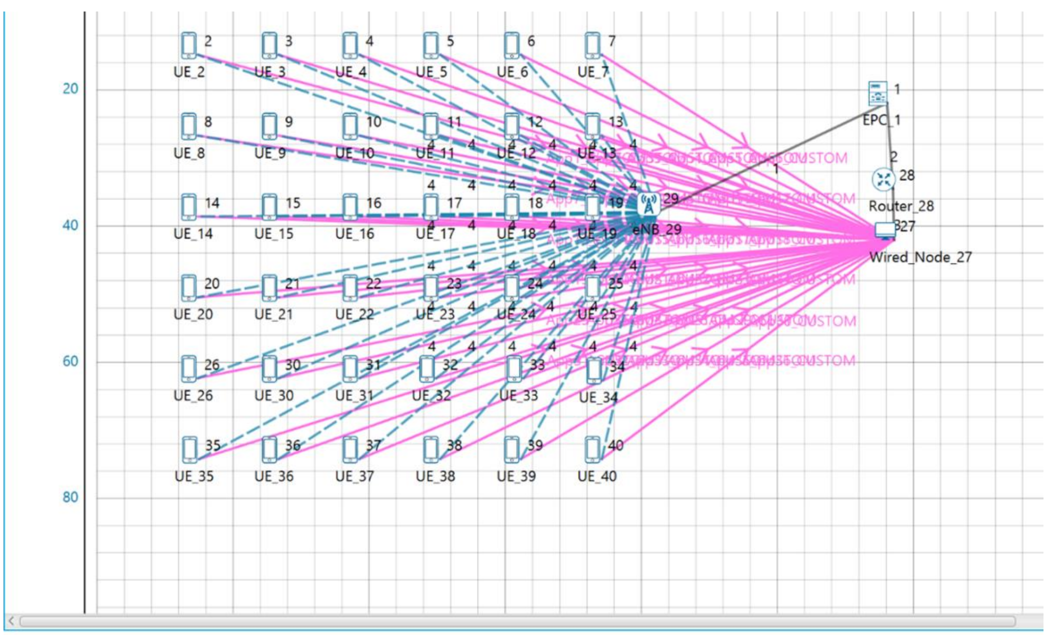


Figure 27. LTE Netsim® example

Application_Metrics_Table

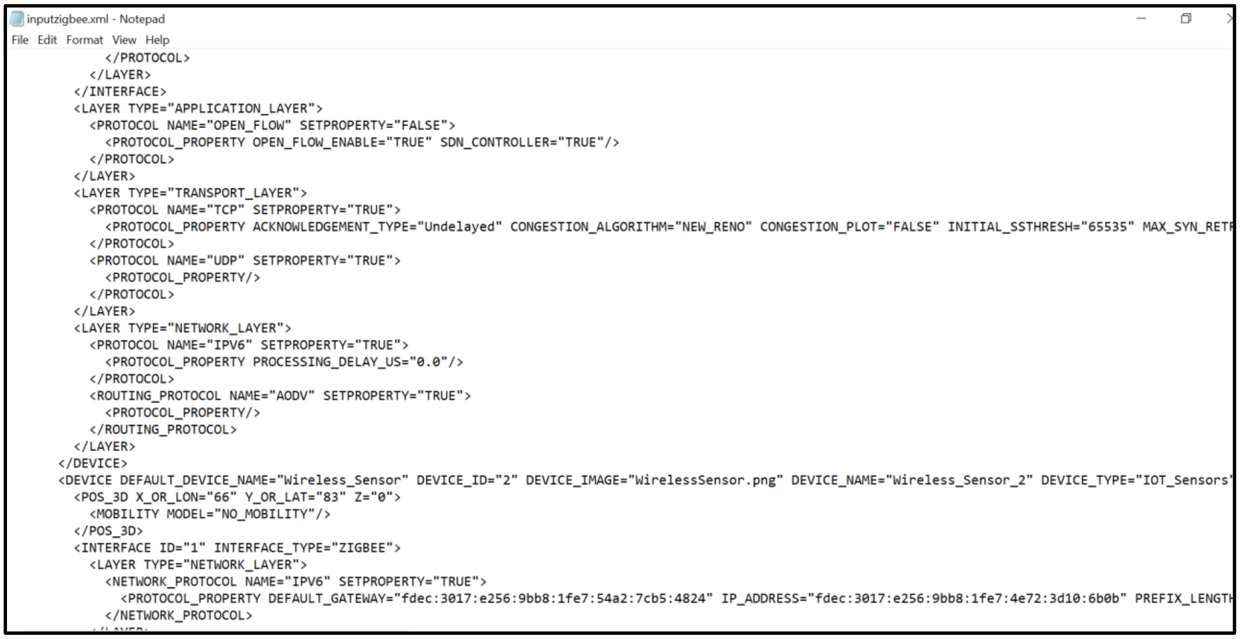
Application_Metrics

Application Id	Application Name	Packet generated	Packet received	Throughput (Mbps)	Delay(microsec)	Jitter(microsec)
8	App8_CUSTOM	1505	1501	0.010900	615.616806	237.762107
1	App1_CUSTOM	1577	1575	0.011444	701.106348	356.299565
2	App2_CUSTOM	1515	1512	0.011112	775.530238	278.038782
4	App4_CUSTOM	1542	1538	0.011446	622.168271	232.668341

Figure 28. Results provided by Netsim® simulation for each iteration

Due to the large quantity of information needed for the NFIS methodology, a special tool from Netsim was used to recreate each scenario and get and ordered data in excel file. The tool used is the "Multiparameter sweeper" which is working under Phyton and configuration file utilized by Netsim to create the code for each scenario. Figure 29 shows a configuration file example. Results provided from Multiparameter Sweeper are presented in Appendix A. Notice from Figure 28, that percentage of packet loss is not an output from Netsim file, but it is easy calculated according to Eq. 14.

$$\%\ of\ packet\ loss = \frac{Pkt\ generated - Pkt\ received}{Pkt\ generated}\ x100 \qquad (14)$$



inputzigbee.xml - Notepad

File Edit Format View Help


```xml
        </PROTOCOL>
      </LAYER>
    </INTERFACE>
    <LAYER TYPE="APPLICATION_LAYER">
      <PROTOCOL NAME="OPEN_FLOW" SETPROPERTY="FALSE">
        <PROTOCOL_PROPERTY OPEN_FLOW_ENABLE="TRUE" SDN_CONTROLLER="TRUE"/>
      </PROTOCOL>
    </LAYER>
    <LAYER TYPE="TRANSPORT_LAYER">
      <PROTOCOL NAME="TCP" SETPROPERTY="TRUE">
        <PROTOCOL_PROPERTY ACKNOWLEDGEMENT_TYPE="Undelayed" CONGESTION_ALGORITHM="NEW_RENO" CONGESTION_PLOT="FALSE" INITIAL_SSTHRESH="65535" MAX_SYN_RETR
      </PROTOCOL>
      <PROTOCOL NAME="UDP" SETPROPERTY="TRUE">
        <PROTOCOL_PROPERTY/>
      </PROTOCOL>
    </LAYER>
    <LAYER TYPE="NETWORK_LAYER">
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        <PROTOCOL_PROPERTY PROCESSING_DELAY_US="0.0"/>
      </PROTOCOL>
      <ROUTING_PROTOCOL NAME="AODV" SETPROPERTY="TRUE">
        <PROTOCOL_PROPERTY/>
      </ROUTING_PROTOCOL>
    </LAYER>
  </DEVICE>
  <DEVICE DEFAULT_DEVICE_NAME="Wireless_Sensor" DEVICE_ID="2" DEVICE_IMAGE="WirelessSensor.png" DEVICE_NAME="Wireless_Sensor_2" DEVICE_TYPE="IOT_Sensors"
    <POS_3D X_OR_LON="66" Y_OR_LAT="83" Z="0">
      <MOBILITY MODEL="NO_MOBILITY"/>
    </POS_3D>
    <INTERFACE ID="1" INTERFACE_TYPE="ZIGBEE">
      <LAYER TYPE="NETWORK_LAYER">
        <NETWORK_PROTOCOL NAME="IPV6" SETPROPERTY="TRUE">
          <PROTOCOL_PROPERTY DEFAULT_GATEWAY="fdec:3017:e256:9bb8:1fe7:54a2:7cb5:4824" IP_ADDRESS="fdec:3017:e256:9bb8:1fe7:4e72:3d10:6b0b" PREFIX_LENGTH
        </NETWORK_PROTOCOL>
```


Figure 29. Configuration file example from Netsim®

4.2 Neuro-Fuzzy Inference System implementation

To develop the Neuro-Fuzzy Inference System we had some considerations:

1. Membership functions used for inputs and output are triangles and trapezoids
2. Values related to the membership functions scales are taken and adjusted according to data generated by Netsim, congestion and regular scenarios.
3. For throughput and delay, logarithm is applied to the data in order to obtain a linear scale for the NFIS.
4. NFIS system was trained manually to obtain the classifier system but must be tuned and verified as a future work.
5. Fuzzy Logic Designer from Matlab®, is used to implement the NFIS system.

4.2.1 Membership Function Characterization

4.2.1.1 Inputs for WIFI Technology

To create the linguistic variables required for NFIS, input parameters were grouped into a different cluster in order to create a logic organization for the outputs and the rules. Starting with number of nodes, we assigned five (5) linguistic variables for each numerical interval which include the number of sensors proposed in Table 3. Then, variable linguistic “VL=Very Low” was selected for the interval between 0 to 9, where 4 is the central value used for the triangular membership. Table 7 shows the linguistic variables for the rest of the numerical cluster values, interval and central value.

Table 7. Linguistic Variables for No. of Nodes (Input)

Linguistic Variable	**Interval**
VL = Very Low	[0 4 9]
L= Low	[4 9 16]
M= Medium	[9 16 25]
H= High	[16 25 36]
VH= Very High	[25 36 40]

Similar linguistic variables were designated for interarrival time (IAT) and packet size. Tables 8 and 9 show the intervals and linguistic elements.

Table 8. Linguistic Variables for Packets Size (Input)

Linguistic Variable	**Interval**
VS= Very Short	[1 30 60]
S=Short	[40 90 150]
M=Medium	[100 501 800]
H=High	[700 1100 1500]

Table 9. Linguistic Variables for IAT

Linguistic Variable	**Interval**
UL = Ultra Low	[0 1000 2000]
VL=Very Low	[1000 3000 5000]
L= Low	[3000 5000 10000]
M=Medium	[6000 10000 20000]
H= High	[18000 500000 1000000]

4.2.1.2 Inputs for Zigbee Technology

Analogous to the WIFI technology, Zigbee NFIS inputs linguistic components are assigned based on database generated previously by Netsim®. Tables 10 displays the linguistic groups.

Table 10. Linguistic Variables for Zigbee

No. of Nodes		**Packet Size**		**IAT**	
Linguistic Variable	**Interval**	**Linguistic Variable**	**Interval**	**Linguistic Variable**	**Interval**
VL Very Low	[0 4 9]	VS Very Short	[1 30 60]	UL Ultra Low	[0 1000 2000]
L= Low	[4 9 16]	S=Short	[40 50 75]	VL Very Low	[1000 3000 5000]
M=Medium	[9 16 25]	M=Medium	[60 75 90]	L= Low	[3000 5000 10000]
H= High	[16 25 36]	H=High	[80 100 120]	M=Medium	[6000 10000 20000]
VH Very High	[25 36 40]	--	--	H= High	[18000 50000 120000]
--	--	--	--	VH Ultra High	[110000 500000 1000000]

4.2.1.3 Inputs for LTE Technology

Comparable to WIFI and Zigbee technologies, LTE inputs were defined on Table 11.

Table 11. Linguistic Variables for LTE

No. of Nodes		Packet Size		IAT	
Linguistic Variable	**Interval**	**Linguistic Variable**	**Interval**	**Linguistic Variable**	**Interval**
VL Very Low	[0 4 9]	VS Very Short	[1 30 60]	UL Ultra Low	[0 1000 2000]
L= Low	[4 9 16]	S=Short	[40 90 150]	VL Very Low	[1000 3000 5000]
M=Medium	[9 16 25]	M=Medium	[100 501 800]	L= Low	[3000 5000 10000]
H= High	[16 25 36]	H=High	[700 1100 1500]	M=Medium	[6000 10000 20000]
VH Very High	[25 36 40]	--	--	H= High	[18000 50000 120000]
--	--	--	--	VH Ultra High	[110000 500000 1000000]

4.2.1.4 Outputs for WIFI, Zigbee, LTE

Outputs for each technology were selected according to the numerical values obtained from the simulation's processes. Congestion scenarios were analyzed in detail because the data provide special features such as high percentage packet loss, high throughput and delay. These events can be presented when a combination of some input's parameters are presented, for example, IAT is short (e.g. less than 5000 μs), packet size is high, near to the border based on the technologies standard (1000 Bytes for WIFI and LTE technologies and 100 for Zigbee), and high number of nodes (25 or more). Table 12 and Figures 30, 31 and 32 show the scale for the percentage packet loss for WIFI, Zigbee and LTE.

Table 12. Linguistic Variables for Percentage of packet loss (Output)

Linguistic Variable	**Interval**
L=Low	[0 1]
M=Medium	[1 10]
H=High	[10 100]

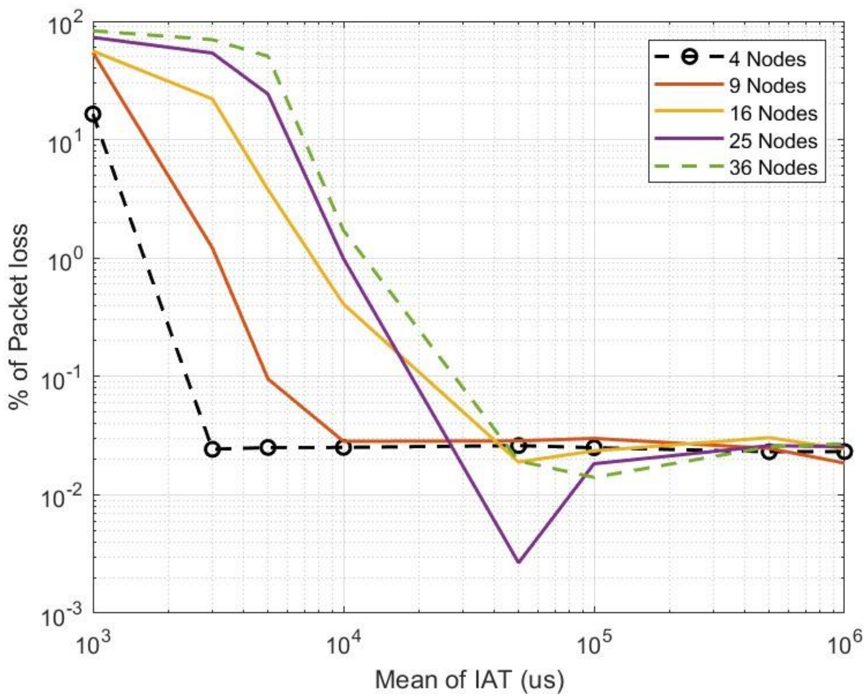


Figure 30. Percentage of Packet loss vs. IAT(μs) for Packet Size =100 Bytes – WIFI

As Figures 30 and 31 are shown, the percentage of packet loss is increasing according to the packet size and IAT . For example, for network size = 4 nodes, packet size = 30 bytes and IAT= 1000 μs, the % of packet loss is 9.83%, while for the same combination except network size=36 the % of packet loss is 80%. This parameter is changed because of data packets retransmission and data rate. Appendix A is shown the simulation results. Figure 32. Presents the comparison of the packet loss output between 36 and 16 nodes.

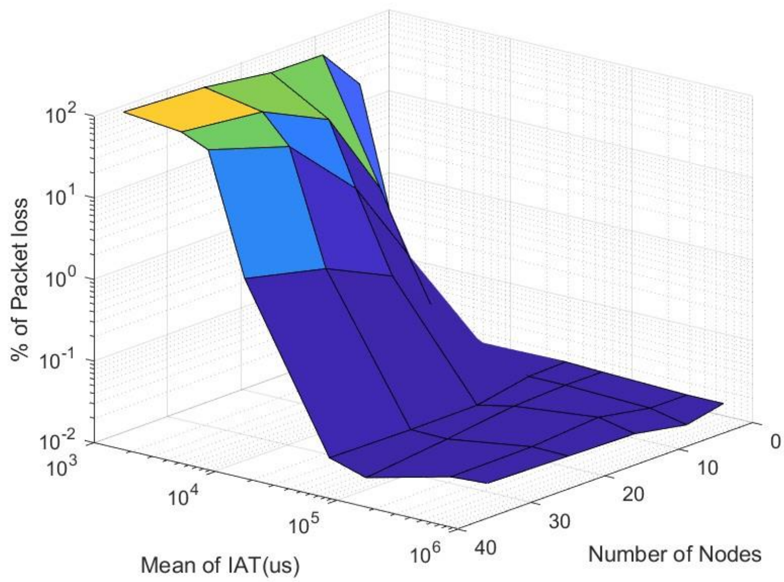
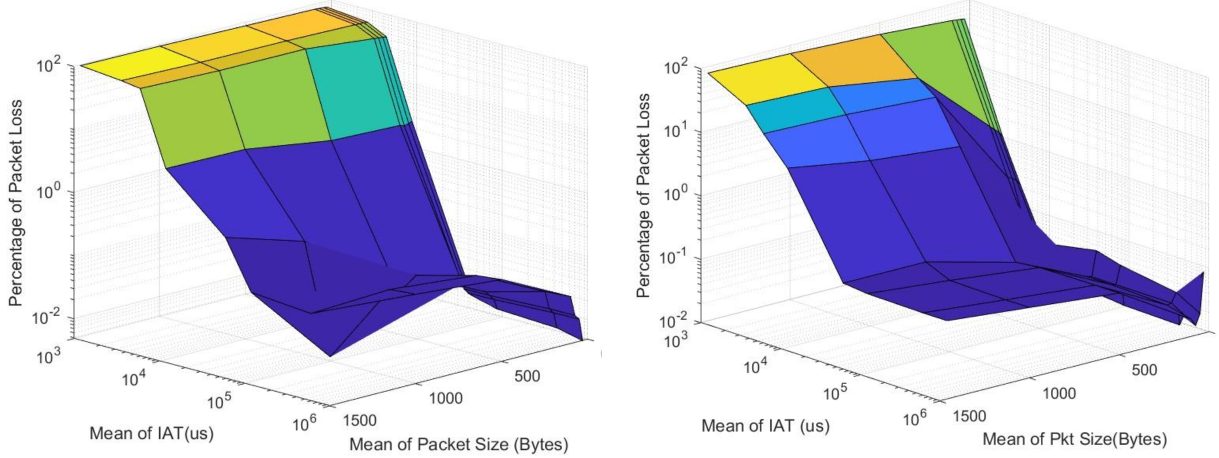


Figure 31. Percentage of Packet loss vs. IAT(μs) for Packet Size =100 Bytes – WIFI – Surface Graph



36 Nodes

16 Nodes

Figure 32. Percentage of Packet loss vs. IAT(μs) and Packet Size- comparison for WIFI

Another output evaluated for the network performance was the delay of the packets in the networks. This parameter, also, depends on the number of nodes deployed in the field, IAT, and packet size. Due to the wide range of the delay output (from μs to hours), a logarithm process was employed to obtain an affordable scale for measuring and comparing the values. Table 13 presents the linguistic variables for this output.

Table 13. Linguistic Variables for the Delay

Linguistic Variable	**Interval from**	**to**
UH	7	MORE
VH	6	7
H	5	6
MH	4	5
MM	2.9	4
ML	2.65	2.9
L	2.3	2.65
VL	0	2

Figure 33. shows the delay behavior for different IAT when packet size is equal to 100 bytes.

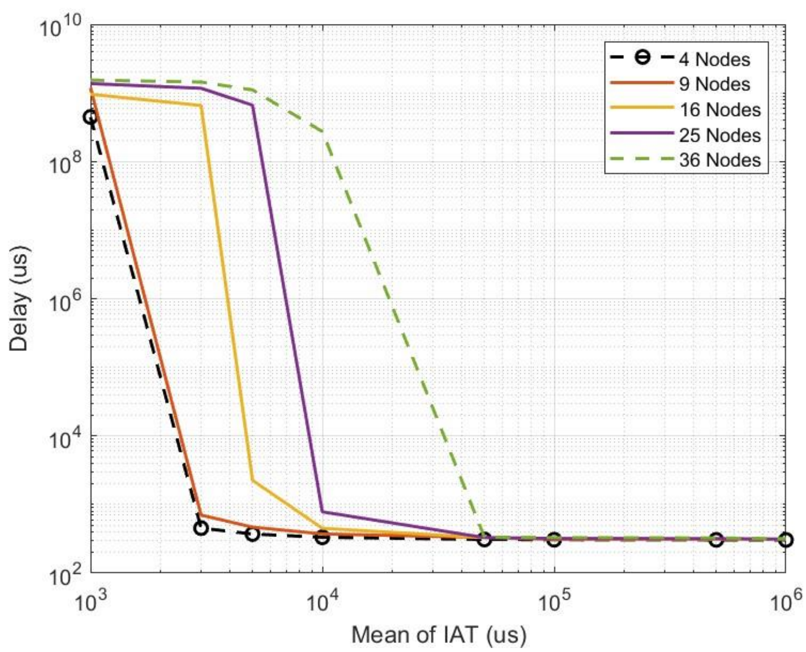


Figure 33. Delay vs. IAT(μs) for Packet Size =100 Bytes – WIFI

According to Figure 33, the delay is low (e.g. 312 μs) when the IAT (500000 μs) is high, pacet size is low (100bytes) and number of nodes is low (9 nodes) , in other words, when the traffic is low. In addition, it is increasing when the IAT is low, or traffic is high. Figure 34 displays the surface graph for Figure 33 example.

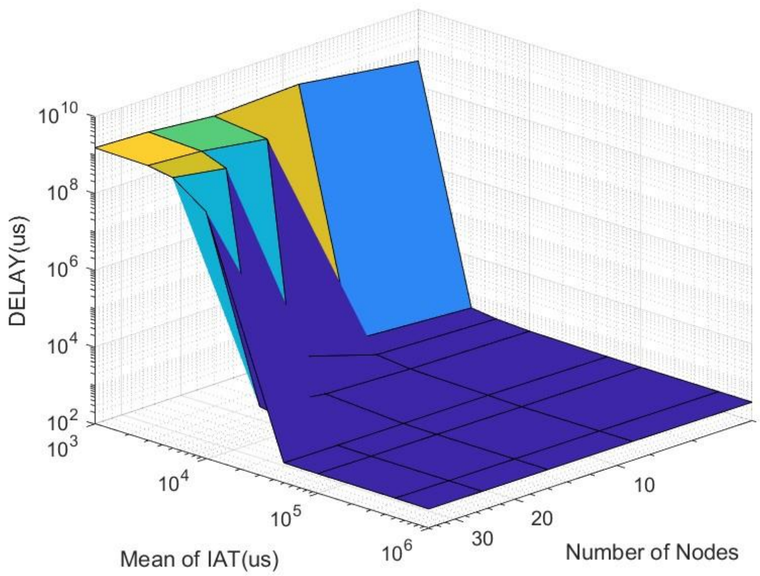


Figure 34. Delay vs. IAT(μs) for Packet Size =100 Bytes – WIFI

Figure 35 demonstrates that the trend obtained in Fig 33 is the same for different scenarios.

The last parameter evaluated in this study was the aggregate throughput in the network. This parameter is increasing when network is begun saturating because of the IAT, or the packet size or the combination of two or three inputs parameters.

Figures 36, 37 and 38 present the network behavior with different scenarios and the comparison between 36 nodes and 16 nodes. Table 14 shows the linguistic variables considered according to the values simulated. Because of the scales obtained, logarithm process were applied for the NFIS process.

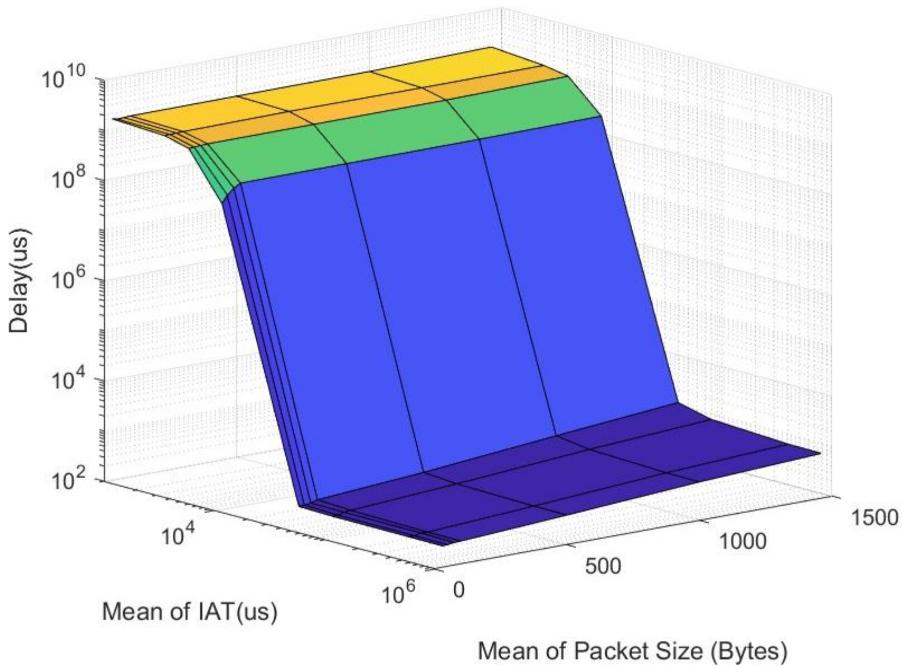


Figure 35. 36 Nodes scenario with IAT vs Packet Size vs Delay

Table 14. Linguistic Variables for the Throughput in WIFI technology

Linguistic Variable	**Interval from**	**to**
VH	5	5.5
H	4.5	5
M	4	4.5
L	3	4
VL	0	3

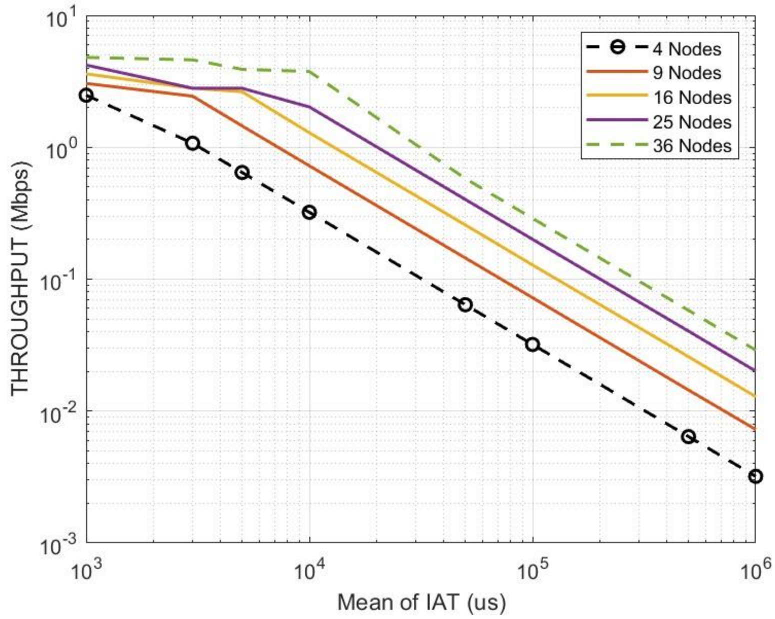


Figure 36. Throughput trend for WIFI technology

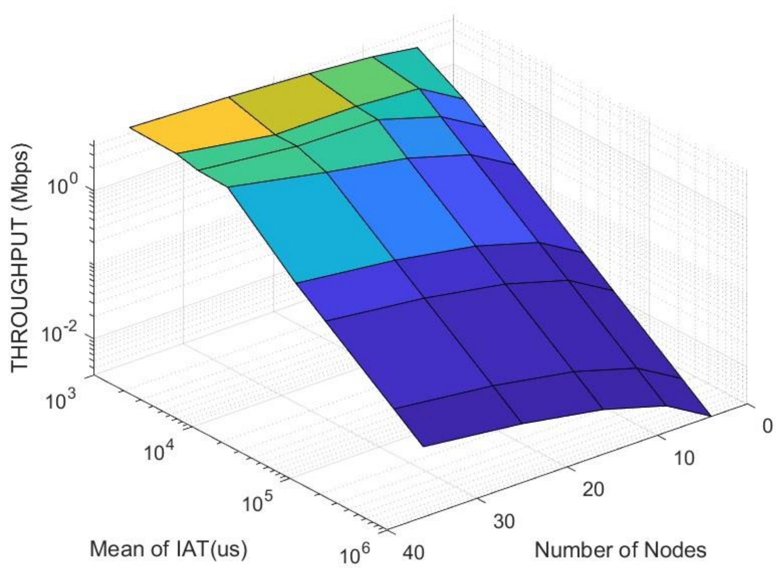
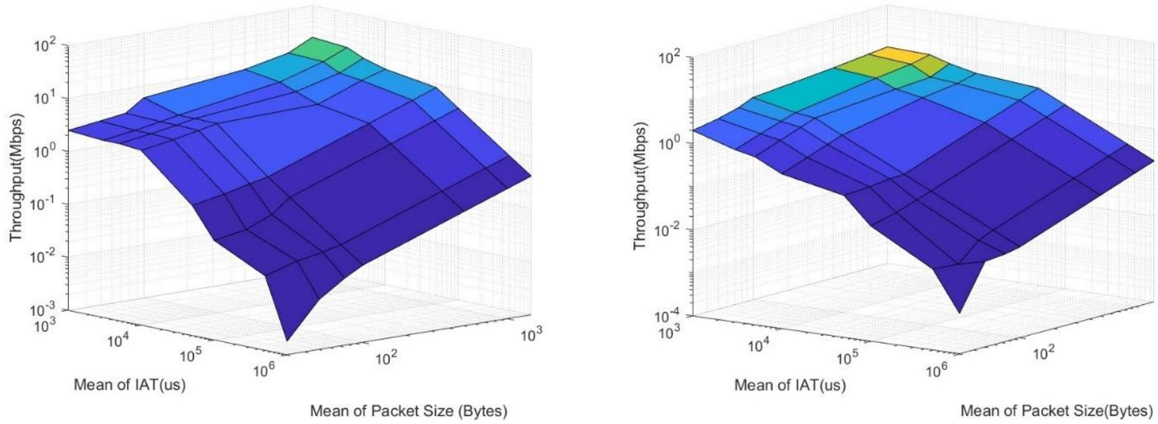


Figure 37. Throughput trend for WIFI technology-Surface graph



36 Nodes 16 Nodes

Figure 38. Throughput vs Packet Size vs. IAT(μs) - comparison for WIFI

Linguistic variables and intervals for percentage of packet loss and delay used for Zigbee were equals as WIFI, however, the throughput intervals values changed because of the technology features. Throughput for Zigbee is measured in Kbps instead of Mbps, then the logarithm process provides different values compared with WIFI. Figures 39, 40 and 41, shows percentage of packet loss for Zigbee in different scenarios.

According to Figures 39, 40 and 41, for IAT's below to 10000μs the percentage of packet loss is close to 97%, also, if the packet size is more than 75 Bytes in combination with low IAT, the percentage of packet loss is high.

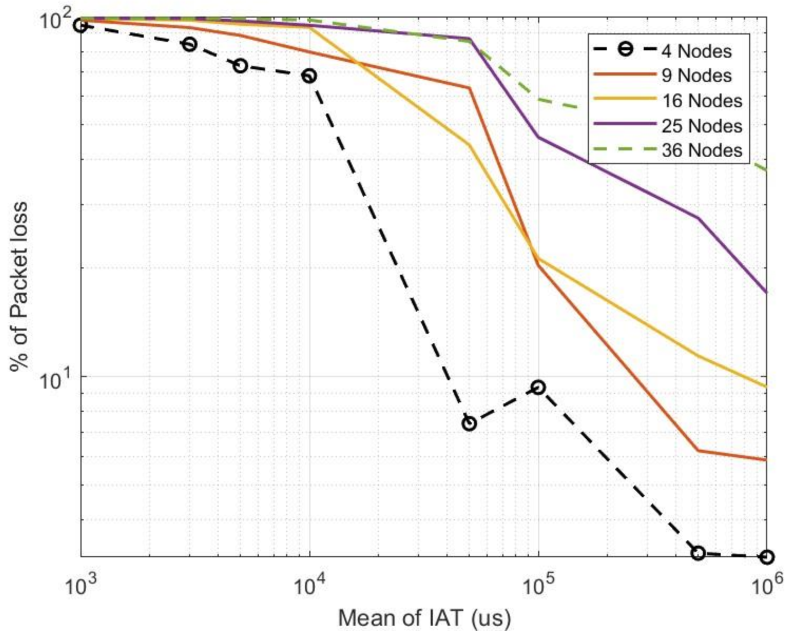


Figure 39. Percentage of Packet Loss for Zigbee – Packet Size = 50Bytes

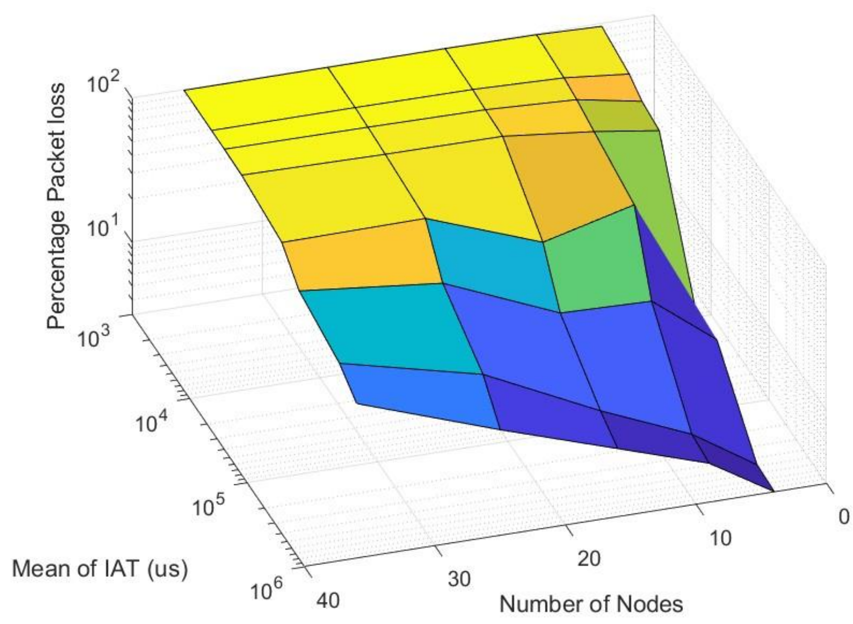
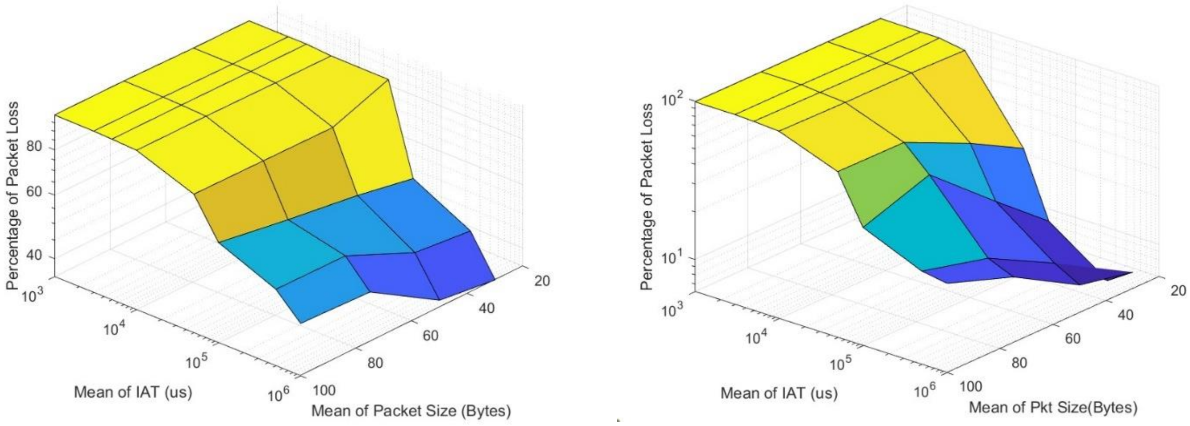


Figure 40. Percentage of Packet Loss for Zigbee surface graph – Packet Size = 50Bytes



36 Nodes 16 Nodes

Figure 41. Comparison of % of Packet Loss between 36 Nodes and 16 Nodes (Zigbee)

Based on Figure 42, if IAT is under 50000 µs the delay is decreasing until 13000 µs approximately, otherwise, the delay is increasing exponentially. Figures 43 and 44 show some examples of the delay behavior.

Throughput analysis is displayed in Figures 45, 46 and 47. Same as Delay, this output is increasing if IAT is below to 10000 µs.

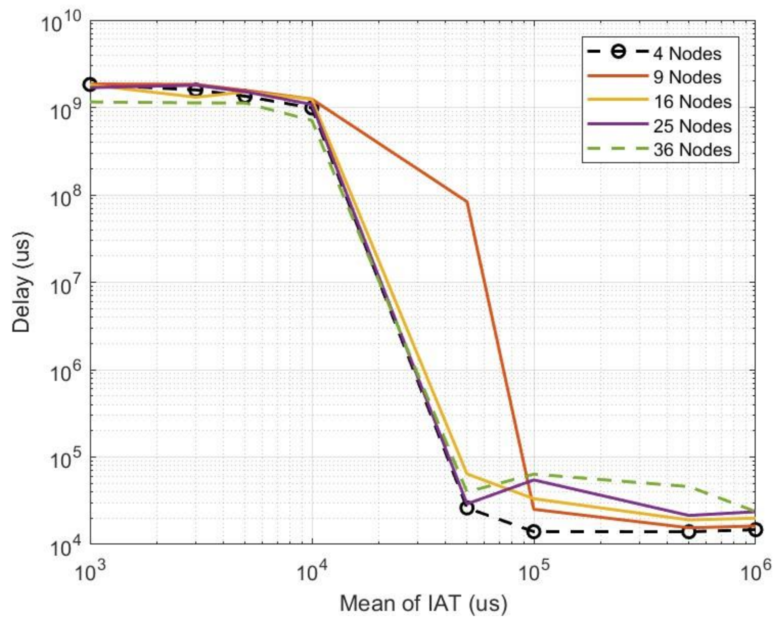


Figure 42. Delay for Zigbee – Packet Size = 50Bytes

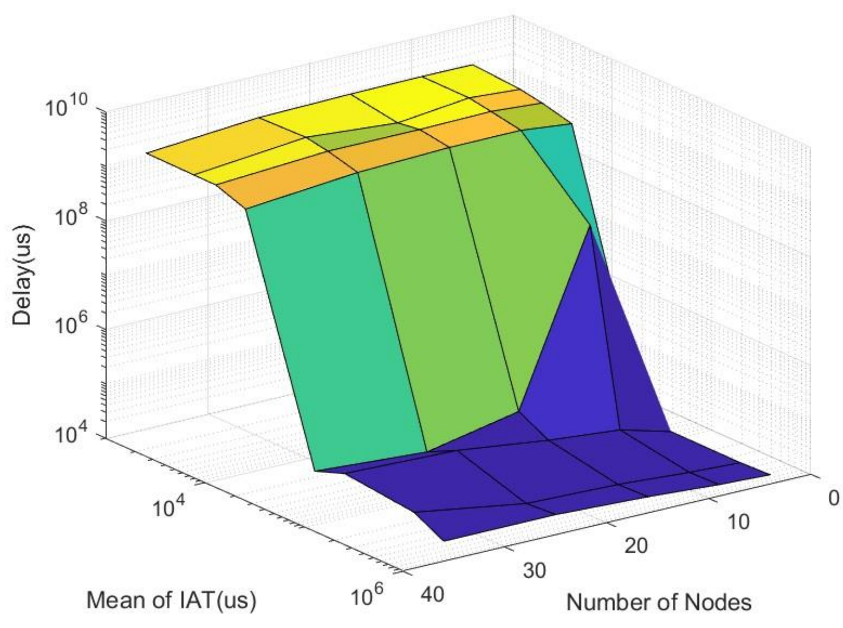


Figure 43. Delay for Zigbee surface graph – Packet Size = 50Bytes

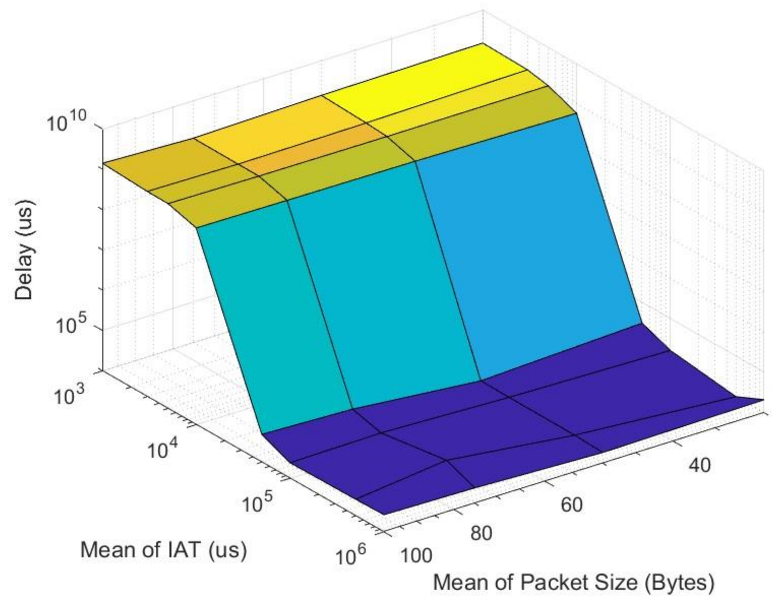


Figure 44. Delay Analysis for Scenario of 36 Nodes

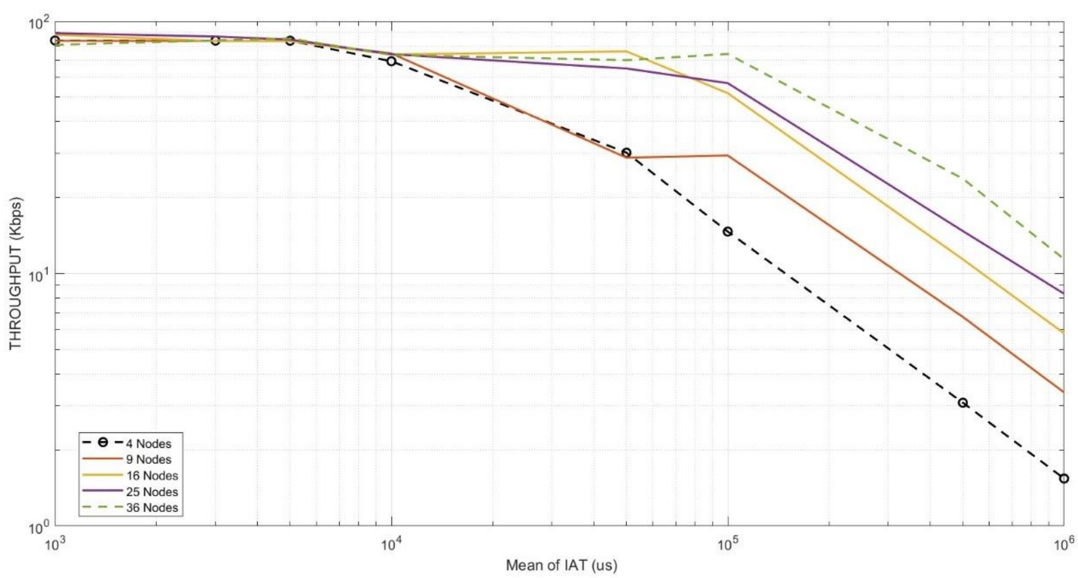


Figure 45. Throughput analysis for Zigbee – 50 Bytes

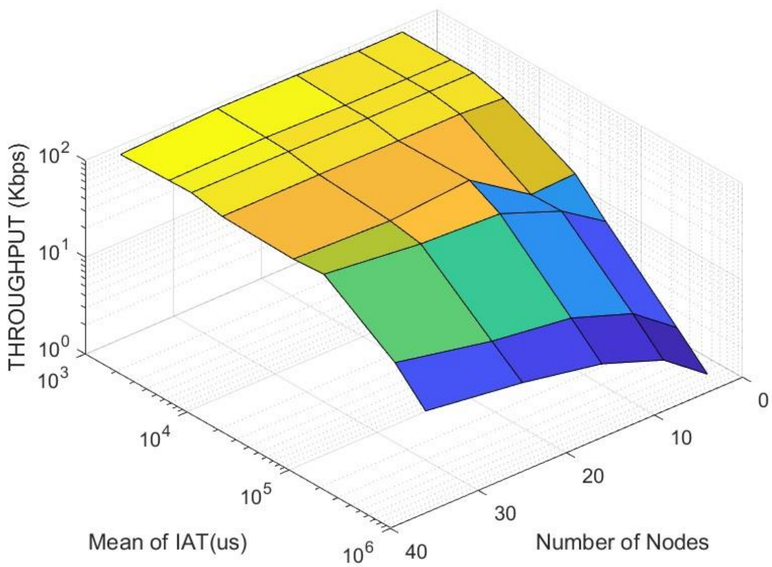
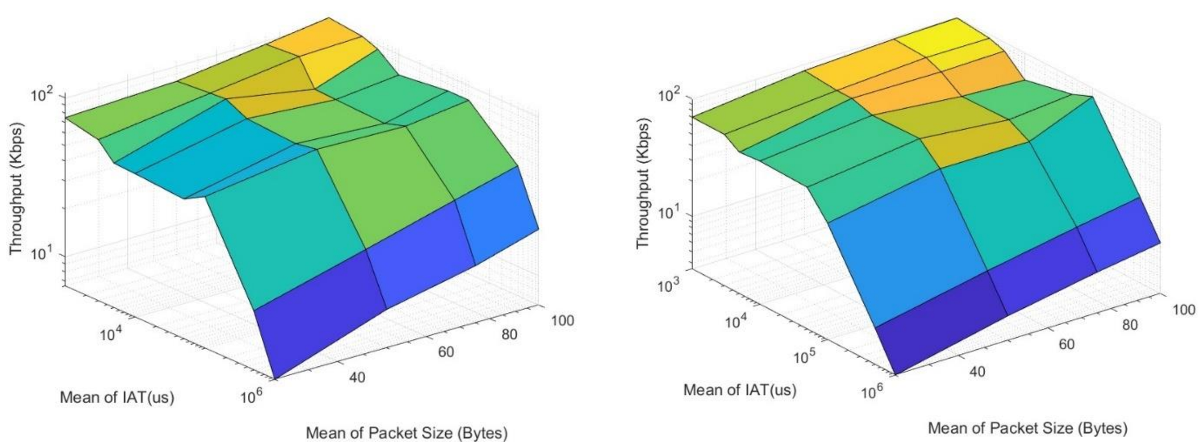


Figure 46. Throughput analysis for Zigbee – 50 Bytes. Surface Graph



36 Nodes

16 Nodes

Figure 47. Comparison of Throughput between 36 Nodes and 16 Nodes (Zigbee)

Similarly to Zigbee and WIFI, Figures 48,49 and 50 show the LTE behavior for packet loss.

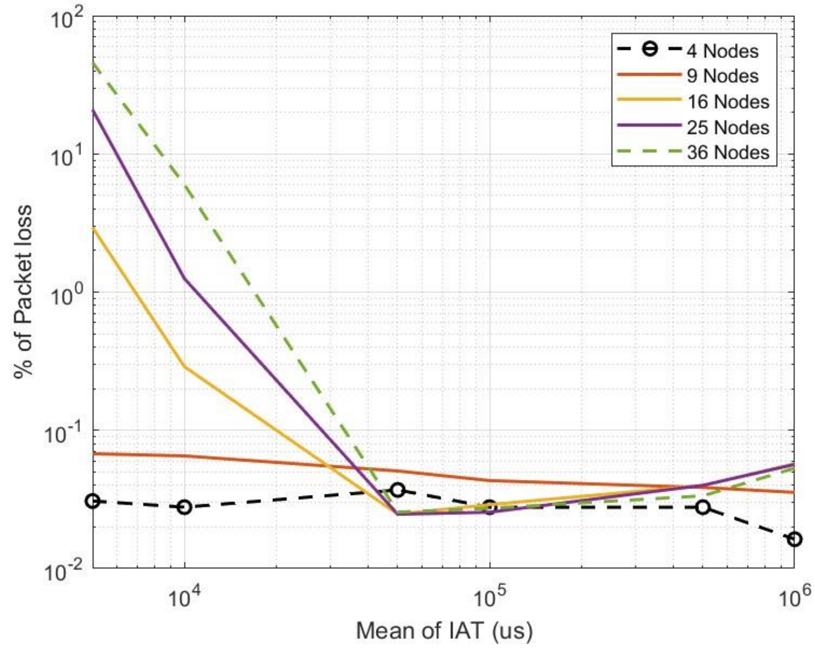


Figure 48. LTE-Packet loss behavior for 100 Bytes

For low IATs (below 5000us), the percentage of packet loss is below to zero for 4 and 9 nodes. If the number of nodes is increasing the % of packet loss is increasing because of the congestion of control and data packets. Figures 49 and 50 present the packet loss from another perspective in surfaces graph.

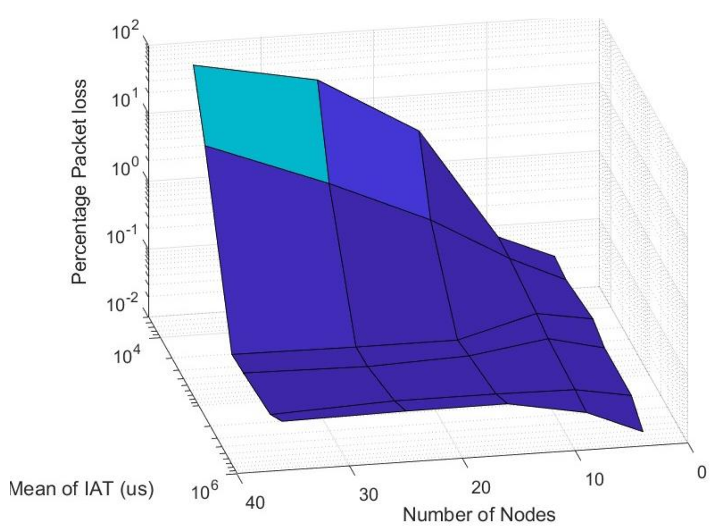


Figure 49. LTE-Packet loss behavior for 100 Bytes – Surface graph

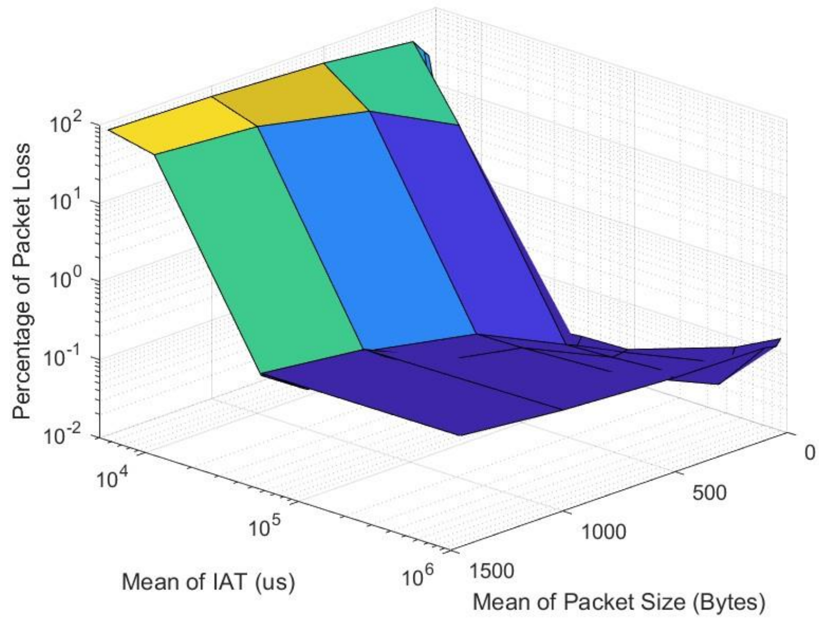


Figure 50. LTE-Packet loss behavior for 36 Nodes

Figures 51,52 and 53 are shown the delay performance for LTE technology.

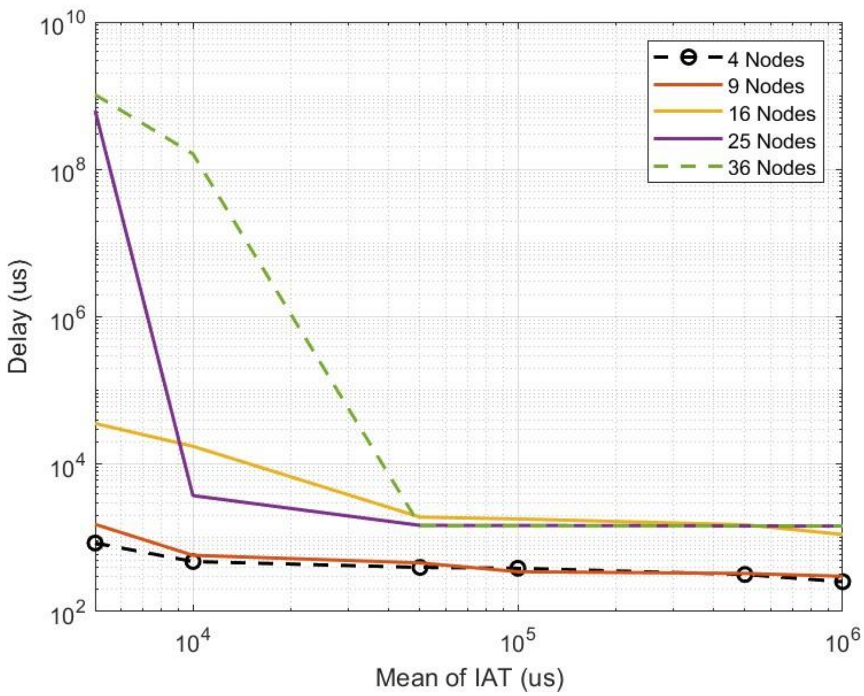


Figure 51. LTE-delay performance for 100 Bytes

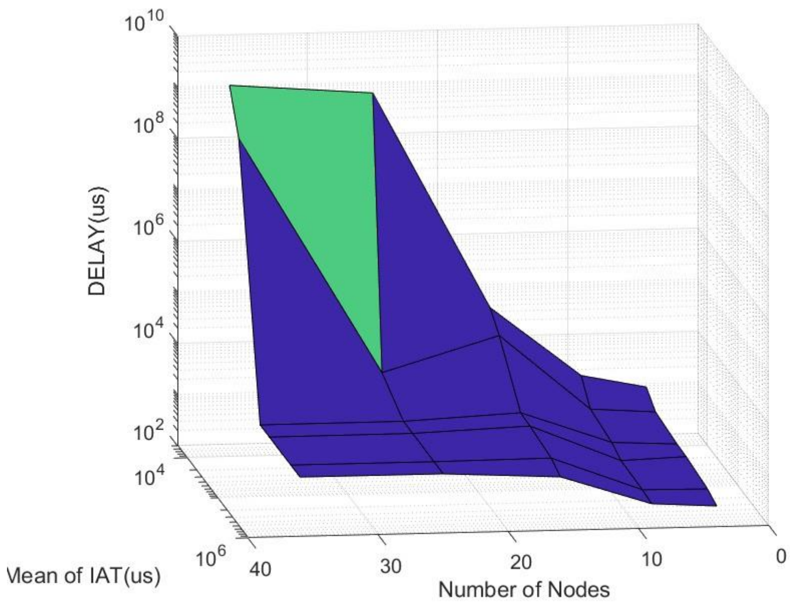


Figure 52. LTE-delay performance for 100 Bytes-Surface Graph

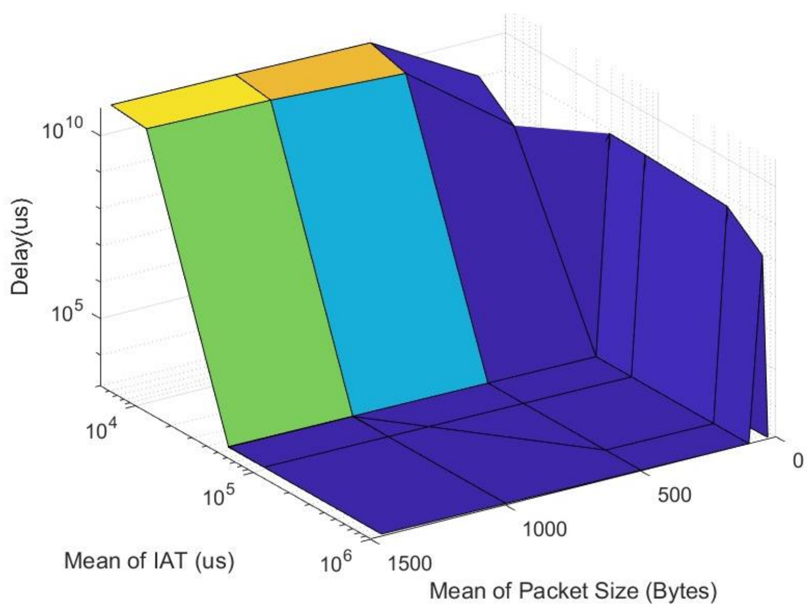


Figure 53. LTE-delay performance for 36 Nodes-Surface Graph

According to Figures 51, 52 and 53 the delay is increasing when the IAT is low and packet size is high between 500 to 1460Bytes. The throughput performance is presented in Figures 54, 55 and 56.

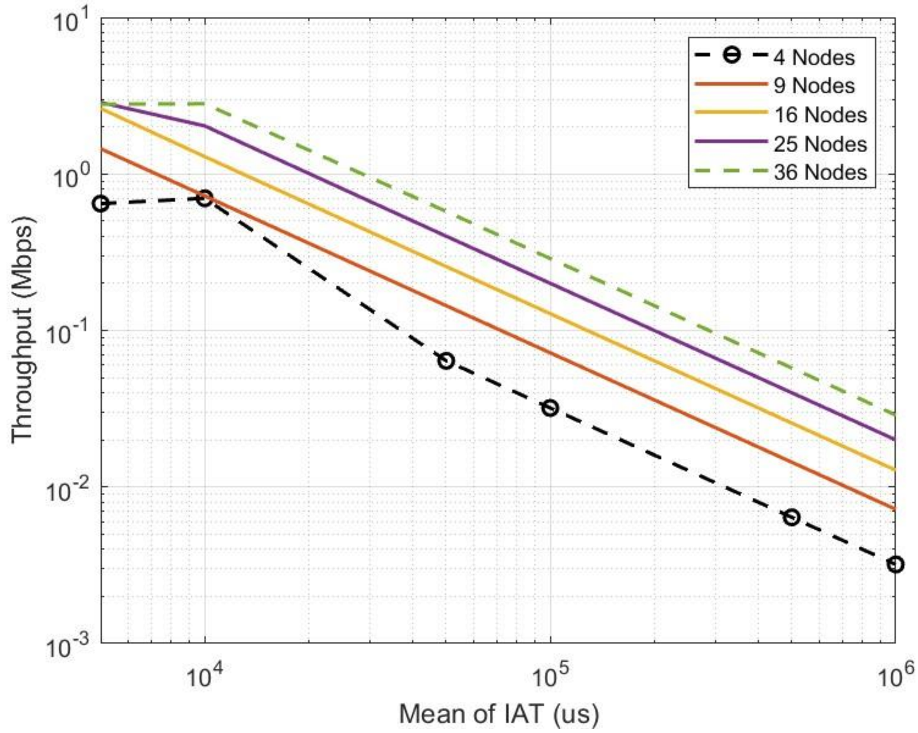


Figure 54. LTE-Throughput performance for 100 Bytes

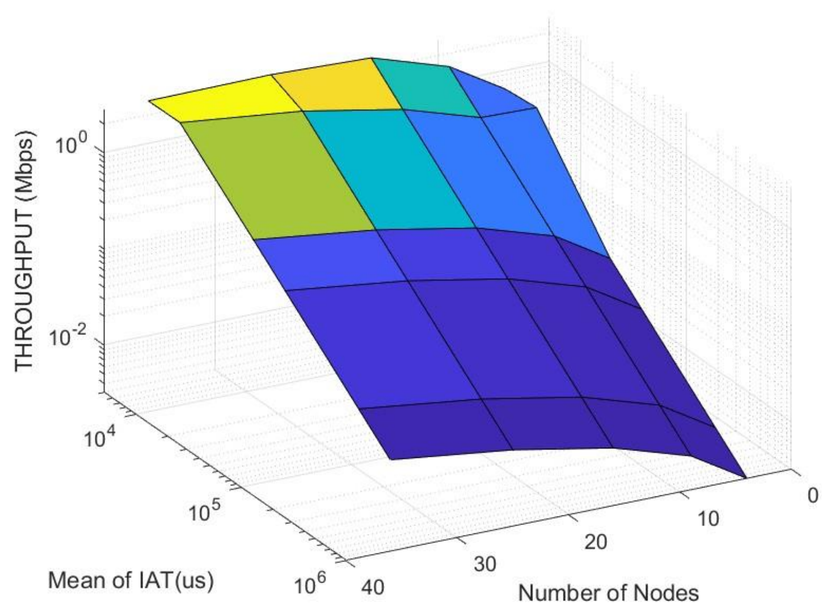


Figure 55. LTE-Throughput performance for 100 Bytes-Surface Graph

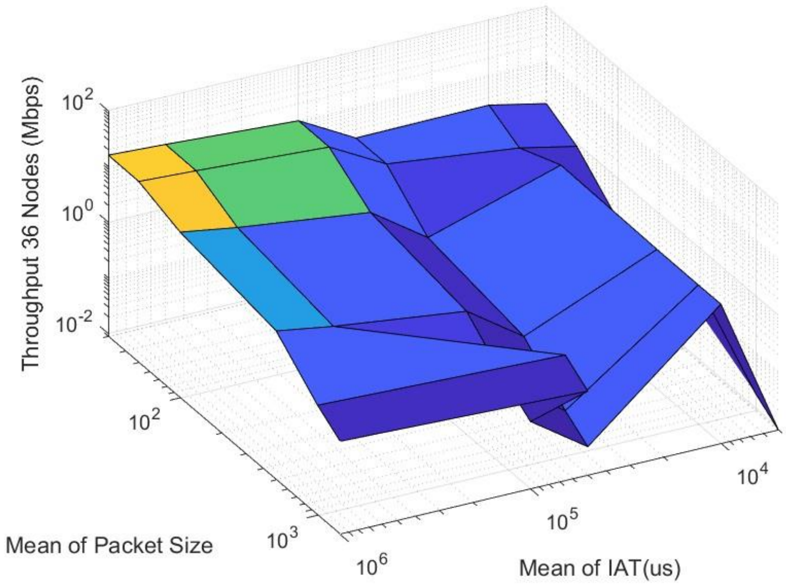


Figure 56. LTE-Throughput performance for 36 Nodes-Surface Graph

This parameter is increasing when IAT is below to 5000us for any quantity of nodes.

4.3 Rules for the Defuzzification process – Classifier

According to the NFIS a defuzzification process must be executed in order to obtain the crisp result for the final decision in Level 1. To run this process a set of rules must be created to cover all the possible combinations derived from the data generated in Netsim® and Tables 7 to 14. Table 16 shows an example of the rules for percentage of packet loss for Zigbee.

Table 16. Zigbee Rules Example – Percentage of packet loss

Rule1		Rule2		Rule3		Rule4		Rule5	
# of nodes	none	# of nodes	none	# of nodes	none	# of nodes	none	# of nodes	VL
Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	30-VS
IAT	1000-UL	IAT	VL	IAT	L	IAT	M	IAT	H
Output	H	Output	H	Output	H	Output	H	Output	M

Rule6		Rule7		Rule8		Rule9		Rule10	
# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	VL
Pkt size	VS	Pkt size	S	Pkt size	S	Pkt size	H	Pkt size	H
IAT	VH	IAT	H	IAT	VH	IAT	H	IAT	VH
Output	M	Output	M	Output	M	Output	H	Output	M

Rule11		Rule12		Rule13		Rule14		Rule15	
# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L
Pkt size	VS	Pkt size	VS	Pkt size	S	Pkt size	M	Pkt size	M
IAT	H	IAT	VH	IAT	H	IAT	H	IAT	VH
Output	H	Output	M	Output	M	Output	H	Output	M

4.4 Scenario 1

Following the AHP process described in Chapter 2, two scenarios were created to compare the Hybrid Multicriteria decision Methodology with Saaty methodology [4].

Table 16. Parameters for Scenario 1

Project Area	50000 m^2
Application	Agriculture/Temp. Sensing
Type of Data	Telemetry
Distance between nodes	100m
Budget	US$30000
Infrastructure available	LTE/Satellite
Indoor/Outdoor	Outdoor
Project duration	10 years
Data Center	In-Situ
Sample rate	1 sample per second

For AHP methodology, the average vector for each criteria and the matrix criteria must be created. Tables 17,18,19 and 21 show the step-by-step procedure. Based on the client requirements, Variable bit rate could be use for this application and low packet size because of the type of data. We assumed 50 bytes and 1 sample per second, then IAT = 1000000µs.

Table 17. Coverage area analysis

Technology	Zigbee	WIFI	LTE	Normalized matrix			Average vector
Zigbee	1	2	0.5	0.285714286	0.4	0.25	0.311904762
WIFI	0.5	1	0.5	0.142857143	0.2	0.25	0.197619048
LTE	2	2	1	0.571428571	0.4	0.5	0.49047619
SUM	3.5	5	2				

Table 18. Data Rate analysis

Technology	Zigbee	WIFI	LTE	Normalized matrix			Average vector
Zigbee	1	0.5	0.5	0.2	0.25	0.142857	0.197619048
WIFI	2	1	2	0.4	0.5	0.5714285	0.49047619
LTE	2	0.5	1	0.4	0.25	0.2857142	0.311904762
SUM	5	2	3.5				

Table 19. Type of Data analysis

Technology	Zigbee	WIFI	LTE	Normalized matrix			Average vector
Zigbee	1	0.5	0.5	0.2	0.2	0.2	0.2
WIFI	2	1	1	0.4	0.4	0.4	0.4
LTE	2	1	1	0.4	0.4	0.4	0.4
SUM	5	2.5	2.5	0.2	0.2	0.2	0.2

Table 20. Criteria Matrix for Scenario 1-AHP

Parameter	Coverage Area	Data rate	Type of data	Normalized matrix			Average vector
Coverage Area	1	3	2	0.545454545	0.666666667	0.4	0.537373737
Data rate	0.333333333	1	2	0.181818182	0.222222222	0.4	0.268013468
Type of data	0.5	0.5	1	0.272727273	0.111111111	0.2	0.194612795
SUM	1.833333333	4.5	5				

Table 21. Final Score

Final Decision	**Coverage Area**	**Data rate**	**Type of data**	**Score**
Zigbee	0.311904762	0.197619048	0.2	0.305618854
WIFI	0.197619048	0.49047619	0.4	0.272951982
LTE	0.49047619	0.311904762	0.4	0.421429164

According to the AHP the best option for the scenario 1 is the LTE technology, based only in expert opinions. No technical parameters such as delay, throughput, and packet loss were analyzed.

Using the Hybrid Multicriteria Decision Methodology proposed the results from NFIS system are showing in Figures 58, 59 and 60. Comparing packet loss parameter, WIFI technology obtain less than 1% of the packet loss, while Zigbee got between 1 to 10% of the packet loss. For the delay, in WIFI the scenario got 2.36 points, that it is equivalent to 229.08µs, Zigbee obtained 3.79 that is equivalent to 6165 µs approximately. And the throughput score is 1.45 for WIFI, which equivalent is 28Kbps, for Zigbee, 0.545 is equivalent 3.5Kbps. The percentage of packet loss in LTE technology is 0.834, delay is 2.45 points equivalent to 281ms and Throughput is 1.45 points equivalent to 0.02818Mbps.

4.4.1 Costs Analysis for Scenario 1

The second level con cycle 1 and 2 is the economic study of the project. Table 22 shows the costs for the different process and components in the operational and implementation parts. These costs are related to USA and values were taken from market.

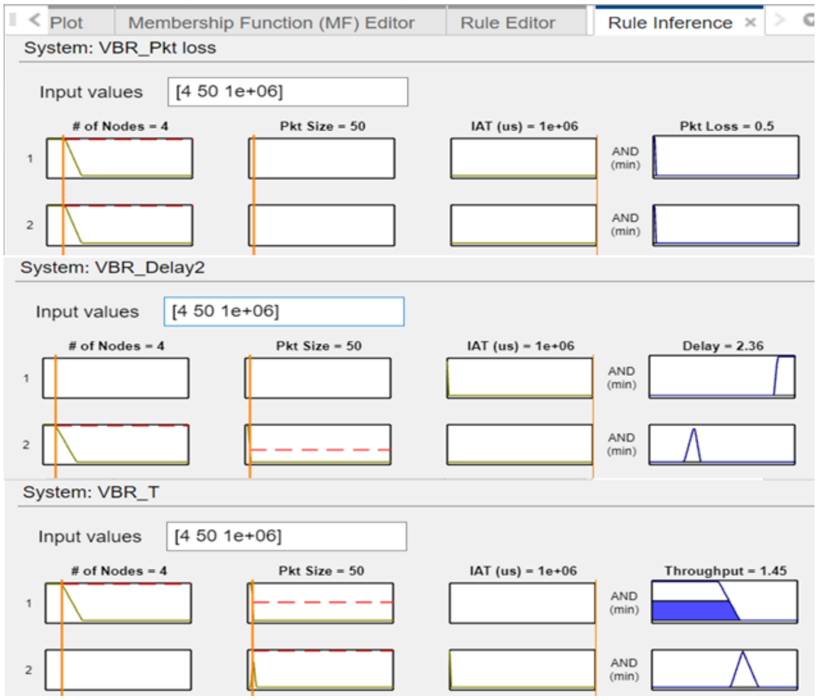


Figure 58. WIFI results

Figure 59. Zigbee results

Figure 60. LTE Results

Table 22. Costs Analysis

	WIFI	LTE	Zigbee
Components	U$3800	U$3500	U$1630
Installation and transportation	U$1500	U$1500	U$1500
Operation and Maintenance (per year)	U$600	U$2000	U$600

Also, the backhaul technology must be considered according to the type of the control center. If the center is in situ, a wired backhaul could be used, low cost and high speed, but if satellite or LTE technologies are used, then operational costs for carrier services and maintenance must be added to table 22.

Finally, regulatory, and environmental risks must be reviewed depending on the specific project specification and location.

4.5 Scenario 2

Table 23 shows the parameters required for customer in scenario 2

Table 23 Parameters for Scenario 2

Project Area	100000 m^2
Application	Petroleum exploration/seismic waves
Type of Data	Seismic waves
Distance between nodes	50m
Budget	US$200000
Infrastructure available	No
Indoor/Outdoor	Outdoor/Remote
Project duration	1 year
Data Center	In-Situ
Sample rate	1 sample per 1ms

According to AHP method Table 24, the best technology is for this project is WIFI.

Table 24. AHP Scores for Scenario 2

	Coverage Area	Data rate	Type of data	Final Score
Zigbee	0.631773399	0.07494759	0.071770335	0.114326
WIFI	0.3158867	0.59958071	0.645933014	.592994
LTE	0.052339901	0.3254717	0.282296651	0.29268

Applying Hybrid Method, the inference result is showed from Figure 61, 62 and 63 for each technology.

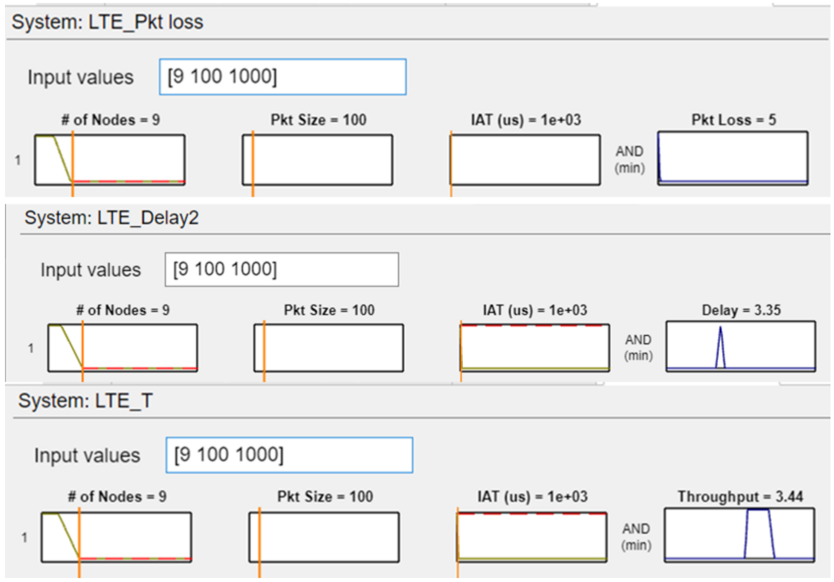


Figure 61. LTE Results for scenario 2

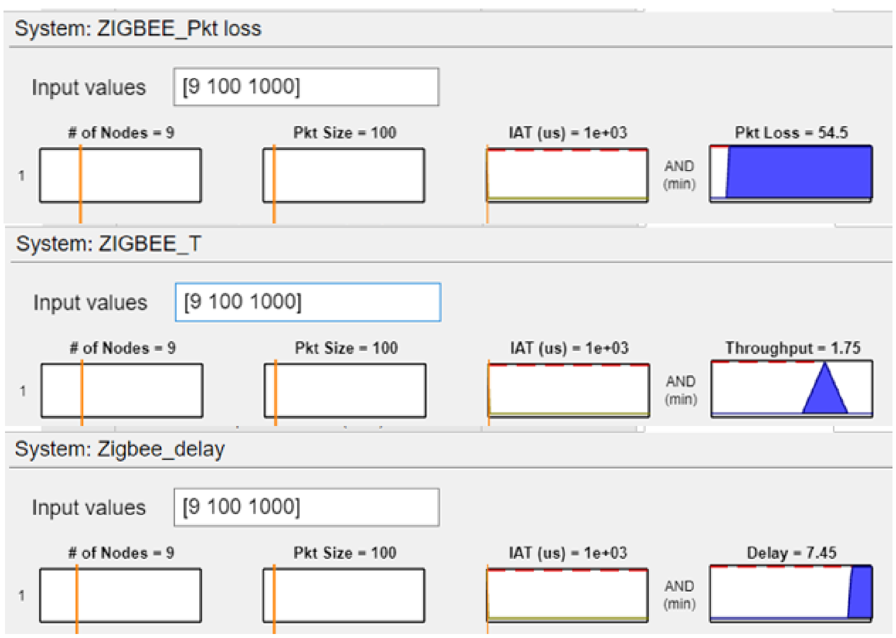


Figure 62. Zigbee Results for scenario 2

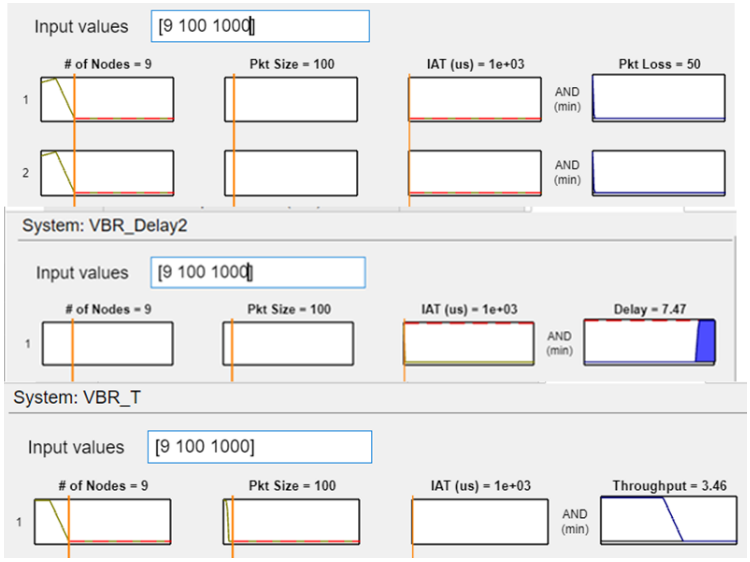


Figure 63. WIFI Results for scenario 2

According to the results for Scenario 2, Zigbee network will be in saturation mode because of the parameters data rate interval needed for this project, WIFI has high percentage of packets loss (50%), it is in saturation mode equal to Zigbee with high delay. Then, the better technology for this application is LTE. Table 25 shows the economic study for this example.

Table 25. Costs Analysis Scenario 2

	WIFI	LTE	Zigbee
Components	U$4600	U$3800	U$2300
Installation and transportation	U$1500	U$1500	U$1500
Operation and Maintenance (per year)	U$600	U$2000	U$600

Chapter 5. Discussions and Conclusions

5.1 Discussion

For selecting the most convenient technology in WSN projects, Multicriteria Decision Methods (MCDM) have been included in the election processes taking the customers` requirements under consideration and the project quality as the purpose of the decision. However, the strategies adopted, such as weighted and by comparison methods, only include qualitative approaches from the technical literature review and expert opinions. Then, unexpected technical, regulatory, economic, or environmental facts may occur in the implementation or operation project steps, incurring in quality communication problems and high costs. Hybrid model proposed includes a deep analysis of the more relevant technical parameters in WSN as throughput, delay, percentage of packet loss, besides an extensive economical and risk study. This study increases the decision´s reliability because quantitative results, based on simulation responses, are included in the analysis. However, more time will be spent in the evaluation.

NFIS implementation provides a systematic and optimized model increasing the efficiency and reliability of the system. AHP model has been used as a comparison tool for neural network training only, in cycle one.

Table 26 shows the comparison between the models used in the present time and the hybrid method proposed in this dissertation.

Table.26 Comparison between currently selecting models and Hybrid model

Model / **Parameter**	**Current Selecting Models**	**Hybrid Model**
Analysis and final decision based on expert opinions and theoretical information only	•	-
Combination of qualitative and quantitative network parameters analysis for the final decision	---	•
Technical simulation and risk analysis for technologies selected	---	•
Neuro Fuzzy Inference System to optimize the selection process	---	•

5.2 Conclusions

Hybrid model is a novelty selection methodology where several and important project parameters are taking under consideration to prevent future problems and high costs on the implementation and operation processes. Some components to be studied are environmental factors (type of terrain, climate conditions), technical elements taking from most realistic scenarios (throughput, delay, packets generated, packets loss), regulatory aspects (right of way or licensing), and economic aspects (budget, operational fees). The implementation of the neural network, simulations and economical surveys optimize the model procedure providing an optimal and efficient system response according to the client requirements. The analysis includes theoretical information, customer needs, real data from the project scenario and risk evaluation to obtain sensitive points and tradeoffs. All these parameters have not been taking under consideration in current models, such as AHP, ANP, Vikor and others, only theoretical parameters and opinions from experts are used for the final decision. In addition, this model provides a detail technical analysis in minutes with delay, throughput and packet loss as outputs and IAT, number of packets and packets size to generate the network traffic, without complex simulations. The sensitivity points of the models are number of packets, IAT, and packets size. The trade off point is the total traffic which affects the model outputs.

5.3 Future Work

For future work we can consider some processes:

1. Simulations must be running in a robust computer for IAT = 1000µs.
2. The Neuro Fuzzy inference system must be trained using the tunning process to adjust the membership function values to increase the quality of the methodology and generate the similar Netsim® values.
3. Simulations with different seems should be running to obtain enough statistical data for both training and verification processes in NFIS.
4. Different Membership Functions could be tested in order to obtain the better tool for the project.

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Appendix A

Table 27. WIFI simulation values from Netsim®.

No. of Nodes	Size (bytes)	IAT(us)	Delay(us)	Throughput (Mbps)	% pkt loss
4	30	1000	326540657.9	0.811783	9.83528
4	30	3000	406.852086	0.325128	0.013544
4	30	5000	341.1771613	0.195254	0.013084
4	30	10000	307.938581	0.097512	0.01411
4	50	1000	362460559.9	1.31602	11.82625
4	50	3000	419.518535	0.53843	0.01594
4	50	5000	349.6165115	0.32308	0.015284
4	50	10000	314.9536995	0.161555	0.015004
4	75	1000	404846428.5	1.913511	14.18289
4	75	3000	435.1169365	0.804445	0.019575
4	75	5000	360.5269443	0.483221	0.020862
4	75	10000	323.7314635	0.242171	0.019842
4	100	1000	445515074.1	2.47958	16.46213
4	100	3000	452.4352103	1.072111	0.024248
4	100	5000	371.433687	0.643578	0.025097
4	100	10000	332.6460045	0.321367	0.025154
4	100	50000	309.0554073	0.063985	0.026042
4	100	100000	306.7677983	0.031994	0.025
4	100	500000	304.9450305	0.0064	0.023125
4	100	1000000	303.882249	0.0032	0.023178
4	500	1000	445515074.1	2.47958	25.7
4	500	50000	470.2552655	0.319723	0.087848
4	500	100000	465.8407553	0.15986	0.085028
4	500	500000	463.078535	0.031977	0.083533
4	500	1000000	460.9332245	0.015992	0.083333
4	1000	1000	445515074.1	2.47958	50
4	1000	50000	767.9368108	0.638874	0.177085
4	1000	100000	753.5611258	0.319424	0.172639
4	1000	500000	738.8223755	0.063884	0.164444
4	1000	1000000	735.2637323	0.031949	0.1675
4	1460	1000	445515074.1	2.47958	65
4	1460	50000	1056.130489	0.932	0.258336
4	1460	100000	1024.443771	0.465986	0.2525
4	1460	500000	1003.821472	0.093229	0.239583
4	1460	1000000	997.1181658	0.046622	0.236111
9	30	1000	1114559724	0.988971	51.64072

9	30	3000	1151.284372	0.737608	1.140483
9	30	5000	480.1046644	0.439685	0.248081
9	30	10000	358.3695524	0.219595	0.035451
9	50	1000	1134556816	1.604841	52.53383
9	50	3000	1292.648641	1.222228	1.387321
9	50	5000	494.6008652	0.728058	0.292681
9	50	10000	365.8770864	0.363909	0.040879
9	75	1000	1156075932	2.3408	53.63166
9	75	3000	1492.204439	1.828772	1.580501
9	75	5000	512.6487921	1.088867	0.337044
9	75	10000	374.4013838	0.544201	0.018686
9	100	1000	1176316461	3.047289	54.69441
9	100	3000	1789.946234	2.439228	1.840589
9	100	5000	532.3105291	1.450891	0.356699
9	100	10000	383.4154482	0.723348	0.047556
9	100	50000	323.1367788	0.144717	0.025155
9	100	100000	317.2823898	0.072357	0.025129
9	100	500000	312.8564306	0.014428	0.023221
9	100	1000000	312.9451597	0.007252	0.018546
9	500	1000	1176316461	3.047289	65
9	500	50000	458.8427612	0.718897	0.083648
9	500	100000	447.6234723	0.359014	0.091613
9	500	500000	439.0734668	0.072242	0.093789
9	500	1000000	438.9369121	0.03625	0.093444
9	1000	1000	1176316461	3.047289	75
9	1000	50000	720.4013621	1.437621	0.195969
9	1000	100000	691.7205767	0.720081	0.133093
9	1000	500000	667.809322	0.143424	0.127654
9	1000	1000000	669.4776822	0.071858	0.128212
9	1460	1000	1176316461	3.047289	80
9	1460	50000	987.9707834	2.10517	0.196735
9	1460	100000	927.6718631	1.047557	0.178292
9	1460	500000	884.7754729	0.20947	0.172192
9	1460	1000000	879.912993	0.103016	0.171874
16	30	1000	964727719.7	2	20
16	30	3000	564727719.7	0.991082	18.1976
16	30	5000	704.657	0.792367	2.118661
16	30	10000	417.9661651	0.390514	0.264764
16	50	1000	900016246.5	2	21
16	50	3000	600016246.5	1.611397	19.24614
16	50	5000	1498.668122	1.315393	2.679625
16	50	10000	427.6121513	0.647472	0.327695
16	75	1000	931518358.5	3	22

16	75	3000	631518358.5	2.341385	20.65877
16	75	5000	1831.015918	1.973881	3.256879
16	75	10000	438.5634277	0.968254	0.373389
16	100	1000	954588647.2	4	56
16	100	3000	654588647.2	3.017409	22.01599
16	100	5000	2252.419096	2.634997	3.774821
16	100	10000	450.0564184	1.288133	0.408379
16	100	50000	318.1659698	0.257587	0.018914
16	100	100000	307.5036704	0.128153	0.023518
16	100	500000	300.1788251	0.025808	0.030363
16	100	1000000	299.3638872	0.012859	0.024378
16	500	1000	954588647.2	4	70
16	500	50000	448.2410423	1.280445	0.046521
16	500	100000	427.4961729	0.639373	0.073282
16	500	500000	413.0281046	0.128113	0.087341
16	500	1000000	411.9489503	0.063903	0.105449
16	1000	1000	954588647.2	6	80
16	1000	50000	716.2841442	2.560297	0.014081
16	1000	100000	662.9043874	1.280629	0.07881
16	1000	500000	626.6284947	0.255888	0.120827
16	1000	1000000	622.0125228	0.127645	0.108972
16	1000	1000	954588647.2	6	89
16	1460	50000	1011.862229	3.741753	0.090965
16	1460	100000	900.0699729	1.864155	0.061937
16	1460	500000	829.652085	0.371275	0.161023
16	1460	1000000	821.0324474	0.184688	0.153023
25	30	1000	1305375830	1.2	70
25	30	3000	1105375830	0.910182	51.10639
25	30	5000	565839419.2	0.905767	19.68802
25	30	10000	660.9499184	0.612502	0.612678
25	50	1000	1125932315	1.6	71
25	50	3000	1125932315	1.477948	51.88135
25	50	5000	596112432.9	1.458494	20.93952
25	50	10000	694.0024043	1.014523	0.77071
25	75	1000	1346896664	2.5	72
25	75	3000	1146896664	2.159166	52.85453
25	75	5000	629973476.3	2.120374	22.59736
25	75	10000	738.179938	1.519061	0.898409
25	100	1000	1366453683	3	73
25	100	3000	1166453683	2.811712	53.84525
25	100	5000	662254526.7	2.758483	24.2181
25	100	10000	782.1262467	2.021193	0.98967
25	100	50000	325.5732482	0.401917	0.002663

25	100	100000	306.6455569	0.200607	0.01831
25	100	500000	294.0029264	0.040364	0.026006
25	100	1000000	292.5683611	0.020079	0.025524
25	100	1000	1366453683	3	83
25	500	50000	460.7663059	2.000541	0.001756
25	500	100000	422.9962716	0.998079	0.057182
25	500	500000	398.4274705	0.200422	0.089901
25	500	1000000	396.3581508	0.100395	0.093108
25	1000	1000	1366453683	3	87
25	1000	50000	770.254588	4.009205	0.162656
25	1000	100000	662.8626391	1.999569	0.020401
25	1000	500000	600.9675569	0.399892	0.122258
25	1000	1000000	595.5228839	0.20023	0.145
25	1460	1000	1366453683	3	92
25	1460	50000	1169.313376	5.858841	0.424749
25	1460	100000	922.2566822	2.919428	0.060923
25	1460	500000	798.4617182	0.583185	0.132613
25	1460	1000000	785.2166236	0.290569	0.164841
36	30	1000	1599409754	2.5	80
36	30	3000	1399409754	2.210751	68.32283
36	30	5000	1040846202	2.214651	47.99575
36	30	10000	124477339.2	2.008422	2.807718
36	50	1000	1512026824	3	81
36	50	3000	1412026824	2.710821	68.73052
36	50	5000	1062807247	2.707418	48.68274
36	50	10000	175080443.5	2.541191	2.486171
36	75	1000	1525773953	3.5	82
36	75	3000	1425773953	3.299986	69.29083
36	75	5000	1085214336	3.27939	49.56543
36	75	10000	228203289.3	3.160516	2.046203
36	100	1000	1537159773	4	83
36	100	3000	1437159773	3.847297	69.84355
36	100	5000	1104852672	3.826952	50.5235
36	100	10000	273277806.9	3.750803	1.710276
36	100	50000	335.8112861	0.579277	0.019292
36	100	100000	309.0894707	0.289013	0.014048
36	100	500000	291.6115249	0.058	0.025416
36	100	1000000	289.6578346	0.028938	0.027002
36	500	1000	1537159773	4	87
36	500	50000	481.6144731	2.880103	0.040473
36	500	100000	426.7882957	1.438669	0.049397
36	500	500000	393.9972679	0.289005	0.087207

36	500	1000000	391.0436709	0.144706	0.096179
36	1000	1000	1537159773	4	93
36	1000	50000	848.2980294	5.772055	0.300686
36	1000	100000	678.6839202	2.883272	0.005658
36	1000	500000	594.1016221	0.575248	0.118102
36	1000	1000000	586.9493835	0.287877	0.126486
36	1460	1000	1537159773	4	96
36	1460	50000	1393.059162	8.461755	0.732082
36	1460	100000	960.2884491	4.198269	0.12638
36	1460	500000	790.8671666	0.835909	0.103271
36	1460	1000000	777.6036803	0.419187	0.156872

Table 28. Zigbee simulation values from Netsim®.

No. of Nodes	Size	IAT(μs)	Throughout (Mbps)	Delay(μs)	%Pkt Loss
4	30	1000	0.065143	1.76E+09	93.08971
	30	3000	0.065048	1.39E+09	79.2936
	30	5000	0.065061	1.02E+09	65.52967
	30	10000	0.038539	7.39E+08	59.63022
	30	50000	0.017592	11153.85	7.412148
	30	100000	0.009529	5886.603	2.513273
	30	500000	0.001907	7138.62	1.543803
	30	1000000	0.000949	9197.511	1.202643
	50	1000	0.083864	1.8E+09	94.58793
	50	3000	0.083767	1.49E+09	83.76337
	50	5000	0.083676	1.19E+09	72.98742
	50	10000	0.049382	9.93E+08	68.44669
	50	50000	0.030133	10050.65	7.396014
	50	100000	0.014675	13933.99	9.325702
	50	500000	0.00308	10578.04	3.228356
	50	1000000	0.001542	12122.98	3.146337
	75	1000	0.095642	1.83E+09	95.83216
	75	3000	0.095684	1.59E+09	87.48856
	75	5000	0.095611	1.35E+09	79.1698
	75	10000	0.075344	9.85E+08	67.31875
	75	50000	0.038928	26167.79	20.48838
	75	100000	0.022327	13998.72	9.834782
	75	500000	0.004521	13964.76	5.366846
	75	1000000	0.00226	14753.17	5.161791
	100	1000	0.101903	1.85E+09	96.63945

	100	3000	0.101927	1.65E+09	89.91385
	100	5000	0.101876	1.45E+09	83.19972
	100	10000	0.101738	9.48E+08	66.50361
	100	50000	0.0585	15739.18	19.4656
	100	100000	0.029705	14609.82	7.313118
	100	500000	0.005935	14343.68	5.502183
	100	1000000	0.002882	17977.23	3.111171
9	30	1000	0.066815	1.81E+09	97.03657
	30	3000	0.066641	1.52E+09	91.13764
	30	5000	0.052878	1.37E+09	88.33403
	30	10000	0.028152	1.1E+09	87.97623
	30	50000	0.028134	24878.25	38.9781
	30	100000	0.017865	14170.61	9.307578
	30	500000	0.004067	12518.4	6.906916
	30	1000000	0.002086	10475.63	3.938633
	50	1000	0.083586	1.83E+09	97.71522
	50	3000	0.083559	1.59E+09	93.15194
	50	5000	0.083546	1.36E+09	88.58695
	50	10000	0.074502	8.65E+08	79.71322
	50	50000	0.028797	203654.9	63.30886
	50	100000	0.029372	15720.23	20.35775
	50	500000	0.006736	11624.08	6.218462
	50	1000000	0.003382	12648.73	5.855626
	75	1000	0.093276	1.85E+09	98.25742
	75	3000	0.083716	1.84E+09	97.9259
	75	5000	0.073344	1.57E+09	93.15832
	75	10000	0.056869	1.25E+09	89.46971
	75	50000	0.040216	83541487	64.23722
	75	100000	0.038428	25213.1	30.16859
	75	500000	0.009692	15505.76	10.02704
	75	1000000	0.004892	16253.69	9.260607
	100	1000	0.086451	1.87E+09	98.77185
	100	3000	0.076697	1.77E+09	97.14488
	100	5000	0.07657	1.59E+09	94.56278
	100	10000	0.057735	1.45E+09	91.79551
	100	50000	0.074788	98720.29	69.61816
	100	100000	0.051078	26053.1	29.87758
	100	500000	0.012175	19841.84	14.78034
	100	1000000	0.006296	19238.6	11.66096
16	30	1000	0.069848	2.64E+09	97.8846
	30	3000	0.069505	1.78E+09	97.17675
	30	5000	0.027196	1.64E+09	96.95024
	30	10000	0.039237	1.03E+09	91.13005

	30	50000	0.057612	10276.39	28.83954
	30	100000	0.035111	7154.204	11.26717
	30	500000	0.007328	9057.829	6.247016
	30	1000000	0.00358	12990.84	7.942857
	50	1000	0.088323	1.7E+09	98.8456
	50	3000	0.08342	1.68E+13	97.674
	50	5000	0.066426	1.47E+09	95.22664
	50	10000	0.038435	1.71E+08	93.29462
	50	50000	0.075901	16943.61	43.96844
	50	100000	0.051868	12050.96	21.27239
	50	500000	0.011391	13513.55	11.40369
	50	1000000	0.005798	14211.24	9.341241
	75	1000	0.095736	1.81E+09	98.8764
	75	3000	0.928483	1.31E+09	96.4367
	75	5000	0.081901	1.5E+09	95.89166
	75	10000	0.062389	1.24E+09	93.77766
	75	50000	0.064109	64091.61	68.93525
	75	100000	0.051473	33339.95	48.4754
	75	500000	0.015645	19078.25	18.94829
	75	1000000	0.007969	19963.8	16.22698
	100	1000	0.098775	1.97E+09	98.9937
	100	3000	0.09244	1.6E+10	97.84743
	100	5000	0.08401	1.57E+09	96.74263
	100	10000	0.058628	1.4E+09	95.47376
	100	50000	0.091991	41723.78	69.7541
	100	100000	0.084963	20961.17	34.85101
	100	500000	0.019224	23374.17	24.29295
	100	1000000	0.009645	24876.33	22.86382
25	30	1000	0.071847	1.45E+09	96.98447
	30	3000	0.06543	1.35E+09	96.58485
	30	5000	0.053868	1.34E+09	96.39473
	30	10000	0.053195	7.2E+08	92.90768
	30	50000	0.020538	1.78E+08	85.60915
	30	100000	0.043471	11900.84	31.35707
	30	500000	0.009722	16414.3	21.41397
	30	1000000	0.005287	14965.08	13.46619
	50	1000	0.069636	1.95799	1.95799
	50	3000	0.066939	1.65E+09	98.75757
	50	5000	0.064582	1.43E+09	97.23448
	50	10000	0.063965	9.04E+08	94.54615
	50	50000	0.064957	34482.89	86.79082
	50	100000	0.056818	18818.22	46.20234
	50	500000	0.014742	19622.78	27.53984

	50	1000000	0.008323	17824.69	17.02993
	75	1000	0.07636	1.68E+09	97.9464
	75	3000	0.069636	1.79E+09	97.8585
	75	5000	0.067933	1.51E+09	97.93453
	75	10000	0.067453	1.08E+09	95.91017
	75	50000	0.088985	29089.21	87.66183
	75	100000	0.034731	54681.13	58.62378
	75	500000	0.021517	21438.48	28.9328
	75	1000000	0.010308	23677.34	34.94255
	100	1000	0.073749	1.85E+09	99.9448
	100	3000	0.068746	1.69E+09	98.58
	100	5000	0.067951	1.58E+09	98.38165
	100	10000	0.067474	1.21E+09	96.78667
	100	50000	0.067663	96949.93	89.42257
	100	100000	0.082066	29688.17	60.53383
	100	500000	0.02653	24698.77	33.91917
	100	1000000	0.013672	27194.59	30.83504
36	30	1000	0.074903	1.49E+09	98.7653
	30	3000	0.067576	1.4E+09	98.64654
	30	5000	0.053246	1.11E+09	98.66839
	30	10000	0.052359	5.79E+08	97.49617
	30	50000	0.049661	30556.96	97.15012
	30	100000	0.05893	16116.31	55.10215
	30	500000	0.015443	9795.668	85.72525
	30	1000000	0.006532	20704.92	88.67994
	50	1000	0.95799	1.85E+09	98.87646
	50	3000	0.063985	1.2E+08	98.79758
	50	5000	0.06539	1.09E+09	98.7302
	50	10000	0.06351	6.71E+08	97.7815
	50	50000	0.100958	20274.98	85.27339
	50	100000	0.094164	12947.89	58.93676
	50	500000	0.023767	13468.91	87.42039
	50	1000000	0.011417	18185.73	87.30429
	75	1000	0.04567	1.16E+09	99.76645
	75	3000	0.043985	1.13E+09	99.48485
	75	5000	0.068421	1.12E+09	99.09845
	75	10000	0.067385	7.11E+08	98.33363
	75	50000	0.095409	39850.13	85.75361
	75	100000	0.10472	23754.98	62.80171
	75	500000	0.033768	15902.3	87.77846
	75	1000000	0.014965	23761.36	88.89207
	100	1000	0.076543	1.4E+09	99.87746
	100	3000	0.078959	1.21E+09	99.62004

	100	5000	0.074444	1.19E+09	99.2051
	100	10000	0.074368	7.43E+08	98.40567
	100	50000	0.104485	47857.43	86.2315
	100	100000	0.120978	25797.46	67.49425
	100	500000	0.043	19097.9	88.06899
	100	1000000	0.019608	26103.33	89.79945

Table 29. LTE simulation values from Netsim®.

No. of Nodes	**Size**	**IAT (μs)**	**Throughput (Mbps)**	**Delay (μs)**	**% Pkt loss**
4	30	1000	0.975166	1356.911	0.0180591
	30	3000	0.326037	1536.457	0.0177463
	30	5000	0.195089	1331.676	0.0132026
	30	10000	0.097648	329.019	0.0143132
	50	1000	1.616083	1566.94	0.0218019
	50	3000	0.539195	1540.798	0.0223852
	50	5000	0.36587	765.76	0.01975
	50	10000	0.161712	333.2657	0.0165352
	100	1000	3.216422	1594.598	0.0306334
	100	3000	1.074844	1556.759	0.030609
	100	5000	0.645986	849.3907	0.0308017
	100	10000	0.69876	476.97	0.0278
	100	50000	0.063978	396.7931	0.0370372
	100	100000	0.031991	386.8207	0.0277778
	100	500000	0.006399	318.2445	0.0277778
	100	1000000	0.0032	253.675	0.0162963
	500	50000	0.314265	1100	0.0432732
	500	100000	0.15723	1100	0.0322778
	500	500000	0.031971	1100	0.0201852
	500	1000000	0.015985	1100	0.0181852
	1000	50000	0.614969	1100	0.0712964
	1000	100000	0.308995	1100	0.0621296
	1000	500000	0.06344	1100	0.0231481
	1000	1000000	0.031947	1100	0.0196667
	1460	50000	0.883167	1100	0.0135209
	1460	100000	0.443452	1100	0.0121667
	1460	500000	0.092246	1100	0.0118519
	1460	1000000	0.046596	1100	0.0100269
9	30	5000	0.439199	1477.527	0.1159654
	30	10000	0.219712	356.381	0.010274
	50	5000	0.727735	1490.533	0.1453964
	50	10000	0.363799	363.0636	0.0124615

	100	1000	7.233039	1661.854	0.0808113
	100	3000	4.897764	1588.876	0.0645
	100	5000	1.448364	1526.138	0.0677119
	100	10000	0.72317	579.7928	0.0652874
	100	50000	0.143913	456.9788	0.0508028
	100	100000	0.071957	346.97	0.0432716
	100	500000	0.014398	328.55	0.0385802
	100	1000000	0.007199	300.75	0.0355556
	500	50000	0.712309	1856	0.1087698
	500	100000	0.359354	1500	0.0881821
	500	500000	0.071882	1400	0.0774691
	500	1000000	0.035933	1300	0.0512346
	1000	50000	1.413163	1987	0.168989
	1000	100000	0.706716	1945	0.158899
	1000	500000	0.141035	1876	0.062963
	1000	1000000	0.071758	1746	0.0364198
	1460	50000	2.021819	2276	0.2133968
	1460	100000	1.019477	1980	0.19987
	1460	500000	0.208904	1876	0.0649691
	1460	1000000	0.103215	1736	0.0450617
16	30	5000	0.788021	1472.545	1.4304529
	30	10000	0.390936	422.5656	0.1697377
	50	5000	1.309837	1553.452	1.9764708
	50	10000	0.647369	1432.115	0.222157
	100	5000	2.61957	1909.808	2.9341351
	100	10000	1.289429	1805.424	0.2887137
	100	50000	0.25594	1505.425	0.0247397
	100	100000	0.127964	1310.424	0.0289931
	100	500000	0.025595	1198	0.0399306
	100	1000000	0.012798	1114	0.0572917
	500	50000	1.278834	1535	0.0925351
	500	100000	0.639416	1436	0.0939236
	500	500000	0.127878	1342	0.109375
	500	1000000	0.063957	1298	0.1006944
	1000	50000	2.555766	1598	0.1667542
	1000	100000	1.277778	1596	0.1763889
	1000	500000	0.255556	1480	0.1875
	1000	1000000	0.127779	1460.987	0.1996528
	1460	50000	3.728462	1698.75	0.2458344
	1460	100000	1.864144	1687	0.2517361
	1460	500000	0.372892	1676	0.2456597
	1460	1000000	0.186447	1672.76	0.2604167
25	30	5000	0.949733	1508.987	17.072956

	30	10000	0.612575	633.0428	0.6780171
	50	5000	1.521177	1590.675	17.949438
	50	10000	1.015443	1663.216	0.9187096
	100	5000	2.86248	6.28E+08	20.836709
	100	10000	2.026346	3740.278	1.2517456
	100	50000	0.399907	1475.239	0.0247224
	100	100000	0.199953	1472.052	0.0255556
	100	500000	0.039994	1472.052	0.04
	100	1000000	0.019998	1472.052	0.0566667
	500	50000	1.998195	1549.798	0.0915561
	500	100000	0.999105	1538.931	0.0922222
	500	500000	0.199812	1538.931	0.1061111
	500	1000000	0.099913	1538.931	0.1188889
	1000	50000	3.993288	1642.998	0.1691676
	1000	100000	1.99657	1622.531	0.1742222
	1000	500000	0.399291	1622.531	0.1911111
	1000	1000000	0.199672	1622.531	0.1911111
	1460	50000	5.825851	1728.741	0.2436125
	1460	100000	2.912788	1699.443	0.2496667
	1460	500000	0.582475	1599.765	0.275
	1460	1000000	0.291337	1564.97	0.2555556
26	30	1000	8.786122	1803.938	15.97886
	30	3000	2.92728	1556.859	0.0185708
	30	5000	1.759148	1581.34	25.86
	30	10000	0.879774	1553.509	0.0201244
	30	50000	0.175806	1531.41	0.0277733
	30	100000	0.087841	1528.955	0.0291538
	30	500000	0.017687	1524.649	0.085476
	30	1000000	0.008878	1589.021	0.1704519
	50	1000	14.545307	1865.731	35.215428
	50	3000	4.847407	1763.9	0.0221857
	50	5000	2.908882	1597.386	30.016008
	50	10000	1.454755	1563.399	0.0159605
	100	1000	3.0874393	1.5E+09	75.87
	100	3000	2.819839	1.62E+08	67.295002
	100	5000	2.789104	1.03E+09	45.723341
	100	10000	2.80598	1.62E+08	5.988566
	100	50000	0.57586	1461.27	0.0256175
	100	100000	0.287927	1455.368	0.0273148
	100	500000	0.057593	1455.368	0.0335648
	100	1000000	0.028797	1455.368	0.0532407
	500	5000	10.057564	4.72E+10	61.231637
	500	10000	9.943002	2.44E+10	23.001925

	500	50000	2.877489	1550.477	0.0886194
	500	100000	1.438727	1530.354	0.0912809
	500	500000	0.28773	1530.354	0.1068673
	500	1000000	0.143885	1530.354	0.1111111
	1000	5000	14.11844	5.46E+10	73.149832
	1000	10000	13.942163	3.87E+10	46.707352
	1000	50000	5.750329	1661.988	0.1691755
	1000	100000	2.875125	1624.087	0.1719136
	1000	500000	0.575041	1624.087	0.1801698
	1000	1000000	0.28751	1624.085	0.1975309
	1460	5000	15.982357	5.85E+10	79.376104
	1460	10000	15.782931	4.62E+10	59.022114
	1460	50000	8.389344	1764.577	0.2421698
	1460	100000	4.194525	1710.321	0.2471451
	1460	500000	0.838915	1710.323	0.257716

Appendix B

Table 30. Rules for percentage of packet loss - WIFI

Rule1		**Rule2**		**Rule3**		**Rule4**		**Rule5**	
# of nodes	none	# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	VL
Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none
IAT	UL	IAT	L	IAT	M	IAT	H	IAT	VL
Output	H	Output	L	Output	L	Output	L	Output	L
Rule6		**Rule7**		**Rule8**		**Rule9**		**Rule10**	
# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	M
Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none
IAT	VL	IAT	H	IAT	M	IAT	H	IAT	VL
Output	M	Output	L	Output	L	Output	L	Output	H
Rule11		**Rule12**		**Rule13**		**Rule14**		**Rule15**	
# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	H	# of nodes	H
Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none
IAT	L	IAT	M	IAT	H	IAT	VL	IAT	L
Output	M	Output	L	Output	L	Output	H	Output	H
Rule16		**Rule17**		**Rule18**		**Rule19**		**Rule20**	
# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	H
Pkt size	VS	Pkt size	S	Pkt size	M	Pkt size	M	Pkt size	none
IAT	M	IAT	M	IAT	M	IAT	H	IAT	H
Output	L	Output	L	Output	M	Output	M	Output	L
Rule21		**Rule22**		**Rule23**		**Rule24**			
# of nodes	VH	# of nodes	VH	# of nodes	VH	# of nodes	VH		
Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none		
IAT	VL	IAT	L	IAT	M	IAT	H		
Output	H	Output	H	Output	M	Output	L		

Table 31. Rules for the Delay- WIFI

Rule1		**Rule2**		**Rule3**		**Rule4**		**Rule5**	
# of nodes	none	# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	None
Pkt size	none	Pkt size	VS	Pkt size	VS	Pkt size	VS	Pkt size	VS
IAT	UL	IAT	VL	IAT	L	IAT	M	IAT	H
Output	UH	Output	L	Output	L	Output	L	Output	L
Rule6		**Rule7**		**Rule8**		**Rule9**		**Rule10**	
# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	none	# of nodes	VL
Pkt size	S	Pkt size	S	Pkt size	S	Pkt size	S	Pkt size	M
IAT	VL	IAT	L	IAT	M	IAT	H	IAT	VL
Output	L	Output	L	Output	L	Output	L	Output	MM

Rule11		**Rule12**		**Rule13**		**Rule14**		**Rule15**	
# of nodes	VL	# of nodes	VL	# of nodes	none	# of nodes	VL	# of nodes	VL
Pkt size	M	Pkt size	M	Pkt size	M	Pkt size	H	Pkt size	H
IAT	L	IAT	M	IAT	H	IAT	VL	IAT	L
Output	ML	Output	ML	Output	ML	Output	MH	Output	MM
Rule16		**Rule17**		**Rule18**		**Rule19**		**Rule20**	
# of nodes	VL	# of nodes	none	# of nodes	L	# of nodes	L	# of nodes	L
Pkt size	H	Pkt size	H	Pkt size	VS	Pkt size	VS	Pkt size	VS
IAT	M	IAT	H	IAT	VL	IAT	L	IAT	M
Output	MM	Output	MM	Output	MM	Output	ML	Output	L
Rule21		**Rule22**		**Rule23**		**Rule24**		**Rule25**	
# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L
Pkt size	S	Pkt size	S	Pkt size	S	Pkt size	500M	Pkt size	M
IAT	VL	IAT	L	IAT	M	IAT	VL	IAT	L
Output	MM	Output	ML	Output	ML	Output	MM	Output	MM
Rule26		**Rule27**		**Rule28**		**Rule29**		**Rule30**	
# of nodes	L	# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M
Pkt size	M	Pkt size	VS	Pkt size	VS	Pkt size	VS	Pkt size	S
IAT	M	IAT	VL	IAT	L	IAT	M	IAT	VL
Output	ML	Output	UH	Output	MM	Output	L	Output	UH
Rule31		**Rule32**		**Rule33**		**Rule34**		**Rule35**	
# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M
Pkt size	S	Pkt size	S	Pkt size	M	Pkt size	M	Pkt size	M
IAT	L	IAT	M	IAT	VL	IAT	L	IAT	M
Output	MM	Output	L	Output	UH	Output	MM	Output	ML
Rule36		**Rule37**		**Rule38**		**Rule39**		**Rule40**	
# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	H
Pkt size	none	Pkt size	none	Pkt size	VS	Pkt size	S	Pkt size	M
IAT	VL	IAT	L	IAT	M	IAT	M	IAT	M
Output	UH	Output	UH	Output	ML	Output	ML	Output	MM
Rule41		**Rule42**		**Rule43**		**Rule44**			
# of nodes	H	# of nodes	VH	# of nodes	VH	# of nodes	VH		
Pkt size	H	Pkt size	none	Pkt size	none	Pkt size	none		
IAT	M	IAT	VL	IAT	L	IAT	M		
Output	MH	Output	UH	Output	UH	Output	UH		

Table 32. Rules for the Throughput- WIFI

Rule1		Rule2		Rule3		Rule4		Rule5	
# of nodes	VL	# of nodes	None	# of nodes	VL	# of nodes	VL	# of nodes	VL
Pkt size	VS	Pkt size	S	Pkt size	S	Pkt size	S	Pkt size	S
IAT	NONE	IAT	UL	IAT	VL	IAT	L	IAT	M
Output	VL	Output	L	Output	VL	Output	VL	Output	VL
Rule6		**Rule7**		**Rule8**		**Rule9**		**Rule10**	
# of nodes	NONE	# of nodes	NONE	# of nodes	VL	# of nodes	VL	# of nodes	VL
Pkt size	S	Pkt size	M	Pkt size	M	Pkt size	M	Pkt size	M
IAT	H	IAT	UL	IAT	VL	IAT	L	IAT	M
Output	VL	Output	L	Output	L	Output	L	Output	L
Rule11		**Rule12**		**Rule13**		**Rule14**		**Rule15**	
# of nodes	NONE	# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	VL
Pkt size	M	Pkt size	H	Pkt size	H	Pkt size	H	Pkt size	H
IAT	H	IAT	UL	IAT	VL	IAT	L	IAT	M
Output	VL	Output	M	Output	L	Output	L	Output	L
Rule16		**Rule17**		**Rule18**		**Rule19**		**Rule20**	
# of nodes	NONE	# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L
Pkt size	H	Pkt size	VS	Pkt size	S	Pkt size	S	Pkt size	S
IAT	H	IAT	NONE	IAT	VL	IAT	L	IAT	M
Output	VL	Output	VL	Output	L	Output	L	Output	L
Rule21		**Rule22**		**Rule23**		**Rule24**		**Rule25**	
# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L
Pkt size	M	Pkt size	M	Pkt size	M	Pkt size	M	Pkt size	M
IAT	VL	IAT	VL	IAT	L	IAT	M	IAT	H
Output	M	Output	M	Output	L	Output	L	Output	VL
Rule26		**Rule27**		**Rule28**		**Rule29**		**Rule30**	
# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L
Pkt size	H	Pkt size	H	Pkt size	H	Pkt size	H	Pkt size	H
IAT	UL	IAT	VL	IAT	L	IAT	M	IAT	H
Output	H	Output	M	Output	M	Output	L	Output	L
Rule31		**Rule32**		**Rule33**		**Rule34**		**Rule35**	
# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M
Pkt size	VS	Pkt size	VS	Pkt size	VS	Pkt size	VS	Pkt size	VS
IAT	UL	IAT	VL	IAT	L	IAT	M	IAT	H
Output	L	Output	L	Output	L	Output	VL	Output	VL

Rule36		Rule37		Rule38		Rule39		Rule40	
# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M
Pkt size	S	Pkt size	S	Pkt size	S	Pkt size	M	Pkt size	M
IAT	VL	IAT	L	IAT	M	IAT	VL	IAT	L
Output	L	Output	L	Output	VL	Output	M	Output	M
Rule41		**Rule42**		**Rule43**		**Rule44**		**Rule45**	
# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M
Pkt size	M	Pkt size	M	Pkt size	H	Pkt size	H	Pkt size	H
IAT	M	IAT	H	IAT	UL	IAT	VL	IAT	L
Output	L	Output	L	Output	H	Output	H	Output	M
Rule46		**Rule47**		**Rule48**		**Rule49**		**Rule50**	
# of nodes	M	# of nodes	M	# of nodes	H	# of nodes	H	# of nodes	H
Pkt size	H	Pkt size	H	Pkt size	VS	Pkt size	VS	Pkt size	VS
IAT	M	IAT	H	IAT	UL	IAT	VL	IAT	L
Output	M	Output	L	Output	L	Output	VL	Output	VL
Rule51		**Rule52**		**Rule53**		**Rule54**		**Rule55**	
# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	H
Pkt size	VS	Pkt size	VS	Pkt size	S	Pkt size	M	Pkt size	M
IAT	M	IAT	H	IAT	NONE	IAT	VL	IAT	L
Output	VL	Output	VL	Output	L	Output	M	Output	M
Rule56		**Rule57**		**Rule58**		**Rule59**		**Rule60**	
# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	H
Pkt size	M	Pkt size	M	Pkt size	H	Pkt size	H	Pkt size	H
IAT	M	IAT	H	IAT	UL	IAT	VL	IAT	L
Output	M	Output	L	Output	H	Output	M	Output	M
Rule61		**Rule62**		**Rule63**		**Rule64**		**Rule65**	
# of nodes	H	# of nodes	H	# of nodes	VH	# of nodes	VH	# of nodes	VH
Pkt size	H	Pkt size	H	Pkt size	VS	Pkt size	S	Pkt size	M
IAT	M	IAT	H	IAT	NONE	IAT	NONE	IAT	VL
Output	M	Output	L	Output	L	Output	L	Output	M
Rule66		**Rule67**		**Rule68**		**Rule69**		**Rule70**	
# of nodes	VH	# of nodes	VH	# of nodes	VH	# of nodes	VH	# of nodes	VH
Pkt size	M	Pkt size	M	Pkt size	M	Pkt size	H	Pkt size	H
IAT	L	IAT	M	IAT	H	IAT	UL	IAT	VL
Output	M	Output	M	Output	L	Output	H	Output	H
Rule71		**Rule72**		**Rule73**					

# of nodes	VH	# of nodes	VH	# of nodes	VH
Pkt size	H	Pkt size	H	Pkt size	H
IAT	L	IAT	M	IAT	H
Output	M	Output	M	Output	L

Table 33. Rules for Percentage of Packet loss Zigbee

Rule1		**Rule2**		**Rule3**		**Rule4**		**Rule5**	
# of nodes	none	# of nodes	none	# of nodes	none	# of nodes	none	# of nodes	VL
Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	VS
IAT	UL	IAT	VL	IAT	L	IAT	M	IAT	H
Output	H	Output	H	Output	H	Output	H	Output	M
Rule6		**Rule7**		**Rule8**		**Rule9**		**Rule10**	
# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	VL
Pkt size	VS	Pkt size	S	Pkt size	S	Pkt size	H	Pkt size	H
IAT	VH	IAT	H	IAT	VH	IAT	H	IAT	VH
Output	M	Output	M	Output	M	Output	H	Output	M
Rule11		**Rule12**		**Rule13**		**Rule14**		**Rule15**	
# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L
Pkt size	VS	Pkt size	VS	Pkt size	S	Pkt size	M	Pkt size	M
IAT	H	IAT	VH	IAT	H	IAT	H	IAT	VH
Output	H	Output	M	Output	M	Output	H	Output	M
Rule16		**Rule17**		**Rule18**		**Rule19**		**Rule20**	
# of nodes	L	# of nodes	L	# of nodes	M	# of nodes	M	# of nodes	M
Pkt size	H	Pkt size	H	Pkt size	VS	Pkt size	VS	Pkt size	S
IAT	H	IAT	VH	IAT	H	IAT	H	IAT	H
Output	H	Output	M	Output	H	Output	M	Output	H
Rule21		**Rule22**		**Rule23**		**Rule24**		**Rule25**	
# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M
Pkt size	S	Pkt size	M	Pkt size	M	Pkt size	H	Pkt size	H
IAT	VH	IAT	H	IAT	VH	IAT	H	IAT	VH
Output	M	Output	H	Output	H	Output	H	Output	H
Rule26		**Rule27**							
# of nodes	H	# of nodes	VH						
Pkt size	none	Pkt size	none						
IAT	none	IAT	none						
Output	H	Output	H						

Table 34. Rules for the Delay- Zigbee

Rule1		Rule2		Rule3		Rule4		Rule5	
# of nodes	none	# of nodes	none	# of nodes	none	# of nodes	none	# of nodes	none
Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none	Pkt size	none
IAT	1000-UL	IAT	VL	IAT	L	IAT	M	IAT	H
Output	UH	Output	UH	Output	UH	Output	UH	Output	MH
Rule6		**Rule7**		**Rule8**		**Rule9**		**Rule10**	
# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	VL	# of nodes	L
Pkt size	VS	Pkt size	S	Pkt size	M	Pkt size	H	Pkt size	none
IAT	VH	IAT	VH	IAT	VH	IAT	VH	IAT	VH
Output	MM	Output	MH	Output	MH	Output	MH	Output	MH
Rule11		**Rule12**		**Rule13**					
# of nodes	M	# of nodes	H	# of nodes	VH				
Pkt size	none	Pkt size	none	Pkt size	none				
IAT	VH	IAT	VH	IAT	VH				
Output	MH	Output	MH	Output	MH				

Table 35. Rules for the Throughput- Zigbee

Rule1		Rule2		Rule3		Rule4		Rule5	
# of nodes	none	# of nodes	none	# of nodes	none	# of nodes	none	# of nodes	VL
Pkt size	none	Pkt size	none	Pkt size	NONE	Pkt size	none	Pkt size	none
IAT	UL	IAT	VL	IAT	L	IAT	M	IAT	H
Output	M	Output	M	Output	M	Output	M	Output	L
Rule6		**Rule7**		**Rule8**		**Rule9**		**Rule10**	
# of nodes	VL	# of nodes	L	# of nodes	L	# of nodes	L	# of nodes	L
Pkt size	NONE	Pkt size	VS	Pkt size	S	Pkt size	M	Pkt size	H
IAT	VH	IAT	H	IAT	H	IAT	H	IAT	H
Output	VL	Output	L	Output	L	Output	M	Output	M
Rule11		**Rule12**		**Rule13**		**Rule14**		**Rule15**	
# of nodes	L	# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	M
Pkt size	NONE	Pkt size	VS	Pkt size	M	Pkt size	H	Pkt size	VS
IAT	VH	IAT	H	IAT	H	IAT	H	IAT	VH
Output	VL	Output	L	Output	M	Output	M	Output	VL
Rule16		**Rule17**		**Rule18**		**Rule19**		**Rule20**	
# of nodes	M	# of nodes	M	# of nodes	M	# of nodes	H	# of nodes	H

Pkt size	S	Pkt size	M	Pkt size	H	Pkt size	none	Pkt size	VS
IAT	VH	IAT	VH	IAT	VH	IAT	H	IAT	VH
Output	VL	Output	L	Output	L	Output	M	Output	VL
Rule21		**Rule22**		**Rule23**		**Rule24**		**Rule25**	
# of nodes	H	# of nodes	H	# of nodes	H	# of nodes	VH	# of nodes	VH
Pkt size	S	Pkt size	M	Pkt size	H	Pkt size	NONE	Pkt size	VS
IAT	VH	IAT	VH	IAT	VH	IAT	H	IAT	VH
Output	VL	Output	L	Output	L	Output	M	Output	L
Rule26		**Rule27**		**Rule28**					
# of nodes	VH	# of nodes	VH	# of nodes	VH				
Pkt size	S	Pkt size	M	Pkt size	H				
IAT	VH	IAT	VH	IAT	VH				
Output	L	Output	L	Output	M				

Curriculum Vita

Martha Lucia Torres Lozano obtained her electrical Engineer degree at Universidad El Bosque in Colombia in 1998, her Master Science in Electrical Engineering major in Telecommunications at ITESM (Campus Monterrey, Mx), in 2003 and her PhD in Electrical and Computer Engineering in 2022 at The University of Texas at El Paso (UTEP). She received the Texas Instrument Foundation Grant in six occasions. She participated as an Executive Secretary in Dali Nasa programs review proposals and as Research assistant in Cybersecurity projects at UTEP. In addition, she has experience as a Professor in Colombia and Mexico, and as Teaching assistant and instructor at UTEP, also she worked in the automotive industry for 5 years. Some of her publications are the following:

1. Torres-Lozano, M., González, V.: Optimized Hybrid Model for Making Decision methods in Wireless Sensor Networks., WorldS4, August 2022, London, UK.
2. Torres-Lozano, M., González, V.: From Online to In-person Electrical Circuits Laboratories sessions: Benefits, limitations, and challenges, ASEE Conference 2022, June 2022, Minnesota, USA.
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4. Torres-Lozano, M., González, V.: Hybrid Model for Decision-Making Methods in Wireless Sensor Networks. Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future (SOHOMA-LA, Colombia). doi:10.1007/978-3-030-80906-5_23.

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7. Torres, M., Vargas, C.: Evaluating Connectivity and Quality in Ad-Hoc networks, through Clusterizating and Trellis Algorithms. Conielecomp 2004, Veracruz, México. Computer Society IEEE.

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