

TOWARDS IMPROVING QUALITY OF SERVICE IN INDUSTRIAL NETWORKS: A STUDY ON THE IMPACT OF VARIOUS FACTORS ON PERFORMANCE PARAMETERS

Eng Fidel Ahmad Ibrahim

IT Engineering Department, Faculty of Engineering, Al-Rasheed Private
University

ABSTRACT

Industrial communication networks play a crucial role in ensuring the efficiency and reliability of automated systems. This study presents a practical and simulation-based approach to evaluate the performance of the MODBUS-RTU protocol, one of the most widely adopted industrial protocols. A physical circuit was implemented consisting of two interconnected units— a Master and a Slave—designed to measure key performance parameters such as frame delay and frame rate. In parallel, a simulation model was developed using the OPNET network simulator to replicate the same communication scenario and validate its accuracy. The results showed strong agreement between the real-world measurements and the simulation outcomes, with an error margin not exceeding 0.25%. This confirms both the high performance of the MODBUS-RTU protocol and the reliability of the OPNET simulator for modeling industrial networks. The study further highlights the impact of various factors on network performance, paving the way for future improvements in Quality of Service (QoS) through both experimental and simulation-based methods.

KEYWORDS

MODBUS protocol, industrial network performance analysis, study of factors affecting performance, MODBUS protocol modeling using OPNET, industrial protocol modeling using OPNET.

1. INTRODUCTION

The MODBUS protocol is one of the most popular industrial networking protocols. It has been in use since 1979, enabling millions of industrial automation devices to communicate reliably and efficiently. [1] The MODBUS-RTU protocol is one of the most popular field-bus serial protocols, using the EIA/TIA-485 standard, which allows for multipoint connectivity of up to 247 slave devices. [2] The study and analysis of the behavior of industrial communication protocols is an important topic due to its close connection to the overall performance of the network. Several industrial network test models have been presented to study the impact of various factors on performance parameters with the aim of improving performance. Many modeling tools support the simulation of industrial networks, including the OPNET simulator, which provides many tools in its extensive library for the process of building various types of networks. It allows the ability to model nodes at several hierarchical levels, and also enables the construction of special applications to suit the behavior of the studied protocols. [3] Modelling provides the ability to predict the behavior of network

David C. Wyld et al. (Eds): SIGI, CSTY, AI, NMOCT, BIOS, AIMLNET, MaVaS, BINLP – 2025

pp. 239-253, 2025. CS & IT - CSCP 2025

DOI: 10.5121/csit.2025.151919

communication protocols and enables testing processes that enable safe network expansion and development. Therefore, the choice of a modeling tool is critical to the success of future studies of implemented networks.

2. RESEARCH PROBLEM

- The lack of a practical circuit that operates on the MODBUS protocol and allows for measuring some performance parameters of the industrial network.
- The inability to use the OPNET network simulator to model large industrial networks without first verifying its suitability.

3. RESEARCH OBJECTIVE

- Implement a practical circuit that supports communication using the industrial MODBUS protocol, measure performance parameters, and display them on a computer interface.
- Verify the feasibility of OPNET for modeling industrial networks using the MODBUS protocol by comparing the results.

4. REFERENCES

In the research paper [4], LabVIEW was used to design a control and data acquisition interface consisting of a set of virtual sensors and actuators that provide analog input and output signals. These signals were sent to a set of microcontrollers, which in turn were connected to a programmable logic controller. Through a LAN network, the communication process is managed by the MODBUS-RTU protocol, considering that the microcontrollers represent the dependent devices in the network and the PLC represents the main device. The results showed a slight difference between the virtual and real process with an average absolute error (MAPE) estimated at (5.24%).

The research paper [5] studied several criteria to evaluate the performance of industrial network devices that use the Modbus/TCP protocol. Among the criteria studied were (response time to Modbus requests, the maximum number of requests that can be successfully handled by Modbus devices in a specific time period, and monitoring of Modbus devices when they are exposed to a Distributed Denial of Service attack). Two low-cost practical circuits were used to evaluate the performance of Modbus/TCP.

The research paper [6] dealt with a simplified method for estimating the performance of industrial automation systems in real time using the industrial PROFINET IO protocol. The OPNET network simulator was used to provide two models, the first for PROFINET IO control units and the second for input and output devices. The results showed agreement between the simulation results and the practical results with an error rate not exceeding 3%.

The researchers published the article [7] which shows the implementation process of a practical system that uses the MODBUS protocol in real time. The system consists of three nodes connected via the RS485 bus, one of these nodes is the Master, while the remaining two nodes are Slaves. The practical functions of the MODBUS protocol were programmed and ensured that they meet the real-time requirements without performing performance parameter analysis.

All the previously presented reference studies suffered from ambiguity and lack of clarity in the method of implementing the practical circuits on which the results were based, with the

exception of study [7], which clarified this, but did not pay attention to studying the performance parameters and testing the model ability.

5. MODBUS-RTU PROTOCOL

A type of MODBUS serial line protocol, it is a Master-Slave protocol. This protocol is located at the second layer of the OSI model, as shown in Figure (1).[2]

The Master-Slave system in use contains a single "master" node that issues explicit commands to a "slave" node and processes the responses. Slave nodes will not typically transmit data without a request from the master node.

At the physical level, MODBUS uses different transmission lines for serial bus systems, such as RS485 and RS232, with RS485 being the most common two-wire.[2]

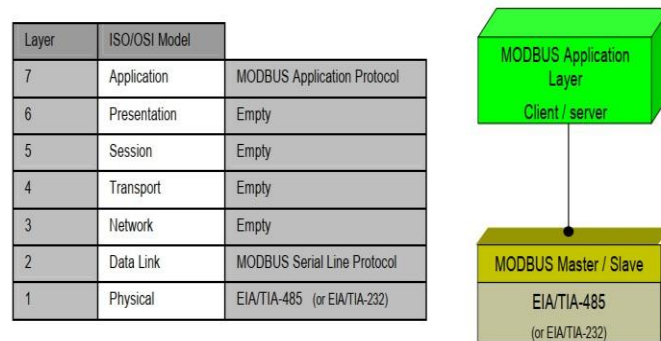


Figure 1. MODBUS protocol layers compared to OSI layers

6. MASTER/SLAVE COMMUNICATION TIMELINE

Figure (2) shows the timeline for three typical Master/Slave communication scenarios.[2]

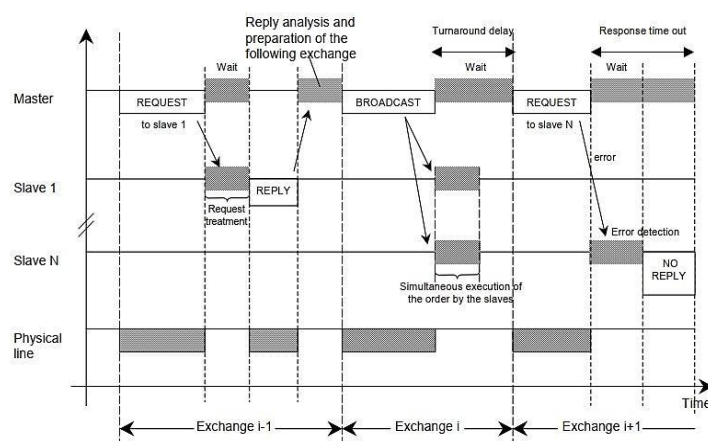


Figure 2. Transmission timeline (Master/Slave)

Scenario 1: The master device sends a REQUEST request to the slave node Slave1, which responds with a REPLY message after a specified period of time. The physical line is busy during the process of sending both the REQUEST and REPLY.

Scenario 2: The master device sends a general BROADCAST request to all slave devices, which respond to the sent request without sending a reply, and the physical line is busy during the BROADCAST transmission process.

Scenario 3: The Master sends a REQUEST to the Slave N, and this request suffers an error that the Slave N detects, so it does not send a response request. When the response delay exceeds the Response Time Out, the Master resends the same request, and the Physical Line is busy during the process of sending the REQUEST.

7. MODBUS RTU FRAME

Figure (3) shows the fields of a MODBUS RTU frame, with a maximum size of (256 Bytes).[2]

Slave Address	Function Code	Data	CRC
1 byte	1 byte	0 up to 252 byte(s)	2 bytes CRC Low CRC Hi

Figure 3. MODBUS RTU frame.

- Address field: It contains only the address of the slave device. The addresses of slave nodes are in the decimal range (0-247). The master device addresses the slave device by placing its address in the message address field. When the slave device returns its response, it repeats placing its address in the response address field to let the master device know that the data arrived at its desired address correctly.
- Function field: Indicates the function code of the client device, i.e., the type of action to be performed.
- Error checking field: The result of a "duplicate check" calculation performed on the message contents.

8. FRAMING MODBUS RTU MESSAGES

A MODBUS message is enclosed by the transmitter in a frame with a known start and end point. This allows devices receiving a new frame to start at the beginning of the message and know when the message is complete. Incomplete messages should be detected and an error should be set as a result.

In RTU mode, message frames are separated by a time interval of at least 3.5 characters, as shown in Figure (4). The time interval is positioned at the beginning and end of the frame, as shown in Figure (4).[2]

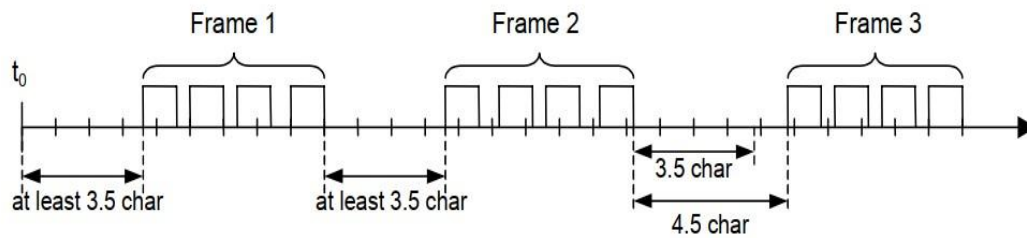


Figure 4. The mechanism of sending frames in MODBUS RTU.

9. PRACTICAL CIRCUIT USING THE MODBUS-RTU PROTOCOL

9.1. Circuit Block Diagram

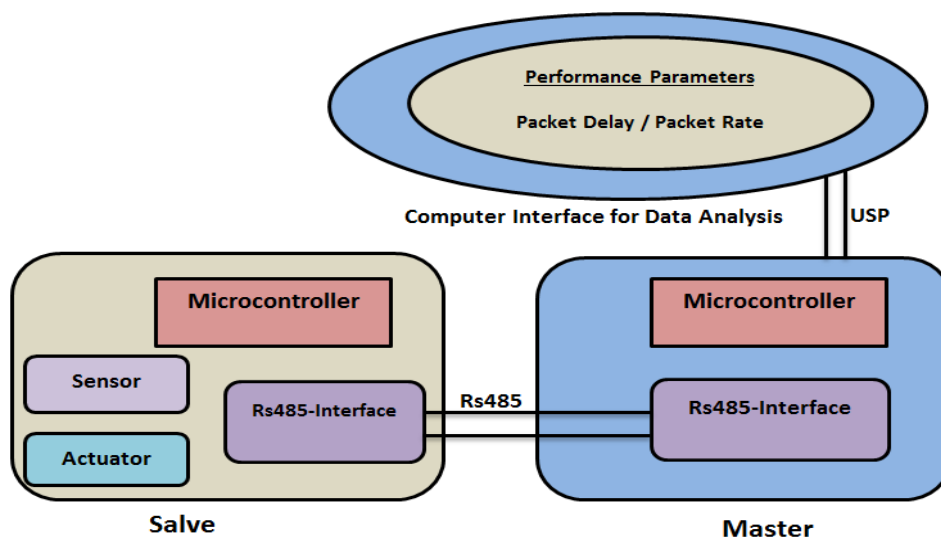


Figure 5. The mechanism of sending frames in MODBUS RTU.

As shown in Figure (5), the circuit consists of two units:

9.1.1 The Master Unit: This unit sends requests to the slave unit using the MODBUS-RTU protocol. We note that it is equipped with a communication port that allows it to be connected to a personal computer equipped with a control and data acquisition interface in order to monitor some performance parameters.

9.1.2 Slave Unit: This unit receives requests sent from the main unit and sends a response according to the type of function required via the MODBUS-RTU protocol. We note that this unit is equipped with a (temperature/humidity) sensor and a (fan) actuator.

9.2. Performance Parameters Studied

9.2.1. Packet delay: This refers to the time required for a frame to travel from the master unit and receive a response from the slave unit. It is measured in seconds (Sec), and is considered one of the most important parameters that reflect the performance of industrial networks and determine the protocol's applicability in real-time systems.

9.2.2. Packet Rate: The number of frames or packets received per unit time. It is also considered an important parameter in determining the performance level of industrial networks, as it is linked to the extent of network utilization and idleness.

10. PRACTICAL DIAGRAM OF THE IMPLEMENTED CIRCUIT

Figure (6) shows the circuit we designed to study the performance of the MODBUS-RTU protocol. Table (1) shows the most important electronic components of this circuit.

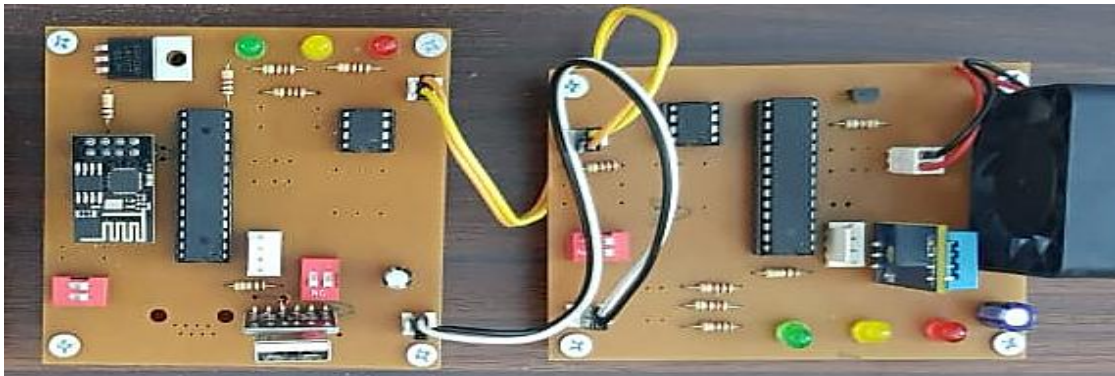


Figure 6. The practical circuit operating on the studied (MODBUS-RTU) protocol.

Table1. Electronic components of the implemented circuit

<i>number</i>	<i>Electronic component of the industrial network</i>	
2	Microcontroller (ATMEGA328p)	1
2	Serial communication module (MAX 485)	2
1	temperature and humidity sensor (DHT11)	3
1	fan	4
1	Transistor (BC337)	5
1	Computer communication unit (CP2102)	6
6	LED indicator	7

10.1. Practical Circuit Control Interface

Figure (7) shows the control interface for the designed system. This interface was implemented using Visual BASIC. The interface allows the selection of the serial communication port with the system, which is set to (COM3). The interface also allows the selection of the communication protocol through the "Connection Mode" drop-down menu. The system also allows you to display the temperature, humidity and frame delay time by clicking the "Temperature Humidity Packet Delay" button. The fan can be turned on and off using the "Fan On" and "Fan Off" buttons. The number of packets per second can be calculated using the "Packet rate Calculation" button, and the program can be exited using the "Exit" button.

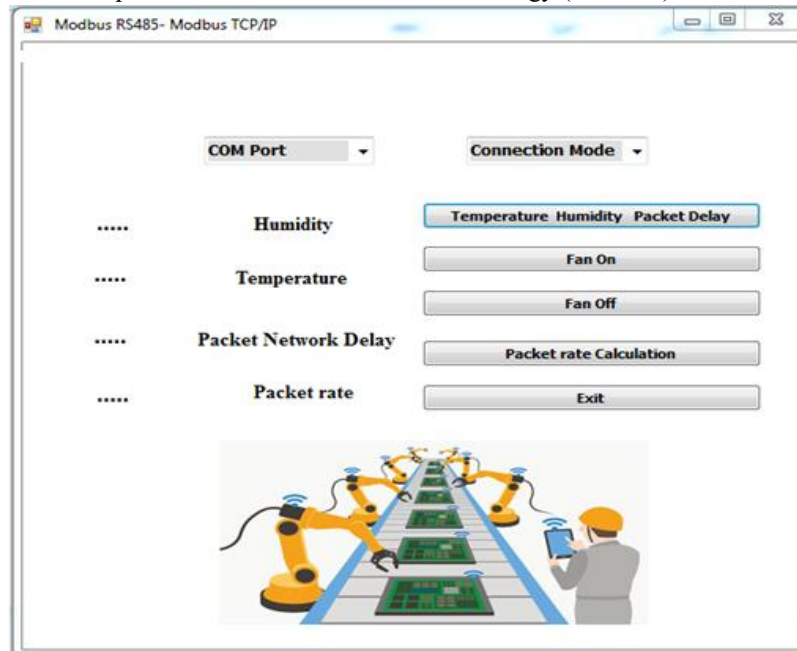


Figure (7) Control interface of the designed system

10.2.Results for the Implemented Practical Network

First case: A command was sent to activate a temperature/humidity sensor. Performance results showed that the average frame delay time ranged around (Packet Delay = 0.06 [MS]) and that the average frame rate per second was (Packet rate = 1050 [Packet/s]). The results demonstrate high performance due to the short delay time and high frame transmission rate, as shown in Figure (8).

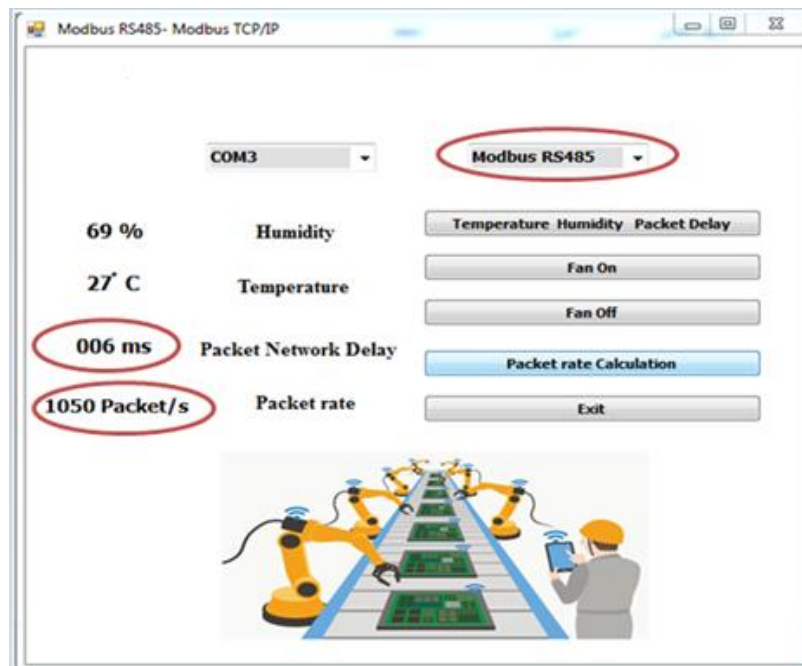


Figure 8. Operating the practical circuit and taking readings of some performance parameters

11. VERIFYING THE OPNET SOFTWARE'S SUITABILITY FOR SIMULATING INDUSTRIAL NETWORKS

The OPNET network simulator is a very suitable environment for building computer networks, as it contains all the necessary components for building these networks and also supports all the protocols, services, and applications required to describe the mechanism of data transfer between these components.

What distinguishes the OPNET program is that it is an open source environment, meaning that new network components can be added to its own library prepared for use, and it also supports making modifications to the properties of existing nodes in a manner that is appropriate to the case being studied.[3]

11.1. OPNET Test Network Model

Figure (9) shows the test industrial network model, which consists of two nodes (Master & Slave) connected by an RS485 bus. The data exchange process is managed by the industrial MODBUS protocol, whose properties are defined through the components (Task, Application, and Profile). The following are the properties of each component in the designed network:

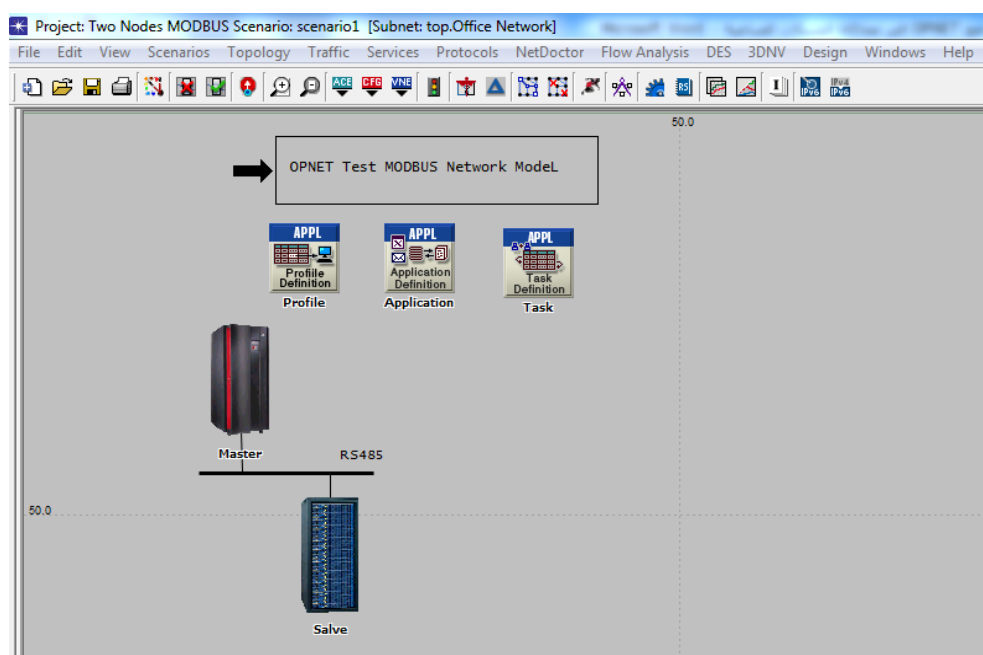


Figure 9. Test industrial network using OPNET

11.1.1. Task Icon Properties

OPNET allows building custom applications through this icon, and by accessing its properties, you can manually set a complete description of the desired application through “Manual Configuration”. The properties of the frames exchanged between the nodes were set in a manner consistent with the properties of the MODBUS protocol, as shown in Figure (10), where we note that the size of the frames sent is 8 bytes and the time between frames is estimated at (1.75 ms), and other values determined by “The Modbus Organization”. [1]

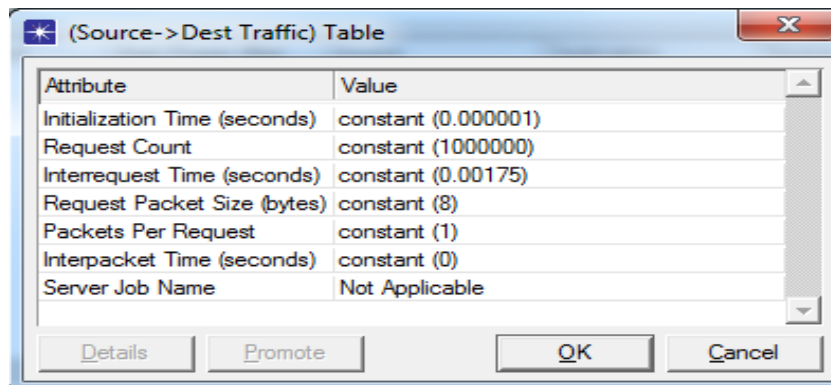


Figure (10): Characteristics of exchanged frames according to the MODBUS protocol.

11.1.2. Properties of The Application Icon

It allows modeling applications according to the studied industrial network and the MODBUS communication protocol used. Six models were modeled that are supported by the MODBUS protocol and differ from each other by the title of the request function sent from the main node “Master” to one of the slave nodes “Salve” as shown in Figure (11):

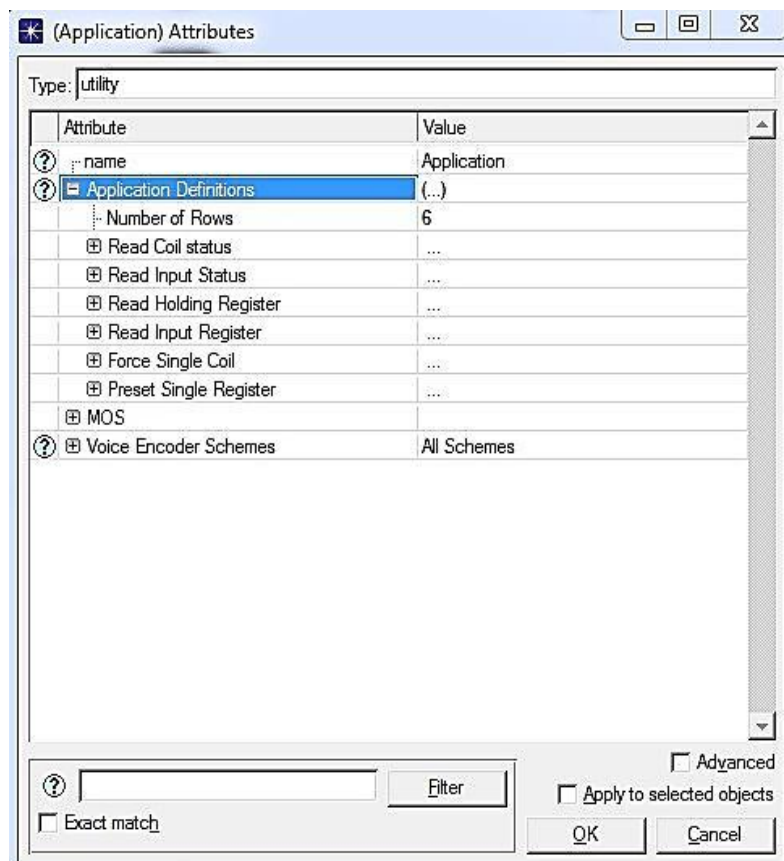


Figure (11): Applications used in the industrial MODBUS network

11.1.3. Node Properties (Master)

It is of the “workstation” type. This type allows the node to specify the desired profile. Through its “Attributes” properties, the “Modbus” profile specified in the “Profile” icon was specified, and the “Application: Supported Profiles” property was placed on “MODBUS Profile” as shown in Figure (12).

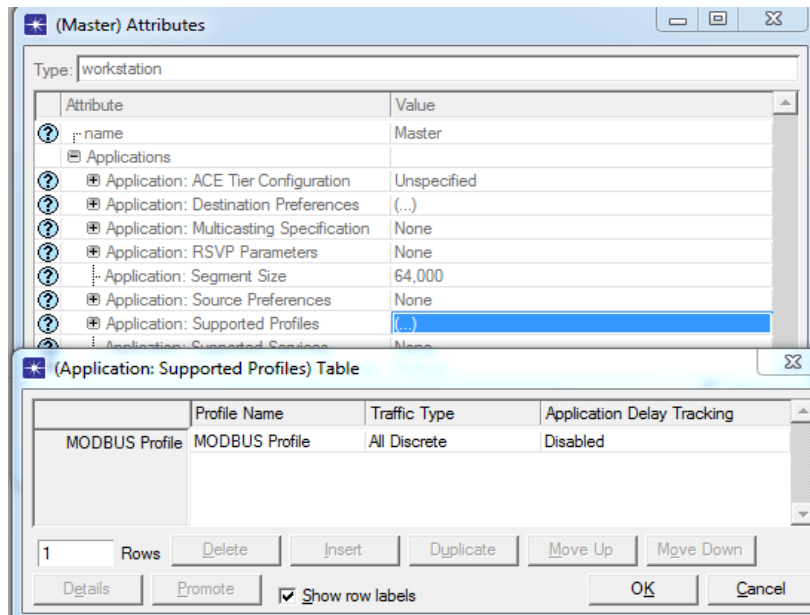


Figure (12): Master node properties in OPNET

11.1.4. Node Properties (Salve)

It is also of the “workstation” type. This type allows the node to specify the desired profile. Through its “Attributes” properties, the “Modbus” profile specified in the “Profile” icon is specified. The “Application: Supported Services” property was set to “MODBUS Profile”, and the “Application: Destination Preferences” property was set to “Office Network: Master” so that the master device would be the transmission destination for the slave device when responding to the request, as shown in Figure (13).

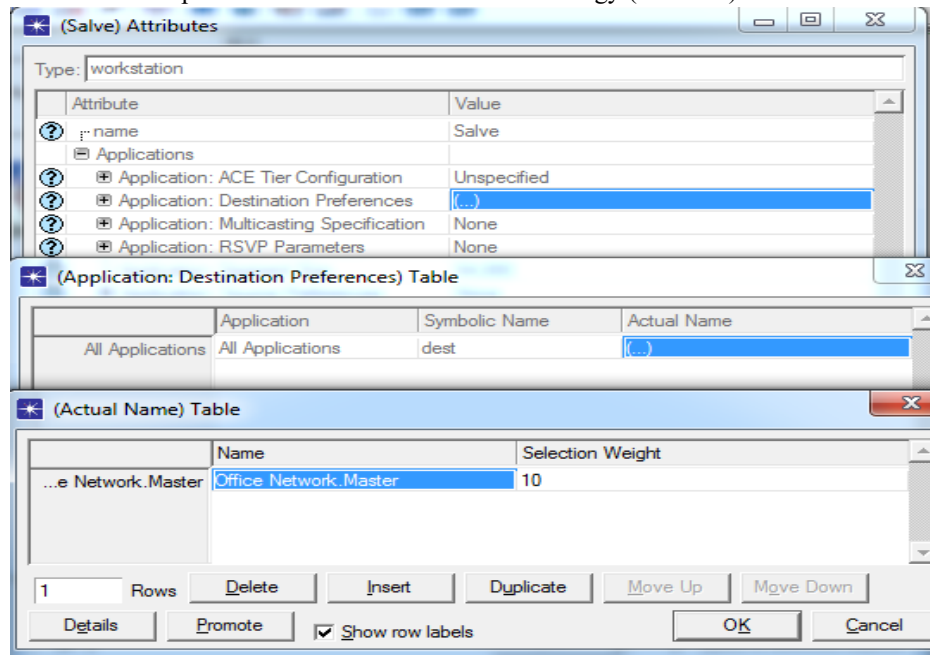


Figure 13. Properties of the Salve node in OPNET

11.1.5. Bus Characteristics (RS485)

It is the main bus in the MODBUS network, and its type has been identified as "Coax-adv", and this type provides several features through which we can monitor many important parameters such as (frame delay time, productivity, utilization) and other important parameters related to the overall performance of the network. The following are the features that have been set for this bus to represent the characteristics of the RS485 bus used in industrial MODBUS networks.

- ✓ The (ber) attribute was set to (10^{-6}) .
- ✓ The (data rate) attribute was set to (19200 bps).
- ✓ The (delay) attribute was set to (0.0001) seconds.
- ✓ The (packet format) attribute was set to (Modbus).
- ✓ The (thickness) attribute was set to (2) mm.

11.1.6. MODBUS Frame

The OPNET program allows you to create a frame for a specific communication protocol. A MODBUS frame is created according to the following steps:

- From the "File" menu, select "New," then select the "Packet Format" frame editor. From the window, select "Create New Field."
- We create a MODBUS frame consisting of four fields, as shown in Figure (14).



Figure (14): The four MODBUS frame fields in the OPNET program.

- We edit four fields and then specify the properties of each field “attribute” as in Figure (15), which shows the properties of the “Address” field.

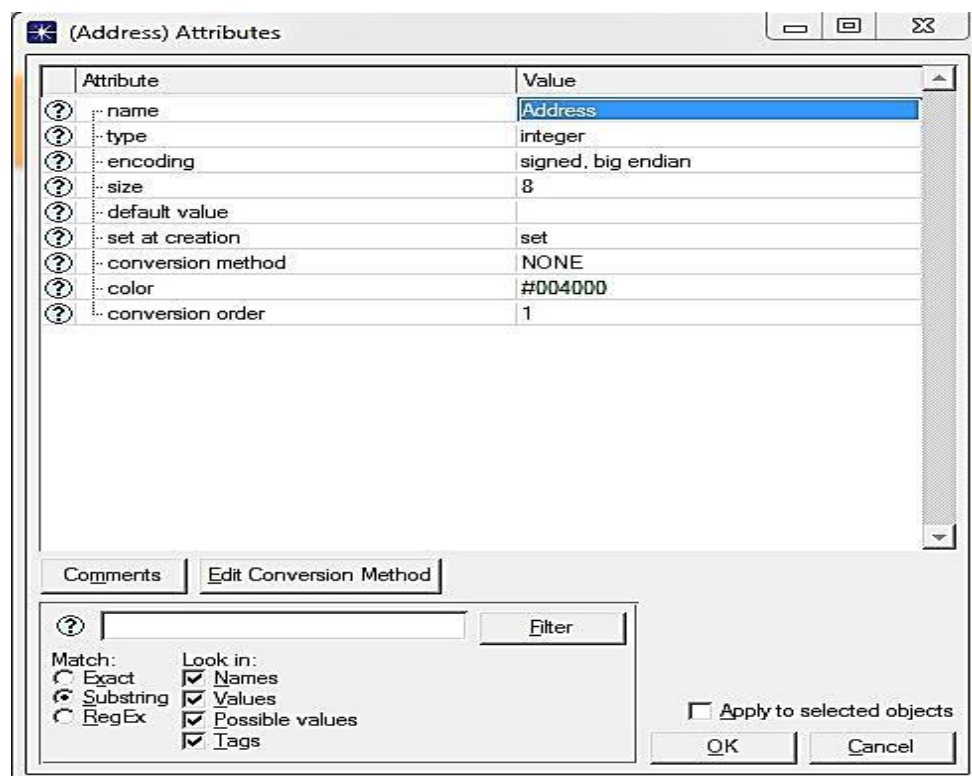


Figure (15): Properties of the “Address” field in the MODBUS-RTU frame

Note: The "Address", "Function Code" and "CRC" fields are all of the same property type, they are all of the type "integer" and differ only in size depending on the properties of the MODBUS protocol.

- For the "Data" field, set the "Type" property to "Packet" and then select "Inherited." The "Inherited" option allows you to set the field size to the actual data size according to the application being used. The "encoding" is set to "signed.big endian," which preserves the sequence of the data sent at the receiving end.
- Save the frame with the name "Modbus." Then, return to the RS485 bus properties and set the "Packet Formats" property to "Modbus," making it "supported."

12.PARAMETERS RELATED TO THE PERFORMANCE OF THE INDUSTRIAL TEST NETWORK

1. Packet Network Delay: This is a Global Statistics type and represents the time required to send a request and receive a response. The delay time is measured between the moment the master node sends the request to the slave node (Salve1) and the moment the response is received. This time delay is measured in seconds and is inversely proportional to network performance. As it decreases, performance increases.
 2. (Traffic Received): This is of the (Node Statistics) type and represents the number of packets received by a node per unit of time. It is estimated as [Packets/Sec] and is directly proportional to network performance. As it increases, performance increases.
- The simulation was run for (100) seconds, and we obtained Figures (16) and (17).

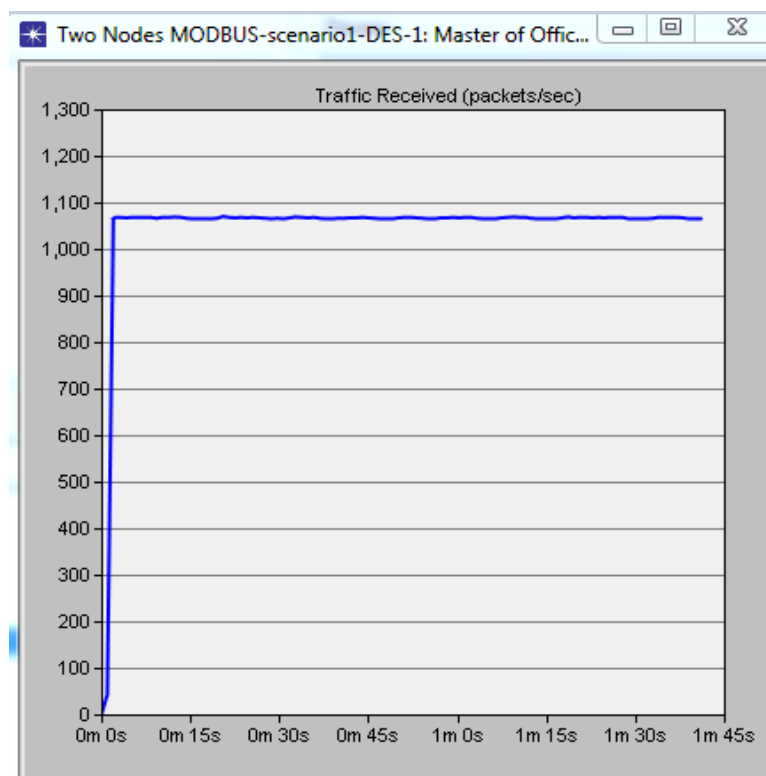


Figure 16. Number of packets received at the main node in one time.

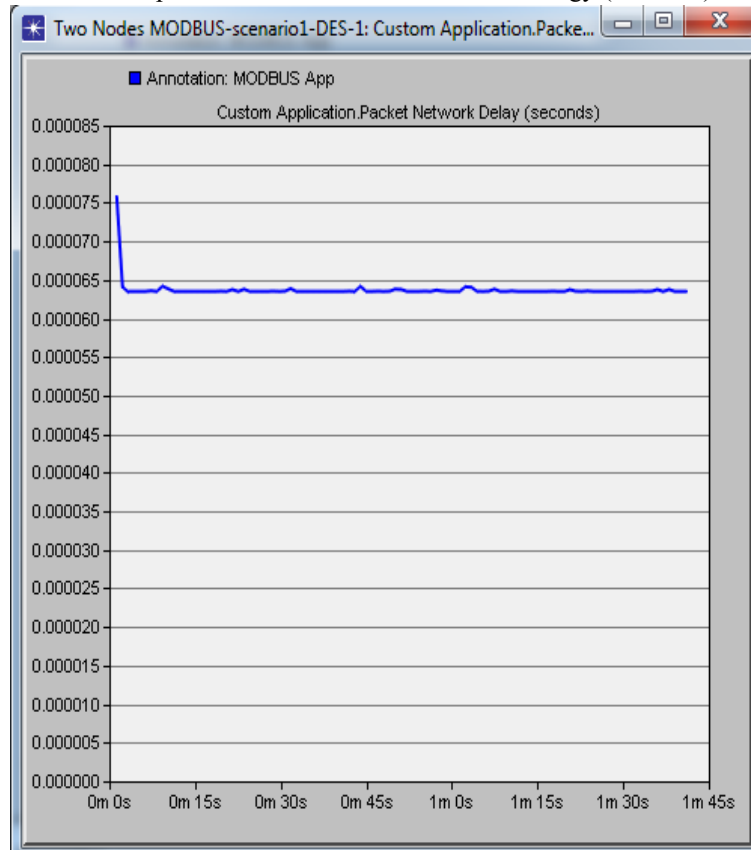
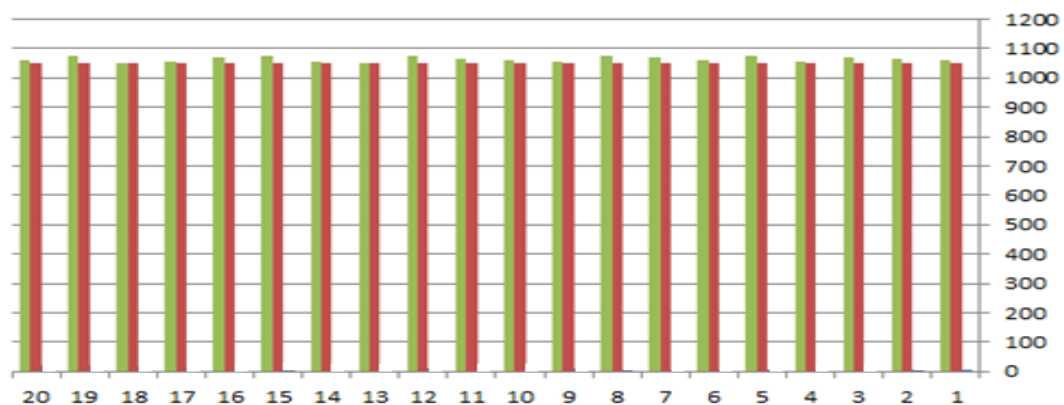


Figure 17. Time delay of the transmitted frame.

13.MODEL VERIFICATION RESULTS

By comparing the results we obtained in the simulation using the OPNET program with the results of the practical circuit, we note a high degree of consistency with an error rate not exceeding 0.25%, confirming the validity of the designed model and the suitability of the OPNET program for simulating industrial networks. This makes it easier for us to later build networks with more nodes, change factors affecting performance parameters, study the impact of these changes on performance, and thus improve the quality of service for the industrial network under study.



14. RECOMMENDATIONS AND FUTURE PROSPECTS

- Implement practical circuits to compare the performance parameters of other industrial protocols.
- Study other factors affecting performance parameters through modeling.
- Use the OPNET program to model realistic networks and study and analyze their performance.

REFERENCES

- [1] MODBUS APPLICATION PROTOCOL SPECIFICATION ,V1.1b3, April 26, 2012. Available at https://modbus.org/docs/Modbus_Application_Protocol_V1_1b3.pdf
- [2] MODBUS over serial line specification and implementation guide V1.02. Available at https://modbus.org/docs/Modbus_over_serial_line_V1_02.pdf
- [3] LU YANG,H2012-Unloking The Power of OPNET Modeler. CAMBRIDGE, UK, 253p.
- [4] Mangkalajan.S, Koodtalang.W, Sangsuwan.T and Pudchuen.N,2019 - Virtual Process Using LabVIEW in Combination with Modbus TCP for Fieldbus Control System. IEEE International Conference on Control System, Computing and Engineering ,Penang, Malaysia.p 21-24
- [5] Gamess.E, Smith.B, and Francia.G,2020-PERFORMANCE EVALUATION OF MODBUS TCP IN NORMAL OPERATION AND UNDER A DISTRIBUTED DENIAL OF SERVICE ATTACK. IJCNC, Florida,US, Vol.12, No.2,21p.
- [6] P. Ferrari, A. Flammini, D. Marioli, A. Taroni and F. Venturini,2007- New Simulation Models to Evaluate Performance of PROFINET IO Class 1 Systems. IEEE, University of Brescia, Dept. of Electronics for Automation,Brescia, Italy,p 237-242
- [7] Shukla.P ,Singh.S , Joshi.T, Kumar.S, Kelkar.S , Das.M, 2017- Design and Development of a MODBUS Automation System for Industrial Applications, IEEE, Bengaluru, India,p 515-520