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FINAL YEAR PROJECT THESIS

EMBEDDED ETHERNET SYSTEM FOR REAL-TIME COMMUNICATION

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BY

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF ABBREVIATION

BEB	Binary Exponential Backoff
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CRC	Cyclic Redundancy Check
CHAP	Challenge Handshake Authentication Protocol
CW	Contention Window
EIED	Exponential Increase Exponential Decrease
EEE	Energy Efficient Ethernet
FPGA	Field Programmable Gate Array
HOL	head-of-line
HIMD	Harmonic-Increase and Multiplicative-Decrease Adaptation
LMILD	Linear/Multiplicative Increase Linear Decrease
LAN	Local Area Network
MAC	Media Access Control
MTU	Maximum Transmission Unit
MAU	Medium Attachment Unit
MBEB	Modified Binary Exponential Backoff
MANET	Mobile Ad Hoc Network
PAP	Password Authentication Protocol
RTC	Real-Time Communication
TCP/IP	Transmission Control Protocol/Internet Protocol
TDMA	Time-Division Multiple Access
WLAN	Wireless Local Area Network

SISTEM ETHERNET EMBEDDED UNTUK KOMUNIKASI MASA NYATA

ABSTRAK

Komunikasi masa nyata (RTC) menunjukkan penghantaran data antara dua medium yang berlaku dengan mengurangkan kelewatan. Terdapat dua jenis komunikasi masa nyata seperti komunikasi masa nyata ringan dan komunikasi masa nyata berat. Sebuah fungsi rangkaian Ethernet berdasarkan (CSMA/CD) sebagai protokol kawalan akses media (MAC) untuk menghantar data antara medium berkongsi. Selain itu, backoff algorithm adalah sebahagian daripada MAC protokol yang digunakan untuk menghantar semula paket selepas berlaku perlanggaran. Model rangkaian Ethernet diubahsuai berdasarkan bilangan nod dan backoff algorithm seperti Binary Exponential backoff (BEB), Modified Binary Exponential backoff (MBEB), Exponential Increase and Exponential Decrease backoff (EIED) dan Linear/Multipicative Increase and Linear Decrease backoff (LMILD). Model rangkaian Ethernet digunakan untuk menganalisis prestasi backoff algorithm mengikut bilangan nod. MATLAB, Simulink dan Stateflow digunakan untuk simulasi rangkaian Ethernet. Selain itu, EIED backoff algorithm menunjukkan prestasi yang baik dalam mengurangkan masa kelewatan penghantaran paket berbanding dengan backoff algorithm yang lain.

EMBEDDED ETHERNET SYSTEM FOR REAL-TIME COMMUNICATION

ABSTRACT

Real-time communication (RTC) indicates the transmission of data or message between two medium that occur with minimum delay or latency. There is two type of real-time communication such as soft RTC and hard RTC. A common Ethernet network functions based on the carrier sense multiple access with collision detection (CSMA/CD) as the media access control (MAC) protocol for data transmission between shared medium. Moreover, a backoff algorithm is the part of MAC protocol which implements for rescheduling the transmission of a packet after a collision occurs. An embedded Ethernet network model is modified with a different number of nodes and backoff algorithms such as Binary Exponential Backoff (BEB), Modified Binary Exponential Backoff (MBEB), Exponential Increase and Exponential Decrease Backoff (EIED) and Linear/Multiplicative Increase Linear Decrease Backoff (LMILD). The Ethernet network model is used to analyze the performance of the backoff algorithm in a different number of nodes. The end delay of each packet, the number of packet collision and number of packet delivered are determined based on the analysis. MATLAB, Simulink, and Stateflow are used for the Ethernet network model simulation. Based on the simulation, EIED backoff algorithm gave better performance in term of average delay compare to other algorithms. In this case, EIED shows 0.0006257s average delay in 5 nodes, 0.0006252s average delay in 10 nodes and 0.0006260s average delay in 20 nodes.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This project is about the real-time communication (RTC) which is divided into categories such as soft real-time communication and hard real-time communication. Soft RTC is related to transmit and receive data which did not cause any fatal failures although there are some delay in the performance of the system. For Hard RTC, the transmitting and receiving of the data must perform within a specific time without any delay which cause fatal failures. Emails and messages do not cause any fatal to the user if there are latency and it is considered as soft RTC. The anti-lock braking system, Electronic Stability Control and Brake Assist in automotive are considered as hard RTC which cause death to the driver or passenger when there are failure in the system. The real-time communication system consists of the embedded sensor network and their application. Besides, the sensor network consists a large number of nodes which need to adapt to the environment for future work [1].

Embedded system is an electronic system which integrates hardware with software programming technique for project solutions. The embedded system is classified into two categories which are shown in Figure 1.1:

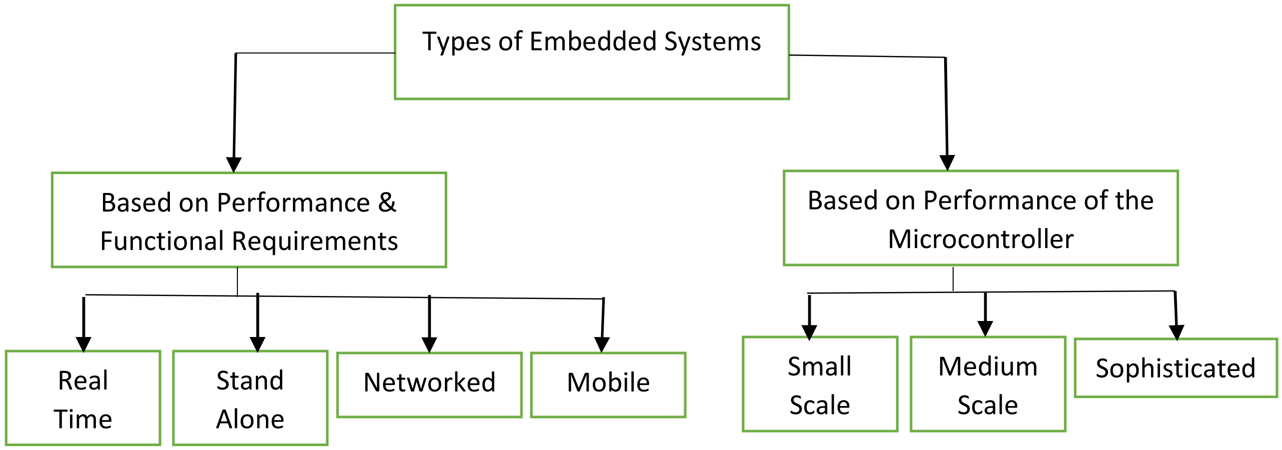

Figure 1.1: Classification of Embedded System

Moreover, the embedded system consists of sensor and actuator which work together to accomplish given task. The sensor used to detect changes in the environment while the actuator reacts to the response of the sensor. The embedded network system refers to the networking and communication which response to the real-time applications. Ethernet which refers to IEEE Std 802.3 standard was first published in the year 1985 which was specified by a half-duplex carrier sense multiple access with collision detection (CSMA/CD) medium access control (MAC) protocol operating at 10Mbps. Similarly, the medium attachment unit (MAU) such as coaxial cable medium and bus topology needs for the end station connection [2]. The Ethernet is not able to perform well in the RTC due to collisions which fail to deliver information at a specific time. Ethernet has been improved to Switched Ethernet which eliminates frame collision and minimizes the latency. Furthermore, the Switched Ethernet becomes a better choice to substitute the Fieldbus such as Process Field Bus (PROFIBUS) and controller area network (CAN) because of low in cost, ease of installation and easy handle of the system [3].

Moreover, backoff algorithm plays an important role in the Ethernet network. When a collision occurs during the transmission, the backoff algorithm is used to reschedule the retransmission of the data. Binary Exponential Backoff (BEB) is a commonly used backoff algorithm in the Ethernet [4, 5]. Besides, a different type of backoff algorithm gives different performance and analysis on the same network model in term of time delay which is related to the RTC [6].

1.2 Problem Statement

The Ethernet becomes the preferable choice for the real-time communication applications because of its own benefits such as expandability, robustness and self-configuration capability. Besides, it is very important to study about Ethernet to enhance the performance of real-time communication. The main purpose of this project is to examine the different type of backoff algorithm which might enhance the performance of Ethernet. In [7], BEB and linear algorithm were used in the simulation of Ethernet network model to study its performance under certain criteria. So, some of the backoff algorithms of wireless local network area (WLAN) is proposed for the Ethernet [8-10]. It is applied to the Ethernet network model to identify the performance of Ethernet (LAN). There are some problems and issues highlighted in this project which are shown below:

1. How to modify and construct the given embedded Ethernet network model for our simulation?
2. How the proposed backoff algorithms perform in the embedded Ethernet network model?

3. How is the backoff algorithms affect the performance of the embedded Ethernet network model with a different number of nodes?

1.3 Objectives

1. To model the half-duplex CSMA/CD embedded Ethernet network model with a different number of nodes for simulation.
2. To implement a different type of backoff algorithms and identify the performance of embedded Ethernet network model.
3. To investigate the performance of different backoff algorithms and the number of nodes in the embedded Ethernet network model in term of delay.

1.4 Project scope

This project is carried out based on the software simulation method. The MATLAB software is used by Simulink, Stateflow and MATLAB function for this project. The embedded Ethernet network model is modified and constructed with a different number of nodes using Simulink with suitable block diagrams. Then, the backoff algorithm is implemented in the Ethernet network model using Stateflow and MATLAB function which is integrated into a block diagram. The performance analysis of the Ethernet network model compared with the different aspects such as throughput, channel utilization, packet delay, packet collision and packet delivered. Besides, the different type of backoff algorithms are simulated and analyzed with the different number of nodes of Ethernet network model to indicate the improvement of the performance.

1.5 Thesis Outline

The thesis is divided into five main chapters which explain the whole project flow. The first chapter describes the introduction of real-time communication and Ethernet network. Similarly, problem statement, objective, project scope and project outline are also included in the first chapter. Then, the software used for this project is also mentioned briefly in this chapter.

The second chapter explains the literature review that are studied for this project. The literature review usually stated the past research details that related to this project which used for further development. The type of real-time communication, communication protocol, protocol layering and backoff algorithm such as MBEB, LIMILD and EIED are discussed in this chapter.

The third chapter describes the methodology of the project. The method and project flow are noted and explained in this chapter. Besides, this chapter is very vital because other researchers can continue developed this project or make this project as a reference to improve the similar project. Furthermore, the modified and reconstructed embedded Ethernet network model is briefly elaborated with the Simulink block diagram to fulfil the above purpose.

The fourth chapter explains the result of the project based on the Simulink analysis. The gathered results from the simulation are shown in graph form for further discussion of the analysis. Then, the performance of backoff algorithms is compared under different conditions.

The fifth chapter elaborates about the conclusion of this project after the discussion of results. The final findings and future works are stated in this chapter for further improvement of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The basic and fundamental information about this project is further explained in this chapter. Then, the related researches are also revised in this chapter. In section 2.2, the basic concept and knowledge of real-time communication are discussed. In section 2.3 and 2.4, the communication protocol and protocol layering of the network are elaborated. Moreover, the Ethernet and Switched Ethernet has been discussed in section 2.5 and 2.6 respectively. In section 2.7, the CSMA/CD media access protocol is explained briefly to understand the transmission process. Then, different type of backoff algorithms are discussed in section 2.8. The concept delay and jitter are explained in section 2.9 and the summary of this chapter is placed in the section 2.10.

2.2 Real-Time Communication

The real-time communication is divided into three main categorize such as hard real-time communication, soft real-time communication and non-real-time communication. The real-time communication is emphasized the keyword low latency and time constraints which indicate the data is delivered within a specific time period. The real-time communication supports half-duplex and full-duplex transmission. Figure 2.1 shows the data transmission of half-duplex and full-duplex.

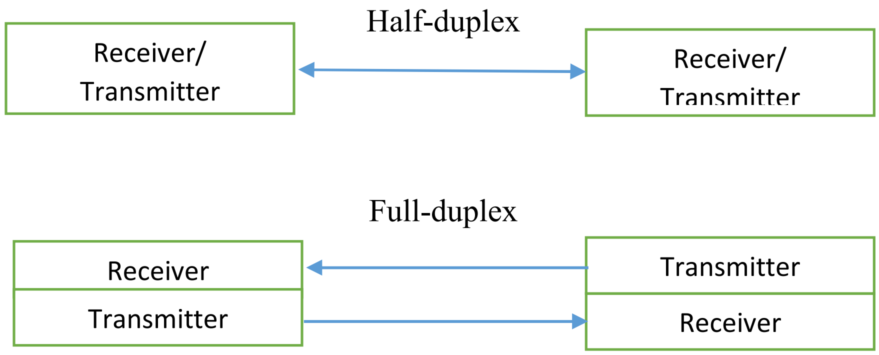

Figure 2.1: half-duplex and full-duplex transmission

The half-duplex system can transmit and receive data at the different timing through a single channel while the full-duplex system can transmit and receive data at the same time through a single channel.

In [11], the deterministic real-time communication of Switched Ethernet is explained. The Ethernet has non-deterministic character that known from the nature of its collision recovery mechanism which shows moderate performance during heavy load traffic. Then, the deterministic behaviour of Ethernet can achieve by eliminating the random CSMA/CD arbitration. Therefore, the Ethernet switch technology is used to improve the Ethernet by dividing the collision domain into the simple one-to-one connection between network components to stations. So, usage of backoff algorithm is not required for the Ethernet switch technology as mention above. This supports transmission and enhances the traffic capability of the Ethernet. Moreover, there are many network topology is used for the Switched Ethernet but the star and line topology are given importance in this paper. The star topology is simplest topology which is used only one switch and it is used maximum cabling for industrial applications. Initially, Fieldbus system designed with star topology to change the parallel cabling of sensors and actuators. Furthermore, line topology is designed by assigning every switch to one device which reduces cabling cost and infrastructure. Besides, line topology consists of large number of switches which not suitable for real-time response.

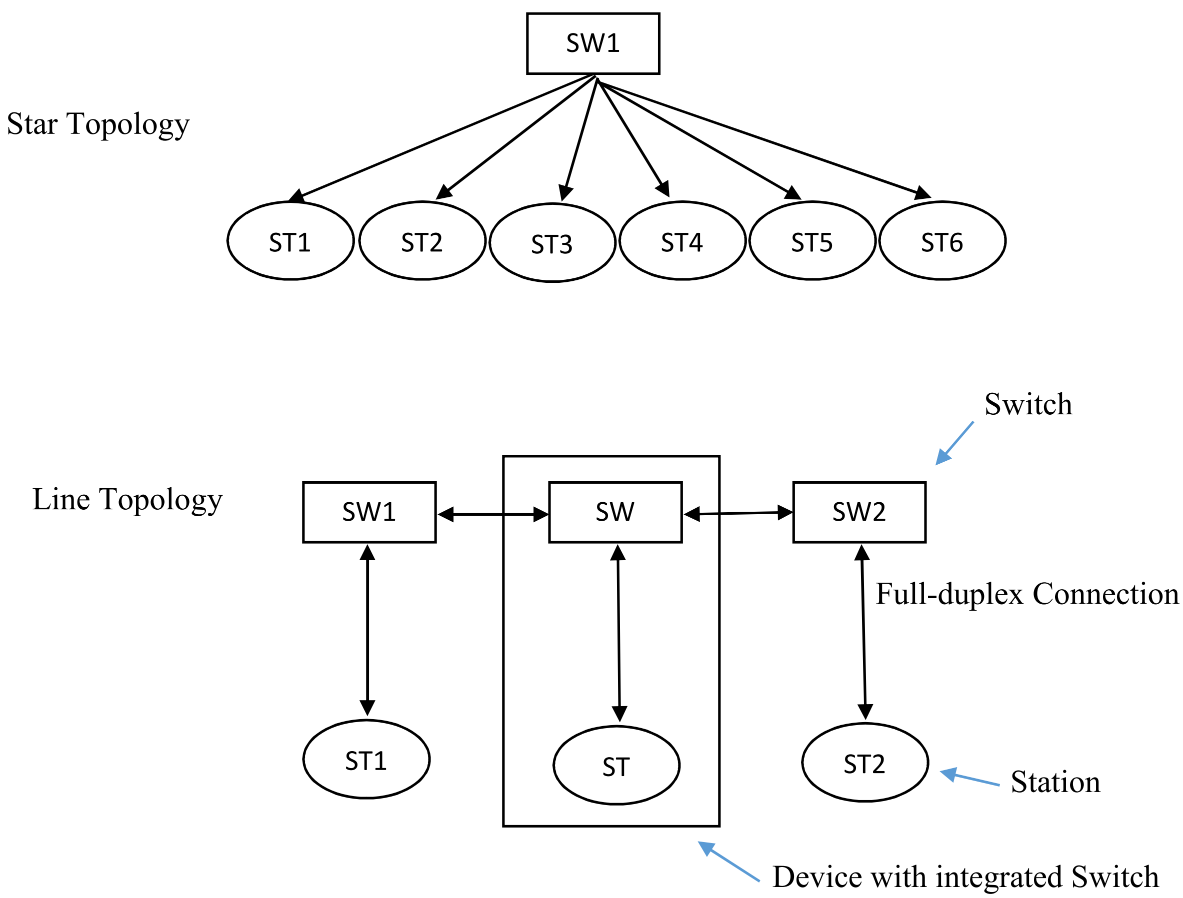

Figure 2.2: Star and Line Topology [11]

The real-time capability of the Ethernet depends on the specification of a technical process. Meanwhile, the transmission time for 50 devices within milliseconds on the medium access control could achieve the real-time capability [11].

The Ethernet has an unbalanced delay with the 1-persistent CSMA/CD protocol. When the real-time and non-real-time packets are transferred over the same Ethernet, the real-time packets undergo larger delay. This is because the non-real-time packets are dominated by the real-time packets in the node and collision between real-time packets and a non-real-time packets from different nodes. This problem can solve using the adaptive traffic smoothing as mention in [12]. The traffic smoother is assembled between the TCP/IP layer and the Ethernet MAC layer. This makes sure the real-time packets are given first priority than a non-real-time packet in order to reduce contention and collision in the same and different nodes respectively. The traffic smoother also provides acceptable non-real-time throughput and traffic generation rate which adapt to the different network load condition. Moreover, the adaptive-rate traffic smoother varies the station input limit at each local node based on the network traffic arrival rate.

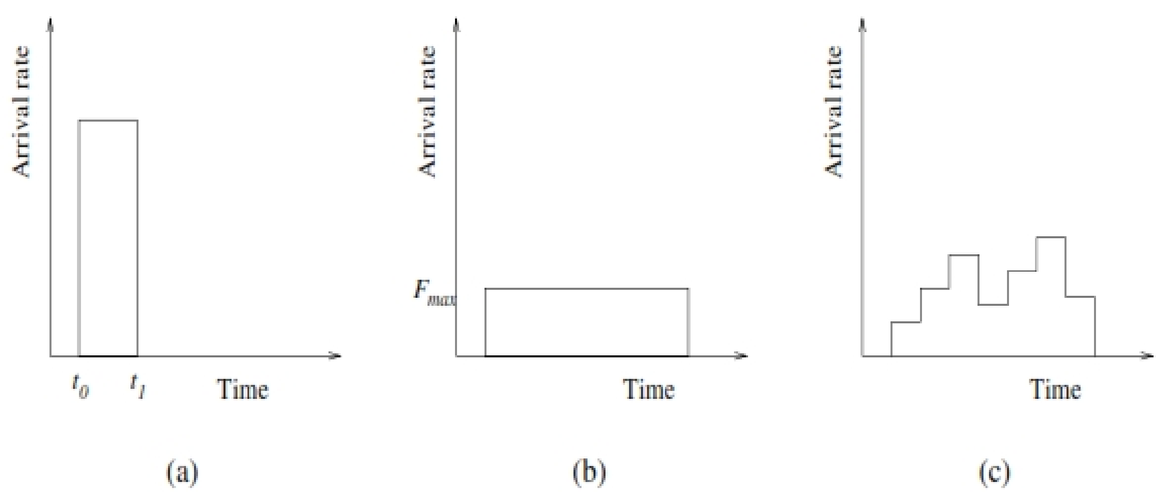

Figure 2.3: Traffic smoothing [12]

Figure 2.3(a) indicates the short traffic arrival duration and high arrival rate from a burst Transmission Control Protocol (TCP) window. Figure 2.3(b) shows arrival rate has been smoothed by the fixed-rate traffic smoother and input station limit set to the F_{max}. Then,

Figure 2.3(c) indicates arrival rate has been smoothed by an adaptive-rate traffic smoother which forms piece-wise constant function of time. The adaptive-rate traffic smoother functions with the fixed-rate traffic smoother but station input limit varies with time. The adaptive traffic smoothing is implemented using a mechanism called Harmonic-Increase and Multiplicative-Decrease Adaptation (HIMD). Figures 2.4 and 2.5 show the procedure of traffic smoothing and refreshing parameter which initializes a system.

```
Procedure smoothing
If (Packet.TypeOfService = RealTime) then {
        send_to_NIC;
        CurrentNetworkShare := CurrentNetworkShare
        −Packet.FrameSize;   }
else if (LastCollisionTime ≥ CurrentTime − α) then {
        send_back_to_queue;
        CurrentNetworkShare := 0;
        RP = min(RP_max, 2 × RP); }
else if (CurrentNetworkShare > 0) then {
        send_to_NIC;
        CurrentNetworkShare := CurrentNetworkShare
        −Packet.FrameSize; }
else send_back_to_queue;
```

Figure 2.4: Procedure of traffic smoothing [12]

```
Procedure refresh
RP := max (RP_min, RP − Δ);
if (CurrentTime = NextRefreshTime) then {
        CurrentNetworkShare
        := min(CurrentNetworkShare + CBD, CBD);
        NextRefreshTime := CurrentTime + RP; }
```

Figure 2.5: Procedure of refreshing parameter [12]

2.3 Communication Protocol

The communication protocol can elaborate as transmitter and receiver must work together to create an effective communication environment. There are three elements must be considered in the communication protocol such as syntax, semantic and timing. The syntax is a framework or format of the data. Then, the semantic indicates each segment of the bits. The timing is related to the period of data transmission within a specified bandwidth. The communication protocol briefly explained the following criteria as shown below [13]:

- Data Routing.

  The main purpose of the data routing is to identify the effective path between a source and destination. The routers are used when the source and destination did not connect directly to each other. This connecting network is known as internetworking which aid the source and destination communicate to transfer data.

- Data Formatting.

  The data formatting is a group of bits which represents a packet which consists of data, control and addressing. Basically, a packet categorizes into two parts such as header area and a data area. The data area carries actual information while the header area carries the information of communication protocol.

- Data Sequencing.

  The data sequencing is used to detect the lost packets or duplicate packets by the receiver. If a packet longer than maximum transmission unit (MTU), the packets are separated into small parts before transmitting on the network. Sometimes, the separated packets may get loss or delay during the packets transmitting to the destination. Similarly, the separated packets travel in a different path to reach destination due to network criteria and environmental changes which lead the packets out of sequence. So, the data sequencing is vital to detect loss packets or duplicate packets during the transmission occur.

- Flow Control.

  The flow control is used to ensure data transmission and protect from the heavy network traffic load by modulating the flow of data on the channel. This can be justified when flow control notifies the transmitter about the overwhelming of incoming packets at the destination. Thus, transmitter pauses the transmission of data.

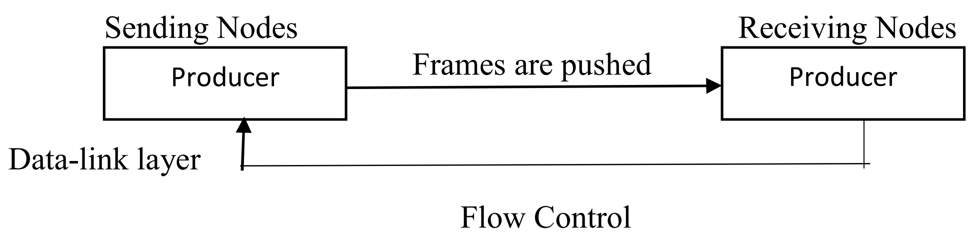

Figure 2.6: Flow control at the data link layer

- Error Control

  The error control is used to detect or identify the errors in a data. This error control can be applied using cyclic redundancy check (CRC) at end of a packet. The receiver can notify the data error by detecting the differences at CRC and inform transmitter for retransmission of data.

- Precedence and order of transmission

  The precedence and order of transmission known as medium access control which directs the nodes for transmitting data and receiving data from other nodes. This makes sure all the nodes involved in the transmitting and receiving data process, especially for the half-duplex system. Figure 2.7 shows types of media access control protocol.

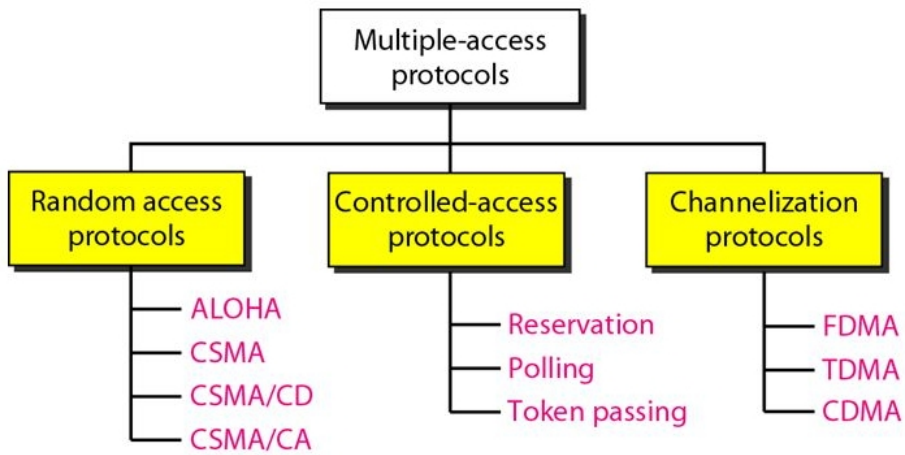

Figure 2.7: Type of Media Access Control [13]

- Connection establishment and termination

  Before the transmission begins, the connection of one node to other must be established first. After the transmission ends, the related connection for transmission must be terminated. Figure 2.8 shows an example of connection establishment and termination.

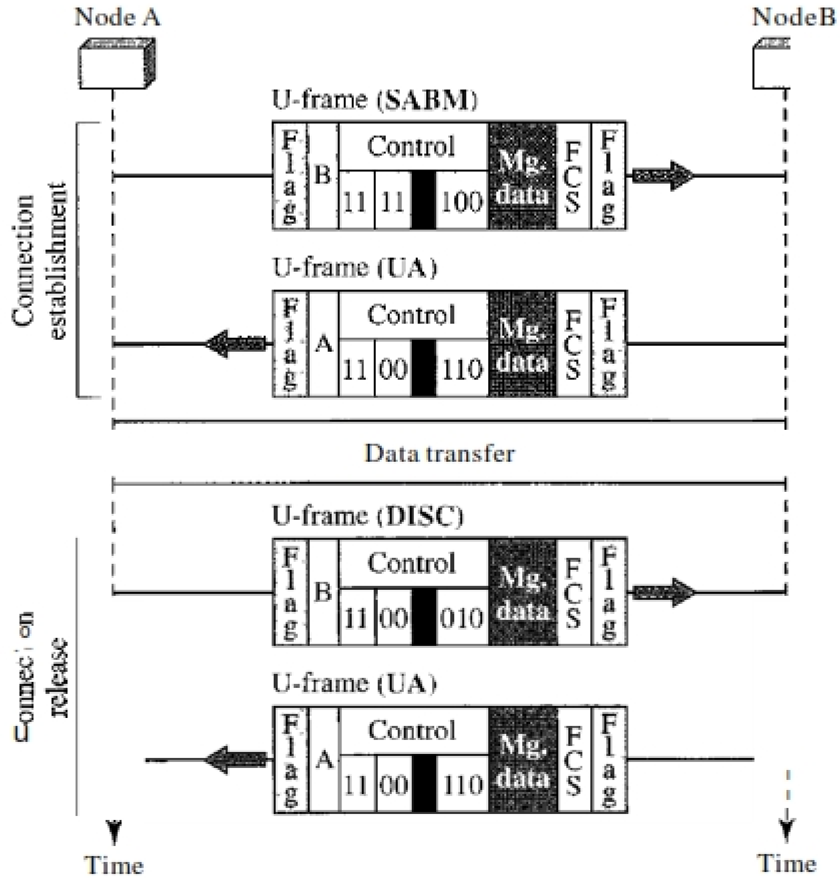

Figure 2.8: Example of connection establishment and connection [13]

- Data Security

  The data security is used to protect data from the unauthorized users. The Challenge Handshake Authentication Protocol (CHAP) and Password Authentication Protocol (PAP) are an example of data security and shown in Figures 2.9 and 2.10 respectively.

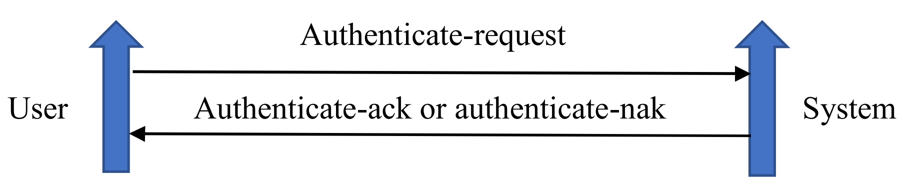

Figure 2.9: Example of Challenge Handshake Authentication Protocol [13]

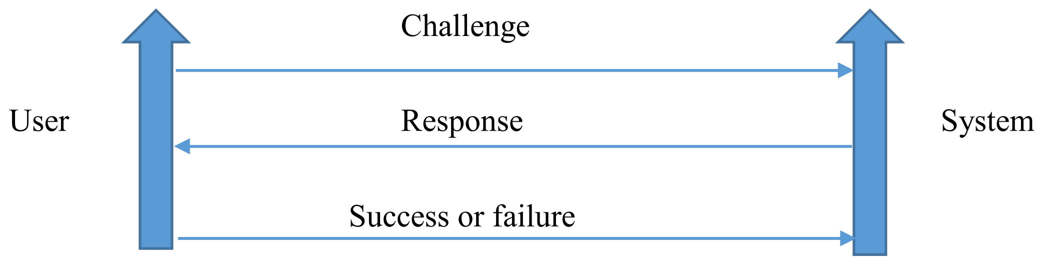

Figure 2.10: Example of Password Authentication Protocol [13]

2.4 Protocol Layering

The protocol layering is very important in the real-time communication which represents the structure of the communication network. There are two types of protocol layering such as Open System Interconnection Reference (OSI) model and TCP/IP protocol suite. Figure 2.11 shows the layer of the protocol.

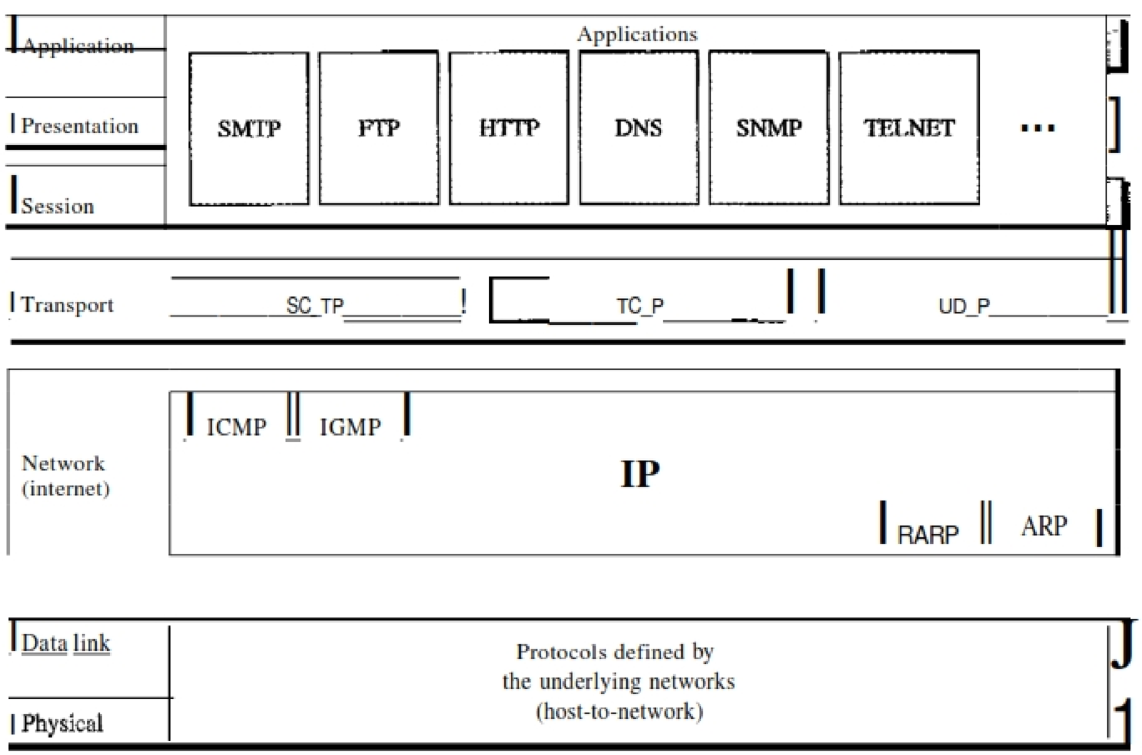

Figure 2.11: OSI Model and TCP/IP Model [13]

The number of layers differentiate the OSI model and TCP/IP model. The OSI model has seven layers while the TCP/IP model has four layers. The transmitter and receiver must have same protocol layering for transmission of data. Besides, the bidirectional communication is implemented when each layer performs the task in opposite direction. The application layer is used to provide network support for application processes such as web browsers and emails. The presentation layer makes sure the receiver able to read the transmitted data by converting data into a suitable format. The session layer has implemented the process of establishment and termination of the applications. In this transport layer, the process error control and flow control are taking place for data transfer. The network layer is responsible for selecting a suitable path for two end stations by implementing routing function. The data-link layer provides error control and synchronization for efficient transmission. There are two sub-layers such as medium access control (MAC) and logical link layer (LLC). The physical layer is used for implementation of physical components such as topology, electrical cable, electronic components and hardware components.

2.5 Ethernet

For the last 30 years, the IEEE Std 802.3Ethernet has been improved the speed and capacity of the Ethernet links by developing shared medium CSMA/CD systems to point-to-point Switched Ethernet. Then, multilane technology is introduced and the Ethernet shared media over passive optical networks. The evolution of the Ethernet started since 1985 which specifying a half-duplex carrier sense multiple access with collision detection (CSMA/CD) as medium access control (MAC) protocol operating at 10Mb/s and the end stations connected using the coaxial cable medium that supports bus topology. The Ethernet is known as fast Ethernet in 1995 with adding operation at 100Mb/s over fibre optic and twisted pair cabling. In 1997, the MAC protocol was operated in full duplex which supports switching and cost-effective for a large number of device integration. In 1998 and 1999, the speed of Ethernet has been increased to 1000Mb/s and support operation over twisted pair cabling respectively. From 2002 to 2010, the speed of Ethernet upgraded from 10Gb/s to 100Gb/s which only supports full duplex operation. The data transmission medium of the Ethernet was specified base on the speed and distance of end stations as shown in Figure 2.12. Then, the energy-efficient Ethernet (EEE) introduced in 2010 which reduce the power consumption of attached device [2].

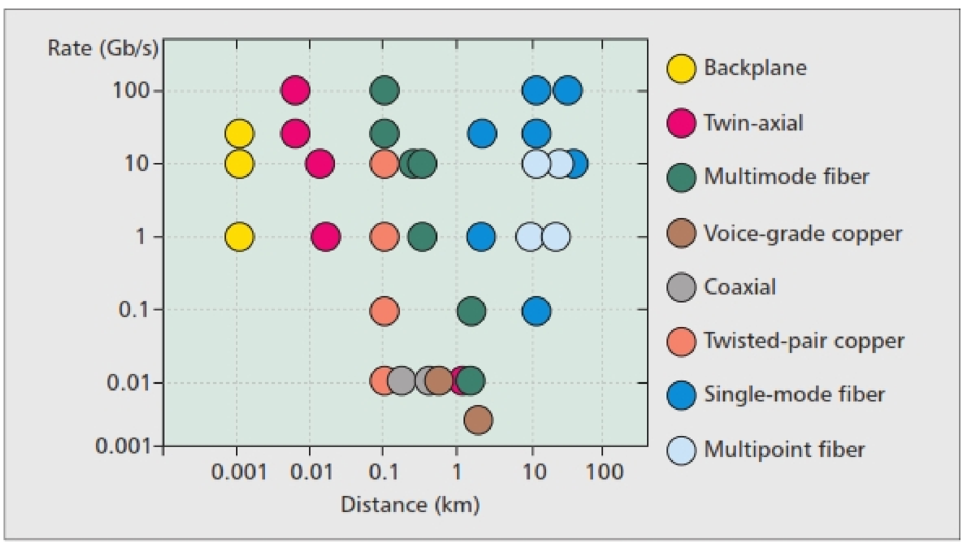

Figure 2.12: Speed and reach for various IEEE Std 802.3 MAUs and PHYs [2].

Moreover, the Ethernet hub is a passive device which transmits data from the input port to all output ports. This action increases the collision rate and delays the data transmission to the destination port. The Ethernet uses half-duplex link.

2.5.1 Non-Real Time Ethernet

Non-real time Ethernet did not have any time limit to transfer any data from the receiver to the transmitter. The non-real time Ethernet make sure the delivered data did not have any error or duplication. Program download, emails, and messages are examples of non-real time data. Besides, the non-real time Ethernet did not cause any fatal or serious problem when there is a delay in latency.

2.5.2 Real-Time Ethernet

Real-time data need a very precise time limit for delivering data to avoid any unwanted event which causes fatal. The real-time system required sensors, actuators, and controllers to become more intelligent and flexible for the industrial network. There are some features required to adapt the Ethernet technology such as time deterministic communication, time-synchronized actions between field devices as mention above, efficient and frequent exchange of very small data records. Moreover, the function of office Ethernet communication fully retained when fulfilling certain requirements such as urge the migration of the office Ethernet to real-time Ethernet and implementation of a standard protocol such as protocol, Ethernet controllers, and bridges. The performance of data transmission improved with limited jitter and disturbance due to TCP/IP data traffic. Performance Indicator (PI) is very vital to differentiate the real-time Ethernet network for different applications. Every performance indicator has its range and the following shows PI for Real-Time Ethernet (IEC 61784-2) [6]:

- Redundancy recovery time
- Non-time based synchronization accuracy

- Time synchronization accuracy
- Throughput RTE
- Non-RTE bandwidth
- Basic network topology
- Number of RTE station
- Number of switches between RTE end-stations
- Delivery time

2.6 Switched Ethernet

Switched Ethernet is improved version of the Ethernet to avoid unstable performance under heavy traffic and unbounded delay distribution. The switched Ethernet is developed because the switching technology can reduce frame collision due to the CSMA/CD medium access protocol. Besides, the switched Ethernet is an active device that identifies destination port before transmitting the data or message. This shows multiple stations can transmit data simultaneously without collision simultaneously as long as the data sent to the destination. The switched Ethernet uses full-duplex link to connect the station and hub while implement store and forward method for switching technology [3]. The switch stores the data in the buffer and sends them one by one to the destination station as shown in Figure 2.13.

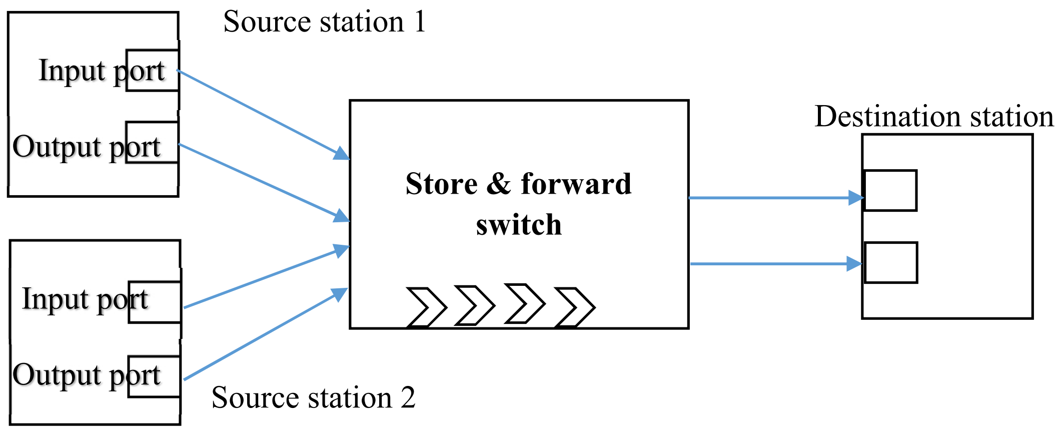

Figure 2.13: Schematic diagram of store & forward switching methods [3]

There are three main architectures of Switched Ethernet such as matrix, bus, and shared memory. Matrix architecture is distributed from the telecommunication switches. This matrix architecture has more ports compared to bus and shared memory but it has a problem when broadcast occur simultaneously. The bus architecture is a high-speed core which shared by modules. The bus access control based on the Time-Division Multiple Access (TDMA) and it supports the broadcast traffic. Besides, this architecture is affected the output buffer overflow when all the inputs transfer to the one output port. Moreover, the shared-memory architecture is used widely and most popular based on the ultra-rapid simultaneous multiple access. The output buffering is used to avoid the head-of-line (HOL) blocking. The output buffer overflow can be minimized using shared-memory queuing due to dynamic adjustment of buffer size. Recently all Ethernet functioning with wire-speed and non-blocking architecture. Wire-speed indicates all switch ports transmit and receive data simultaneously at full bit rates. The switch is non-blocking when the data forwarded to the destination port if the port is free while blocking represents the data cannot forward data although the destination port is free. For example, the input buffering indicates HOL blocking while output buffering indicates non-blocking [14].

2.7 Carrier-Sense Multiple Access with Collision Detection (CSMA/CD)

The CSMA/CD is used as a media access protocol for the Ethernet. In order to transmit data, the source station checks either the output station busy or not. If the output station is busy, the source station withholds transmission and wait until the output station becomes idle to transmit the data. If there is collision during the transmission, a signal sent to the source station to notify the collision. Then, the source station waits for the backoff time to retry the transmission for 16 times. If the transmission did not successful after the retry, the transmission of data is cancelled. Besides, the CSMA/CD causes excessive communication delay under heavy traffic due to the repeated collision. Figure 2.14 is shown the transmission procedure of CSMA/CD.

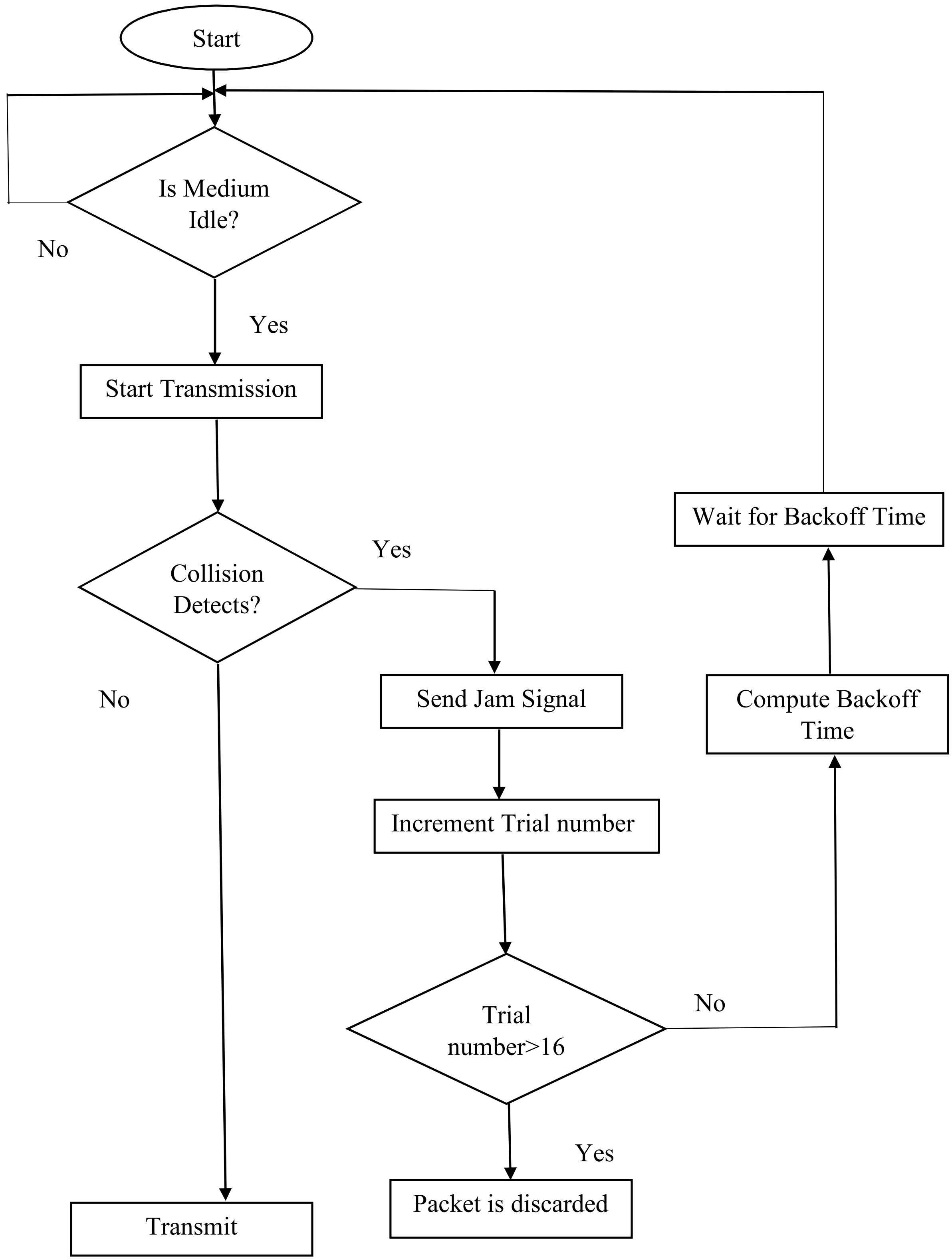

Figure 2.14: Transmission procedure of CSMA/CD [3]

Moreover, there is two type of CSMA such as 1-persistent CSMA and non-persistent CSMA. The 1-persistent CSMA protocol firstly detects a channel to identify the idle channel before transmitting the data. If there any are collision during the transmission, the station waits for random backoff time and transmit the data with a probability of 1 whenever the channel idle. For the non-persistent CSMA, a station senses a channel before transmitting the data. If the channel is busy, the station does not sense the channel again and wait for the end of the previous transmission for a random period of time. Then, it repeats the algorithm again until the transmission ends. Below shown the algorithm of 1-persistent and non-persistent CSMA [15]:

- *Non-persistent CSMA*

```
while true do
        if the channel is free
                transmit the packet;
        else if the channel is busy
                wait for a random time;
then repeat the algorithm;
```

- *1-persistent CSMA*

```
while true do
        if the channel is free
                transmit the packet;
else if the channel is busy
        keep sensing and repeat the algorithm;
if there is a collision
        wait for a random amount of time;
then repeat the algorithm;
```

In [16], the self-similarity of network traffic has been discussed to identify the cause of this phenomenon. The researchers have argued this phenomenon occurred by the CSMA/CD protocol which may cause or at least contribute to the traffic self-similarity. Moreover, the