Backoff Algorithms for Embedded Ethernet Model in Real-Time System

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Abstract- The purpose of the paper is to find a suitable model for working in real time and ensuring the immediate delivery of packets. Several backoff algorithms previously applied over wireless networks will be used and implemented over wired networks to investigate the proper algorithm. Design of the backoff controller of the algorithms depends on Stateflow in MATLAB. The Optimistic Linear Exponential Backoff (OLEB) algorithm with network sizes (5 and 25 active nodes) outperforms the other algorithms. The average end-to-end delay of the OLEB algorithm exceeds that of the Binary Exponential Backoff (BEB) algorithm for small and medium network sizes by approximately 4% and 80%, respectively. By contrast, the average end-to-end delay of the Fibonacci Increase Backoff (FIB) algorithm outperforms that of the BEB algorithm for large network size by approximately 40%. The FIB algorithm also has the highest fairness index and best performance for the network with all network sizes.
Keywords – Real-Time Communications, Ethernet, Embedded System, MAC Controller, Backoff Algorithm.

I. INTRODUCTION

Medicine and engineering have been widely developed in the past century. These developments and advancements meet the requirements of everyday life and lead to an increase in the amount and importance of information transferred, thereby requiring guaranteed and fast communications [1]. Research in control engineering and networking technology are unrivalled in a challenging scope, that is, the development of embedded real-time applications. Many applications such as manufacturing, robotics and medical and social services rely on embedded systems that interact with the real world [2]. In general, communications is one of the most important service factors.

However, communications encounters issues that affect network performance such as delay and the lack of network performance. To solve these issues, most researchers strive for real-time communications to gain the advantages of guaranteed communications [3].

In the past decade, wireless networks have become increasingly and widely used, thereby enabling mobility. Several algorithms have been implemented to improve wireless networks by optimizing network performance. In a wireless network, the backoff algorithms vary from one algorithm to another based on network conditions. Some algorithms are appropriate for large networks sizes, whereas some algorithms provide improved performance for small network sizes [4] [5].

At present, wireless networks achieve all conditions of real-time communication (RTC) by reducing the time delay through the implementation of effective backoff algorithms in the IEEE 802.11 protocol [6] [7].

By contrast, wired communication undergoes high time delay over the network, thereby causing communications properties to be non-guaranteed. The Binary Exponential Backoff (BEB) standard algorithm lacks performance over a wired network and is characterized by high delay time, low throughput rate, high collision rate and low fairness index [8]. Attempts have been made to improve communication over wired networks by improving the medium access control (MAC), but the effect of these improvements have been insufficient to work in real-time properties [9].

Ethernet (IEEE 802.3) is the most popular protocol for wired communication used in LAN. Given Ethernet's importance, some researchers have been interested in adding deterministic handling in the system such as RTC, in its operations [10] [11].

Therefore, the idea of this research draws inspiration from the mechanism of the backoff algorithm for wireless networks and using these mechanisms in wired networks to improve the performance network. The different backoff algorithms will be applied to the Ethernet model, and the results will be analyzed to investigate and determine the most suitable algorithm for a reliable network model in RTC.

The remainder of the paper is arranged as follows. In Sections II and III, the principles of the communication network and increment behaviour are described. In Sections IV and V, the methodology of the research and network performance measurement are clarified. In Sections VI and VII, the results discussionand the conclusions are presented.

II. PRINCIPLE OF THE COMMUNICATION NETWORK

2.1 Real-Time Communication(RTC)

The RTC system is considered one of the most important systems in all of modern science. It is used in advanced medical devices and for critical needs and thus, each system must optimize its properties. The benefits of RTC are a low average delay, high degree of predictability, good performance for a large network, transfer packets or data with less overhead, high powerful transmission capacity use and scheduling to process and organize each packet in a communication system such as multimedia services [12].

RTC uses two types of data transmission, namely half-duplex and full-duplex [13]. RTC is also grouped into two types based on the level of service assurances, namely, hard RTC and soft RTC; respective examples include avionics and instant messaging [14] [15]. RTC can be considered real-time, are guaranteed performance by communication protocol types such as Ethernet, CAN Bus, FlexRay, Profibus and LIN protocols and are applied in different fields[16].

2.2 Ethernet Protocol

Ethernet is one of the most well-known protocols for wired networks used in LAN. The protocol is desirable in communication designs and experiences because it is uncomplicated, scalable, configurable, and multi-purpose [17]. Ethernet uses the CSMA/CD protocol to transmit data packets under half-duplex transmission modes, in which any node can send and receive data but not at the same time [18] [19].

Initially, the Ethernet protocol did not support real-time connections because of the high collision rate for nodes and congestion and because it undergoes high delays and performance shortages when sending data [20]. After improving the backoff algorithms to reduce delay time and increasing the transmission rate, Ethernet became one of the best options for implementing RTC.

III. INCREMENT BEHAVIOUR

This paper proposes to study increment behaviour to obtain an adequate understanding of the behaviour and performance of algorithms that use this aspect. The effect of the increase in the Contention Window (CW) size of the backoff mechanism is directly affected in the balance between lessening the number of attempts to reach the medium and reducing the idle time of the channel [21].

Therefore, the backoff algorithm must avoid long backoff times because it can cause delays and perform many attempts without being useful. Idle time is directly influenced by the backoff period and the traffic that flows through the network is unpredictable. Thus, the algorithm should not incur a long time on the node because the command can also require considerable time, thereby resulting in a busy channel.

The backoff controller mechanism uses different methods of increase to determine the suitable increments of the backoff timer, thereby resulting in effective network performance [22]. To illustrate the effect of increased behaviour in each backoff algorithm, simulation experiments were performed in more than one algorithm that used four different increment types, namely, exponential, linear, Fibonacci and cubical increments.

First, the BEB algorithm uses exponential increments that increase by doubling CW based on the number of attempts taken to reach the channel [23][24]. This type considers the standard backoff algorithm across local networks; the algorithm measures and evaluates other backoff algorithms.

Second, the linear backoff algorithm increases the backoff timer linearly through a fixed gradient based on the number of attempts to access the channel [25]. The linear backoff and impaction will be clarified in detail.

Third, the Fibonacci Increase Backoff (FIB) algorithm, as the name implies, uses a Fibonacci increase and is considered more optimistic compared with the standard algorithm because it resolves the transmission disappointment quickly [26]. Thus, Fibonacci increases are small values designed to improve network performance and maintain a short network lifetime.

Fourth, the cubical increment used in the proposed algorithm is a Pessimistic Fibonacci Backoff (PFB), which will be detailed in this paper. This algorithm provides considerable time before re-transmission. To avoid excessive increasing in the backoff [27], the PFB increases the timer cubically. Therefore, the different backoff algorithms will be explained in the remainder of this Section.

3.1 Binary Exponential Backoff Algorithm (BEB)

At the beginning of the emergence of wired networks, researchers proposed a standard algorithm (BEB) to resolve the weak network performance such as highest delay time and high collision rate across the network. For the backoff procedure [28], the BEB algorithm is designed as shown in Figure 1.

When the node attempts to transmit the first attempt (i=1), the node attempt does not succeed in sending the packet, and each attempt will double the value of contention window size. When the transmission is successful, the backoff timer value is equal to CWmin (reset CW to zero) as depicted in Figure 1.

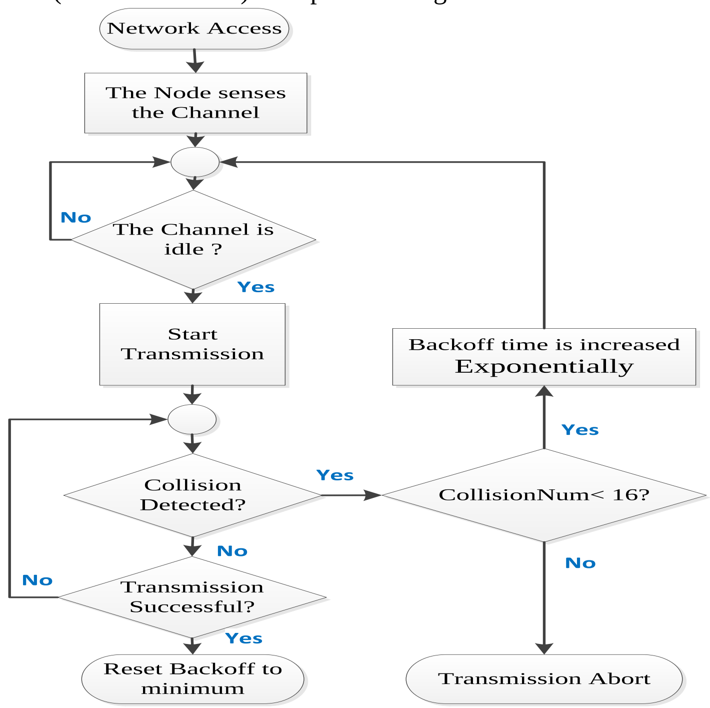

Figure 1. Strategy of the BEB standard algorithm [28].

3.2 Linear Backoff Algorithm

The linear algorithm attempts to reach the minimum delay in the network with the best performance. Specifically, the linear backoff algorithm increases the backoff timer linearly when the number of retransmission attempts is increased [25].

The strength point of the linear backoff algorithm is in providing sufficient time to achieve network performance such as reducing the delay by reducing the number of transmission failures. The general equation of the algorithm across the simulation system is shown as in (1). Here, k is the number of attempts of re-transmission of the node and f is the constant gradient.

Backoff Timer= (f× min ([k, 16])) ×5.12e-5 (1)

Fibonacci Increment Backoff (FIB) Algorithm

The FIB algorithm uses a Fibonacci increase to reduce the increment factor. The Fibonacci series is defined as in (2).

Fib (n) = fib (n-1) + fib (n-20), where fib 0 = 0, fib 1 = 1. (2)

Based on the equation, the FIB algorithm increases the backoff timer through small values designed to process the collisions over the network, whereas the previous algorithms such as the BEB and linear algorithms increase by large values that lead to the reduction of the expected waiting time for a specific node to reach the channel [29].

3.3 Pessimistic Linear Exponential Backoff (PLEB) Algorithm

The PLEB algorithm mechanism combines two parts of the increment methods for the same system to obtain the benefits of two types of behaviour, namely, the exponential and linear increments. The PLEB algorithm assumes that congestion and channel occupancy lead to transmission failure [30]. Therefore, the PLEB algorithm increases the backoff timer exponentially for the specific number of attempts, thereby extending the prolonged waiting period that provides the attempt sufficient time to transmit before the next attempt.

The PLEB algorithm begins to increase the backoff timer linearly for the specific number of remaining attempts to avoid exceedingly expanding the backoff period. The main functionality of the PLEB algorithm is to obtain a non-dramatic expansion of the backoff timer, thereby allowing the nodes to execute more than one attempt to reach the medium after a reasonable backoff period.

3.4 Optimistic Linear Exponential Backoff (OLEB)Algorithm

In certain cases, increasing the number of nodes and high traffic load over a specific area causes failure of many attempts to send. To solve this problem, the OLEB algorithm consolidates the advantages of the linear and BEB algorithms, thereby reversing the action of the PLEB algorithm [31].

When a collision occurs, the algorithm mechanism will increase the backoff timer by using linear increment for the known number of collisions to perform lower dramatic increments with early backoff levels. After linear increments for a certain number of attempts, if the transmission failure continues, then the node will require longer waiting time until it is ready for re-transmission through the exponential increment behaviour for a number of the rest attempt.

The advantage of this algorithm indicate that increments behaviour are adequate for the long backoff periods and reduces the excessive times of the network when idle by using the smaller exponential increment factor.

3.5 Pessimistic Fibonacci Backoff (PFB) Algorithm

Some algorithms use more than one technique to increase the backoff timer value, thereby attaining the best performance as in the PFB algorithm [27]. This algorithm is imposed against congestion in an attempt to regulate the transmission time of the nodes and avoid a high collision rate.

Therefore, the algorithm attempts to apply more than the mechanism of the increase, thereby reducing the factors that affect the efficiency of the network.

The PFB algorithm work mechanism on three levels of increment behaviour are exponential, cubic and Fibonacci. First, the PFB algorithm uses exponential increment behaviour for the backoff timer to provide sufficient values to exploit other tracks for a number of attempts (N). Second, if the transmission failure continues after the exponential increment, the PFB increases the backoff timer by cubical increment behaviour for a specific number of attempts (M), thereby avoiding increasing high values.

Finally, if the node still possesses a collision problem and failure in retransmission of the packet after the cubical increment, then the PFB algorithm designs are as shown in Figure.2. These different techniques are used to facilitate the reduction of reduce break paths and lead the transmitter packet to the true path, thereby avoiding collisions.

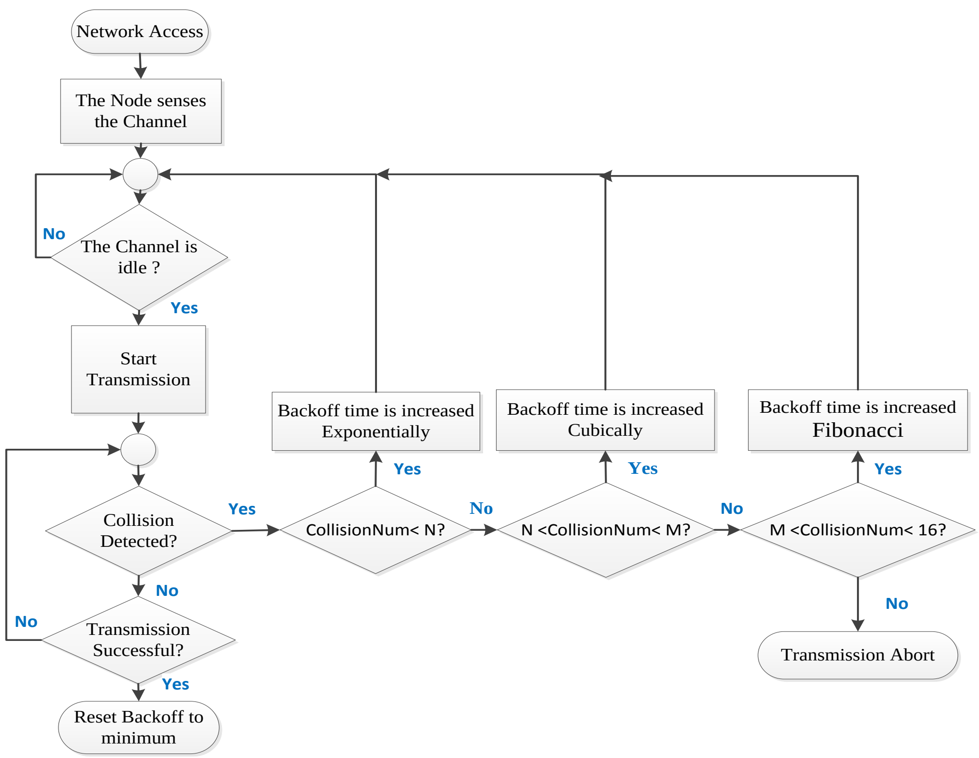

Figure 2.Strategy of the PFB standard algorithm [27].

3.6 Communication Model

The Ethernet network model will be configured by using the MATLAB software through Simulink and is implemented with different conditions through half-duplex communication [32]. The CSMA/CD is applied over the model through the SimEvents library browser [33]. This model uses various backoff algorithms to determine the best performance of the network and includes five important sections explained as follows:

The application network block represents data consumed across devices.

The MAC controller manages the address of the Ethernet module to access the shared channel.

The T-junction is responsible for linking the nodes or units between them for the Ethernet network model.

The terminator block is used to terminate the connection at the end of the path.

The network cable is utilized to connect two network terminals for the nodes.

Therefore, this study focuses on designing the backoff controller of the MAC controller for the Ethernet network model by designing the Stateflow diagram in Simulink. In this study, each algorithm has a different design; therefore, the Stateflow mechanism depends on the fundamentals of the algorithm. The backoff controller standard is achieved through the use of Stateflow as shown in Figure. 3.

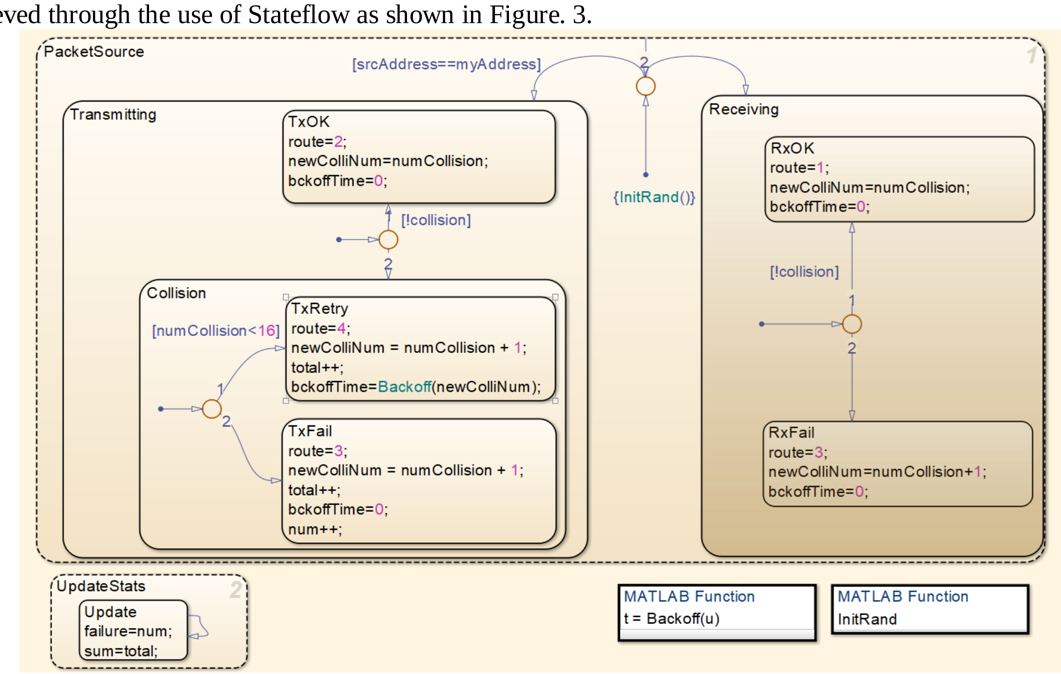

Figure 3.Stateflow of BEB standard algorithm [32].

IV. NETWORK PERFORMANCE MEASUREMENTS

These factors or measurements are calculated to determine the effective performance of the network under different circumstances.

4.1. Average End-To-End Delay

This study focuses on finding the suitable solution to decrease the delay time in the communication model. The end-to-end delay corresponds to the delay in transmitting the packets from the source to the destination, and its unit of measurement is milliseconds. The delay value is presented in (3), where i denotes the present output packet and m represents the whole number of output packets [34].

$$\text{Average Delay} = \frac{\sum_{i=1}^{m} \text{Sum of average delay for the destination}}{m} \quad (3)$$

4.2. Packets Delivered (Throughput)

The network throughput is the most prevalent performance that determines the entire amount of data successfully delivered by the node at a certain period. The unit of measurement is bytes per second as shown in (4). In general, the system with a high network throughput always has better efficiency than other systems [34].

$$\text{Packets Delivered Ratio} = \frac{\text{Total number of packets recieved}}{\text{Total number of packets sent}} \quad (4)$$

4.3. Collision Rate

This factor is used to calculate the collision rate in the model to evaluate and determine the best backoff algorithm. The increase in collision rate provides probability of excluding the packets because the maximum number of attempted collisions is exceeded. A high collision rate commonly implies additional overheads, heavy system load and increasednumber of active nodes.

4.4. Fairness Index

This factor indicates the stability scale in the grid. Thus, the amount of access to the channel will be equal among competing nodes. The fairness index, which is always estimated at a value between 0 and 1, is calculated on the basis of Jain's fairness indicator as presented in (5).

$$\text{Fairness Index} = \frac{(\sum_i Gi)^2}{n * \sum_i (Gi)^2} \tag{5}$$

Where Gi is the throughput of nodes and n represents the number of nodes [35]. For each algorithm, total productivity is measured by the fairness index in each size of the wired network to determine the stability and fairness of the algorithm.

Therefore, the network performance measurements are calculated on the basis of the parameters or conditions of the embedded Ethernet connection model to determine the best performance of the network. Thus, to perform the simulation, the parameters of the Ethernet connection model are set by specific values as shown in Table 1.

Table 1. Parameter simulation of Ethernet model.

Parameter	Value
Number of active nodes	5, 25 and 50 nodes
Traffic load	100 (packet/sec)
Size of transmission buffer	25 packets
Medium bandwidth	50 M bit/sec
Application model	Constant Bit Rate(CBR)
Transmission range	200 meters
Simulation time	300 seconds
Packet size	64–1500 bytes

V. RESULTS AND DISCUSSION

In this study, the model for communications over the Ethernet protocol has simulation results for the evaluation of the performance model. The results are divided into several categories of network sizes, such as small, medium and large networks. The algorithms will be applied to each network sizeand compared with each other by network performance parameters under certain conditions as the values of the model parameters presented in Table1. Simulation results will be analyzed across different algorithms by applying the model to different network sizes as in the following parts.

5.1. Five Active Nodes

The embedded Ethernet network model performed the simulation by designing five active nodes. Therefore, each algorithm will be applied to the model and the results analyzed through the following algorithms: BEB, linear, FIB, PLEB, OLEB and PFB. Subsequently, the results will be displayed for each algorithm and evaluated in accordance with the network performance scales.

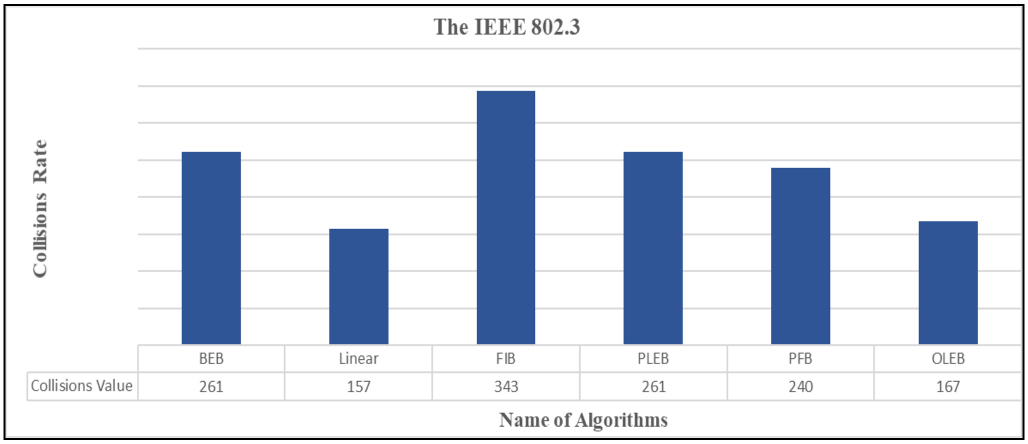

Figure 4. Total average collision rate over the Ethernet connection model for each algorithm with five active nodes.

In Figure 4 shows that the collision rate with five competing nodes increases because the competition rate among the nodes is high in relation to accessing the shared channel, thereby influencing the collision rate and average end-to-end delay.

With this collision rate, the average of packets delivered remains high for all backoff algorithms of the model as shown in Figure 5. Thus, the algorithms have effective access to the channel. All algorithms are approximately equal in terms of the average packets delivered in small network sizes as shown in Figure 5.

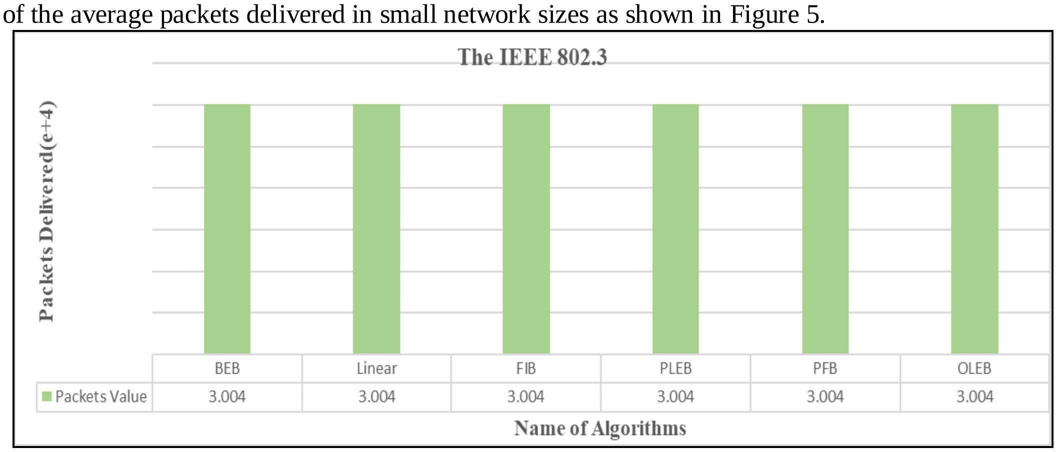

Figure5. Overall average packets delivered over Ethernet network model for each algorithm with five active nodes.

The main objectives of this study are to minimize the average end-to-end delay and achieve an Ethernet network model following a suitable backoff algorithm. In these five network sizes, the algorithms outperform each other in the following sequence, i.e., OLEB > FIB > linear >BEB > PLEB > FIB, as shown in Figure 6.

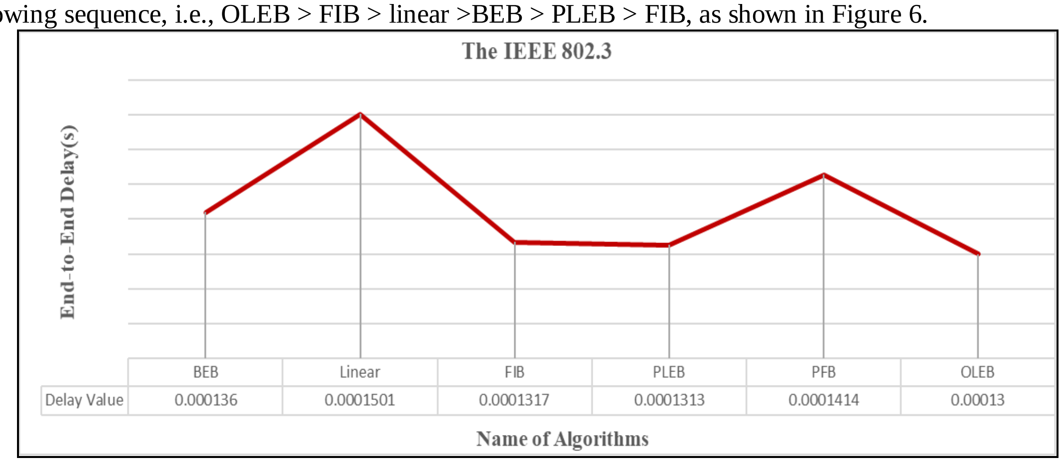

Figure 6. Overall average end-to-end delay over Ethernet networkmodel for each algorithm with five active nodes.

The average end-to-end delay of the OLEB algorithm outperforms that of BEB algorithm for the small network size by approximately 4%. Thus, the OLEB algorithm is more suitable than other algorithms, making the Ethernet network faster and more efficient in achieving the best performance.

5.2. Twenty-Five Active Nodes

The embedded Ethernet network model continues the simulation process by increasing the number of competing nodes to 25 as the medium network size. The average for all results of the algorithms is calculated and the results compared by the same performance measurements.

After increasing the number of competing nodes to 25, the nodes will compete further, causing a high load on the channel to transmit the data packets. In Figure 7 shows, each algorithm has a specific mechanism to manage congestion, which differs from that of other algorithms.

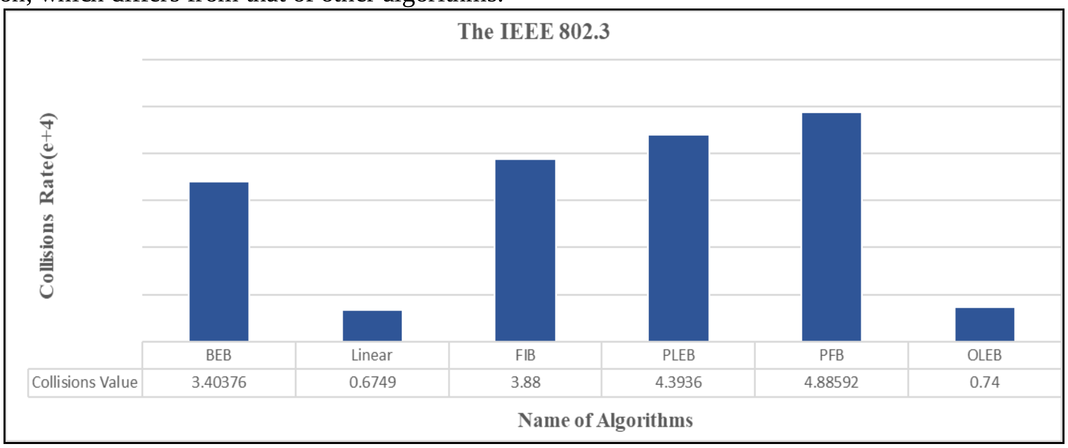

Figure7. Total average collision rate over the Ethernet connection model for each algorithm with 25 active nodes.

Consequently, the average collision rates for each algorithm are different as presented in Figure 7. A high collision rate affects the performance of the network in accordance with the mechanism of the algorithms, and thus, the OLEB algorithm has the best collision rate in terms of the network size and environment of the Ethernet network model.

Therefore, the average end-to-end delay in the medium network size among the algorithms differs from that in the previous network size as presented in Figure 8. The nodes continue with the transmission attempts depending on the average collision rates shown in Figure 7. Thus, additional time is consumed to transmit the packet, which causes a significant delay in the network in accordance with each mechanism of the algorithms.

To determine the most suitable algorithm for a reliable network model for the deterministic systems, the model must follow the backoff algorithm with the smallest average delay and a high efficiency. In 25 nodes, the algorithms outperform each other in the following sequence: OLEB > linear > BEB > FIB> PLEB> PFB as shown in Figure 8.

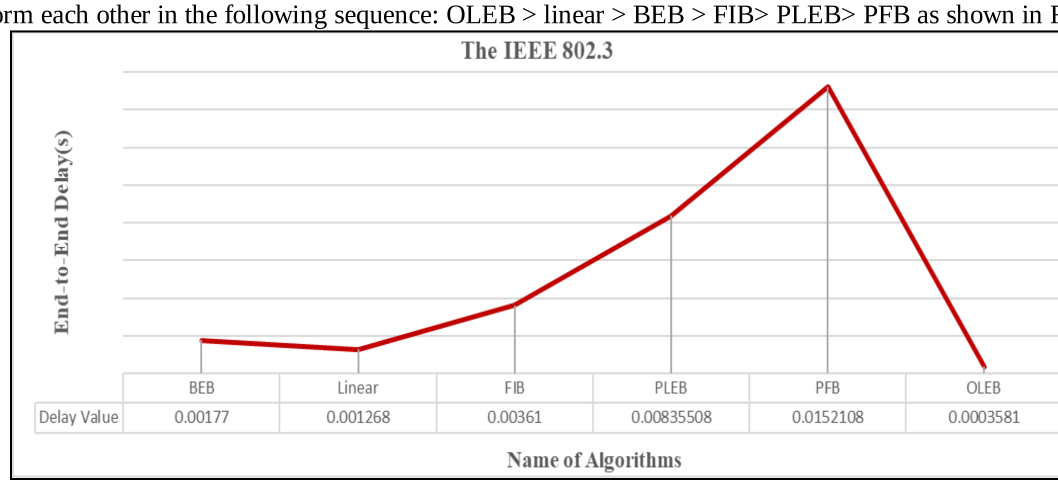

Figure8. Overall average end-to-end delay over Ethernet network model for each algorithm with 25 active nodes.

The average end-to-end delay of the OLEBalgorithm outperforms that of the BEB algorithm for the medium network size by approximately 80%. In this network size, the OLEB algorithm outperforms other algorithms because it has the smallest average end-to-end delay, channel access by a high average of packets delivered and a high response to reduce the average of the collision rate. Hence, the OLEB algorithm has an appropriate mechanism to increase the backoff timer value by adequate periods of long backoff, while reducing excessive times at the same time.
Thus, the OLEB algorithm meets these conditions for the model to work as a deterministic system. Thus, to achieve an Ethernet network model that is fast and further efficient with improved network performance, the OLEB algorithm must be used in this network level.

5.3. Fifty Active Nodes
After increasing the number of active nodes to 50 for the embedded Ethernet network model, the simulation results for each algorithm will be analyzed under the same parameters. The average performance network scales for all backoff algorithms will also be calculated.

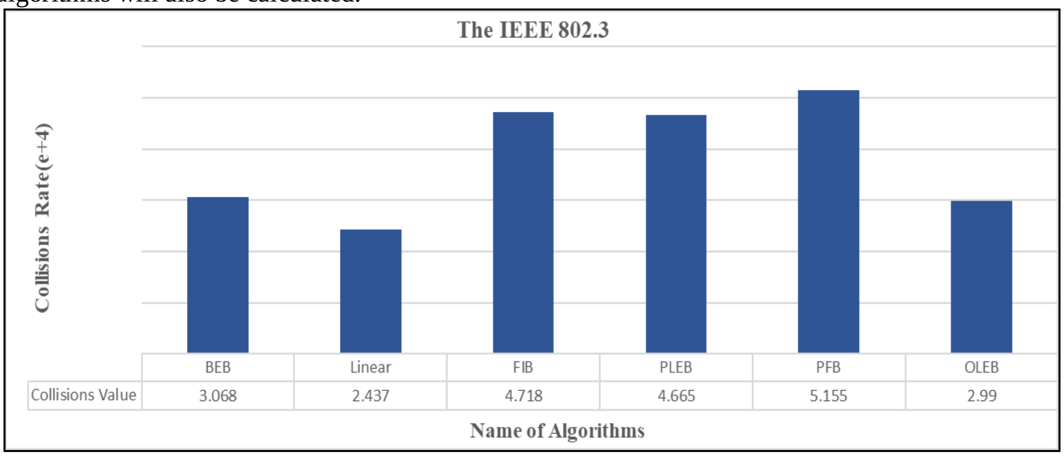

Figure9. Total average collision rate over Ethernet network modelfor each algorithm with 50 active nodes.

In Figure 9, several changes due to the increased number of competing nodes across the network are observed from the simulation results of the previous models. Increasing the number of competing nodes promotes the further competition among them causing a high load on the channel sharing the data. Thus, the average collision rate increases further in a large network size, and thus, different algorithms were used to manage a dense network and resolve the congestion among active nodes to access the channel.
The main factor of this model is the average end-to-end delay because delay time determines efficiency and is deterministic of any communication system. Therefore, the average end-to-end delay in the large network size has increased compared with that in the previous network size as presented in Fig.10. To achieve a reliable Ethernet network model in real-time communications, the backoff algorithm with the smallest average delay must be followed. In 50 active nodes, the algorithms outperform each otherin the following sequence: FIB > PLEB > BEB >OLEB > PFB > linear as shown in Figure 10.

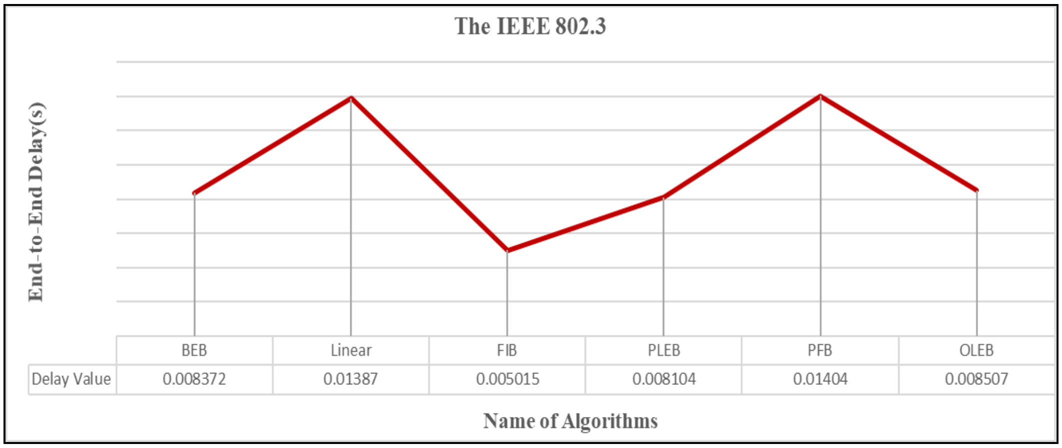

Figure 10. Overall average end-to-end delay over Ethernet network model for each algorithm with 50 competing nodes.

The FIB algorithm outperformed other algorithms because it has the best mechanism to transact with the dense networks. The average end-to-end delay of the FIBalgorithm outperforms that of the BEB algorithm for the large network size by approximately 40%. The main reason for the superiority of the FIB algorithm in the large network size is the mechanism of the algorithm to deal with many collisions. With the rate of high collisions, the FIB algorithm has the minimum average delay value.

Thus, the FIB algorithm is effective in increasing backoff timer values compared with the other algorithms designed to achieve the highest network performance and keep the lifetime network short. Therefore, the FIB algorithm is suitable for the design of the Ethernet network model in real-time communications.

5.4. Fairness Index of the Algorithms

Each algorithm has the specific mechanism to reach the channel access. Some algorithms have a method of distributing equal capacities among nodes to reach the channel. However, some algorithms include nodes with better channel capacity than activating other nodes because of the various understanding of the mechanism event among nodes. The fairness index for each algorithm is computed in each network size to determine which algorithm is suitable for the nodes to reach the channel as shown in Figure 11.

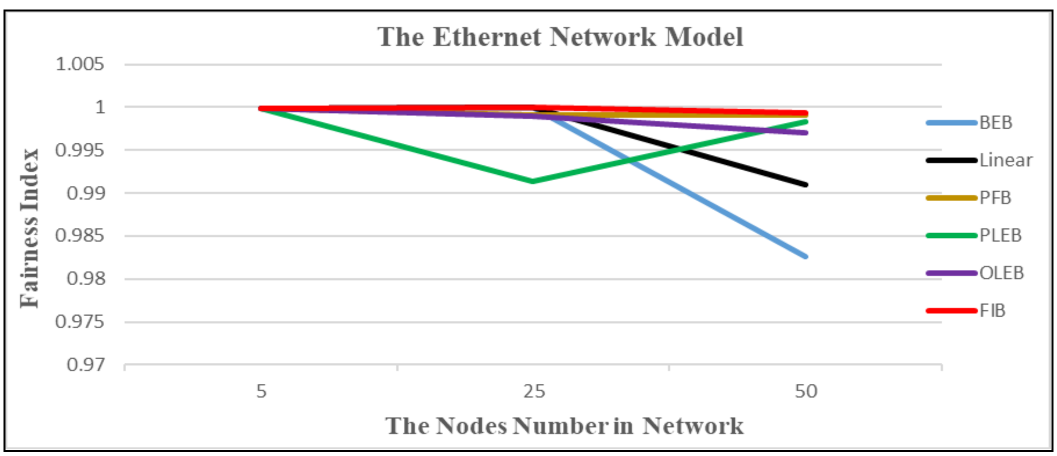

Figure11. Fairness index of the Ethernet model for each algorithm.

On the basis of the fairness index, FIB and PFB algorithms have the best stability compared with other algorithms as shown in Figure 11. Thus, the FIB algorithm is highly stable in all circumstances for the Ethernet network model. The PFB algorithm is stable in all network sizes but suffers significant delay, with small packets delivered and high collision rate. The OLEB algorithm is stable in five and 25 nodes for the network sizes under all circumstances. Thus, the mechanism of the OLEB algorithm has a fully effective network performance in small and medium network sizes, whereas the FIB algorithm is suitable and effective for the Ethernet network model in large network sizes.

VI. CONCLUSION

Due to the non-deterministic system in communications over wired networks, this study designed backoff algorithms to comprehensively evaluate the performance of the Ethernet network model. This study focuses on designing the Ethernet network model as half-duplex and applied CSMA/CD over the model through the Simulink MATLAB software. Therefore, after designing the backoff algorithms on three network sizes, the OLEB algorithm (five and 25 active nodes) outperformed the other algorithms. In addition, the average end-to-end delay of the OLEB algorithm outperformed that of the BEB algorithm for small and medium network sizes by approximately 4% and 80%, respectively.

The average end-to-end delay of the FIB algorithm outperformed that of the BEB algorithm for large network sizes by approximately 40%. Therefore, the FIB algorithm is more suitable than the other algorithms. The OLEB algorithm has the highest fairness index and best network performance with small and medium networks sizes, whereas the FIB algorithm is suitable with large network sizes to design real-time connections across the Ethernet network model.

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