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Comparative Analysis of 100M Switched Ethernet and CAN-FD Networks in Feedback Loop Networked Control System

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Abstract:

To be able to meet the constant rise in demand for high bandwidth and low message response time in real-time networked control system applications a proper operation of the networks used in such systems is imperative. Because when the real-time requirements of transmitted messages in a control system is not achieved, the operation of the control system can be greatly disturbed and can degrade the performance of the control system. The goal of this paper is to evaluate the network influence on feedback loop Networked Control Systems using two communication networks: the Controller Area Network with Flexible Data-rate (CAN-FD) and the 100M Switched Ethernet network. In this research work, simulations were carried out to analyze the stability of the controlled system (DC Servo) and the real-time performance of both networks under four network conditions with the use of network parameters such as packet losses, sampling time and network utility. The TrueTime toolbox with Matlab/Simulink was used for the simulation to analyze the control performance of both networks. The obtained results for each network condition show that the 100M Switched Ethernet technology is a good alternative to the CAN-FD technology for modern NCS applications. Nevertheless, The CAN-FD network may be more suitable for real-time systems in modern automation industry as it meets the requirement for data communication in application areas such as in-vehicle bus communication.

Keywords: Networked Control Systems, CAN-FD, 100M Switched Ethernet, DC Servo, Simulation.

I. INTRODUCTION

A networked control system (NCS) is a control system which consist of a communication network [1]. NCSs are feedback control systems where the sensors, controller and actuators of a discrete controller are separated and placed on different computer nodes interconnected by a communication network with the aim of overcoming the challenges of the traditional digital control system such as challenges involved in cost of maintenance, modification, vulnerability to electrical noise and upgrades, at the level of application.

Although this mechanism helps to solve the above challenges, it introduces its own problems:

1. The communication networks introduces at times unpredictable delays.
2. It also brings along the possibility of data or information loss and corruption.
3. It is still not clear how to separate the algorithms used in the control into parts. Some control systems are not suitable for such separation.

Network induced delays directly increases the delay in the control loop and consequently causes instability in the control system. Data or information loss is also similar in this respect. Therefore research work must be carried out to enable the use of this type of control implementation.

In this paper, we first of all presented the basics of CAN-FD and 100M Switched Ethernet Networks. Secondly, the design of the system showing a delay model of the NCS system and the block diagram of the NCS. Thirdly, we describe the Truetime Simulator and its modus operandi. Fourthly, the network parameters are presented; here we described the type of approach used for the simulation, the parameters of the controller used and the parameters used for the simulation. Fifthly, we show the pictorial diagram of the model in the Matlab/Simulink environment. Lastly simulation results were presented and discussed followed by conclusion and future works.

II. RESEARCH OBJECTIVES

The aim of this research work is to evaluate the network influence on feedback loop Networked Control Systems using two communication networks: the Controller Area Network with Flexible Data-rate (CAN-FD) and the 100M Switched Ethernet network, therefore the research objectives includes:

1. Analyzing the behaviour/performance of the 100M Switched Ethernet and the CAN-FD communication networks in the feedback loop of NCS under several network conditions.

2. To determine a more reliable communication network with higher bandwidth and low message response times in a real-time NCS application, which can be used to overcome the existing barriers in application development of the existing fieldbus protocols.

III. RELATED WORKS

Several research work has been done to show the network influence inside the control system. Majority of the research works done in NCS reviewed the relationships between control system stability and the delay induced by the network [2]. Other works such as [3], has presented the influence of Quality of Service (QoS) on the stability of closed-loop control systems. The QoS technique evaluated include the frame scheduling, task scheduling, packet dropout, and the protocols. Nevertheless, the authors so far considered only the fieldbuses. The authors in [4], studied the impacts of two communication networks (CAN and Switched Ethernet) on the controlled system. The Truetime network simulator was used to simulate the networks under several network conditions. The authors however proposed that the bandwidth capacity of the CAN network is a major limitation when the network medium is being shared with other applications in a real-time process. Therefore the Switched Ethernet network is a better alternative in this case due to its high bandwidth. The authors in [5], classified the network-induced delays for two fieldbuses (ControlNet and DeviceNet) and Ethernet. They analyzed the inherent tradeoffs in network bandwidth and control sampling rates. The authors proposed that the Ethernet network can be used for large data size transmissions and also for non-time-critical applications. For applications that require short and/or prioritized data packets, DeviceNet showed a better control performance. However the authors did not considered the 100M Switched Ethernet network. The major technical limitation of the Ethernet in industrial applications is its non-determinism which makes it inappropriate for real-time applications. However, the 100M Switched Ethernet has shown a very promising possibility for industrial applications, as it overcome the uncertainties in the network operation which significantly improves the performance of the controlled system[6]. The authors in [7] studied the performance of the 100M Switched Ethernet for real-time industrial applications and proposed the feasibility of 100M Switched Ethernet for industrial applications. In their observation the performance of the controlled system was affected very little by the network delay.

Ming in [6] analyzed the delay of NCS based on 100M Switched Ethernet using the Truetime Simulator. The authors analyzed the major factors that affects the upper bound delay of the 100M Switched Ethernet, also they presented the parameters of the upper bound delay. The study demonstrated that the network-induced delay has little influence on the control performance of the system. The authors also proposed that the network-induced delay by multiple-level 100M Switched Ethernet has the possibility of meeting the real-time requirements for different control systems if the node numbers and the number of levels interconnected to switches are properly placed.

Meng in [8], proposed a mechanism based on frame insertion to improve the deterministic characteristic of data frames arrival within an AFDX (Avionics Full-DupleX) Switched Ethernet network. The study addressed the potential failure in the redundant communication management of AFDX Switched Ethernet networks, and a concise evaluation of this approach is carried out. The study in [8] also proposed several techniques related to determinism and reliability improvement.

In [9], the authors carried out performance analysis of a CAN-FD network with SAE Benchmark based message set. The obtained results showed that the CAN-FD network gives a very high control performance to meet the requirements of real-time control systems.

The authors in [10], compared the CAN-FD network and the conventional CAN network and as well analyzed the control performances measured step responses under different network load conditions. The potential advantages of the CAN-FD network was mainly explored. The CAN network had major limitations and very poor performance in terms of predictability when the bus load is increased. However, the CAN-FD network presented good performance even at high bus or network load. Nevertheless, its predictability is compromised beyond certain amount of bus load. The authors observed that for bus load above 98% the CAN-FD network stopped transmitting.

The authors in [11], developed a frame packing problem for CAN-FD with the aim of optimizing bandwidth utilization while meeting temporal constraints. The authors proposed an equation to calculate the best-case and the worst-case transmission periods of the CAN-FD network frames. The obtained results showed that the strategy employed can be used to optimize the CAN-FD network utilization and also useful in situations where the system to be controlled is very communication intensive.

In [12], the authors proposed a genetic algorithm for the CAN-FD network frame packing problem. The algorithm attempts to reduce the utilization of the network bandwidth by taking into consideration the different time-intervals of data packets when putting them in a single frame. The authors also looked into the possibility of scheduling packed frames to ensure the real-time constraints for each frame and as well proposed an algorithm to merge each frames in order to enhance the possibility of scheduling message signal set with high bus load.

In NCSs, the measurement is transmitted via the communication channel. And the channel dynamics plays an important role in control performance. But only very few researchers have considered the channel property in the NCS design [13], [14]. To achieve the optimal performance of NCSs, the co-design of channel and control strategy still needs much more research effort.

IV. CAN-FD AND 100M SWITCHED ETHERNET NETWORKS:

1) Controller Area Network with Flexible Data Rate (CAN-FD):

The CAN-FD protocol was developed to extend the standard Controller Area Network (CAN) protocol [15], due to the increase in the amount of data exchanged in automotive networks which brought CAN to its limit [10]. The motivations behind the development of the CAN-FD network includes:

i. Avoiding the cost and expensive porting effort it will take to migrate from CAN to Ethernet or FlexRay [16], [17].

ii. To implement a protocol which will come in to fill the gap between the high-speed FlexRay (10 – 20 Mbps – maximum bandwidth) which is both complex and expensive and low-speed CAN bus which is cheap with maximum bandwidth of 1Mbps

iii. To meet the increase on bandwidth requirements for automotive network

The CAN-FD protocol extends the payload or length of data in frames to 64 Bytes of data along with higher data transmission rates, having speeds up to 8 Mbps. The CAN-FD network still maintains the inexpensive and retains the good performance and robustness of the original CAN. CAN-FD is backward compatible with CAN as it allows the transmission of standard CAN frames. The CAN-FD network uses the CSMA/CD+AMP (Carrier Sense Multiple Access/ Collision Detection with Arbitration on Message Priority) scheme [10].

To enable the use of large payloads in the CAN-FD network efficiently, there is a need to put several packets or message signals in a single frame. This problem is referred to as the frame packing problem and it is very complicated due to differences in sizes, periods and deadlines or time criticality of individual message signals [11], [12].

2) 100M Switched Ethernet:

The traditional Ethernet uses a shared medium (e.g. hub technology), since then newer versions of the Ethernet has been developed that makes use of switches instead of the hub technology [18] as shown in Fig. 1. This was done in order:

i. To enable the use of full-duplex mode and as well increase the bandwidth.

ii. To avoid collisions. But this only led to a shift from collision problem to congestion problem in 100M Switched Ethernet.

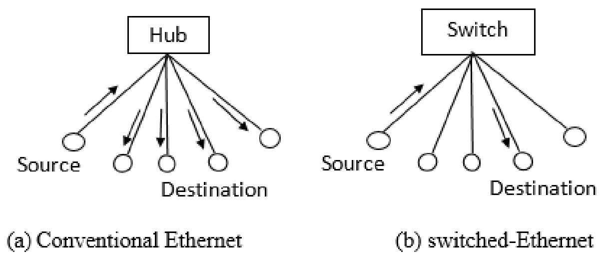

Fig. 1: Comparison of transmission method of Ethernet and 100M Switched Ethernet. Fig. 1 illustrates the operations of hubs and switches when used with Ethernet.

The 100M Switched Ethernet did not require the use of the CSMA/CD protocol any more, as all nodes can access the channels simultaneously and the switches sends the frames to the exact destination node. Switches has the ability to learn the MAC addresses of every single port connected to it and the interface port they are connected to unlike hubs. If two or more nodes are trying to send packets individually to the same destination node, packet that arrives first occupies the receiving or the destination node while the other packet queue up. Packets wait in the buffer till all the packets ahead of it have been transmitted. When the buffer is fully occupied any arriving packet becomes discarded. The delay encountered in this process is not deterministic. For systems with real-time requirements, there is a need for techniques and procedures to handle deterministic communications via Ethernet Switches [6].

V. NETWORK MODEL OF THE NCSs AND SYSTEM PARAMETERS:

1) Block Diagram of NCSs

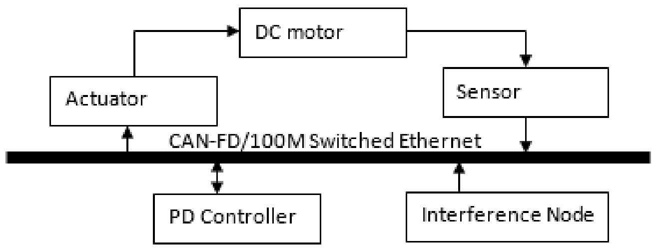

Fig. 2: A block diagram model of the NCSs. Fig. 2 illustrates how the different control components are interconnected through the network.

2) NCS Model

Figure 3. shows the NCS in-built model by Truetime kernel in the environment of Matlab/ Simulink 16b [19].

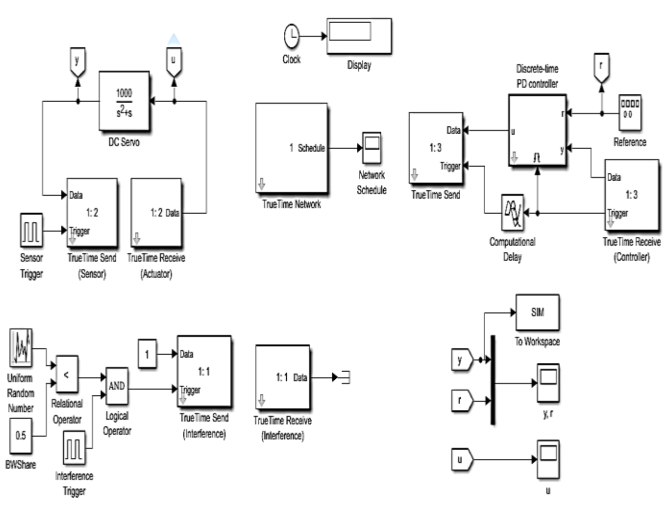

Fig. 3: NCS Model. Fig. 3 shows the NCS in-built model by Truetime kernel in the environment of Matlab/ Simulink 16b.

3) *Process and Controller:* The DC motor is represented analytically by the continuous-time transfer function [19]:

$$G(s) = \frac{1000}{s(s+1)} \quad (1)$$

In order to have a percentage overshoot less than 5%, damping ratio, ζ = 0.7, the PD parameters are set to the following values: $K_P = 1.5$, $K_d = 0.054$, and

Sampling time, h = 0.01secs.

Analytical model of the discrete PD (Proportional Derivative) controller approximation:

$$e(t) = r(t) - y(t)$$
$$p(t) = K_p e(t)$$
$$i(t) = i(t-h) + \frac{K_i h}{2}(e(t) - e(t-h)) \quad (2)$$
$$d(t) = \frac{K_d}{h}\big(e(t) - e(t-h)\big)$$
$$u(t) = p(t) + i(t) + d(t)$$

VI. SIMULATION RESULTS AND COMPARATIVE ANALYSIS

In the simulation, two kinds of networks were simulated with parameters as shown below:

- *100M Switched Ethernet* :

  Bit rate – 100Mbit/s,

  Minimum frame size – 512 bits

- *CAN-FD*:

  Bit rate – 8Mbit/s,

  Minimum frame size – 96 bits.

Four network conditions were considered in studying the control performance of the system: Ideal Conditions, Packet Loss, Sampling Period and Network Utility.

1. Simulation result for each network under ideal condition with sampling period of 0.007s:

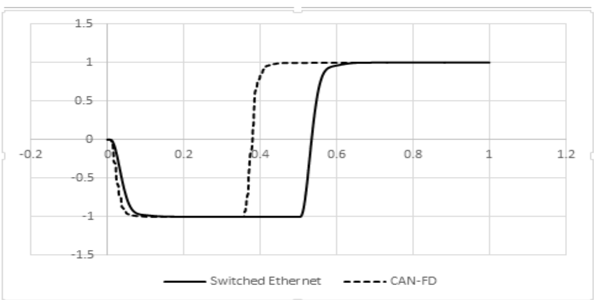

Fig. 4: Simulation result of CAN-FD and 100M Switched Ethernet networks under ideal conditions

Result Analysis: From the simulation results as shown in Fig 4, the output of both networks followed the reference signal and they were both stable under this condition showing a good level of control performance. Nevertheless, the CAN-FD network had a better real-time performance. As shown in Fig. 4, the CAN-FD network is faster than the 100M Switched Ethernet network under ideal conditions.

2. Simulation result for Packet Loss in each network, by varying loss probability

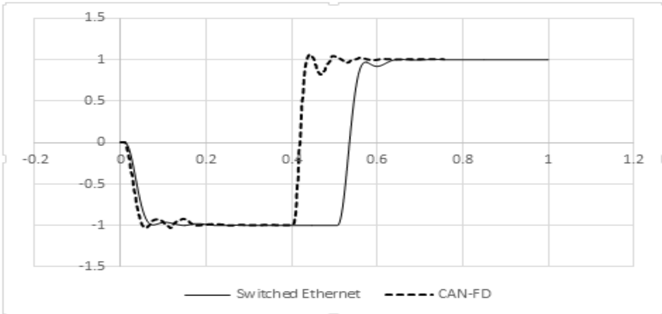

Fig. 5: CAN-FD and 100M Switched Ethernet networks with probability loss of 5%

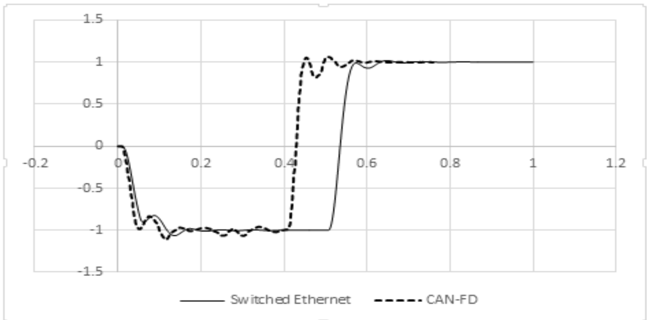

Fig. 6: CAN-FD and 100M Switched Ethernet networks with probability loss of 10%

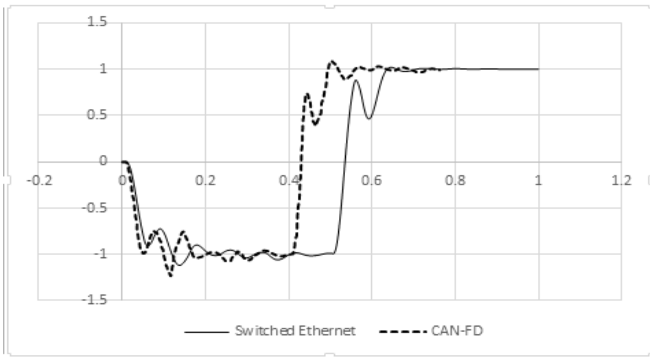

Fig. 7: CAN-FD and 100M Switched Ethernet networks with probability loss of 15%.

Result Analysis: The simulation for each network under different Loss Probability is shown in Fig. 5 to Fig. 7. The loss probability models the behaviour of the networks under different packet loss or information loss conditions. It was observed that as the loss probability increases, the control performance in both network reduced and the output signals became very much unstable. The 100M Switched Ethernet network under this condition demonstrated a better control performance when compared to the CAN-FD network. Though, in terms of latency, the CAN-FD network still maintained a better real-time performance than the 100M Switched Ethernet.

3. Simulation result for each network under different sampling periods.

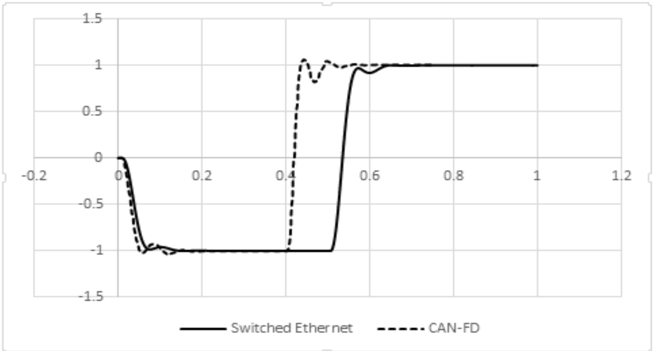

Fig. 8: CAN-FD and 100M Switched Ethernet networks with sampling period = 0.007seconds

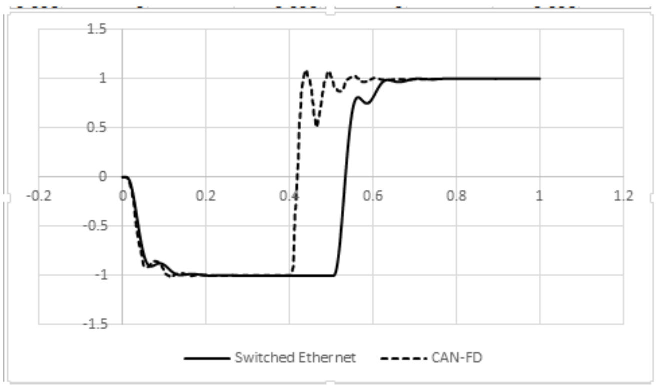

Fig. 9: CAN-FD and 100M Switched Ethernet networks with sampling period = 0.008seconds

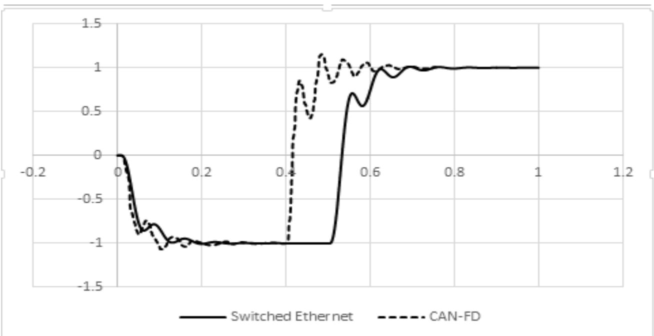

Fig. 10: CAN-FD and 100M Switched Ethernet networks with sampling period = 0.009seconds

Result Analysis: The sampling period at the sensor is varied for each network and the result is shown in Fig. 8 to Fig. 10, for each of the networks. Starting with a sampling period of 0.007s to 0.009s, for both networks good control performance was observed under a lower sampling period. It was observed that as we increased the sampling period at the sensor node, the control performance reduces for both network. Nevertheless, under this condition the 100M Switched Ethernet also performed better in terms of control performance when compared to the CAN-FD network but still demonstrated a higher level of latency than the CAN-FD network.

4. The bandwidth of each of the networks is shared with other applications with an interference of 30% and 50%.

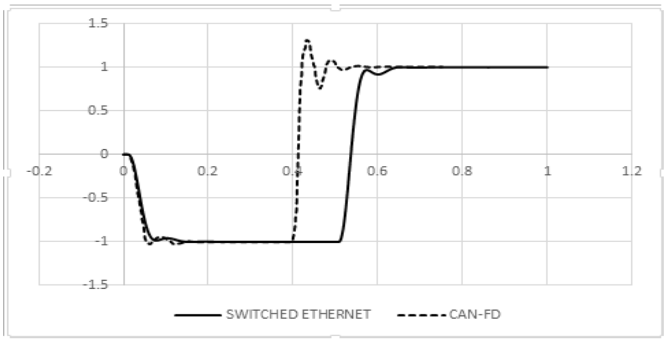

Fig. 11: Simulation results for each network when real-time network process is shared with other applications with an interference of 30%.

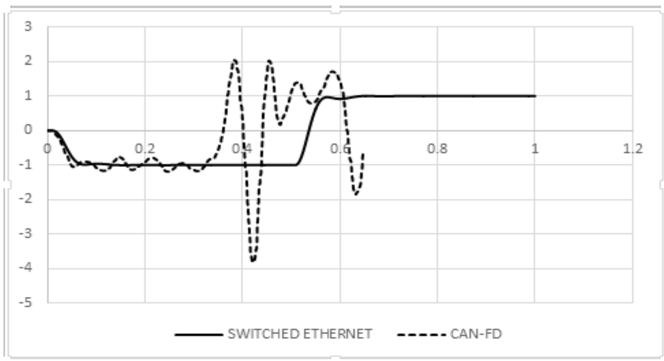

Fig. 12: Simulation results for each network when real-time network process is shared with other applications with an interference of 50%.

Result Analysis: Fig. 11 and Fig. 12 shows the result for the simulation of the 100M Switched Ethernet and CAN-FD networks when the real-time network process is shared with other applications (external interference) with an interference level of 30% and 50% each. This result shows the network performance under the condition that the network is overloaded and also tells of the utilization of the network node. From the simulation result it was observed that the 100M Switched Ethernet network due to its large bandwidth is more efficient and has a better control performance when subjected to external interference by sharing the real-time network medium with other applications. While the CAN-FD network was highly unstable showing a poor control performance for interference level above 40%.

VII. OTHER PARAMETERS USED FOR COMPARING CAN-FD AND 100M SWITCHED ETHERNET NETWORKS

1. Advantages of CAN-FD Over 100M Switched Ethernet:

i. Network Security: Since the 100M Switched Ethernet makes use of IP (Internet Protocol) address, it is therefore a less secure means of data transmission than the CAN-FD network. This implies that the control system may be vulnerable to cyber-attacks. Even though connections done with the 100M Switched Ethernet can be secured with bridges, routers, and firewalls, the vulnerability of this system is one that manufacturers have not face with the CAN-FD network.

ii. Minimum Frame Size of the Network: For industrial automation applications, the high data rate of the 100M Switched Ethernet has not yet improved its efficiency when compared to the CAN-FD. The minimum size of frame for the 100M Switched Ethernet is 64 Bytes. When there is the need to transmit a data of about 0 – 8 bytes, the excessive overhead can make data transmission inefficient, even with its high data rate. But the CAN-FD is very suitable in transmitting small messages of such sizes efficiently.

2. Advantages of 100M Switched Ethernet Over CAN-FD

Some of the primary advantages of the 100M Switched Ethernet over traditional CAN are:

i. 100M Switched Ethernet offers higher data rates up to 1GB/s. This means more data per second can be accessible leading to faster data transfer.

ii. The use of the 100M Switched Ethernet technology is more efficient when the real-time process shares the same medium with other applications due to its large bandwidth.

iii. The maximum allowed length of cable for the 100M Switched Ethernet is 100metres while for the CAN-FD cable length depends on bit rates for a bit rate of 1 Mbit/s the maximum cable length is 40metres and for a maximum bit rate up to 15 Mbit/s the maximum cable is just 10metres

VIII. CONCLUSION

The obtained results for each network condition showed that the 100M Switched Ethernet technology is a better alternative to the CAN-FD technology in terms of control performance especially when the network medium is shared with other applications. Nevertheless, The CAN-FD network is more suitable for real-time systems in modern automation industry as it meets the requirement for data communication in application areas such as in-vehicle bus communication. However, the frame packing problem in the CAN-FD network is still a very complicated issue to contend with, even though research works have been carried out to address this issue, there is need for more works to be done to minimize the bandwidth utilization and as well meet the real-time constraints for the controlled system [11], [12].

The authors has shown the control performance of a networked control system when the 100M Switched Ethernet is used is similar to the traditional control system provided there is no packet loss in the communication. Therefore the single-level 100M Switched Ethernet is feasible for all categories of control systems. However, for the multi-level 100M Switched Ethernet, the required time can be met only when the number nodes and the number of levels interconnected to the 100M switches properly placed.

The drawback in the 100M Switched Ethernet in terms of real-time performance can been compensated through the use of time-scheduled Ethernet Standards. With the use of time scheduling or prioritization packet procedures such as FCFS (First Come, First Served), PQ (Priority Queue); deterministic real-time communication can be achieved in standard IEEE 802 Ethernet and the delay in the 100M Switched Ethernet can be compensated. This implies that in a Deterministic Ethernet network, there is a guarantee of a better real-time performance for significant scheduled communication. [6], [8].

IX. CONTRIBUTIONS

This research work has contributed to the knowledge base in the field of engineering as this will aid engineers and manufacturers in the field of NCSs with a better information on the performance of the two communication networks (CAN-FD and 100M Switched Ethernet) that were analyzed in this research work. Also this research work will enable researchers to be enlightened on the areas of NCS where more research work needs to be done.

X. FUTURE WORKS

1. Analysis of Time-Scheduling Policies: In order enhanced determinism and reliability in the 100M Switched Ethernet an analysis of several time-scheduling policies is necessary. Since there are several means of performing time-scheduling such as the FIFO (First In, First Out), Priority Queuing etc. The principle of the fixed priority is such that the frames that has the highest priority, that are ready for transmission will be transmitted before frames with lower priority. As a result the real-time performance and reliability of the network can be improved.

2. Analysis of Jitters in Switches: Research work could also be focused on the integration of time-scheduling policies in switches as they play an essential role in the overall network performance of the 100M Switched Ethernet network.

3. Frame Packing Problem in CAN-FD: More research work needs to be done to address the issue of frame packing in the CAN-FD networks in order to improve the utilization of the bandwidth of the CAN-FD network.

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