A Test Bed Study of Network Determinism for Heterogeneous Traffic Using Time-Triggered Ethernet

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Abstract—**Future tactical communications involves high data rate best effort traffic working alongside real-time traffic for time-critical applications with hard deadlines. Unavailable bandwidth and/or untimely responses may lead to undesired or even catastrophic outcomes. Ethernet-based communication systems are one of the major tactical network standards due to the higher bandwidth, better utilization, and ability to handle heterogeneous traffic. However, Ethernet suffers from inconsistent performance for jitter, latency and bandwidth under heavy loads. The emerging Time-Triggered Ethernet (TTE) solutions promise deterministic Ethernet performance, fault-tolerant topologies and real-time guarantees for critical traffic. In this paper we study the TTE protocol and build a TTTech TTE test bed to evaluate its performance. Through experimental study, the TTE protocol was observed to provide consistent high data rates for best effort messages, determinism with very low jitter for time-triggered messages, and fault-tolerance for minimal packet loss using redundant networking topologies. In addition, challenges were observed that presented a trade-off between the integration cycle and the synchronization overhead. It is concluded that TTE is a capable solution to support heterogeneous traffic in time-critical applications, such as aerospace systems (eg. airplanes, spacecraft, etc.), ground-based vehicles (eg. trains, buses, cars, etc), and cyber-physical systems (eg. smart-grids, IoT, etc.).**

Index Terms—**Determinism, time-triggered Ethernet, quality of service**

I. Introduction

REAL-TIME computing presents unique difficulties, requiring in-depth study and optimization of key technologies, especially when the infrastructure or resources are limited, as in space networks or avionic networks. The challenge is to achieve highly deterministic behavior while maintaining high performance in a heterogeneous traffic environment [1]. Some of the features of an ideal interconnect network for a system deployed in real-time include:

1) **High Performance** The network must guarantee high throughput and low latency in order to meet real time requirements of complex applications
2) **Determinism** A network is deterministic when there is little or no jitter during packet transmission, an essential requirement for real-time systems.
3) **Fault Tolerance** An important criterion for any aerospace system is to have high reliability. An aerospace network must be able to tolerate both permanent and temporary faults without leading to catastrophic results.
4) **Unified Network** Keeping in mind the constraints for size, weight and power (swap) in aerospace environments, a single network is expected to carry different classes of traffic (critical, sub-critical and non-critical traffic) within the same medium.

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Recently, several vehicular, Ethernet, and Internet-based solutions have been proposed for real-time communications. The premier local area network standard continues to be Ethernet for its higher bandwidth and utilization. However, one of the primary bottlenecks for real-time systems – delay and jitter between the nodes, is particularly observed in Ethernet-based communication systems, which suffer from variable performance and unfairness, depending on how many nodes are transmitting at a given time. Time-Triggered Ethernet (TTE) solutions have been proposed which promise the best of both worlds – deterministic performance, fault-tolerant topologies and real-time guarantees for critical traffic. TTE is therefore seen as an attractive solution for many time-critical applications such as aerospace systems (eg. airplanes, spacecraft, etc.), ground-based vehicles (eg. trains, buses, cars, etc.), or even cyber-physical systems (eg. smart-grids, IoT, etc.). Other proposed systems include Controller Area Network (CAN), Time-Triggered Protocol (TTP), and Local Interconnect Network (LIN), in addition to long standing protocols, such as Avionics Full-Duplex Switched Ethernet (AFDX®).

In this paper, we study the TTE protocol as a networking solution for time-critical applications. We have built a TTE test bed for protocol observation and evaluation. On this test bed, we have implemented a heterogeneous architecture for analysis of various types of traffic with quality of service constraints. In addition, we have examined the synchronization processes of TTE for time-triggered traffic in the presence of heterogeneous traffic. Network performance results from experimentation of TTE system are provided for configured multi-hop and redundant topologies. Finally, this paper will give ideas for future research trends and opportunities for utilizing TTE technology. The rest of the paper is structured as follows, Section II describes the related networks for time-triggered operation. Section III describes the architecture behind the TTE system. Section IV provides details of the TTTech testbed and the network topology experiments configuration. In Section V, the

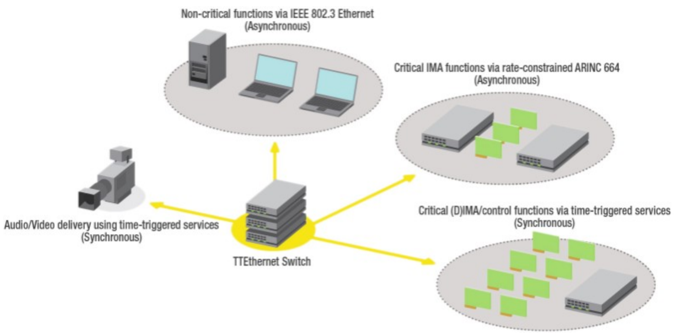


Fig. 1. TTE Networking Concept

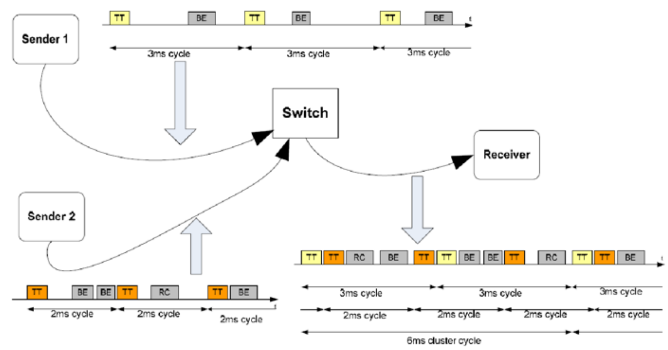


Fig. 2. TTE Synchronized Cycles with Three Classes of Traffic: Time-Triggered (TT), Rate- Constrained (RC), and Best Effort (BE)[7]

network performance metrics and analysis are described, while Section VI provides the numerical results. Finally, Section VII contains the conclusion and future work.

II. Related Work

Controller Area Network (CAN or CAN bus) is a vehicle bus standard designed for micro controllers and other devices to communicate with each other in applications without a host. It is a message-based protocol, created originally for electrical wiring within automobiles. CAN utilizes message arbitration and standard scheduling, where nodes solve contention by sending node information to the CAN bus. CAN lacks deterministic scheduling for real-time events because the message arbitration process in the CAN bus is thought to delay message routing. Time-Triggered CAN (TTCAN) is a CAN bus counterpart that resides primarily in the OSI session layer. Synchronization is accomplished by a single master TTCAN node which assigns time slots to the remaining nodes on the network [2], [3], [4].

The Time-Triggered Protocol (TTP) is a technology developed by TTTech as a real-time field-bus protocol for control systems. TTP provides high-speed, fault-tolerant communication for safety critical networking in vehicles and industrial applications [5]. In contrast, TTE promises similar characteristics to both TTP and TTCAN, but handles timing at the network layer, where the switches distribute the synchronization to the entire network.

The Local Interconnect Network (LIN) was developed as a simpler, more cost-effective alternative field bus technology for low bit rates. LIN has a single master node which coordinates timing across a network of slave nodes. LIN provides sufficient functionality at low cost with a finite number of nodes. It lacks redundancy and has low performance requirements [2], [4]. In contrast, TTE promises a variety of network configurations for redundancy of all nodes. TTE also promises determinism with very low jitter, and high network performance (low latency, high throughputs, etc.), along with its synchronous scheduling.

Avionics Full-Duplex Switched Ethernet (AFDX®) is a data network, patented by international aircraft manufacturer Airbus, for safety-critical applications [6]. It utilizes dedicated bandwidth while providing deterministic quality of service (QoS). The six primary aspects of an AFDX® data network include full duplex, redundancy, determinism, high speed performance, switched, and profiled network. This protocol aims to provide similar features to those of TTE. The main difference is TTE technology is based on a fully synchronous schedule which provides deterministic behavior based on real-time scheduling methods rather than using asynchronous methods such as the AFDX® bandwidth allocation gap (BAG).

III. Network Architecture

As mentioned previously, real-time computing presents unique difficulties, requiring reliable and deterministic behavior from the network while it maintains high performance, even in a heterogeneous traffic environment. In this section, we examine the architectural components of TTE that provide for determinism and heterogeneous traffic.

The Time-triggered Ethernet (TTE) protocol is defined by the standard SAE AS6802 [8]. It is built as an extension of the IEEE 802.3 standard and provides enhanced quality of service for Ethernet networks via deterministic, synchronous and congestion-free communication. Since the TTE protocol is built over IEEE 802.3, TTE devices can send either standard Ethernet packets or TTE packets. The TTE network supports three classes of traffic, where the total bandwidth is shared by the different classes of traffic, as shown in Figure 1:

- Time-triggered (TT) - SAE AS6802
- Rate Constrained (RC) - ARINC 664 p7 or AFDX®
- Best Effort (BE) -IEEE 802.3,

TT traffic is transmitted with no contention in the medium, with each packet in a predetermined assigned slot. Successive TT transfers are offset by a duration that has a minimum and maximum value. If transmission does not occur in the designated slot, the switch recognizes the inactivity and frees up the bandwidth for other classes of traffic. RC traffic does not follow a set schedule. However, successive RC transfers are offset by a minimum duration, which results in more guarantees than normal Ethernet traffic. BE messages do not follow a fixed schedule and do not carry a minimum or maximum duration.

As shown in Figure 2, devices connected to the TTE network may run with different local clocks, requiring periodic synchronization between devices so that the TTE schedule is followed and deterministic behavior is ensured. This period of

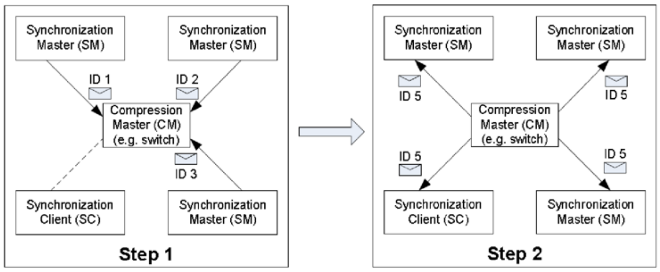
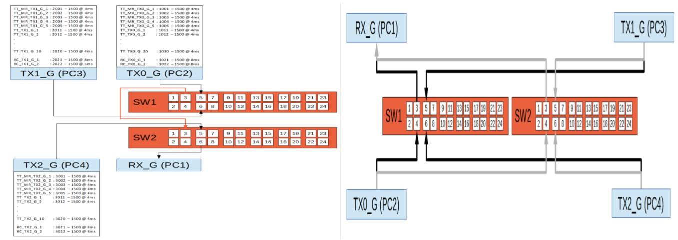


Fig. 3. TTE Synchronization Process



(a) Multi-hop Topology (b)Redundant Topology

Fig. 4. Tested Network Configurations

synchronization is known as the integration cycle. Larger integration cycles can negatively impact determinism. However, each synchronization period has an overhead cost in time and bandwidth, so that a trade-off exists between integration cycle size and synchronization overhead.

A. *Synchronization Process*

Synchronization is established and maintained by exchanging synchronization messages called Protocol Control Frames (PCF) among all devices in the network's Sync Domain. The PCF contains information about the cumulative static and dynamic delay imposed on the transmission of a packet in a particular path. As shown in Figure 3, devices in the TTE network are placed into one of three categories: Synchronization Master, Synchronization Client and Compression Master. One of the switches in the network is configured as the Compression Master while the other switches and additional end-systems behave as Synchronization Clients. Synchronization Masters are a subset of the end system devices generating traffic. In the first step, the Synchronization Masters send the PCF packets to the Compression Master. The packets may be routed to the Compression Master through switches acting as Synchronization Clients. These clients add their delay information to the packets before forwarding them to the next switch. In the second step, the Compression Master compresses the received PCFs and generates a new PCF. This PCF is then sent to all the other Synchronization Masters and Synchronization Clients to establish the current cycle time.

Once synchronization is established, the intermediate switches must make routing decisions that maintain the schedule and the associated priorities of the messages. In common Ethernet technology, if lower priority frames cause contention at the port of a switch that is currently serving higher priority frames, then typically the lowest priority frame is dropped. In the worst case, both low and high priority frames are lost. In TTE, the goal is to use scheduling and routing in order to keep *all* frames that contend at a specific port. Next, we describe two methods TTE implements for routing: shuffling and media reservation.

B. *Shuffling*

Shuffling allows frames being actively transmitted to continue along their transmission path, while the other frames in the congested traffic are sorted out, highest priority first. In this architecture, TT messages will always be transmitted first. The next frames to be transmitted are the RC messages, which have second highest priority. In addition to sorting frames by priority, the switch will also perform traffic policing to enforce the bandwidth allocation gap (BAG) for given RC Virtual Links. BE messages are asynchronously transmitted at the lowest priority, so there is no additional mechanism for controlling message output for BE messages.

C. *Media Reservation*

As the name implies, media reservation is a switching scheme that sets apart an allotted window size for the highest priority frames before the transmission of any other frames. Media reservation can be enabled for each port of the switch, and for different priority traffic. For example, for a particular window, only TT messages can be transmitted, followed by the RC or BE messages, followed by a possible period of congestion, after the slotted window duration is over. No additional jitter or latency is introduced for the TT frames when media reservation is enabled.

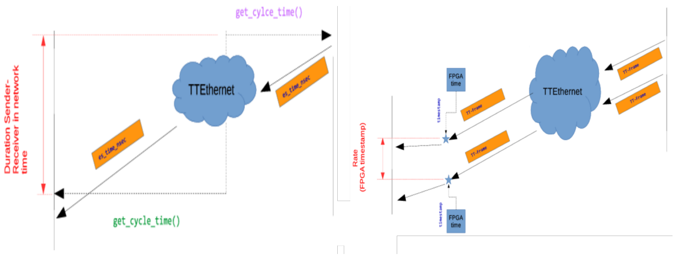
As described above, the TTE architecture sets out to manage deterministic traffic through periods of synchronization/integration and the accommodation of multiple traffic types with different routing techniques. Few studies have tested the ability of TTE to manage the quality of service constraints of heterogeneous traffic using a real-time TTE hardware test bed. In the following sections, we describe our experimental set up with a TTE test bed and analyze the performance of TTE with heterogeneous traffic.

IV. Experimental Test Bed

The experimental testbed consists of a TTE network with 2 TTE switches and 4 end systems. The TTE Switch consists of 24 ports (6 of them supporting 1000 Mbit/s) and uses an Altera ARRIA V GX FPGA as the Switching Engine. As described previously, the switch supports the partitioning of all three traffic classes: TT, RC and BE. The end systems have a Distributed Integrated Modular Avionics (DIMA) Architecture (an architectural approach consisting of distributed hosts connected by a safety-critical communication system that provides different attributes to support modularity and integration).

A. *Network Configurations*

The network topologies tested for this paper are shown in Figure 4. We used a heterogeneous configuration of the TTE



(a) Method 1:Inter-Arrival (b)Method 2: Cycle-Time

Fig. 5. Methods of Measuring Latency and Jitter

system where TT, RC, and BE packets are being transmitted throughout the network together. The system consists of two network configurations: (1) a multi-hop network topology, to test the delay compensation of forwarding messages through multiple switches; and (2) a redundant network topology, to test the network performance when focused on fault tolerance. Each network configuration supports 100 Mbit/s and 1000 Mbit/s (1 Gbit/s) data rates.

V. Performance Analysis

Network performance metrics were observed, including latency, packet loss, throughput, and jitter, as described in each section below, with the goal of determining the particular characteristics of the TTE systems when presented with rigorous and dynamic traffic conditions.

A. Network Jitter

Jitter, the variation in the latency on a packet flow between two nodes, is a crucial network performance metric for time-critical systems. Jitter can lead to unintended deviations or inconsistencies that degrade the quality of communications. Jitter of the TTE system can be measured in multiple ways as the variation of the points in time periodic messages are received by a destination node. The first method is useful for situations where both transmitted and received timestamps cannot be recorded. In this paper, the test bed and timestamps are available. The second method is used for the experiments conducted in this paper.

Method 1: Inter-Arrival Time Histogram Method: The Inter-Arrival Time Histogram Method is used to measure jitter in systems where packets are transmitted from the end systems in constant intervals [9]. The packet-to-packet jitter can be obtained by subtracting the subsequent arrival times and adjusting for the transmission period. For example, suppose end-system 1 (PC1) is transmitting TT messages to end-system 2 (PC2) every Δt seconds. Packet 1 is transmitted at X_{t1} and is received at Y_{t1}, and packet 2 is transmitted at X_{t2} and received at Y_{t2}. The latency for packet 1 is calculated $L_1 = Y_{t1} - X_{t1}$ and the latency for packet 2 is calculated $L_2 = Y_{t2} - X_{t2}$. The packet to packet jitter, $J = L_2 - L_1$, is then calculated as shown:

$$\begin{aligned} Y_{t2} - Y_{t1} &= (X_{t2} + L_2) - (X_{t1} + L_1) \\ &= (X_{t2} - X_{t1}) + (L_2 - L_1) \\ &= \Delta t + J \\ J &= (Y_{t2} - Y_{t1}) - \Delta t \end{aligned} \tag{1}$$

Method 2: Cycle-Time Difference: The cycle-time difference is measured by a source node periodically sending packets to a destination node, which receives the messages along with the timestamps captured by the TTE End-System A664 Lab Cards. The cycle time-difference between the current message and the last received message is the calculated jitter, as shown in Figure 5.

B. Network Latency

Latency definitions vary depending on the factors considered. In this paper, latency for the TTE system is measured as a combination of latencies accumulated during different phases of transmitting a packet, and is calculated:

$$\begin{aligned} T = {} & T_{SNA} + T_{PCIe-send} + T_{TTE-send} + T_{cable-prop} \\ & + n_S T_{switch} + (n_S - 1) T_{mulithop} + T_{recv} \\ & + T_{Dest} + T_{proc} \end{aligned} \tag{2}$$

where T_{SNA} is The source node application latency, $T_{PCIe-send}$ is the source node application to TTE end-system (PCIe) send latency, $T_{TTE-send}$ is the TTE end-system send latency, $T_{cable-prop}$ is the cable latency, $n_S T_{switch}$ is the switch latency through n_S switches, $(n_S - 1)T_{mulithop}$ is the switch to switch latency (if in multi-hop configuration), T_{recv} is the TTE end-system receive latency, T_{Dest} is the TTE end-system to destination node application latency, and T_{proc} is the application processing latency. For the test bed, the PC1 recorded the time-stamp for the packet transmission into the packet payload. The receiving node then records a time-stamp of when the source node message was received. The send time is compared with the received time as illustrated in Figure 5.

C. Throughput

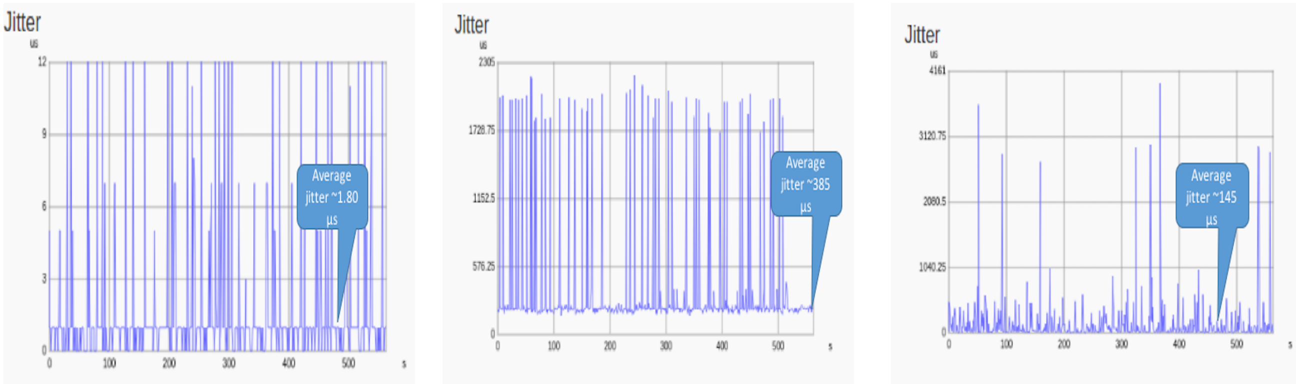
Throughput expresses the amount of data received over a given time period. Here, the test bed calculation for throughput was:

$$Throughput = \frac{n_f * Bits/frame}{period} \tag{3}$$

where n_f represents the number of received frames per period, $Bits/frame$ is the payload size of the received frames, and $period$ is the time in which the frames are received.

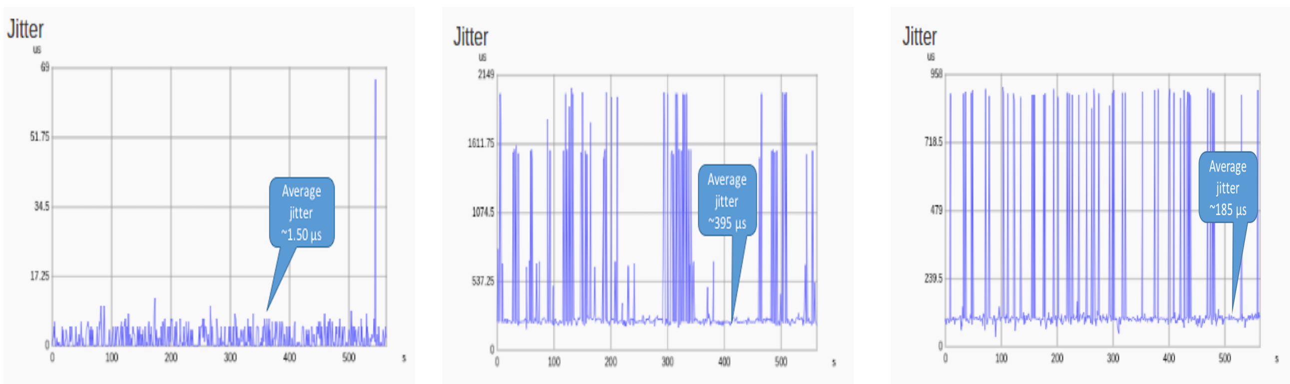
D. Packet Loss

Packet loss occurs for the TTE systems when one or more messages or message classes fails to reach its destination. This is usually caused by network congestion. To measure packet loss for the TTE system, the experiment was to designate three of the four end-node PCs (PC2, PC3, PC4) to generate traffic at their highest bandwidth data rate. This high rate of traffic



(a) TT packets (b) RC packets (c) BE packets

Fig. 6. Jitter in the Multi-hop Network Topology – Time-Triggered (TT), Rate-Controlled (RC) and Best Effort (BE) Traffic at 1Gbit/s



(a) TT packets (b) RC packets (c) BE packets

Fig. 7. Jitter in the Redundant Network Topology – Time-Triggered (TT), Rate-Controlled (RC) and Best Effort (BE) Traffic at 1Gbit/s

which passed through the two system switches to be received by PC1. When the traffic of the senders increased to a high percentage of a single link, the switches started to drop frames. The rate of dropped frames was recorded in the lost frame counters.

VI. Numerical Results

Experiments were conducted on the multi-hop and redundant network topologies for the TTE system. In the interest of space, Figure 6 and Figure 7 show the Jitter results, while the Table in Figure 8 shows all results for network latency, jitter, throughput, and packet loss for the both the 1 Gbit/s and 100 Mbit/s data rate.

Note that each figure shows that all message classes experience outlier packets with jitter values higher than average. The TTE application running during experimentation is partitioned into two major cycles including synchronization, and transceiving. The majority of the outliers are generated mainly from the TTE system's periodic synchronization process, discussed in section III, which could delay queued packets from transmitting on time, depending on the length of the cycle. Within the transceiving cycles, all packets are transmitted and received as scheduled. The average jitter values within the transceiving cycle are shown in the callout boxes in each figure. This issue is a challenge to be addressed in future work.

A. Jitter

The Time-Triggered Ethernet multi-hop and redundant experiments demonstrated that the network configurations were able to provide deterministic behavior for the time-triggered (TT) message class. The average jitter for TT messages remained consistently less than $\approx$2 microseconds for Gbit/s operation. This value increased when the network configurations were operated at 100 Mbit/s. However, as shown in the Table in Figure 8, the TT messages still displayed deterministic characteristics. The jitter value for the rate-constrained (RC) messages remained consistently between $\approx$ 350-450microseconds for both 1Gbit/s traffic and 100Mbit/s traffic. Best effort traffic suffered the most at 100Mbit/s, with jitter values close to 1millisecond, but performed better than rate constrained traffic for 1Gbit/s. However, this value is less reliable, since the BE messages had to be asynchronously transmitted and do not have a mechanism to control the packet transmission rate. The TT traffic used synchronized schedules and the RC traffic used bandwidth allocation gaps (BAGs) and traffic shaping to minimize overloading of the network with a specific link or message.

B. Network Latency and Packet Loss

The network latency for TT messages in the system was observed to be less than $\approx$150 microseconds for both multi-hop and redundant configurations operating at the 1 Gbit/s, confirming low latency for TT traffic for different network topologies due to the synchronous scheduling. The network latency for RC messages in both topological scenarios were observed to be less than that of TT messages, ≈120 microseconds, while the latency for BE messages varied at ≈800 microseconds or more. Since BE messages have the lowest priority and don't use a set schedule or BAG to determine when to transmit messages, packets are vulnerable to being delayed, dropped, or lost, thus increasing the BE message latency. The observed packet loss for TT, and RC message classes in the multi-hop or redundant network configurations were consistently low – only a couple of packets per millions transmitted were dropped or lost within the network. BE messages again took the greatest impact when trying to successfully transmit packets in the heterogeneous network.

Network Topologies	Message Class	Network Latency (µs)	Jitter (µs)	Throughput	Received Frames	Lost Frames
Multi-hop (1 Gbit/s)	TT	130.58	1.84	135.00	14646558	3
	RC	127.85	384.72	17.00	1852427	2
	BE	810.85	147.78	823.28	88465244	64999396
Multi-hop (100 Mbit/s)	TT	570.25	35.52	14.86	2153291	0
	RC	283.59	456.26	5.97	808515	0
	BE	2131.63	966.96	74.19	3562957	393347
Redundant (1 Gbit/s)	TT	78.84	1.55	135.14	23871732	2
	RC	100.94	398.41	17.00	3016385	2
	BE	947.76	187.40	821.00	144493362	106455242
Redundant (100 Mbit/s)	TT	342.93	4.14	15.00	4937962	0
	RC	202.42	464.78	6.00	2023631	0
	BE	1975.17	967.87	76.02	8267383	2410417

Fig. 8. TTE Performance Results

C. Throughput

The throughput varied greatly for each message class based on the change in data rates from 1 Gbit/s to 100 Mbit/s. For both network topologies operating at either data rate, RC messages demonstrated the lowest throughput at roughly ≈17 Mbit/s and ≈6 Mbit/s for 1 Gbit/s and 100 Mbit/s transfer speeds, respectively. BE messages showed the highest throughput at roughly ≈820 Mbit/s and ≈75 Mbit/s, respectively. TT messages were observed to have a small fraction, around ≈15%, of the configured data rate of the system. The throughput for TT and RC is lower because there was only a set volume of traffic configured on a periodic basis (virtually 100% of which is being successfully transfered in this case). BE on the other hand is attempting to transmit more data than there is available remaining bandwidth. If we consider the received frames and lost frames to be the sum total of the transmitted frames from the transmitters, you will see that (in the 1 Gbit/s case) 1.4 Gbit/s of traffic is presented to the link with less than 842 Mbit/s available (after TT and RC). Essentially, BE has a higher throughput because a) there is more bandwidth available to BE than is consumed by the other traffic classes, and b) there is more data being transmitted. Looking at the number of received frames compared to the number of frames transmitted (received + lost frames), then the 1 Gbit/s case shows only 57.6% successful BE transmission, while TT and RC have virtually 100% successful transmission. TT messages have the highest priority, but the TT message class did not require all (or even most) of the network bandwidth available.

VII. Conclusion

Real-time computing presents unique properties and challenges for interconnect networks that rely on advance next-generation systems to manage complex infrastructures. Time-Triggered Ethernet technology promises high performance, determinism, fault tolerance, and heterogeneous networking. Through experimental study, the TTE protocol has been shown to be able to support a heterogeneous network of three different message classes, provide high performance with data rates up to 1 Gbit/s for BE messages, determinism with under 2 microsecond jitter values for TT, and fault-tolerance through redundant networking topologies and error checking features. It is therefore seen as an attractive solution for many time-critical applications.

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