Time-Delay Simulation Analysis of Local Controller Networks

N. Kakanakov, M. Shopov, G. Spasov

Abstract: *In this paper simulation and analytical results for delay bounding and buffer size in switched Ethernet network are presented. Most of the calculations are made for the environment of Distributed Automation Systems where timing constraints are important. The traffic for the tests is from combined type – periodic constant bit rate and stochastic with Poisson distribution. The traffic mixture is made out of four different workloads mapped to the standard communication scenarios in distributed embedded systems environment. The prioritization schemes are mapped to the 802.1p traffic types. The analytical results are made using Network Calculus. The simulation is made using Network Simulator (NS).*

Key words: *Switched Ethernet, Controller Networks, Distributed Automation, Network Calculus, Network Simulator.*

INTRODUCTION

Nowadays, control and automation become more complex due to the tasks and processes that must be managed. Complex automation processes cannot be controlled and monitored by a single controller. This has lead to new research and development in the field of distributed automation. In such systems, the control loop is closed over some network and the network parameters as delay and connection speed must be studied and tuned. As long as Ethernet is the most often used network standard it is applied in distributed automation and local controller networks are build using it. The research efforts are shifted towards congestion in switches, their multiplexing latencies and Ethernet traffic prioritization schemes [2, 5, 9, 12].

The analysis of the application of the Ethernet in local controller networks differs from traditional network analysis, as it needs not a statistical mean values but worst case bounds. An apparatus that deals with the upper bounds on communication delays and buffer requirements is Network calculus. This is a technique to apply system theory to communication analysis. Its main parameters are the arrival curves of the traffic loads and the service curves of the communication elements. It is based on the fundamental work of [1] and [7].

Network Simulator (NS) [13] is one of the most popular tools in academia for evaluation of network protocols and topologies. It represents a discrete, event-based simulator that has an ability to be easily extendible and modifiable due to its open source nature. NS has a good set of supported queue management policies and one of them - Class-based Queueing (CBQ) [14] will be used throughout this paper to simulate IEEE 802.1p (CoS) in Local Controller Networks.

The goal of the paper is to provide some preliminary simulation results on packet delays in local controller networks, based on Fast and Gigabit Ethernet. These simulation results are going to be compared to analytical results to check the analytical model that is based on the work of [1, 4, 7, 8] and current authors.

EXPERIMENTAL SCENARIO AND PARAMETERS

In traditional network applications the main parameters that are evaluated are the performance and the throughput. In distributed real-time and embedded systems the most valuable parameters are the delay of the messages, the probability of error messages and the jitter – the deviation of the delay [3, 5]. These parameters are closely related with the parameters of the local network. On the network nodes main parameters are the message size, packets distribution times, delay from the node's communication stack. On the communication subsystem parameters are network topology, bandwidth, bit error rate, capacity of the switches, switch priority and queue management mechanism [6, 10].

Traffic types and workload distribution

The choice of appropriate traffic types and load distribution is a key factor in evaluation of a communication protocol. In distributed embedded system environment, devices exchange data between each other and with a master controller. Specific characteristics of the exchanged data and the time of exchange are the main differences from the office networks. In a network of controllers there are four main scenarios for data exchange. The first scenario is exchange of request-reply pairs for control or monitoring of devices. The second scenario is sending configuration data to devices. The third scenario is diagnostics – the master request specific parameters and the devices sends their values periodically. The last scenario is sporadic sending of alarms [3, 11].

Based on this exchange scenarios and the probability of their occurrence, the system workload can be defined. Most of the authors define four classes of workloads for controller networks. The first class (WT1 in the paper) is mapped to the exchange of messages for diagnostics, monitoring and control. It is about 75-90% of the overall traffic. The second class (WT2) is mapped to the exchange of event-driven exceptional messages – alarms. It is about 5-15% of the overall traffic and usually has Poisson distribution of the packets inter-arrival times. The third class (WT3) is mapped to the configuration scenario and includes configuration of the device and the network itself (DHCP, STP, CDP, etc.). Its part is under 5%. The last class (WT4), in contrast to other three classes, exchange big-sized messages. Its part is under 1% of the overall traffic and occurs mostly in the initialization part of the lifecycle of the systems. It includes file and/or code upload to devices [4, 6]. The main parameters are shown in Table 1.

Table 1: Switch and flows parameters

SW		WT1		WT2		WT3		WT4	
R [bps]	1.0×10^8	L [bits]	576	b2 [bits]	4096	b3 [bits]	16384	b4 [bits]	48704
S [s]	4.5×10^{-5}	T [s]	1.0×10^{-4}	r2 [bps]	4.0×10^4	r3 [bps]	1.0×10^5	r4 [bps]	1.0×10^6
				M2 [bits]	2048	M3 [bits]	8192	M4 [bits]	12176
				p2 [bps]	1.0×10^8	p3 [bps]	1.0×10^8	p4 [bps]	1.0×10^8

Simulation scenario

In the context of the multi-tier model for distributed automation suggested in [15] the master node in the controller network is represented by a transaction server (TS). The slave nodes are presented by a set of controllers, typically around 15-20 controllers per network segment. Since we assume full-duplex micro-segmented connections and only master-slave communications we can reduce the complexity of the simulated topology to the one shown on figure 1. It could be concluded that the master-slave communication will lead to a highly asymmetric workload in the switch node, thus the connection between TS and switch node is chosen to be 1Gbps and the connections with controllers – 100Mbps (figure 1).

The output buffers of the controller devices are not a subject of interest for the current case and a simple FCFS (First-Come-First-Served) queue management for the links between controllers and the switch is used. Of major concern here is the queue management of the output buffer of the switch port connected to the TS. Performance parameters of all four traffic types are directly influenced by this choice. The queue management to be used is a combination of SP (strict priority) and WRR (weighted round-robin) to retain maximum closeness to the implementation in the off-the-shelf network device (1P3Q1T – Cisco Catalyst 2950 switch). It consists of one SP queue and three queues in WRR (70/25/5 %). Implementation in NS is based on a CBQ/WRR (figure 1). First, the inbound traffic is classified and the SP traffic is forwarded without any hold. The other traffic is forwarded to a CBQ node and further classified in three queues and WRR scheduling is made for the packets in the three queues.

The selection of NS traffic generators should be as much realistic as possible to ensure accurate results. Traffic WT1 is implemented as several UDP/CBR (Constant bit rate). Traffic WT2 is implemented using TCP as transport agent to ensure guaranteed delivery and Exponential application generator to map the sporadic nature of alarm messages. Traffic WT3 is characterized by burst exchange of large packets (during startup and network reconfiguration) and small packets at fixed periods (*keepalive messages*). The first one is implemented as Exponential and the second one as a CBR. Traffic WT4 is implemented as TCP/HTTP/FTP (figure 2).

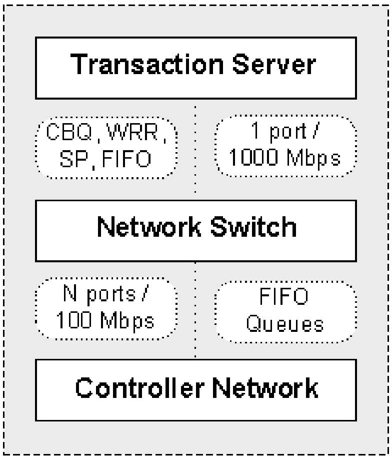

Figure 1. Simulation topology – Abstract view

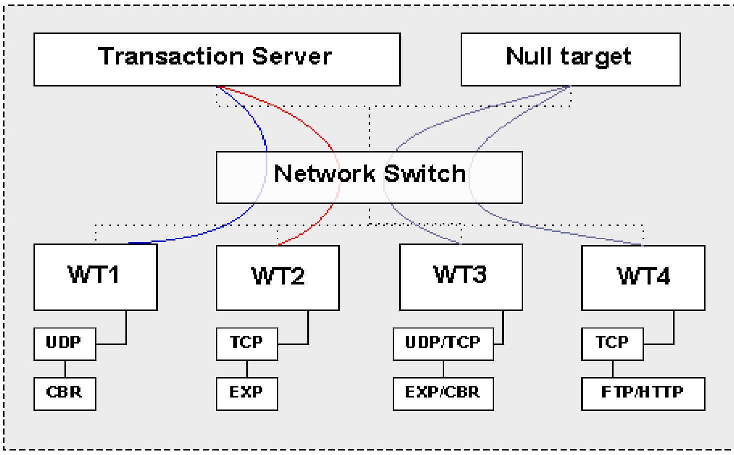

Figure 2. Simulation topology – Traffics view

In the analytical model the traffic loads are described with the parameters M – maximum frame size, p – peak rate, b – burst size, and r – long term average rate. The NS simulator uses the parameters packet size, burst time, idle time, and rate. The mapping between these two sets of parameters is given with the following equations: rate = p, packet_size = M, burst_time = b/p, idle time = b*((p-r)/p*r).

ANALYTICAL RESULTS

The delay from the switch can be complex for calculation when prioritization is applied and there are more than one queues. Then, the delay is calculated for each flow separately and a coefficient is added that described the time waiting for the higher priority packets to release the channel. The parts of the switch delay are from multiplexing and from queuing. Typical switch multiplexing delays are in order of 45 μs for Fast Ethernet and 25 μs for Gigabit Ethernet [8]. Assuming that switch delay is separated in multiplexing delay and queuing delay, we can compute the switch delay bounds with Network calculus.

To apply the Network Calculus to the presented scenario, the right parameters of the different flows (e.g., arrival curve, frame size, average rate) and the switch (e.g. service curve, forwarding rate, latency, queuing discipline) must be selected. Flow WT1 is periodic, so its arrival curve is described with equation (2) with L – frame size and T – the period.

(2) $$\alpha_1(t)=L+\frac{L}{T}.t\ ,$$

The other three flows can be modelled as TSPEC, described with the vector $\{M_i, p_i, b_i, r_i\}$, representing the maximum frame size – M, peak rate – p, burst size – b, and long term average rate – r. The arrival curves are presented with the equation:

(3) $$\alpha_i(t)=\min\{p_i.t+M_i;r_i.t+b_i\}$$

The switch service curve is modelled as RSPEC, described with the forwarding rate – R and slack term (latency) – S. This curve is presented with the equation:

(4) $$\beta(t)=R.[t-S]^+$$

This service is offered to all flows. The service offered to an individual flows in respect to the others depends on the queuing discipline. The service curve is again RSPEC (rate-latency) but the rate and the latency are recalculated for each flow in concurrency with the others. For the Strict Priority queuing the equation are (5) and or the Weighted-Round-Robin discipline the equations are (6) [4]:

(5) $$R_i = R - \sum_{j>i} r_j \qquad S_i = \frac{\sum_{j>i} b_j}{R - \sum_{j>i} r_i} + \frac{\max(M_j : j<i)}{R}$$

(6) $$R_i = R \,.\, \frac{\varphi_i - M_i}{\sum_j \varphi_j - M_i} \qquad S_i = \frac{\sum_{j\neq i} \varphi_j}{R}$$

Using the above equations and parameters for each flow and using theorems from [7] the delay bounds can be calculated. As long as the forms of curves are well known (TSPEC and Periodic arrival curves, RSPEC service curves), the calculation of the delay and backlog bounds can be simplified. The maximum horizontal deviation between arrival and service curves (i.e. the delay bound) for the i-th flow is given by the generalized equation:

(7) $$D_i = S_i + \frac{M_i}{R_i} + \left(\frac{b_i - M_i}{p_i - r_i}\right) . \frac{\left(p_i - R_i\right)^+}{R_i}$$

Using the workload distribution and parameters from the experimental scenario, the respective service rate and latency offered and delay bounds for each flow are calculated. The calculated results are given in Table 2.

Table 2: Delay calculations

Flow	Delay x10^{-6}[s]	Latency x10^{-6}[s]	Rate [Mbps]
WT1	37	11.3	1000
WT2	204	177	678
WT3	470	443	242
WT4	981	561	30

SIMULATION RESULTS

Each simulations run for a period of 120 seconds. CBR traffic generators are sequently started during the first second of the simulation and are stopped at the 100^{-th} second of the simulation. This allows analysis of the influence of the high priority traffic on other traffic types that are running during entire simulation. During the simulation the following information is collected: end-to-end packet delay for each flow, jitter for the periodic flow, bandwidth utilization, backlog, and packets loss of the switch port. The collected traces are then processed to extract minimum, maximum and average delay to compare them to the analytical bounds to examine the correctness of the analytical model – Table 3.

Table 3: Analytical versus Simulation Results

Flow	Simulation results, Delay x10^{-6}[s] min / avg / max	Analytical results, Delay x10^{-6}[s]
WT1	27 / 27 / 35	37
WT2	37 / 38 / 201	204
WT3	28 / 77 / 290	470
WT4	28 / 75 / 248	981

The comparison on table 3 shows that the delay never get over the analytical bounds and thus it can be concluded that the analytical model is correct. For flows WT3 and WT4 the maximum delay is significantly smaller than the analytically calculated bounds. The most probable reason for this is the way the weights for the analytical model for the WRR queue management is choosen. In the simulator the weights are given as proportions and is adaptable, but in the calculations the delay depends on the exact amount of bytes that can be sent on a given turn of the WRR.

For most of the packets the jitter value is zero, only 0.18% experience jitter and only 0.02% – the maximum jitter of 8 μs. This is due to the SP scheduling used for the periodic flow. The jitter only occurs when there is a packet from some other flow that has already occupied the switch. The maximum jitter is observed when the packet needs to wait transmission of maximum sized packet from some other flow 11.5 μs. The distribution of packets according to their jitter is shown on figure 3.

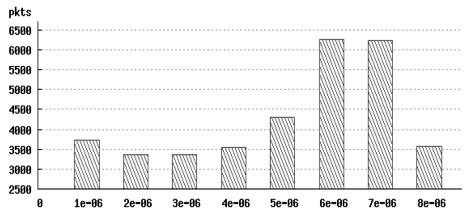

Figure 3: Jitter density

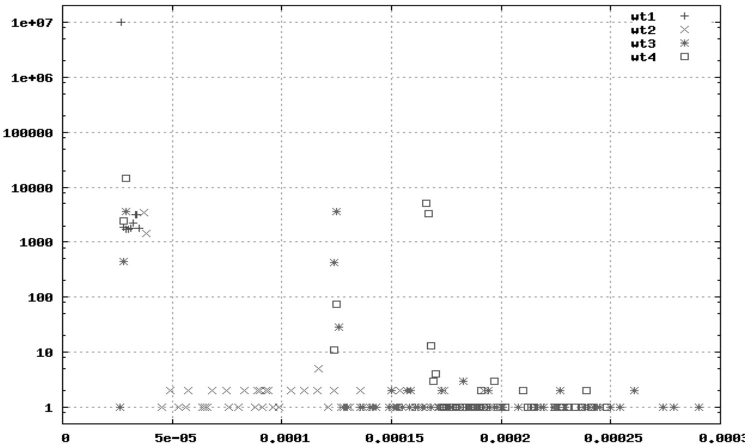

Figure 4: Delay densities

As can be seen from figure 4, most of the WT1 packets examine 27 μs delay which means that they are forwarded without queuing. For WT3 flow packet delays are mostly distributed around two values. The smaller one occurs when they arrive at the switch in the idle period of the WT1 flow. For WT4 flow packet delays are distributed like those of WT3 but are bigger because of its relatively low weight in WRR scheduling. The delay of WT2 flow has little influence from WT3 and WT4 because it has relatively high weight in the WRR scheduling.

The average bandwidth utilization of the link switch-TS is about 80 Mbps during first 100 seconds and 10 Mbps afterwards. After stopping of the WT1 flow in the 100^{-th} second of the simulation the delay of other flows reduces significantly and is becomes closer to its average value.

CONCLUSIONS AND FUTURE WORK

The comparative review of the analytical and simulation result shows that the analytical model is applicable in determination of the delay bounds using flow parameters. The calculated bounds by analytical calculations are correct but for WRR queue management they are not tight enough. A tuning of the analytical model of WRR ought to be made to tighten the bounds. Analytical calculations can be used for the stability analysis of networked control systems. The observed jitter and delay values of the periodic traffic shows that switched Ethernet can be successfully applied in most of the real-time applications in automation systems.

The presented analytical and simulation results must be further checked against corresponding test-bed experiments, using market-available switches and controllers. Further analysis must be made for the other components of the end-to-end delays to obtain a complete view. The results can be used for analysis of the data flows and QoS policies in the context of the multi-tier model for Distributed Automation [15] and especially to model the behaviour of its lowest tier – the Data producing tier.

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