AN STUDY ON THE INFLUENCE OF SOME CHARACTERISTICS OF COMMUNICATION PROTOCOLS ON THE PERFORMANCE OF NETWORKED CONTROL SYSTEMS

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Abstract. *In this work we present an study on the influence of some characteristics of communication protocols on the performance of Networked Control Systems (NCS). The characteristics studied are: sharing bus effect, bandwidth, and data packet dropout rate. The environment used is the TrueTime toolbox for Matlab. The tests performed shown the increasing degradation of that performance by changing those characteristics. After that, we intend to extend such study to the Attitude and Orbit Control System (AOCS) of the Multi-Mission Platform (MMP) satellite operating in the nominal mode. This is an excellent example of the engineering necessary to promote the interaction between universities and enterprises in the future.*

Keywords*: networked control systems, communication protocols, attitude and orbit control system, multi-mission platform*

1. INTRODUCTION

A major trend in modern industrial and commercial systems is to integrate computing, communication and control into different levels of machine/factory operations and information processes. Control loops that are closed over a communication network have become more and more common as the hardware devices for networks and network nodes have become cheaper.

The traditional communication architecture for control systems, which has been successfully implemented in industry for decades, is point-to-point; that is, a pair of wires connects the central control computer with each sensor or actuator point. However, expanding physical setups and functionality are pushing the limits of the point-to-point architecture. Hence, a traditional centralised point-to-point control system is no longer suitable to meet new requirements, such as modularity, decentralization of control, integrated diagnostics, quick and easy maintenance and low cost. The introduction of common bus network architectures can improve the efficiency, flexibility and reliability of these integrated applications through reduced wiring and distributed intelligence; and so reduce the installation, reconfiguration and maintenance time and, overall, costs (Raji, 1994).

However, the common bus architecture has new factors than can degrade the performance of the control system by the embedded characteristics of the network. With this new architecture, any control project that do not consider the network characteristics will not be able to guarantee its performance. That's why, we decided to study the influence of some characteristics of a communication protocol in the control system performance.

2. NETWORKED CONTROL SYSTEMS

Feedback control systems wherein the control loops are closed through a network are called Networked Control Systems (NCSs), (Walsh *et al.*, 1999) (Zhang *et al.*, 2001). Fig. 1 shows this kind of interconnection. NCSs can deal with all the continuous, discrete and hybrid control asynchronous processes, and support various topologies, including bus, star and tree, which are more flat and stable than the structure used in hierarchical control systems. As an alternative to traditional point-to-point communication, the common bus network architecture of NCSs offer more efficient reconfiguration, better resource utilization, and also reduce installation and maintenance costs.

However the common bus architecture has new factors than can degrade the performance of the control system by the embedded characteristics of the network. Among these characteristics we have: sharing bus effect (or the percentage of bus occupation by the interference), bandwidth (or bit rate transfer), data packet dropout rate, Medium Access Control (MAC) policies, latency, jitter, etc. We call interference the use of the network by another device which is not related with the control process.

In the literature reviewed so far, it is not well known how these new characteristics affect the control system performance or even if they could cause its instability.

2.1 Sharing Bus Effect

As we said before, we call interference the use of the network by another device which is not related with the control process. Now imagine that the controller computes the signal control but the network is used by other device. Under this scope, it is not clear how much of interference can be tolerated such that this do not affect the control system performance.

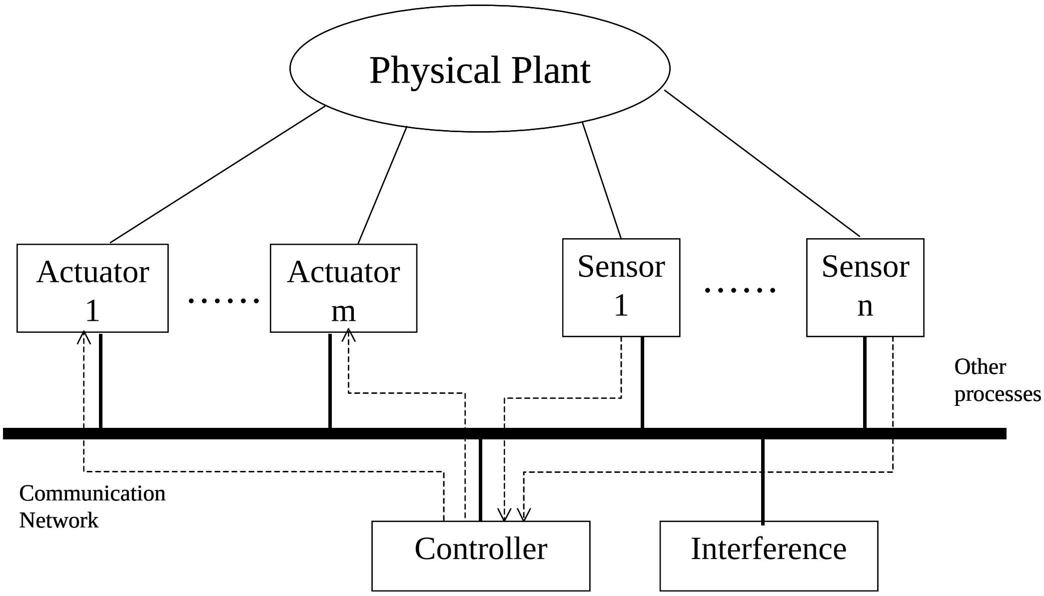


Figure 1. A Networked Control System setup and its typical information flows.

In the protocol layers, the layer responsible for who determines how, when and who is going to transmit/receive is the Medium Access Control sub-layer, see Fig. 2. In the OSI model, the Data Link Layer is divided in two sub-layers: the MAC and the Logical Link Control (LLC); the LLC sub-layer is concerned with providing a connectionless or connection-oriented protocol, (Burns and Wellings, 2001).

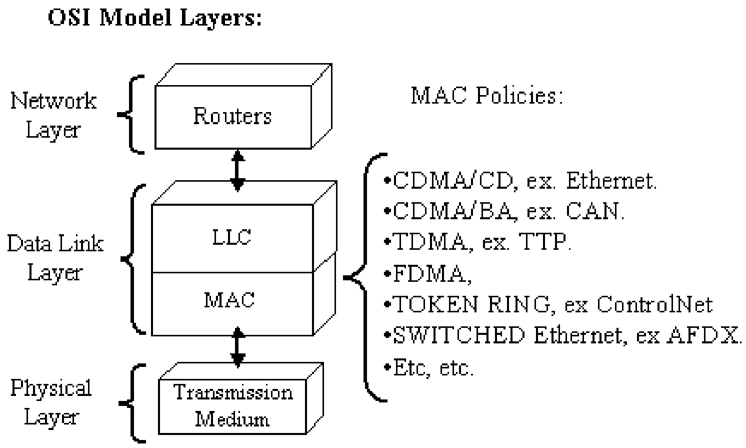


Figure 2. The MAC and LLC sublayers allocation in the OSI Model.

There are many MAC policies established. The most well known are CSMA/CD, CSMA/BA, Token passing, TDMA, etc. An extensive explanation on these methods is found in (Wikipedia, 2007). Based on it, we present a brief explanation of each one of them ahead.

Carrier Sense Multiple Access with Collision Detection (CSMA/CD) is a network control protocol in which a transmitting data station that detects another signal while transmitting a frame, stops transmitting that frame, transmits a jam signal, and then waits for a random time interval (known as "backoff delay") before trying to send that frame again. Collision detection is used to improve CSMA performance by terminating transmission as soon as a collision is detected; and by reducing the probability of a second collision on retry. Ethernet is based on CSMA/CD.

Carrier Sense Multiple Access with Bitwise Arbitration (CSMA/BA) protocol is often implemented too. Here, if two or more devices start transmitting at the same time, there is a priority based arbitration scheme to decide which one will be granted permission to continue transmitting. The solution to this is prioritised arbitration (and for the dominant message, delay free), that makes it better suitable for real time purposes. CANbus and DeviceNet are based on CSMA/BA.

Time Division Multiple Access (TDMA) is a channel access method for shared medium networks. It allows several users to share the same channel by dividing the signal into different timeslots. The users transmit in rapid succession, one after the other, each using his own timeslot. This allows multiple stations to share the same transmission medium (e.g. radio frequency channel or bus network) while using only the part of the bandwidth they require.

Frequency Division Multiple Access (FDMA) is an access technology that is used by radio systems to share the radio spectrum. The terminology "multiple access" implies the sharing of the resource among users, and the "frequency division" describes how the sharing is done: by allocating users with different carrier frequencies of the radio spectrum.

Token Pass is a technique where a user only is permitted to transmit to other when its possess a "token", a permission to transmit. Once finished the transmission of the data, its passes the "token", the permission for some another device that wants to transmit. An example that illustrates this technique is: imagine a conference where only one can speak, who that has the microphone; after finishing his intervention, he passes the microphone to other person.

Finally, new Ethernet versions (Switched Ethernet) have been developed and proposed to replace the hub by switches, to connect all the devices in point to point to the switches, to generalise the use of full-duplex mode and to increase the bandwidth. The interest of these technological evolutions is to avoid collisions. But the collision problem is shifted to a congestion problem in switches.

2.2 Bandwidth

In telecommunications and computing, bit rate is the number of bits that are conveyed or processed per unit of time. Bit rate is often used as synonym to the terms connection speed, transfer rate, channel capacity, maximum throughput and digital bandwidth capacity of a communication system.

Someone could said that a greater transmission speed of a network implies in a smaller delay, but this, unfortunately, it is not true. According to (Jianyong *et al.*, 2004), there are several delays involved in a communication processes. Two classes of time delays are included in an NCS: (I) the delay from a sensor to a corresponding controller, T_{sc}; (2) the delay from a controller to a corresponding actuator, T_{ca}. These network-induced delays may vary widely according to the transmission time of messages and the overhead time. But these delays are not unique: we also have delays at the moment of packing/unpacking the frames in the transmission/reception of messages and, as we explained previously, the network access policy induces a delay too. A higher transmission rate is not enough to solve all the delays envolved.

2.3 Data Packet Dropout Rate

According to (Jianyong *et al.*, 2004), network packet drops occasionally happen in NCSs when there are node failures or message collisions. Although most network protocols are equipped with transmission-retry mechanisms, they can only retransmit for a limited time. After this time has expired, the packets are dropped. Furthermore, for real-time feedback control data such as sensor measurements and calculated control signals, it may be advantageous to discard the old, non-transmitted message and transmit a new packet if it becomes available. In this way, the controller always receives fresh data for control calculation. Normally, feedback-controlled plants can tolerate a certain amount of data loss, but it is valuable to determine whether the system is stable when only transmitting the packets at a certain rate and to compute acceptable lower bounds on the packet transmission rate.

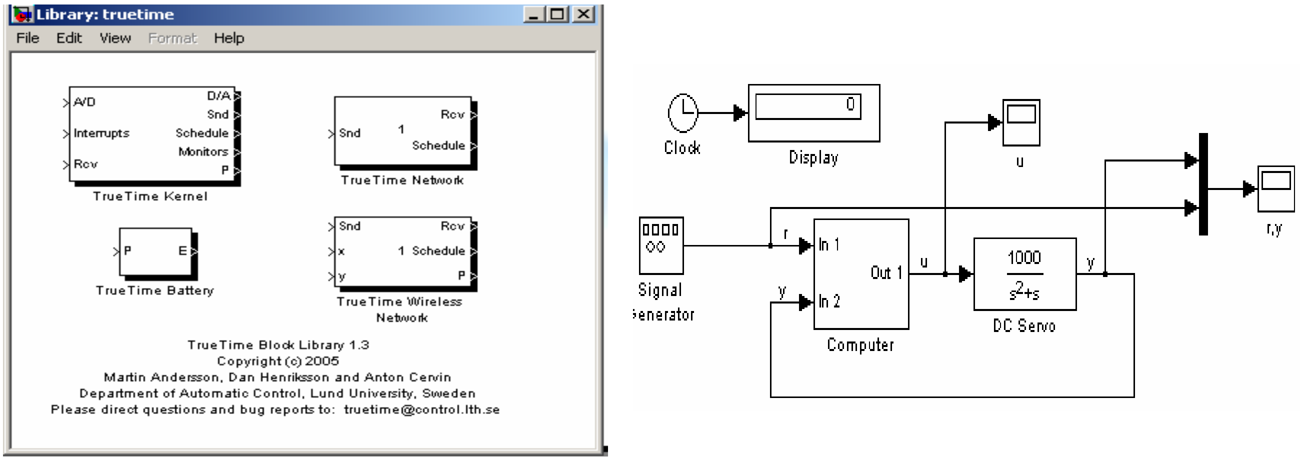
3. TRUETIME

TrueTime is a Matlab/Simulink-based simulation tool. Using TrueTime it is possible to simulate the temporal aspects of multi-tasking real-time kernels and wired or wireless networks within Simulink, together with the continuous time dynamics of the controlled plant. The approach allows simulation at the same level of detail as in the true system.

TrueTime consists of a set of library blocks, as shown in Fig. 3a. The blocks are variable step, discrete, Matlab S-functions written in C++. The kernel block executes user defined tasks and interrupt handlers representing, e.g., I/O tasks, control algorithms, and network interfaces. The scheduling policy of the kernel block is arbitrary and decided by the user. The network blocks distribute messages between computer nodes according to a chosen network model. The blocks are connected with ordinary continuous time Simulink blocks to form a real-time control system.

The kernel block S-function simulates a computer with a simple but flexible real time kernel, A/D and D/A converters, a network interface, and external interrupt channels. The execution of tasks and interrupt handlers is defined by code functions, written either in C++ or MATLAB code. Control algorithms may also be defined graphically using ordinary discrete Simulink block diagrams. A control system using of a servo motor using TrueTime kernels blocks is shown in Fig. 3b.

The TrueTime network blocks distribute messages between computer nodes according to chosen network models. For wired networks, six of the most common medium access control protocols are supported (CSMA/CD (Ethernet), Switched Ethernet, CSMA/CA (CAN), Token-Ring, FDMA, and TDMA). The wireless network block supports simulation of the IEEE 802.11 WLAN and IEEE 802.15.4 ZigBee standards.



(a) (b)

Figure 3. (a) TrueTime Block Library; (b) Control System built in Matlab/Simulink with TrueTime kernel blocks.

4. SIMULATIONS

In this section, the goal is to show the influence of a Ethernet network on a simple closed loop control system. The modeling and simulation are done by using a TrueTime simulator (Cervin *et. al*. 2003)

Firstly, a servo problem is chosen. The purpose is to follow a step command signal. Consider the PD control of a DC servo described by the following continuous time transfer function:

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

Following the specified requirements to have a percentage overshoot less than 5%, the PD parameters are tuned at the following values: K_p=1.5, K_d=0.054. Once the PD controller has been designed in the continuous-time domain and with the appropriate sampling period (T=10ms), we obtained its PD discrete approximation through Tustin aproximation:

$$e(kT) = r(kT) - y(kT) \tag{2.a}$$

$$p(kT) = K_p e(kT) \tag{2.b}$$

$$d(kT) = d(kT-T) + \frac{2*K_d}{T}(e(kT) - e(kT-T)) \tag{2.c}$$

$$u(kT) = p(kT) + d(kT) \tag{2.d}$$

The closed loop system on a Ethernet network modelled by the TrueTime simulator is shown in Fig. 4.

4.1 Network used with ideal assumptions

Firstly, the system is simulated in the ideal case. It is means that the network introduces no packets losses and the delay depends only on traffic generated by the real-time system. Then, the network is not shared with other applications.

Fig. 5 shows the behaviour of the system on a Ethernet network. In this case, the output follows the reference and the system is stable. The parameters used in the simulation are: a bit rate of 100 Kbit/s and a frame size of 64 Kbytes.

4.2. Shared Network

In this section, the network supports the traffic of other applications. This traffic overloads the medium, and this increases the delay of the packets exchanged between the controller and the actuators and sensors of the servo system.

The bandwidth occupation of traffic overload is constant, in all evaluated scenarios. The simulations are analysed with 25% and 50% bandwidth occupation by interference. The period of these perturbations is 7 ms. Fig. 6 shows the effects of bus sharing.

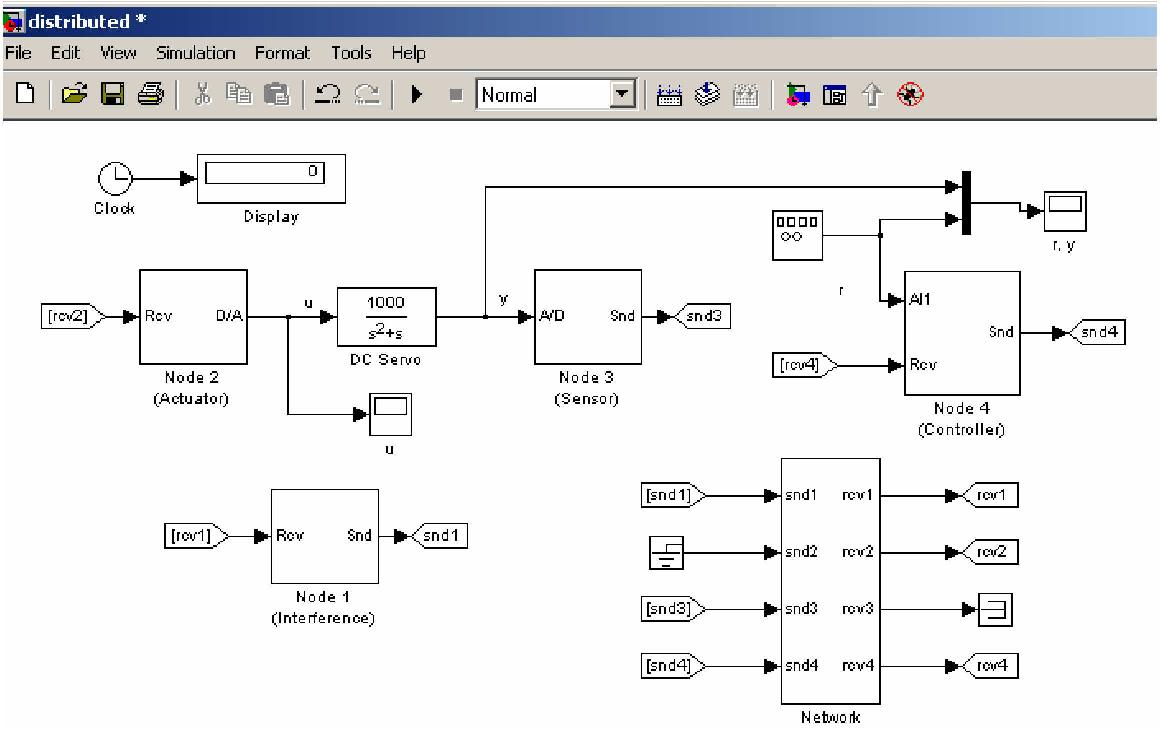


Figure 4. Closed loop control system on Ethernet network using TrueTime.

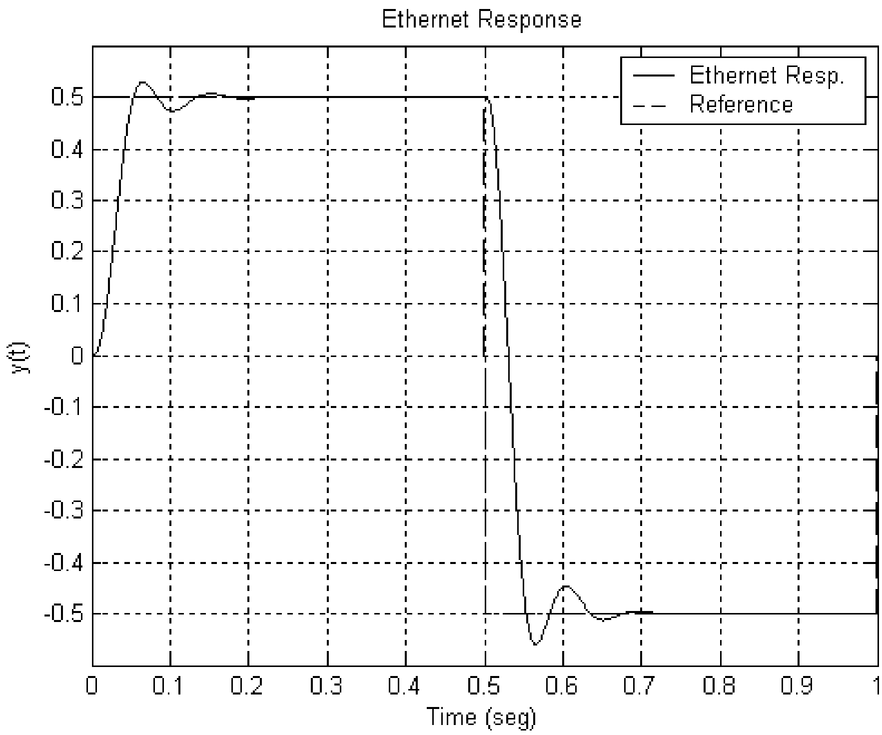


Figure 5. Ethernet response under ideal situation.

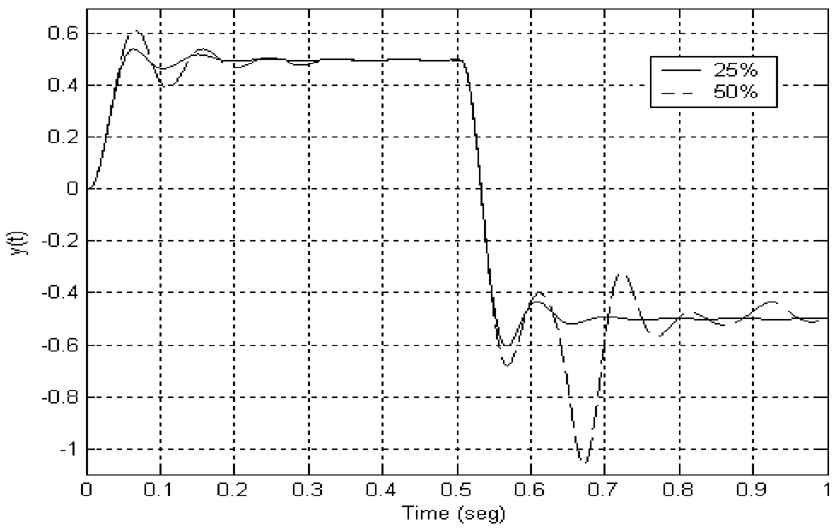


Figure 6. System response when the bus bandwidth is shared with other devices.

Fig. 6 shows an overshoot of 10% in the case with 25% bandwidth occupation by interference; and more than 100% in the case with 50% bandwidth occupation by interference. Also Fig. 6 shows that aside the overshoot of transition, a second overshoot (0.63-0.7 seg) is present in the system response, this overshoot could be caused by the unavailable of the network turning the response highly unpredictable; exactly what was not wanted of the system.

4.3. Transfer Bit Rate

In this case, we compare two different transfer bit rates. The rates used in the simulation were 100 Kbit/s and 1 Gbit/s. This parameter becomes important when the distances between the devices are considerably longer, so higher bit rates could decrease the transmission time delay.

Fig. 7 shows that the overshooot was improved from 6% to near 1% when this characteristic improves in more than one thousand times. Under this scope, other characteristics that produces the same or better improvements with less effort could be better modified.

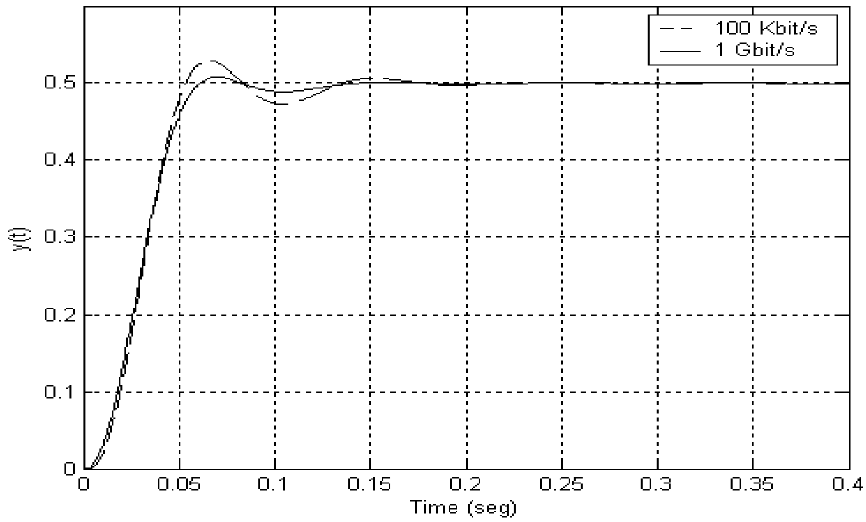


Figure 7. Transfer bit rate comparison.

4.4 Data Packet Dropout Rate

In this section, two percentages of packet losses are analysed, 10% and 15% respectively. In the first case, Fig. 8 shows a small overshoot but the system is stable. In the second case, the system still is stable, but the system response is highly degraded. Of all characteristics shown in this work, the data packet dropout rate has the largest influence on system performance. So, many studies are focussed on techniques like retransmission, queue introduction, etc, to avoid its effects.

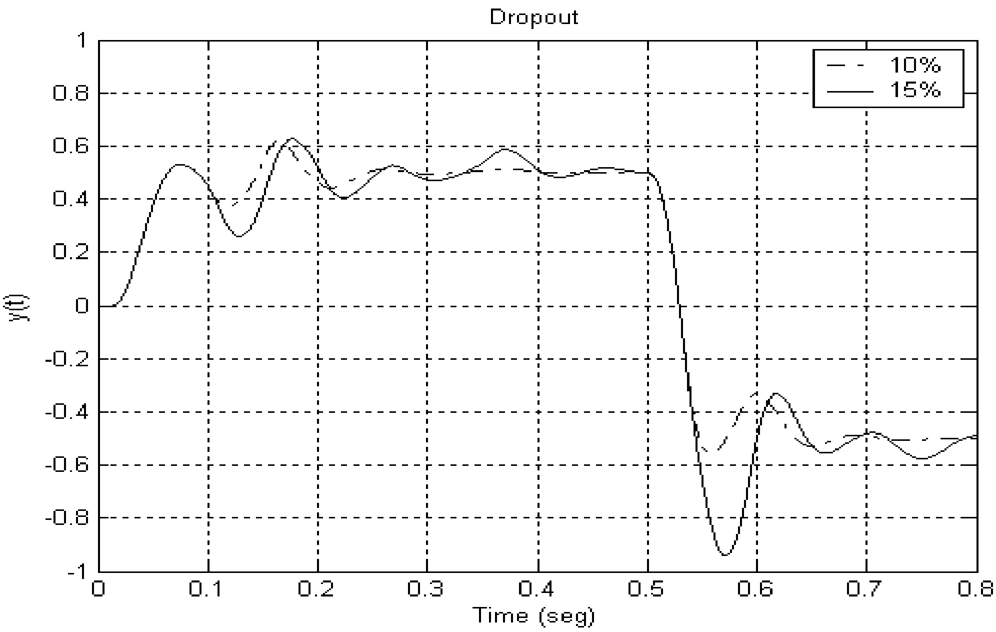


Figure 8. Dropout effect.

5. CONCLUSIONS

In this paper, we gave, at first, an overview on the NCS research field. And, to show the influences of three characteristics of the Ethernet protocol on a networked controlled system, many simulations were carried out with TrueTime.

The results obtained show that the behaviour of a NCS depends heavily on the kind of characteristics. Then a NCS study has to integrate the specificities of networks such as: sharing bus effect (or the percentage of bus occupation by the interference), bandwidth (or bit rate transfer), data packet dropout rate, medium access control (MAC) policies, latency, jitter, etc. Our intention was to study, understand and show these network characteristics to consider them in future projects like the Multi-Mission Platform (MMP) satellite.

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