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An Agent-Based Modelling Simulation Approach to Calculate Processing Delay of GEO Satellite Payload

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***Abstract*—**The global coverage of broadband multimedia and internet-based services in terrestrial-satellite networks demand particular interests for satellite providers in order to enhance services with low latencies and high signal quality to diverse users. In particular, the delay of on-board processing is an inherent source of latency in a satellite communication that sometimes is discarded for the end-to-end delay of the satellite link. The frame work for this paper includes modelling of an on-orbit satellite payload using an agent model that can reproduce the properties of processing delays. In essence, a comparison of different spatial interpolation methods is carried out to evaluate physical data obtained by an GEO satellite in order to define a discretization function for determining that delay. Furthermore, the performance of the proposed agent and the development of a delay discretization function are together validated by simulating an hybrid satellite and terrestrial network. Simulation results show high accuracy according to the characteristics of initial data points of processing delay for Ku bands.

***Keywords*—**Terrestrial-satellite networks, latency, on-orbit satellite payload, simulation.

I. Introduction

DESIGNING satellite payload is a strenuous task that can be expensive and risky. The use of modelling and simulation tools can enhance this process by providing a platform for performing engineering trade studies, conducting research and gathering information. The diverse nature of propagation environments has great impact on the design, real−time operation and signal processing of satellite payload. Therefore, modelling of the latency is necessary for the performance assessment of satellite systems such as shown recent studies in [1]-[4]. For example, authors investigated in [4] latency estimation using regression and numerical models based on the distance between two locations. However, the calculation of the latency should include other factors such as propagation delay, processing delay, data protocols, routing or switching, queuing and management of the buffer. Major differences between one of each type of delay is explained in [5] as follows: the processing delay is the amount of time required for the router to push out the packet. It is a function of the length of the packet and the transmission rate of the link regardless of the distance between routers. On the other hand, the propagation delay is the time it takes a bit to propagate from one router to the next one. In this case, the delay depends on the distance between source and destination, instead of the length of the packet or the transmission rate of the link. In particular, this paper addresses the modelling of the processing delay of a satellite payload, in which the limiting factor in transmitting information over radio−based channels is the bandwidth of the channel. The study of the propagation delay in satellite links is beyond this paper.

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The frame work for most of the recent developments in satellite communications includes Agent-Based Modelling and Simulation (ABMS) technology. ABMS is an approach to modelling systems using autonomous interacting agents that can enhance the effect of changes of internal parameters of distributed model. Additionally, the modular architecture of this type of agent model is highlighted as main advantage to support decision−making attributes for satellite payload designers.

This paper is organized as follows: with the purpose of determining a discretization function as processing delay, the validation of numerical interpolation polynomials is described in Section II by comparing results of numerical methods with real data given by the space agency of the VENESAT-1 satellite. Additionally, an agent model is built in Section III for integrating the processing delay feature of the GEO satellite payload. Using the flexibility of an open-source simulation network, the implementation of the proposed agent model with the developed discretization delay function is accomplished in Section IV. Simulation results and conclusion are discussed in Section V.

II. The Discretization Function

This section describes the comparison of two numerical techniques for determining an efficient numerical solution that can define a discretization function for modelling processing delay in an satellite payload. Data of processing delay has been provided by measurements of three Ku channels (Ku1A, Ku2A and Ku3A) of the $VENESAT-1$ (GEO satellite). Considering numerical techniques for discrete events, the Newton′s divided difference polynomial and the Lagrangian Interpolation methods are used to retrieve the delay function from the Ku bands of each transponder.

In particular, data was given only at discrete points as follows $(x_0, y_0), (x_1, y_1), ...(x_n-1, y_n-1), (x_n, y_n)$ and such as shown in Table I. In this table, the delay of the mentioned satellite payload is given as a function of the frequency offset. Thus, the strategy is to find delay functions at any value of

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TABLE I
PROCESSING DELAY AS FUNCTION OF THE FREQUENCY OFFSET

Frequency Offset	Theoretical Processing Delay (ns)		
(MHz)	$Ku1A$	$Ku2A$	$Ku3A$
x_0=-27	37,990	50,990	48,00
x_1=-24	18,510	21,490	23,390
x_2=-21	10,760	10,970	12,450
x_3=-18	5,656	7,626	5,824
x_4=-15	3,051	6,341	3,191
x_5=0	1,650	0,681	1,353
x_6=15	5,943	0,866	3,994
x_7=18	8,068	1,359	5,879
x_8=21	13,530	6,195	12,190
x_9=24	22,880	14,570	22,880
$x_1$0=27	48,210	35,820	46,040

frequency, based on function $f(x)$ that represents the $n+1$ data values with $f(x)$ passing through the $n+1$ points.

A. The Lagrange Interpolating Polynomial

The Lagrange interpolating polynomial is the polynomial $P(x)$ of degree $\leq (n-1)$ that passes through the n points $(x_1, y_1 = f(x_1)); (x_2, y_2 = f(x_2)); ...; (x_n, y_n = f(x_n))$ and is given by

$$P(x) = \sum_{j=1}^{n} P_j(x) \tag{1}$$

where

$$P_j(x) = y_j \prod_{k=1, k\neq j}^{n} \frac{x - x_k}{x_j - x_k} \tag{2}$$

The calculation of the Lagrange Polynomial for the Ku1A channel is carried out as follows: First, eleven (11) polynomials $(P_0, P_1, ..., P_9, P_{10})$ are computed by using (1). For example, (3) shows the polynomial function $P_0(x)$ in which x is the frequency offset of the Ku1A band. The polynomial $P_0(x)$ represents the interpolation value for a $X_0 = -27$.

$$P_0(x) = \frac{(x-27)(x-24)(x-21)(x-18)(x-15)(x+24)...(x+15)x}{(-27-27)(-27-(-24))(-27-24)....(-27-15)(-27)} \tag{3}$$

Second, the Lagrange Interpolation polynomial for the Ku1A channel $(T_L^{1A}(x))$ is obtained by the sum of the 11th polynomials which is obtained by (1). Thus, the result is given by,

$$T_L^{1A}(x) = 2,1776.10^{-21}x^{10} + 7,1115.10^{-21}x^9 - 3,7995.10^{-18}x^8 - 1,2731.10^{-17}x^7 + 2,4547.10^{-15}x^6 + 9,1880.10^{-15}x^5 - 6,3123.10^{-13}x^4 - 3,0490.10^{-12}x^3 + 6,8046.10^{-11}x^2 + 4,4190.10^{-10}x + 1,65.10^{-10}$$

B. Newton's Divided Difference Polynomial

The general form of the Newton's divided difference polynomial for $n+1$ data points $(x_0, y_0)); (x_1, y_1); ...; (x_n - 1, y_n - 1); (x_n, y_n)$ is expressed as

$$f_n(x) = b_0 + b_1(x - x_0) + ..b_n(x - x_0)(x - x_1).(x - x_{n-1}) \tag{4}$$

where

$$\begin{aligned} &b_0 = f[x_0]; b_1 = f[x_1, x_0]; b_2 = f[x_2, x_1, x_0] \\ &b_{n-1} = f[x_{n-1}, x_{n-2}, ..., x_0] \\ &b_n = f[x_n, x_{n-1}, ..., x_0] \end{aligned} \tag{5}$$

where the definition of the m^{th} divided difference is represented by

$$b_m = f[x_m, ..., x_0]) = \frac{f[x_m, ..., x_1] - f[x_{m-1}, ..., x_0]}{x_m - x_0} \tag{6}$$

Considering the data plotted in Table I and using (5) and (6), the Newton interpolation polynomial for the Ku1A channel $(T_N^{1A}(x))$ is finally obtained by the followed equation:

$$T_N^{1A}(x) = 2,1819.10^{-21}x^{10} + 7,1119.10^{-21}x^9 - 3,7983.10^{-18}x^8 - 1,2724.10^{-17}x^7 + 2,4539.10^{-15}x^6 + 9,1977.10^{-15}x^5 - 6,3101.10^{-13}x^4 - 3,0462.10^{-12}x^3 + 6,8081.10^{-11}x^2 + 4,4287.10^{-10}x + 1,6481.10^{-9}$$

C. Comparison of Numerical Methods

This section shows results of the comparison between the Newton′s divided difference polynomial and the Lagrangian Interpolation method for the Ku1A channel that are represented by the functions $T_N^{1A}(x)$ and $T_L^{1A}(x)$, respectively. These methods are compared in Table II according to their relative error functions that are represented as Δ_N^{1A} and Δ_L^{1A}.

TABLE II
ACCURACY VALUES OF NUMERICAL METHODS

Frequency	Processing Delay (ns)			Relative Error	
(MHz)	$Theorical$	$T_L^{1A}(x)$	$T_N^{1A}(x)$	Δ_L^{1A} %	Δ_N^{1A}%
x_0=-27	37,990	37,122	37,996	2,2845	0,0168
x_1=-24	18,510	18,283	18,511	1,2263	0,0054
x_2=-21	10,760	10,728	10,760	0,2992	0,0046
x_3= -18	5,656	5,667	5,655	0,2104	0,0088
x_4=-15	3,051	3,066	3,050	0,4916	0,0196
x_5= 0	1,650	1,650	1,648	0	0,1151
x_6= 15	5,943	5,8929	5,942	0,8430	0,0100
x_7= 18	8,068	7,9674	8,068	1,2469	0
x_8= 21	13,530	13,3012	13,531	1,6910	0,0044
x_9= 24	22,880	22,3103	22,833	2,4899	0,0135
$x_1$0= 27	48,210	46,7506	48,218	3,0263	0,0174

The previous comparison shows that when these numerical polynomials are applied to determine the discretization function, similar convergence rate and approximation error are obtained, in which the accuracy of Lagrange is below 3% and the accuracy of Newton is less than $0,15\%$. However, It is important to mention that the main disadvantage of Lagrange is the overfitting [6]. This phenomenon is based on a significant variation of the points obtained by the interpolation polynomials with respect to the original points. Basically, the increased degree of the polynomial is directly related to the number of points to be interpolated. Based on the previous comparison, the Newton′s divided difference polynomial is selected in the rest of this paper as discretization delay function $(T(x))$ in order to represent the processing delay for the Ku transponders of the mentioned satellite payload. Considering the above calculation procedures, the discretization delay functions for the Channel Ku2A $(T_N^{2A}(x))$ and Ku3A $(T_N^{3A}(x))$ are similarly calculated as,

$$T_N^{2A}(x) = 1,7465.10^{-21}x^{10} + 3,0976.10^{-20}x^9 - 3,1643.10^{-18}x^8 - 6,2580.10^{-17}x^7 + 2,2718.10^{-15}x^6 + 4,3347.10^{-14}x^5 - 6,8574.10^{-13}x^4 - 1,2059.10^{-11}x^3 + 8,3841.10^{-11}x^2 + 9,6979.10^{-10}x + 6,7982.10^{-10}$$

$$T_N^{3A}(x) = 2,7999.10^{-21}x^{10} + 8,9047.10^{-21}x^9 - 5,0936.10^{-18}x^8 - 1,7231.10^{-17}x^7 + 3,4445.10^{-15}x^6 + 1,2011.10^{-14}x^5 - 9,2494.10^{-13}x^4 - 3,6725.10^{-12}x^3 + 9,4590.10^{-11}x^2 + 4,1847.10^{-10}x + 1,3498.10^{-9}$$

Subsequently, the discretization functions were programmed using the language C ++ with the purpose to be integrated in an opensource simulation network in order to validate their performance in an hybrid terrestrial and satellite networks.

III. Development of the Payload Agent

In Fig. 1, a general block diagram of satellite communication system is represented as follows: the uplink frequencies are used for transmission from the earth station to the satellite payload. The antenna receives the uplink signal to be amplified and filtered. Then, the uplink frequencies are converted to lower frequencies by the mixer and local oscillator.

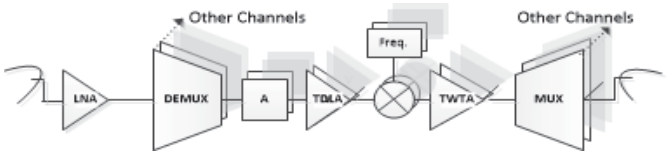


Fig. 1 Block Diagram of Satellite Payload

The goal is to develop a Payload Agent that can represent how the satellite communication payload described in Fig. 1 interacts with the components through the model for representing an input-output system. In this system, the inputs are signals or data received by the payload agent and outputs are signals or data sent from it. Furthermore, individual components of the satellite payload are designed with a fixed overall delay from input to output, in which this delay fluctuates with changes depending on the actions described in Fig. 1 as filtering, analog-to-digital conversion, buffering, digital signal processing, and digital-to-analog conversion. In this section, an Agent-Based Modelling and Simulation (ABMS) is developed as an approach to model autonomous interacting agents for satellite payload. In this study, the *MobileNode* Agent [7] is considered as reference by its extensive toolkit for network simulation. This *Mobilenode* is the basic node of the network simulator [8] that represents an object with functionalities like movement, ability to transmit and receive on a wireless channel that allows it to be used to create mobile wireless or satellite simulation environments [9].

In Fig. 2, the schematic illustrates the architecture to model the Payload Agent in *ns-2* based on the *MobileNode* extension [7].

Four basic layers are shown in Fig. 2 as follows: the **Physical Layer** which contains the Network interface, the

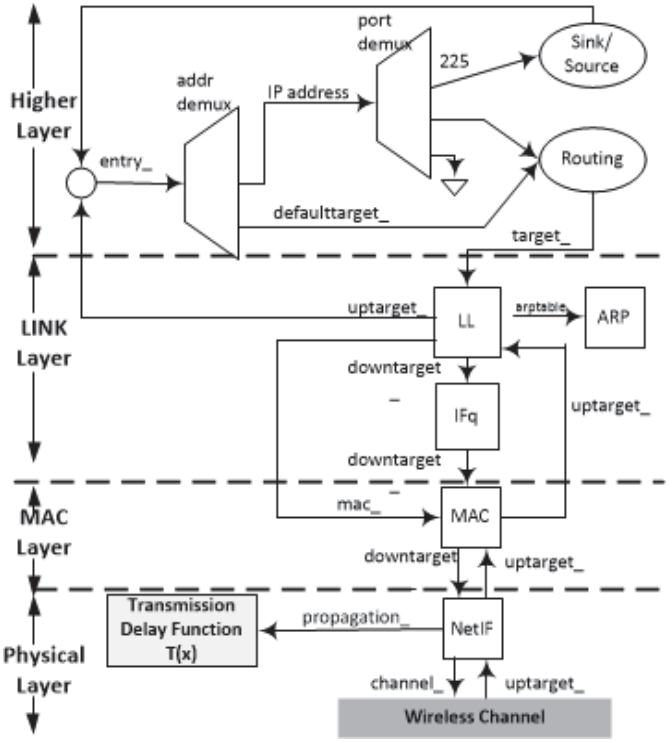


Fig. 2 MobileNode Architecture for the Payload Agent

Wireless Channel and our approach using the discretization delay functions represented by $T_N^{1A}(x)$, $T_N^{2A}(x)$ and $T_N^{3A}(x)$. More precisely, our main contribution was to develop these functions inside the network simulator by programming an Application Programming Interfaces (API) that includes software libraries in order to emulate the delay features obtained in Section II. Afterwards, the **Mac Layer** modelling the MAC protocol and the **Link Layer** applying Interface Queue. Finally, the **Higher Layer** implements source or sink agents, buffer (port_demux) and routing mechanisms.

Following with Fig. 2, it is important to clarify the meaning of the uptarget_ and downtarget_ flags, which determine whether the data packet is incoming from the terrestrial satellite station to the payload using the uptarget_. Basically, packets are sent down to the link layer setting the downtarget_ flag.

IV. Performance Evaluation in a Simulation Tool

This section depicts the implementation of the Payload Agent using a network simulator. For this purpose, the network simulator *ns-2* [8] was used to implement the agent described in Section III. The network simulator *ns-2* is an object-oriented and discrete even-drive network simulator that has incorporated powerful tools in the recent year, such as, protocols and modules in the area of satellite networks. Using two programming languages as C++ and OTcl, *ns-2* increases the flexibility and efficiency to simulate networks. On one hand, C++ mainly provides the complex functionality relies to simulate protocols based on the performance of objects

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such as agents, links, queue, wired nodes, mobiles, satellite nodes and so on. On the other hand, the OTcl contributes to configure the scenario script. Using simulation scripts (OTcl) allow users change the configuration parameters of a scenario without recompiling the C++ code.

A. Scenario Configuration for the Simulation

In order to evaluate the performance of the Payload Agent described in section III, the simulation scenario is characterized by the communication of two terrestrial ground control stations through a bent-pipe satellite. More precisely, the geo-location of the VENESAT-1 satellite was configured by its position in -78.03°. Similarly, the two ground stations for the VENESAT-1 satellite were also located in the scenario by their geographical positions given by $5.74° - 61.51°$ and $9.38° - 67.05°$, respectively. As mentioned above, the configuration depends on several basic parameters, such as follows:

- The *simulation time* specifies the duration of a entire run. In this paper, the total real simulation time is setting in 100 seconds following the study in [10].
- An independent random number generation is used to achieve realistic results by running simulation sequentially during an appropriate number of times. Moreover, statistically independent sequences of pseudo-random numbers (PRNG)[11] are used in our simulations as sources of elementary randomness in different replications of the simulation.
- Each simulation scenario was run at least 25 times using different PRNG, and only the average values are shown in the simulation results.
- Each terrestrial node as well the payload agent has a buffer size of 140 packets for the forwarding and originating buffers (where packets are queued before being sent).
- Each flow transmits CBR (Constant Bit Rate) traffic in which each data payload contains 512 bytes.
- The network loads are performed by using transmission rate (T_x) as 15Kbps, 65Kbps and 130Kbps.
- The link availability is evaluated considering different uplink and downlink fluctuating between minimum value of 80 Kb and maximum value of 2 Mb.

In this section, six (6) simulation scenarios are defined based on the parameter described in Table III.

TABLE III
CONFIGURATIONS OF THE SIMULATION SCENARIOS

	Simulation Scenario				
	A	*B*	*C*	*D*	*E*
Uplink	2 Mb	500 Kb	500 Kb	250 Kb	2 Mb
Downlink	2 Mb	80 Kb	80 Kb	160 Kb	2 Mb
T_x Rate	15 Kbs	65 Kbs	130 Kbs	130 Kbs	130 Kbs

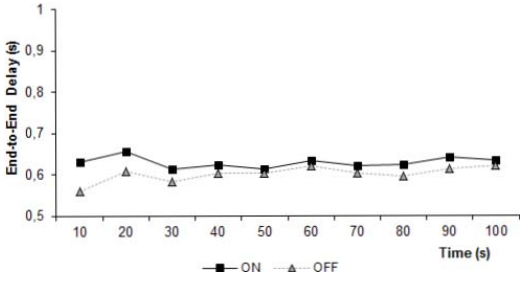
B. Simulation Terms

The performance of the presented Payload Agent is evaluated through metrics as throughput and the average end-to-end delay. Before proceeding with the simulation results, there are several important terms used in our analysis that must first be defined:

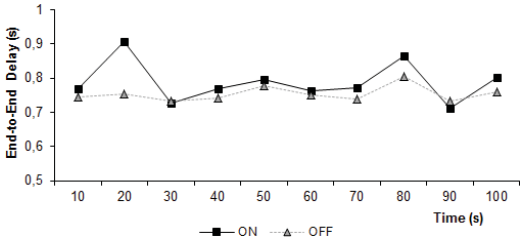
- A data packet is any transmitted packet containing message data that is generated by the source nodes.
- The end-to-end delay or latency shows the average one-way latency observed between transmitting and receiving data packets. The minimization of this parameter is important for many applications as multimedia, ip telephony, etc. These applications need a small latency to deliver usable results showing the suitability of the routing protocol.
- The throughput refers to the amount of data packets that are received by sink nodes in a given interval of time. Moreover, this parameter is commonly measured in bits per second.

C. Accuracy of the Newton′s Divided Difference Polynomial

As a first approach, the accuracy of the Newton′s divided difference polynomial is evaluated in this section by implementing in the simulator the processing delay function of the Ku1A channel. In the rest of the section, simulation runs that contain active the payload agent with the processing delay function (Newton interpolation polynomial) is denoted with the label “ON”. Otherwise, simulation runs marked with label “OFF” represent the original source of the simulator without considering processing delay in the payload.



(a) Transmission Rate of 15 Kbps



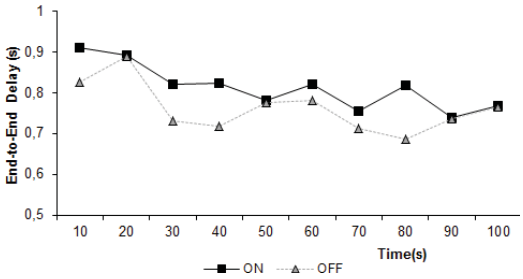
(b) Transmission Rate of 130 Kbps

Fig. 3 Study of End-to-End Delay

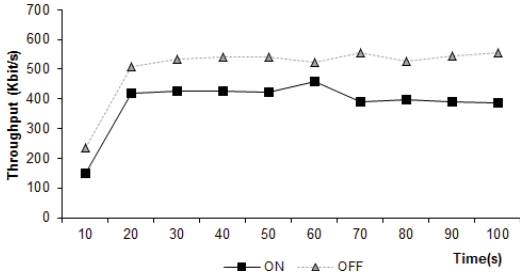
In this simulation, the scenarios A and E were selected using TCP as the protocol transport layer with the followed

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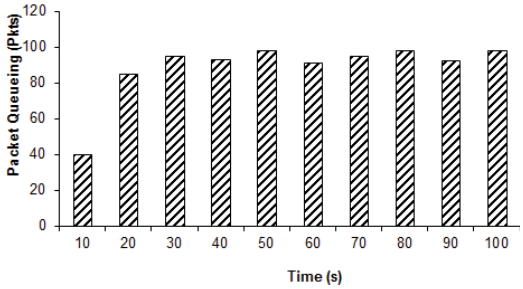
configuration: symmetric links uplink and downlink with 2 Mb, and transmission rate of 15Kbps and 130 Kbps. It is important to observe in Figs. 3 (a) and (b) the differences of the latency values when the transmission delay function is activated in the simulation tool by using the label "ON". This means that the end-to-end delay is better calculated introducing the interpolated value of the transmission delay of the payload than when this parameter is not considered such as shown in the results labelled with the "OFF" trace.



(a) End-to-end Delay



(b) Throughput



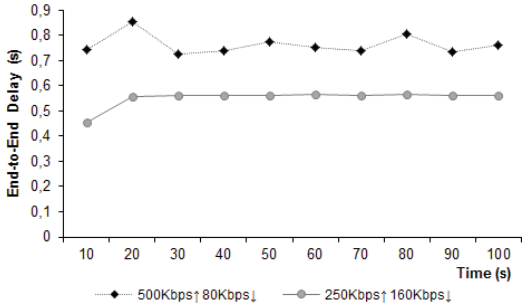
(c) DATA Packet Queueing

Fig. 4 Study of Asymmetric Link for Simulation Scenario "B"

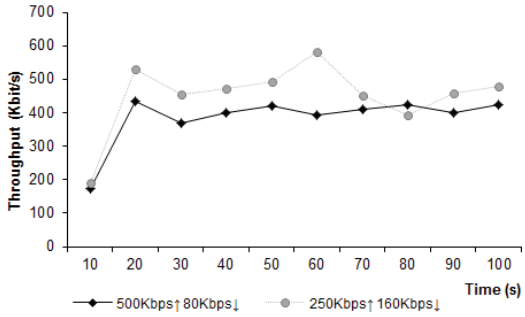
D. Evaluation of the Payload Agent in Asymmetric Satellite Link

The term asymmetric refers to a satellite system in which the data speed or quantity differs in the uplink direction as compared with the downlink direction, averaged over time. This section describes an experimental evaluation of the developed Payload Agent over asymmetric space links by transferring a large user file, leading to its steady performance.

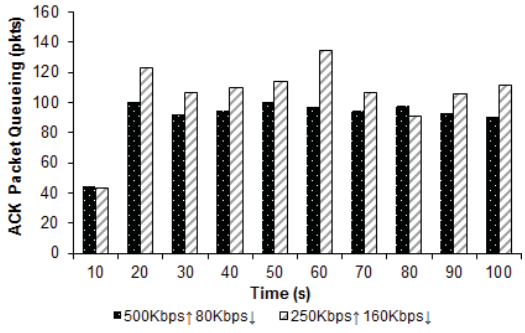
In particular, the end-to-end delay is composed in our simulation results of three main parts: propagation delay, transmission delay and queuing delay. In Figs. 4 (a) and (b), the latency and throughput are plotted by evaluating the



(a) End-to-end Delay



(b) Throughput



(c) ACK Packet Queueing

Fig. 5 Comparison Study for Simulation Scenario "C and D"

performance of the payload agent with the label "ON" and using the simulation scenario "B" in Table III.

As known, when the uplink and downlink channel on the satellite are asymmetric; its causes an overhead of the ACK and DATA traffic and therefore a reduction of the bandwidth available for the data traffic. For this purpose, the scenario C and D of Table III are also considered to simulate asymmetric links using a transmission rate of 130 Kbps. More precisely, the ACK packets were monitored in Fig. 5 (c) to observe the buffer occupancy in the satellite payload. In this case, the buffer size in the satellite payload was set to 150 packets.

Fig. 4 shows the descriptive statistic for the latency, which is determined as consequence of the delay in the propagation channel, processing delay and buffering in the payload. The precision and accuracy of Newton interpolation polynomial was again demonstrated for the case of topologies with asymmetric satellite links. Finally, the relationship between the downlink and uplink (80Kbps / 500Kbps) is crucial in

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generating congestion in the satellite node. This behavior can be observed in Fig. 4 (c), in which the average of the buffer in the payload agent is over 60% .

As a second approach in our simulation results, Fig. 5 shows the latency, throughput and queueing delay when the TCP protocol is used in asymmetric links. In this case, the uplink has more available capacity than the downlink, in which this asymmetry may have an impact on TCP performance due to the congestion in the satellite payload. The TCP protocol may take a long time for a sender in order to determine by using ACK packets if a data packet was successfully received at the final destination.

By increasing the relationship between $uplink/downlink$ there is a notable increase in the latency and reduction of the throughput due to the fact that the number of packages both data and control are queued in the satellite node. In Fig. 5 (c), the average of the packages for both asymmetric scenarios is over 100 ACK packages.

V. Conclusions

In this paper, numerical analyses for determining processing delay were conducted to demonstrate the accuracy of the Newton′s divided difference polynomial when is compared with the Lagrange numerical method. Afterwards, a payload agent was developed to evaluate end-to-end delay. Then, this agent model allows to introduce processing delay inside a terrestrial-satellite scenario based on a complete simulation study. The simulation results are summarized as folllows:

- As satellite payload requirements become more complex and include on-board processing of signals, additional delays need to be considered specially for broadband multimedia services. This paper describes a methodology to modelling and simulate these delays that sometime are discarded for the end-to-end delay calculation.
- The latency can be increased by other factors in the network, such as the transmission time, propagation time of the satellite links and the queueing delay in the satellite payload. All these variables can be monitored in the proposed Payload Agent.
- A tempting ”fix” to the problem caused by delayed ACKs is to simply develop congestion control mechanism for satellite links that can manage the receiver ACK of each incoming segment.

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