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Performance Evaluation of a Single Microsatellite Data Collection System using Small Ground Terminals

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In the scientific literature, much work has been done dealing with the study of low earth satellite constellations but very few have studied the capacity of a single LEO microsatellite. The use of a single LEO microsatellite for data collection implies a complex hardware and software architectures both of the satellite payload and the ground terminals, especially when they are designed to be small, lightweight and economical. To keep the system overall cost very low, the satellite payload is kept very simple whereas all the complexity is brought back to the ground terminals. In a store and forward satellite communication system for data collection the number of the end user ground terminals is of major concern in order to maximize the benefit drawn from the field deployed network. The spatial dynamic behavior of the LEO system makes it difficult to work out this parameter with an analytical method. Therefore simulations must be run to show the capacity of the network in terms of traffic delivered by the ground terminals to the satellite. This paper describes a store and forward satellite system for data collection using low cost intelligent ground terminals. Discrete event simulations with OPNET software show the maximum number of ground terminals that can be served by the satellite along with the delays experienced in the data transfer.

Nomenclature

t_{ACK}	time for on board processing and Acknowledge sending
t_D	transmission delay
t_{down}	propagation time for downlink
t_{packet}	packet processing time
Tr	retransmission time
t_{up}	propagation time for uplink

I. Introduction

THE use of a single microsatellite in a low earth orbit combined with low cost ground terminals allows getting a very economical space communications system. Large rural areas especially in developing countries could

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be covered by the satellite and be supplied with various services, such as data collection, messaging and mobile localization. A central ground station could gather data via the microsatellite from worldwide remote sites.

The store-and-forward communication payload allows taking advantage of the global coverage of the satellite in a low earth orbit by reducing the ground infrastructure. By making the ground terminals autonomous and intelligent, the ground station receives data regularly from inaccessible zones where human presence is expensive and difficult to support.

Today, the store-and-forward communication payload of a microsatellite is simple and easy to build within a minimum timeframe.[1] The ground terminals in charge of collecting and sending data to the satellite are more complex due to the non-permanent visibility of the single satellite. The terminal has to predict the satellite passes by means of orbit calculation. Existing ground terminals like for Orbcomm and Argos systems do not need to know the satellite position to begin transmitting data.[2–4]

In this paper we try to evaluate the performance of an experimental LEO satellite data collection system which is presented in,[5] and simulate the orbit and data traffic in order to get an evaluation of the maximum number of terminals processed in a given area (Moroccan territory) as well as the performances of the used protocol.

II. System Architecture Description

A. Store-and-Forward Communication Overview

The network consists of a sun-synchronous polar orbit microsatellite (altitude 1000 Km, inclination 99.5°) and many fixed and mobile end user ground terminals.

Digital Store-and-forward communication via LEO (Low Earth Orbit) satellites is a method for non- real-time communication of digital information. The originating ground terminal sends the collected data message to the LEO satellite, the satellite stores this message in its on-board memory, and the destination ground station later retrieves it. Between the storage and the retrieval of the message, the LEO satellite moves around its orbit and the Earth rotates on its axis. These movements change the satellite's communications footprint, bringing it to different areas of the Earth (Fig. 1). Thus, the satellite physically carries the message from one ground station to the other, and the destination ground station is not necessarily in the satellite footprint at the same time as the originating ground station.

The Store-and-forward communication concept has been used with much success in different missions including health and education applications where the microsatellite ties together medical centers and schools within rural and developing areas with those in developed areas.[6]

The drawback of a single-satellite LEO system is the delay in the message transfer from the ground terminal to the central station due to the non permanent visibility of the satellite. The originating ground terminal must wait for the satellite to come into range before it can upload a message, and then the message must be stored on-board the satellite until the destination ground station comes into its footprint. These combined delays are not suitable

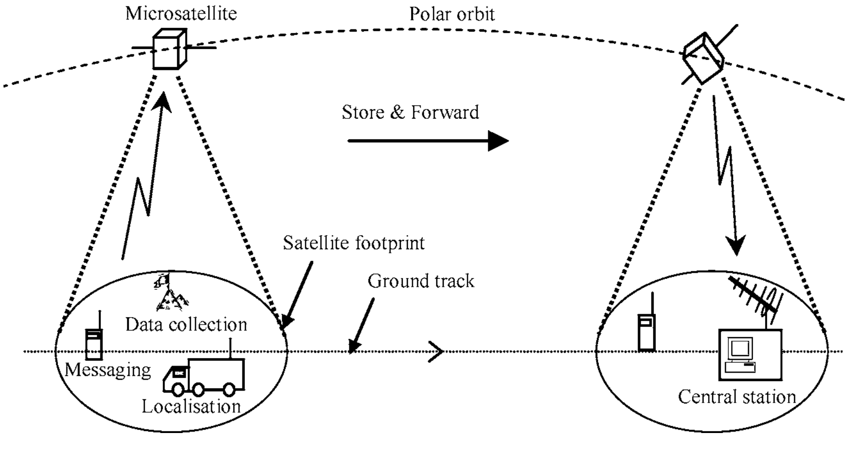


Fig. 1 Store-and-forward applications for a microsatellite.

for telephone communication but are rather dedicated to other applications such as messaging or data-platform monitoring with limited financial budget.

The main missions achieved by the system are data collection, localization (position reporting), and messaging. The data collection mission consists of collecting various data from remote sites. Examples include drifting buoys for oceanography and autonomous weather stations in inaccessible sites. The messaging mission allows message exchange between two ground terminals or between a terminal and a central station. This is useful in the areas not covered by any other communication system: examples include latitudes above 80 degrees where the GEO satellites coverage is no longer available.[7] Any mobile with a localization ground terminal can be tracked by the central station which plots its path on a map using data received from the terminal. Ground terminals for all the three missions have the same hardware, except the message source which is a keyboard for messaging, sensors for data collection and a GPS (Global Positioning System) receiver for mobile localization.

B. Ground Terminal Operation

During the non visibility of the satellite, the designed ground terminals collect data (position or sensor value) at regular intervals and store it in its memory.[5,8] When the satellite comes into range the whole data stored is packetized and transmitted. The amount of data that a ground terminal is allowed to transmit depends on the capacity of the satellite RF channel and the number of terminals we want to operate.

An orbit calculation algorithm is implemented inside the ground terminal to predict the satellite passes.[9] At any time the terminal is able to predict any satellite pass and its elevation angle relative to its current position. This feature has many advantages. First, the terminal can operate in an automatic manner without any human operator or any interrogation from satellite. Second, there is no need for a PC or laptop which makes the terminal heavy and difficult to carry. Third, a power saving method is achieved: the terminal transmitter is keyed only when the satellite is in good visibility range. Fourth, since each terminal calculates the satellite elevation angle, a certain priority in the transmission protocol can be implemented for the terminals in order to increase the system capacity in terms of number of terminals processed.

C. Satellite Communication Session

Once the satellite comes into range the ground terminal starts a communication session to transmit all the collected data in its memory using a stop-and-wait ARQ (automatic repeat request) protocol. Data is segmented into packets with constant length (256 data bytes) which are successively sent to the satellite along with a calculated CRC (Cyclic redundancy check). The same packet is retransmitted until an ACK (acknowledge) is received. During the period of the ACK sending, no packet can be received by the satellite (Push to talk transceiver). Each time any packet is to be transmitted, the terminal calculates satellite elevation to check if it is still visible. The communication session ends when all previously stored packets are acknowledged by the satellite or when the satellite is out of visibility. The ground terminal then returns to stand-by mode for power saving.

The access to the satellite channel is purely random. All the ground terminals using the satellite transmit their packets without caring about the other terminals. When a collision occurs the packet is retransmitted after a random interval time. The Aloha multiple access is chosen for its simplicity in implementing the hardware and software of ground terminals as well as the satellite payload.

III. Satellite and Ground Terminals Modeling

As mentioned above, the network consists of a microsatellite and fixed or mobile terminals dispatched over a geographical area. The aim of the simulations is to evaluate the performances of the network in terms of traffic delivered by the ground terminals, number of terminals used and delays in data transfer.

For the simulations we use the OPNET software which is an event driven software that presents a communication network as models of different hierarchical levels: network level, node level and process level.[10]

To keep the satellite cheaper and easy to build the communication payload is Store-and-Forward and uses a low cost commercial half duplex VHF transceiver. The satellite link uses a 1200 baud AFSK (Audio Frequency Shift Keying) modulation. Both the satellite and the ground terminals have a 5 Watts RF power output.

To keep the network easy to implement an Aloha channel access method with a stop-and-wait protocol is used. A CRC check algorithm is implemented on board the satellite for error control.

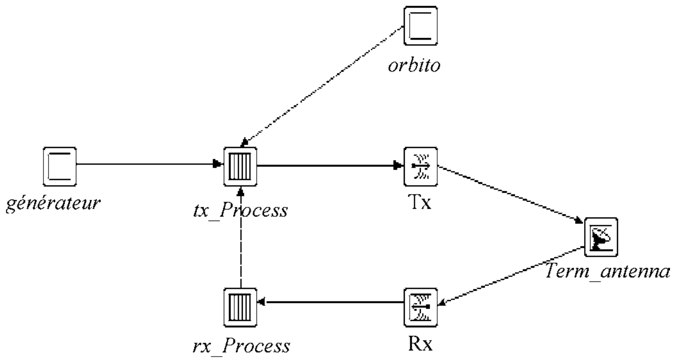


Fig. 2 Ground terminal node model.

A. Satellite and Ground Terminal Nodes

OPNET software treats each communication node as a set of objects connected with data streams and interrupt wires as shown in Fig. 2 and Fig. 3.

Terminals are allowed to send messages only when the satellite is in the visibility range. Therefore terminals have an orbit calculation process *orbito* in the terminal node which is able to calculate the elevation of the satellite and warn the terminal via a statistic wire when it is higher than a specified value. The process *générateur* generates data packets at a specified rate according to the data collection mission. The process *tx_Process* is in charge of managing the terminal packets queue and the *rx_Process* checks the reception of ACKs from the satellite.

The satellite node acts like a mailbox. Its *OnBoard_Process* receives packets from ground terminals, checks for errors and sends ACKs to the corresponding terminals. The process *Nb_terminals* records the instantaneous number of terminals located in the satellite ground footprint.

B. Ground Terminal Processes

In OPNET, each process is defined as a finite state machine where different states are connected with conditional or unconditional transitions.

The main process in the terminal node is the *tx_Process*. This process handles packets arriving from the Generator, queue them and wait for the satellite visibility. When this event occurs and the queue isn't empty the transmission begins. During this state, a packet is sent and a timer is set on. The process waits for an acknowledge packet from the satellite (via *rx_Process*) according to the stop-and-wait protocol. If the acknowledge is received, the process goes on with the next packet in the transmission queue, otherwise it continues to resend the same packet until receiving acknowledge or until the satellite goes out of visibility.

Another important process in the terminal node is the *orbito* process. This process calculates the satellite elevation each 10 s, and instructs the *tx_process* to begin a communication session when the elevation is higher than the specified elevation mask. A self interrupt is used because OPNET is event oriented rather than time oriented. OPNET

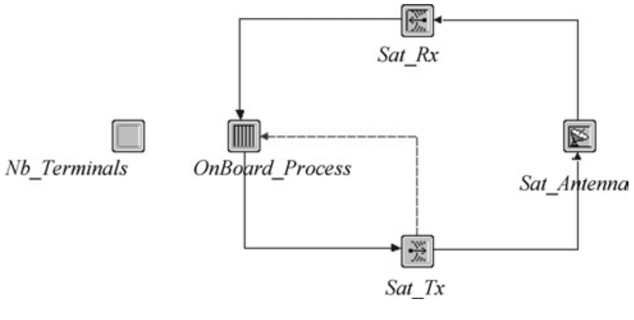


Fig. 3 Satellite node model.

provides the satellite coordinates using an STK (Satellite Tool Kit software) file and the process calculates the terminal-satellite vector coordinates in the ECF (Earth Centred Fixed) system. By means of a transformation matrix, the terminal-satellite vector is expressed in the topocentric coordinate system relative to the terminal location.[11,12] The satellite elevation is then derived using simple trigonometric formulas. If the satellite elevation is greater than the desired mask, the process generates an interruption to the *tx_process* via a statistic wire (Fig. 2).

Each ground terminal then knows exactly when the satellite is coming into its range. The time point at witch a terminal begins its communication session is not the same for all the terminals, and the session stops as soon as all the data packets stored in the terminal queue are successfully transmitted. The number of terminals simultaneously present in the satellite footprint is then constantly changing during the satellite pass.

C. Satellite Processes

The Satellite node consists of 1 processor, 1 subqueue, 1 transmitter, 1 receiver and 1 antenna module (Fig. 3). After the initialisation, the *OnBoard_Process* module enters a wait state and waits until receiving a packet. If the received packet is valid, then an Acknowledge packet is sent to the terminal. Otherwise, the packet is destroyed and the process comes back to the wait state.

Onboard the satellite a push to talk transceiver is used, allowing just transmitting or receiving.

At the end of the simulation the statistics are recorded before the exit.

The process *Nb_Terminals* calculates periodically the number of the terminals able to communicate with the satellite.

IV. Assumptions and Rough Analytical Prediction

Let us assume that the system must allow each terminal to send 4.5 packets per day. Each packet consists of 310 bytes including data and control headers. We'll try to find out the theoretical number of terminals able to work successfully in the considered geographical area under those assumptions.

During one day, the satellite is passing 5 times over the chosen geographical location (6.79314° W, 34°.0537 N) with different visibility time durations. The total visibility time equals 5027s during the considered day.

The time t_{packet} to get one packet processed (sent to the satellite and acknowledged) is given by:

$$t_{packet} = t_D + t_{up} + t_{ACK} + t_{down}$$

The transmission delay t_D depends on the packet size (2480 bits) and the bit rate of the satellite link which is 1200 bits/sec. The propagation time for both uplink t_{up} and downlink t_{down} are approximately equal and depend on the satellite range from the terminal; the maximum is about 9 milliseconds at 10° elevation.[13] The on board processing and ACK sending time t_{ACK} in our case is approximately 0.7 seconds.

With theses figures the total time to get one packet acknowledged is approximately 2.78 seconds.

Therefore the number of packets that can theoretically be processed by the satellite (no packet collisions) during a day equals the visibility time (5027 sec.) divided by the packet time (2.78 sec.). This means that the network can handle up to 1808 packets per day.

Each terminal has to transmit 4.5 packets, so the number of terminals that can be serviced by the satellite is about 401 ground terminals.

Taking into account that the efficiency of the Aloha protocol is 18.4%, the maximum number of terminals that can be successfully deployed over the defined geographical area is approximately 74 terminals.[14]

V. Simulation Results

A. Communication Channel Characterization

The Communication time on the satellite single channel is not regular, due to the dynamic behaviour of the system. Satellite passes and their durations depend on the terminal geographical location. On the other hand, for the same terminal, satellite visibility time depends on the pass number. Obviously, for some passes the satellite visibility footprint covers the whole area of the considered region and for others only a part of that region is covered. Subsequently, the number of ground terminals communicating simultaneously with the satellite varies from one pass to another. This makes the traffic load on the network completely erratic and variable.

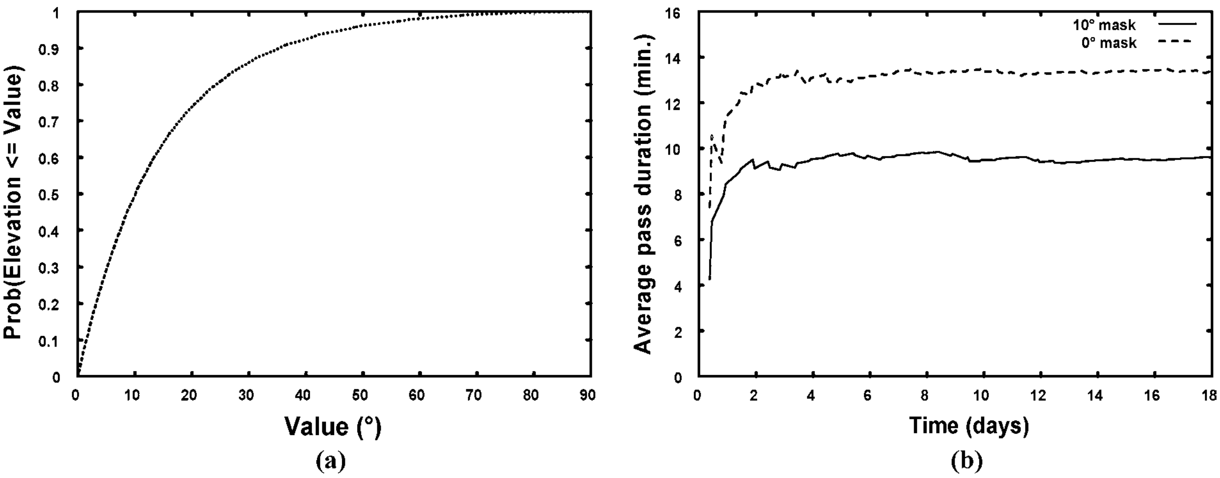


Fig. 4 Cumulative distribution function of the elevation angle (a), and average pass time duration of the satellite (b).

To get viable results from the simulations, the simulation time should be long enough to ensure stable results. If the satellite orbit is repetitive, the simulation time should be at least equal to the period of the repeating pass pattern.

For all the simulations the Moroccan LEO microsatellite (MAROC-TUBSAT) orbit is chosen as an example. It is a 1000 Km high sun synchronous orbit with an inclination of approximately 99.5° and an ascending node at 9:30 A.M.

B. Satellite Visibility Time Duration

With simulations run over a long time period, the collected elevations statistics for any terminal, allowed us to draw the cumulative distribution function shown in Fig. 4a. The probability that the elevation angle is less than 20° equals 0.75 which means that 75% of time the satellite is below 20° elevation. The graph shows also that for 50% of time the elevation is below 10°. For budget link considerations as well as geographical masking around the ground terminals, these are programmed to transmit only when the satellite elevation is above 10°. By using this elevation mask the communication time over the satellite channel is divided by two.

The average visibility time duration of the satellite passes is around 13.5 minutes whereas it is only 9.5 minutes when using a 10° mask (Fig. 4b).

The elevation mask influences dramatically the network capacity because it is proportional to the communication time over the channel. For Aloha protocol, the channel is efficiently used by the ground terminals for only 18% of time. So, using a 10° mask divides by two the total network capacity. The number of terminals that can be processed by the satellite is only half that when no mask is used.

C. Visibility Time Shift Between Ground Terminals

The satellite footprint evolution on the ground induces a visibility time shift between ground terminals. The time shift is that much important that ground terminals are distant from each other. For the Moroccan territory (latitudes between 21° and 36° N) the visibility time shift between one terminal in the north and another in the south is considerable. Figure 5 shows elevations observed by four different ground terminals during a satellite pass. The pass is a high elevation pass and shows approximately 300 seconds of time shift between terminal 1 and terminal 3.

The visibility time shift improves the Aloha efficiency because at a given time only part of the whole terminals is communicating with the satellite and therefore much less packet collisions occur.

D. Visible Terminals Density

The number of ground terminals in the satellite view depends on the type of the visible pass. The random channel access protocol used takes advantage from this situation in that way sometimes only few terminals are

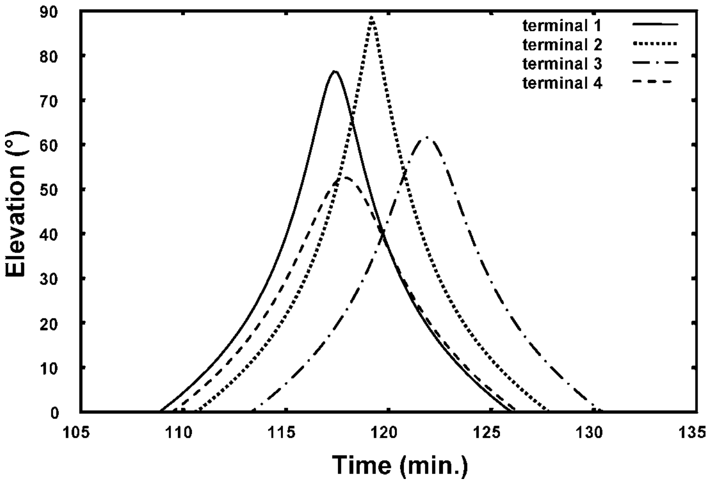


Fig. 5 Satellite elevations during one pass for four different geographical locations.

using the satellite making the traffic load lighter and resulting in better throughput. Figure 6 shows the number of ground terminals simultaneously present in the satellite footprint during 2 consecutive passes. The graph illustrates 2 situations where the traffic load on the channel can be very different. In the first pass, the satellite is covering only a part of the Moroccan territory and only a maximum of 40% of the ground terminals are communicating over the channel. The second pass is a high elevation pass; the satellite is covering the whole territory and gradually all the terminals can reach the satellite.

E. Network Capacity Optimisation

The traffic requirement of the microsatellite network is 4.5 packets a day for each terminal. Several simulations have been made to find out the maximum number of ground users that can be serviced over a geographical area limited to Morocco. Given random access protocol is used, the optimisation parameter is the retransmission time *Tr*.

Figure 7 shows the number of packets received onboard the satellite versus retransmission time *Tr* for three scenarios with different numbers of terminal nodes. For small values of *Tr*, a lot of collisions occur and the amount of successfully transmitted packets is also small. For bigger values of *Tr*, the number of received packets onboard the satellite is limited by the time of the visibility pass. The maximum number of onboard received packets is reached for an optimum *Tr* which depends on the number of ground terminals. More terminals in the network yields higher *Tr*.

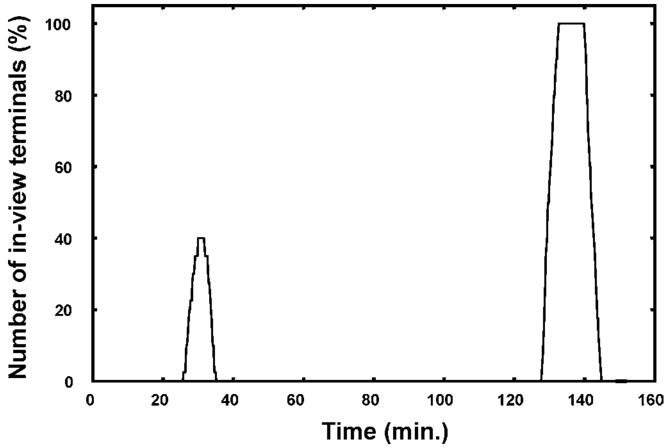


Fig. 6 Number of ground terminals simultaneously present in the satellite footprint during two consecutive passes.

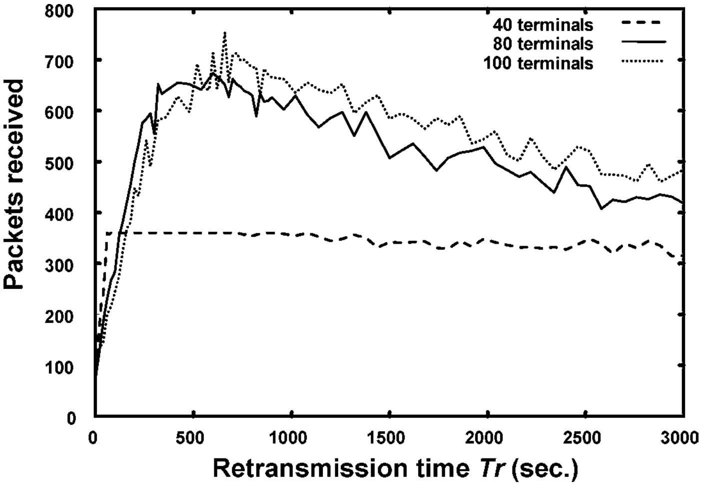


Fig. 7 Number of packets received onboard the satellite as a function of the retransmission time *Tr*.

To determine the network capacity, the maximum number of satellite received packets must match the number of the generated packets by all the ground terminals.

Scenarios with different number of terminals have been simulated and showed that for the required traffic a maximum of 80 terminals can be handled by the satellite using an optimum *Tr* of 500 seconds. All the terminals queues are regularly emptied during the satellite passes (Fig. 8), thus successfully transferring the data generated by the terminals to the satellite.

A long time simulation showed a stable network where the terminals succeed in transmitting all their generated packets.

Using more than 80 terminals makes the network unstable leading to traffic congestion. Figure 8 shows that when using 100 terminals, packet queues sizes are permanently growing.

F. Packet Transfer Delay

A part from network stability, another important parameter to be considered is the packet transfer delay which defines the time a packet is waiting in the terminal queue before being successfully transmitted to the satellite. Figure 9a and 9b show the average and the cumulative distribution of the ETE (End To End) delay for the three

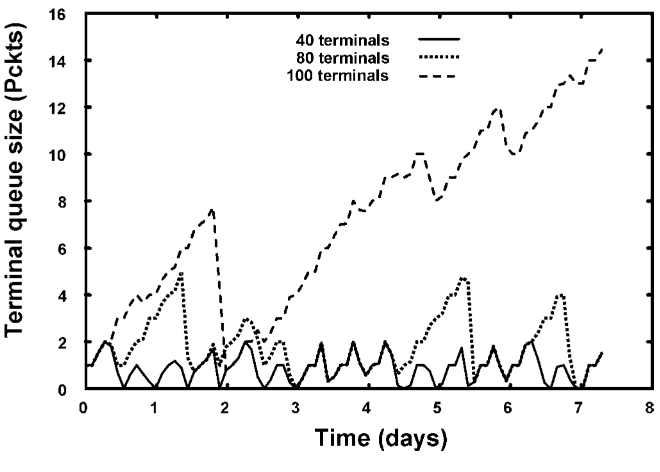
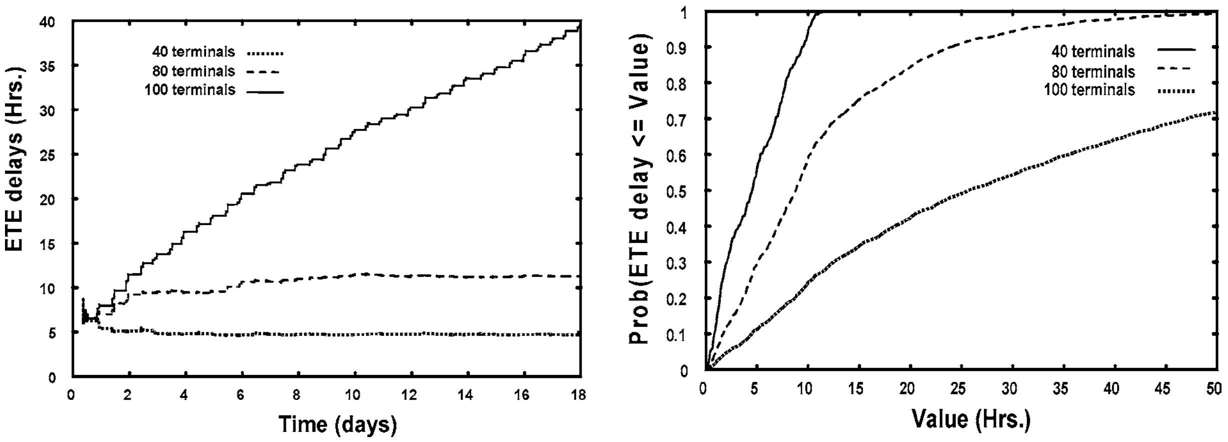


Fig. 8 Terminal queue size for scenarios with different number of ground terminal nodes.



(a) (b)

Fig. 9 Average (a) and cumulative distribution function (b) of the end-to-end delay in packet transfer.

scenarios. In the 100 terminals scenario, network saturation leads to an infinite delay in packet transfer. When using 80 terminals, the average transfer delay is approximately 11 hours and has a maximum of 2 days. By reducing the number of terminals to 40, the delay is cut down to a maximum of 11 hours which is the natural limit whereas the average is around 5 hours.

G. Channel Throughput

Aloha channel is characterized by its familiar S/G channel throughput as a function of channel traffic curve which shows a maximum of 18% throughput when the channel traffic equals 0.5.[14,15] In other terms 36% of the total packets transmitted to the satellite (including retransmitted packets) are successfully received by the satellite. Running several simulations, we got the graph of Fig. 10 representing packets received onboard the satellite versus the total submitted packets. The maximum yield effectively reaches 36% validating the theoretical figure.

For a 40 terminals scenario, the curve is flattened because the maximum number of received packets reaches the total packets generated by the terminals for different values of *Tr*. This means that the satellite is still able to handle

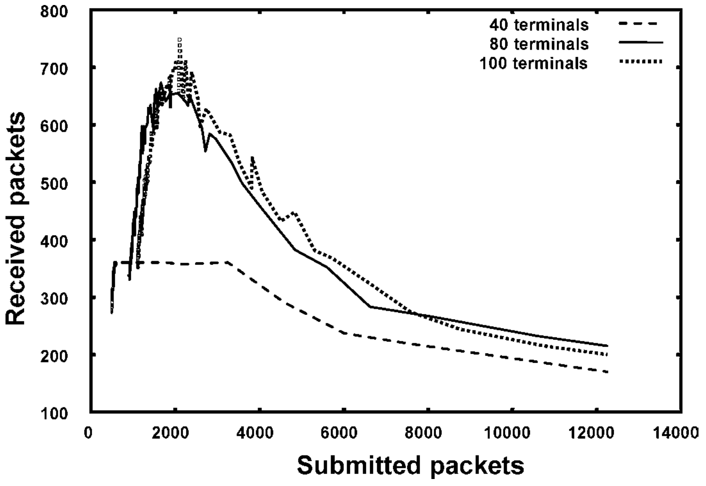


Fig. 10 Channel throughput expressed by packets successfully received by the satellite as a function of the total submitted packets.

packets while all the traffic generated by the terminals has been processed. We can put more terminals to generate more traffic but at the expense of increasing transfer delay.

VI. Conclusion

Simulations have been carried out to study the capacity of a single LEO microsatellite based system for data collection using intelligent ground terminals. These simulations have been made for a population of ground terminals located in given geographical area. Using pure ALOHA with a stop-and-wait access protocol, it is possible to handle 80 ground terminals with a traffic load of 4.5 packets (256 data bytes) a day for each terminal that matches the figure given out by analytical calculations. Data transfer delay which is not critical in this application is approximately two days. To cut down the transfer delay to the natural limit of 11 hours, the number of ground terminals must be reduced down to 40. This number is particularly determined by the Aloha multiple access protocol used on the satellite link. Much more terminals could be processed by the satellite using other more efficient protocols, but at the expense of higher complexity and cost.

The store and forward communication concept used allows data collecting terminals to be deployed worldwide. In this case the number of end user ground terminals that can be serviced by the satellite is much higher.

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