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# Design and Analysis of Store-and-Forward Data Collection Network Using Low-cost LEO Small Satellite and Intelligent Terminals

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**There have been a lot of studies about Low Earth Orbit satellite constellations but very few have dealt with a single LEO satellite. The Picosatellite, as small as the Cubesat concept, requires employment of a simple store-and-forward payload whereas all the complexity is brought back to the terminals. This paper describes the design and analysis of store-and-forward data collection network using low-cost LEO Picosatellite and intelligent ground terminals. The study will employ the Slotted Aloha multiple access in the uplink and will assess its efficiency in terms of the maximum number of ground terminals that can be served by the satellite. In this work, we will establish a mathematical model for evaluating the performance of the Slotted Aloha system and then we will present some simulation results by using discrete event simulations. In such a system, two appropriate measures of the performance are the throughput and the average delay; thus, we will use these measures in this paper. A good correlation between analytical model and the discrete event simulations was found.**

## I. Introduction

FOR more than two decades, the Slotted Aloha multiple-access protocol received the attention of not only computer network engineers, but also communications network researchers.[1,2] For LEO satellite systems, Aloha protocol should have promise, even though its basic idea may require some modifications. The basic idea of the Aloha protocol, even with its low capacity feature, has been employed in some satellite systems,[3] which is evidence that aloha protocol can match the special features of satellite systems. Although this kind of transmission results in large numbers of collisions between simultaneously transmitted packets and low performance, but its simplicity is strong enough that even now we see some research on its basic idea. In the paper,[4] we evaluated the use of Unslotted Aloha by terminals situated in specific limited area (Morocco country). Here we will evaluate the use of a variant Slotted Aloha by terminals situated in general satellite service area. Also, the constraint here is to use one frequency for both uplink and downlink in order to keep the system overall cost very low.

The principle of Slotted Aloha multiple access protocol is that terminals start the transmission of their information in the form of the fixed-length packets at synchronized common clock instances whenever they have information to

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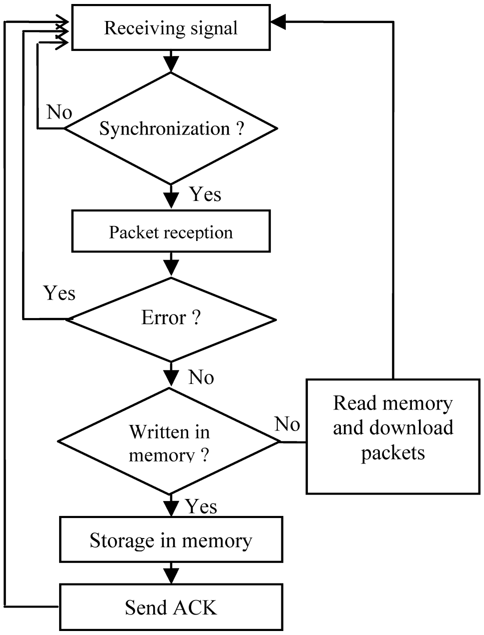


**Fig. 1 Store-and-forward payload flowchart.**

send. In our system, the synchronization of all the terminals will be done by using the Global Positioning System (GPS) receiver integrated in each terminal.

The Picosatellite carries aboard a store-and-forward payload operating in half-duplex mode with Amateur VHF uplink/downlink frequency band. The store-and-forward payload provides various services, such as mobile localization of ships and data collection from autonomous weather stations in inaccessible sites. In our case, the terminals initiate, control and terminate all communication sequences automatically, whereas the Picosatellite store-and-forward payload is designed to take orders.

The terminals use the Slotted Aloha multiple access to send their packets to the Picosatellite payload, which stores the correct packets in an on-board storage system, and delivers this to the destination Central Ground Station (CGS) in a later time. Between the storage and the retrieval of the packet, the Picosatellite moves around its orbit and the earth rotates on its axis. These movements change the location of the satellite's footprint, and the Picosatellite effectively carries the packet from terminals to the CGS station. The stored packets are to be formatted for download when the right telecommand is given from the CGS station.

When the terminal transmits its packet, it will wait for acknowledgement and will set its timer. If this timer expires without reception of an acknowledgement, the entire packet is scheduled for retransmission after a random interval time. An acknowledgement indicates a complete success of the transmission.

The design of the store-and-forward payload is designed to take orders (see Fig. 1). The payload always listen to the receiver. The preamble, that is, the beginning of a packet must be detected first. The synchronization will be achieved after the preamble is detected. The received packet will be tested if there is an error in the packet. The erroneous packet will be rejected and the correct packet will be stored. It is obvious that the destination CGS station is not necessarily in the Picosatellite footprint at the same time as the originating terminals. The destination CGS station needs to wait for the satellite to come into range before they can send a request to download their packets.

## II. System Description

Consider a communication network comprising one LEO satellite and a finite number of terminals wanting to communicate with the CGS station through that satellite. In this system, the limiting direction is the uplink multiple access, from terminals to satellite, which is established according to Slotted Aloha. Packet length and slot size are assumed to be equal.

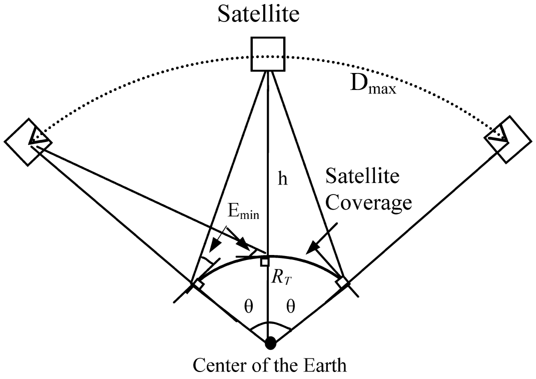


**Fig. 2 Satellite coverage area.**

The instantaneous coverage of the satellite depends on the minimum angle of elevation $E_{min}$ under which any user can be serviced by the satellite. Because of the spherical shape of the earth and natural obstacles, such as mountains, any location with an elevation angle less than $E_{min}$ can not be easily seen from the satellite. Figure 2 shows the satellite coverage of any satellite with the altitude $h$ between 300 Km and 36 000 Km.

In the satellite system model, we assume a satellite in circular orbit at the altitude $h = 650\,\text{km}$ with a minimum elevation angle $E_{min} = 10°$.

The satellite coverage is determined by the half-sided angle of the footprint $\theta$ which is measured at the center of the Earth by reference to the geometric relations shown in Fig. 2.

$$\theta = \left[\text{Arcos}\left[\frac{R_T}{R_T + h}\cos(E_{min})\right] - E_{min}\right] \text{(radians)} \tag{1}$$

where $R_T$ is the effective Earth radius with $R_T = 6378.137\,\text{km}$.

The period time for one complete orbit of the satellite is related to the semi-major axis $a$ of the satellite orbit by the Kepler's third law:[5]

$$T_{sat} = 2\pi\left[\frac{a^3}{\mu}\right]^{\frac{1}{2}} \tag{2}$$

Where $\mu$ is the gravitational constant with $\mu = 3.986 \times 10^{14}\,\text{m}^3\text{s}^{-2}$, and $a$ is the semi-major axis of the satellite orbit with $a = h + R_T$. We have $T_{sat} = 97.7$ min for the altitude $h = 650\,\text{km}$.

The speed of the satellite, for circular orbit, is constant[6] and is given by the following equation.

$$V_{sat} = \frac{2\pi a}{T_{sat}} \tag{3}$$

We assume that the earth is fixed in comparison with the high speed of the satellite of about 7.53 Km/s at the altitude of $h = 650\,\text{Km}$. With the assumption that users $N_u$ are distributed on the subsatellite line, the time of the visibility for each terminal is given by.

$$T_u = \frac{T_{sat} \times \theta}{\pi} \tag{4}$$

When $h = 650\,\text{Km}$ and $E_{min} = 10°$, the time period of the visibility is equal to $T_u = 542.93\,\text{s}$. The distance covered by the satellite between the two extremities terminals in the satellite coverage area is:

$$D_{max} = 2 \times (R_T + h) \times \theta \tag{5}$$

The satellite time shift between the two extremities terminals in the satellite coverage area is given by:

$$T_{sh} = \frac{D_{max}}{V_{sat}} \tag{6}$$

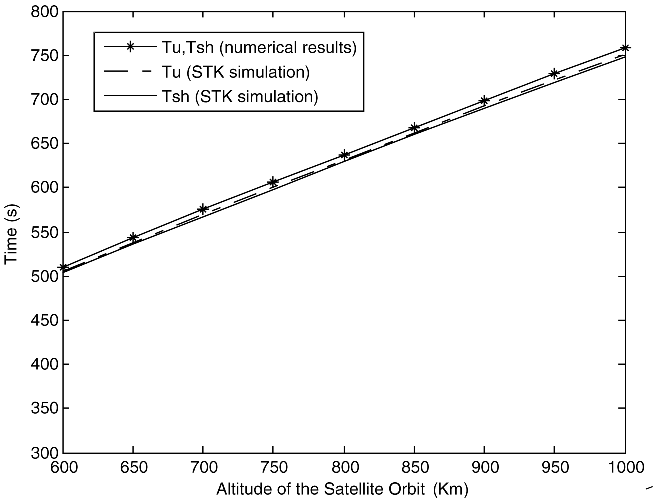


**Fig. 3 Comparison between the numerical results and STK simulation results of $T_u$ and $T_{sh}$.**

From Eqs. (3), (4), (5) and (6), we have:

$$T_{sh} = T_u \tag{7}$$

We found that the satellite time shift between the two extremities terminals is equal to the time of the satellite visibility for each terminal. Figure 3 illustrates a comparison between the numerical results and Satellite Tool Kit (STK) simulation results of both the time of the satellite visibility $T_u$ and the satellite time shift $T_{sh}$. The STK software takes into account the earth's oval and the earth's rotation. The simulation results are almost the same as the numerical results as shown in the Fig. 3.

Therefore, the global time $T_{sv}$ of the satellite visibility over its service coverage area is equal to:

$$T_{sv} = T_{sh} + T_u = 2T_u \tag{8}$$

The Picosatellite requires employment of a simple store-and-forward payload whereas all the complexity is brought back to the terminals. The terminals[7] are equipped with a processing unit which uses the orbitography software to recognize the moments of the satellite passage. To make its calculations, the orbitography software needs three parameters to know, terminal geographical position, UTC time and the NORAD-Keplerian Elements. The first two parameters are given by internal GPS receiver. The third parameter is given by the central ground station which regularly communicates (1 to 2 times per about fifteen days) the updated NORAD-Keplerian Elements of the satellite to all the terminals. The functional architecture of the terminals is given by Fig. 4.

A block diagram of the proposed Nanostellite payload Architecture is shown in Fig. 4. The Nanosatellite[8], as small as a Cubesat[9] concept with dimensions 10 cm × 10 cm × 10 cm and mass one kilogram, requires employment of limited small boards. The approach, which has been taken, is based on two design directives: the integration of the store-and-forward APRS payload and On Board Data Handling (OBDH) subsystems within the same unit, and the elimination of nonessential elements to cut down the cost of the Nanosatellite. An active attitude control and pointing system have been avoided by using omnidirectional antenna. Therefore, the Picosatellite will carry a combination of passive and active solutions for the thermal control. The solar cells will be attached to the satellite structure, thus avoiding the need for solar panels and the necessary deployment system. The surface area for mounting solar cells is significantly reduced compared to conventional satellites, which results in less power generation ability. Due to their extremely low weight, small size, and good capacity, Li-ion batteries were chosen as the onboard satellite battery.

## III. Radio Link

At VHF frequencies the atmosphere and the ionosphere have little effect on the propagating radio wave.[10] Also, antennas, receivers and transmitters for both the ground and the space segment are readily available and inexpensive.

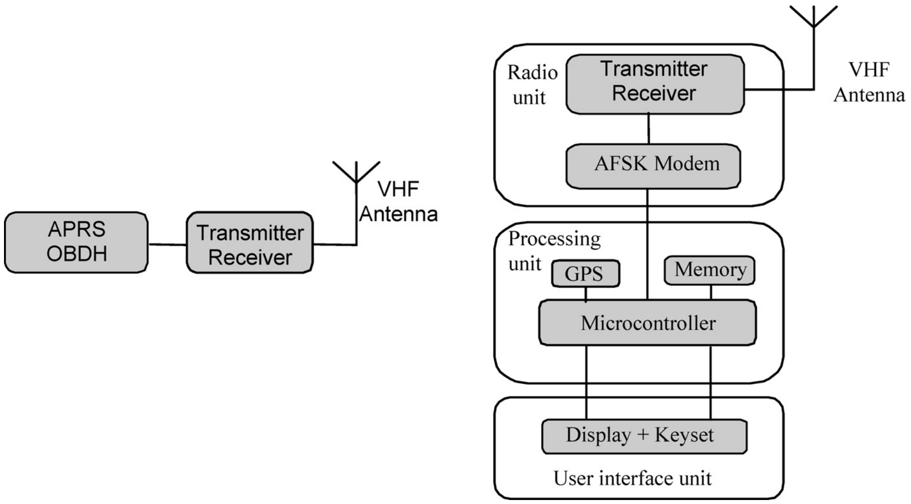


**Fig. 4 Functional architectures of the nanosatellite and the ground terminals.**

The Doppler shift is about ±3 KHz maximum, which can be ignored[11] for the Nanosatellite parameters with altitude of 650 Km and operating frequency of 145.825 MHz.

The link budget, shown in Table 1, is calculated in the worst case when the satellite is just rising above the horizon with the elevation angle $\mathrm{E} = 10^\circ$.

If one looks at the Cubesat projects they generally use about one watt of output power while limiting the data rate to 1200 baud. Since the central station Yagi antenna will be tracking the satellite, it will always be pointing in such a way that the maximum gain, in our case 13 dB gain, is achieved.

The scheme, which used the FSK modulation in conjunction with a Send-and-Wait Automatic Repeat Request (ARQ) protocol, provides error free communications between the terminals and the Picosatellite.

## IV. Throughput Analysis

The problem with the Slotted Aloha scheme that limits its capacity is the collisions of the packets. Any approach to enhance the capacity of the Slotted Aloha scheme should consider either how the number of the collisions can be decreased or how the collision can be managed so they have less effect on the capacity of the system. Dividing the time axis used in Slotted Aloha method limits the number of transmissions during each specific interval or slot.

In our system, the uplink multiple access from terminals to satellite is the limiting direction which is established according to Slotted Aloha. Terminals start the transmissions of their information in the form of the fixed-length packets at common clock instances whenever they have information to send.

In conventional Slotted Aloha, the throughput can be defined as the expected number of successful packets in each time slot, with the dimension of packets per slot. A transmitted packet can be received incorrectly or lost completely because of two different types of errors: 1) random noise errors and 2) errors caused by packet collision. In this paper, we assume that the first type of error can be ignored, and we shall be concerned only by errors caused by packet collision. In this system, however, a terminal can always find out whether a packet was destroyed by monitoring its timer $\mathrm{T}_t$, which will be defined later in section V. If the packet was involved in a collision and destroyed, the terminal waits for random delay and then retransmits the packet.

Let $\mathrm{G}_{\mathrm{ui}}$ be the probability that the $i$th terminal will send a packet, including newly generated and retransmitted packets in each time slot and $\mathrm{S}_{\mathrm{ui}}$ the probability that the $i$th terminal will transmit a packet successfully in each time slot. If all terminals are identical, i.e. $\mathrm{G}_{\mathrm{ui}} = \mathrm{G}_{\mathrm{u}}$ for each $i = \{1, \ldots, \mathrm{N}_{\mathrm{u}}\}$, so the probability that the number of the transmitted packets by terminals, during each time slot, is equal to k, follows the binomial law[14] with parameters $\mathrm{G}_{\mathrm{u}}$

**Table 1 Budget link.**

| | |
|---|---|
| Terminal parameters | |
| Antenna gain | 0 dBi |
| Transmitted power | 5 W |
| Antenna Feed Loss | 0.5 dB |
| $T_{syst}$ | 2000 k |
| Channel parameters | |
| Free Space Loss | −141 dB*[1] |
| Bandwidth | 15000 Hz |
| Additional Losses | 3.5 dB |
| Satellite parameters | |
| Antenna gain | 0 dBi |
| Transmitted power | 1 W |
| Antenna Feed Loss | 0.5 dB |
| $T_{syst}$ | 5000 k |
| Operational parameters | |
| Baud Rate | 1200 baud |
| $E_b/N_0$ required | 13.6 dB*[2] |
| Link margin for uplink | |
| $E_b/N_0$ estimated | 21.42 dB*[3] |
| Margin | 7.82 dB |
| Link margin for downlink | |
| $E_b/N_0$ estimated | 18.42 dB*[3] |
| Margin | 4.82 dB |

*[1] Free space loss, FSL[12] is calculated by:

$$FSL_{db} = 32.45 + 20\log(D_{km}) + 20\log(F_{MHz}) \quad (9)$$

where $F_{MHz}$ is the transmit frequency, and $D_{km}$ is the distance or range of the satellite, calculated by:

$$D_{km} = \sqrt{(R_T + h)^2 - (R_T.\cos(E))^2} - R_T.\sin(E) \quad (10)$$

*[2] Required $E_b/N_o$ gives a bit error rate of $2.10^{-5}$,[13] assuming non-coherent demodulation of FSK.

*[3] An estimation of the $E_b/N_o$ is obtained from:

$$\frac{E_b}{N_o} = \frac{P.L_i.G_t.L_s.L_a.G_r}{k.T_s.R} \quad (11)$$

Where:

P = Transmitted Power

$G_t$ = Transmit antenna gain

$L_s$ = Free Space Loss (FSL)

$G_r$ = Receive antenna gain

$T_s$ = System temperature

$L_i$ = Feed Losses

$L_a$ = Miscellaneous Losses

K = Boltzmans constant

R = Data rate

and k as:

$$P(k; G_u) = \begin{cases} C_k^{N_u} G_u^k (1 - G_u)^{N_u - k} & k \le N_u \\ 0 & k > N_u \end{cases} \quad (12)$$

Note that $G_u \le 1$ because the terminal can not transmit more than one packet in a time slot. The probability of success $P_{suc}$ that terminal transmits successfully a packet, is equal to the probability that $(N_u - 1)$ other terminals

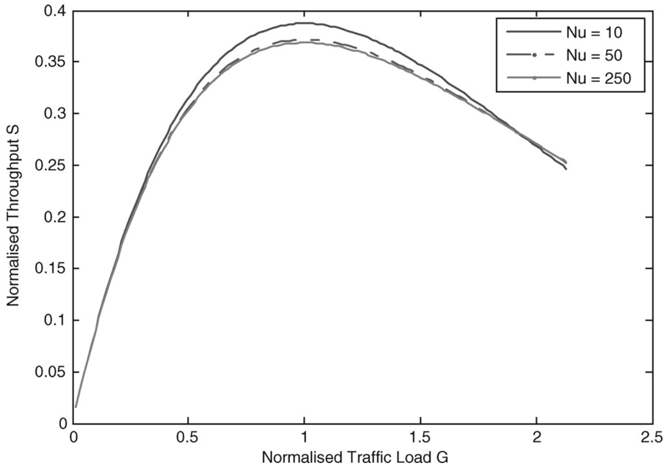


**Fig. 5 Throughput vs traffic load for a Slotted Aloha with different number of terminals.**

don't send any packet during time slot to avoid the collision, which corresponds to the probability P (0; $G_u$):

$$P_{suc} = P(0; G_u) = (1 - G_u)^{N_u - 1} \tag{13}$$

The probability of a successful transmission $S_u$ by the terminal is equal to the probability $G_u$ that the terminal sends a packet multiplied by the probability of success $P_{suc}$.

$$S_u = G_u\,(1 - G_u)^{N_u - 1} \tag{14}$$

We define the normalised channel Throughput $S$ and the normalised Traffic Load $G$ for the Slotted channel as:

$$S = \sum_{i=1}^{N_u} S_{ui} \quad \text{and} \quad G = \sum_{i=1}^{N_u} G_{ui} \tag{15}$$

Since all terminals are identical, we have $S_u = S/N_u$ and $G_u = G/N_u$. So, Eq. (14) can be written

$$S = G(1 - G_u)^{N_u - 1} \tag{16}$$

$\mathrm{d}S/\mathrm{d}G = 0$ for $G = 1$. So the maximum throughput $S_{max}$ is:

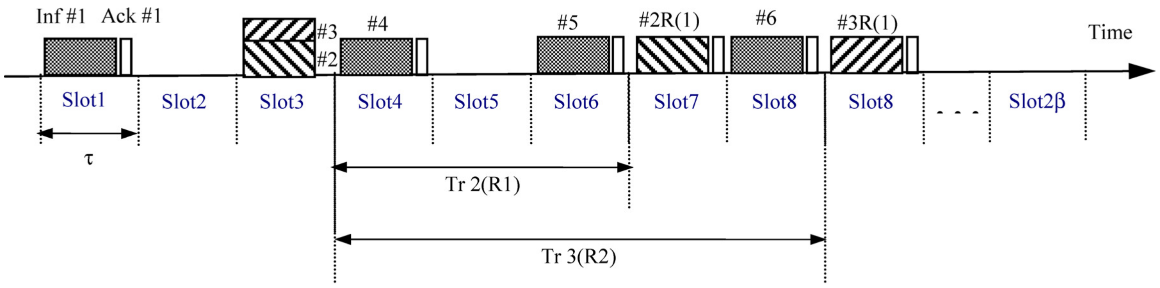
$$S_{max} = \left(1 - \frac{1}{N_u}\right)^{N_u - 1} \tag{17}$$

The relation between the offered traffic load and the throughput of the Slotted Aloha scheme of Eq. (16) is plotted in Fig. 5, which shows that the throughput $S$ depends almost only on $G$ and doesn't depend on the number of terminals $N_u$. It is intuitively reasonable because, the throughput per user who depends on the number of users.

As can be seen in the Fig. 5, the peak of the throughput for the Slotted Aloha occurs at $G = 1$. That means that if the system is operating at $G = 1$, the probability of empty slot is 0.368. Operating at higher traffic loads reduces the number of empties but increases the number of collisions exponentially.

## V. Satellite Communication System

The share of the satellite channel by all the terminals on the ground is done according to the random access protocol Slotted Aloha. All the ground terminals transmit their packets at common clock instances without caring about the other terminals. When a collision occurs the packet is retransmitted after a random interval (see Fig. 6).



τ : slot duration.
2β : number of total slots available during the satellite pass over the satellite service area.
#i : number of the packet
Tri(Rj) : waiting time before the j$^{th}$ retransmission of the packet i.
#iR(j) : j$^{th}$ retransmission of the packet number i.

**Fig. 6 Satellite communication session.**

The Slotted Aloha multiple access is chosen for its simplicity in implementing the hardware and software of ground terminals as well as the satellite store-and-forward payload.

Once the satellite comes into range, the ground terminal starts a communication session to transmit the packet of duration $T_{\text{inf}}$ using a Send-and-Wait ARQ protocol. We used the packet format of AX.25 packet format.[15] For the sake of simplicity in calculations, Zero-guard time is assumed here.

In the case of the packet successful reception, the satellite sends an acknowledgment packet of duration $T_{\text{ack}}$. In Unslotted Aloha, to avoid the loss of the acknowledgment packet, each terminal uses two different frequency bands, one band to send the information packet and the other band to receive the acknowledgment packet the implementation of the Slotted Aloha in our system has the advantage to use only one frequency band for both the uplink and the downlink in order to keep the system overall cost very low. Taking advantage of the halh-duplex communications, each terminal transmits and the satellite replies with the same frequency band. This procedure avoids the loss of the acknowledgment packet due to collisions with the information packets sent by other terminals because they are all synchronised.

From the moment of the sending of the packet, a timer starts to receive the acknowledgment and it is equal in our system to the duration of a slot $\tau$, which is given by the following relation:

$$\tau = T_{\text{up}} + T_{\text{inf}} + T_{\text{tr}} + T_{\text{ack}} + T_{\text{down}} \tag{18}$$

with $T_{\text{up}}$ and $T_{\text{down}}$ the propagation time for uplink and downlink respectively. They are obtained by dividing the satellite range by the speed of light: the maximum is about 6.8 ms at 10° elevation, which is negligible compared to the packet duration $T_{\text{inf}} = 1.66$ sec, which is obtained by dividing the packet length $L = 250$ bytes by the transmission bit rate $R = 1200$ bps. The duration of the acknowledgment packet is $T_{\text{ack}} = 0.126$ sec, by using an acknowledgment packet length equals 19 bytes. According to the equation (18), the duration of a slot is $\tau = 2$ sec, with the assumption that the processing time on board the satellite is $T_{\text{tr}} = 200$ ms. The second GPS signal is used to synchronize the transmission of the packets.

If the acknowledgement packet is not received, a retransmission of the same packet is carried out after a random time $T_{\text{r}}$. In the case of Slotted Aloha protocol, we have $T_{\text{r}} = \delta\tau$, where $\delta$ is an integer number limited by the number of the slots $\beta$ available during the period of the satellite visibility by each terminal, and it is given by the following relation:

$$\beta = \frac{T_{\text{u}}}{\tau} \tag{19}$$

In our case, we find that $\beta = 271$. According to Eq. 8, the total number of slots available during the satellite pass over the service area is equal to $2\beta = 542$ slots, taking into account the time shift between the two extreme points of the satellite service area.

## VI. Stability Analysis

The condition of the stability[16] states that the departure rate $\lambda$ (new packets rate) is equal to the arrival rate $S$ (Throughput). With $\lambda < S_{\max}$, we have:

$$\lambda = G\left(1 - \frac{G}{N_{\mathrm{u}}}\right)^{N_{\mathrm{u}}-1} \tag{20}$$

Let $\lambda$ be the probability that a terminal generates new packet in each time slot and $T_{\mathrm{u}}$ the time of the visibility of the satellite by each terminal. In the model presented in this paper, it is assumed that the terminals have the same traffic requirements. Each terminal transmits maximum one new packet during the visibility period of the satellite. We have $\lambda$ expressed by:

$$\lambda = \frac{N_{\mathrm{u}}}{2\beta} \tag{21}$$

We could define the normalized traffic load $G$ and the normalized throughput $S$ as:

$$G = \frac{N_{\mathrm{t}}}{2\beta}, \quad S = \frac{N_{\mathrm{suc}}}{2\beta} \tag{22}$$

where, $N_{\mathrm{t}}$ is the total number of transmitted packets (new and retransmitted packets) during the time of visibility of the satellite $T_{\mathrm{sv}}$ over its service coverage area and, $N_{\mathrm{suc}}$ is the number of successfully transmitted packets during $T_{\mathrm{sv}}$ the time of the satellite visibility over the servive coverage area.

In our case, with $\beta = 271$, the network will be unstable for the required traffic when the number of terminal exceeds 200 terminals, as shown in Fig. 7.

If the number of users in a system is large, collisions are an unavoidable feature, although we may limit the number of collisions. In this work, we weaken the effect of collision by using random waiting time interval before each transmission of the information packet.

We will randomize the transmission procedure from the beginning. A random time chosen uniformly in the interval $[0\tau, \delta_{\max}\tau]$. with maximum $\delta_{\max}$ (integer number) which is limited by the time of visibility of the satellite $T_{\mathrm{u}}$. The maximum $\delta_{\max}$ is equal to $\beta$ which is the number of time slot available during the satellite visibility for each terminal. Given random access protocol is used, the optimization parameter is the random time $\delta_{\max}$. To evaluate the throughput we used NS-2 software[17] which is a discrete event simulation tool. The Unslotted Aloha included in NS-2 was modified to support a Slotted Aloha. Figure 8 shows the number of packets received onboard the satellite versus $\delta_{\max}$ for three scenarios with different numbers of terminals. For small values of $\delta_{\max}$, a lot of collisions occur and the amount of successfully transmitted packets is also small. For bigger values of $\delta_{\max}$, the number of received packets onboard the satellite is limited by the time of the satellite visibility. The maximum number of onboard received

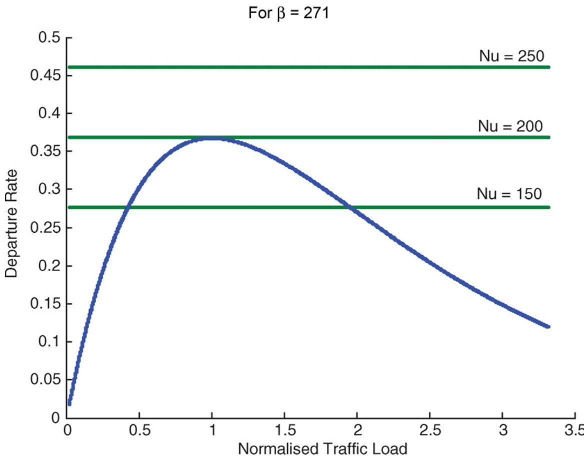


**Fig. 7 Traffic load versus departure rate for Slotted Aloha.**

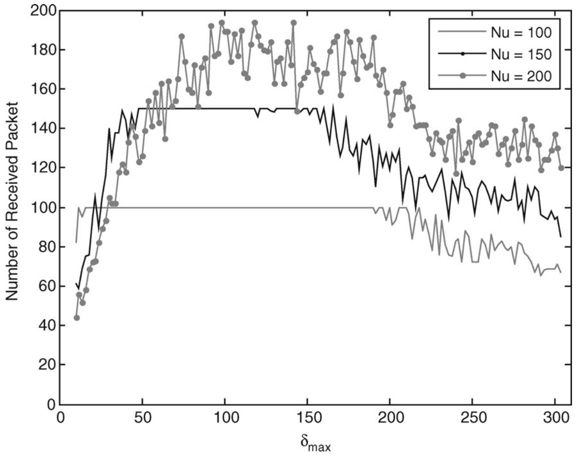


**Fig. 8 Number of packets received on board the satellite as a function of $\delta_{\text{max}}$.**

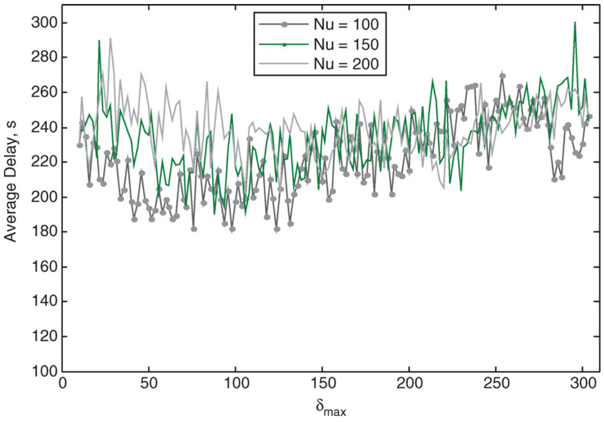


**Fig. 9 Average delay to access to a satellite as function of $\delta_{\text{max}}$.**

packets is reached for an optimum $\delta_{\text{max}}$ which depends on the number of ground terminals. For the required traffic, the simulation in Fig. 8 shows a stable network with long interval of $\delta_{\text{max}}$ where the number of terminals is equal to 150. Using more than 150 terminals makes the network unstable. Figure 8 shows that when using 200 terminals, the throughput doesn't reach its maximum.

According to Fig. 8, by using the proposed scheme, we found that the throughput reaches its maximum for 150 terminals with stable network but the only drawback is a long average delay (see Fig. 9) which is acceptable for many applications which use a store-and-forward LEO. In the next section, we will evaluate the average delay which is another parameter to be considered to measure the performance of the proposed scheme.

## VII. Delay Analysis

When timing is not a critical issue, a store-and-forward service, such as data collection, may be adequate to handle the traffic because they do not depend on immediate data delivery service. Terminals need to wait for the satellite to come into range before they can upload their message, and then the message must be stored on-board the satellite until the destination CGS station comes into the footprint. Here continuous coverage service zone is not necessary.

The delay defined as the time between the decision to send information and the collection of data depends on three largely independent times: the time spent by a terminal waiting for access to a satellite, the time to access to a satellite and finally the time until a satellite is in the view of the CGS station. In this paper, we evaluate the average delay performance of the Slotted Aloha involved in the time to access to a satellite.

The time that the entire information packet enters the channel equals $T_{\text{inf}}$. The packet travels through the uplink satellite channel and is subjected to the one-hop satellite delay, $T_{\text{up}}$. In the case of successful reception of the packet by the satellite, on average $T_1 = T_{\text{inf}} + T_{\text{up}}$ seconds elapse between transmitting of the packet and its full acceptance by satellite. In this case, the satellite sends an acknowledgment packet with duration of $T_{\text{ack}}$, and the user receives that packet after $T_{\text{up}} + T_{\text{inf}} + T_{\text{ack}} + T_{\text{tr}}$ seconds, where $T_{\text{tr}}$ is the required satellite processing time. From the moment of sending packet, the user starts a timer of duration $T_{\text{t}} = T_{\text{up}} + T_{\text{inf}} + T_{\text{proc}} + T_{\text{ack}} + T_{\text{down}}$, expecting to receive the acknowledgment packet. It is reasonable to assume that the probability of loss of the acknowledgment packet is very small. We have $T_{\text{t}}$ equal to the slot duration $\tau$. If the attempt is successful, the user clears the packet. If an acknowledgment packet is not received, the user considers the packet lost and starts the process of reattempting transmission after expiring of his timer $T_{\text{t}}$. The maximum number of attempt $\alpha_{\max}$ is limited by the time of visibility of the satellite $T_{\text{u}}$ available for each terminal. The lost information packet is retransmitted at the end of a random time chosen uniformly in the interval $[0\tau, \delta_{\max}\tau]$.

The number of terminals presented simultaneously in the satellite same footprint varies as the satellite moves on its orbit. At the beginning of the satellite pass over its service area, this number is null, increases to reach a maximum at the center of the satellite service area, and then it decreases to be null when the satellite leaves its service area visibility.

To avoid packet collisions we will randomize the transmission procedure from the begining of the satellite pass. A random time chosen uniformly in the interval $[0\tau, \delta_{\max}\tau]$.

The average delay of the packet during the visibility of the satellite can be expressed as follow:

$$D = \left(\delta_{\text{moy}}\tau + T_1\right) P_{\text{suc}} + \sum_{k=1}^{\alpha_{\max}} \left(\delta_{\text{moy}}\tau + T_1 + k\ \delta_{\text{moy}}\tau\right) (1 - P_{\text{suc}})^k\, P_{\text{suc}} \tag{23}$$

$(1 - P_{\text{suc}})^k P_{\text{suc}}$ is the probability that a packet being received in the $(k + 1)$th attempt of transmissions after k times of failures retransmissions, with $\text{P}_{\text{suc}}$ the average of the probability of packet success during the visibility period of the satellite.

And $\delta_{\max}\tau + \text{T}_1 + \text{k}\delta_{\max}\tau$ is the time elapsed between the generation of the information packet and its full acceptance after $(1 + k)$th attempt.

In the lower value of $\delta_{\max}$, employing the proposed scheme increases the number of retransmissions and hence decreases the probability of success. In this case, the maximum number of attempt $\alpha_{\max}$ tends to infinte. By developing Eq. 23 and using the properties of the geometric series and the derivative functions, we obtain:

$$\begin{aligned}
D &= \sum_{k=0}^{\infty} \left(\delta_{\text{moy}}\tau + T_1 + k\delta_{\text{moy}}\tau\right) (1 - P_{\text{suc}})^k\, P_{\text{suc}} \\
&= \left(\delta_{\text{moy}}\tau + T_1\right) P_{\text{suc}} \sum_{k=0}^{\infty} (1 - P_{\text{suc}})^k + \delta_{\text{moy}}\tau P_{\text{suc}}\,(1 - P_{\text{suc}}) \left(\sum_{k=0}^{\infty} (1 - P_{\text{suc}})^k\right)' \\
&= \left(\delta_{\text{moy}}\tau + T_1\right) + \delta_{\text{moy}}\tau\,(1 - P_{\text{suc}})\,\frac{1}{P_{\text{suc}}} \\
&= T_1 + \frac{\delta_{\text{moy}}}{P_{\text{suc}}}\tau
\end{aligned}$$

So, the expression of the average delay (Eq. 23) becomes:

$$D = T_1 + \frac{\delta_{\text{moy}}}{P_{\text{suc}}}\tau \tag{24}$$

At higher values of $\delta_{\max}$, however, the number of retransmissions decreases and hence increases the probability of success. In this case, the maximum number of attempt $\alpha_{\max}$ tends to zero. By neglecting the second part of the

Eq. 23 and neglecting the parameter $T_1$ compared to $\delta_{\max}\tau$, the Eq. 23 becomes:

$$D \approx \delta_{\mathrm{moy}} P_{\mathrm{suc}} \tau \tag{25}$$

We used the NS-2 simulator to evaluate the average delay. Figure 8 shows that employing the proposed scheme, the average delay still varing at the same interval for large number of $\delta_{\max}$ independent of the number of terminals involved in the network.

## VIII. Conclusion

Using Slotted Aloha with a stop-and-wait access protocol, it is possible to handle 150 ground terminals situated in the same coverage area of a LEO satellite with a traffic load of 1 packet of 250 bytes for each terminal per satellite pass. But the only drawback is a long average delay which is acceptable for store-and-forward systems. By using a low-cost Nanosatellite and Intelligent communications terminals, store-and-forward systems can be kept at the extreme low end of the satellite communications cost spectrum. Also, by having a small Cubesat design that might be replicated by other universities, each satellite will add reliability to a growing constellation mutually serving the Data Collection Network.

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