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Performance Evaluation of Enhanced Slotted AlohaCA Protocol on Planet Mars

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ABSTRACT The launch and successful operation of the Mars Cube One (MarCO) CubeSat in May 2018 heralded a new era in solar system exploration and the setup of the first Interplanetary CubeSat Network (ICN). The success of this mission could give rise of an Interplanetary DTN–Based CubeSat network, in which the CubeSat Nanosatellite, as DTN custody node, plays the role of Data Mule to collect data from rovers on a planet such as Mars. In order to maximize the contact volume which is the amount of transmitting data from rovers to the CubeSat during its pass over their service zone, we will need to design an efficient MAC protocol. This research focuses on the simulation and evaluation of the performance of the Slotted AlohaCA MAC Protocol on the planet Mars compared to Earth taking into account the different properties between the two planets, such as radius, mass and speed of rotation of the Nanosatellite in its orbital at the same altitude. We have conducted many simulations using the NS2 simulator that takes into consideration the spatial dynamic behavior of the Nanosatellite, which is dependent on motion of the Nanosatellite in its orbit. Three appropriate performance measures are evaluated: Throughput, stability and power consumption. The obtained simulation results on the planet Mars show an improvement on performance of the Slotted AlohaCA on the planet Mars compared to Earth.

KEYWORDS Media Access Control (MAC); LEO Satellite communication; Nanosatellite; Mars; WSN; Slotted AlohaCA.

I. INTRODUCTION

As we know, Mars is one of the most explored planets in our solar system. It is close to Earth, which made scientists interested to do a lot of research by sending rovers on it via space missions. The main scientific goal of theses missions is to determine if life ever arose on Mars[1] by determining the role of water, and studying the climate and geology of Mars. The mission results will also help the preparation for human exploration.

Interplanetary CubeSats could enable small, low-cost missions for solar system exploration [2, 3]. The launch and successful operation of the two MarCO CubeSats in May 2018 heralded a new era in solar system exploration. The CubeSat standard was developed in 2000 by Robert Twiggs and Jordi Puig-Suari who are professors at Cal Poly and Stanford universities respectively [4]. Currently, over 800 nanosatellites are launched into Low Earth Orbit (LEO), with the majority of those launches occurring after 2010. The next major step for CubeSats is the exploration of outer space. CubeSats are being used in ambitious missions to investigate the Moon, Mars, and nearby asteroids. These initiatives are being spearheaded by university research groups, research labs, and businesses in addition to government space organizations [4].

MarCO faces new challenges in the field of planetary research missions: independent interplanetary flight navigation, integration into large missions, long-distance long-latency communication, short development time, small development team [5]. The MarCO Cubesats are accompanying the InSight lander mission by recording and forwarding of InSight UHF radio data to Earth [6]. Knowing that the InSight lander mission is NASA's mission to study the interior of Mars and listen for Marsquakes [7].

In fact, the Deep Space Network (DSN), part of the MarCO project, will fly independently to Mars to relay data from InSight to Earth during entry, descent, and landing (EDL). During the EDL, InSight will send telemetry data at 8 kbps over UHF. At the top, the Mars Reconnaissance Orbiter (MRO) will receive and store this data on board, but it is unable to transmit simultaneously [6].

The main limitation of employing a single Nanosatellite as MarCO project is that the latter is visible for just a limited time for a particular place on the Mars. Many Rovers, located at the same service zone, share the uplink to the Nanosatellite and require the deployment of a multiple access protocol [8–10] to optimally use the Nanosatellite channel during the Nanosatellite's short visible time [11].

The Figure 1 shows an architecture for interplanetary DTN-based CubeSat Mars Network in which the CubeSat Mars network plays an important role to collect data from rovers distributed on Mars. In this article, we will focus on evaluation of performance of one single CubeSat that plays the role of Data Mule to collect data from sensors on board rovers on a Planet Mars. Then, we will compare the obtained results on Mars with those obtained on Earth [12].

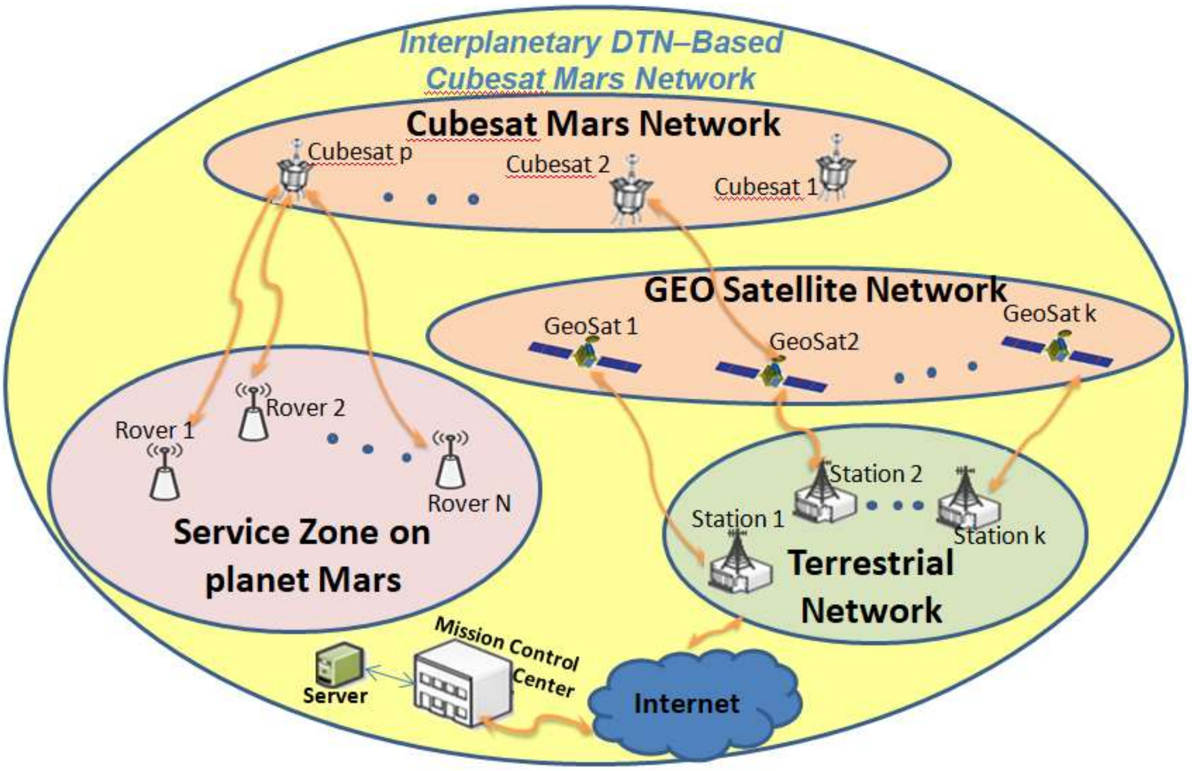


Figure 1. Interplanetary DTN–Based CubeSat network

The remainder of this paper is organized as follows:

Section 2 presents the system description of rovers on the ground of Mars that are willing to send their collected data to a Nanosatellite. Section 3 presents the simulation results between planet of mars and earth and discussion of the protocol Slotted AlohaCA, and also the energy consumption per rover during satellite communication session. Section 4 is reserved for the conclusion.

II. SYSTEM DESCRIPTION

We take a limited number of rovers on the surface of Mars that are willing to send their collected data to a Nanosatellite[13]. The issue is that the rovers can see the Nanosatellite directly for a short period, allowing them to successfully communicate all of their obtained data to the Nanosatellite. We suppose in our study that the satellite orbital plane includes the rotation axis of the planet Mars and the satellite orbit is circular at 650 km altitude. By using the STK (Systems Tool Kit) software [14], we find that the nanosatellite covers the same service zone on the planet Mars four times per day (which is the same as on Earth [15]), with each pass having a different visibility period (9 minutes with a minimum elevation angle $E_{\min}= 10°$) [16].

The Picosatellite visibility time over a given service area depends on the minimum angle of elevation $E_{\min}$ so that a reliable communication can be realised. In fact, any location on the Mars with an elevation angle less than $E_{\min}$ cannot be easily seen from the Nanosatellite because of the spherical shape of the earth and natural obstacles, such as mountains.

Earth is the fifth largest planet in the solar system and the largest terrestrial planet. On the other hand, Mars is the second-smallest planet in the Solar System, being larger than only Mercury. The equatorial radius of Mars is about 3396 kilometers (3376 kilometers in the polar regions), which is about 0.53 of Earth's. However, its mass is only 6.4185×10^{23} kg, which is about 15% of Earth's mass.

A single Nanosatellite is visible for just a limited time for a particular place on the Mars and it is related to radius and gravitational constant. The Nanosatellite visibility time for each rover is 1492 seconds during the nanosatellite pass which is calculated by Equation (1) (Jamalipour, 1998):

$$T_v = 2.\left(\frac{(R_M+h)^3}{\mu}\right)^{\frac{1}{2}}.\left[Ar\cos\left[\frac{R_M}{R_M+h}\cos(E_{\min})\right]-E_{\min}\right] \qquad (1)$$

where μ is the gravitational constant of Mars with $\mu = 42828$ km^3/s^2, $h=650\ km$ is the Picosatellite altitude, and R_M is the Mars radius with $R_M = 3396$ km.

For Mars planet, we have some differences in radius and in gravitational constant compared to Earth. These two reasons made the visibility time for Mars greater than Earth where the visibility time T_v for Mars is 24 minutes and for earth is 14 minutes. This time helps rovers to communicate with the

Nanosatellite longer duration and to stay in touch with him longer which enables to send a large amount of information.

However, in terms of their stellar rotation (the time it takes for a planet to complete one rotation around its own axis), Earth and Mars are almost the same. While Earth takes 23 hours, 56 minutes and 4 seconds to complete one sidereal revolution (0.997 Earth days), Mars also takes about 24 hours and 40 minutes. This means that a day on Mars is very close to a day on Earth.

The speed of satellite is given by:

$$V_m = \sqrt{\frac{GM}{R_m + h}} \qquad (2)$$

At the altitude of 650 km, the speed of Nanosatellite around the planet Mars is equal to V_m=3.252 km/s which is less than its speed around Earth V_t=7.531km/s due to the difference between the masses of the two planets, as well as gravitational forces and the radius.

The (instantaneous) coverage area of the Nanosatellite is determined by the half-angle of the foot print measured at the center of the earth. The half-angle is given by Equation (3).

$$\theta = \left[Ar\cos\left[\frac{R_T}{R_T+h}\cos(E_{min})\right] - E_{min}\right] \qquad (3)$$

In this paper, we assume that each rover keeps the same visibility time (see Figure 2).

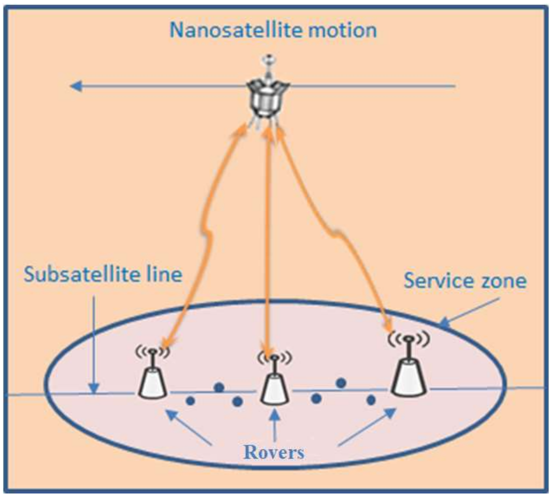


Figure 2. Nanosatellite service zone

In this same figure, for the Picosatellite to route the information collected by the rovers to the central station, it uses the Store-and-forward mode, which is a mode of digital data communications in deferred time[17]. Indeed, the Picosatellite moves in its orbit. These two movements change the location of the instantaneous coverage of the Picosatellite, which in this way routes the information collected from the rovers located anywhere in the globe to the central station.

The major constraint in this type of network is that a LEO satellite is only visible for a short time.

The data collected from rovers is maximum contact rover volume $C_{V\max}$ and is given by the following formula expressed by Equation (4).

$$C_{v\max} = T_v.R \qquad (4)$$

where R is the rate of data transmission and T_v is the visibility time when the Nanosatellite pass over its service area which is the amount of time each rover can see a nanosatellite, multiplied by two [16]. The visibility time on Mars is longer than on Earth, and the maximum contact volume is also large. The thing that prompts us to verify the accuracy of this information by simulating this experience using NS2 simulator.

A. SLOTTED ALOHACA PROTOCOL

A protocol for multiple access is called Slotted AlohaCA (Slotted Aloha with Collision Avoidance). It avoids collisions, as its name suggests. This technique initially randomly distributes the channel between all rovers [13, 18] and the time. Persist in checking the busy channel trying to get its transmission through, hence the name. This approach reduces the chance of collision. Time is divided into timeslots, and in Slotted Aloha, the rovers only communicate at the start of each timeslot [13, 19, 20] (see Figure 3).

The following equation is the analytical expression of the Slotted AlohaCA protocol using throughput S versus traffic load G. (5) [18].

$$S = \frac{MGe^{-G}}{(M-1)Ge^{-G}+1} \qquad (5)$$

M represent number of packets sent by rover. Moreover, the number of rovers Nr send collected packets during the pass of Nanosatellite on planet Mars, the stability study gives us by satisfying the inequality (6)[18].

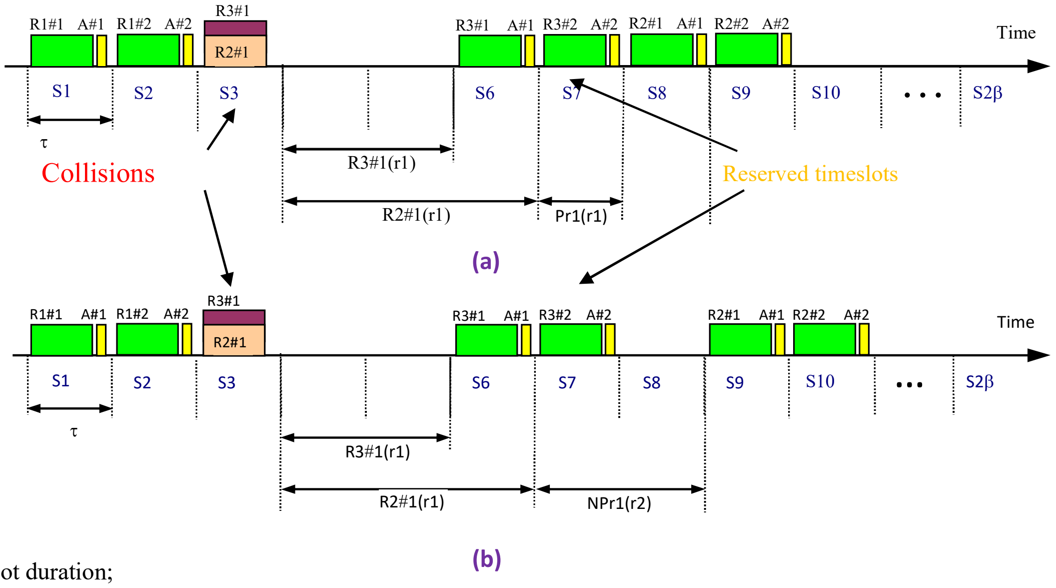
$$M \le 1 + \frac{2\beta}{N_r} - \left(1 - \frac{1}{N_r}\right)^{1-N_r} \qquad (6)$$

Figures 4 and 5 shows the variation of the throughput against the average number of rovers transmitting frames per time step (traffic load), respectively for M=4 and M=2.

The stability condition states that the departure rate λ (new packets rate) is equal to the arrival rate S (Throughput). For Slotted AlohaCA protocol the departure rate λ is given by the equation (7).

$$\lambda = \frac{MGe^{-G}}{(M-1)Ge^{-G}+1} \qquad (7)$$

According to Figures 4 and 5, the maximum throughput of Slotted AlohaCA white M=4 and M=2 is respectively 71% and 54% and becomes unstable when the number of rovers exceeds 94, and 145.



τ : timeslot duration;
2β : number of total timeslots
Ri#jA#j: Rover number i transmits a packet number j and receives its j acknowledgement;
Rk#i(rj): random waiting time before the j^{th} retransmission of the packet i sent by rover k ;
Pri(rj): added waiting time due to the mode before the j^{th} retransmission of the packet i ;
NPri(rj) : added random waiting time due to the 1- mode before the j^{th} retransmission of the packet i.
Si : Time slot number i.

Figure 3. Rovers-Nanosatellite communication session: (a) Persistent Slotted AlohaCA (b) Slotted Aloha

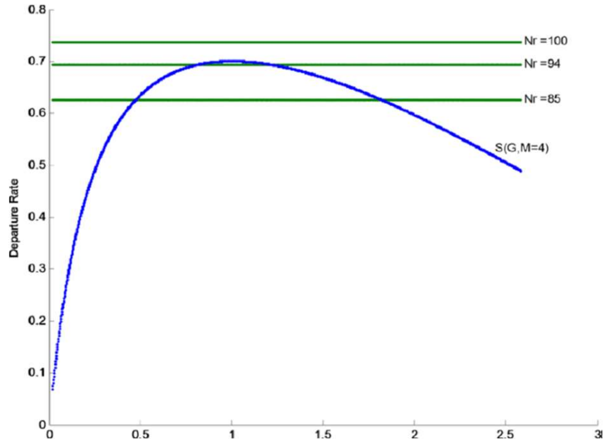


Figure 4. Departure Rate λ vs Traffic Load G for Slotted AlohaCA

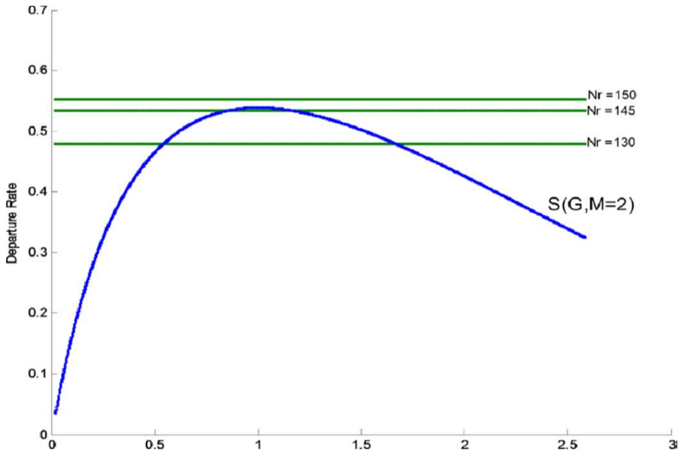


Figure 5. Departure rate λ vs Traffic load G for Slotted AlohaCA with M = 2

III. SIMULATION RESULTS AND DISCUSSION

There are many points of differences and similarities between planets Mars and Earth and the following table will show us these points:

Table 1. Differences and similarities between planets Mars and Earth.

Attributs	Mars	Earth
Masse	6,41× 10^{23} kg	5,97×10^{24} kg
Altitude	650 km	650 km
Minimum élévation angle E_{min}	10°	10°
Half-angle thêta	34,41°	26,87°
Radius	3396 km	6378 km
Orbit period of the satellite	1492sec	875sec
Satellite speed	3,252 km/sec	7,53 km/sec
Visibility time of the satellite	1492 sec	875 sec
Data Rate	9600 bps	9600 bps
Contact Volume	1.7 GByte	1 GByte

Using NS2 simulator we evaluate the performance of the Slotted AlohaCA protocol[21] on Mars Planet. due to the existence of a range of different characteristics between the two planets (Mars and Earth) such as radius and mass, the obtained results will be compared to those found based on Earth planet. NS2 is an open-source discrete event simulator targeted at networking research. NS2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks[22].

A. SIMULATION ON MARS PLANET

In order to simulate this system on Mars, we must change some parameters that differ between Earth and Mars in NS2 simulator, among the big differences between them radius and gravitational constant.

The obtained simulation results on Mars, extracted from Figure 6 and 7, shows the number of successfully received packets opposite maximum time of retransmission for different numbers of rovers, whithe M=2 and M=4 packets, at first, after analysis it seems that there is a difference between the results obtained on Mars compared to the results obtained on Earth. This difference occurred because there is a difference between the characteristics of the Earth and the planet Mars. Among the differences that we have identified, there is the diameter and mass of the planet Mars also there is the speed of rotation .Also, the time it takes for a satellite to orbit the planet.

The calculations of the speed of the nanosatellite around mars and the coverage area of the nanosatellite show that the results obtained from the simulation on the planet Mars will be better than those obtained from the earth. The thing confirmed by the simulation through the simulator NS2.

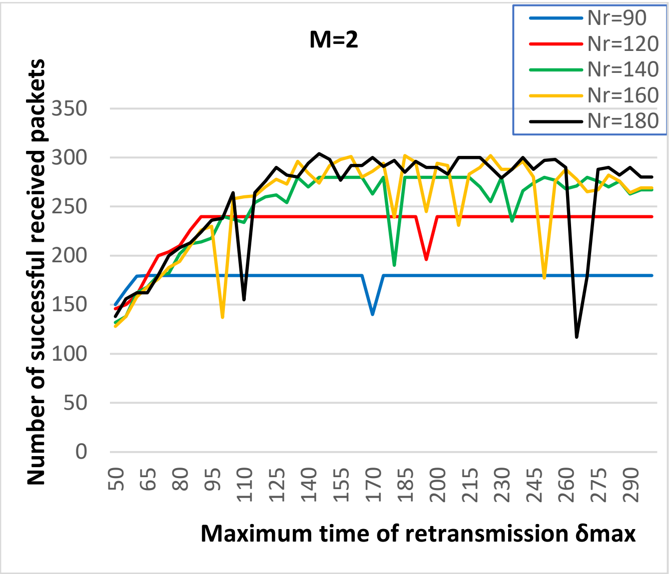


Figure 6. The Number of successful received packets in Mars planet opposite maximum time of retransmission.

On the planet Mars as we can see from the figure 6 that we can reach a number of stations up to 140 terminals The thing is that we can send 280 packets without any collisions, but whene the numbers of terminals exeeds 140 terminals we notice that there is instability, due to the increase in the number of stations, which leads to the occurrence of many collisions between them. By analyzing the results that appear on figure 7, when each station can send four messages, it becomes clear to us for M=4 that we can use a larger number of terminals. With 95 terminals we note that there is stability in the network, but if we exceed 95 rovers, we notice that there is instability in the network .

The thing that enables us to send up to 360 packets, which is a larger number of messages that we can send by programming each station to send only two messages.

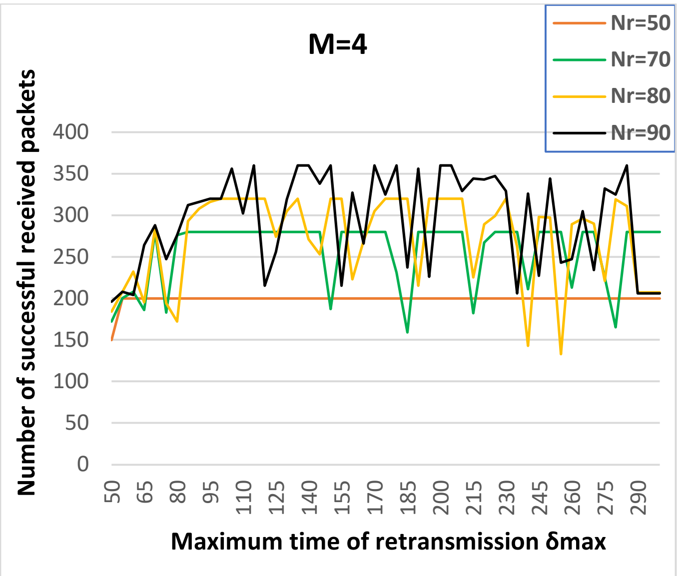


Figure 7. The Number of successful received packets in Mars planet opposite maximum time of retransmission.

B. SIMULATION ON EARTH PLANET

According to Figure 8, when the value of M=4, simulations demonstrate a stable network with the number of rovers approaching 50. In this case, a maximum number of received packets is 200, can be easily reached, with a long interval of δ_{max}. But when their sum exceeds 50 rovers, the stability interval shortens at the maximum for 65 rovers and leads to instability When their sum exceeds 65 (see Figure 8).

In conclusion, the results on the planet Mars better compared to those obtained on Earth. That is due to the existence of difference between the parameters related to these two planets.

On the planet Mars, we can use a larger number of rovers compared to Earth because the difference between the two planets.Where we can use 95 rovers, each one of them can send four messages, as we note that there is stability in the network, but if we exceed 95 rovers, we notice that there is instability in the network.

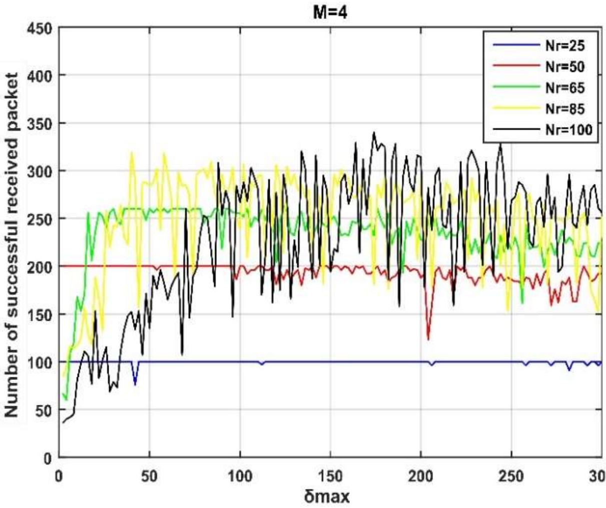


Figure 8. The Number of successful received packets in Earth planet opposite maximum time of retransmission.

C. ENERGY CONSUMPTION ANALYSIS

Energy consumption and high efficiency is some of the most important parameters in wireless sensor networks for Media Access Control (MAC) protocols[23]. In this section we are going to study the energy consumption in Mars and Earth using these two protocols Slotted AlohaCA and slotted aloha.

A. Addaim et al. [24] proposed an important study about the energy consumption for the slotted Aloha protocol. The authors advocated turning off the receiver during the random waiting period to reduce energy consumption[25]. The average energy consumption per rover during the Nanosatellite visibility time is lowered to the following expression given by equation (8).

$$E_{sc} = E_1 . \frac{S}{G} = E_1 . N_{tp} \qquad (8)$$

Where E_1 is the amount of energy consumed when the Nanosatellite successfully receives the first transmission attempt of a newly generated data packet [26], and N_{tp} is a real number that represents the average number of transmissions of the same packet (new and retransmitted packets) per rover during the Nanosatellite visibility time. For the Persistent Slotted AlohaCA protocol, the same expression applies.

Figures 9 and 10 represent the simulation results of the average power consumption, of Slotted Aloha and Slotted AlohaCA, as a feature of the most range δmax of timeslots to wait for retransmission for several generated packets in line with M equals to 2 and 4 respectively.

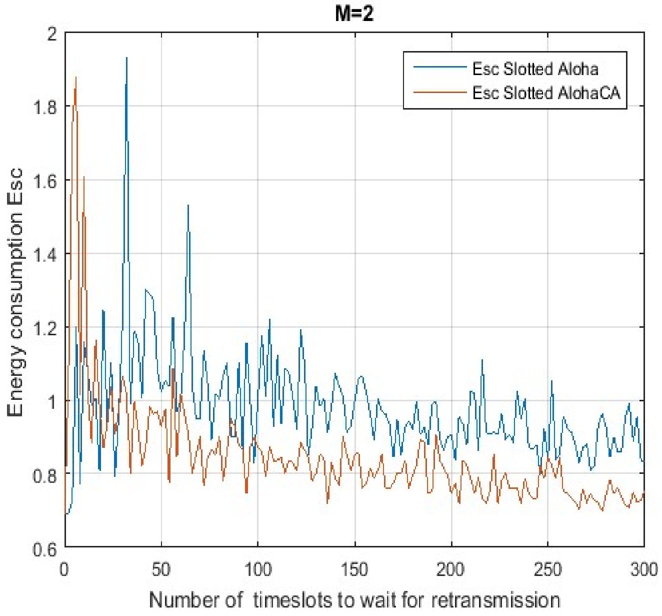


Figure 9. Energy consumption per rover during satellite communication session as a function of δmax with M=2.

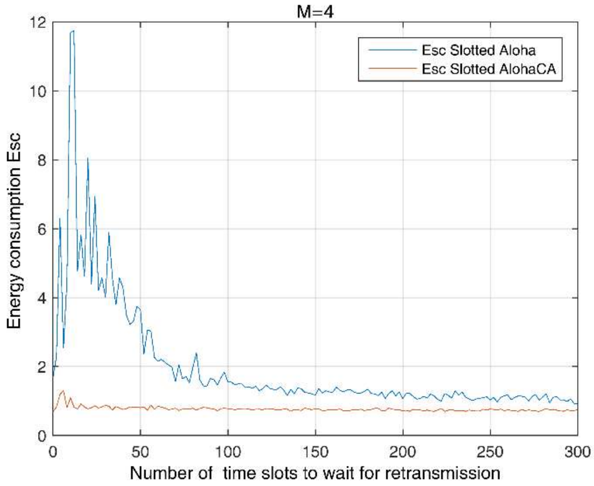


Figure 10. Energy consumption per rover during satellite communication session as a function of δmax with M=4.

As seen from the same figures, for small values of δ_{max}, the energy intake may be very high due to a higher number of collisions for Slotted Aloha compared to Slotted AlohaCA. Consequently, one can conclude that Slotted AlohaCA protocol is more efficient in terms of energy intake than the traditional Slotted Aloha in Mars planet.

IV. CONCLUSION

In this paper, we have focused on the simulation of rovers on the surface of Mars that are willing to send their collected data to a Nanosatellite using slotted AlohaCA protocol on the planet mars. The obtained results based on Earth planet and the energy consumption, related to these two planets, of the Persistent Slotted AlohaCA MAC protocol for LEO Nanosatellite are also compared. All the simulations, proposed in this paper, are carried out using proposed NS2 simulator.

We have proved with simulations that the results on Mars planet are better than on Earth.

In our upcoming work, we'll concentrate on studying the performance of Mars CubeSat network constellation.

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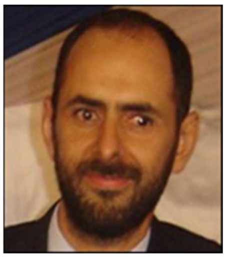

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