Performance Analysis of Randomized MAC for Satellite Telemetry Systems

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Abstract— **The overwhelming success of the Internet provides scientists new tools to understand our mother nature. Argos is a worldwide satellite system dedicated to Earth observation and environmental research. Argos system has an excellent track record for data collection, processing and dissemination to the scientific and international community and gains popularity steadily. However, when the number of Argos users exceeds certain limit, the transmission success rate is reduced significantly, which results in the severe dead-station problem. To solve the problem, a randomized transmission scheme has been proposed: stations transmit in their designated repetition rate but with a random deviation. We quantify and compare the probabilities of successful reception during a satellite pass and the system capacity for deterministic, independent, and randomized transmissions. How the random level affects the system performance is evaluated and verified by simulation. The results provide important guidelines for future growth and success of the satellite telemetry system and other sensor networks.**

I. Introduction

The overwhelming success of the Internet provides scientists new tools to understand our mother nature. Satellite and radio telemetry systems now become widely used in environmental research. On February 2005, 61 countries agreed to establish a Global Earth Observation System, by integrating telemetry and remote sensing systems from all around the world into a system of systems, which will revolutionize the understanding of Earth in the following decade [1]. The current members include 80 countries and the European Commission. 58 international organizations also support this agreement which helps all nations involved produce and manage their information over the combined satellite and Internet system that benefits the environment [2].

The Argos system is one of the most popular telemetry systems worldwide, which is dedicated to Earth observation, scientific and environmental research. It has an excellent track record for data collection, processing and dissemination to the scientific and international community. It offers a robust tool for understanding environmental factors. The Argos system fits perfectly into the framework defined by the emerging Global Earth Observation System of Systems (GEOSS). In the last thirty years, the Argos system has migrated with three generations: Argos 1, 2, and 3.

With the ever-increasing popularity of the Argos system, more devices share and compete for the premium uplink satellite communication bandwidth. As many of these devices are sensor nodes with limited power supply, they do not have the receiving function. Therefore, the design dimension left for the medium access control protocol is very limited, as it is impossible to rely on carrier-sensing or TDMA type of MAC protocols.

Currently, Aloha MAC protocol is adopted in Argos system, and the number of devices that can be supported by the Argos system is very limited in order to maintain reasonable performance. If the number of devices in an area exceeds certain limit, most transmissions may fail due to collisions, which results in the dead station problem. To solve the problem and ensure the effectiveness and efficiency of the system, the maximum number of devices in an area should be quantified to allow appropriate control of the density of devices.

The performance of Aloha protocol has been heavily investigated in the literature [4]–[7]. However, they all assumed that nodes are transmitting independently, so the aggregate data traffic in the system is a random variable and follows Poisson or other known distributions. However, in telemetry systems, the periodical readings from specific sensors are expected. Transmissions are required in a periodical manner rather than totally independent. To the best of our knowledge, in the literature, no existing work has quantified the performance of Aloha considering the periodic traffic characteristics of the telemetry systems.

The main contributions of this paper are as follows. First, we address the periodical transmission collisions problem happened between Argos transmitters, which results in the long term missing of certain transmitters. We quantify the probability of successful reception in the Argos system and the system capacity, i.e., the maximum number of users that can be supported in an area for achieving a given success rate. Then, we analyze the performance of the randomized transmission scheme. The randomized scheme itself is simple to implement, and it can also significantly improve the system capacity. The relationships between the randomized level and the success probability and system capacity are investigated and verified by simulation.

The rest of this paper is organized as follows. In Section II, we briefly introduce the architecture of the Argos system and its air interface, explain the concepts and terminologies. We identify the periodical transmission collision problem of the

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existing Argos system, which uses a deterministic transmission pattern. A randomized transmission scheme is then introduced to improve the system performance. In Section III, to evaluate the effectiveness of the randomized scheme, we obtain the theoretical capacity of the system with and without the randomized transmission scheme. The analytical results are verified by simulation in Section IV, followed by concluding remarks in Section V.

II. Architecture and air interface of Argos System

A. System architecture

The Argos system has three interactive subsystems [3]: a) user devices, which are called the Platform Transmitter Terminals (PTTs) for the first and second generation Argos system, and called the Platform Messaging Transceiver (PMT) for the third generation; b) the space segment; and c) the ground segment.

User Devices: Argos operation begins with the transmissions from PTTs and PMTs attached to sensor equipments and the platform from which data is collected. The difference between PTTs and PMTs is that PTTs only have transmitters, whereas, PMTs have both transmitters and receivers. PTTs and PMTs have been used for applications such as tracking migratory birds, monitoring ice floes in harsh environments, etc [8]. They are configured by size, weight, power consumption, and housing according to applications. For instance, the smallest PTTs, used to track birds, have the weight of 22 grams including a GPS. By setting the proper duty cycle and repetition rate, these PTTs can achieve up to three years operation time [9].

Space Segment: Argos instruments are flown on board the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellites (POES) and Metop satellite from European Meteorological Satellite organization (Eumetsat) [3]. The Argos satellites orbit the earth in near-polar, sun-synchronous orbits. They can see the North and South Poles on each orbital revolution. Each satellite passes within visibility of any given transmitter at almost the same local solar time each day. The time required to complete one revolution around the Earth is approximately 102 minutes. Because of the near-polar orbit, the number of daily passes over a transmitter increases with latitude. At the poles, each satellite passes approximately 14 times a day for a total of 28 times (with two satellites). At the equator, there are totally 6 to 7 passes per day [8].

Ground Segment: The ground segment comprises of three parts: a) ground antennas relay data from satellites to processing centers; b) processing centers collect all incoming data, process them and distribute them to customers; and c) Argos users receive data or send command to their PMTs through the Internet.

B. Air Interface

Frequency Allocation: PTTs and PMTs are all working on the same center frequency at 401.65 MHz. The bandwidth are 24, 80 and 110 KHz for Argos-1, Argos-2 and Argos-3, respectively. Because Argos-2 is the current system on duty and it has its advantage over Argo-3 for simpler user device design (which is particularly desirable for sensor nodes), our analysis focuses on it. Our analytical approach can be easily extended to other generations of Argos systems.

Transmission Scheme: PTTs in the ground segment transmit encoded messages periodically. The interval is fixed according to the application in a range between 45 s and 200 s. Transmission burst length is in the range of 360 ms to 920 ms, depending on the applications as well.

The duration window of a satellite visible to a transmitter is called a pass. Each pass lasts between 8 and 15 minutes (with the average of 10 minutes). In this window of time, a receiver on board satellites can receive the transmissions of the customer terminals [3]. The uplink has a number of channels at different frequencies. Each PTT will be initialized to use one of the channels randomly, and it will repeat transmissions at a constant rate during the pass of a satellite.

C. Randomized transmission scheme

Since the user devices of the Argos system should be simple and energy-conservative, PTTs are equipped with transmitters only. Therefore, all carrier-sense based MAC protocols and resource allocation schemes are not applicable. PTTs share the uplink satellite channel using the Aloha MAC protocol.

When there are more than one devices transmitting at the same channel simultaneously, collision occurs and all colliding transmissions are failed. If all of these devices transmit periodically with the same interval, once the collision of the first attempt occurs, all the following retransmissions might be collided due to the deterministic intervals.

Ideally, if each device can set their transmission times to be independent (e.g., using exponential inter-arrival distribution), the success probability for a number of transmissions during a pass can be maximized. However, such independent transmission is not only difficult to implement, but also cannot guarantee the maximum interval for retransmission, which is not desirable for sensor applications.

To solve the problem, a randomized transmission scheme has been recommended for Argos [10], which can overcome the periodical overlapping problem that leads to low success rate and low system capacity, and it is also simple to implement. The randomized transmission scheme let devices transmit in their repetition rate but with a random deviation.

To effectively reduce the correlation between consecutive transmissions during a satellite pass, random deviation is chosen to be uniformly distributed. Thus, the randomized transmission interval is

$$R_r = R\left(1 + L_r(X - 0.5)\right), \tag{1}$$

where R is the average transmission interval, L_r is the random level of the transmission interval, choosing from 0% to 100%, and X is a random variable uniformly distributed between 0 and 1. R is a constant assigned by Argos according to

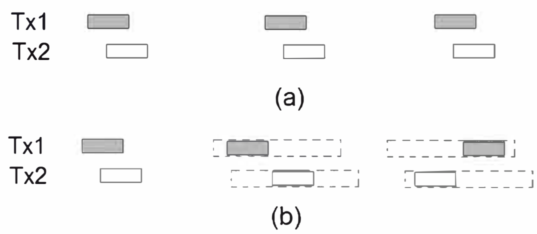

Fig. 1. Deterministic transmission scheme (a) vs randomized transmission scheme (b)

applications, e.g., R is set to 60 s for animal tracking, and 100 s for ocean temperature monitoring. The deterministic transmission scheme is illustrated in Fig. 1 (a) and the randomized transmission scheme in Fig. 1 (b) for comparison.

In the following section, we will analyze and compare the system performance with the deterministic, independent, and randomized transmission schemes.

III. PERFORMANCE ANALYSIS

We define the probability that the satellite successfully receive a copy of the message transmitted by a device during a satellite pass as P_s. It is determined by the following system parameters:

- N: number of active users in a satellite footprint;
- T_p: duration time of a pass;
- R: average interval of two consecutive transmissions;
- T_b: duration for transmitting a message;
- F_{ch}: number of uplink channels.

To simplify the analysis, the above parameters are assumed constant which is true for homogeneous systems. For heterogeneous systems, our analysis needs to be extended slightly.

In the following, we investigate the successful reception probability during a pass, which can be used to determine the maximum number of user devices that can be supported in the same footprint under the constraint of the success rate of each device.

A. Deterministic transmission scheme

A PTT transmission can be successfully received by the satellite receiving unit if there is no other same-channel PTTs transmitting during its transmission time. Since there is no time-synchronization among PTTs and the user devices may not be equipped with a receiver, the up-link medium access uses the pure Aloha protocol. We assume that the messages have a constant frame size, and with a fixed transmission time T_b. With the pure Aloha MAC protocol, the vulnerable time of a transmission is $2T_b$.

With the deterministic transmission scheme, during a satellite pass, each device may start to transmit at different time, with the rate of one transmission per R. The success probability with the deterministic scheme is straight-forward to obtain.

The probability that a PTT starts to transmit within any T_b interval is given as:

$$\tau = T_b/R. \tag{2}$$

The probability that a PTT transmits in a specific frequency channel in a specified T_b interval is:

$$p_a = \tau/F_{ch}. \tag{3}$$

If there are N active users in the footprint, we can get the success probability of a single transmission, p_s, which equals the probability that all the other $N-1$ users do not transmit in its vulnerable time using the same frequency channel.

$$\begin{aligned} p_s &= (1-p_a)^{2(N-1)} \\ &= (1-T_b/(RF_{ch}))^{2(N-1)}. \end{aligned} \tag{4}$$

As all devices use the deterministic transmission pattern and have the same transmission interval, once the first attempt fails due to collision, the following retransmission will be collided as well. In this case, $P_s = p_s$.

To ensure that the success probability is larger than a threshold P, we should limit the number of users according to (4), i.e.,

$$N_{\max} = 0.5 \log P / \log(1 - T_b/(RF_{ch})) + 1. \tag{5}$$

B. Independent transmission scheme

Consider the independent transmission scheme, where each user uses exponential inter-arrival time for transmissions, so the retransmissions of all users are independent of the previous transmissions. The average interval of two consecutive transmissions is R. The traffic of this scheme becomes Poisson and its performance using pure Aloha has been heavily investigated, so we just present the results below.

The success probability during each pass is

$$P_s = 1 - [1 - (1 - T_b/(RF_{ch}))^{2(N-1)}]^{T_p/R}, \tag{6}$$

and the maximum number of users that can be supported is

$$N_{\max} = 0.5 \log[1 - (1-P)^{R/T_p})] / \log(1 - T_b/(RF_{ch})) + 1. \tag{7}$$

C. Randomized transmission scheme

The independent transmission scheme is easy to understand but not simple to implement and it cannot ensure the maximum interval of two transmissions. To simplify the implementation, a random level of transmission intervals (for example, 10% or 20%) is used to ensure less correlation among different transmissions and that the maximum interval of two transmissions is bounded.

Next, we investigate the effectiveness of the randomized transmission scheme. As each user transmits $K = T_p/R$ times during a satellite pass. The probability of fail during a pass equals the probability of all K transmissions are failed due to collisions.

How to quantify the system performance for such a retransmission scheme with a given random level is a difficult open issue. The difficulty is that how to quantify the correlation of collision events in different rounds, which affect the successful transmission probability of transmissions after the first collision.

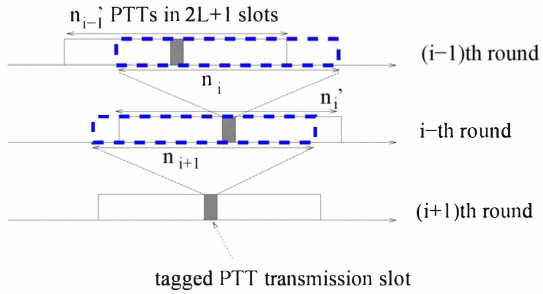

Fig. 2. Randomized transmission scheme

To solve the problem, we construct a discrete time Markov model for the system. Time is discretized into slots with slot duration of T_b. The number of PTTs using the tagged frequency band is denoted by M. For simplicity, we assume $M = N/F_{ch}$.

To further simplify the notation, we denote R as the number of slots of the average interval, and each node can choose an interval from $R-L$ slots to $R+L$ slots (totally $2L+1$ slots) for retransmission. We define the period around the i-th (re)transmission of the tagged PTT the i-th round.

As shown in Fig. 2, the shadowed slots are the slot transmitted by the tagged PTT. The number of PTTs transmitting in the $2L+1$ slots in the i-th round may collide the tagged PTT in the $(i+1)$-th transmission. Considering the pure Aloha protocol, the collision probability of each of these devices with the tagged PTT is $\frac{2}{2L+1}$. Now we need to track the number of active PTTs in the $2L+1$ slots for different rounds of transmissions by the tagged PTT, n_i. We can build a Markov chain where the state at round i represents n_i.

Given the state n_i, we can derive the state transition probability and thus obtain the probability n_{i+1}. However, the state transition probability depends on the random interval chosen by the tagged PTT in each round, and those intervals by all other PTTs. The calculation is quite tedious. Also, the possible number of traces for n_1, n_2, ..., n_K is M^K which increases exponentially.

To make the problem tractable, we further simplify the problem by two steps. First, we assume that the user density near the slot that the tagged PTT chose to transmit is the same. Second, we only consider those traces where n_{i+1} equals its mean value of $E[n_{i+1}|n_i]$. That is, given n_i, the next state is $E[n_{i+1}|n_i]$ with probability one.

As shown in Fig. 2, the reason to make the first assumption is that we can approximate the average number of PTTs in the $(2L+1)$ slots which may collide with the tagged PTT in the next round by the average number of PTTs in the $(2L+1)$ slots centered at the slot the tagged PTT chose in the i-th round (denoted by $E[n_i']$). That is, $E[n_{i+1}|n_i] = E[n_i'|n_i]$.

For the second step simplification, we now only consider M traces from n_1 to n_K only. Given the value of n_i, we can derive n_{i+1} using the assumption of $E[n_{i+1}|n_i] = E[n_i'|n_i]$ as follows,

$$\begin{aligned} n_{i+1} &= E[n_{i+1}|n_i] = E[n_i'|n_i] \\ &= E[n_{i-1}'|n_{i-1}] - E[n_{i-1}'|n_{i-1}]\frac{L(L+1)}{(2L+1)(2L+1)} \\ &\quad +(M-1-E[n_{i-1}'|n_{i-1}])\frac{L(L+1)}{(R-2L-1)(2L+1)} \\ &= E[n_i|n_{i-1}] - E[n_i|n_{i-1}]\frac{L(L+1)}{(2L+1)(2L+1)} \\ &\quad +(M-1-E[n_i|n_{i-1}])\frac{L(L+1)}{(R-2L-1)(2L+1)} \end{aligned} \quad (8)$$

The probability of the initial state n_1 can be derived as

$$p(n_1 = i) = \binom{M-1}{i}(\frac{2L+1}{R})^i(1-\frac{2L+1}{R})^{M-1-i}. \quad (9)$$

Given all M state transition traces (from n_1 to n_K), we can calculate the probability that all K transmissions are failed as

$$P_c = \sum_{i=1}^{M-1} p(n_1 = i)\pi_{k=1}^{K}[1-(1-\frac{2}{2L+1})^{n_k}], \quad (10)$$

where $n_k = E[n_k|n_{k-1}]$ can be derived recursively using (8).

The success probability P_s is $1-P_c$ which is a function of M. Then, the maximum number of PTTs in each channel can be directly obtained from the function of P_s.

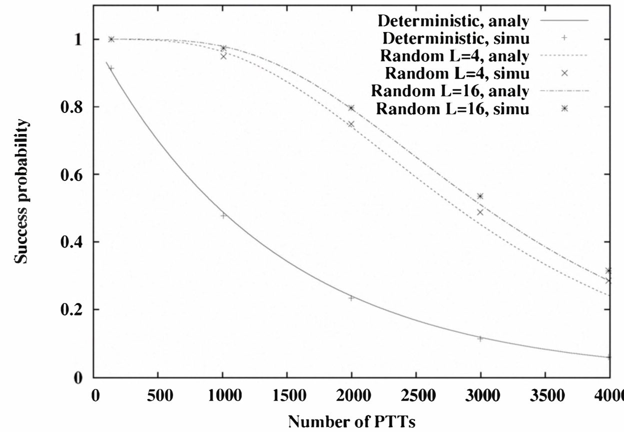

Fig. 3. Success probability during one pass, analysis vs. simulation

IV. Performance Evaluation

To verify the analytical results and investigate how the random level affects system capacity, Monte Carlo simulation is used which is written in C. For each simulation setting, we repeat the simulation for ten times to obtain the average.

The simulation parameters are chosen according to the Argos system setting as follows. The average pass duration, T_p, of an Argos satellite is 10 minutes. Transmission time of a message (which is the slot duration) is 500 ms. The average interval between two transmission is 100 second, or 200 slots. For Argos-2, there are 14 standard channels with 2 KHz bandwidth, so we set $F_{ch} = 14$.

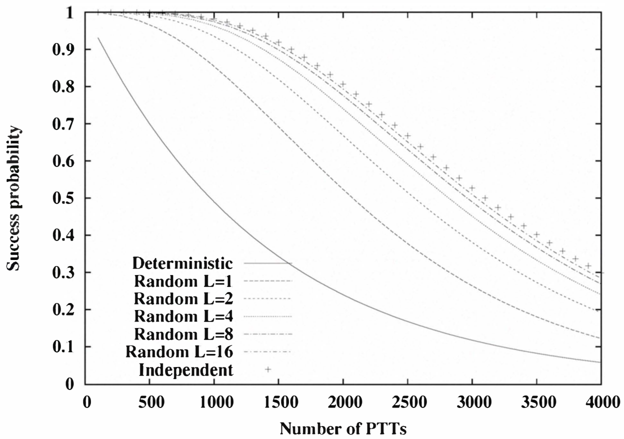

Fig. 4. Success probability during one pass, three schemes

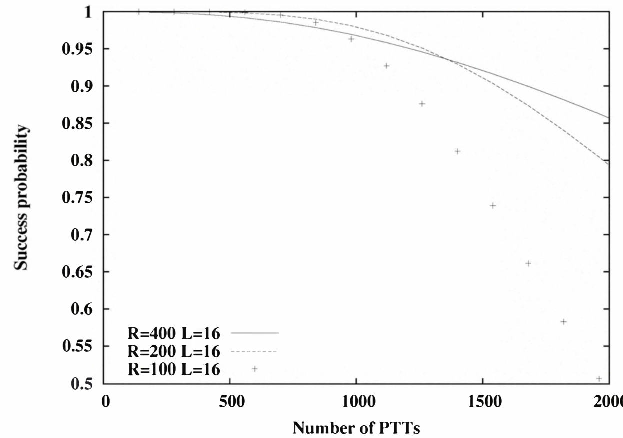

Fig. 5. Success probability during one pass, different R

In Fig. 3, we compare the simulation and analytical results of the success probability with the randomized transmission scheme. We choose two random level $L = 4$ and $L = 16$ for comparison. In the figure, the x-axis is the number of PTTs in a satellite footprint so they compete for the uplink during the pass. Here, we let all PTTs be evenly distributed to 14 channels. As shown in Fig. 3, the analytical results and the simulation ones match well. Therefore, although our analysis is based on the two-step simplification and assumption, the analytical results are close to the simulation ones and they can provide important insight for system planning.

Next, we compare the performance of the different transmission schemes in Fig. 4. We have the following observations. First, the success probability during one pass of the deterministic transmission scheme is significantly lower than the other schemes. Second, the independent transmission scheme can achieve the highest success probability, which can be viewed as an upper bound. More importantly, its performance is very close to the random transmission scheme when L is larger than 8. Third, for the random transmission scheme, increasing L can achieve better performance, but the increment diminishes when L is larger than 8.

From Fig. 4, if we want to ensure that $P_s \geq 0.9$, the capacity for the deterministic scheme, the randomized scheme ($L = 8$), and the independent transmission schemes are 148, 1500, and 1600, respectively.

From the above observation, we can conclude that the random transmission scheme with a small variation (e.g., $L = 10$ slots which corresponds to $L_r = 10.5\%$) can achieve the performance and capacity close to the upper bound.

The analytical results can also be used to optimize other system parameter such as R. In Fig. 5, we compare the success probability with R equal to 400, 200, and 100 slots, and the corresponding number of transmissions per pass equal to 3, 6, and 12, respectively. As shown in the figure, if the desirable success rate is at least 0.95, $R = 200$ (and $K = 6$) has the best performance; if the success rate of 0.9 is acceptable, $R = 400$ (and $K = 3$) is the best.

V. Conclusion

In this paper, we have investigated the randomized Aloha scheme used in the Argos system, considering the traffic characteristics in telemetry systems. Our analytical and simulation results show that the randomized scheme can effectively enhance system capacity and improve the success probability. The analysis reveals the relationship between system capacity and the key parameters, which can provide important guidelines for network planning and design. The results can be extended for other wireless sensor network applications.

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