

Channel-adaptive random access for LEO satellite communication

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Abstract—In this paper, the performance of Channel-Adaptive Random Access (CARA) was investigated in Low Earth Orbit (LEO) communication systems. The simulation results show that the performance improvements can be achieved with CARA compared to conventional random access.

Keywords—random access, channel-adaptive, LEO, correlation coefficient, Doppler

I. INTRODUCTION

In the development of 6G systems, the importance of LEO satellite communication becomes significant. Due to the limited access time between satellites and ground terminals, random access is essential in LEO satellite systems. Random access is employed by user terminals for initial network access and uplink resource requests. Therefore, efficient random access procedures play a critical role in determining the overall system throughput and latency.

Most existing satellite communication systems are based on Frequency Division Duplex (FDD) [1]. However, driven by the performance requirements of 6G systems and developments in LEO satellite technology, Time Division Duplex (TDD)-based satellite communication is now being seriously considered. Channel adaptive random access (CARA) is one of the techniques proposed for TDD-based communication systems to reduce the power consumption of random access [2]–[4]. With CARA, a remote station determines whether to attempt random access based on channel conditions. CARA is notably suitable for applications such as massive Machine-Type Communication (mMTC), Internet of Things (IoT) and Ultra-Reliable Low Latency Communication (URLLC) in 6G networks.

There has been no previous analysis on the performance of CARA in satellite communication systems, since previous research has been limited to terrestrial communication systems. In this paper, the performance of CARA is evaluated for LEO satellite communication systems.

II. SYSTEM MODEL

In this section, a system model is presented. The system is assumed to be composed of a satellite and a user terminal. The user terminal measures the downlink channel by receiving the pilot signal transmitted by the satellite, such as Reference Signal (RS) or synchronization signal. Under the assumption of channel reciprocity, the user terminal estimates the uplink channel gain

using the measured downlink channel. Based on the estimated uplink channel gain, the user terminal determines whether to transmit a random access packet. Denote by P_o the outage probability, defined as the probability that the estimated uplink channel gain is smaller than the channel threshold g_{th} .

In this paper, it is assumed that the user terminal transmits random access packet composed of a preamble. In LEO satellite systems, the length of the preamble is about 72 μ s when using preamble format A1 with 30 kHz subcarrier spacing [5].

Table 1. Doppler shift for LEO at 600 km altitude

Frequency (GHz)	Max Doppler	Max Doppler shift variation
2	+/- 48 kHz	- 544 Hz/s
20	+/- 480 kHz	- 5.44 kHz/s
30	+/- 720 kHz	- 8.16 kHz/s

In LEO satellite systems, a significant Doppler shift results from the rapid relative motion between the satellite and user terminal. Since LEO satellites typically move at speeds of approximately 7.7 km/s, the Doppler shift can reach up to several tens of kHz. For example, as shown in Table 1, the Doppler shift can reach up to ± 48 kHz at a carrier frequency of 2 GHz [6]. This leads to performance degradation in preamble detection and synchronization.

To overcome this problem, System Information Block type 19 (SIB19) was introduced in 3rd Generation Partnership Project (3GPP) Release 17 to support Doppler shift pre-compensation. SIB19 contains essential information such as satellite ephemeris data and Global Navigation Satellite System (GNSS)-based timing information [7]. Based on SIB19, the user terminal transmits a random access packet after the Doppler pre-compensation.

However, even after Doppler pre-compensation, a residual Doppler frequency Δf_D remains due to factors such as imperfect channel estimation and inaccuracy of the GNSS-based position and timing information. In this paper, a slow time-varying channel with a residual Doppler frequency Δf_D is assumed. Under this assumption, the channel gain g is assumed to be approximately constant over the duration of the preamble transmission. The channel gain g is normalized to satisfy $\mathbb{E}\{g\} = 1$ as in [4]. In this paper, it is assumed that the preamble experiences a Rician fading channel. Then, the Probability Density Function (PDF) of the channel gain can be expressed as

$$f(g) = (1 + K) \exp(-K - (1 + K)g) I_0 \left(2\sqrt{K(K + 1)g} \right),$$

where K is the ratio between the power of the direct Line-of-Sight (LoS) component and that of Non-Line-of-Sight (NLoS)

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components. $I_0(x)$ is the modified Bessel function of the first kind of order zero. In a Rician fading channel, since the channel gain g follows a non-central chi-square distribution, the outage probability P_o can be expressed in terms of the Marcum-Q function as

$$P_o = \Pr\{g < g_{th}\} = 1 - Q_1(\sqrt{2K}, \sqrt{2(1+K)g_{th}}),$$

where $Q_A(x, y)$ is a generalized Marcum-Q function of order A .

Denote by h_1 and h_2 the uplink channel estimated at the user terminal and the uplink channel when the preamble is received at the satellite, respectively. In a typical LEO satellite scenario with an altitude of 600 km, the one-way propagation delay ranges from 2 to 10 ms depending on the elevation angle. Then, there is a non-negligible time delay between channel estimation and preamble reception. The correlation coefficient ρ between h_1 and h_2 can be expressed as

$$\rho = J_0(2\pi\Delta f_D\tau),$$

where τ is one-way propagation delay between the terminal and the satellite.

It is assumed that the satellite uses an energy detector that computes the correlation energy and compares it to a detection threshold η to detect the presence of a preamble. The detection threshold η is determined based on the false-alarm probability, which is defined as the probability that the correlation energy due to noise exceeds the threshold in the absence of a transmitted preamble.

The detection probability can be derived based on the joint PDF $f(g_1, g_2)$ of squared channel gains, $g_1 = |h_1|^2$ and $g_2 = |h_2|^2$. Based on the joint PDF, the detection probability P_D can be expressed as

$$P_D = \int_0^\infty \int_{g_{th}}^\infty Q_1\left(\sqrt{\frac{2g_2PT_p}{N_0}}, \sqrt{\frac{2\eta}{N_0}}\right) f(g_1, g_2) dg_1 dg_2.$$

In [3], the detection probability in Rayleigh fading channels was analytically derived. However, in Rician fading channels, the joint PDF of the channel gains does not have a closed-form expression. Therefore, in this paper, the detection performance is evaluated by simulation.

III. RESULTS

In this section, the simulation results are presented for the detection performance under Rician fading channels. Table 2 summarizes the parameters used in the simulation. Preamble format A1 was employed with a preamble length of 0.14 ms. The Rician fading channel was modeled using K-factor values of 3 and 6. The channel threshold g_{th} is set to satisfy the outage probability of 0.5. The detection threshold η is set to satisfy the false-alarm probability of 0.1%.

Figs. 1 and 2 show the missing probability for conventional random access and CARA when $K = 3$ and 6, respectively. With CARA, the correlation coefficient ρ is set to 0.3, 0.6, and 0.9. In addition to the results for various ρ values, the result for $\rho = 1$ is also shown in the figures as the theoretical upper bound. The performance of the conventional scheme is equivalent to the uncorrelated case of CARA ($\rho = 0$).

Table 2. Simulation parameters

Name	Value
Preamble format	format A1
Preamble length	0.14 ms
Fading channel	Rician
K factor	3, 6
Outage probability	0.5
False-alarm probability	0.1%

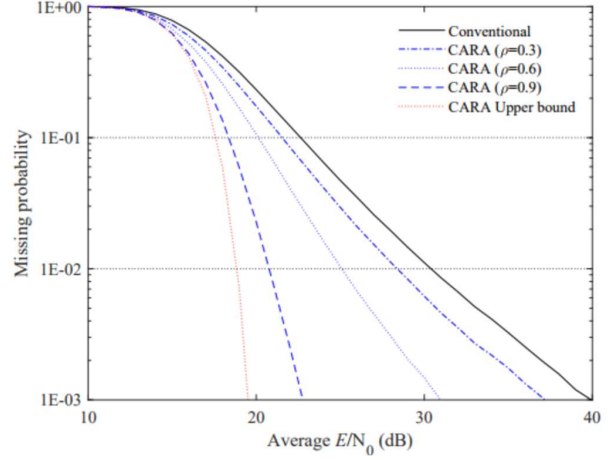


Fig. 1. Missing probability in Rician fading channel ($K = 3$)

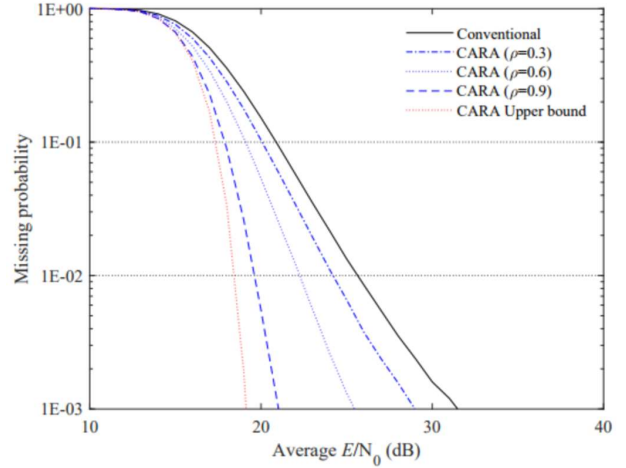


Fig. 2. Missing probability in Rician fading channel ($K = 6$)

From the results of Figs. 1 and 2, it can be observed that approximately 2 to 10 dB performance gain can be achieved with CARA compared to conventional random access for 99% detection probability. In addition, the detection performance of CARA is further enhanced as ρ increases. Given a constant residual Doppler value Δf_D , ρ increases with elevation angle. This implies that, under the same residual Doppler conditions, better performance is achieved by CARA as the elevation angle increases.

IV. CONCLUSION

In this paper, the detection performance of CARA was simulated. The simulation results show that the required receiver power consumption can be reduced with CARA compared with conventional random access.

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