Capacity Analysis of Panoramic Multi-beam Satellite Telemetry and Command System

Yilun Liu(✉) and Lidong Zhu

National Key Laboratory of Science and Technology on Communications,
UESTC, Chengdu 611731, Sichuan, China
lyl6205@163.com, zld@uestc.edu.cn

Abstract. Compared with the Tracking beam satellite Telemetry and Command system, the Panoramic Multi-beam satellite Telemetry and Command system has the advantages that the spacecrafts can be measured and controlled when they enter the coverage area and the system capacity is large. It uses Code-Division Multiple Access (CDMA) to distinguish users. Since the spreading codes are not completely orthogonal, the received signals will introduce Multiple Access Interference (MAI) and affect the system performance. Based on the panoramic multi-beam satellite telemetry and command system, this paper deduces the formula of ranging error in the presence of MAI, and analyzes the system capacity considering the two cases of perfect power control and imperfect power control. The theoretical and simulation results show that the system can support over 500 space-crafts at the same time, but the system performance deteriorates by 1.6 dB when the power control error occurs.

Keywords: Satellite telemetry and command system · Panoramic multi-beam · System capacity · Ranging error · Multiple access interference

1 Introduction

The next generation constellation program represented by the satellite Internet and the Space-terrestrial integrated network has developed rapidly. However, with the rapid increasement in the number of low-orbit spacecraft, the existing tracking beam satellite telemetry and command system, limited by the number of tracking beams, is difficult to meet the telemetry and command requirements of many spacecrafts in the future. Therefore, the concept of a panoramic multi-beam satellite telemetry and command system has been proposed. The beam coverage of the panoramic multi-beam satellite telemetry and command system is unchanged, and the spacecraft can be telemetered within the beam range. Besides, the panoramic multi-beam telemetry and command system uses CDMA to distinguish spacecrafts. Since it is no longer limited by the number of tracking beams, the system capacity will exceed that of satellite telemetry and command system with tracking beams.

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Due to the imperfect orthogonality of the spreading code, the received signal of the telemetry and command system will produce Multiple Access Interference (MAI), which may cause the performance degrading of the telemetry and command system.

Tracking loop performance and multi-beam satellite system capacity have attracted the attention of scholars for long time [1, 2]. In recent years, there have been many new research results [3, 4], but there are few literatures on panoramic multi-beam satellite telemetry and command systems. This paper analyzes the capacity of the telemetry and command system in the presence of MAI. According to the ranging error formula and the bit error rate (BER) formula in the presence of MAI, the system capacity formula under the two limiting factors of ranging accuracy and bit error rate (BER) is deduced. Finally, numerical results show that the system can meet telemetry and command requirements of 500 spacecrafts at the same time.

2 The System Model

This paper is based on the panoramic multi-beam satellite telemetry and command system, as shown in Fig. 1. The system achieves full coverage of 200–2000 km with only three satellites, and the interference between adjacent satellites is small. The interference mainly comes from the interference between adjacent beams of the same satellite and other ones in the same beam.

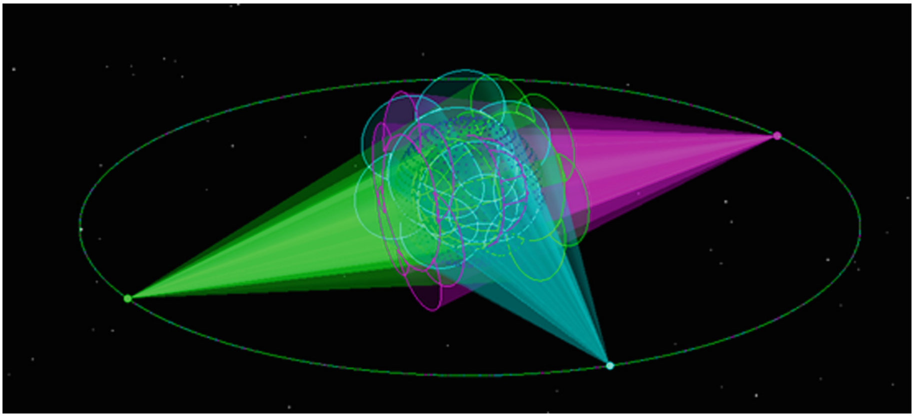

Fig. 1. Schematic diagram of panoramic multi-beam satellite telemetry and command system

The block diagram of the multi-target ranging system using pseudo-code ranging is shown in Fig. 2.

It is known from Fig. 2, the main factor affecting the accuracy of ranging is the synchronization accuracy, which can be divided into acquiring and tracking, and the tracking accuracy is the main factor. This paper analyzes the capacity of the panoramic multi-beam telemetry and command system under the two constraints of ranging accuracy and BER.

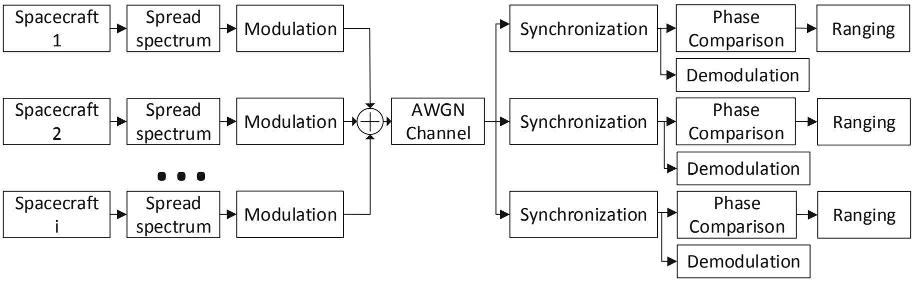

Fig. 2. Block diagram of multi-target ranging system

The parameters of the system are shown in Table 1.

Table 1. System parameters

Parameter	Value
Orbital altitude	35786 km
Number of satellites	3
Orbital position	E176.8°, E77°, E10.6°
Number of single satellite beams	21
Frequency reuse	Three-color frequency reuse
Spacecraft height	200–2000 km
Reverse link rate	10 kbps
Spreading code rate	10.23 M chips/s
S-band center frequency	3 GHz
Modulation	BPSK

3 Capacity Analysis

3.1 SINR

In this part, the power interference of other spacecrafts under the single beam to the target spacecraft is derived, and then the interference of the spacecraft in the other beams to the target spacecraft is analyzed. Assuming the total number of spacecrafts is K, the user power of spacecraft i is $P_{si}(1 < i < K)$. Without loss of generality, if the signal of spacecraft 1 is the target signal, and the power is $P_s = P_{s1} = \min\{P_{si}, 1 < i < K\}$. The Gaussian white noise power is P_n, then the input SINR of the correlator is

$$(\frac{S}{I+N})_i = \frac{P_s}{\sum_{j=2}^{K} P_{sj} + P_n} \tag{1}$$

The correlator has a different MAI suppression gain G_{MAI} [5] than the Gaussian white noise suppression gain G_N, as shown in the following equation.

$$G_{MAI-j} = 20\lg(N_c/R_{j1}(\tau)) \tag{2}$$

$$G_N = 10\lg(R_c/R_b) \tag{3}$$

In Eq. (2), $R_{j1}(\tau)$ represents the cross-correlation function of spacecraft j and spacecraft 1 when the phase difference is τ chips, N_c is the period of spreading code. Therefore, after passing through the correlator, the output SINR will become

$$(\frac{S}{I+N})_o = \frac{P_s}{\sum_{j=2}^{K} \frac{P_{sj}}{G_{MAI-j}} + \frac{P_n}{G_N}} = \frac{P_s}{\sum_{j=2}^{K} \frac{G_N P_{sj}}{G_{MAI-j}} + P_n} G_N \tag{4}$$

From Eq. (4), the MAI can be equivalent to Gaussian white noise with an input power of $\sum_{j=2}^{K} G_N P_{sj}/G_{MAI-j}$, which is the basis for analyzing the ranging error and BER later.

Now consider the interference of spacecraft in other beams. It is assumed that the frequency reuse is reasonable, there is no interference between the beams of different frequencies, and only the beams of the same frequency will cause interference. Besides power interference, the received signal power of the interference in other beams is related to the antenna gain. The input SINR of the multi-beam system can be described as the following.

$$SINR = \frac{P_s}{\sum_{i=1}^{M} \frac{G_N}{G_{MAI-i}} f \cdot P_{si} + \sum_{j=2}^{K} \frac{G_N P_{sj}}{G_{MAI-j}} + P_n} \tag{5}$$

In Eq. (5), M is the total number of other beam interference spacecraft, and f is the neighbor cell interference factor to estimate the interference power of other cells, which is defined as

$$f = P_{Ia}/P_{Ie} \tag{6}$$

In Eq. (6), P_{Ia} is the total interference power of "other cells", and P_{Ie} is the total interference power of the "self-cell".

In imperfect power control, the power control error coefficient α_{j1} is introduced, which is define as

$$\alpha_{j1} = P_{sj}/P_s \tag{7}$$

Then, Eq. (5) can be rewritten as follows.

$$\begin{aligned}(E_b/N_0)_{eff} = SINR &= P_s\left(\sum_{i=1}^{M}\frac{G_N}{G_{\mathrm{MAI-i}}}fP_{si} + \sum_{j=2}^{K}\frac{G_N P_{sj}}{G_{\mathrm{MAI-j}}} + P_n\right)^{-1} \\ &= \left(\sum_{i=1}^{M}\frac{G_N}{G_{\mathrm{MAI-i}}}f\alpha_{i1} + \sum_{j=2}^{K}\frac{G_N\alpha_{j1}}{G_{\mathrm{MAI-j}}} + P_n\right)^{-1} \\ &= \left(\sum_{i=1}^{M}\frac{R_{j1}^2(\tau)f\alpha_{i1}}{N_c} + \sum_{j=2}^{K}\frac{R_{j1}^2(\tau)\alpha_{i1}}{N_c} + \frac{N_0}{E_{\mathrm{b}}}\right)^{-1}\end{aligned} \tag{8}$$

In Eq. (8), $(E_b/N_0)_{eff}$ is the equivalent E_b/N_0 when MAI exists, and the actual E_b/N_0 is on the right side of the equation.

3.2 Ranging Error and BER

The implementation of the ranging system mainly relies on the phase difference between the ranging signal and the local signal during synchronization. After the acquisition is successful, the code phase difference between the local sequence and that of the received signal is less than half a chip, but it is not enough for the system's requirements of ranging accuracy. For example, if the spreading code rate is 10 M chips/s, then the maximum range error will reach 7.5 m, so it is necessary to enter the tracking phase for better accuracy. The expression of the ranging error is

$$\Delta = c(T_c \cdot \sigma)/2 \tag{9}$$

In Eq. (9), T_c is the time of one chip; σ is the minimum resolution obtained by the synchronization technique, and c is the speed of light. The error of the non-coherent delay-locked loop comes from two aspects: thermal noise error and dynamic stress error, and the total error is less than the threshold. Once the total error of the delay-locked loop is greater than the threshold, then it will be in unlocked state and needs re-acquisition. The relationship between the total error and the threshold is as follows.

$$3\sigma_{DLL} = 3\sigma_{tDLL} + R_e \le d \tag{10}$$

In Eq. (10), σ_{DLL} is the root mean square error of all errors in the code ring (unit: chip); σ_{tDLL} is the error caused by the loop thermal noise; R_e is the dynamic stress error; d is the threshold, and the value generally is 0.5. In general, the dynamic stress error is negligible.

The classical analysis can get the thermal noise error σ_{tDLL} as follows [6].

$$\sigma_{tDLL} = \sqrt{\frac{2d^2B_L}{C/N_0}[2(1-d) + \frac{4d}{TC/N_0}]} \quad (chip) \tag{11}$$

In Eq. (11), B_L is the loop equivalent noise bandwidth; T is the pre-detection integration time; C/N_0 is the carrier-to-noise ratio $(dB \cdot Hz)$, which can be calculated as follows [7].

$$C/N_0 = \frac{S}{N} \cdot B_L = \frac{E_b \cdot R_b}{N_0 \cdot B_L} \cdot B_L = \frac{E_b}{N_0} \cdot R_b \tag{12}$$

The curve of the ranging error as a function of E_b/N_0 can be obtained by the Eqs. (8), (9) and (11). In addition to the ranging error, the BER of the synchronous demodulation under BPSK can be obtained by [4].

$$P_{b-BPSK} = Q(\sqrt{\frac{2E_b}{N_0}}) \tag{13}$$

In this way, we get the equation of ranging error and bit error rate with E_b/N_0, which is the basis for calculating the capacity.

3.3 The Capacity

It is assumed that the spacecraft is evenly distributed within the satellite coverage. The number of spacecrafts in each beam is equal. The three-color frequency multiplexing is used, and the number of interference beams at the same frequency is L. $R_{j1} = 1$ (Gold sequences are mutually the ideal case for related functions). K is the number of spacecrafts in a single beam. Next, we will analyze the system capacity considering perfect power control and imperfect power control.

In perfect power control, the received signal power of each spacecraft is equal. If the BER is fixed, the system capacity N_{bpsk} per satellite at BPSK modulation can be obtained by Eqs. (8) and (13).

$$N_{BPSK} = 3(L+1)K = \frac{6(L+1)N_c}{fL+1}\left(\frac{1}{Q^{-1}(BER)^2} - \frac{N_0}{2E_b}\right) + 3L + 3 \tag{14}$$

According to Eqs. (8), (9), (11) and (12), the system capacity N_{DLL} per satellite using the non-coherent delay-locked loop can be obtained.

$$\sigma = \frac{2\Delta}{cT_c} \tag{15}$$

$$C/N_0 = \frac{4d^2(1-d)B_L + \sqrt{16d^4(1-d)^2 B_L^2 + 16d\sigma^2/T}}{2\sigma^2} \tag{16}$$

$$N_{DLL} = 3(L+1)K = \frac{3(L+1)N_c}{fL+1}\left(\frac{R_b}{(C/N_0)} - \frac{N_0}{E_b}\right) + 3L + 3 \tag{17}$$

Therefore, the system capacity N per satellite is

$$N = \min\{N_{DLL},\ N_{BPSK}\} \tag{18}$$

Compared with the perfect power control, the closed solution of the system capacity in BPSK modulation cannot be obtained because the power control error coefficient α_{j1}. According to Eqs. (8) and (13), the number of users K_{BPSK} in a single beam needs to be satisfied.

$$f\sum_{i=1}^{LK_{BPSK}} \alpha_{i1} + \sum_{j=2}^{K_{BPSK}} \alpha_{j1} \leq 2N_c\left(\frac{1}{Q^{-1}(BER)^2} - \frac{N_0}{2E_b}\right) \tag{19}$$

Equations (15) and (16) are unchanged in the analysis of the existence of power control errors. When the ranging accuracy is constant, the number of users K_{DLL} in a single beam using the non-coherent delay tracking loop needs to be satisfied.

$$f\sum_{i=1}^{LK_{DLL}} \alpha_{i1} + \sum_{j=2}^{K_{DLL}} \alpha_{j1} \leq N_c\left(\frac{R_b}{(C/N_0)} - \frac{N_0}{E_b}\right) \tag{20}$$

Therefore, the system capacity N per satellite is

$$N = \min\{3(\mathrm{L} + 1)\mathrm{K}_{DLL},\ 3(\mathrm{L} + 1)\mathrm{K}_{BPSK}\} \tag{21}$$

4 Numerical Calculation Results

4.1 Ranging Error in Single Beam Scene

Here we consider the worst case, that is, all spacecrafts are in the same beam, and other beams have no spacecrafts. At this time, the MAI is the strongest and the ranging error is the largest.

Let $R_b = 10$ kbps, $T = 1$ ms, $d = 0.5$, $B_L = 30\,\mathrm{Hz}$, $R_{j1} = 1$, $\alpha \sim U(0.5, 2)(\mathrm{dB})$ [8], K is the number of spacecrafts and it is a parametric variable, and the variation of the ranging error value with E_b/N_0 can be obtained, as shown in Figs. 3 and 4.

It can be seen from Figs. 3 and 4 that the ranging error is less than 1 m when the number of perfect power control and spacecraft is different, as well as power control error exists. When there is power control error, the accuracy of ranging is significantly lower than that of perfect power control. The difference is not so large because $R_{j1} = 1$, which makes the MAI between spacecrafts smaller. In other words, Fig. 4 is the ranging error when the MAI is minimum. Therefore, perfect power control can improve the accuracy of ranging.

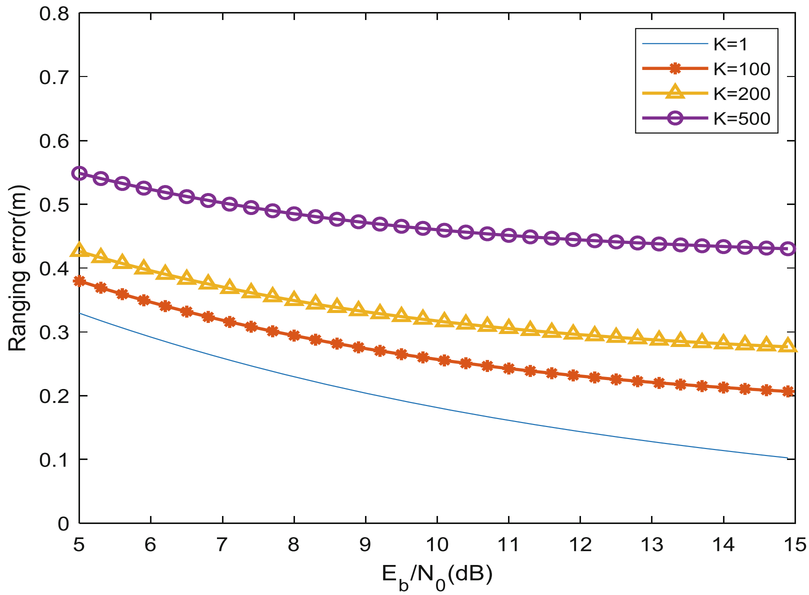

Fig. 3. Ranging error with perfect power control

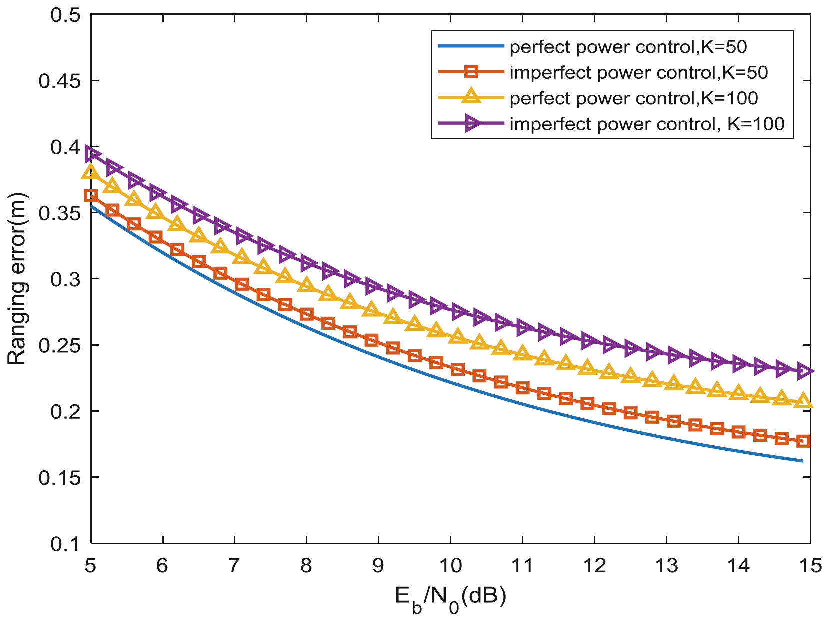

Fig. 4. Ranging error with imperfect power control $(\alpha \sim U(0.5,\ 2)(\mathrm{dB}))$

4.2 The Capacity of the System with Perfect Power Control

Given the BER and ranging accuracy, we can get the curve of capacity per satellite with E_b/N_0. Let L = 6, $BER = 10^{-5}$, $\Delta = 0.25\,\mathrm{m}$, $B_L = 50\,\mathrm{Hz}$, $N_c = 1023$, $R_c = 10.23$ M chips/s, $R_b = 10$ kbps/s, $f = 0.65$ [9]. The capacity variation curve is shown in Fig. 5.

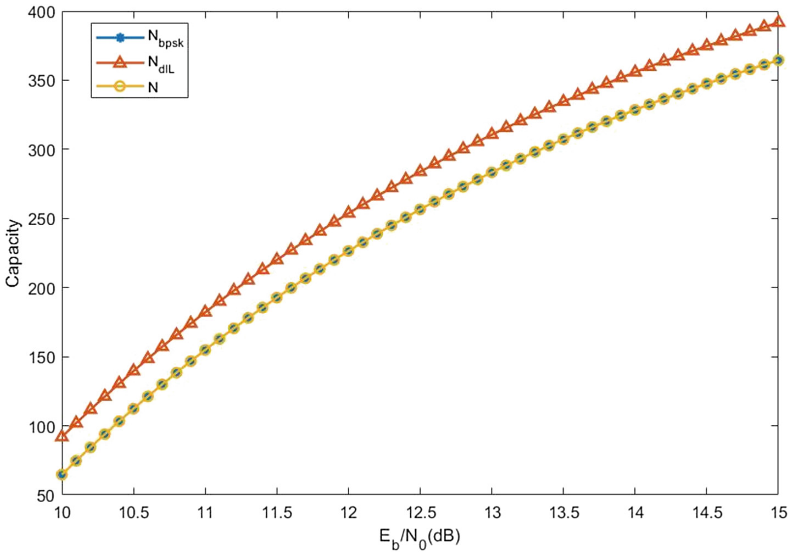

Fig. 5. Capacity with perfect power control

As can be seen from the above figure, the capacity is mainly limited by the BER. Of course, the above result is related to the BER and ranging accuracy. If the accuracy of ranging is improved, the capacity will be mainly limited by the accuracy of ranging. When $E_b/N_0 = 11.4$ dB, the capacity of one satellite is 186, then the total capacity of the three satellites of the panoramic multi-beam satellite telemetry and command System is 558, which meets the needs of 500 targets.

4.3 Capacity with Power Control Error Exists

Since the power error exists, the capacity formula has no closed solution, and the intermediate value is set:

$$V_N = f\sum_{i=1}^{LK}\alpha_{i1} + \sum_{j=2}^{K}\alpha_{j1} \tag{23}$$

$$V_{BPSK} = 2N_c\left(\frac{1}{Q^{-1}(BER)^2} - \frac{N_0}{2E_b}\right) \tag{24}$$

$$V_{DLL} = N_c\left(\frac{R_b}{(C/N_0)} - \frac{N_0}{E_b}\right) \tag{25}$$

Note that in Eqs. (23), (24) and (25), V_N, V_{bpsk}, V_{DLL} is dimensionless. Let $\alpha \sim U(0.5, 2)(\text{dB})$, we Simulates 100 times by MATLAB and the numerical calculation result of V_N is shown in Table 2.

Table 2. Numerical calculation result of V_N

Item	Value								
K	3	4	5	6	7	8	9	10	11
V_N	18.33	24.91	31.55	38.07	44.63	51.06	57.74	64.32	70.83

Similarly, the numerical results of V_{BPSK} and V_{DLL} are shown in Table 3.

Table 3. Numerical results of V_{BPSK} and V_{DLL}

Item	Value					
E_b/N_0	10 dB	11 dB	12 dB	13 dB	14 dB	15 dB
V_{BPSK}	10.18	31.22	47.94	61.21	71.76	80.13
V_{DLL}	16.55	37.59	54.30	67.57	78.12	86.49

Therefore, the system of panoramic multi-beam satellite telemetry and command System is shown in Table 4.

Table 4. Numerical result of one satellite capacity

Item	Value					
E_b/N_0	10 dB	11 dB	12 dB	13 dB	14 dB	15 dB
Capacity	<63	84	147	189	231	>231

As can be seen from the above figure, the capacity is mainly limited by the BER. When $E_b/N_0 = 13$ dB, the capacity of one satellite is 189, then the total capacity of the three satellites of the panoramic multi-beam satellite telemetry and command System is 567, which meets the needs of 500 targets and performance deteriorates by 1.6 dB than perfect power control.

5 Conclusion

Based on the panoramic multi-beam satellite measurement and control system, this paper analyzes the ranging error in the presence of MAI, and analyzes the system capacity when the range accuracy and BER are limited. The results show that for perfect power control, MAI will deteriorate the ranging accuracy, but less than 1 m; when power control error occurs, it will be more deteriorated. When the system capacity is 500, the performance of imperfect power error is 1.6 dB worse than the perfect power control.

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