The Research on Multi-objective TT&C Technology

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Space multi-objective TT&C system plays an important role in the future space TT&C field. With the development of space technology, more and more satellites, especially mid or low orbit and constellation satellites launch to the space. Because the mid or low orbit satellites has the characteristics of the short integral time between each TT&C event. So the requirement of multi-objective TT&C simultaneously is more and more. Traditionally earth TT&C equipment such as USB can only support one satellite and can not satisfy the requirement. This paper proposes a configuration design of the multi-objective TT&C system which adopting multi-beam antenna and CDMA technology. Firstly, the working principles of the multi-objective TT&C system and adaptive DBF algorithm are introduced. Then computer simulates the multi-objective searching and tracking performance of DBF. The simulation results show that LMS and RLS algorithms can form several beams based on the satellites location adaptively and suppress the interference effectively. Compare with the LMS algorithm, RLS adaptive algorithm has faster convergence speed. But the computation amount is larger than LMS. Thirdly, we deduce the performance of the multi-objective TT&C system in the presence of MAI. The theoretical equation of the MAI is easier to calculate the MAI influence than the traditional method when the different links have the different receiving power. So totally considering, the multi-beam CDMA system can satisfy the multi-objective TT&C requirements and can reduce the MAI effectively.

Nomenclature

USB	=	United S-band
DBF	=	digital beamforming
LMS	=	Least Mean Squares Algorithm
RLS	=	Recursive Least Squares Algorithm
MAI	=	multiple access interference

I. Introduction

WITH the development of space technology, more and more satellites are on orbit. The pass interval in succession among the satellites becomes shorten and shorten. In addition, the minimum distance between the satellites of the constellation is several kilometers. So two or more satellites appear during the same pass. Multi-objectives demand transmission to or through a common point simultaneous. This calls for higher systems capacities and the TT&C station has multi-satellite TT&C ability. Traditionally USB earth station can only support one satellite. A multi-beam antenna and CDMA system is presented to achieve the multi-objective TT&C simultaneous.

The paper is organized as follows. In the first part of this paper, we built and introduced the model of the multi-beam antenna and CDMA system, which simultaneously provides coverage to different regions using common frequency channels. Secondly, the multi-beam antenna is dependent on DBF technology for their practical implementation. We introduced the LMS and RLS digital beamforming (DBF) algorithms and compared the characteristics between the two algorithms. Simulation results show the validity. Thirdly, the influence of the

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multiple access interference to the multi-objective TT&C system is deduced and simulated. Finally, concludes the paper.

II. Configuration Design of the multi-objective TT&C system

This section gives the configuration of the multi-objective TT&C system, as well as the implementation of digital beamforming in the system with a CDMA scheme. The configuration design of the multi-objective TT&C system adopts multi-beam antenna and CDMA technology. Firstly, array antenna adopts adaptive DBF technology to form the space multi-beam at some desired angle to direct to the satellites, namely, space division multiple access (SDMA). This ensures the space separation among the satellite TT&C signals. Secondly, CDMA technology realizes to transmit several independent code division channels in a single beam. These channels can take different information such as telecommand, telemetry and ranging information. So we can track and command several satellites at the same time. The CDMA scheme can solve the electromagnetic compatibility (EMC) problem such as adjacent frequency interference and inter-modulation interference brought out by the multiple transmitting carriers in an earth station. DBF technology calculates and adjusts the weighs to separate signal in the spatial domain and steer the beams towards the correspondence satellites. It can power the desired signal and suppress the interference. The convergence of the DBF technology and the CDMA technology increases the multi-objective TT&C ability and anti-jam ability.

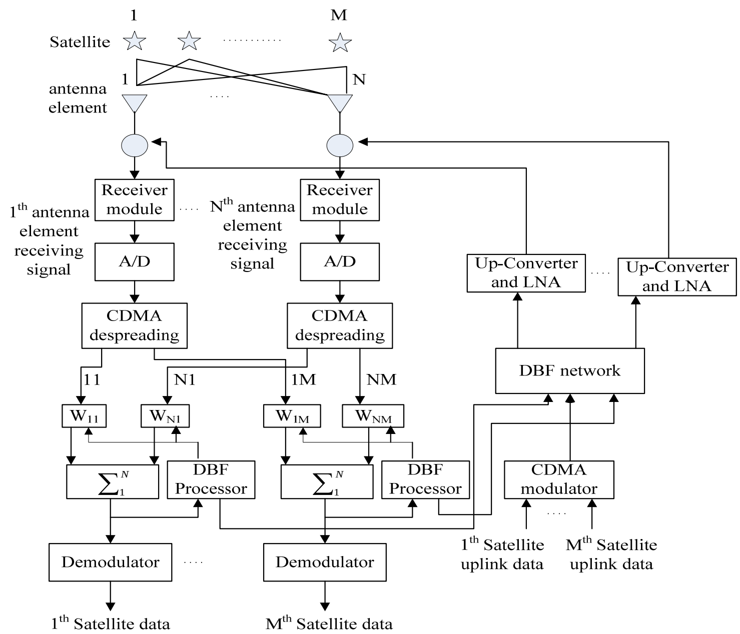

Figure 1. Basic configuration for multi-objective TT&C system.

Fig. 1 shows the configuration of a digital multi-beam forming network that is used for uplink transmitting and the downlink receiving. Assuming there are M satellites need to be tracked in the space. The multi-beam antenna has N antenna elements. Each antenna element receives signals from the M satellites and transmits signal to each satellites.

For uplink, there are M message signals to be transmitted to the M satellites at the same carrier frequency. That is, M uplink and downlink beams are required to be formed simultaneously at the particular frequency. To carry out beamforming in the transmitting mode, each of the M signals to be transmitted to the satellites is divided into N branches, which are multiplied by a set of complex weights $\{w_n^m(t), n=1,\ldots,N, m=1,\ldots,M\}$. This particular set of weights represents the m^{th} downlink beam to be formed. Again, it is desirable that the M sets of weights be mutually orthogonal $(i.e., (w^k)^H w^m = 0)$ to minimize the interference between the M signals that are to be transmitted. The weighted signals are then grouped and combined in the way in the figure. The output signal of the n^{th} combiner, which is given by

$$x_n(t) = \sum_{m=1}^{M} w_n^m(t) y_m(t)$$

Then the carrier and the modulated signal is fed to the n^{th} antenna element for transmission.

For downlink, the receiving M satellites' signals from each antenna element pass to the frequency down-conversion, filtering, amplification, ADC and CDMA despreading. Then the N output of the CDMA despreader from one satellite will be weighted and combined to represent this satellite signal. Then the M satellites' signals can be obtained.

III. DBF Algorithm and Simulation

The DBF is the key technology of the multi-beam antenna. Adaptive beamforming used for steering and modifying an array's pattern in order to enhance the reception of a desired signal, while simultaneously suppressing interfering signals through complex weight adjustment. The weights for the antenna elements are carefully chosen to give the desired peaks and nulls in the radiation pattern of the antenna array. The beamforming is carried out by weighting these digital signals, thereby adjusting their amplitudes and phases such that when added together they form the desired beam.

Currently, adaptive beamforming algorithm has attracted many researchers' interest. There are many textbooks and papers devoted to general concepts and its application. The section introduces and simulates two basic adaptive techniques that can be used in the multi-objective TT&C system. That is LMS and RLS algorithm.

A. LMS Algorithm[1,2]

The most common adaptive algorithm is the LMS algorithm. Let us consider a uniformly spaced linear array, which operates in a signal environment where there is a desired communication signal $s(t)$, as well as N_u interfering signals $\{u_i(t)\}_{i=1}^{N_u}$. The array output is represented by

$$x(t) = s(t)v + u = s + u \tag{1}$$

where v is the array propagation vector for the desired signal,

$$v^T = [1, e^{jkd\sin\theta_0}, \cdots, e^{jk(K-1)d\sin\theta_0}] \tag{2}$$

u represents the sum of all the interfering signal vectors,

$$u = \sum_{i=1}^{N_u} u_i(t)\eta_i \tag{3}$$

and η_i is the array propagation vector for the i^{th} interfering signal,

$$\eta_i^T = [1, e^{jkd\sin\theta_i}, \cdots, e^{jk(K-1)d\sin\theta_i}] \tag{4}$$

$d(t)$ is the reference signal. The weights are chosen to minimize the mean-square error between the beamformer output and the reference signal:

$$\varepsilon^2(t) = [d^*(t) - w^H x(t)]^2 \tag{5}$$

Taking the expected values,

$$E\{\varepsilon^2(t)\} = E\{d^2(t)\} - 2w^H r + w^H R w \tag{6}$$

where $r = E\{d^*(t)x(t)\}$ and $R = E\{x(t)x^H(t)\}$. R is usually referred to as the covariance matrix. The minimum MSE is given by setting the gradient vector of Eq. (6) with respect to w equal to zero:

$$\begin{aligned}\nabla_w(E\{\varepsilon^2(t)\}) &= -2r + 2Rw \\ &= 0\end{aligned} \tag{7}$$

LMS algorithm uses a steepest-descent method and computes the weight vector recursively using the equation

$$w(n+1) = w(n) + \frac{1}{2}\mu[-\nabla(E\{\varepsilon^2(n)\})] \tag{8}$$

It follows from Eq. (7) that

$$w(n+1) = w(n) + \mu[r - Rw(n)] \tag{9}$$

In reality, a prior knowledge of both R and r is not possible to be obtained. So we use their instantaneous estimates.

$$\hat{R}(n) = x(n)x^H(n) \tag{10}$$

$$\hat{r}(n) = d^*(n)x(n) \tag{11}$$

The weights can then be updated as

$$\begin{aligned}\hat{w}(n+1) &= \hat{w}(n) + \mu x(n)[d^*(n) - x^H(n)\hat{w}(n)] \\ &= \hat{w}(n) + \mu x(n)\varepsilon^*(n)\end{aligned} \tag{12}$$

The weights can be chosen to directly maximize the signal-to-interference ratio (SIR). Assuming that $R_s = E\{ss^H\}$ and $R_u = E\{uu^H\}$ are known, we may choose to maximize the ratio of the output signal power σ_s^2 and the total interfering signal power σ_u^2. The output signal power may be written as

$$\sigma_s^2 = E\{|w^H s|^2\} = w^H R_s w \tag{13}$$

and the output noise power is

$$\sigma_u^2 = E\{|w^H u|^2\} = w^H R_u w \tag{14}$$

Therefore, the SIR is given as

$$SIR = \frac{\sigma_s^2}{\sigma_u^2} = \frac{w^H R_s w}{w^H R_u w} \tag{15}$$

Taking the derivative of Eq. (15) with respect to w and setting it to zero, we obtain

$$R_s w = \frac{w^H R_s w}{w^H R_u w} R_u w \tag{16}$$

which appears to be a joint eigen problem. The value of the $\frac{w^H R_s w}{w^H R_u w}$ is bounded by the minimum and maximum eigenvalues of the symmetric matrix $R_u^{-1} R_s$ .The maximum eigenvalue $\lambda_{\max}$ satisfying

$$R_u^{-1} R_s w = \lambda_{\max} w \tag{17}$$

is the optimum value of SIR(SIR=$\lambda_{\max}$). Corresponding to this value, there is a unique eigenvector, w_{opt} ,which represents the optimum weights. Therefore,

$$R_s w_{opt} = \mathrm{SIR} R_u w_{opt} \tag{18}$$

Noting that $R_s = E\{d^2(t)\} v v^H$, we obtain

$$w_{opt} = \beta R_u^{-1} v \tag{19}$$

where

$$\beta = \frac{E\{d^2(t)\}}{\mathrm{SIR}} v^H w_{opt} \tag{20}$$

That is the maximum SIR criterion.

B. RLS Algorithm[1,2]

The RLS algorithm estimates R_{xx} and $\hat{p}_{xd}$ using weighted sums so that

$$\hat{R}_{xx} = \sum_{i=1}^{N} \gamma^{n-i} x(i) x^H(i) \tag{21}$$

and

$$\hat{p}_{xd} = \sum_{i=1}^{N} \gamma^{n-i} d^*(i) x(i) \tag{22}$$

The inverse of the covariance matrix can be obtained recursively, and this leads to the update equation

$$\hat{w}(n) = \hat{w}(n-1) + q(n)[d^*(n) - \hat{w}^H(n-1)x(n)] \tag{23}$$

where

$$q(n) = \frac{\gamma^{-1} R_{xx}^{-1}(n-1) x(n)}{1 + \gamma^{-1} x^H(n) R_{xx}^{-1}(n-1) x(n)} \tag{24}$$

and

$$R_{xx}^{-1}(n) = \gamma^{-1}[R_{xx}^{-1}(n-1) - q(n) x(n) R_{xx}^{-1}(n-1)] \tag{25}$$

Table 1 compares the two adaptive DBF algorithm. RLS algorithm has faster convergence speed beyond the LMS algorithm. But the computational load of RLS is relatively heavier than LMS.

Table 1. Summary of adaptive beamforming algorithms

Algorithm	Weight update equations	Advantages	Disadvantages
LMS	$\hat{w}(n+1) = \hat{w}(n) + \mu x(n)[d^*(n) - x^H(n)\hat{w}(n)]$ $= \hat{w}(n) + \mu x(n)\varepsilon^*(n)$	Always converges, but slowly if the eigenvector spread is large.	Requires reference signal.

Algorithm	Weight update equations	Advantages	Disadvantages
RLS	$\hat{w}(n)=\hat{w}(n-1)+q(n)[d^{*}(n)-\hat{w}^{H}(n-1)x(n)]$ $q(n)=\dfrac{\gamma^{-1}R_{xx}^{-1}(n-1)x(n)}{1+\gamma^{-1}x^{H}(n)R_{xx}^{-1}(n-1)x(n)}$ $R_{xx}^{-1}(n)=\gamma^{-1}[R_{xx}^{-1}(n-1)-q(n)x(n)R_{xx}^{-1}(n-1)]$	Always converges, faster than LMS.	Requires reference signal and initial estimate of R_{xx}^{-1}.

C. Simulation

We simulate five-element antenna using the LMS and RLS algorithms in Fig. 2-5. In Fig. 2 and Fig. 4, assume that the interested signal comes from the direction of 0 degree, and an interference signal comes from the direction of 10 degrees, 20 degrees, -10 degrees. The signal-to-noise ratio is equal to 15dBW in the direction of the desired signal. The interference-to-noise ratio is equal to 15dB. Fig. 2-5 show that the two algorithms can suppress the interference effectively. The weights for the antenna elements are adjusted to give the desired peaks to the useful signal and the nulls to the interference signal in the radiation pattern of the antenna array.

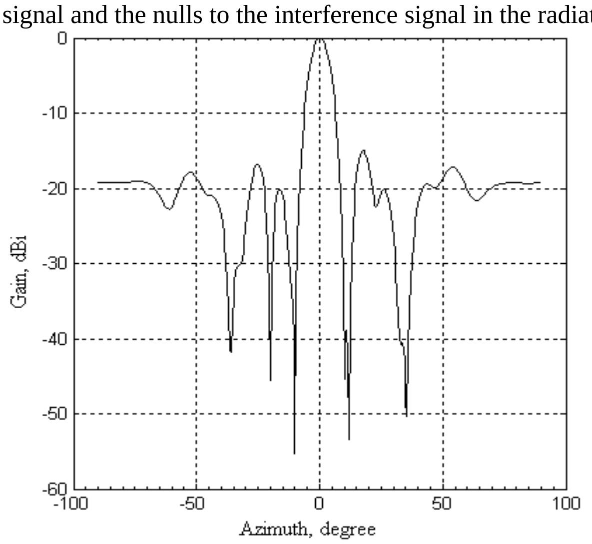

Figure 2. The single-beam pattern using LMS adaptive beamforming.

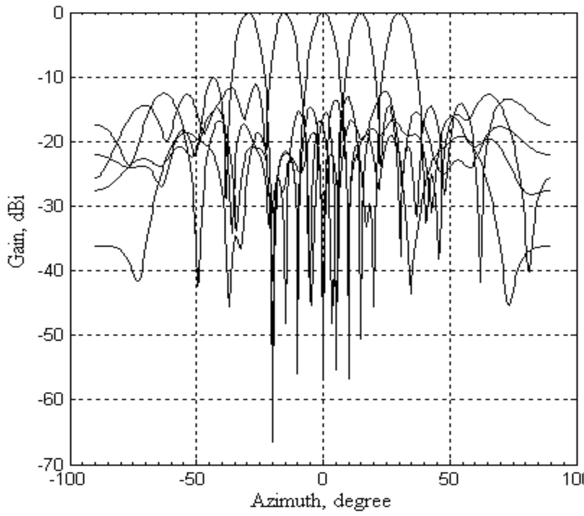

Figure 3. The multi-beam pattern using LMS adaptive beamforming.

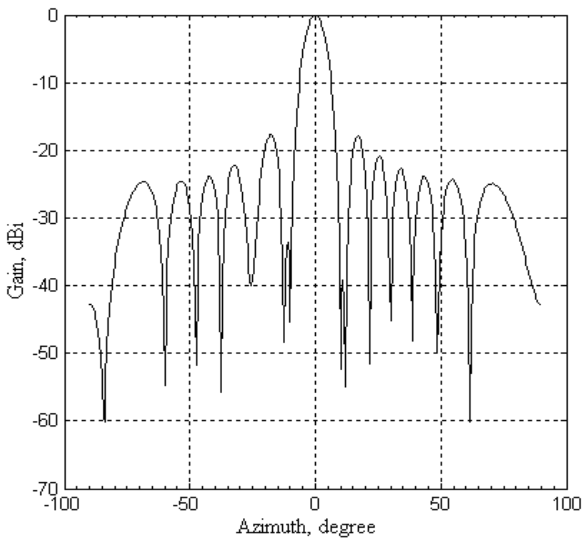

Figure 4. The single-beam pattern using RLS adaptive beamforming.

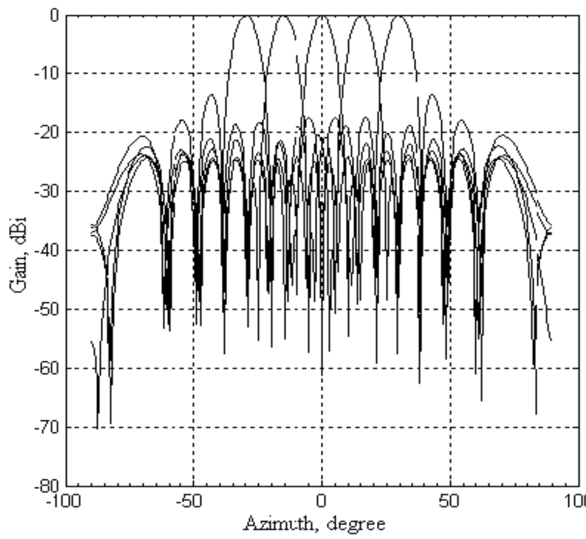

Figure 5. The multi-beam pattern using RLS adaptive beamforming.

IV. The Performance of the Multi-Objective TT&C System in The Presence of MAI

The section deduces the performance of the multi-objective TT&C System in the presence of MAI. And then simulate the MAI influence on the multi-objective TT&C system.

A. Theory Performance of the Multi-Objective TT&C System in The Presence of MAI

When one beam wants to receive one of the satellites' signals, there will be M satellites' signals that enter the beam. So the M-1 satellite signals will form multiple access interference to the desired signal. Such as downlink, each satellite has more than two code division channels that are the telemetry channel and the tracking channel. These channels will also form the MAI each other. So the MAI includes: (1) the several satellites' signals entering the same beam will form the MAI. (2) the different channels from the same satellite will form the MAI. The receiving power of MAI may be different in the receiver. The traditional calculating method is based on the same power among the MAI signals[7,8]. This paper gives the feasible method to calculate the MAI of the different power.

Assuming the multi-objective TT&C system received K satellites' CDMA signals each beam. The received signal is defined as

$$r(t)=\sum_{i=1}^{K}a_i(t)d_i(t)PN_i[t-\tau_i(t)]\cos[j(w_ct+\theta_i(t))]+n(t) \tag{26}$$

where $PN_i(t)$ is the i^th spreading code, w_c is the carrier centre frequency. $d_i(t)$ 、 $a_i(t)$ 、 $\tau_i(t)$ and $\theta_i(t)$ are the data , amplitude, time delay and phase of the i^th spreading signal, respectively. The data $d_i\in\{-1,1\}$.

These signals are then passed through integrator of duration T belonging to satellite 1 to produce the decision variable

$$\begin{aligned} z(t)=&\int_0^T\sum_{i=1}^{K}a_id_i(t)PN_i[t-\tau_i(t)]\cos[j(w_ct+\theta_i(t))]\\ &\cdot 2PN_1[t-\tau_1(t)]\cdot\cos(w_ct+\varphi_1)dt\\ &+\int_0^T n(t)\cdot 2PN_1(t-\tau_1)\cdot\cos(w_ct+\varphi_1)dt \end{aligned} \tag{27}$$

$$\begin{aligned} z(t)=a_1d_1(t)\cdot T+&\int_0^T\sum_{i=2}^{K}a_id_i(t)PN_i[t-\tau_i(t)]\cos[j(w_ct+\theta_i(t))]\\ &\cdot 2PN_1[t-\tau_1(t)]\cdot\cos(w_ct+\varphi_1)dt\\ &+\int_0^T n(t)\cdot 2PN_1(t-\tau_1)\cdot\cos(w_ct+\varphi_1)dt \end{aligned} \tag{28}$$

Note that the first term is the useful signal. The second term is the multiple access interfere (MAI) from the K-1 users except for the 1^th user. The third term is the noise interference.

Assuming the receiver is locked and synchronized and the integral time T is not more than the symbol interval T_s, so $\tau_1=0$, φ_1=0. Then, we have

$$z(t)=a_1d_1\cdot T+\sum_{i=2}^{K}a_id_i\int_0^T\sum_{i=2}^{K}I_{i1}(\tau_i,\varphi_i)dt+N(T) \tag{29}$$

where

$$I_{i1}(\tau_i,\varphi_i)=\cos(\varphi_i)\int_0^T PN_i(t-\tau_i)\cdot PN_1(t)dt \tag{30}$$

$$N(T)=\int_0^T n(t)\cdot 2PN_1(t-\tau_1)\cdot\cos(w_ct)dt \tag{31}$$

So the MAI $I_{i1}(\tau_i,\varphi_i)$ is mainly determined by the cross-correlation between the user codes. In practice, the codes are not perfectly orthogonal. So $I_{i1}(\tau_i,\varphi_i)$ is not equal to zero and will introduce performance degradation.

So we obtain the following results

$$(\frac{S}{N+I})_{out} = \left(\frac{S}{N+\sum_{i=1}^{K-1} I_i}\right)_{out} \tag{32}$$

$$= \left(\left(\frac{S}{N}\right)_{out}^{-1} + \sum_{i=1}^{K-1}\left(\frac{S}{I_i}\right)_{out}^{-1}\right)^{-1}$$

$$\left(\frac{S}{N}\right)_{out} = \left(\frac{S}{N}\right)_{in} \cdot \frac{R_{ss}}{R_b} \tag{33}$$

$$\sum_{i=1}^{K-1}\left(\frac{S}{I_i}\right)_{out} = \sum_{i=1}^{K-1}\left(\frac{S}{I_i}\right)_{in} \cdot \left(\frac{C_{auto}^{1}}{C_{corr}^{i1}}\right)^2 \tag{34}$$

where $(\frac{S}{N+I})_{out}$ is the output of the ratio of the signal and the sum of the noise and the MAI after despreading. $\left(\frac{S}{N}\right)_{out}$ is the output of the ratio of the signal and the noise after despreading. $\sum_{i=1}^{K-1}\left(\frac{S}{I_i}\right)_{out}$ is the output of the sum of all the ratios of the signal and the MAI after despreading. $\left(\frac{S}{N}\right)_{in}$ is the input of the ratio of the signal and the noise before despreading. $\sum_{i=1}^{K-1}\left(\frac{S}{I_i}\right)_{in}$ is the input of the sum of all the ratios of the signal and the MAI before despreading. R_{ss} is the code chip rate of the spread spectrum system. R_b is the data rate. C_{auto}^{1} is the auto-correlation value of the 1th user. C_{corr}^{i1} is the cross-correlation value between the 1th user and the ith user.

So the average bit error probability is

$$P_e = Q(\sqrt{\left(\frac{S}{N+\sum_{i=1}^{K-1} I_i}\right)_{out}}) \tag{35}$$

Substituting Eq. (32),(33) and (34) into (35), then gives the average bit error probability in the presence of the MAI.

$$P_e = Q(\sqrt{\left(\left(\left(\frac{S}{N}\right)_{in} \cdot \frac{R_{ss}}{R_b}\right)^{-1} + \sum_{i=1}^{K-1}\left(\left(\frac{S}{I_i}\right)_{in} \cdot \left(\frac{C_{auto}^{1}}{C_{corr}^{i1}}\right)^2\right)^{-1}\right)^{-1}}) \tag{36}$$

B. Simulation

Assuming the CDMA spreading codes use the balance Gold codes and the period is 1023. So the max absolute value of the cross-correlation value is 65 and the max auto-correlation value is 1023. Fig. 6 is the correlation performance of the spreading codes between the space links. It is clear that for the Gold codes, the auto-correlation value is 1023 and the cross-correlation values are 63,-65,-1. So the max absolute value of the cross-correlation values is 65.

Considering the most worst case, namely, the correlation values are always the max in the integral time T . Let $\left(\frac{S}{N}\right)_{in}$ =15dB, R_{ss} =5.115Mchip/s , R_b =4096bit/s, the input power of each MAI is the same , and each satellite has a telecommand channel and a ranging channel for uplink and a telemetry channel and a ranging channel for downlink, we simulate the bit error probability versus $\left(\frac{S}{I_i}\right)_{in}$ in the presence of the MAI from Eq. (36)and have plotted it in Fig. 7.

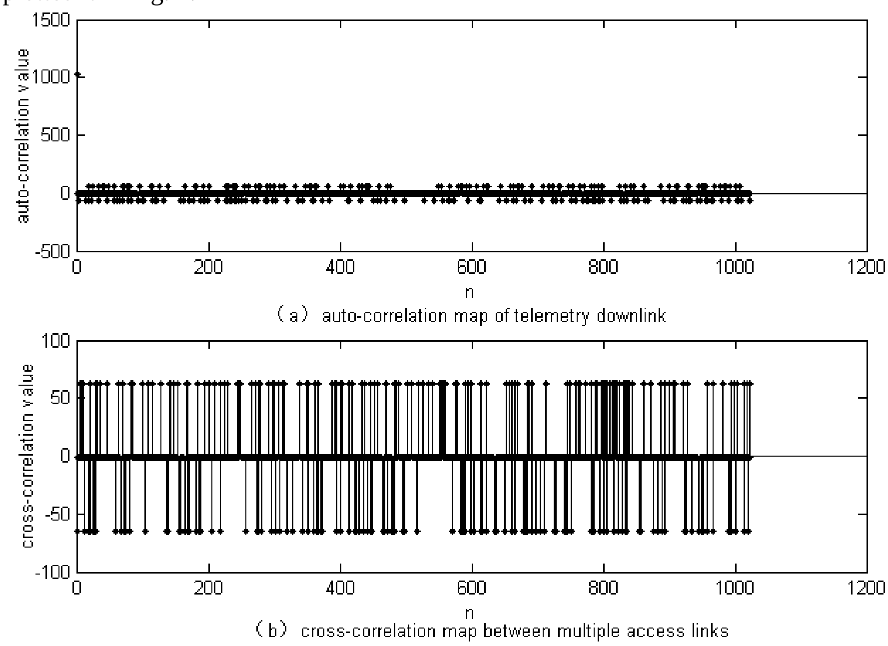

Figure 6. The correlation performance map between space links.

For the curves in Fig. 7, as the number K of the satellites increases, a larger bit error probability is achieved within the same $\left(\frac{S}{I_i}\right)_{in}$. When the bit error probability is 10^{-5}, $\left(\frac{S}{I_i}\right)_{in}$ is equal to -4dB with 3 satellites and -6dB with 5 satellites. In other words, for insuring the good signal receiving quality, $\left(\frac{S}{I_i}\right)_{in}$ of each MAL should be more than -4dB with 3 satellites and -6dB with 5 satellites. The multi-objective TT&C system has received the satellites' signals from the multiple-beam. The satellites' signals are distinguish with space division and code division. So the MAI power between the different satellites has been weaken by the space division. In Figure 3 and Figure 5, the peak power of the main lobe is higher 15dB than the side lobe at least. So totally considering, the multi-beam CDMA system can satisfy the multi-objective TT&C requirements and can reduce the MAI effectively.

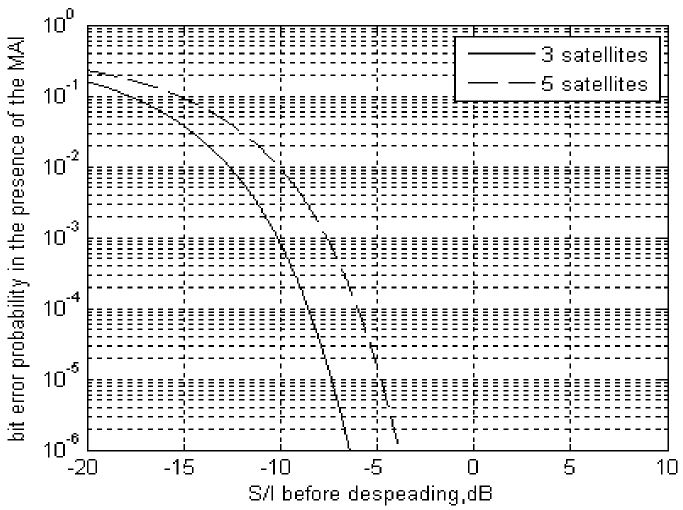

Figure 7. Worst case P_b versus $(S/I)_{in}$ in the presence of MAI with $\left(\frac{S}{N}\right)_{in}$ =15dB.

V. Conclusions And Future Work

Multi-objective TT&C is the key technology that needs to be broken through in the future development of the TT&C systems. In this paper a detailed research on the configuration design of the multi-objective TT&C system, the adaptive DBF algorithm and the analysis of the performance of the multi-objective TT&C system in the presence of MAI. Introducing multi-beam antenna using DBF technology and CDMA technology into the satellite systems can increase the tracking range and solve the difficult problem of the space multi-objective TT&C simultaneous.

The multi-objective TT&C system has the following advantages: 1) Adaptive multi-beam forming can control beam's direction and increase space multi-objective tracking ability. 2) Compared with the single beam CDMA, multi-beam CDMA system can reduce MAI power and yet achieve better signal transmission performance or quality. 3) Adopting CDMA and spread spectrum technology can increase the anti-jam ability. 4) Adopting CDMA and spread spectrum technology can realize telecommand, telemetry and range simultaneously in a single beam.

In the near future, with the speed of microprocessors increasing, adaptive DBF processing will have a quick calculation and realize a faster or real-time multi-satellite tracking. In addition, adaptive DBF is hope to have a further research on reducing the calculation amount.

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