DIGITAL COMPUTER SIMULATION OF MODERN AERONAUTICAL DIGITAL COMMUNICATION SYSTEMS

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Abstract

A Monte Carlo simulation method for modern aeronautical digital communication systems is described. Important results about the various effects on it are obtained. The various effects include filtering, limiting, carrier frequency offset, bit time jitter, and multipath effects in A/G and A/A communications.

I. Introduction

In this paper, a Monte Carlo simulation method for modern aeronautical digital communication systems is described. The objective of the simulation is to find the various effects on the system performance which is in terms of the bit error rate and the signal to noise ratio relations. The various effects include filtering, limiting, carrier frequency offset, bit time jitter, and the multipath effects in air-to-ground and air-to-air communications etc.

Because of the complexity of modern aeronautical communication systems, the analytical resolution of various effects on it is very difficult. But the Monte Carlo method is very helpful in solving this problem.

In the following sections, we shall describe the block diagrams of the typical communication system and its simulation, discuss the various effects in detail, and point out the important results obtained by the simulation.

II. Description of the Communication System and its Simulation Block Diagram

Let the typical aeronautical digital communication system under simulation is a 1 Ghz band, time division multiple access (TDMA) system using spread spectrum techniques and concatenated coding. The information data are encoded in a codeword with 32-bits and then modulated. The data rate of the channel is R=5 Mhz. A Monte Carlo simulation had been done for evaluating the modem performance under various effects on it.

The modulation method is minimum (frequency) shift keying (MSK).(1)-(3) Theoretically, its ideal performance is consistent with that of the optimal binary system— bi-phase shift keying (BPSK). MSK modulation takes the advantage of its power spectrum with rapidly falling side lobes. Recently, more attention has been paid to this new technique of modulation.(4)-(5)

The MSK modulation signal is a constant amplitude carrier with frequency (either f_1 or f_2) conveying information on it. Its central frequency is $f_c=\frac{1}{2}(f_1+f_2)$, and f_1, f_2 are spacing $\frac{1}{2}R$ apart. The phase of the carrier holds continuity when the frequency is changing. The wave-form of MSK signal is shown in Fig.1(c), and expressed by

$$y(t)= u \cos 2\pi(f_c \pm 1/4T_b)t \quad (1)$$

where $T_b=1/R$ is the bit time, and

$$f_c-1/4T_b= f_1 \quad (2)$$

$$f_c+1/4T_b= f_2 \quad (3)$$

$$f_2 - f_1 = 0.5/T_b \tag{4}$$

and u takes +1 or -1, its sign depending upon the fact that y(t) must hold the continuity of the phase when the frequency of the carrier is changing.

Expression (1) can be rewritten as follow,

$$y(t) = u_I |\cos 2\pi(t/4T_b)| \cos 2\pi f_c t \quad u_Q |\sin 2\pi(t/4T_b)| \sin 2\pi f_c t \tag{5}$$

where u_I, u_Q takes +1 or -1. There are proper relationships between u_I, u_Q and f_1, f_2 in the time sequence. It is evident that the two terms of (5) can be transmitted in the so called "I-channel" and "Q-channel" of the modem respectively. There is a 90 degree phase shift between these two carriers, and thier wave-form are shown in Fig.1 (a), (b). This is a special form of quadrature phase shift keying (QPSK), the envelopes of the carriers in the I-channel and the Q-channel are sinusoidal and staggered. It can also be called "offset QPSK" with sinusoidal envelope carriers in the I-channel and the Q-channel. But the offset QPSK in regular form is with constant envelope carriers in the I-channel and the Q-channel.

The power spectrum of MSK signal is shown in Fig.2 and expressed by

$$P(f) = \frac{16T_b}{\pi^2}\left(\frac{\cos 2\pi f T_b}{1-16f^2 T_b^{\,2}}\right)^2 \tag{6}$$

The bandwidth of the main lobe is $1.5/T_b$, and wider than that of QPSK. But its side lobes fall down rapidly (with f^{-4}), and more rapid than that of QPSK. The bandwidth containing 99% power is $1.17/T_b$, and the channel bandwidth used to transmit MSK signal can be much narrower than that. Later on, we shall show that even $0.6/T_b$ can be chosen with small degradation of the system performance.

The block diagram of the communication system under simulation is shown in Fig.3. The encoded data signal is sent to the time-division demultiplexer, which splits and staggers the signal and gives u_I, u_Q to the I-channel and the Q-channel repectively. Through the sinusoidal pulse shapers and the amplitude modulators, these two offsetting carriers in the I-channel and the Q-channel compose the MSK signal sent out after filtering and amplifying. With white Gaussian noise added, the signal is filtered and amplified by the receiver, and processed by demodulation, sampling and decision in the I-channel and the Q-channel, and recover the data stream by the time-division multiplexer.

The equivalent base band model shown in Fig.4 is used for digital simulation. The low frequency envelopes in I-channel and Q-channel are the real part and the imaginary part of the low frequency complex envelope $\tilde{S}(t) = S_I(t) + jS_Q(t)$ respectively.[6]

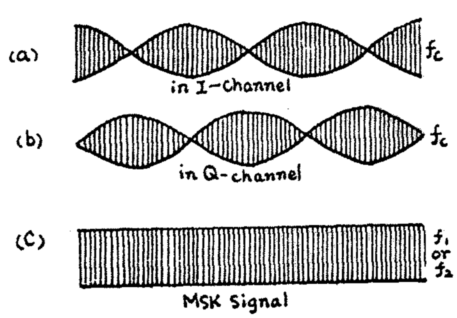

Fig.1. MSK signal and its components

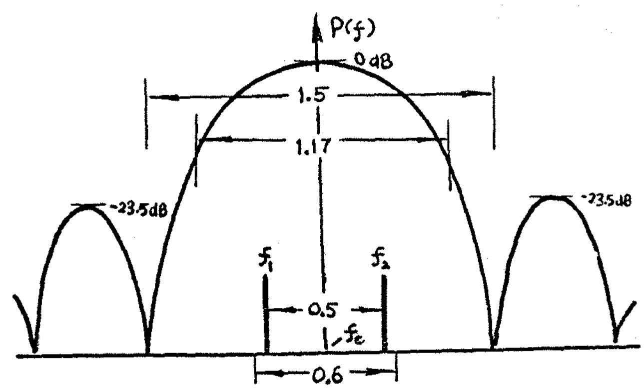

Fig.2. MSK signal power spectrum

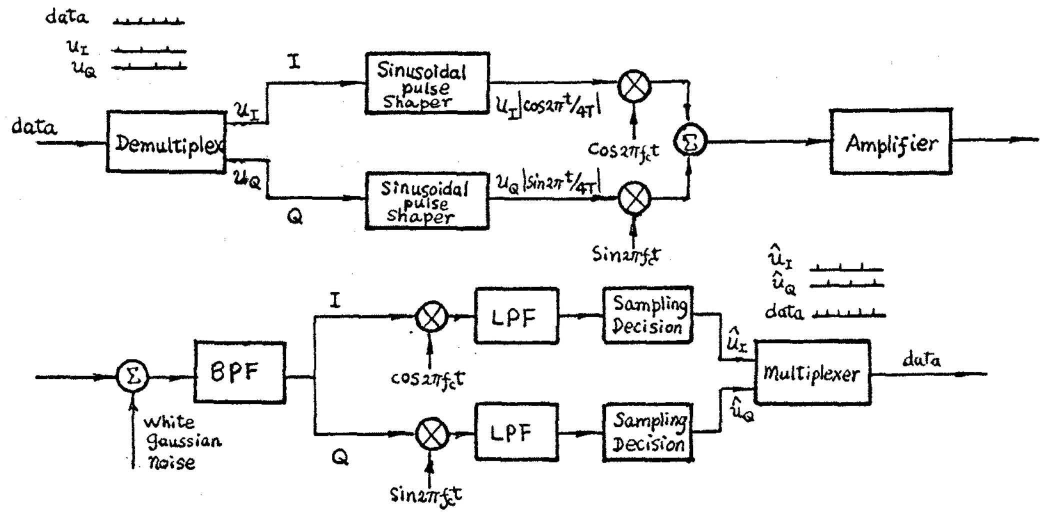

Fig.3. System block diagram

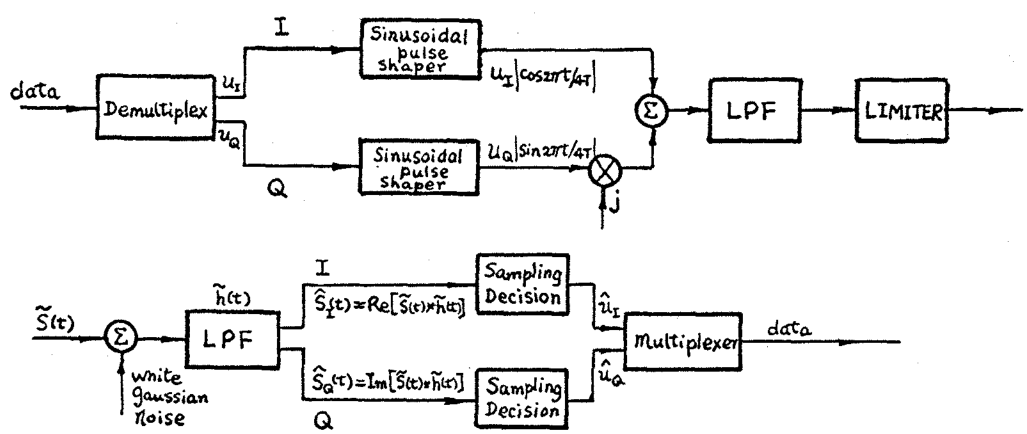

Fig.4. Model of based-band equivalence

Through the low pass filter and limiter, with the white Gaussian noise added, it passes to the low pass filter of the receiver. Because it must includes the case of existence of frequency offset, the asymmetrical low pass filter must be used. Its impulse response is in complex form.(7) After convolution, the real part of the filter output is the low frequence envelope $\hat{S}_I(t)$ in the I-channel, and the imaginary part, $\hat{S}_Q(t)$ in the Q-channel. After sampling and decision, $\hat{u}_I$, $\hat{u}_Q$ are recovered into the data stream by the time multiplexer.

The data rate is R=5 Mhz, i.e., T_b=200 ns. The sampling frequency f=40 Mhz is chosen. For the sake of the low side lobes character, MSK power spectrum at the folding frequency (20 Mhz) is at sufficiently low level (-48 dB). Each half period of the sine wave envelope is 400 ns, and the signs of them depend upon u_I and u_Q repectively. The decision points on the I-channel and the Q-channel are offsetting (see Fig.5).

In the hard decision case, $\hat{u}_I$ and $\hat{u}_Q$ takes +1 or -1 and decided by the sign of

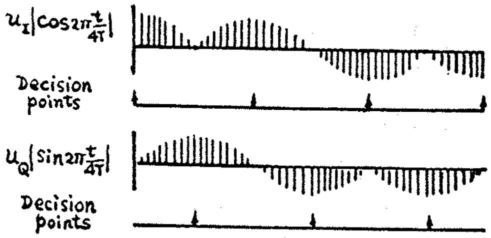

Fig.5. The low frequency envelopes

the values $\hat{S}_I(t)$ and $\hat{S}_Q(t)$ at thier decision points respectively.

In the soft decision case, a small region around the zero-level is selected. If the value of $\hat{S}_I(t)$ and $\hat{S}_Q(t)$ at thier decision points is fallen into this region, the output status of $\hat{u}_I$ and $\hat{u}_Q$ is "erasure". Otherwise they take +1 or -1. This will be done when using the auto-correlation function of the signal to achieve the detection gain.

The thermal noise is added before the receiver filter (see Fig.4). This is the case in the actual situation, but the computation work is time consuming because a great many times of convolution must be done for the decision making. It can also be added after filter and before the detector, for example, as it had been done in (8). Much time for computing the convolution of the noise can be saved in this case. But it is rather difficult to simulate the post-filter colored Gaussian noise exactly by the direct way. In this paper, the white Gaussian noise is added to the pre-filter point as shown in Fig.4. In order to reduce the time for computing, the convolution of the signal and of the noise are computed seperately. For the great many times of the noise computing, a direct convolution method is applied, only the convolution values at the decision points are computed. An order of the convolution time reducing can be achieved in this way.

III. Simulation for Various Effects on the Communication System

Filtering and Limiting

In the ideal case, MSK signal has a constant envelope. The magnitude of the complex envelope of it is $|\tilde{S}(t)| = \sqrt{S_I^2(t)+S_Q^2(t)}$. Because of the nonlinearity of the power amplifier, some distortion may occur. In order to simulate this effect, a limiter is used. As a matter of fact, it is a multiplier which multiplies a factor of $1/\sqrt{S_I^2(t)+S_Q^2(t)}$ whenever the signal passes through it.

It is of importance to choose the bandwidth of the communication system. It should not be too wide for the reason of frequency spectrum preservation, and on the other hand, it should not be too narrow, because the intersymbol interference will degrade the system performance. It had been pointed out by the fact that the main lobe of the power spectrum of the MSK signal is wider than that of QPSK and Offset QPSK.(5) And if bandwidth is narrower than $0.725/T_b$, the degradation of performance of MSK case will be slightly greater than that of QPSK and Offset QPSK*.

In this paper, low pass filters with linear phase reponse and Weber-Cappellini window are used.(9) An impulse response length of 65 is chosen, the transition band of its frequency response is small, and attenuation at stop band is greater than 60 dB. The filters of the same type are used both in the transmitter and the receiver.

The simulation results for various bandwidth are shown on the bit error rate P_e--E_b/N_o curves in Fig.6, where E_b is the signal energy for each bit, and N_o is the double-side noise power spectrum density. For the purpose of comparison, a P_e--E_b/N_o

* When 4-pole Butterworth filters are used.

curve of the ideal MSK system without bandlimiting is also shown in Fig.6. This curve is consistent with that the case of optimal binary system—BPSK, $P_e = \frac{1}{2}[1-\mathrm{erf}(\sqrt{2E_b/N_o})]$. As the bandwidth decreases, P_e will increase and the degradation of system becomes greater. It can be seen that in the case $\Delta f=0.6/T_b$, the performance degradation is slightly greater than that for $\Delta f=1.0/T_b$. But in the case of $\Delta f=0.5/T_b$, the performance degradation will increase rapidly. By comparing with the ideal MSK system without bandlimiting at $P_e=10^{-6}$, degradation for $\Delta f=1.0/T_b$ system performance is about 0.6 dB, and for $\Delta f=0.6/T_b$ is about 1.5 dB, which is acceptable.

Carrier Frequency Offset

Frequency offset of the carrier is always unavoidable because of Doppler frequency shift and some circuit detuning. An asymmetrical low pass filter (Fig.7d) is derived from the original symmetrical one (Fig.7c) in the base band. Let $\tilde{h}_L(t)$ be the impulse response of the original filter. For the asymmetrical one, $\tilde{h}(t) = \tilde{h}_L(t)e^{-j2\pi\delta ft} = p(t)+jq(t)$, where δf is the carrier frequency offset. This filter is also called the complex filter. In the discrete case, the impulse response is $h(n)e^{-j2\pi n\,\delta f/f_s}$, where $\delta f/f_s$ is the ratio of the frequency offset to the sampling frequency.[10]

The output of the complex filter is

$$\begin{aligned}\tilde{S}(t)*\tilde{h}(t) &= [S_I(t)+jS_Q(t)]*[p(t)+jq(t)] \\ &= S_I(t)*p(t) - S_Q(t)*q(t) \\ &\quad +j[S_Q(t)*p(t)+S_I(t)*q(t)] \qquad (7)\end{aligned}$$

where * denotes the operation of convolution. The real part of the output of the complex filter is passed through the I-channel of the receiver, while the imaginary part of it, the Q-channel.

In general, the frequency offset δf is rather small, $q(t)$ is small, and $p(t)$ is the main part of the impulse response of the complex filter. $S_Q(t)*q(t)$ and $S_I(t)*q(t)$ represent the internal interference "cross-talk" between the I-channel and the Q-channel.

Simulation is done for various frequency offset under system bandwidth $\Delta f=0.6/T_b$, and the results are shown in Fig.8. It

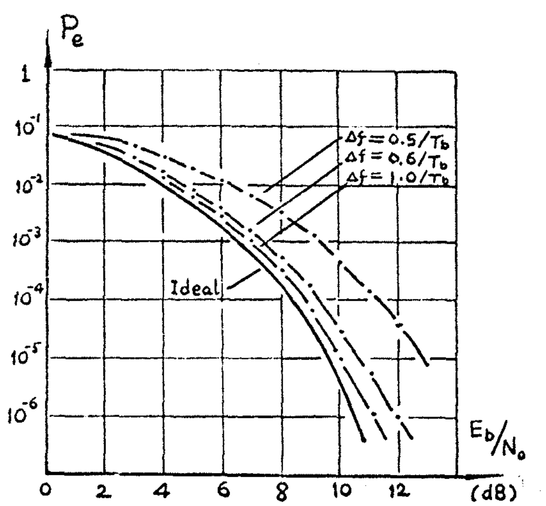

Fig.6. Bit error rate P_e—E_b/N_o curves for various bandwidths.

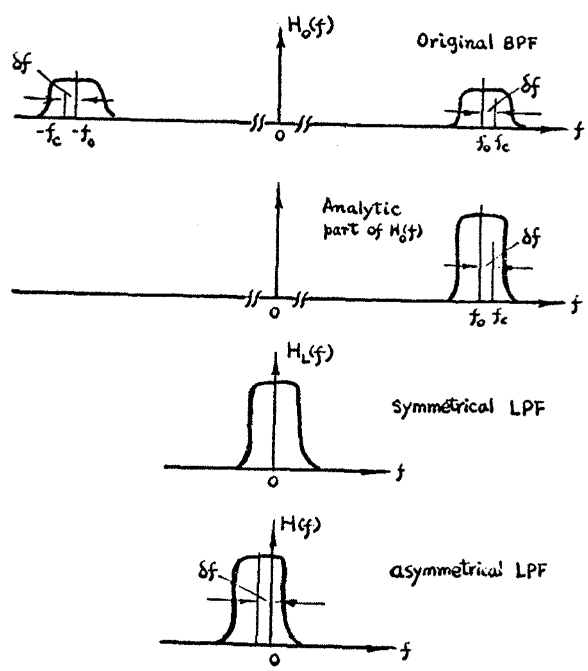

Fig.7. Asymmetrical L.P.F. and its original symmetrical L.P.F.

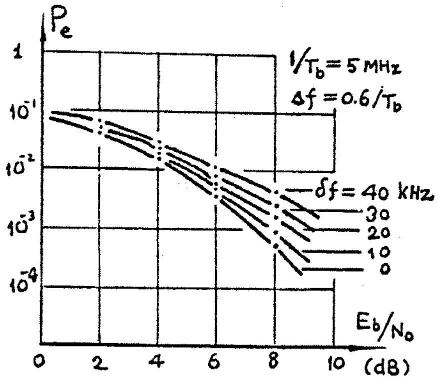

Fig.8. Bit error rate P_e—E_b/N_o curves for various frequency offset.

can be seen that the larger the frequency offset, the greater is the performance degradation. As δf=10 khz, it causes only a little performance degradation. As the Doppler Frequency shift is of the order of 1 khz, it will not cause much degradation. In fact, this communication system is of wide-bandwidth nature, it is not susceptible to small frequency drifts.

Bit Time Offset and Jitter

It simulates the imperfection of the bit timing and is to find its effects on system performance. When the bit time offsets are within ±25 ns (that is one-eighth of the bit time), there is no significant performance degradation.

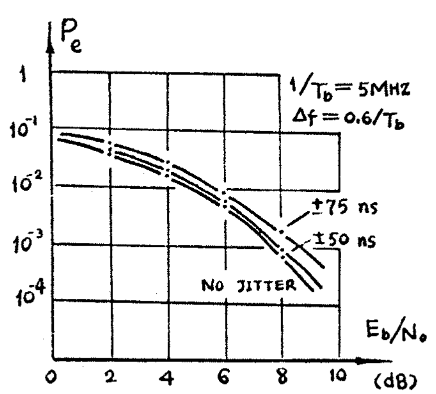

Fig.9. Bit error rate P_e—E_b/N_o curves for various bit time jitter.

Some simulation results for bit time jitter with various bit time swinging amplitude under $\Delta f=0.6/T_b$ are shown in Fig.9. When the jitter amplitude is ±50 ns, (that is one-fourth of the bit time), there is some performance degradation. This fact must be taken into account in the communication system designing.

Multipath Propagation

In the 1 Ghz band, there are two main paths of the radio wave propagation, the direct ray and the earth reflected ray.(11) Some of the two-path time delay difference in the air-to-ground and air-to-air communications are shown in table 1 and table 2 respectively*. The reflected coefficient of the earth reflected wave is depending

Airborne Altitude(m) \ Distance(km)	50	100	200	400
20 000	27	13	6.0	1.7
10 000	13	7.0	3.0	0.1
5 000	6.7	3.7	0.5	—

Table 1. Two-path time difference in nano-second for A/G communications (at ground antenna height 10 m)

Airborne Altitude(m) \ Distance(km)	50	100	200	400
20 000	47	26	13	5.2
10 000	13	6.0	3.0	0.1
5 000	3.3	1.6	0.7	0.1

Table 2. Two-path time difference in micro-second for A/A communications (Two aeroplanes on the same altitude)

* The culvature of the radio waves in the atmosphere is considered here, assuming that the equivalent earth radius is 4/3 earth radius.

upon the earth surface condition and the polarization direction of the radio waves. Simulation has been done for various ratios of the amplitude of the two-path waves, and the worst case that the 180 degree phase difference between them has been considered.

Some simulation results under $\Delta f=0.6/T_b$ condition are shown in Fig.10. The two-path amplitude ratio equals to 0.3 under the worst phase condition. It can be seen that, when the delay time difference of two-path τ=50 ns (i.e. one-fourth of the bit time), the performance degradation takes the maximum value. It is referred to as the worst case.

In air-to-ground communications (see table 1, for example), evident performance degradation occurs at the short distance. But it is not very harmful to communication because the signal is rather strong at this range.

In air-to-air communications (see table 2, for example), evident performance degradation occurs at the fringe area of the line of sight communication. For system design, this effect can not be neglected.

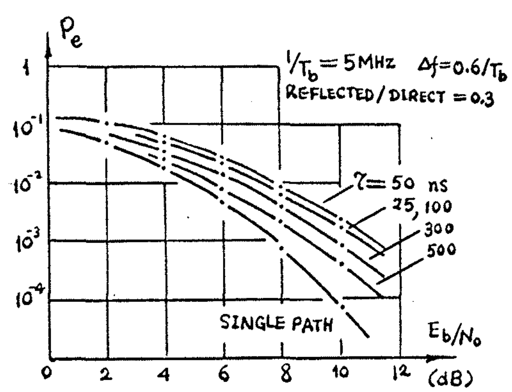

Fig.10. Bit error rate P_e--E_b/N_o curves for various earth reflected rays

Multiple Effects

Simulation for many effects acting on the system simutaneously has been done. For example, the multiple effects are as follows: limiting and filtering with system bandwidth $\Delta f=0.6/T_b$, carrier frequency offset 5 khz, bit time jitter with $\pm$50 ns, multipath effect of signal amplitude ratio of earth reflected ray to direct ray is 0.2 and time delay difference between them is 25 ns.

The total effect on the system performance is illustrate in terms of P_e--E_b/N_o curve in Fig.11. By comparing with the ideal case, the system degradation at $P_e=10^{-6}$ for the total effect is about 4 dB.

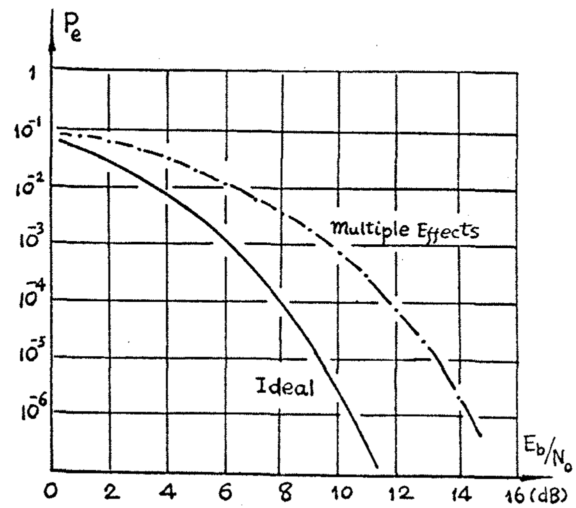

Fig.11. Bit error rate P_e--E_b/N_o curve for multiple effects.

From this example, we can see the flexibility of the Monte Carlo method. It is also helpful in solving the problem even for such a complicated case.

IV. Conclusion

The Monte Carlo simulation for modern aeronautical digital communication systems has been done. One can predicts the effects of various factors on the complex systems.

The results of simulation are useful for system design. From the above discussion, one can see the effectiveness and flexibility of this Monte Carlo method. It is believed that not only helpful to system design, but can also indicate the effectiveness of the new concepts of the communication techniques.

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