An Adaptive Transmission Scheme for Deep Space Communication

SUN Zezhou[1], *WANG Le*[2*], *WANG Chenghua*[2], *ZHU Qiuming*[2], *ZHANG Xiaofei*[2], *LIU Weiqiang*[2], *LI Xiangyu*[2]

1. Institute of Spacecraft System Engineering, China Academy of Space Technology, Beijing 100094, P.R. China;
2. Key Laboratory of Radar Imaging and Microwave Photonics of Ministry of Education, College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China

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Abstract: Deep space communication is quite different from conventional ground communication due to its time-varying, complexity and large signal delay, which consequently affects communication quality and system efficiency. Adjusting the transmission parameters when the channel environment changes during the communication can guarantee the performance index of the system, and therefore improve communication efficiency. An adaptive transmission scheme of transceiver based on Consultative Committee for Space Data Systems (CCSDS) protocols is proposed in this paper. According to the variation of the deep space channel, the symbol rate of transmission data is adjusted dynamically by estimating the signal-to-noise ratio (SNR) of the receiver in real time and adjusting the channel environment. This scheme can improve the channel utilization and system throughput under the premise of limiting the system bit error rate. Furthermore, this scheme is successfully implemented in Xilinx Virtex-5 FPGA board.

Key words: deep space communication; adaptive; signal-to-noise ratio (SNR) estimate; Consultative Committee for Space Data Systems (CCSDS)

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0 Introduction

As space technology keeps progressing, many countries has deployed space exploration. In order to make the multi-spacecraft missions feasible, the Consultative Committee for Space Data Systems (CCSDS) was established by the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) [1] in early 1980s. According to the characteristics of deep space communication, CCSDS proposed the Proximity-1 Space Link Protocol[2-4], which aims at a unified standard to regulate communication protocols, data exchanges and processing among spacecraft, spacecraft and ground equipment. It also promotes cooperations among countries and space organizations.

According to the definition of International Telecommunication Union (ITU) Radio Regulations, the transmission distance of the terrestrial space is less than 2×10^6 km, while the distance of deep space communication is greater than or equal to it. Because of its far communication distance, the signal of deep space communication is weak, and the delay is not stable. Therefore, how to improve the quality of deep space communication is critical, especially in the premise of limiting the transmission bit error rate (BER) to improve the system throughput.

In the field of wireless mobile communications, the adaptive signal processing is widely used to improve system communication quality by adaptively changing signal power, transmission rate, and coding modulation, etc[5]. The adaptive transmission strategy can adaptively change the transmis-

*Corresponding author, E-mail address: nuaa2015wl@nuaa.edu.cn.

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sion parameters to adjust to the characteristics of the channel in the time domain and the frequency domain. The system transmits at a faster data rate when the channel quality is better or improves the anti-interference ability of the data and reduces the system bit error rate (BER) when the channel quality is poor, thus finally improves the communication performance. In order to adjust to the complex channel environment of deep space communication, the signal transmission parameters can be changed in real time according to the channel condition, therefore to improve the performance of communication systems[6]. This paper combines the requirements of the proximity-1 space communication protocols to design a symbol rate adaptive transmission system scheme that meets the requirements of the CCSDS protocol. The scheme can solve the problem of poor communication quality and low system efficiency by using fixed rate in deep space communication environment and by adjusting the transmission symbol rate to the optimal state under the premise of satisfying the requirement of system BER. It can provide a useful reference for the design of the deep space communication digital transponder.

1 Deep Space Communication Characteristics and Scheme Description

Proximity space communication link refers to a short, two-way, fixed or mobile wireless link that is commonly used for communications between probes, landers, monitors, orbital constellations, and orbital relay satellites. The proximity space link has short delay and moderate signal power. This is suitable for short and functionally independent communications. When the characteristics of the deep space communication environment is involed, the performance of the communication system will be affected. The uplink and downlink communication links are asymmetric in the channel. The impact of communication discontinuities is also challenging.

Compared to the traditional link communication protocol, the CCSDS Proximity-1 Link Protocol has an obvious advantage that it supports real-time tuning of physical parameters during communication[7]. The Proximity-1 Link Protocol can change the parameters in real time through the "handshake" process, and the "handshake" is absolutely necessary before user data transmission.

In a proximity space wireless communication system, the channel condition is time-varying. The channel capacity and the signal-to-noise ratio (SNR) of the receiver will change at random. When using the same transmission mode, the communication system is unable to meet the change in channel conditions, thereby restricts the quality of data transmission. The basic principle of adaptive transmission is to enhance the channel utilization, to reduce BER and to improve the system throughput by changing the parameters such as the transmission power, the symbol rate, the modulation mode, the encoding mode, and the frame length.

By estimating the changes in the channel, the adaptive transmission scheme changes the transmission rate of the transceiver of the communication system in real time. When the communication link channel quality is satisfying, the adaptive transmission system upgrades symbol rate to improve throughput. When the channel condition is poor, it drops the symbol rate to reduce the BER. Meanwhile, the spectrum utilization can also be improved. There are several ways to change the transmission rate. The first is to change the symbol rate[8]. The second is to change the modulation mode[9-10]. The third is to change the encoding mode[11-12]. This paper focuses on the analysis and design of the first method.

The adaptive transmission scheme is a hardware of a closed loop simulation verification system. To adapt to the instable and changeable environment of space communication, the scheme uses the channel simulation unit to simulate Inter device communication link environment and provides test signal source for communication devices. The scheme carries out data transmission with designed BER and simultaneously changes the transmission rate according to the channel in real time.

2 Adaptive Transmission System Model

According to the characteristics of deep space communication environment between inter device communication links, under the Proximity-1 Link protocol[13-14], this paper presents a semi physical simulation system scheme for inter device communication of deep space exploration in ultra high frequency (UHF) band. The semi physical simulation system integrates transmitters, receivers, and control modules. The radio software of digital communication incorporates a general digital deep space transponders through the FPGA or DSP device with strong programming ability. In this paper, the adaptive transmission scheme is verified by the FPGA hardware circuit and implemented using Xilinx Virtex-5 FPGA chip (i.e., XC5VSX95T). The logic synthesis and layout routing of FPGA is performed in ISE 12.2. The BER requirement designed for this system is 1×10^{-6}. The schematic diagram of the semi physical simulation system is shown in Fig.1.

The protocol transmitting unit generates an intermediate frequency signal that then goes into the proximity space channel simulation unit. The channel simulation unit of the semi physical simulation system connect under short-circuit condition corresponds to the absence of channel conditions. The output signal is passed through a band-pass filter and an amplifier. Next, an up mixing is made to the radio frequency (RF) and the channel propagation attenuation is simulated. Then, the received radio frequency signal is mixed down to intermediate frequency and the mirror frequency is filtered out. Finally, the protocol receiver unit demodulates the signal and evaluates the performance of the signal.

The protocol baseband transceiver unit is a communication subsystem, which is based on a hardware platform. Each communication subsystem contains a transmitter and a receiver for baseband signal processing. By simulating the variation of radio wave propagation characteristics of aircraft in deep space environment, the channel simulation unit can provide test signal source for communication devices of the surround and Lander. The channel simulation unit is used for simulating Inter device communication link environment.

As a special scene of wireless communication, deep space channel has the general characteristics of wireless channel, including propagation loss, channel fading and noise interference. Doppler effect is also one of the influencial factors because of the huge relative motion between stars in the universe. It is noticed that the wireless mobile channel is usually based on the multipath component model, while the number of deep space communication links is much less. In addition, the speed and the range of the motions of deep space spacecraft are much larger than those of traditional transceivers. The test signal source of the channel simulation unit can be modeled as

$$y(t)=\sum_{l=0}^{L(t)}\alpha_l(t)\beta_l(t)\mathrm{e}^{-\mathrm{j}\phi_l(t)}x(t-\tau_l(t))+n(t) \tag{1}$$

where $\alpha_l(t)$ represents the propagation loss of each path, which is up to propagation distance, frequency, scene and other factors; $\beta_l(t)$ the time varying channel fading envelope of each path, which relies on shadow fading and small scale fading; $\varphi_l(t)$ the time varying phase rotation of each path, which depends on the time delay and the Doppler frequency shift; $\tau_l(t)$ the time varying delay of each path, which is affected by the propagation scene; and $n(t)$ the channel noise, which indicates system thermal noise and stellar noise.

This model considers the communication links and the speed and the range of spacecraft motions in

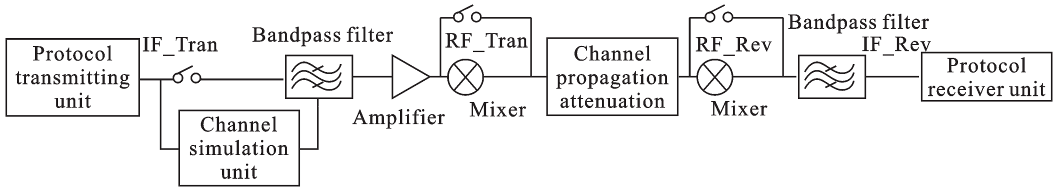

Fig. 1 The semi physical simulation system

deep space. The deep space communication channel environment is simulated in the channel simulation unit, such as the number of channels, the number of multipaths, multipath delay, channel attenuation, Doppler frequency shift and Doppler spread, and the simulation is in accordance with the expected channel theory model.

When data is transmitted in the system, proximity link transmission unit (PLTU) is the basic unit of data transmission. The length of PLTU is variable. It consists of the attached synchronization marker (ASM)、Version-3 transfer frame and 32-bit cyclic redundancy check (CRC). The data field of Version-3 transfer frame can be divided into service data unit (SDU) and supervisory protocol data unit (SPDU). The frame format of SPDU contains the control information of the physical layer, such as modulation mode, and data rate, etc. The length of SPDU can be fixed or variable. This paper uses a variable length. The SPDU data field contents are shown in Table 1. The transmitter and the receiver can be identified by the value in the directive type field contained in the 13th—15th bit . The data rate in the 3rd—6th bit is used to set transmitter and receiver rates.

Table 1 Transmitter parameter directive

Parameter	Mode 3 b	Data rate 4 b	Modulation 1 b	Data encoding 2 b	Frequency 3 b	Directive type 3 b
Bit	0—2	3—6	7	8—9	10—12	13—15

According to the CCSDS Proximity-1 link protocol, if either part in the process of communication requests changing parameters, the local transmitter interrupts the transmission of SDU and switches to the state of transmitting parameter directive. If the remote receiver fails to receive SPDU, the local transmitter will resend it due to timeout until the remote receiver receives SPDU correctly. At the same time, if either part receives SPDU, it changes the parameters of the local transmitter and receiver according to the received parameters directive. After changing the parameters successfully, the local transmitter switches to the state of transmitting user data. The adaptive transmission scheme for deep space communication systems is proposed and shown in Fig.2.

Firstly, the local receiver estimates SNR of the signal which is output from frame synchronization, and compares its estimation with the reference value. The comparison result maps the rate control words, which are sent to the local transmitter. The local transmitter completes the framing of SPDU. When the local transmitter detects that SPDU is prepared, the working mode will be switched on. Next, the local transmitter stops sending SDU and begins sending SPDU. The remote receiver obtains the data rate, which is extracted from SPDU. Then, the remote transmitter and the receiver change the data rate. Finally, the local receiver resets the data rate, and the rate of the local receiver and the remote transmitter is matched. The remote transmitter begins transmitting the carrier wave, and then begins sending the capture sequence. After carrier synchronization and symbol synchronization are completed, the communication link is restored.

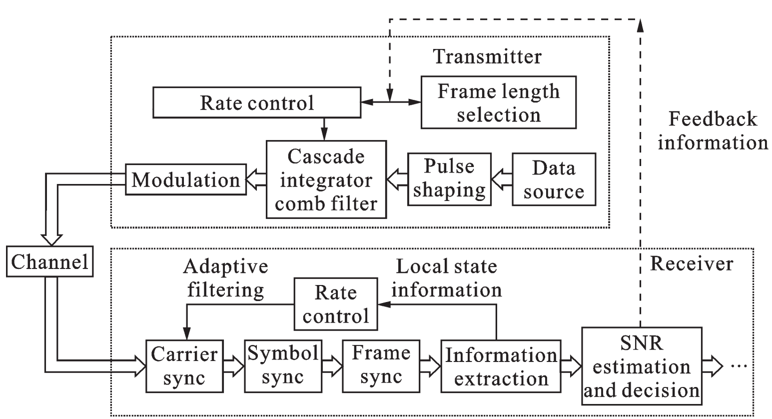

Fig. 2 The proposed adaptive transmission scheme for deep space communication system

The adaptive transmission systems adjust to the corresponding transmission data rate.

3 Rate Adaptation Algorithm

In this paper, the rate adaptive transmission scheme is based on changing symbol rate. In deep space communication, the quality of channel can be reflected by SNR of the receiver. Therefore, a new algorithm for SNR estimation with low complexity is proposed to conform to the requirements of the system. The rate is switched dynamically by comparing the estimation with the threshold that is set by the requirement of the actual communication system. In addition, the difference of the throughput performance is analyzed by comparing this scheme with conventional fixed rate methods.

3.1 SNV_DF estimation

There are several classical SNR estimation algorithms, such as, the second and fourth-order moments (M2M4) estimation[15], the signal-to-variation ratio (SVR) estimation[16], the square signal and noise variance (SNV) estimation[17] and the data fitting (DF) estimation[18]. Among them, SVR and M2M4 are better than SNV and DF in terms of performance. However, they are also more difficult to implement in hardware due to the expensive biquadrate and square root operations. Besides, quadratic and cubic polynomial can be used in DF instead of quintic polynomial. In this work, the SNV and DF estimation algorithms are combined to estimate SNR, and its basic principle is shown in Fig.3.

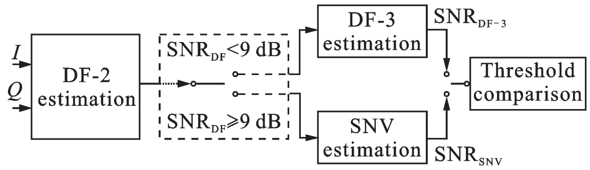

Fig. 3 SNV_DF estimation

Based on the DF estimation algorithm, the signal received by the transceiver can be represented as

$$x(n)=s(n)+v(n)=A\alpha(n)+v(n) \tag{2}$$

where $s(n)$ is the constellation signal; $v(n)$ the additive white Gaussian noise with zero mean and σ^2 variance; A the amplitude of the signal, and $\alpha(n)$ the constellation mapping point.

The received signal can be divided into two orthogonal signals of I and Q and expressed as

$$x_{I/Q}(n)=\pm A+v(n) \tag{3}$$

The SNR expression of the real and imaginary parts of the signal is described as

$$\mathrm{SNR}_{I/Q}=\frac{Re\left(\left|A\alpha(n)\right|^2\right)}{\sigma^2}=\frac{Im\left(\left|A\alpha(n)\right|^2\right)}{\sigma^2}=\frac{A^2}{\sigma^2} \tag{4}$$

We can find out that SNR of the entire complex signal is the same as the SNR of the real part and the imaginary part, and only one of the ways needs to be estimated. And a variable is defined as

$$z=\frac{E\left[x_{I/Q}^2(n)\right]}{E^2\left[\left|x_{I/Q}(n)\right|\right]} \tag{5}$$

Assuming that the signal and noise are independent of each other and satisfy the random distribution process, we can get that

$$E\left[x_{I/Q}^2(n)\right]=E^2(x_{I/Q}(n))+\mathrm{Var}(x_{I/Q}(n))=A^2+\sigma^2 \tag{6}$$

$$E\left[\left|x_{I/Q}(n)\right|\right]=\frac{1}{\sigma}\sqrt{\frac{\pi}{2}}\mathrm{e}^{-\frac{A^2}{2\sigma^2}}+A\left[\mathrm{erf}\left(\sqrt{\frac{A^2}{2\sigma^2}}\right)\right] \tag{7}$$

From Eqs.(4)—(7), we can get

$$z=\frac{1+\lambda}{\left\{\sqrt{\frac{2}{\pi}}\mathrm{e}^{-\frac{\lambda}{2}}+\sqrt{\lambda}\left[\mathrm{erf}\left(\sqrt{\frac{\lambda}{2}}\right)\right]\right\}^2}=f(\lambda) \tag{8}$$

By solving the inverse function of Eq. (8), SNR can be estimated as

$$\lambda=f'(z) \tag{9}$$

In this scheme, DF-2 and DF-3 polynomials are used for data fitting. The expression can be described as

$$\lambda=-196.238\,192\,866\,11z^3+766.680\,537\,499\,06z^2-1\,019.120\,183\,683\,80z+464.668\,628\,515\,33 \tag{10}$$

$$\lambda=7.954\,671\,851\,172\,83z^2-46.679\,013\,283\,835\,83z+51.545\,297\,241\,807\,40 \tag{11}$$

Above 5 dB, the performance of SNV estimation is close to SNR standard value. Below 10 dB, the performance of DF estimation is approximate to the standard value. The complexity of DF-2 polynomials is lower, so it can be used to estimate the rough range of the SNR. DF-3 can be used when the SNR is below 9 dB, while SNV is used when the SNR is over 9 dB. The SNV_DF estimation is similar to the standard value, meeting the accuracy requirements of the SNR estimation. The joint estimation method can significantly reduce the complexity and hardware cost.

Fig.4 compares performances of SNV_DF and M2M4. It can be seen that the performance of the joint estimation of SNV and DF is close to that of the M2M4 estimation, and it is consistent with the actual SNR.

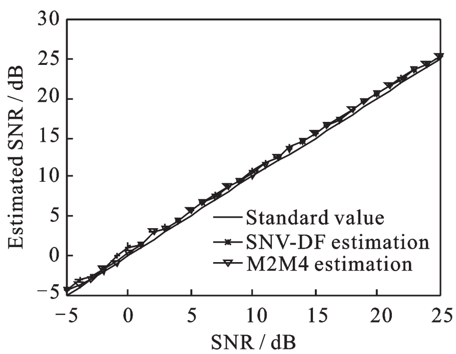

Fig. 4 Performance comparison of SNV_DF and M2M4

3.2 Threshold of rate adaptation

The selection for the SNR threshold of rate switching is mainly based on the system BER. At one rate, according to the relationship between the BER and the output SNR, we can identify the output SNR threshold value of the current rate. Similarly, the threshold values for different rates can be determined. When one rate is twice bigger than the other, the difference of their thresholds is 3 dB. In the actual transmission process, when the difference between the estimated SNR and the theoretical value corresponds to the system BER, we can determine the rate that should be switched to.

The symbol rate of the system is divided into 12 levels in a range of 1—2 048 kb/s (i.e., 1 kb/s, 2 kb/s, 4 kb/s, ⋯, 2 048 kb/s). Fig.5 shows the relationship between the BER and the output SNR of the quadrature phase shift key (QPSK) signal in the additive Gauss white noise channel. According to the matlab simulation results, when the system BER is 1×10^{-6}, the corresponding SNR is required to reach 15.5 dB without error correction.

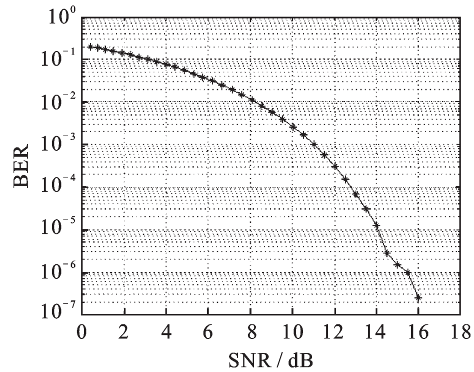

Fig. 5 Relationship between BER and the output SNR

Fig. 6 shows the input SNR and the output SNR of QPSK signal with 12 symbol rates. The input SNR is the channel attenuation produced by the channel simulation unit. It is used for simulating the signal attenuation caused by various noises and propagation losses in Inter device communication environment. The signal passes through the channel simulation unit. The protocol receiver unit demodulates the signal and evaluates the performance of the signal to get the output SNR.

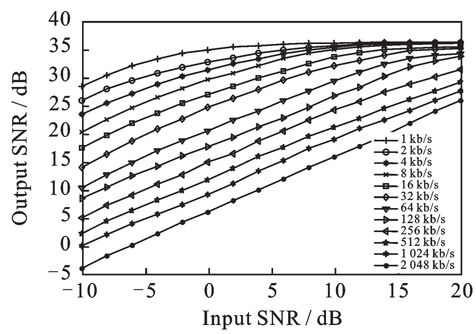

Fig. 6 Relationship between the input and output SNRs of QPSK signal with 12 symbol rates

It can be seen that the output SNR of QSPK signal increases when the symbol rate decreases, and the difference of SNR in two adjacent rates is close to 3 dB. Therefore, by calculating the difference between the estimation of SNR and 15.5 dB, the rate is increased or decreased to ensure the difference is within 3 dB so that BER can satisfy the system requirement during the actual data transmission. The adaptive rate expression formula can be modeled as

$$\text{rate}_{\text{esti}} = \begin{cases} \text{rate}_{\text{curr}} + \text{floor}\left(\dfrac{\text{SNR} - 15.5}{3}\right) & \text{SNR} \geqslant 15.5\ \text{dB} \\ \text{rate}_{\text{curr}} - \text{ceiling}\left(\dfrac{15.5 - \text{SNR}}{3}\right) & \text{SNR} < 15.5\ \text{dB} \end{cases} \tag{12}$$

where $\text{rate}_{\text{curr}}$ represents the current symbol rate of transmission data. $\text{rate}_{\text{esti}}$ the estimated symbol rate; floor(x) the rounding down function. and ceiling(x) the rounding up function. When the SNR is less than 15.5 dB, the system will decrease the symbol rate. When the SNR estimation is higher than 15.5, the system will maintain or increase the symbol rate.

3.3 Rate switching principle

There are two basic ways of rate switching. One is the step jump and another is the direct jump. Step jump method is based on the estimated SNR and the threshold value. When the SNR is less than the threshold, the rate will drop one level, and vice versa. While the direct jump method calculates the difference between estimation and threshold, then finds out the direct level that the look-up table should jump to, which is depicted in Fig.6. However, in long-distance communication, when the channel condition changes frequently, too many step jumps can easily cause the clock jitter of the device and lead to instability of the system. Therefore, in this work, direct jump method is used to switch rates adaptively.

Based on the above principle, the rate switching for the transceiver is shown in Fig.7. The way of rate switching is mainly embodied in two aspects, namely, changing the interpolation and extraction factors of cascade integrator comb (CIC), and changing the data clock. According to the received state information, the ratio of the signal sampling rate and the symbol rate can remain unchanged after the CIC filter.

3.4 Performance analysis of throughput

During the actual transmission process, switching the symbol rate affects the throughput of the deep space communication system. Assuming the transmitted symbols are independent and identical distribution, R represents the symbol rate and its unit is b/s; P the SNR. Thus the throughput (T) in the unit time can be expressed as

$$T = R*(1-P)^{R} \tag{13}$$

In one period, R can be estimated by the average rate of transmission, that is

$$\overline{R} = \frac{R_1\tau_1 + R_2\tau_2 + \cdots + R_n\tau_n}{\tau_1 + \tau_2 + \cdots + \tau_n} \tag{14}$$

where $\bar{R}$ is the average rate of the statistical time; $R_1, R_2, \cdots, R_n$ are the rates that corresponding to τ_1; $\tau_2, \cdots, \tau_n$. The total time of the statistics process is $T = \tau_1 + \tau_2 + \cdots + \tau_n$.

Suppose that the channel remains stable for a

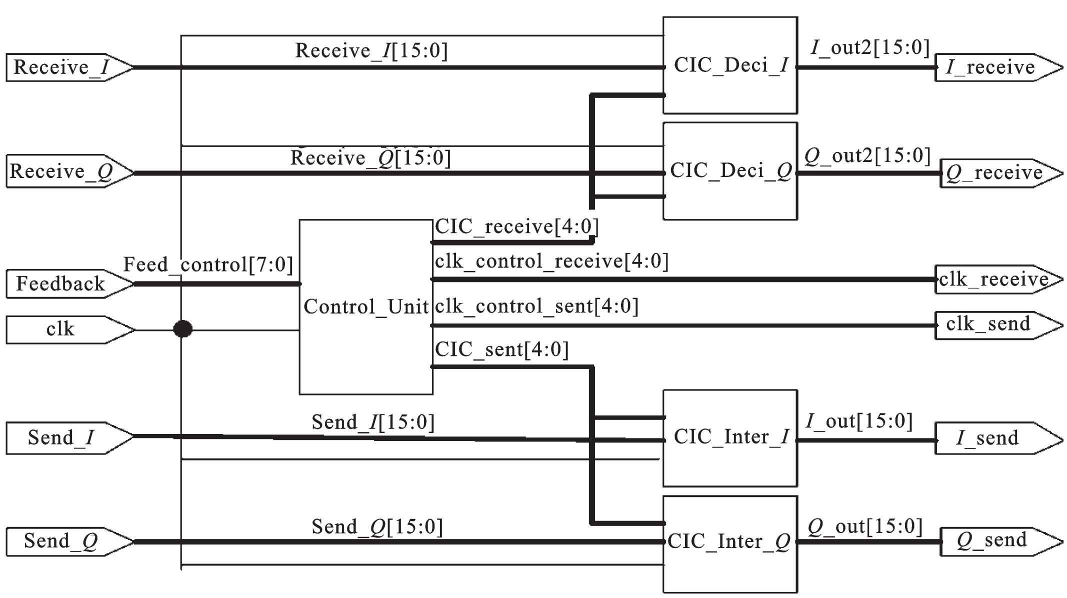

Fig. 7 Rate switching for transceiver

duration of 1 s in the statistical process. The following assumptions are used for the simulation. Update cycle time is 1 s; the modulation mode is QPSK; the noise is Gaussian white noise; and the SNR threshold is 15.5 dB. The initial symbol rate are 256 kb / s and 512 kb / s, and statistics time of throughput is 10 s. Figs.8, 9 show the data throughput with different SNR curves of the two initial symbol rates.

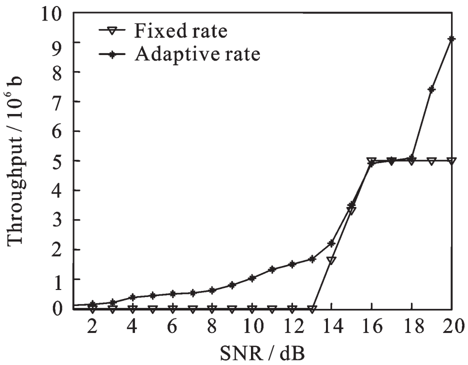

Fig. 8 Relationship between the throughput and SNR (with symbol rate=256 kb/s)

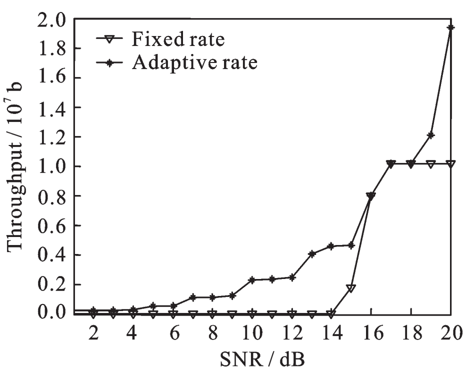

Fig. 9 Relationship between throughput and SNR (with symbol rate=512 kb/s)

It can be seen that the throughput performance using adaptive transmission rate is much better than the fixed rate in terms of the two initial rates. With the increase of SNR, throughputat the adaptive rate is different from that at the fixed rate. When SNR is less than the threshold, the throughput of the adaptive adjustment is better than the fixed rate. When SNR gradually approaches the threshold, and exceeds the threshold of 15.5 dB but still less than 18.5 dB, the adaptive symbol rate is the same as the fixed process, so the throughput performance is coincident. When SNR is higher than 18.5 dB, the adaptive adjustment process will automatically increase the transmission rate and can keep a low bit error performance while ensure the high efficiency of the transmission. In addition, the size of the initial rate also affects the throughput performance. Under the same SNR condition, the throughput of the initial rate with 512 kb / s is higher than that with 256 kb/s.

In the two initial symbol rates with the 6.5 dB and 19 dB, the curves of rate values and SNR versus time are shown in Figs. 10, 11. It can be seen that when the initial SNR is less than the threshold value of 15.5 dB, the symbol rate is dropped, and then SNR is increased. When SNR is larger than the threshold value, it will fall into a range of 15.5—18.5 dB. Then the symbol rate will be stable with a fixed rate.

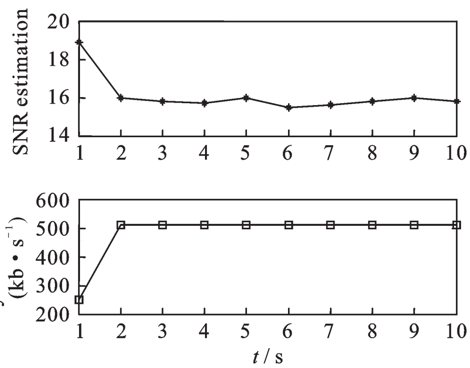

Fig. 10 Variation curves of symbol rate and SNR (SNR=19 dB, Rate=256 kb/s)

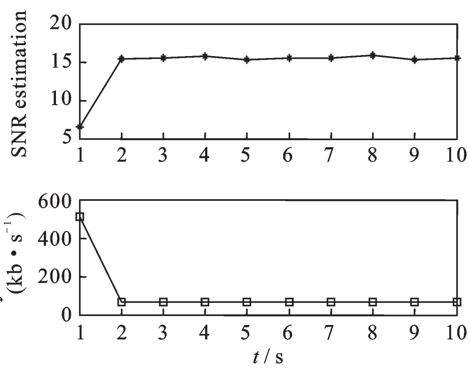

Fig. 11 Variation curves of symbol rate and SNR (SNR=6. 5 dB, Rate=512 kb/s)

According to the Eq. (14) , the corresponding average rates of 256 kb / s and 512 kb / s are 435.2 kb / s. So we can see that the average rate of the whole statistical process is not only determined by the initial rate, but also related to the corresponding initial SNR.

4 Conclusions

This paper presents an adaptive transmission scheme of transceiver based on CCSDS 211 protocol. The adaptive mechanism can obtain the adaptive symbol rate by estimate the output SNR from the receiver in real time. And the local receiver extracts the control information from the remote transmitter to adjust the symbol rate of local transceiver dynamically. The SNR estimation of the adaptive transmission scheme used in FPGA can simplify the hardware circuit while meeting the performance of estimation. Further, the proposed scheme can improve the channel utilization and the system throughput by adjusting the symbol rate of transceiver dynamically. It is a useful reference for the design of deep space communication system.

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Authors Mr. **SUN Zezhou** is the Deputy Chief Designer of China's "Chang'e-1" satellite, Chief Designer of the second phase detector system of the lunar exploration project, Chief Designer of China's "Chang'e-3" detector system.

Mr.**WANG Le** received his Master degree of Science in Nanjing University of Aeronautics and Astronautics. He is currently engineerer at Huawei Research Institute. His research focuses on wireless digital communication system.

Prof. **WANG Chenghua** is professor and doctoral superviser at Nanjing University of Aeronautics and Astronautics. He has been tilteld as national "10, 000 people plan" teaching teacher, government special allowance expert. His research focuses on communication and information system.

Dr. **ZHU Qiuming** received his Master degree of Science in Nanjing University of Aeronautics and Astronautics. He has been titiled as outstanding postdoctoral fellow in Henan Province. His research focuses on communication and information systems, electromagnetic field and microwave technology, aerospace biomimetic science and technology.

Prof. **ZHANG Xiaofei** is professor and doctoral superviser at Nanjing University of Aeronautics and Astronautics. He is Executive Deputy Director of the Institute of Communication Engineering, Executive Deputy Director of the Key Laboratory of Electromagnetic Spectrum Space Dynamic Cognition System. His research focuses on mobile communication, array signal processing, communication signal processing.

Dr. **LIU Weiqiang** is associate professor at Nanjing University of Aeronautics and Astronautics. He is currently the editorial board member the IEEE Transactions on Multi-Scale Computing Systems, and the IEEE Transactions on Emerging Topics in Computing, and guest editor of Microelectronics Journal. His research direction focuses on circuits and systems.

Mr. **LI Xiangyu** is a postgraduate at Nanjing University of Aeronautics and Astronautics. His research focuses on hardware implementation of communication system.

Author contributions Prof. **SUN Zezhou** designed the study, complied the models, conducted the analysis and interpreted the results. Mr. **WANG Le** contributed data for the analysis of estimation and wrote the manuscript. Prof. **WANG Chenghua** contributed data and model components for the adaptive transmission system. Dr. **ZHU Qiuming**, Prof. **ZHANG Xiaofei** and Dr. **LIU Weiqiang** contributed to the discussion and background of the study and participated in project research. Mr. **LI Xiangyu** contributed to the revision of the manuscript. All authors commented on the draft and approved the submission.

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