Chapter 2
The Investigation of a Novel Reentry Telemetry System

Xingwen Ding, Ming Chen, Xifu Huang and Ling Wu

Abstract With the development of the missile experimental research, the measurement bandwidth of super-fast-signal demands more and more (expected up to 100 MHz) in the reentry telemetry. However, the ability of the current PCM-PPK reentry telemetry system is limited. Also the PCM-PPK system is a non-universal system and impedes the improving of the telemetry technology. Based on the analysis of various modulation systems, the PCM-FM modulation system is proposed as a novel reentry telemetry system. The principle prototype of PCM-FM reentry telemetry baseband equipment is successfully developed with the code rate range from 10 to 100 Mbit/s.

Keywords Reentry telemetry · Novel modulation system · PCM-FM · High code rate

2.1 Introduction

As an important part of telemetry, the reentry telemetry is a kind of special telemetry technology which mainly measures various physical parameters of the aircraft (such as warhead) in the course of atmospheric reentry [1]. Its basic principle is the same as the telemetry technology of ballistic missiles during boost phase and the spacecrafts during operational segment, but its work environment

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and measurement requirements are different from those of general telemetry. The reentry telemetry is more complicated and difficult than general telemetry.

In years' missile experiment, various receiving systems and methods are summarized according to the characteristics of reentry signal. Especially after a long-term study, the PCM-PPK system has solved those super-fast-signal telemetry problems. However, with the development of the missile experimental research, there appear more and more measurement requirements for super-fast-signal, and the measurement bandwidth is approximately up to 100 MHz. But the ability of PCM-PPK system is limited, so it is necessary to carry out relevant research on the telemetry technology of super-fast-signal in reentry telemetry system, in order to meet the demands of the developing experiment. The research work should also give consideration to both common signal telemetry and super-fast-signal telemetry, and seek ways to construct a unified telemetry system, so that it can reduce the amount of equipment and system complexity.

The passage first analyses the specificity and complexity of reentry telemetry, and then proposes the PCM-FM modulation system as a novel reentry telemetry system based on the analysis of various modulation systems. Finally, a principle prototype of PCM-FM reentry telemetry baseband equipment is developed with excellent performance.

2.2 Characteristics of Reentry Telemetry

When ballistic missile warhead is re-entering the dense layer of the atmosphere, it will encounter adverse mechanical, thermal and electromagnetic environment. The overload of warhead is up to tens of times of gravitational acceleration, and its vibration spectrum up to thousands of Hertz. The temperature of warhead shell can reach thousands of centigrade because of the friction between the high-speed reentry warhead and the surrounding air, so that the surrounding air conducts ionization and forms plasma sheath around the warhead, also called the "blackout", which can prevent the radio wave transmission. When hitting the ground, the overload of warhead will be up to tens of thousands of times of gravitational acceleration. Meanwhile, because of harsh electromagnetic environment in the warhead, the interference current on the ground wire can be up to tens of amps and it seriously interferes with the telemetry equipment.

Besides the poor mechanical, thermal and electromagnetic environment, the reentry telemetry still faces another serious problem: very short time for measurement. After the warhead flies out from the blackout area, the time for measurement is only about 3 s. During such a short time, it not only transmits real-time measurement parameters, but also need transmit the kept measurement parameters in the blackout area. Even more, the time for measurement of touch-down signals has only several hundred microseconds.

Obviously, the particularity of reentry telemetry mainly comes from three aspects: the particularity of the measurement parameters, the special internal environment in warhead and the special external environment caused by warhead reentry to atmosphere. Due to the particularity of the reentry telemetry, it has the following characteristics [1, 2]:

1. Certain signals have a very wide frequency band.
2. The super-fast-signal has only one-time measuring chance and high-precision interval measuring requirement.
3. The height of warhead is low after flying out from the blackout area, so the time for transmitting signal and receiving signal is very short.
4. The layout of the telemetry components in the missile has strict requirements, so it is not easy to be destroyed by the detonation debris or stress wave.
5. The telemetry components in the missile should be small and light.
6. Because of the signal interruption caused by black-out area, the reentry telemetry system should have strong capability of the retransmission and large storage memory for retransmission.
7. The channel of reentry telemetry is a kind of variable parameter channel due to the movement and rotation of the warhead.
8. The reentry telemetry system has some features of high overload telemetry.
9. The reentry telemetry system should have sufficient power margin.

2.3 Investigation of the Novel Reentry Telemetry System

The novel reentry telemetry system must be greatly adapted to the characteristics of the reentry telemetry so as to ensure the completion of the reentry telemetry tasks. However, various modulation systems have different adaptability to reentry telemetry, so that it is necessary to carry out theoretical analysis and simulating study of various modulation schemes in order to select one (or more) modulation system which is suitable for the burst transmission of high code rate and also has high spectrum efficiency.

2.3.1 Phase Modulation System

In the reentry telemetry, the carrier modulation generally does not adopt phase modulation which is not suitable for time-varying channel. In addition, the PM demodulator needs a certain setting time to recover carrier, which is very unfavorable to reentry storage telemetry [1]. Phase modulation system generally uses coherent demodulation technique which should not be used in the reentry telemetry. Therefore, the phase modulation, such as PM, BPSK, QPSK, OQPSK, UQPSK, 8PSK, FQPSK, QAM, APSK, etc., (among them, QAM, APSK belong to both amplitude modulation and phase modulation) is not suitable as a novel reentry telemetry system.

2.3.2 Amplitude Modulation System

PCM-AM is not sensitive to carrier phase, but is rarely used in conventional telemetry. That is because its transmit power is proportional to the square of signal amplitude ($P = I^2R$). In order to ensure the transmission quality of the low amplitude telemetry signal, the transmission system needs additional power margin. Once the maximum-to-minimum ratio of the measured signal amplitude is large, its transmitter power will encounter big problems in design.

PCM-PPK, which is currently used in the reentry telemetry system, is just a kind of PCM-AM. Some data shows that PCM-FM transmitter power (for code rate 102.4 kbit/s) is required only less than 5 W; but PCM-PPK transmitter power (for code rate 51.2 kbit/s) requires no less than 300 W (pulse power) which is 60 times more than PCM-FM. Moreover, as the reentry telemetry further promotes the requirement of code rate (up to tens of Mbit/s and even hundreds of Mbit/s), it needs to further increase the PCM-PPK transmitter power, which leaves the system more difficult to be realized.

2.3.3 Spread Spectrum System

Spread spectrum system is a widely used TT&C system. It can complete different tasks such as ranging, velocity measurements, telemetry, security control, etc. It has the advantage of low power spectral density, anti-intercept, anti-jamming, security, multiple access communications, etc. However, spread spectrum system adopts coherent demodulation technique and needs three synchronization process: carrier synchronization, PN code synchronization and information code synchronization. Considering this factor, spread spectrum system is even less suitable for reentry telemetry system than the phase modulation system mentioned above.

2.3.4 OFDM System

The basic principle of OFDM system is to divide the whole channel into several orthogonal sub-channels, and then convert the high-speed serial data stream to multiple parallel transmission data streams which will be modulated on each sub-channel with low-speed.

Because of the orthogonality between each sub-channel, OFDM improves the band efficiency greatly. In addition to the high band efficiency, OFDM system also has some other advantages, such as resistance to multi-path delay spread, frequency selective fading, anti-inter-symbol interference, etc. But OFDM system

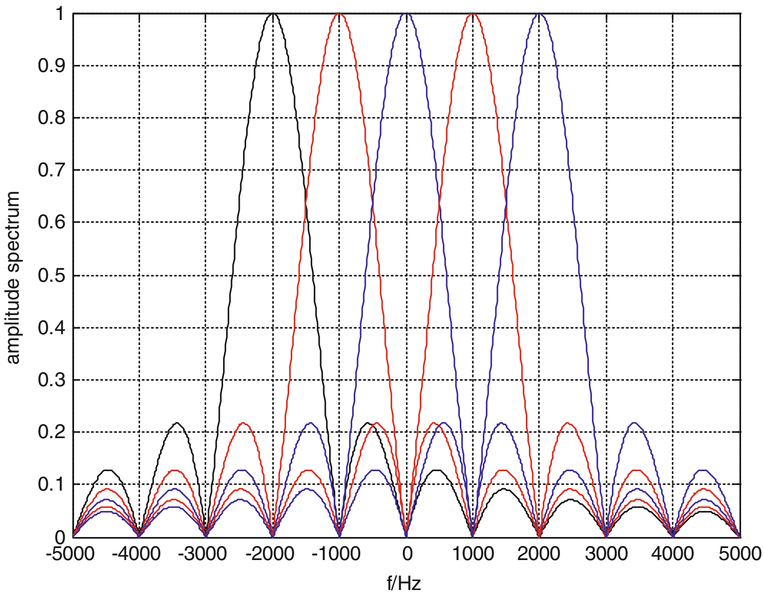

Fig. 2.1 The spectrum of OFDM signal

usually adopts coherent demodulation technique, and furthermore it has two serious shortcomings: sensitive to the frequency offset and high Peak to Average Power Ratio (PAPR). Therefore, OFDM system is not suitable for reentry telemetry either.

The spectrum of OFDM signal is shown in Fig. 2.1. Each sub-carrier spectral peak appears at other channels spectral null, so it requires the strict frequency synchronization. Once the system has frequency offset, the orthogonality among sub-carriers will be destroyed. That will cause serious "floor effect" on system performance. That means, no matter how to increase the transmitter power, it can not improve the system performance significantly.

Another disadvantage of OFDM system is that the PAPR is high. Figure 2.2 shows a diagram of OFDM signal in time domain. It shows that the envelope of OFDM signal has the fluctuation characteristic. That's because OFDM signal is a weighted sum of all the sub-carrier signals. When the phases of multiple sub-carriers are identical, the instantaneous signal power will be much greater than the average signal power, so its envelope dynamic range is large. That is, Peak to Average Power Ratio (PAPR) is high. High PAPR causes a high requirement of the linear range of the amplifier and D/A converter. If the linear range of the system can not meet the requirement, it will cause signal distortion and system performance degradation.

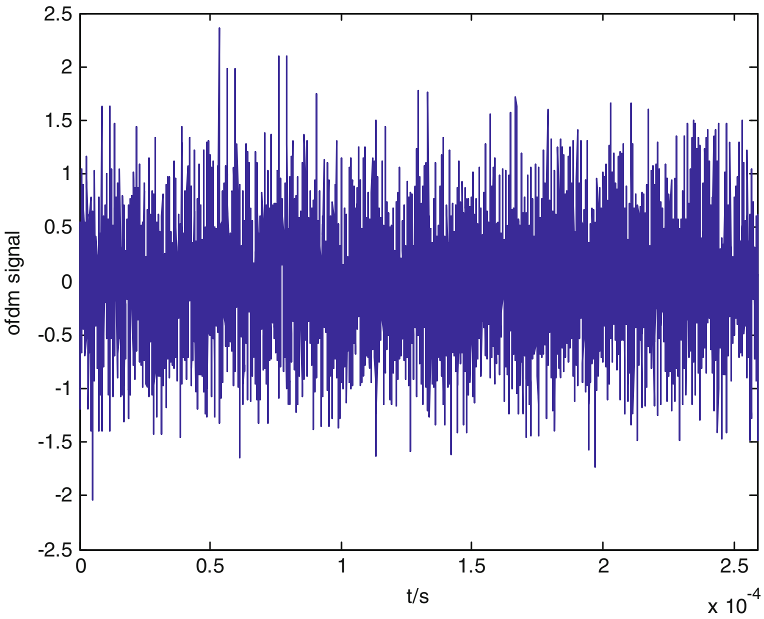

Fig. 2.2 OFDM signal in time domain

2.3.5 Continuous Phase Modulation System

Continuous Phase Modulation (CPM) system has constant envelope and excellent spectral characteristics. CPM is not sensitive to non-linear of the power amplifier, so the system can use non-linear power amplifier in practical applications. Furthermore, CPM signal can adopt non-coherent demodulation technique, which greatly simplifies the design complexity of telemetry system. Table 2.1 compares several common CPM systems: PCM-FM, MSK, GMSK and ARTM CPM. Among them, PCM-FM has the lowest complexity, the best demodulation performance and the lowest band efficiency, while ARTM CPM has the highest complexity, the worst demodulation performance and the highest bandwidth efficiency.

PCM-FM has been the main modulation system in the launch vehicle range telemetry system in china and abroad. That is because PCM-FM modulation system has the advantages of short acquisition time and strong capability of anti-flame, anti-fading, anti-jamming. Meanwhile, it can improve the bandwidth efficiency nearly 35 % using pulse shaping pre-modulation filter technology [3]. In addition, as shown in Fig. 2.3, the PCM-FM telemetry system with "MSD (Multi-symbol Detector) + TPC (Turbo Product Code)" technology can have nearly 9 dB channel gain at the bit error rate of 10^{-7}, compared to conventional Limiter Discriminator (LD) demodulation techniques [4]. Such a high channel gain can

Table 2.1 Performance of several common CPM systems

CPM system	99 % of Normalized bandwidth	Minimum euclidean distance	System complexity
PCM-FM	1.78R[a]	2.43	★[b]
MSK	1.18R	2	★★
GMSK (BT = 0.5)	1.04R	1.9	★★★
ARTM CPM	0.56R	1.39	★★★★★

[a] R represents signal code rate
[b] The more number of ★ represents the higher system complexity

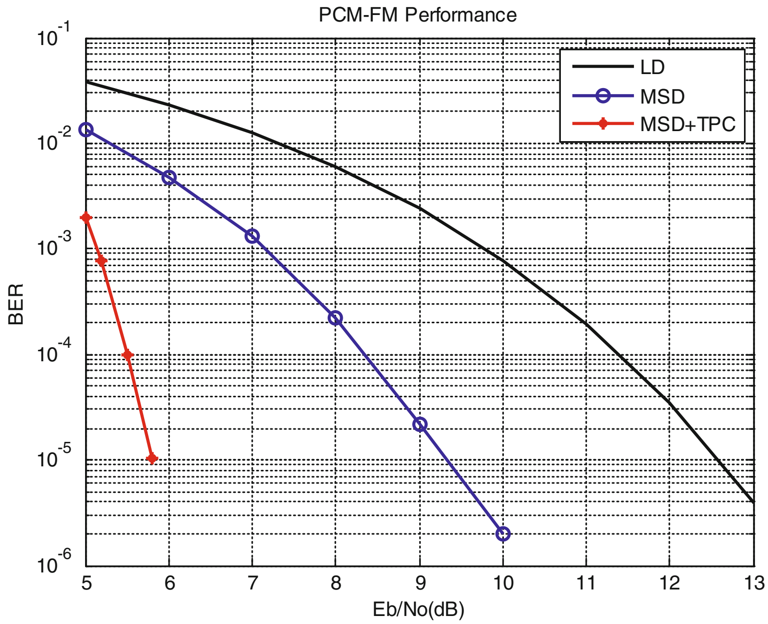

Fig. 2.3 PCM-FM performances with different demodulation technique (The parameters of PCM-FM modulation system are modulation index h = 0.7, the observation interval N = 5 and TPC (64, 57) × (64, 57))

significantly improve the transmission rate under the conditions of not increasing antenna aperture and transmitter power, and thus it can save cost for telemetry system.

Summarizing the modulation systems' adaptability to reentry telemetry above, PCM-FM can be chosen as a novel reentry telemetry system to unify modulation system, decrease equipment quantity and reduce system complexity.

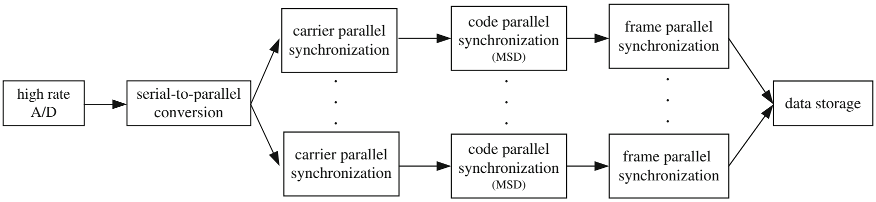

Fig. 2.4 The parallel demodulation process of the principle prototype

2.4 Principle Prototype of PCM-FM Reentry Telemetry Baseband Equipment

In order to meet the measurement requirements for the future reentry telemetry, it is estimated that the principle prototype of PCM-FM reentry telemetry baseband equipment needs to adapt the code rate up to 100 Mbit/s, which puts forward technical challenges on both hardware architecture and software architecture.

Firstly, the carrier center frequency of the traditional baseband equipment is 70 or 140 MHz, but the center frequency of the principle prototype needs to be higher in order to adapt to high code rate transmission. In the remote sensing system, the center frequency of baseband equipment with high code rate transmission (modulation system: QPSK, DQPSK, SQPSK, UQPSK, 8PSK, and total code rate: 10–600 Mbit/s) is 720 MHz. Therefore, the center frequency of the principle prototype for reentry telemetry can be also selected at 720 MHz.

Secondly, the traditional baseband equipment can complete demodulation of low code rate signal with serial processing, but the principle prototype for reentry telemetry with high code rate must adopt the parallel processing technique to reduce the processing rate, including serial-to-parallel conversion technique, carrier parallel synchronization technique, code parallel synchronization technique (parallel MSD technique), frame parallel synchronization technique, high code rate data storage technique, etc. The parallel demodulation process of the principle prototype is shown in Fig. 2.4.

With the use of advanced software radio architecture and parallel processing technology, the principle prototype of PCM-FM reentry telemetry baseband equipment has been developed:

1. Modulation system: PCM-FM (modulation index: $h = 0.7$);
2. Center frequency: 720 MHz;
3. Code rate: 10–100 Mbit/s, with step of 1 bit/s;
4. Demodulation method: non-coherent multi-symbol detection (MSD), the observed interval $N = 5$;
5. Carrier acquisition performance: Doppler range: ±1 MHz, Doppler rate-of-change: ±200 kHz/s, acquisition time: ≤1 ms;
6. Demodulation performance: the bit error rate $P_e \leq 1 \times 10^{-4}$ at $E_b/N_0 = 9$ dB.

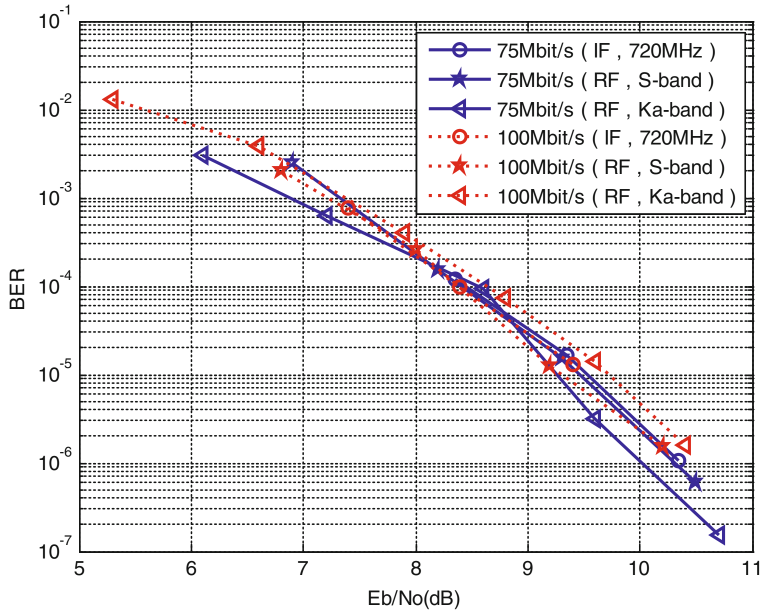

Fig. 2.5 The testing performance of the principle prototype

The principle prototype has been verified at IF (720 MHz) and RF (S-band and Ka-band) with wire connection in the laboratory, and its performance is shown in Fig. 2.5. It can be seen that the principle prototype of PCM-FM reentry telemetry baseband equipment has excellent performance and the demodulation loss is less than 0.5 dB compared with the theoretical performance ($P_e \leq 1 \times 10^{-4}$ at $E_b/N_0 = 8.4$ dB). Moreover, it can adapt to different radio frequency with very short acquisition time, so it is suitable for the burst transmission with high code rate in the reentry telemetry.

2.5 Conclusion

With the development of the missile experimental research, there appear more and more demands for the measurement bandwidth of super-fast-signal (expected up to 100 MHz) in the reentry telemetry. However, the ability of the current PCM-PPK reentry telemetry system is limited. According to the characteristics of super-fast-signal and reentry telemetry, the paper discusses various modulation systems' adaptability to reentry telemetry. On this basis, the PCM-FM modulation system is proposed as a novel reentry telemetry system. And the principle prototype of PCM-FM reentry telemetry baseband equipment has been successfully developed with excellent performance and the code rate range from 10 to 100 Mbit/s.

It achieves the anticipated goal of constructing a unified telemetry system to reduce the amount of equipment and system complexity, and also meeting the measurement requirement for the development of the missile experiment research.

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