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A review of link budget analysis of satellite communication systems

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Abstract. At present, the link budget of satellite systems has become an essential part of the engineering design of satellite communication systems. Through the link budget, the performance of communication equipment and the loss of signal attenuation and interference during transmission can be comprehensively analysed, and the equipment resource configuration and device parameters can be continuously optimised to meet the user's communication capacity and quality requirements while leaving appropriate margins. This study aims to explore the link budget of the satellite system, study the parameters, channel characteristics and application of the satellite link budget, and provide a theoretical basis and practical reference for the design and performance optimisation of the satellite communication system. Firstly, the research background and significance of satellite communication links are introduced, and the characteristics and advantages of other communication systems are analysed and compared from multiple dimensions. The main factors affecting the link budget, such as path loss, related atmospheric attenuation, and carrier-to-noise ratio, were mainly discussed using the parameter estimation method and comparative analysis. Then, from the perspective of channel characteristics, the critical issues of satellite link budget, including signal-to-noise ratio, code rate and other factors, are discussed. Based on the above research, this paper summarises the performance evaluation of satellite communication systems and provides a reference for practical applications.

Keywords: satellite systems, link budget, signal transmission, Modulation optimisation, Frequency planning.

1. Introduction

Satellite communication involves transmitting or reflecting radio waves between multiple ground stations, utilising artificial earth satellites as relay stations.

Compared with other communication methods, satellite communication has the following characteristics:

The first one is that the communication distance is long, and the cost of building the station has nothing to do with the communication distance. Secondly, Flexible networking is convenient for multiple access connections and large communication capacity. Then another characteristic is that the quality of communication lines is stable and reliable. Finally, the last notable feature is good manoeuvrability [1].

Therefore, satellite communication has developed rapidly in recent years and has become one of the most potent modern means of communication, playing an essential role in satellite television, broadcasting, communication and multimedia systems. When carrying out satellite communication, proper planning and design of satellite transmission links is an essential basis for satellite users to ensure the system's stability.

Before planning the satellite link system, it is necessary to calculate the link and reasonably equip the ground station equipment according to the calculation results so that the equipment parameters can not only meet the communication needs but also save costs.

The link budget can be summarised as a basis for weighing gains and losses

Detailed ratios of transmitter and receiver, noise sources and signal gain and attenuation, and the impact of each device on the overall link process.

2. Relevant parameters and influencing factors

2.1. Basic path loss

2.1.1. Free space path loss. The basic path loss mainly covers two parts: free space propagation loss between satellite-ground links and shadow fading [2].

Radio waves usually propagate in free space in the form of electromagnetic waves. The energy of electromagnetic waves during the propagation process will spread with the increase of propagation distance, and the propagation loss generated is called free space path loss. The propagation distance of radio waves is d (km), the carrier frequency is f_c (GHz), and the free space path loss is L_{FSP} (dB) can be expressed as

$$L_{FSP}(d, f_c) = 32.45 + 20\,lg(f_c) + 20\,lg(d) \tag{1}$$

For satellite-ground communication systems, the distance from the satellite d can be determined by the satellite altitude L_{FSP} (km) and the elevation angle θ (°) can be expressed as

$$d = \sqrt{R_E^2 \sin^2\theta + h_0^2 + 2h_0R_E} - R_E\,sin\,\theta. \tag{2}$$

Among them, the radius of the earth R_E is 6371km.

2.1.2. Shadow fading. Shadow fading refers to the signal fading caused by enormous obstacles absorbing and diverging signal energy during satellite wireless signal transmission. The shadow fading model follows a log-normal distribution, which, when measured in dB, is a normal distribution with a mean of zero and a standard deviation of $\boldsymbol{\sigma_{SF}}$:

$$lnSF \sim N(0, \sigma_{SF}^2) \tag{3}$$

Among them, *N* represents a normal distribution.

2.2. Atmospheric attenuation

Atmospheric attenuation refers to the signal attenuation phenomenon caused by the scattering and absorption of atmospheric molecules when radio waves propagate in the air. Atmospheric attenuation is affected by factors such as frequency, distance, weather conditions, etc. For example, as the frequency increases, atmospheric attenuation increases. In severe weather conditions such as thunderstorms and haze, atmospheric attenuation is more serious [3].

2.3. Carrier signal-to-noise ratio

The signal-to-noise ratio is the ratio of useful signal power to noise signal power (in the same frequency band), and the size of SNR is the decisive factor for whether we can accurately extract useful information from the received wireless signal. A commonly used representation that represents the ratio of signal energy to noise power spectral density in each bit of time. Different signal modulation methods have different signal-to-noise ratios. That is, the bit error rate performance that can be achieved is different, so there are different ones.

For QPSK, the most commonly used modulation method in satellite communications, If the required bit error rate is not higher than10^{-5}, The required signal $[E_b/N_o]$ is 9.598dB. This value is usually 10dB in the satellite communication link budget.

2.4. Simplified handling of interference estimation

In link budget calculation, in addition to the C/T or C/N of the uplink and downlink, factors such as cross-polarization interference, adjacent satellite interference, and intermodulation interference should also be considered. When considering cross-polarization interference, the ratio of the power spectral density of the interfered signal to that of the interference signal, as well as the comprehensive effects of the polarisation isolation of the ground antenna and the satellite transceiver antenna, should be considered. Assuming that two polarisation transceivers have the same operating status, and both polarisation carriers only occupy the average power of the transceiver, the carrier-to-interference ratio of cross-polarization interference can be simplified as the comprehensive impact of the antenna polarisation isolation. In general, in adjacent satellite interference, downlink interference plays a decisive role. The C/I of adjacent satellite interference is determined by the ratio of the downlink EIRP spectral density of the two carriers at the receiving site and the difference in off-axis gain of the receiving antenna (the difference between the maximum receiving gain of the ground antenna pointing to the satellite and the off-axis receiving gain pointing to the adjacent satellite). The calculation of the above three interference factors is difficult to obtain accurate results due to insufficient data. As the impact of these factors on the link budget result is limited, a simplified estimation method is usually adopted, which only calculates the comprehensive C/N of the uplink and downlink and then subtracts 0.5 to 2dB of interference factors or does not deduct at all. The link budget estimation result obtained in this way generally has an error within 1dB compared to the different results calculated by various satellite companies [4].

3. Coding analysis

3.1. Overall overview

In digital satellite communication systems, in order to improve the transmission quality of information and improve the performance of the system, bit error rate and channel coding is usually used. Due to the influence of noise and interference in the actual channel, bit errors will inevitably occur during transmission. In memoryless channels, noise affects each transmission element independently and randomly, so errors occur independently and randomly in the received sequence. The use of forward error correction coding (FEC) can effectively correct such errors.

Commonly used FECs are packet codes and convolutional codes and their cascading use. At present, the most widely used binary block code in satellite communication is BCH code, and the multi-base block code is RS code. For convolutional codes with too long a constraint length, in the case that the bit error rate is low, the convolutional code and Viterbi decoding algorithm are not only simple in equipment but also suitable for high information rates. They can be closely combined with demodulation algorithms through soft decision decoding to significantly reduce the demodulation detection threshold [5].

3.2. Convolutional encoding

Convolutional codes are dust-producing sequences of sent information through a linear, finite-state shift register. The convolutional code gives three integers n, k, and K description, where k/n represents the encoding efficiency of the packet code (the information contained in each encoded bit); K is called the constraint length and represents the number of stages of the k-tuple in the encoding shift register. The encoder of the convolutional code has memory. That is, the n-tuple produced by the convolution encoding process is not only a function of the input k tuple but also a function of the previous K-1 input k tuple. In practice, n and k often take smaller values, and the ability and complexity of coding are controlled by changes in k [6].

In satellite communication systems, short-constraint length convolutional codes with a code rate of 1/2 or 3/4 are mostly used as the internal codes of FEC or cascade codes, and the reasons for this analysis are rough as follows:

Firstly, in the case of medium signal-to-noise ratio, the short-constraint-length convolutional code using soft decision Viterbi decoding has a higher coding gain than the packet code of the same code rate, the implementation is simple, and the decoding delay is not significant.

Secondly, convolutional codes with a code rate of less than 1/2 decrease rapidly with the further decrease of the code rate, while the coding gain does not increase significantly. Therefore, convolutional codes with a bit rate of less than 1/2 are rarely used.

Finally, due to the continuous improvement of the information rate, it is necessary to adopt a pattern with a high bit rate and good performance. The truncated convolutional code with a code rate of 1/2 has a higher bitrate, the implementation is simple, and the performance is better than other 1/V (v>2) truncated codes, so more 1/2 truncated convolutional codes are used. The cut-off Shortcodes, together with 1/2 codes, also provide easy adaptive bitrate adjustment [7].

3.3. Viterbi decoding

The decoding of convolutional codes is divided into two categories: algebraic decoding and probabilistic decoding. Algebraic decoding is rarely used at present because it needs to make full use of convolutional codes. Among the probability decoding, Viterbi decoding is widely used in satellite communication equipment. When the length of the coding constraint is not too large, or the bit error rate requirements are not too high (about 10~), its equipment is relatively simple, the calculation speed is fast, and it can currently achieve tens of megabits or even hundreds of megabits per second, so it is especially suitable for correcting random errors in the satellite near-white noise channel [8].

Viterbi decoding is further divided into the hard decision (i.e., using a two-level quantisation decision) and soft decision (i.e., using a multilevel quantisation decision) s.

Through theoretical calculations, it can be obtained: the use of soft decision decoding is higher than the gain obtained by hard decision decoding, and the more quantisation levels are used, the greater the gain obtained, but this means that the complexity of the decoder increases, and the soft decision gain increases very slowly after greater than eight-level quantisation, so eight-level quantisation is generally used, and the decoder is not too complicated, and there is a soft decision gain of 2dB.

3.4. Combined use

Combining convolutional code and Viterbi decoding has become almost a universal standard for satellite communications. Intelsat/International China Excellent Master's Dissertation Full-text Database No. 51, 2011 Information Technology Series 1136-540-48 INTELSAT IESS 308/309 standard, using a Viterbi code with a limited length of 7. It provides very useful encoding gain, and its short decoding delay and error burst to make it ideal for low-rate encoded speech applications. For all encoding rates, its short limit length is a fixed value of 7. Choose a different encoding rate (1/2,3/4 or 7/8); the user exchanges the bandwidth expansion with the coding gain. Encoding rate 1/2 provides the best improvement in bit error rate but multiplies the transmission rate, so the bandwidth consumed by the signal also doubles. In some extreme cases, an encoding rate of 7/8 provides the most appropriate performance improvement but only extends the transmission bandwidth by 14%. A major advantage of Viterbi's decoding method is that the performance is independent of the data rate, and there is no significant threshold effect [9].

3.5. The reed-solomon code

The Reed-Solomon code (R-S) is a linear grouping code based on symbols on the finite field GF(2b); each symbol consists of bits with a code length N=2b-1, an information symbol length of K, and a coding rate R=K/N. If we assume that the minimum code distance of the RS (N, K) code is d, then d=N-K+1, and the error correction ability of this code is t=0.5(N-K).

The main reasons why RS codes are widely used and used as foreign codes are:

Firstly, it has good distance characteristics and is a maximum distance division code.

Secondly, there is an effective hard judgment decoding rule, which makes RS codes with longer codes practical. We know you can only achieve considerable coding gain at high bit rates when you have a long code length. Therefore, in actual use, it is desirable to use a more extended code.

Thirdly, since the RS code is a symbol code built on a valid domain, it is convenient to integrate and improve the working speed. At present, the practical RS code machine has reached hundreds of megabytes.

Fourthly, RS code has a strong ability to correct burst errors, and both the Viterbi decoder and satellite fading channel output errors are multi-burst errors, so it is very suitable for the RS decoder.

Finally, the bit error rate performance curve of the RS code on the AWGN channel is at E/N. Higher is steeper, so its excellent error correction performance can only be reflected in the case of a higher signal-to-noise ratio, so it is mostly used as an external code [10].

3.6. Chapter summary

Channel coding is the key technology to improve system performance; satellite communication often uses forward error correction (FEC) technology to achieve channel coding; this chapter first for INTELSAT recommended for fixed satellite communication convolutional code and Viterbi decoding analysis, respectively give the principle and some cases of application, and introduce the cascade use of the two. Then, the application of RS coding is introduced and analysed.

4. Conclusion

Through the analysis of the influencing factors of the link budget of satellite communication, this paper introduces the main attenuation and interference losses in the process of radio wave transmission and summarises the main influencing factors to meet the communication capacity and quality requirements of users while leaving appropriate margins. This paper does not carry out a specific quantitative analysis but only proposes a comprehensive consideration of the above factors. Then, the important coding methods are discussed and analysed, including convolutional code, Viterbi decoding, and The Reed-Solomon code, which provides a theoretical basis and practical reference for the design and performance optimisation of satellite communication systems. However, for each channel coding method, an exact bit error rate formula cannot be given like the modulation method, nor can only the theoretical curve be given, which varies with different coding construction methods. Judging the advantages and disadvantages of a coding method can only rely on the closer to the Shannon limit, the better. Still, the practical application also needs to consider the complexity of the equipment implementation, and the two factors of the performance of the system and the complexity of the equipment should be comprehensively evaluated. As technology continues to advance, satellite communication is becoming more diverse and efficient. High-throughput satellite systems with flexible coverage and low cost per bandwidth are gaining popularity and driving the development of higher frequency bands and diversified orbits. The progress of multi-beam antennas and communication loads is also contributing to the growth of satellite communication capabilities. With the continuous breakthrough of cutting-edge technology, satellite communication will continue to evolve in a more intelligent direction in the future.

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