Analysis of GEO Satellite Relay Coded Systems

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***Abstract*—The recent development of the low Earth orbit (LEO) satellite constellation construction has accelerated the research on applications associated with LEO satellites. One such typical application is to transmit high-resolution remote-sensing images from LEO satellites to ground stations (GS). However, the stringent visible time and the complicated antenna manipulation between LEO satellites and GS makes it challenging for a LEO satellite to complete its full transmission mission within a specified stringent deadline. As such, this paper introduces a geosynchronous equatorial orbit (GEO) satellite as a relay and explores the distributed coding-decoding schemes to assist reliable and high-speed transmission. Specifically, four types of GEO-satellite-relay coded schemes are proposed and analyzed, including three PHY-only coding systems with GEO-full-decoding on board, decoding on ground only, and GEO-partial-decoding on board and one layered coding system. Through simulations, the comparative insights among the four schemes are provided from three dimensions: effectiveness, reliability, and relay complexity. The trade-offs concerning the four schemes in terms of the three indexes are also revealed.**

***Index Terms*—satellite relay, layered coding system, PHY-only coding system, link modeling**

I. Introduction

Even though the emergence of 5G terrestrial networks have achieved a breakthrough over massive connectivity, ultra reliable and low latency communications, as well as enhanced mobile broadband, the current terrestrial-concentric paradigm is far from enabling seamless coverage due to the challenge in deploying base stations in some complex terrains, such as isolated island, distant oceans, and desolate deserts, etc. To this end, it is imperative to orchestrate the satellites with terrestrial networks.

A typical application of such an idea is based on the recent achievements on constructing the LEO satellite constellation. In this case, the LEO satellite consecutively observes the terrestrial data and transmits the remote-sensing Earth image to the ground. However, the visible time between a LEO satellite and a GS is limited, and also, the LEO satellite requires complex steerable antennas to establish connections with the GS. These issues result in difficulty in direct high-speed data transmission between LEO satellites and terrestrial networks. Therefore, introducing a GEO satellite as a relay between the LEO satellite and the GS would be an efficient alternative.

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Notice that directly stepping the terrestrial network into the original radio frequency (RF) band of the satellite will fall into spectrum interference, it is necessary to upgrade the downlink band to the optical band, which substantially improves the LEO satellite data throughput and enhances the anti-interference capability. Experiments have been conducted in several countries, and the Consultative Committee for Space Data Systems (CCSDS) is working on standardization to promote global cooperation in this area [1].

The breakthrough of high-speed relay satellite communications can be traced back to the late 1990s, when several companies began developing optical communication terminals for LEO and GEO satellite missions. As the first, the SILEX project involved two satellites, SPOT-4 (LEO) and ARTEMIS (GEO), with the aim of proving the feasibility of the inter-satellite link (ISL), as well as relaying data from the LEO satellite to GS [2]. The laser terminals used intensity modulation, direct detection and allowed for 50 Mbps data rate transmission. Since the first bidirectional ISL was established in 2005, ESA and JAXA have conducted several ISL communications between ARTEMIS (GEO) and OICETS (LEO), returning observations at 2 Mbps using binary pulse position modulation (BPPM) [3]. Later, the first coherent optical communication terminal was carried by TerraSAR-X (LEO), which implemented binary phase shift keying (BPSK) by optical phase-locked Loop (OPLL) [4]. In November 2015, EDRS transmitted data from the LEO satellite to GS via a set of GEO satellites. The launch of Alphasat (GEO) [5] and EDRS-A (GEO) marked the establishment of the first satellite relay constellation. The former achieved frequency-only transparent transmission, while the latter required framing, encrypting, and channel coding tasks. NASA is focusing on the LCRD mission with the main goal of achieving high-speed bidirectional communications between the GEO satellite and GS, examining the feasibility of PPM for the ISL and differential phase shift keying (DPSK) for the SGL [6].

The current GEO satellite relay coded system is still in the development stage, mainly focusing on modulation and optical links, while the research on system coding methods is not yet sufficient. Currently, there are only studies related to the PHY-only coding system with decoding on ground only, such as the system with EDRS-A as a GEO in EDRS. As such, it is necessary to further explore the performance gains of distributed decoding schemes. Also, we notice that the existing works focus on the physical layer coding only, and there is little work analyzing the cross-layer coding scheme.

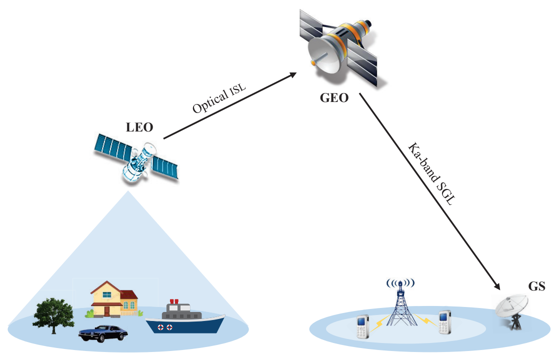

Fig. 1. GEO satellite relay coded system model.

Motivated by the above, we propose four types of GEO satellite relay coded systems, including three PHY-only coding systems, namely GEO-full-decoding on board, decoding on ground only, and GEO-partial-decoding on board; and one cross-layer coding scheme, namely layered coding system. We begin with detailed link analysis, where the ISL and the satellite-ground link (SGL) adopts optical band and Ka-band RF signals respectively. For the PHY-only coding system, we use the concatenated code of the Reed-Solomon (RS) code and the convolutional code (CC). And the layered coding system is coded with the RS code at the PHY layer and the Luby transform (LT) code at the packet (PKT) layer. Next, we innovatively synthesize three indexes: effectiveness, reliability and relay complexity to analyze four above systems to provide ideas for the design of the actual system under different application scenarios.

The rest of this paper is organized as follows. Section II introduces the system and link model. Four satellite relay systems are established in Section III. In Section IV, we articulate three evaluation indexes. In Section V, simulation results are provided, followed by conclusions in Section VI.

II. System Model and Link Analysis

The GEO satellite relay coded system model is shown in Fig. 1, which contains three nodes: LEO, GEO, and GS, as well as two links: ISL and SGL.

A. ISL

The ISL uses optical signals that enable greater data throughput and anti-interference capability. However, this means that the GEO satellite receiver need a photoelectric converter device, so the light coupling efficiency needs to be considered. Also, the microvibrations of the transmitting platform must be taken into account due to the narrow light beam and the fast movement of the LEO satellite. In addition, considering the actual values of LEO and GEO satellite orbital altitudes, the ISL hardly passes through the atmosphere, so we don't need to consider the effect of it. In summary, towards the ISL, we consider the free space path loss (FSPL), the light coupling efficiency, the microvibrations of the transmitting platform and the additive white Gaussian noise (AWGN).

According to the Friis transmission equation, the FSPL is given by

$$L_p = (\frac{\lambda}{4\pi d})^2, \tag{1}$$

where λ is the wavelength of light and d is the ISL length.

The light coupling efficiency reveals the signal power ratio before and after the photoelectric conversion. Since the atmospheric turbulence effect of the ISL can be neglected, the atmospheric coherence radius, which is inversely proportional to the atmospheric turbulence intensity, is much larger than the telescope aperture. Thus, light coupling efficiency is approximated by a constant of $\eta_c = 0.815$ [7].

Assuming the pointing bias of zero, the probability density function (PDF) of the channel signal amplitude for the microvibrations of the transmitting platform is given by [8]

$$f_H(h) = \begin{cases} \alpha h^{\alpha-1}, & 0 \le h \le 1 \\ 0, & others \end{cases}, \tag{2}$$

where h is the channel signal amplitude, α denotes the random microvibrations of the transmitting platform, and

$$\alpha = \frac{{W_0}^2}{4{\sigma_e}^2}, \tag{3}$$

where W_0 is the radius of the transmitting laser beam, σ_e is the root mean square (RMS) of the random jitter. Substituting the typical value of $W_0 = 7.5$cm, $\sigma_e^2 = 4 \times 10^{-4}\text{rad}^2$ [9] yields $\alpha = 3.5156$.

The PDF of the AWGN is

$$f_N(n) = \frac{1}{\sigma\sqrt{2\pi}}\exp[-\frac{(n-\mu)^2}{2\sigma^2}], \tag{4}$$

where μ is the mean taken as zero and σ^2 is the variance, corresponding to the average power of the noise.

B. SGL

Unlike the ISL, the SGL passes through the complete atmosphere and tropospheric clouds seriously affect the transmission of optical signals, so Ka-band RF signals are chosen here. Thus, there is no need to consider the microvibrations of the transmitting platform and the light coupling efficiency. Instead, we need to analyze the attenuation caused by atmospheric absorption, rain, snow, and the tropospheric scintillation caused by the atmospheric turbulence. Overall, towards the SGL, we consider the FSPL, the atmospheric absorption attenuation, the rain attenuation, the tropospheric scintillation and the AWGN.

The FSPL is calculated by (1). The atmospheric absorption attenuation of the inclined path is given by [10]

$$L_{ATM} = \frac{\gamma_0 h_0 + \gamma_w h_w}{\sin\theta}, \tag{5}$$

where γ_0, γ_w are oxygen and steam attenuation coefficients, and h_0, h_w are oxygen and steam equivalent heights. θ is the elevation angle.

The rain attenuation is given by

$$L_{rain} = KR^a L_s r_p \text{ dB}, \tag{6}$$

where R is the amount of rainfall in the region with 0.01% probability at a certain time period, K and a are the correlation coefficients. They can be all obtained from the regional look-up table. L_s and r_p can be calculated according to [11].

Because a considerable amount of aperture averaging is performed at the GS receiver, the atmospheric turbulence can be considered as the weak one. At this time, the channel signal amplitude follows a log-normal distribution. The PDF is [12]

$$f_H(h) = \begin{cases} \dfrac{1}{h\sigma\sqrt{2\pi}} \exp[-\dfrac{(\ln h - \mu)^2}{2\sigma^2}], & h > 0 \\ 0, & others \end{cases}, \quad (7)$$

where h is the channel signal amplitude, μ and σ^2 are the mean and variance of H after taking the logarithm, and we can obtain their typical values according to [13].

The AWGN is analyzed here as above, so the PDF can be calculated according to (4).

III. Establishment of GEO Satellite Relay Coded Systems

A. Choice of Codes

For the choice of codes, both the error correction capability and the decoding complexity should be considered. Especially for satellite relay systems, the relay complexity should not be too large.

1) Three PHY-only Coding Systems: Some forward error correction (FEC) codes for point-to-point links in near-Earth and deep-space communication situations are defined in the CCSDS standard, such as: RS codes, RS-CC concatenated codes, turbo codes, low-density parity check (LDPC) codes, etc. The satellite relay system can be split into two subsystems of inter-satellite and satellite-ground point-to-point links, and the PHY-only coding system with decoding on ground only in [14] is coded with RS-CC concatenated codes. Therefore, for these three PHY-only coding systems, we use RS-CC concatenated codes on both LEO and GEO satellites, and interleave the RS-encoded symbols to counteract correlated fading channels.

2) Layered Coding System: The layered coding system can effectively weaken the contradiction between the reliability and the relay complexity. Since the relay only decodes at the PHY layer, simpler codes can be used in order to reduce the relay burden, here RS codes are chosen. Meanwhile, the overall system reliability is compensated by adding the upper (PKT) layer, which experiences an erasure channel and to which rateless codes can be well applied. Typical rateless codes include LT and raptor codes. The latter improves the coverage of original symbols by precoding the former with LDPC codes, so it can eliminate the error floor of LT codes. However, towards the layered coding system, there are two reasons why raptor codes are not suitable.

- The PKT layer experiences an erasure channel and cannot obtain soft information, so only hard verdict decoding can be used for LDPC codes. But its performance is much worse than soft verdict decoding.

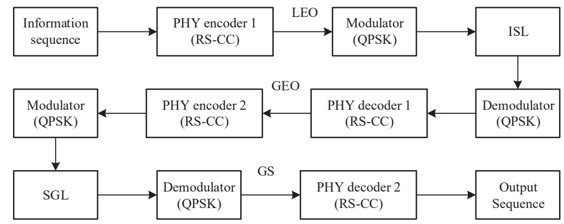

Fig. 2. The PHY-only coding system with GEO-full-decoding on board.

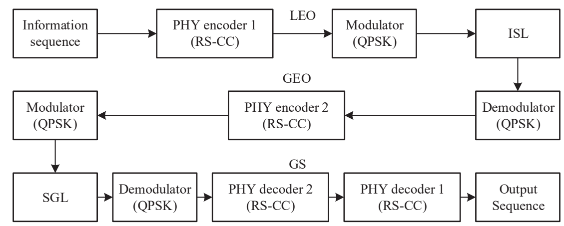

Fig. 3. The PHY-only coding system with decoding on ground only.

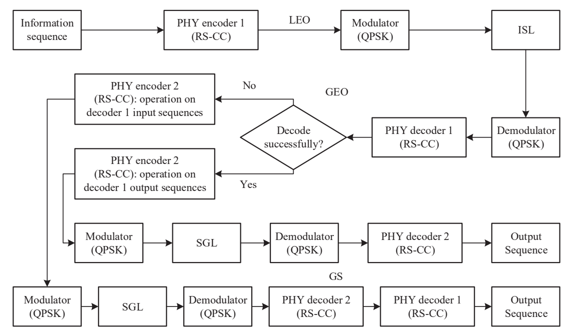

Fig. 4. The PHY-only coding system with GEO-partial-decoding on board.

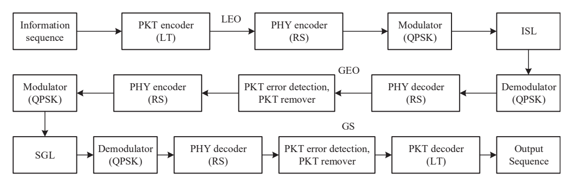

Fig. 5. The layered coding system.

- The LDPC code rate (CR) is fixed, so each bit of the decoding input sequence cannot be lost. However, the LT code decoding output sequence has lost PKTs, so it cannot be used as the LDPC code decoding input directly.

B. Description of System Architectures

1) PHY-only Coding System with GEO-full-decoding on Board: As depicted in Fig. 2, on the LEO satellite, the observed image data is converted into a bit sequence by the source encoder. It is sequentially encoded by RS-CC concatenated codes and modulated by quadrature phase shift keying (QPSK) at the PHY layer, and subsequently sent to the ISL. We adopt the link model constructed in Section II, so for the ISL, we consider the FSPL, the light coupling efficiency, the microvibrations of the transmitting platform and the AWGN. On the GEO satellite, the received signals are demodulated and decoded to correct bit errors caused by the ISL. Then, they are encoded and modulated to counteract the effects of the SGL and sent to the link. Refer to Section II, for the SGL, we consider the FSPL, the atmospheric absorption attenuation, the rain attenuation, the tropospheric scintillation and the AWGN. On the GS, the receiver demodulates and decodes the signals to obtain the output sequence.

The two links of this scheme are independent in terms of FEC coding, minimizing the overall redundancy and therefore occupying less spectrum resources. If powerful FEC codes are used, the system can achieve an overall optimum in the effectiveness and the reliability. However, this also implies the complex decoding operation on the relay, which is difficult, at least for the present.

2) PHY-only Coding System with Decoding on Ground only: As shown in Fig. 3, this scheme is characterized by no decoding on the relay, only coding, and the GS has to perform two decoding operations to obtain the output sequence. It imposes little burden on the relay and is more flexible as the FEC coding scheme can be changed independently of the relay. However, since the coding on the LEO satellite has to counteract two links, it is bound to impose more redundancy if the reliability is guaranteed to be certain.

3) PHY-only Coding System with GEO-partial-decoding on Board: This system is a compromise between the two aforementioned systems, and the key to its performance is whether the relay decoding is successful or not. As depicted in Fig. 4, if the relay decoding succeeds, it then encodes the decoder output sequence, and the GS only needs once decoding. At this time, its architecture is equivalent to the PHY-only coding system with GEO-full-decoding on board. On the contrary, if the relay decoding fails, the decoder input sequence is encoded, and two consecutive decoding operations have to be performed on the GS. At this moment, its architecture is equivalent to the system with decoding on ground only.

4) Layered Coding System: As shown in Fig. 5, the system has the PHY and PKT layers. On the LEO satellite, the original information sequence is first divided into PKTs of the fixed length and encoded by LT codes at the PKT layer. Subsequently, PKTs are sent to the PHY layer for encoding of simple FEC codes, i.e. RS codes. The data is modulated by QPSK and sent to the ISL established in Section II. On the GEO satellite, the demodulated data is first decoded at the PHY layer. After that, error detection takes place in PKT units and the wrong PKTs are discarded. Subsequently, the reserved PKTs are sent to the PHY layer for encoding, modulation, and transmitted to the SGL established in Section II. On the GS, the same operations as the GEO satellite are performed first, including: demodulation, PHY decoding, PKT error detection, PKT discard, and then the receiver decodes the remaining PKTs with LT codes to obtain the output sequence.

If the signal processing steps at the PKT layer is removed, the PHY system of the layered coding system is obtained and its architecture is the same as the PHY-only coding system with GEO-full-decoding on board (only the code is different). Since no decoding operation at the PKT layer of the relay, adding the PKT layer achieves the improvement of system reliability without increasing the relay burden. In another way, the layered coding system can achieve lower relay complexity by using simpler FEC codes at the PHY layer when the reliability of the systems is guaranteed to be the same.

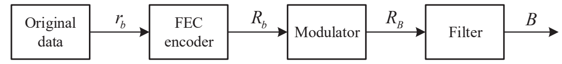

Fig. 6. Transmitter structure.

IV. Description of Evaluation Indexes

The common evaluation indexes for communication systems mainly include the reliability and the effectiveness, but for GEO satellite relay coded systems, the relay complexity must also be considered. In this section, we will discuss these three indexes.

A. Effectiveness

For digital communication systems, the effectiveness is measured in the frequency band utilization. The general transmitter structure with the encoder and modulator is shown in Fig. 6. Assume that the original data bit rate is r_b and the FEC CR is r. Therefore, the rate of encoded data is given by

$$R_b = \frac{r_b}{r}. \tag{8}$$

For the modulation module of the satellite communication system, multiple phase shift keying (MPSK) is often used, so the modulated symbol rate is

$$R_B = \frac{R_b}{\log_2 M}. \tag{9}$$

In a real system, the signal must be filtered to limit its bandwidth before it is sent to the channel, and here a raised-cosine Nyquist filter is chosen that minimizes the inter-symbol interference (ISI). Assume that the roll-off factor is α, so the filtered signal bandwidth is

$$B = (1+\alpha)R_B. \tag{10}$$

Combining (8), (9) and (10), the final band utilization of the original data is

$$\eta_b = \frac{r_b}{B} = \frac{\log_2 M}{1+\alpha} r. \tag{11}$$

Equation (11) shows that when the transmitter modulator and filter is fixed, the band utilization is proportional to the CR.

B. Reliability

The communication system reliability is measured in the error rate (ER). For PHY-only and layered coding systems, we study the bit error rate (BER) and the PKT error rate (PER) respectively. Assume that bits are independent of each other and the PKT length is L bits, so PER is related to BER as

$$\text{PER} = 1 - (1 - \text{BER})^L. \tag{12}$$

In real systems, the ER is related to the input signal-to-noise ratio (SNR) of the demodulator, so the system reliability is often characterized by a SNR-ER curve. For the four systems in this paper, there are all demodulators on the relays, so the noise in the input SNR of the GS demodulator only comes from the SGL. We define K as

$$K = \frac{N_{01}}{N_{01} + N_{02}}, \tag{13}$$

where N_{01} is the noise average power accumulated at the input of the GEO satellite demodulator for the ISL, and N_{02} is accumulated at the input of the GS demodulator for the SGL. K characterizes the relative magnitude of the noise for two links, and it can be determined by the actual link conditions.

C. Relay Complexity

Unlike the GS, which are very rich in computing resources, the complexity on the relay is limited. Relay complexity generally refers to the in-orbit operation complexity regarding decoding, and can be measured directly in decoding complexity. The most intuitive way to compare them of different systems is to count the time consumed by the relay to complete the decoding operation for an equal amount of data.

V. Simulation Results

The parameters of simulation process are chosen as follows. The information sequence is 223×8×5 bits long. The RS code is decoded by the hard verdict through the Berlekamp-Massey (BM) and the Chien search algorithm, and its CR is taken as 223/255. The CC CR is taken as 1/2, and the Viterbi hard verdict decoding is used. LT codes are encoded with the Robust Soliton distribution (RSD) and decoded with the message passing (MP) algorithm. Its CR is chosen as 1/2. We choose 5 symbols as the PKT interleaving depth. The value of K is taken as 0.45.

A. Reliability

Fig. 7 shows the SNR-BER curves for the three PHY-only coding systems. We found two phenomena. First, as the SNR increases, the PHY-only coding system with GEO-partial-decoding on board changes from equating to the system with decoding on ground only to the one with GEO-full-decoding on board. This is because different SNRs affect the success of its relay decoding, so the intersection point A and B appear. Second, the curves of the PHY-only coding systems with decoding on ground only and GEO-full-decoding on board have the intersection point C. This is because two factors combine to affect the reliability of both systems: the SGL effectiveness and the system architecture. The former is significant at high SNRs and makes the system with decoding on ground only more reliable. And the latter is opposite. Considering the acceptable BER order of magnitude (10^{-4}) for image transmission, the system with decoding on ground only has a reliability gain of about 0.6 dB.

According to the three SNR-PER curves shown in Fig. 8, on the one hand, it shows that adding the PKT layer can increase the overall reliability of the layered coding system, and that brings about 0.5 dB gain, considering the acceptable PER order of magnitude (10^{-2}∼10^{-3}). The error floor is caused by LT codes. On the other hand, the layered coding system reliability is not as good as the PHY-only coding system under the current parameters, which mainly comes from the different error correction capability between RS and RS-CC concatenated codes.

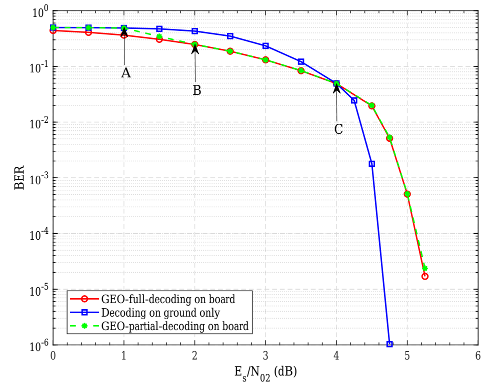

Fig. 7. The reliability of the three PHY-only coding systems.

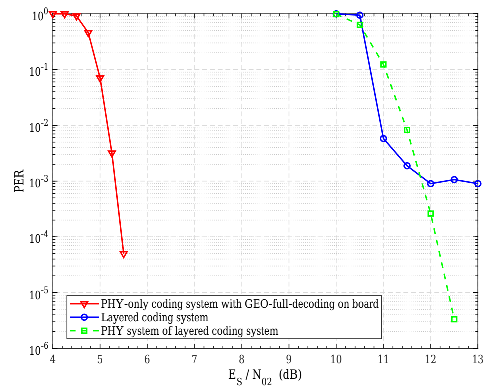

Fig. 8. The reliability of the PHY-only coding system with GEO-full-decoding on board and the layered coding system.

B. Effectiveness

The effectiveness of the four systems on the ISL is consistent according to the parameters, so the overall system effectiveness depends on the SGL, and Table I shows it with different SNRs. We find three phenomena. First, only the PHY-only coding system with GEO-partial-decoding on board is related to the SNR. In fact, the SNR is divided by its equivalent system, consistent with the description in Section III. Second, the PHY-only coding system with decoding on ground only has the lowest overall effectiveness due to no decoding on the relay. Finally, the layered coding system is as effective as the PHY-only coding system with GEO-full-decoding on board under the current parameters. There are two reasons. On the one hand, we chose the same CR for the CC and LT code. On the other hand, Fig. 9 shows the reliability curves of the three PHY-only coding systems encoded with RS codes, which reveals that the ISL effect can be completely eliminated

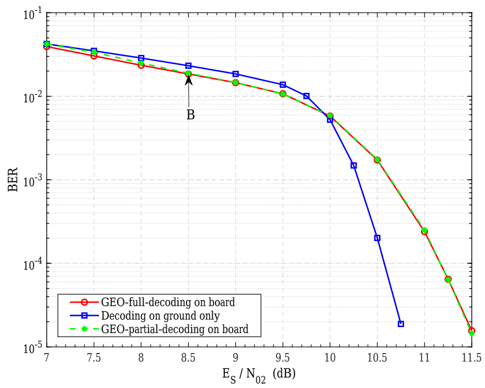

Fig. 9. The reliability of the three PHY-only coding systems using RS codes.

TABLE I
THE EFFECTIVENESS OF THE FOUR SYSTEMS ON THE SGL

System	SNR	CR
GEO-full-decoding on board	low	223/510
	high	223/510
Decoding on ground only	low	49729/260100
	high	49729/260100
GEO-partial-decoding on board	low	49729/260100
	high	223/510
Layered coding system	low	223/510
	high	223/510

TABLE II
THE RELAY COMPLEXITY OF THE FOUR SYSTEMS

System	Relay decoding time(s)
GEO-full-decoding on board	2.5781
Decoding on ground only	0
GEO-partial-decoding on board	2.5775
Layered coding system	1.1847

by demodulation and decoding on the GEO satellite when the SNR is greater than 8.5 dB. Therefore, all the PKTs on the GEO satellite of the layered coding system are correct and reserved.

C. Relay Complexity

Table II shows the relay complexity of the four systems. The PHY-only coding system with decoding on ground only has the lowest relay complexity due to no decoding on the relay. Within a reasonable range, we can consider that the relay complexity of the PHY-only coding systems with GEO-full-decoding and GEO-partial-decoding on board are the same. This is because for the latter, decoding operation is objectively required regardless of success or not. At the PHY layer, simpler codes are chosen for the layered coding system, so its relay complexity is low.

In summary, the PHY-only coding system with decoding on ground only is optimal in terms of reliability and relay complexity, but the effectiveness is the lowest. The PHY-only coding system with GEO-full-decoding on board is overall optimal in terms of effectiveness and reliability, but the relay complexity is too high. The layered coding system compromises the two systems above in terms of the three indexes as a whole, and it has more potential advantages in the current scenario, with certain reliability and avoiding the excessive relay complexity and spectrum resource occupation.

VI. CONCLUSION

In this paper, we analyze the actual influencing factors of the ISL and SGL in detail, and then establish four GEO satellite relay coded systems, and comprehensively compare them from three indexes of the effectiveness, the reliability, and the relay complexity. We find that the layered coding system has more advantages in the current scenario, and we can also provide ideas for selecting systems among the four ones in this paper according to needs of the three indexes in other application scenarios.

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