Power Allocation Method for Satellite Communication Based on Network Coding

Jin Liu[1], Zhuoming Li[1](✉), and Gongliang Liu[2]

[1] School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin 150001, China
Zhuoming@hit.edu.cn

[2] School of Information Science and Engineering, Harbin Institute of Technology at Weihai, Weihai 264209, China

Abstract. With the development of aerospace technology, more and more application tasks require satellite communications for information transmission. In space communication, the resources on the star are very precious, and it is particularly urgent to improve the utilization of resources on the star. The application of network coding in satellite communication can not only solve the traditional routing problem, but also greatly improve the reliability and efficiency of communication. So the power allocation method on satellite based on network coding is proposed. Two power allocation algorithms can improve the utilization of inter-satellite resources, and the network coding of relay nodes can reduce the bit error rate and the packet loss rate of the communication system. The simulation results show that network coding can reduce the bit error rate of the system and the impact of different power allocation algorithms on the bit error rate of the system.

Keywords: Network coding · Satellite communications · Game theory · Water injection method

1 Introduction

Inter-satellite communication is one of the hottest issues in the field of satellite communication. Although there are many satellites in the sky, most of them are self-contained and it is difficult to achieve resource sharing. However, it is difficult for a single satellite to meet various needs. The realization of multi-point communication between satellites is an inevitable trend in the development of satellite communications. Network coding is a new technology of network communication, which can optimize the transmission performance of the network. Research shows that the application of network coding in satellite communication can not only solve the traditional routing problem, but also greatly improve the reliability and efficiency of communication.

In terms of satellite resource allocation methods, Literature 2 designs a bandwidth and power allocation algorithm to ensure efficient use of satellite resources. In the third paper, considering the QoS requirement, the Lagrangian heuristic algorithm is used to solve the subcarrier allocation problem of low-orbit satellite networks. Literature 4 considers the impact of delay on real-time services, and proposes a power and

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bandwidth resource allocation method to achieve a balance between throughput and delay. Document 5 proposes a power and bandwidth allocation method for a multi-beam satellite network to improve the fairness of the capacity among beams. The above method is mainly for downlink resources and is not suitable for inter-satellite links. The application of network coding technology in satellite communication can not only solve the traditional routing problem, but also greatly improve the reliability and efficiency of communication.

Aiming at the problem of high bit error rate of satellite communication, considering the application of network coding to satellite communication, two power optimization methods on satellite based on network coding are proposed. With the goal of reducing the bit error rate, the network coding satellite communication system is optimized for power, and the bit error rates of the two methods are compared.

The following is a brief introduction to the contents of each section. The second part introduces the concept of network coding. The third part introduces three kinds of satellite communication system based on network coding. The fourth part introduces a satellite communication system combined with network coding and power allocation algorithm.

2 Network Coding

Taking the "butterfly net" model as an example, the basic concepts of network coding are analyzed. As shown in the following figure: assume that the capacity of each link is 1, y and z are both sink nodes, s is the source node, and the rest are intermediate nodes. In Fig. 1(a), the traditional route transmission mode is used. Node w is only responsible for the operation of storage and forwarding. Figure 1(b) uses the network coding method. The node w is mainly responsible for encoding the input information, and then adding module 2 to b1 and b2, and transmitting the operation result b1 ⊕ b2 to the node x. The result of the operation is finally transmitted to the nodes y and z through the links xz and xy. After the node y receives the information b1 and the information b1 ⊕ b2, it can decode the b1 ⊕ (b 1 ⊕ b2), so that the information b2 can be solved. Similarly, the node z can decode the complete information in this way, and the resulting transmission has a capacity of 2. It can be seen that the application of network coding to satellite communication can theoretically achieve the maximum amount of information transmission. At the sink node, this can be done by performing the inverse of the decoding and will eventually be able to be sent from the source of the original data.

Based on the characteristics of satellite communication networks, network coding is particularly suitable for the field of satellite communication networks. If a node generates interest in different data packets of neighboring nodes, it can effectively save satellite communication by encoding these different data packets so that it and all neighboring nodes can receive information of the data packets in them. Therefore it effectively saves satellite communication resources. In addition, the application of network coding in the satellite communication network can also significantly reduce the times of transmitting data packets, so that the transmission energy is greatly reduced.

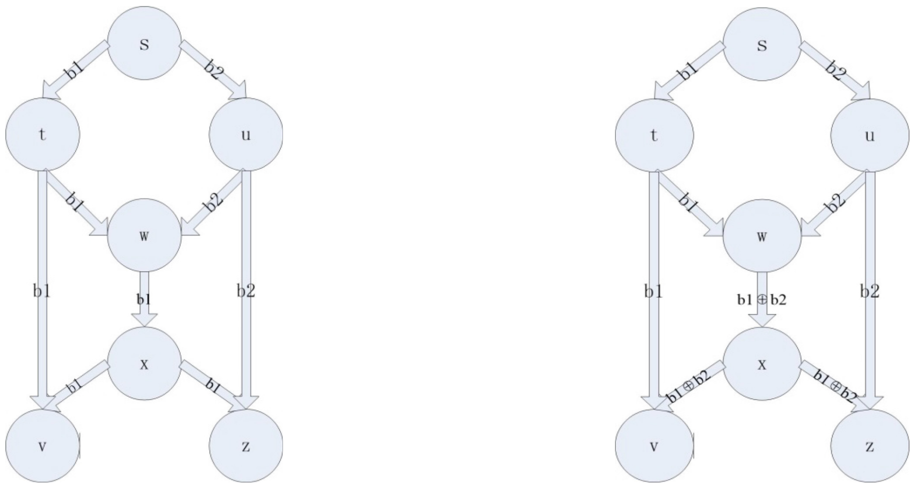

Fig. 1. (a) Traditional routing. (b) Network coding method.

And we will briefly introduce two power allocation algorithms which include game theory and water injection method in the forth section.

3 Satellite Communication System Simulation Based on Network Coding

3.1 ARQ Mechanism Based on Network Coding

System Model and Principle

In recent years, many scholars at home and abroad have been concerned about the problem of service transmission performance in satellite communications. However, the environment in which satellite channels are located is very complex, and these complex environments can significantly reduce the communication quality of satellite channels. Due to the particularity of satellite channels, many terrestrial protocols are often inefficient when applied to satellite networks. In order to overcome this problem, the researchers have made in-depth analysis and improved the ARQ for the satellite environment based on the idea of terrestrial ARQ. ARQ mainly has three modes: stop waiting, backward N step and selective retransmission. In addition, network coding has been widely used in the field of wireless communications. A large number of studies have shown that network coding in wireless communication can reduce the number of packet retransmissions and packet loss rate. In order to further reduce the transmission delay and the number of packet loss of the satellite channel, the network coding is applied to the ARQ of the satellite network, and a network coding-based ARQ (Sat-NC-ARQ) mechanism suitable for the satellite network is proposed. In Sat-NC-ARQ, in addition to transmitting the data packets of the real service terminal, the satellite terminal also creates a virtual service terminal to send the network coded data packets, so that the receiving terminal can decode the data packets as long as it receives enough data packets. So it can reduce the number of retransmissions.

As shown in Fig. 2, the source service terminals S1 and S2 are connected to the source satellite terminal through the terrestrial link, and the destination service terminals D1 and D2 are connected to the destination satellite terminal through the terrestrial link, and the source satellite terminal connect with the destination satellite terminal through satellite link.

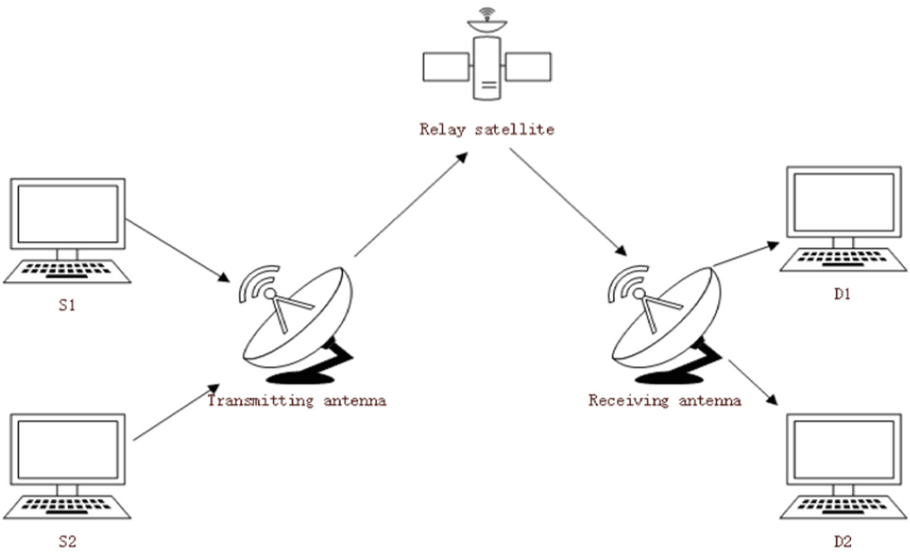

Fig. 2. System model of ARQ mechanism.

It is assumed that the source service terminal S1 is to send the data packet 1101 to the destination service terminal D1, and the source service terminal S2 is to send the data packet 1001 to the destination service terminal D2. First, S1 and S2 respectively send data packets to the source satellite terminal through the terrestrial link. When the source satellite terminal receives the data packets of S1 and S2, it can perform network coding on the data packets of S1 and S2, that is XOR, i.e. 1101 XOR 1001 = 0100; then the data packets 1101, 1001 and the network coded packet 0100 are sent together to the destination satellite terminal. When the destination terminal receives any two of the three data packets, the original data packet can be decoded by using the network coding. For example, it is assumed that the destination satellite terminal receives the data packet 1101 of S1 and the network coded data packet 0100, and the data packet 1001of S2 is lost, and the destination satellite terminal can decode the data packet of S2 by XOR operation 1101XOR0100 = 1001. The destination satellite terminal can then send the packets of S1 and S2 to D1 and D2 respectively. It can be seen from the example that when the packet of S2 is lost, the Sat-NC-ARQ mechanism does not need to retransmit the packet data by S2, so the transmission delay and the number of lost packets of the satellite network can be reduced.

Simulation Analysis

To simplify system processing, we can adjust the length of the packet to send one packet every 1 ms. At the same time, it can be assumed that each source service terminal polls the packets at each moment in turn. In order to introduce the network coding, after the source satellite terminal receives the data packets of the two source service terminals, the two data packets are network coded (XOR operation), and then the two data packets and the network coding packets are sequentially sent to destination satellite terminal. To formalize the problem, a virtual source service terminal s and a virtual destination service terminal d are created. The virtual source service terminal is responsible for performing a network coding task and transmitting a network coding packet of two data packets when each of the two source service terminals transmits a data packet.

When attention is paid to the packet loss rate, the data is continuously transmitted, and when an error occurs, no retransmission is performed (that is, no delay is considered). The method of packet loss is that when the crc check fails, the packet considers the data invalid. Therefore, under this condition, the bit error rate is 0, and only the packet loss rate is concerned. Figure 3 shows the simulation.

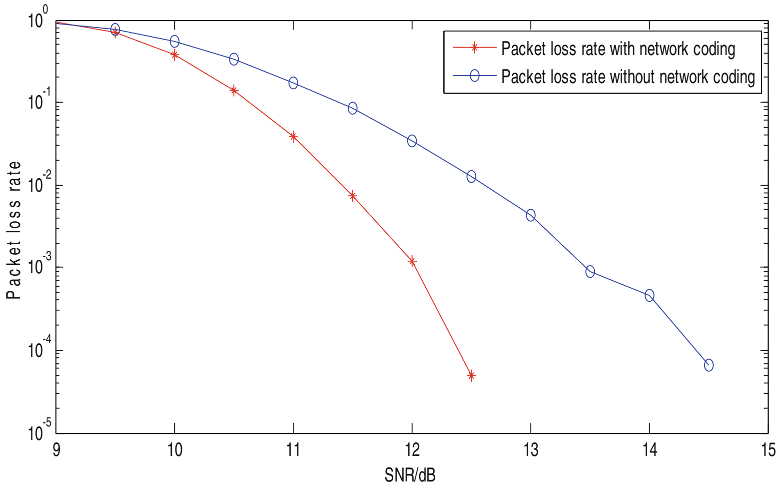

Fig. 3. Comparison of packet loss rate under ARQ mechanism.

The ARQ mechanism based on network coding achieves the goal of reducing the number of packet loss on the satellite channel by reducing the number of retransmissions of data packets. The simulation results also show that network coding can reduce the packet loss rate of satellite networks.

3.2 Satellite Physical Layer Network Coding System

System Model and Principle

Two low-orbit satellites are used as the data source of the system, and the schematic diagram of the satellite physical layer network coding system is shown in Fig. 4. In the MAC phase, the source nodes S1 and S2 simultaneously transmit data to the ground relay node R and the destination node within the respective coverage area, wherein the source node S1 covers the relay node R and the destination node T1, and the source node S2 covers the relay node R and destination node T2. In the BC phase, after the relay node R is processed in the forwarding mode, the superposed signal is broadcasted to the destination nodes T1 and T2.

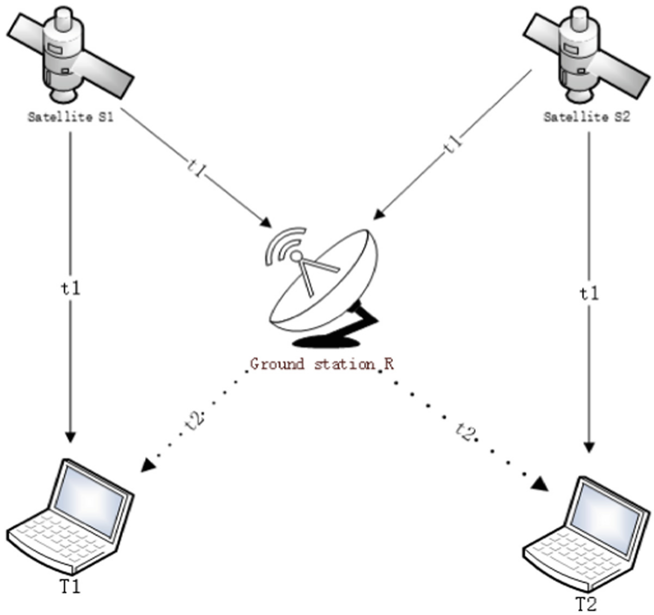

Fig. 4. Satellite physical layer network coding system model.

System Description: The transmission process of the system data is divided into two phases: one is the multiple access phase (MAC), in which the satellite source node transmits its own data to the destination node and the relay node; the second is broadcast phase (BC). After the relay node uses the function to process the superimposed signal, the signal is broadcasted to the two destination nodes, and the destination node uses the known information of the destination as the reference information to extract the transmitting information of the other end to complete the decoding process.

In the MAC phase, the signals of the relay node R receiving the signals X_1 and X_2 from S1 and S2 can be expressed as:

$$Y_R = \sqrt{\mathrm{P_{S1}}}\mathrm{h_1}X_1 + \sqrt{\mathrm{P_{S2}}}\mathrm{h_2}X_2 + n_g \tag{1}$$

Among them, $\mathrm{P_{S1}}$ and $\mathrm{P_{S2}}$ are the transmission powers of the source nodes S1 and S2, $\mathrm{h_1}$ and $\mathrm{h_2}$ are the channel gains between the source nodes S1 and S2 and the ground relay R, and X_1 and X_2 are the transmission information of the source nodes S1 and S2, and n_g is the relay node R receives the superimposed noise of the signals X_1 and X_2.

In the case of a sunny day, it is assumed that the channel gains between the nodes in the same coverage area and the satellite are the same, so the signals the terminal nodes T1 and T2 receive are represented by Eqs. (2) and (3), respectively.

$$Y_{T1} = \sqrt{\mathrm{P_{S1}}}\mathrm{h_1}X_1 \tag{2}$$

$$Y_{T2} = \sqrt{\mathrm{P_{S2}}}\mathrm{h_2}X_2 \tag{3}$$

At about 10 GHz or more, rain attenuation is the main attenuation of satellite wireless communication. This paper uses the ITU-R rain attenuation model, as shown in Eq. (4):

$$\mathrm{A} = \left(\frac{\mathrm{C}}{\mathrm{N_0}}\right)_{\mathrm{t.e}} - 10\log_{10}\left(\frac{1}{10^{\frac{\mathrm{S_u - A_u}}{10}}} + \frac{1}{10^{\frac{\mathrm{S_d - A_d}}{10}}}\right)^{-1} \mathrm{dB} \tag{4}$$

Among them, $\left(\frac{C}{N_0}\right)_{t.e}$ is the signal-to-noise ratio of sunny day, the unit is dB, S_u and S_d are the uplink and downlink signal-to-noise ratios on sunny days, and A_u and A_d are the up and down attenuation due to rain attenuation.

In the BC phase, the relay node R amplifies and forwards the received signal to the two destination nodes, and the received signals of T1 and T2 can be expressed as Eqs. (5) and (6), respectively.

$$Y_{T1} = \mathrm{Gh_3}Y_R + n_{T1} = \mathrm{Gh_3h_1}\sqrt{\mathrm{P_{S1}}}X_1 + \mathrm{Gh_3h_2}\sqrt{\mathrm{P_{S2}}}X_2 + \mathrm{Gh_3}n_R + n_{T1} \tag{5}$$

$$Y_{T2} = \mathrm{Gh_4}Y_R + n_{T2} = \mathrm{Gh_4h_1}\sqrt{\mathrm{P_{S1}}}X_1 + \mathrm{Gh_4h_2}\sqrt{\mathrm{P_{S2}}}X_2 + \mathrm{Gh_4}n_R + n_{T2} \tag{6}$$

While G is the amplification gain, $\mathrm{h_3}$ and $\mathrm{h_4}$ are the channel gains of the relay node R and the destination nodes T1 and T2, and n_{T1} and n_{T2} are the additive white Gaussian noise of the destination node, $n_{T1}, n_{T2} \sim \mathrm{CN}(0, \sigma_\mathrm{T}^2)$.

$$G = \sqrt{\frac{\mathrm{P_R}}{\mathrm{P_{S1}}|\mathrm{h_1}|^2 + \mathrm{P_{S2}}|\mathrm{h_2}|^2 + \delta_R^2}} \tag{7}$$

Simulation Analysis

Two low-orbit satellites are used as data sources, one ground station is used as a relay node, two destination nodes are base stations in the respective coverage areas of two satellites, and the channel between the satellite and the relay node uses a wireless channel, and the channel from the relay node to the destination node uses a wired channel. The wireless channel noise n of the source node to the node in the coverage domain is set as additive white Gaussian noise, and the channel gain is a Gaussian random variable with a mean of 0 and a variance of 1. Refer to Feng Yun No.3 Constellation, the satellite constellation parameters are shown in Table 1. The orbital height is 836.4 km, two orbital planes. The two satellites will send data to the ground synchronously in six equal time segments within 24 h. It is assumed that the two satellite communication bands adopt the Ka band, and the satellite downlink transmission power is the same and the system is completely synchronized. The Ka band frequency range is 37.5–40.5 GHz. When the Ka band is transmitted, the channel performance is greatly affected by the rainfall environment, and the ITU-R rain attenuation model is used in the simulation. The modulation and demodulation method are BPSK.

Table 1. Satellite parameter.

Parameter	Parameter value
Track height/km	836.4
Orbital inclination/degree	98.753
Cycle/min	101
Number of satellites	2
Number of tracks	2
Constellation type	Feng Yun No.3 Constellation

Figure 5 shows the error rate simulation.

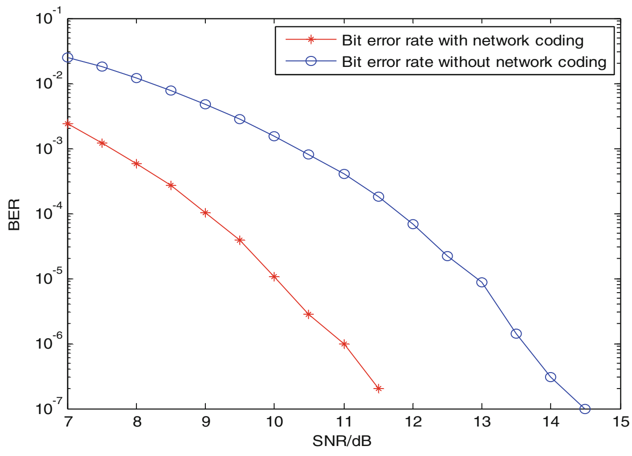

Fig. 5. Bit error rate comparison between network coding and no network coding.

As can be seen from the figure, network coding can significantly reduce the system's bit error rate.

3.3 Network-Coded Satellite Broadcast Retransmission System

System Model and Principle

Figure 6 shows a model of a satellite broadcast retransmission system.

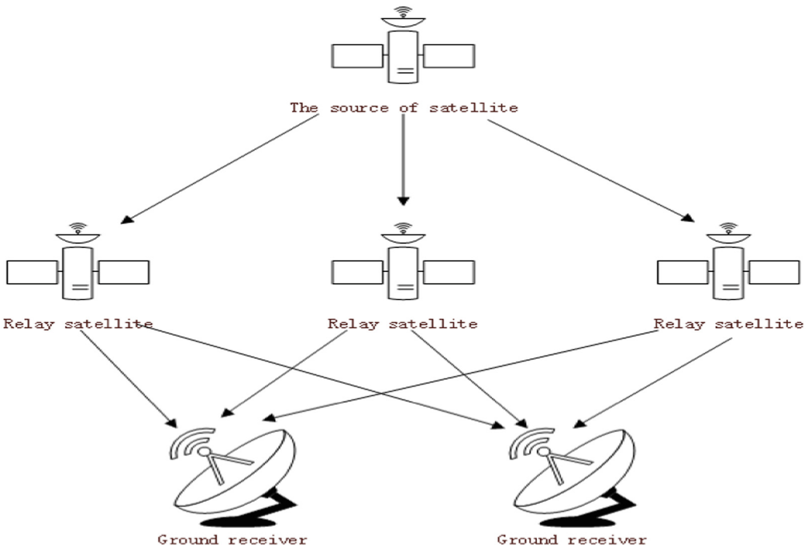

Fig. 6. Model of satellite broadcast retransmission system.

The satellite broadcasting system is an information publishing platform based on packet transmission. Due to atmospheric fading, multipath fading, etc., the channel has a higher error rate, and the corresponding packet error probability is higher. In order to ensure reliable distribution, the traditional method is that each user feeds back his or her receiving status to the satellite, and the satellite then retransmits the lost packets based on the feedback information, and the channel utilization rate is extremely low.

At present, satellite communication mainly adopts the broadcasting communication mode. The satellite broadcasts the data to the ground. When the local area receives the error, it needs to apply for data retransmission to the satellite. This mechanism is shown in the figure above.

The source satellite transmits the signal of S = [S1, S2, S3 …. Sn] to the relay satellite, and the relay satellite forwards it. When the signal is continuously transmitted, the signal ground receives will have errors at different times. And the wrong frame numbers different ground receiving devices receive may be different due to the uncertainty of satellite communication transmission during actual reception. For example, the first ground receiving device has an error in the S1 frame, and the second one is in the S2 frame. In the original broadcast mode, any frame error in any device needs to be retransmitted, which brings great obstacles to satellite communication. The network coded retransmission can wait for each device to appear up to two frames of error before retransmission. It is assumed that during the retransmission process, the receiving node can receive the data packet broadcast by the source node without error.

Simulation Analysis

In order to verify the superiority of network coding, we carried out simulation comparison of packet loss rate. Figure 7 shows the comparison of packet loss rates.

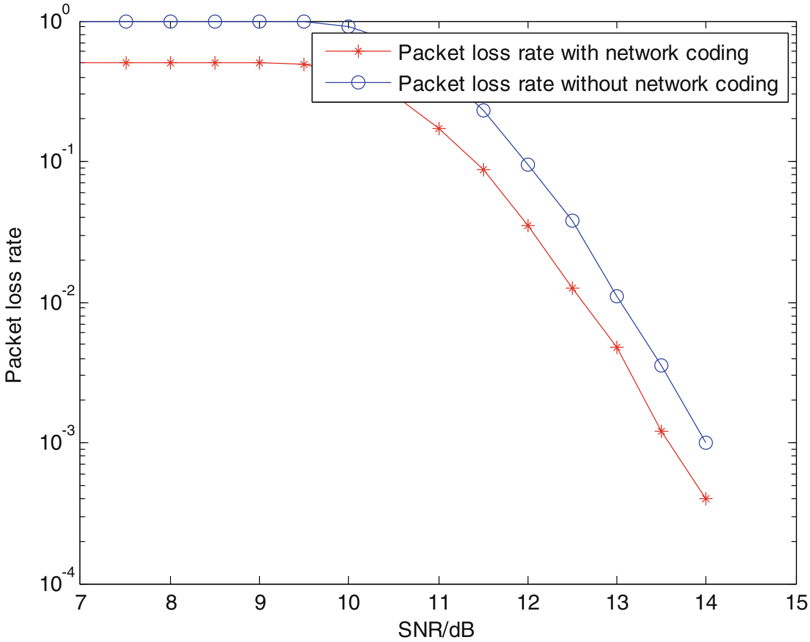

Fig. 7. Comparison of packet loss rate with and without network coding.

It can be seen from the above figure that network coding can significantly reduce the packet loss rate of the satellite broadcasting system.

3.4 Summary

Through the analysis and simulation of three kinds of satellite communication methods using network coding, and observing the optimization effect of network coding on satellite communication, it can be seen that the application of network coding to satellite communication can improve the data transmission rate and improve the robustness of communication. When the satellite communication delay is large and the bit error rate is high, the network coding can effectively reduce the bit error rate of the satellite broadcast communication system and reduce the times of retransmission.

4 Power Allocation Method on Satellite Based on Network Coding

4.1 System Model and Basic Description

We used the same satellite model as the second case in the previous section. Figure 8 shows the system model.

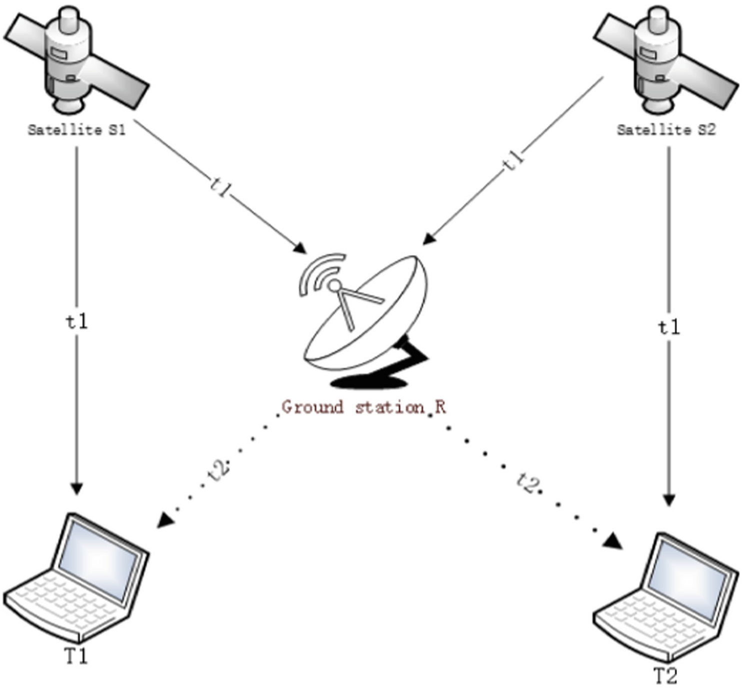

Fig. 8. System model of power allocation method on satellite based on network coding.

The model and the basic principle are exactly the same as the second case of the previous part. The difference is that two resource allocation algorithms are added to further optimize the system performance. The power of S1 is $P1$, the power of S2 is $P2$, the power of R is $P3$ and $P1+ P2+ P3<$ P_all. P_all is the maximum total power.

The transmission method without network coding is as follows:

Divided into four time gaps, in t1, the information of S1 is sent to R, in t2, R broadcasts the information it receives to T2, in t3, the information of S2 is sent to R, in t4, R broadcasts the information it receives to T1.

The transmission method with network coding is as follows:

Divided into three time gaps, in t1, the information of S1 is sent to R, in t2, the information of S2 is sent to R, in t3, R broadcasts network coded information to T1and T2.

The power allocation method adopts the game function-based utility function optimal method and the greedy water injection method:

The utility function allocation method based on game theory adopts the game theory. Under the condition of fixed total power and total transmission bandwidth, the lowest bit error rate T1 and T2 receive is the target utility function, that is, the utility function is:

$$U = \frac{err_{T1} + err_{T2}}{\mathrm{data}_{\mathrm{T1}} + \mathrm{data}_{\mathrm{T2}}} \tag{8}$$

In order to achieve the minimum utility function, the power of T1 and T2 are distributed by means of game distribution to achieve the result of Nash equilibrium, and the utility function is minimized.

The greedy water injection method is based on the greedy resource allocation method. The independent target criterion is adopted for different receiving sources. The error rate of each of T1 and T2 which reaches a target threshold is regarded as the judgment condition to adjust the power allocation. No adjustments are made when the target value is reached.

4.2 Simulation Analysis

It is assumed that S1 is to send the data packet 1101 to the destination service terminal T1, and S2 is to send the data packet 1001 to the destination service terminal T1. First, S1 and S2 need to send data packets to the ground station through the satellite link. When R receives the information of both, it can perform network coding on the data packets of S1 and S2, that is, XOR operation. It is 1101 XOR 1001 = 0100. Then it directly broadcasts a coded data result.

If network coding is not used, the dual-worker network needs to adopt the method of time division multiplexing or frequency division multiplexing to achieve the dual power effect, so that the required transmission power is twice as much as the original. Therefore, pay attention to the difference in the bit error rate between the two when the transmission power is the same.

Game-Based Power Allocation Without Network Coding

In the case of no network coding, when the power distribution of S1 and S2 is optimal, the bit error rate is the lowest, and the game is used for resource optimization. As shown in Fig. 9, when there is no network coding, the relationship between BER and the power of S1 and S2 are both convex function, so the optimal solution in the figure below is:

P1 = 0.165
P2 = 0.150
P3 = 0.185
Lowest bit error rate is 1.01×10^{-3}.

In the game mode, S1 and S2 respectively increase the power. After each additional power increase, the error rate is checked. If the bit error rate decreases, the power

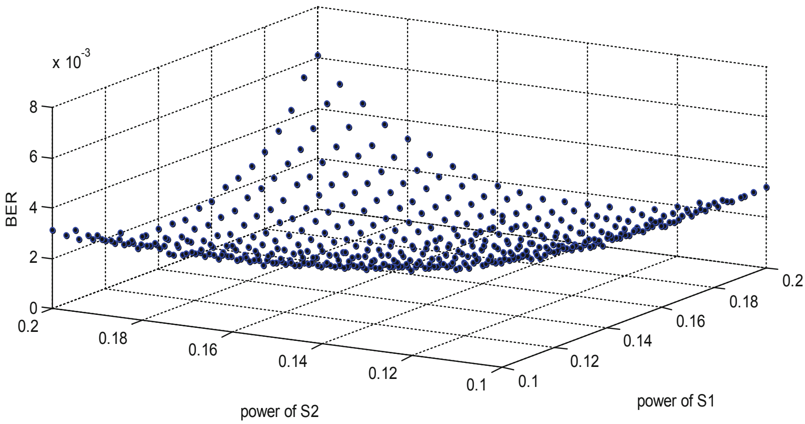

Fig. 9. Relationship between game-based power allocation and bit error rate without network coding.

operation is continued. If not, the previous step is returned, and the power of the other end is adjusted.

Water-Based Power Allocation Without Network Coding

Without the network coding, the resource allocation of S1 and S2 adopts the water injection mode. Under the greedy water injection mode, S1 and S2 only care about the error rate they receive, so they will continuously increase their power to achieve the expected result of the error. Due to S1 and S2 is uncorrelated, a single power is used as the abscissa. As shown in Fig. 10, when there is no network coding, the optimal solution in the following figure is:

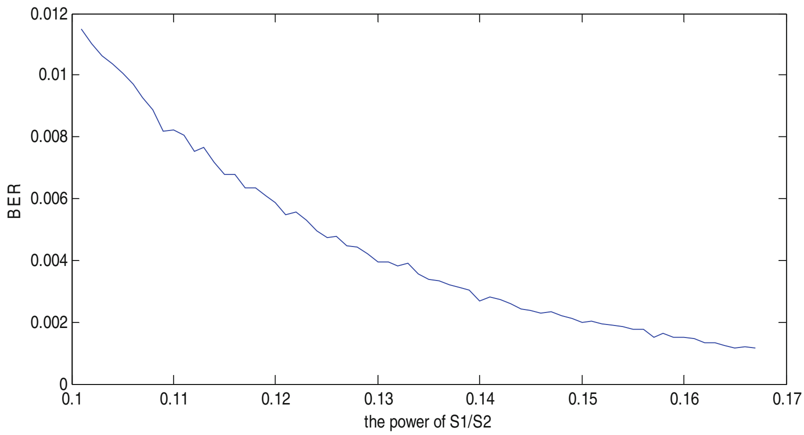

Fig. 10. Relationship between power distribution based on water injection and bit error rate without network coding.

P1 = 0.167
P2 = 0.167
P3 = 0.167
Bit error rate is 1.22×10^{-3}.

In the water injection mode, S1 and S2 increase power at the same time, and when the power is increased, it is checked whether its error rate has reached the expected value. Since the error rate setting in the program is expected to be 1×10^{-4}, in this state, S1 and S2 will continue to improve their own power.

Game-Based Power Allocation with Network Coding
After the network coding is used, the output data R broadcasts is changed from the original 1000 bit to 500 bit, and the Eb/n0 is increased by 3 dB under the same power. So the optimal solution of the resource allocation is changed. Figure 11 shows the error rate simulation.

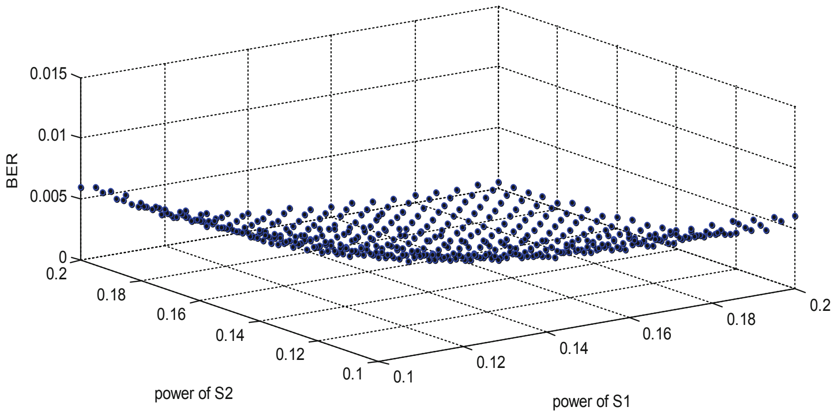

Fig. 11. The relationship between power allocation and bit error rate based on game theory with network coding.

From Fig. 11, the optimal solution is:

P1 = 0.1900
P2 = 0.1950
P3 = 0.1150
Bit error rate is 4.9×10^{-4}.

Due to the use of network coding, the bit error rate is reduced under the limit of the same maximum power.

Water-Based Power Allocation with Network Coding
With the network coding, the output data R broadcasts is changed from the original 1000 bit to 500 bit, and the Eb/n_0 is increased by 3 dB under the same power. However, under the water distribution mode, the power allocation of the optimal

solution has not changed because the expected bit error rate is not achieved, but the bit error rate has been reduced. Figure 12 shows the error rate simulation.

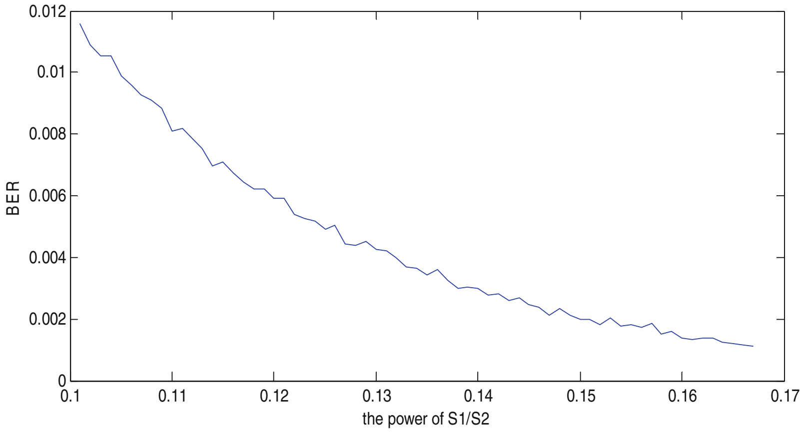

Fig. 12. Relationship between power allocation based on water injection and bit error rate with network coding.

The optimal solution is:
P1 = 0.167
P2 = 0.167
P3 = 0.167
Bit error rate is 1.00×10^{-3} (Table 2).

Table 2. Comparison of bit error rate in 4 ways.

Bit error rate	Game theory	Water injection
Network coding	4.9×10^{-4}	1.0×10^{-3}
No network coding	1.01×10^{-3}	1.22×10^{-3}

4.3 Summary

Through the comparison of the bit error rates in the above four cases, it can be seen that the network coding rate in the resource allocation mode is lower than that in the case of no network coding, that is, the performance is improved. The superiority of network coding is illustrated. The bit error rate of game-based resource allocation method in this particular satellite scenario is lower than that of the water injection-based system. So the game theory has certain advantages.

5 Conclusion

By analyzing and simulating three common satellite communication methods with network coding, and observing the optimization effect of network coding on satellite communication, it can be seen that network coding applied to satellite communication can improve data transmission rate and improve communication robustness. At the same time, in the case of satellite communication delay and high bit error rate, the use of network coding can effectively reduce the number of retransmissions and reduce the bit error rate of satellite broadcast communication system. In addition, by comparing the two types of resource allocation methods with or without network coding in a specific satellite scenario, that is, the comparison of the bit error rates in four cases, it can be seen that the network coding is better than the case of no network coding in any resource allocation mode. The bit error rate has been reduced to a certain extent, that is, the performance has been improved, indicating the superiority of network coding. The bit error rate of power allocation method based on the game theory is lower than that of power allocation method based on the water injection. The game theory has certain advantages, that is, the choice of resource allocation method also has a certain impact on system performance.

References

1. Nakahira, K., Abe, J., Mashino, J.: Novel channel allocation algorithm using spectrum control technique for effective usage of both satellite transponder bandwidth and satellite transmission power. IEICE Trans. Commun. **95**(11), 3393–3403 (2012)
2. Wu, X.L., Chen, Y.Y., Gao, L.Q., et al.: A utility-based OFDM resource allocation scheme for LEO small satellite system. In: International Conference on Cyberspace Technology, pp. 68–73. IET, Stevenage
3. Ji, Z., Wang, Y.Z., Feng, W., et al.: Delay-aware power and bandwidth allocation for multiuser satellite downlinks. IEEE Commun. Lett. **18**(11), 1951–1954 (2014)
4. Wang, H., Liu, A.J., Pan, X.F.: Optimization of joint power and bandwidth allocation in multi-spot-beam satellite communication systems. Math. Probl. Eng. **20**(4), 1–9 (2014)
5. Kaveh, A., Bakhshpoori, T., Afshari, E.: An efficient hybrid particle swarm and swallow swarm optimization algorithm. Comput. Struct. **14**(3), 40–59 (2014)
6. Fujii, H., Asai, T., Okumura, Y., et al.: Capacity achievable by spectrum sharing with adaptive transmit power control: based on field measurements. In: 2009 4th International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CROWNCOM 2009, pp. 1–6. IEEE (2009)
7. Cheung, K., Lau, C., Lee, C.: Link analysis for space communication links using ARQ protocol. In: Aerospace Conference, pp. 1–8. IEEE
8. Fong, S.L., Yeung, R.W.: Variable-rate linear network coding. In: Proceedings of IEEE Information Theory Workshop (ITW), Chengdu, pp. 409–412
9. Jaggi, S., Sanders, P., Chou, P.A., et al.: Polynomial time algorithms for multicast network code construction. IEEE Trans. Inf. Theory **51**(6), 1973–1982 (2005)
10. Bahramgiri, H., Lahouti, F.: Robust network coding using diversity through backup flows. In: 4th Workshop on Network Coding. Theory and Applications, NETCOD 2008, Hongkong, pp. 1–6
11. Eritmen, K., Keskinoz, M.: Improving the performance of wireless sensor networks through optimized complex field network coding. IEEE Sens. J. **15**(5), 2934–2946 (2015)