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Optimization of Transmission Control of Heterogeneous Integrated Satellite Networks and Terrestrial Multi-hop Networks

Mengyao He[1], Liang Zong[2] and Gaofeng Luo[2,*]

[1]*College of Mechanical and energy Engineering, Shaoyang University, Shaoyang 422000, China*
[2]*College of Information Engineering, Shaoyang University, Shaoyang 422000, China*

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Abstract

High bit error rate (BER), long delay, dynamic networking and multi-hop nature of satellite networks can affect the transmission performance of integrated networks, which poses a great challenge to the transmission performance of space-air-ground integrated networks constructed by satellite networks and terrestrial multi-hop networks. In order to improve the transmission rate of heterogeneous converged satellite networks and terrestrial multi-hop networks, this study proposed a scheme applicable to the transmission characteristics. By analyzing the transmission characteristics of satellite networks with long delay and high BER and terrestrial wireless multi-hop networks, the data delivery in the slow start-up phase was improved, and the type of lost data in the congestion avoidance phase was discriminated to enhance the transmission performance of the heterogeneous integrated network. The performance of the proposed scheme was further verified by simulation on OPNET software. Results show that, the proposed scheme not only can effectively reduce the queuing delay of nodes but also can enhance the transmission efficiency of multi-hop network terminals and the data transmission rate in the long delay network environment. With the increase in the number of hops, the transmission rate of the proposed protocol is about twice those of other protocols. Therefore, the proposed scheme can help improve the transmission performance of heterogeneous integrated satellite networks and terrestrial multi-hop networks.

Keywords: Satellite network, Data transmission, Multi-hop network, Heterogeneous fusion

1. Introduction

The rapid development of wireless network technology has increased the demands for network access services in social production and human lives. Satellite networks can satisfy the demands of end customers for emergency communications after disasters in isolated regions and maritime settings. Terrestrial multi-hop networks have the capability to extend network coverage without the need for preexisting network infrastructure, which greatly reduces the loss of manpower and material resources. The heterogeneous integration of satellite networks and terrestrial multi-hop networks significantly facilitates the implementation in some special environments.

However, some transmission conditions in unfavorable circumstances further aggravate the delay and loss of data transmission rate, and the network has more obvious reliability and instability. The poor utilization of network resources leads to paralysis and excessive congestion of the network. These problems are challenging to heterogeneous integrated wireless communication networks [1].

Extensive research has been undertaken on the transmission efficiency of heterogeneous integrated satellite networks and terrestrial multi-hop networks [2-4]. Considering different communication protocols and transmission characteristics, the way to effectively integrate satellite networks and terrestrial multi-hop networks and realize seamless integration and interoperability is a problem that has not yet been solved. Although satellite networks can realize global coverage, some challenges arise in the communication performance in complex terrain and dangerous environmental conditions. Therefore, improving the transmission performance in special environments is an urgent concern.

By analyzing the distinct network characteristics of heterogeneous integrated satellite networks and terrestrial multi-hop networks, this study delved into their transmission performance, and the optimization theory of transmission control was comprehensively analyzed. A model was proposed from the perspectives of reducing data transmission delay and improving data transmission rate. The problem was decomposed, and a network control strategy was designed for the proposed model. The findings of this study offer valuable insights for enhancing the transmission performance of satellite networks and multi-hop networks.

2. State of the Art

2.1 Transmission control of satellite networks

At present, scholars are conducting numerous studies on satellite network transmission control. Data transmission performance in different environments has been optimized, particularly in maritime environments with difficulty in network deployment. Zong [5] proposed a transmission control protocol (TCP)/IP-based transmission scheme in view of large bandwidth delay product, high delay, and high bit error rate (BER) of satellite networks, but the damage to communication facilities after disasters was ignored. Nguyen [6] established a comprehensive analytical model,

*E-mail address: gfluo12@163.com
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grounded in cross-layer TCP performance, that quantitatively demonstrated the influence of transmission errors on the last mile link. Ensuring the continuity of communication is particularly important in the face of post-disaster damage to infrastructure communication facilities. Pervez [7] proposed an alternating iterative algorithm based on block descent method thereby achieving a faster solution to the optimization problem for each time period by jointly optimizing the user associations, transmission power, and trajectories to maximize the average throughput between users by taking into account different restrictions and quality of service (QoS) constraints. Wang [8] developed a networking approach leveraging support vector machine (SVM) for LSN, aiming to enhance the performance of NTC. The dynamic planning transmission contact planning scheme based on SVM can attain superior NTC performance and ensure uninterrupted service continuity, but a large amount of computational resources are needed for model training, which may increase network response latency. Nguyen [9] discussed the performance of the TCP for FSO/RF-based hybrid satellite network and analyzed the impact of different types of cloud on TCP throughput performance. However, FSO link is completely broken and inoperative under some extreme weather conditions.

In addition, transmission control of heterogeneous networks has been extensively studied. Xia [10] analyzed the existing heterogeneous network convergence architecture and discussed the use of technology for heterogeneous network convergence, but heterogeneous convergence could increase the risk of network security. Lubna [11] introduced a scheduler designed for low latency and high data rates, effectively utilizing real-time information on latency, path loss, and capacity to make informed scheduling decisions. Thus, throughput was increased, and data transmission rate was decreased. However, it was more sensitive to dynamic changes in the network, which brought more difficulty in accurate scheduling and thus affected the performance.

Hu [12] provided a network architecture presenting network functions in a polymorphic way at each layer. These solutions are capable of fundamentally fulfilling the business demands for network intelligence, diversity, personalization, enhanced robustness, and efficiency. However, improper resource management of dynamic networks could lead to resource wastage and performance degradation. Homssi[13] provided a systematic analysis of the next generation of LEO satellite constellations and provided an overview of the analytical model, emphasizing modern simulation methods for next generation satellite constellations. Lafta[14] used enhanced and effective optimal routing protocols to reduce or avoid congestion, which improved the service quality in terms of data loss, traffic loss, queuing delay, and throughput. However, complex routing protocols could increase the security risk. In addition, Gures[15] identified challenges pertaining to 5G mobility management and suggested potential solutions to address them.

2.2 Transmission control of multi-hop networks

Extensive studies have been conducted in the field of multi-hop network transmission control. Combined with the existing network protocols or systems, Jude[16] developed a network-assisted congestion control method based on window utilization, namely, feedback-assisted improved recovery. However, compatibility and interoperability problems may arise, which lead to additional costs.

Jude[17] introduced an innovative congestion avoidance approach that integrated the accumulation of intermediate node queues, a transmission rate reduction method based on TCP growth, and a rapid recovery mechanism. However, fast recovery mechanism was triggered in severe congestion condition. León[18] proposed a distributed congestion control mechanism for general multi-hop networks. Various service requirements have been raised for different types of data, and the system was correctly functionalized and improved in terms of packet delivery rate, network transmission time, and traffic differentiation. However, the sharing and exchange of information in distributed systems could increase the risk of security and privacy protection. Nguyen [19] proposed a joint frequency scheduling and power control scheme to enhance connectivity in multi-hop vehicular networking networks. The proposed scheme outperformed the existing schemes in terms of connectivity enhancement, number of service restoration attempts and average realized throughput by employing linear programming approach and greedy algorithm.

The abovementioned study results focused on the optimal transmission control of heterogeneous integrated satellite networks and terrestrial networks. On the one hand, the security and cost of data transmission should be further improved. On the other hand, fewer studies have discussed the way to improve the transmission performance, especially in remote areas with difficulty in terrestrial network deployment. In view of the low transmission rate of satellite networks, this study substantially improved data transmission rate in multi-hop networks by combining the information of confirming data, round-trip time, and congestion window. Simulation comparison and analysis were also conducted. The outcomes obtained serve as valuable references for enhancing the transmission efficiency of satellite networks.

The remainder of the study is structured as follows: Section 3 delves into the analysis of existing TCP mechanisms and introduces a proposed protocol mechanism. In Section 4, simulations and comparisons are undertaken to confirm the proposed mechanism's ability to boost data transmission rates. Finally, Section 5 recapitulates the key findings of this study and offers concluding remarks.

3. Methodology

3.1 Protocol mechanism of TCP Reno

Congestion control is a key part of TCP. Given that the IP layer does not provide network congestion feedback to the end system, TCP employs end-to-end congestion control mechanisms rather than relying on network-assisted congestion control approaches. The TCP Veno[20] algorithm is still a combination of three parts, namely, slow start, congestion avoidance, and fast reply, with slow start and congestion avoidance being the mandatory parts of TCP.

When TCP interface enters a congestion state, which is a member function of the congestion structure, will be executed to update the slow start and halve the congestion window. If the current congestion window is insufficient, then no processing will be performed. In the slow-start phase, the TCP interface has a function to process the growth of the congestion window. When the slow start is over, the number of acknowledgment messages is used for window processing in the congestion avoidance phase. In the slow-start phase, the new congestion window is equal to the original window plus the number of acknowledged (ACK) messages. However, if the resultant value exceeds the slow-start threshold then the exceeding part will not perform the window-increase operation, and the algorithm of the congestion avoidance phase will be performed.

In the phase of congestion avoidance, if the congestion count surpasses the current window size, then the count is cleared, and the current congestion window is added by one. Conversely, if the congestion count is less than the current window, then the count is added by ACK. When the count is greater than the current window, the new window increase is the integer value of the count divided by the current window, with the remainder remaining in the window count variable. In the congestion avoidance phase, for each ACK message, the window growth follows the following formula:

$$cwnd+=\frac{1}{cwnd} \quad (1)$$

3.2 Protocol mechanism of TCP Vegas

TCP Vegas [21] is a common TCP congestion avoidance algorithm that primarily solves the problem of cyclic packet loss in wireless communication networks. It emphasizes packet delay rather than loss. As a signal helps confirm the packet sending rate, Vegas check whether the corresponding segment is ready for retransmission after a timeout each time a repeated ACK arrives.

The retransmitted segment is dispatched using a congestion window of the previous size, without reducing the size of the congestion window by half. This way avoids the degradation of transmission performance caused by the congestion window being excessively reduced. Vegas compares the current time with the timestamp recorded for the segment to determine if the elapsed time exceeds the preset timeout value. If the difference is greater, then Vegas does not need to wait for three duplicate ACK messages to retransmit the segment. In many cases, the sender does not receive three duplicate ACK messages because of the huge loss or the small window, and Reno relies on the abovementioned coarse-grained timeout.

Upon receiving a non-duplicate ACK that is either the first or second following a retransmission, Vegas perform an additional check to determine if the elapsed time since the segment's transmission exceeds the preset timeout value. If this condition is met, Vegas proceed to retransmit the segment. This process ensures that any segments potentially lost prior to the retransmission are captured promptly, without awaiting the receipt of a duplicate ACK.

On links with large bandwidth and high latency, Vegas can reduce the number of retransmissions and timeouts by increasing bandwidth utilization.

3.3 TCP segmentation for satellite networks

TCP stands as a dependable, connection-oriented communication protocol operating at the transport layer and centered on byte streams. Positioned in the networking stack, the TCP layer serves as a bridging layer, situated atop the IP layer and beneath the application layer. While a reliable, pipeline-style connection exists between the application layers of distinct hosts, the IP layer lacks such a mechanism and instead offers an unreliable packet-switching service. When the application layer sends byte stream, which is represented in 8-bit bytes, to the TCP layer for inter-network transmission, TCP divides the continuous data stream into discrete message segments, each of an appropriate length. Typically, the maximum size of these segments is constrained by the maximum transmission unit specified by the data link layer of the network the computer is attached to. Subsequently, TCP hands off these packets to the IP layer, which is responsible for relaying them across the network to the TCP layer of the intended recipient.

TCP assigns a unique serial number to each packet to guarantee reliable transmission and maintain the order of received packets at the receiving entity. Once the receiving entity successfully receives a set of bytes, it sends back an acknowledgment (ACK). If the sending entity fails to receive an ACK within a reasonable round-trip time (RTT), it assumes that the corresponding data has been lost and proceeds to retransmit the lost data segments.

In a satellite network, when the transmitted data message exceeds a certain length, TCP needs to split the data into pieces for sending, instead of sending all data at once. Each piece of data is placed in a separate network packet, added with TCP header information, and then sent by the IP module.

TCP will segment data when transmitting some large data segments to avoid data loss in the transmission process and improve the transmission performance.

3.4 Protocol mechanism of TCP Veno and TCP Hybla

By modifying the Reno algorithm, the main idea of TCP Veno becomes different. Reno considers the stage of the connection based on the increase in congestion window. When the quantity A of compressed messages within the queue surpasses the preset threshold B, the congestion algorithm will change from increasing 1 in each RTT of the previous Cwnd to increasing 1 in every two RTTs. Cwnd is the dimension of the congestion window. RTT is the last measured round trip delay. This threshold comprises three distinct components: the time taken for transmission over the link, the duration of processing within the end system, and the time spent in queuing and processing within the router's buffer.

Caini et al.[22] proposed a new TCP algorithm called TCP Hybla, which is a protocol to enhance TCP performance. It addresses TCP performance degradation in the case of large RTT. According to TCP connection transfer rate of RTT, loss can be attributed to either network congestion or random factors. Although a larger congestion window can be achieved, frequent packet losses may be observed within a window, which can significantly impact the transmission rate.

3.5 Improved algorithmic protocol mechanism

For the proposed scheme, the sender needs to measure two important values during data transmission: the actual data transmission rate (Actual) and the expected data transmission rate (Expected).

$$Except=\frac{cwnd}{MRTT} \quad (2)$$

$$Actual=\frac{cwnd}{RTT} \quad (3)$$

The MRTT mentioned here is the minimum measured RTT value. Diff is the discrepancy between the intended transmission rate and the actual achieved rate:

$$Diff=Excepted-Actual \quad (4)$$

If the RTT is greater than the MRTT, that is, RTT > MRTT, then a message backlog is generated in the data transmission process. The length of message backlog in the queue is denoted as A:

$$RTT = MRTT + \frac{A}{Actual} \tag{5}$$

$$A = \left(RTT - MRTT\right) \times Actual \tag{6}$$

$$A = \frac{cwnd}{RTT} \times RTT - Actual \times MRTT \tag{7}$$

$$A = \frac{cwnd}{MRTT} \times MRTT - Actual \times MRTT \tag{8}$$

$$A = \left(Excepted - Actual\right) \times MRTT = Diff \times MRTT \tag{9}$$

With the assumption MRTT=1/4xRTT:

$$A = \frac{3RTT}{4} \times \frac{cwnd}{RTT} = \frac{3}{4} cwnd \tag{10}$$

With the assumption MRTT=1/2x RTT:

$$A = \frac{RTT}{2} \times \frac{cwnd}{RTT} = \frac{1}{2} cwnd \tag{11}$$

When the difference between RTT and MRTT is larger, the value of A is greater, and the network is more congested. The value of A can represent the congestion degree. If A > = B, then the packet is considered to be congestion lost. If A < B, then the packet is random lost, and the threshold value B is generally 3.

The data are constantly updated during transmission, the RTT and MRTT values measured at different time vary, and the smallest RTT value is compared and recorded to keep the data updated.

The proposed scheme is designed according to the TCP connection transmission rate of RTT. When a TCP connection rate of RTT is large, the transmission rate B(t) is the same:

$$B(t) = \frac{cwnd(t)}{RTT} \tag{12}$$

To reduce the effect of transmission delay during the data transmission process of satellite links, p is introduced here as the normalized round trip delay. p is the ratio of RTT to RTT_0 , and RTT_0 is the round trip delay of the reference link defined to achieve the compensation effect:

$$P = \frac{RTT}{RTT_0} \tag{13}$$

To minimize the effects of RTT on congestion window, let represent the threshold value, and denote the time elapsed in reaching that threshold value. When the threshold value is not reached:

$$cwnd(t) = \begin{cases} 2\frac{t}{RTT} 0 < t < t_s, ss \\ \frac{t - t_s}{RTT} + s, t >, ca \end{cases} \tag{14}$$

where SS is the slow start and also called the exponential growth phase. As a blocking control mechanism, it indicates that, each time, the TCP receive window to receive an ACK will grow; CA is the congestion avoidance phase, and it is also a blocking control mechanism.

Time t is multiplied by the normalized RTT p to obtain the RTT-independent Cwnd (pt):

$$Cwnd(\mathrm{pt}) = \begin{cases} p2\frac{t}{PPT}, 0 < t < t_s, ss \\ p\left[\frac{t - t_s}{RTT} + S\right], t > t_s, ca \end{cases} \tag{15}$$

The resulting congestion window is multiplied by p to obtain the RTT-independent B(t):

$$Cwnd(pt) * p = \begin{cases} p2\frac{pt}{RTT}, 0 < t < t_s, ss \\ p\left[p\frac{t - t_s}{RTT} + S\right], t > t_s, ca \end{cases} \tag{16}$$

is simplified and substituted as:

$$Cwnd(pt) * p = \begin{cases} p * 2\frac{t}{RTT_0}, 0 < t < t_s, ss \\ P\left[\frac{t - t_s}{RTT_0} + s\right], t > t_s, ca \end{cases} \tag{17}$$

According to the data transmission formula B(t) = Cwnd(t) /RTT, the actual transmission rate is:

$$\frac{Cwnd(pt) * p}{RTT} = \frac{Cwnd(pt)}{RTT_0} = \begin{cases} \frac{1}{RTT_0} * 2\frac{t}{RTT_0}, 0 < t < t_s, ss \\ \frac{1}{RTT_0}\left[\frac{t - t_s}{RTT_0} + s\right], t > t_s, ca \end{cases} \tag{18}$$

The following formula is obtained by multiplying both sides by:

$$Cwnd(pt) = \begin{cases} 2\frac{t}{RTT_0}, 0 < t < t_s, ss \\ \frac{t - t_s}{RTT_0} + s, t > t_s, ca \end{cases} \tag{19}$$

As shown in the formula, the congestion window for data transmission is unrelated to RTT but related to RTT_0.

To streamline the configuration of the congestion window and uphold compatibility with established transport protocols, the congestion window during the slow-start phase (SS) is updated as $Cwnd^{i+1} = Cwnd^i + 2^p - 1$ and the window for the congestion avoidance (CA) phase is updated as $Cwnd^{i+1} = Cwnd + \frac{p^2}{Cwnd^i}$.

The algorithm maintains the ACK mechanism used in the standard TCP window to achieve a larger congestion window. However, this condition leads to more frequent multiple packet losses in the window, which can have a greater impact on the transmission rate, especially in the case of large RTT.

In the traditional scheme, data loss in the transmission process is considered to be caused by congestion. Based on data loss strategy, the proposed scheme can effectively discern whether data loss is attributable to network congestion or random factors. TCP Hybla efficiently leverages the satellite network's substantial bandwidth, taking into account its latency characteristics. However, when more nodes are present, the random loss of data will also increase. A novel algorithm is introduced to enhance the volume of data transmission, while accurately distinguishing between data loss stemming from network congestion and random losses, thereby addressing the aforementioned challenges.

4. Result Analysis and Discussion

The software used for experimental simulation is OPNET14.5, and the simulation model is shown in Fig. 1. The data transmission mode is as follows: Server-1 is connected to the lower node (node-3), the receiver of the data (gateway-1) through network, and the pc side, which is composed of 5-hop nodes. The BERs of downlink (from node-3 to gateway-1) and uplink (from gateway-1 to node-3) in the satellite network are set to 1E-005 to 1E-009, respectively. In the experiment, the satellite link sent the data, and the results of the receiver completing the download response and the change in the throughput in the satellite link with the BER in the satellite link are summarized. The experiment is tested on 1–5-hop nodes.

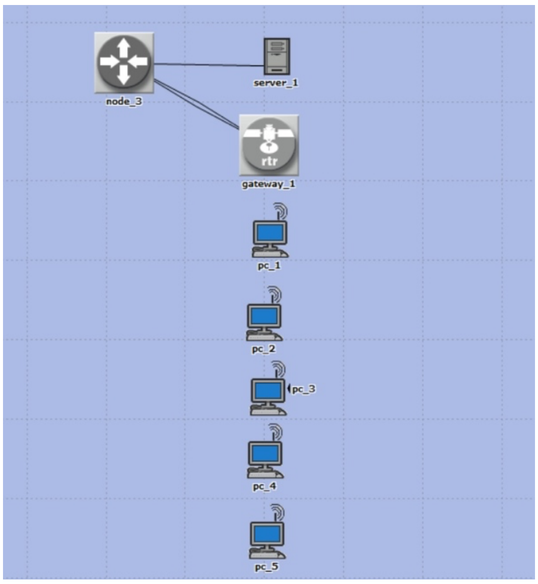

Fig. 1. Structure of simulation model

4.1 Data analysis when BER 1E-005

Four schemes are compared in the experiment. The vertical coordinate is the packet transmission rate per second, and the horizontal coordinate is the data on the 1-hop node to the 5-hop node. The experimental simulation assesses the transmission speed of the limiting link within the heterogeneous network, and its transmission performance can be reflected from the abovementioned parameters. Figure 2 shows the data transmission speed of the satellite link in the heterogeneous network, given a bit error rate (BER) of 1E-005 for the satellite connection.

As shown in Figure 2, the link transmission rates of the four schemes vary with the node hop. In Scheme 1, the link transmission rate is 5 packets per sec at different node hops, which is interconnected with its approach to transmitting data. In the case of data loss, congestion is assumed to occur in the network. The Slow Start mechanism is employed to mitigate further accumulation of unsent data, resulting in a direct reduction of the data transmission window by half. Furthermore, the linear growth of data during the Slow Start phase falls short in handling satellite networks characterized by significant latency and varying bandwidths within heterogeneous networks. Consequently, the transmission strategy of Scheme 1 significantly impacts the overall performance of data transmission within these networks.

Scheme 2 adopts the strategy of distinguishing data loss. As observed from the bar chart in Figure 2, the transmission rate of Scheme 2 is maintained 6 packets per sec on different hop links. Compared with Scheme 1, the link transmission rate is increased from 1 hop 1 to 5 hops. In Schemes 1 and 2, data transmission occurs in a wireless setting, significantly elevating the likelihood of unpredictable data loss. Moreover, distinct transmission strategies are employed to address data loss arising from congestion within heterogeneous networks and random losses occurring in wireless links. These tailored strategies effectively enhance the overall efficiency of network transmission.

In Scheme 3, the data transmission amount is increased, and the link transmission rate is substantially increased. The transmission rate is maintained around 11.8 packets per sec for different hops. The transmission rate nearly doubles compared with those in Schemes 1 and 2. As the number of nodes increases from 2 hops to 5 hops, the transmission rate gradually decreases. Evidently, the likelihood of packet loss increases during data transmission, particularly when the number of nodes is substantial, resulting in a reduction in the data transmission rate.

The proposed scheme increases the data transmission amount while distinguishing the data loss categories, which is obviously beneficial for heterogeneous network transmission in satellite networks and industrial IoT. The speed of information transfer in Scheme 4 is maintained at 12.4 packets/sec for different numbers of hop links. The figure shows that the speed of information transfer in the link in Scheme 4 is also improved compared with the three other schemes, but the transmission rate decreases with the increase from 2 hops to 5 hops.

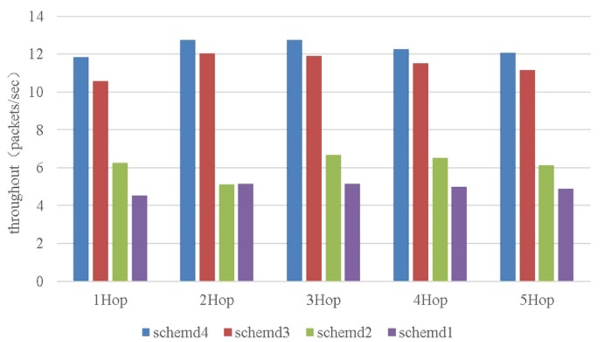

Fig. 2. BER of 1E-005

4.2 Data analysis for BER of 1E-006

Table 1 shows that the proposed scheme (Scheme 4) exhibits an enhanced throughput in comparison to the three alternative schemes. With a great advantage under 1E-006, the throughput increases by 34.75%, 30.22%, and 3.13% compared with those of Schemes 1, 2 and 3, respectively. Increasing data transmission amount and recognizing data loss under high BER can significantly enhance the transmission capabilities of satellite networks.

Table 1. 1E-006 Throughput Improvement Percentage

	Scheme 1	Scheme 2	Scheme 3
1E-006	34.75%	30.22%	3.13%

4.3 Data analysis for BER 1E-007

Figure 3 demonstrates the transmission efficiency of satellite connections in a heterogeneous network, exhibiting a bit error rate (BER) of 1E-007. With the decrease in BER, The transmission rate rises the four schemes are improved, and the transmission rates of Schemes 1, 2, and 3 are generally maintained at about 15 packets/sec.

The transmission rate rises newly proposed algorithm is generally maintained at about 16 packets/sec. Although the newly proposed algorithm does not show a great advantage at 1 hop and 2 hops, the transmission rate augments obviously from 3 hops to 5 hops. As the number of hops increases, the transmission rates of all the four schemes decrease.

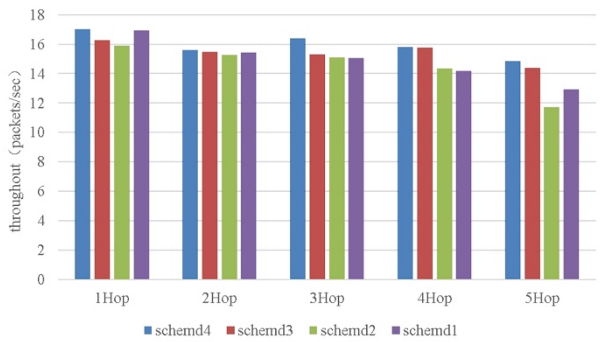

Fig.3. BER of 1E-007

4.4 Data analysis for BER 1E-008

Table 2 compares the throughput of the four schemes at 5 hops. The throughput of Scheme 4 is improved by 200.46%, 137.43%, and 33.70% compared with those of Schemes 1, 2, and 3, respectively. The transmission performance of satellite networks significantly improves.

Table 2.1E-008 Throughput Improvement Percentage

	Scheme 1	Scheme 2	Scheme 3
1E-008	200.46%	137.43%	33.70%

4.5 Data analysis for BER 1E-009

Figure 4 shows the transmission speeds of satellite connections within a heterogeneous network with a BER of 1E-009. The transmission rates of the four schemes show a more obvious difference at 5 hops, and the transmission rates at 1 hop and 2 hops of Schemes 3 and 4 are equal but better than those of Schemes 1 and 2.

According to the simulation results, the data transmission rates of the four algorithms increase with the gradual decrease in BER, while the proposed algorithm has a strong stability. For the heterogeneous networks constructed by satellite networks and industrial IoT, increasing data transmission amount can improve the transmission rate more effectively than distinguishing data loss. Taking into account the distinct features of satellite networks and the industrial IoT, the presented approach offers the most favorable transmission rate when compared to the other three schemes.

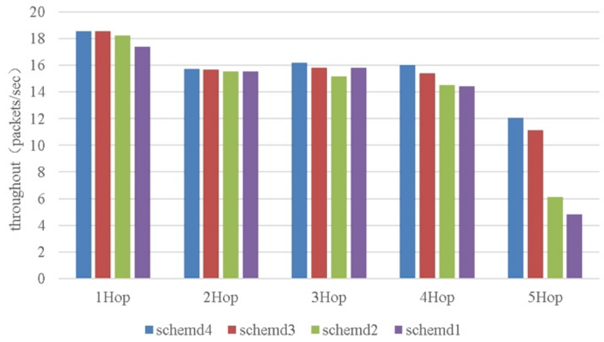

Fig.4. BER of 1E-009

5. Conclusions

An in-depth analysis and optimization of satellite network control was needed to reduce data transmission delay and increase data transmission rate for improving user experience. This study established satellite networks and multi-hop network models combined with modeling technology and experimental analysis, and different network protocols were compared and analyzed. The following conclusions could be drawn:

(1) Under the same BER, the data transmission rate of satellite networks of the proposed scheme at 5 hops doubles those of the three other schemes.

(2) The improved algorithm increases data transmission amount and distinguishes data loss because of network congestion or random loss.

(3) Regardless of the change in BER or the increase and decrease in the number of hops, the change in transmission rate of the proposed algorithm is as small as 2–3 packets/sec, which indicates its strong stability.

Combined with indoor experiments and theoretical analysis, this study proposed a new TCP. An experimental model fitting well with the realistic model was constructed, which can provide references for future study on data transmission in satellite wireless networks. Considering the lack of field data, the proposed model will be further improved by combining it with satellite wireless data transmission in future studies. This way will allow for a more accurate study of optimal transmission control in heterogeneous integrated satellite networks and terrestrial multi-hop networks.

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