End-to-End Transmission Control for Cross-Regional Industrial Internet of Things in Industry 5.0

Liang Zong, Fida Hussain Memon, Xingwang Li, *Senior Member, IEEE*, Han Wang, *Senior Member, IEEE*, and Kapal Dev

***Abstract*—Data transmission for the industrial Internet of Things (IoT) is crucial for industrial production, especially in the Industry 5.0 era, where human–machine collaboration is increasingly intensive. To ensure the continuity and robustness of industrial IoT communications in the case of damaged infrastructure communication facilities postdisaster, the industrial IoT can be connected with satellite networks in emergencies. This article presents a cross-regional, end-to-end, transmission control scheme for satellite-supported, multihop industrial IoT. The proposed scheme adjusts the window of data transmission from two phases, slow start and congestion avoidance, to accommodate the low-transmission performance caused by a long delay and high bit error rate in converged networks. The window of data transmission is also adjusted to increase the amount of data transmission for the slow start to fill the high bandwidth-delay product of the converged network, while adjusting the threshold of data transmission based on feedback information to distinguish different data losses during congestion avoidance. The feasibility of the heterogeneous network transmission model is experimentally verified. The results show that the scheme can achieve good performance in heterogeneous networks of industrial IoT and satellite networks. The scheme is effective in ensuring the continuity and stability of intelligent machine production in Industry 5.0 in emergency communication cases.**

***Index Terms*—Industrial Internet of Things (IoT), Industry 5.0, satellite network, transmission control.**

Manuscript received June 3, 2021; revised October 3, 2021 and November 4, 2021; accepted December 2, 2021. Date of publication December 10, 2021; date of current version February 18, 2022. This work was supported by the Scientific Research Fund of Hunan Provincial Education Department under Grant 19B512, in part by Henan Scientific and Technological Research Project under Grant 212102210557, and in part by Key project of Guizhou Science and Technology Support Program under Grant Guizhou Key Science and Support [2021]-001. Paper no. TII-21-2349. *(Corresponding author: Xingwang Li.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TII.2021.3133885.

Digital Object Identifier 10.1109/TII.2021.3133885

I. Introduction

THE fifth industrial revolution (Industry 5.0) will enable further integration of man and machine. This new manufacturing paradigm requires frequent data exchange between manufacturing machines and industrial information systems via networks, which creates new challenges to the design of various industrial network protocols [1]–[3]. The current fourth industrial revolution (Industry 4.0), which is the "cyber-physical" manufacturing plant, will be transformed into a "human-cyber-physical" system using new technology for Industry 5.0. The mechanization and automation of machine production are further combined with networking and intelligence and accompanied by close integration of human–machine intelligence [4]–[6]. This approach will further hinder the application of network technology in Industry 5.0 and distinguish it from previous industrial revolutions.

In the era of Industry 5.0, intelligent sensors collect a large amount of data, and through intelligent computing and analysis of the data, machines are directed increasingly toward serving people. In this new model, people will work with collaborative robots to promote the intelligent operation of machines [7]. At this time, the industrial Internet of Things (IoT) is built by intelligent sensors, and the IoT further deepens the interoperability of data. The amount of data transmission will rise dramatically, and the transmission of data is directly related to the efficiency of industrial production. The system with highly integrated, human–machine intelligence collaboration is susceptible to attacks on external networks, causing the entire network to collapse. Other special cases, such as damaged telecommunication infrastructure in postdisaster factories or remote areas and marine environmental operations, require robust and continuous network architecture to ensure the stability of production operations under Industry 5.0. An efficient data transmission mechanism is required to improve the transmission efficiency of the IoT.

Based on this information, research on network transmission in an industrial IoT environment focuses on the IoT with multihop characteristics [8], [9]. The blockchain and wireless communication technologies provide the technical support for the application of Industry 5.0 [10]–[12]. However, effective solutions for enhancing heterogeneous converged network transmission research of industrial IoT and satellite networks are still lacking. Therefore, establishing an efficient and simple satellite-assisted industrial IoT transmission scheme that adapts to cross-regional characteristics has become an urgent problem for Industry 5.0. This article focuses on network connectivity and data transmission control for the multihop industrial IoT in emergency situations.

II. Related Work

A. Various Applications of Industry 5.0

Industry 5.0 was proposed as a further expansion of Industry 4.0, aiming to more intelligently provide personalized services to people. Researchers have envisioned and investigated various applications of Industry 5.0, such as the design of smart cities, aviation industry, medical improvement, transportation, bioenergy, etc. These exploratory studies have deepened people's understanding of the application of Industry 5.0 on various occasions and provided feasible solutions for the overall promotion and popularization of Industry 5.0.

Kiran *et al.* [13] discuss how the concept of Industry 5.0 affects smart cities from the perspective of smart cities, highlighting the structure of smart cities and possible expected changes. In a complex and intelligent environment, Carayannis *et al.* [14] investigated the aviation industry in combination with Industry 5.0 to determine the best solutions for implementing the new human-centered logic of Industry 5.0 and to analyze this logic in the context of the aviation industry. During the Coronavirus Disease 2019 (COVID-19) pandemic, Javaid *et al.* [15] identified and explored the main technologies of Industry 5.0 and examined the major challenges of Industry 5.0 technologies for the COVID-19 pandemic. In addition, Industry 5.0 technologies can help physicians and medical students to obtain the medical training that is necessary to meet the specific needs of patients and physicians. The paradigm shift from Industry 4.0 to Industry 5.0 is discussed in detail by ElFar *et al.* [16] for customized services as well as the production and processing of algal bioenergy. Majid *et al.* [17] point out that Industry 5.0 in the field of transportation can further its role through robotic cars and that Industry 5.0 focuses on the interaction between humans and machines.

B. Multihop Intelligent Machines to Build the Industrial IoT in Industry 5.0

The IoT is an emerging field that connects various devices to the internet to form an expansive network. The IoT paves the way for the creation of widely connected network infrastructures to support innovative services and promises greater flexibility and efficiency. Such advantages are attractive not only for consumer applications but also for industry. In the era of Industry 5.0, the level of intelligence will be more deeply applied, and the connection between humans and machines will be deepened. Sisinni *et al.* [18] elucidated the concepts of the IoT, Industrial IoT, and Industry 4.0, highlighting the opportunities presented by this transformation. The authors also provided a systematic overview of the latest research findings and potential research directions to address industrial IoT challenges. Considering the limited resources and functionality of devices in the industrial IoT, the security of the IoT is increasingly challenging. He *et al.* [19] proposed a blockchain-based, software state monitoring system that aims to monitor the software state of industrial IoT devices to detect and respond to identified malicious behaviors. From artificial intelligence (AI) perspective, Industry 5.0 relies heavily on the IoT for sensing, perception, cognitive behavior, and causality. Tripathy *et al.* [20] pointed out that the IoT and AI can be breakthroughs for Industry 5.0.

C. Satellite Network in the Industrial IoT

With the rise of the industrial IoT, the demand for various applications of networks has become increasingly intense, thereby increasing the requirements for the transmission performance of these networks, and in remote areas and postdisaster communication infrastructure damage areas, satellite network access greatly facilitates the needs of the industrial IoT.

Bahri *et al.* [21] selected the IoT in Industry 4.0 as a context to discuss the main technologies in the IoT, illustrating the main differences between the two ecosystems based on the IoT and industrial IoT according to the standards and applications of wireless technologies. Huang [22] proposed a quality of service (QoS)-oriented resource allocation algorithm. Most industrial monitoring and data acquisition systems use proprietary communication protocols, which create barriers to interconnecting networks in different industrial environments. Jaloudi [23] investigated polling and event-based protocols to ensure an open and interoperable industrial IoT environment. The authors propose two schemes to build an industrial IoT environment, developing different transmission schemes for each of the two modes of request-response and publish-subscribe to suit their applications in the industrial IoT. Baumann *et al.* [24] presented a perspective on control and coordination over wireless networks. To ensure the QoS of the satellite industrial IoT for wide-area coverage and long-distance transmission, Liu *et al.* [25] proposed a Ka-band, multibeam satellite, industrial IoT scheme with optimized beam power to match the theoretical transmission rate with the service rate.

The rest of this article is organized as follows. Section III describes the heterogeneous network architecture of multihop networks constructed by intelligent machines with satellite networks and analyzes the limitations of traditional satellite performance enhancement proxy (PEP). Section IV constructs an end-to-end transmission control scheme. Section V analyzes the simulations. Finally, Section VI concludes this article.

III. Heterogeneous Network Composed of a Satellite Network and a Multihop Network

The industrial IoT is a special kind of multihop network. Multihop networks are built as a closed autonomous system due to their inherent self-organizational characteristics. Therefore,

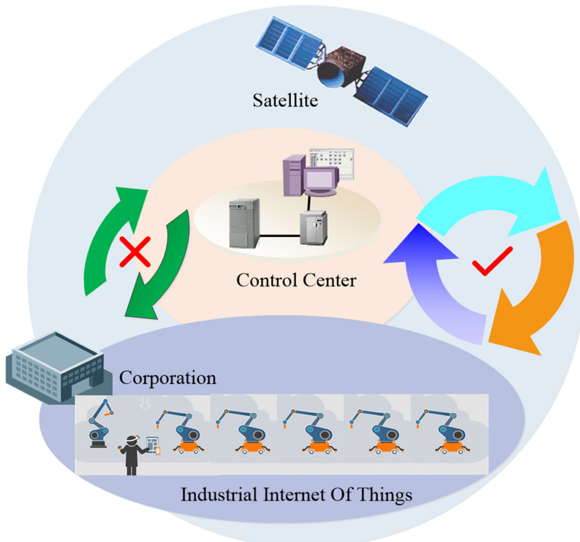

Fig. 1. Network architecture for damaged facilities in post-disaster situations.

when multihop networks communicate with the outside world, they must be heterogeneous with other networks.

A. Heterogeneous Network Model

In the integrated network of satellite and multihop networks, the multihop network of terminals can be a wireless sensor network, which facilitates network access for Industry 5.0. Here, the multihop network of terminals can integrate the production, monitoring equipment, and surveillance network of a factory into a production system. This integration can achieve autonomous decision-making for the entire production line process when combined with machine learning and intelligent control. The introduction of satellite networks is an ideal approach in situations where cross-regional information interaction or control is required. Satellite networks have global coverage and can provide network connectivity at any time and place. Especially in the case of infrastructure damage to communication postdisasters, the communication service provided by satellite networks can be seamlessly connected to the multihop network production system of a factory to ensure the continuous and stable production of the industry. As shown in Fig. 1, in the case of damaged communication facilities in the post-disaster period, the network connection between the control center and the industrial IoT is not possible. At this point, a satellite network can provide seamless connection between control center and industrial IoT in Industry 5.0. This heterogeneous network of satellites and multihop networks can meet the all-weather production needs of Industry 4.0 and provide a more robust network service for intelligent production systems.

In the heterogeneous network model, satellite networks provide full-coverage services for the industrial IoT with the control center at the core. Remote control of the industrial IoT is performed based on personalized services requested by people using intelligent computing and data analytics. There will be a large

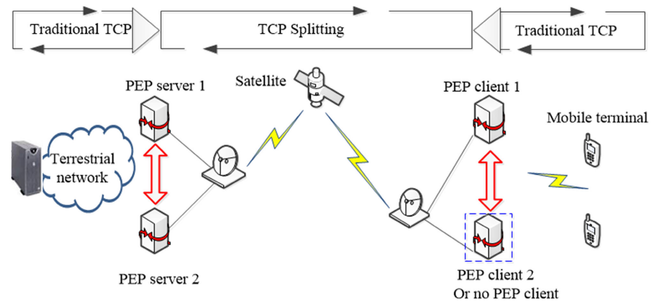

Fig. 2. PEP client switch problem.

amount of data interaction between intelligent computing and data analytics, as well as industrial IoT. The transmission of data will affect the performance of the heterogeneous network, which has a direct impact on factory production under Industry 5.0. As shown in the figure, the satellite network in a heterogeneous network is in a key position to relay the transmission of various data. Therefore, improving the transmission performance of the satellite network is crucial to enhance the performance of the heterogeneous network.

B. Limitations of Traditional Satellite PEP

For heterogeneous networks with satellite participation, the most ideal way is to use the PEP scheme to split the data transmission network to avoid the mutual influence of different networks. If the terminal is the ground wired network, the PEP scheme can effectively improve the performance of the heterogeneous network. However, for wireless multihop networks composed of mobile devices, their mobility makes the PEP gateway in satellite networks more complex [26].

When the wireless multihop network and terrestrial-satellite network constitute a heterogeneous network, the terminal equipment forms a multihop network. When the terminal mobile network is connected from one network to another network, the gateway of the PEP must be able to handle the mobile handover of data, which involves the physical layer, access layer, network layer, and transport layer.

In addition, it is important that the server of the land-based PEP gateway is equipped to handle the same data switching problem, as shown in Fig. 2. When the mobile terminal switches from the network connected with the PEP client 1 to the gateway without the PEP client (or PEP client 2), the ground PEP server on the land also needs to switch, that is, from the PEP server 1 to the gateway without the PEP server (or PEP server 2), as shown in Fig. 3. For the communication connection, the communication connection established between the land PEP server and the mobile terminal PEP client must be canceled, and the communication connection between the land server and the mobile terminal must be re-established. At this time, the synchronization of communication connections has a great impact on the transmission performance of the whole network. The scheme of PEP is not ideal.

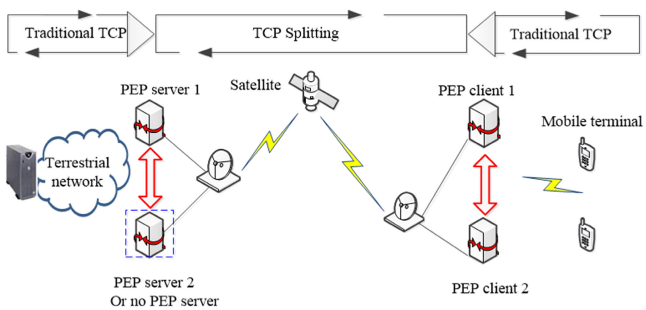

Fig. 3. PEP server switch problem.

IV. End-to-End Transmission Scheme for the Heterogeneous Network

The end-to-end transmission scheme of the satellite network is a widely applied solution. Satellite networks have to be designed for long latency and high bit error rate (BER) characteristics, while the industrial IoT in heterogeneous networks with terminals consisting of multihop intelligent machines also induces a high BER, which inevitably further degrades transmission performance in heterogeneous networks.

A. Congestion Window Adjustment for Long Delays

In early standard transmission protocols, during the slow start and congestion avoidance, the sender's data sending window is the congestion window, which follows certain rules, and the congestion window increases exponentially during the slow start when no data loss event occurs. Thus, the sending congestion window doubles for each round-trip time (RTT) that is experienced. After the congestion window reaches a threshold value, the congestion window increases linearly and enters congestion avoidance, which increases by one maximum segment size (MSS) after one round trip to ensure that the network data are in a stable interaction state and to avoid congestion in the network.

To cope with the long delays of satellite networks in heterogeneous networks, the impact of the RTT on the congestion window needs to be reduced [27]. To reach this goal, we let S be the threshold value and let t_S be the time experienced to reach the threshold value, which is known according to the rule of slow start

$$t_S = \mathrm{RTT}\log_2 S. \tag{1}$$

Until the threshold is reached, the congestion window C_{wnd} change rule for the slow start is expressed as follows:

$$C_{wnd}(t) = 2^{\frac{t}{\mathrm{RTT}}}, 0 \le t < t_S. \tag{2}$$

After the congestion window reaches the threshold, the rule for the change in the congestion window in congestion avoidance is

$$C_{wnd}(t) = \frac{t - t_S}{\mathrm{RTT}} + S, t \ge t_S. \tag{3}$$

To reduce the effect of the RTT on the satellite link, we introduce α as the ratio of the RTT to the $\mathrm{RTT}_{\mathrm{Ref}}$, the latter being the RTT of the reference network; e.g., the average delay of the terrestrial network can be represented as $\mathrm{RTT}_{\mathrm{Ref}}$.

From the abovementioned congestion window rules for slow start and congestion avoidance, α is multiplied by time to obtain the congestion window independent of the RTT

$$C_{wnd}(\alpha t) = \begin{cases} 2^{\frac{\alpha t}{\mathrm{RTT}}}, 0 \le t < t_{\alpha S} \\ \frac{\alpha * t - t_{\alpha S}}{\mathrm{RTT}} + S, t \ge t_{\alpha S} \end{cases}. \tag{4}$$

Here, $t_{\alpha S}$ is the time needed to reach αS. Thus,

$$t_{\alpha S} = \mathrm{RTT}_{\mathrm{Ref}}\log_2 S. \tag{5}$$

Multiplying (4) by α yields a congestion window independent of RTT as

$$C_{wnd}(\alpha t) * \alpha = \begin{cases} \alpha * 2^{\frac{\alpha t}{\mathrm{RTT}}}, 0 \le t < t_{\alpha S} \\ \alpha * \left[\frac{\alpha * t - t_{\alpha S}}{\mathrm{RTT}} + S\right], t \ge t_{\alpha S} \end{cases}. \tag{6}$$

Equation (6) is simplified as follows:

$$C_{wnd}(\alpha t) * \alpha = \begin{cases} \alpha * 2^{\frac{t}{\mathrm{RTT}_{\mathrm{Ref}}}}, 0 \le t < t_{\alpha S} \\ \alpha * \left[\frac{t - t_{\alpha S}}{\mathrm{RTT}_{\mathrm{Ref}}} + S\right], t \ge t_{\alpha S} \end{cases}. \tag{7}$$

The actual transmission rate is (7) divided by the RTT

$$\frac{C_{wnd}(\alpha t)}{\mathrm{RTT}_{\mathrm{Ref}}} = \begin{cases} \frac{1}{\mathrm{RTT}_{\mathrm{Ref}}} * 2^{\frac{t}{\mathrm{RTT}_{\mathrm{Ref}}}}, 0 \le t < t_{\alpha S} \\ \frac{t - t_{\alpha S}}{\mathrm{RTT}^2{}_{\mathrm{Ref}}} + \frac{S}{\mathrm{RTT}_{\mathrm{Ref}}}, t \ge t_{\alpha S} \end{cases}. \tag{8}$$

Both sides of (8) are simultaneously multiplied by the $\mathrm{RTT}_{\mathrm{Ref}}$

$$C_{wnd}(\alpha t) = \begin{cases} 2^{\frac{t}{\mathrm{RTT}_{\mathrm{Ref}}}}, 0 \le t < t_{\alpha S} \\ \frac{t - t_{\alpha S}}{\mathrm{RTT}_{\mathrm{Ref}}} + S, t \ge t_{\alpha S} \end{cases}. \tag{9}$$

As shown in (9), the congestion window no longer depends on the RTT but is related to the $\mathrm{RTT}_{\mathrm{Ref}}$. To simplify the setting of the congestion window and to maintain compatibility with traditional transport protocols, the update rule of the congestion window in the slow start is $C_{wnd}^{i+1} = C_{wnd}^{i} + 2^{\alpha} - 1$, and the window update rule for the congestion avoidance phase is $C_{wnd}^{i+1} = C_{wnd}^{i} + \alpha^2 / C_{wnd}^{i}$.

In the abovementioned scheme, only the data sender needs to modify the rules of the congestion window, which is a typical end-to-end scheme, and only one variable $\mathrm{RTT}_{\mathrm{Ref}}$ is added, which reduces the memory footprint.

The proposed scheme is subdivided on the basis of the abovementioned congestion window, and considering that the end-to-end scheme obtains less network information, the proposed scheme fully considers the parameters on the sender side and the parameters contained in the acknowledged message returned by the receiver side.

The parameters on the sender side are the congestion window and threshold, and the acknowledgment message contains the parameters on the receiver side, which are the receiver's advertised window and the size of unacknowledged bytes. The size of the broadcast window and unacknowledged bytes on the receiving side reflects the size of the data being transmitted in the network.

Therefore, to accurately reflect the data transmission in the network, the abovementioned four parameters are considered simultaneously to accurately reflect the state of the network. When the congestion window is less than one-quarter times the threshold and the unacknowledged bytes are less than one-quarter times the receiver's advertised window, the amount of data injected into the network by the sender is small, and the receiver still has a large reception window, while the number of unacknowledged bytes in the network is also small. The sender doubles the congestion window. Similarly, when the congestion window is greater than three-quarters times the threshold or the unacknowledged bytes are greater than three-quarters of the receiver's advertised window, the sender injects a larger amount of data into the network. In addition, the receiver has only a smaller receive window, while the number of unacknowledged bytes in the network is also large. At this time, the network is in a saturated state, and the sender must reduce the amount of data sent and halve the congestion window for sending. Other cases maintain the original value of the congestion window.

In the industrial IoT, intelligent computing and data analysis will generate a large amount of data for transmission. In the heterogeneous network of satellites and the industrial IoT, the subdivision of the network state is helpful to accurately judge the transmission situation in the heterogeneous network and provide a reference for data transmission at the sending terminal.

B. Threshold Adjustment for High BERs

In heterogeneous networks composed of industrial IoT and satellite networks, random data loss caused by a high BER of the wireless link during data transmission is an important factor that causes network performance degradation. Network congestion is also prone to data loss. If the sender mistakenly believes that random data loss is caused by congestion, the congestion window is halved at the sender's terminal, which can significantly reduce the network transmission rate. Therefore, it is crucial to distinguish between the two situations [28], [29].

The RTT is a parameter that is easily obtained by the sender from the received acknowledgment message. The proposed scheme uses a congestion window and RTT to calculate the backlog value in the network to distinguish data loss. Let σ be the backlog value in the heterogeneous network, which is the product of the congestion window transmission rate and data transmission delay time (difference between the RTT and the minimum RTT

$$\sigma = \frac{C_{wnd}}{\mathrm{RTT}} * (\mathrm{RTT} - \mathrm{RTT}_{\min}) \tag{10}$$

C_{wnd} is the congestion window, and RTT and $\mathrm{RTT}_{\min}$ are the current RTT and minimum RTT, respectively. The abovementioned equation is simplified as follows:

$$\begin{aligned}\sigma &= C_{wnd} * \left(1 - \frac{\mathrm{RTT}_{\min}}{\mathrm{RTT}}\right) \\ &= C_{wnd} * \left(\frac{\mathrm{RTT}_{\min}}{\mathrm{RTT}_{\min}} - \frac{\mathrm{RTT}_{\min}}{\mathrm{RTT}}\right) \\ &= \left(\frac{C_{wnd}}{\mathrm{RTT}_{\min}} - \frac{C_{wnd}}{\mathrm{RTT}}\right) * \mathrm{RTT}_{\min}. \end{aligned} \tag{11}$$

In (11), the minimum RTT is a deterministic value, and the larger the current RTT relative to the minimum RTT is, the larger the backlog value, and vice versa. The size of σ requires only the current RTT to be determined, which reflects the data backlog in the heterogeneous network. When the backlog value in the network is small, the congestion probability caused by the data backlog is small, and the sender considers the data loss random, so a larger threshold can be set to allow the congestion window to transmit more data before reaching the threshold. In contrast, when the backlog value in the network is large, the probability of data congestion in the heterogeneous network is larger, and data loss is most likely caused by congestion. In this case, the sender sets the threshold to a smaller value to avoid the sender from injecting more data volume into the heterogeneous network to alleviate possible congestion. Setting different thresholds by different backlog values can alleviate the fluctuation of the congestion window when data are lost, which is beneficial to the smoothness of data delivery in heterogeneous networks.

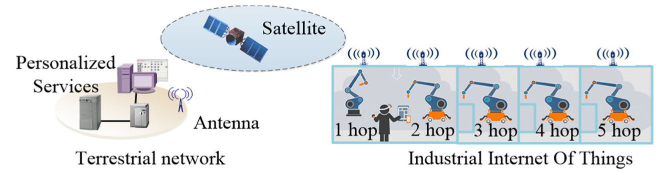

Fig. 4. Topology of simulation.

The industrial IoT and satellite networks are two typical wireless networks that have a high BER, a long delay, and a great impact on the transmission performance of heterogeneous networks. The proposed scheme aims to solve the network performance degradation caused by a long delay and high BER and provide strong support to improve the network performance under Industry 5.0.

V. Experiment Simulation and Analysis

In the cross-regional heterogeneous network composed of the industrial IoT and satellite networks, the satellite network is the core part as well as the bottleneck link. The experimental simulation topology is shown in Fig. 4, where the remote terrestrial network provides various personalized services and is connected to the industrial IoT through the satellite network. The latter consists of five hop nodes. The terrestrial network consists of a wired network that connects to the satellite network through an antenna. The bandwidth of the bottleneck link in the satellite network is 1.54 Mbps, and the time delay for one-way propagation is 250 ms. The BER of the satellite link is set to 10^{-8} and 10^{-6} scenarios in the simulation. The five hop nodes in the industrial IoT use the IEEE 802.11 standard to complete the multihop transmission of data. The experimental simulations are separately tested for one hop node to five hop nodes. The parameters tested are the transmission rate in the heterogeneous network and the file download time in the multihop nodes.

A. Link Transmission Rate

The experimental simulation compares four schemes: TCP Reno, TCP Veno, TCP Hybla, and the proposed scheme. To

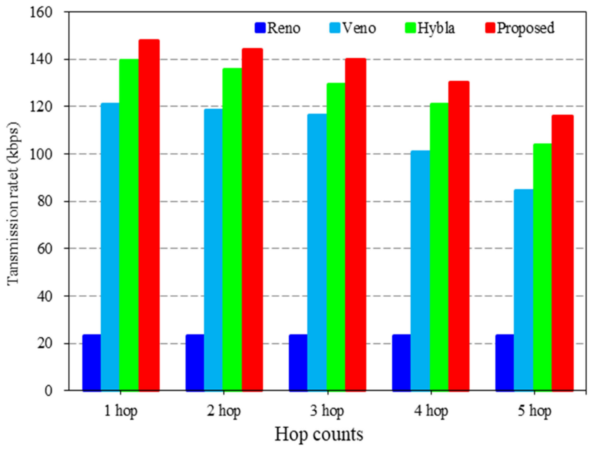

Fig. 5. Link transmission rate when the BER is 10^{-8}.

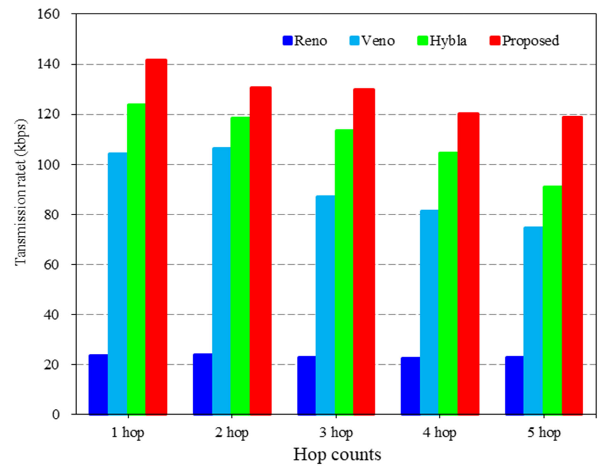

Fig. 6. Link transmission rate when the BER is 10^{-6}.

simplify the simulation of personalized services in terrestrial networks, the file transfer protocol (FTP) application is chosen. The one hop node to five hop nodes in the industrial IoT is connected to the FTP application. The bottleneck link transmission rate of the heterogeneous network is tested in the experimental simulation. This parameter reflects the transmission performance of the heterogeneous network from a macro perspective. Fig. 5 shows the transmission rate of the satellite link in the heterogeneous network when the BER of the satellite link is 10^{-8}.

As shown in the figure, the link transmission rate decreases to some extent as the number of node hops increases for all three schemes, except TCP Reno, which maintains a link transmission rate of approximately 23.25 kbps at different hop counts. This result is related to its transmission strategy. When data loss occurs during transmission, TCP Reno directly assumes that congestion occurs in the heterogeneous network and turns on slow start to alleviate further data backlog, and the data sending window is directly halved. In addition, this scheme uses a linear increase in data during the slow start and is unable to cope with long-delay satellite networks in heterogeneous networks. Therefore, this transmission scheme of TCP Reno greatly affects the transmission performance of heterogeneous networks.

TCP Veno, due to the strategy of differentiating data loss, has greatly increased the link transmission rate of nodes in the industrial IoT from one to five hops relative to TCP Reno. At 1 to 3 hops, the link rate of TCP Veno increases by approximately 4.10 times compared to TCP Reno. At four hops and five hops, the link rate also increases by 3.34 times and 2.63 times, respectively. In a heterogeneous network composed of the industrial IoT and satellite networks, both perform data transmission in a wireless environment, which greatly increases the probability of random data loss. After adopting the strategy to differentiate data loss, different transmission strategies for data loss caused by congestion and random loss in heterogeneous networks can greatly improve the transmission efficiency of the network.

TCP Hybla also achieves a significant increase in the transmission rate due to its strategy of increasing the amount of data transmission. The increased data transfer amount can take advantage of the high bandwidth-delay product of the satellite network. At one to two hops, the transmission rate of TCP Hybla increases by approximately 4.91 times compared to TCP Reno. At three hops, the transmission rate increases by a factor of 4.57, and at four hops and five hops, the link transmission rate also increases by a factor of 4.21 and 3.47, respectively. As the number of node hops increases within the industrial IoT, the link transmission rate of TCP Hybla gradually decreases, similar to the TCP Veno scheme. The increase in nodes means that the data access medium is more intense in a multihop IoT, which causes more random data loss. Increasing the number of data transfers in TCP Hybla further increases the probability of data loss. There is a vast contradiction between the data loss probability and the transmission amount in TCP Hybla.

The proposed scheme increases the amount of data transmission while distinguishing among kinds of data loss. This scheme facilitates the transmission of heterogeneous networks composed of satellite networks and the industrial IoT. The scheme also shows a significant increase in the link transmission rate compared to TCP Veno and TCP Hybla. The link transmission rate of the proposed scheme increases by 5.36 times, 5.19 times, and 5.02 times compared to TCP Reno for one hop, two hops, and three hops, respectively. At four hops and five hops, the link rate also increases by 4.61 and 3.98 times, respectively. Similar to TCP Veno and TCP Hybla, the transmission rate of the link decreases to varying degrees as the number of nodes increases.

Fig. 6 shows the transmission rates of satellite links in a heterogeneous network when the BER of satellite links is 10^{-6}. Compared with Fig. 5, the link transmission rate of TCP Reno has less variation and remains at 23.14 kbps, while the transmission rates of the other three schemes decrease to different degrees. Although the TCP Veno scheme can distinguish between different types of data loss, the increase in the BER of the satellite link still has an impact on the data transmission. TCP Hybla relies on increasing the amount of data transmission, and although it cannot effectively distinguish data loss, the transmission rate of the link is still significantly higher than that of TCP Veno. According to the simulation results, for the heterogeneous

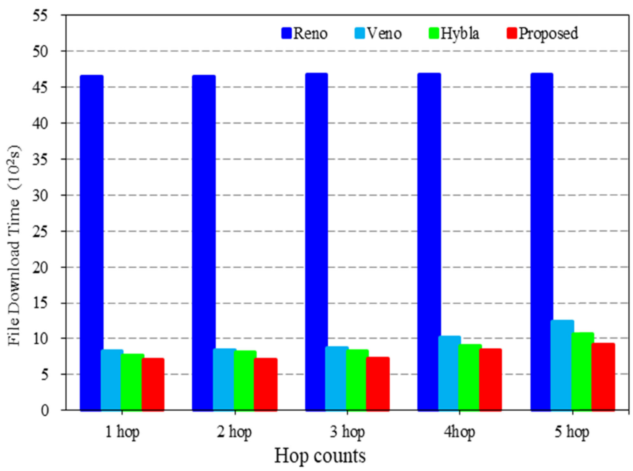

Fig. 7. File download time when BER is 10^{-8}.

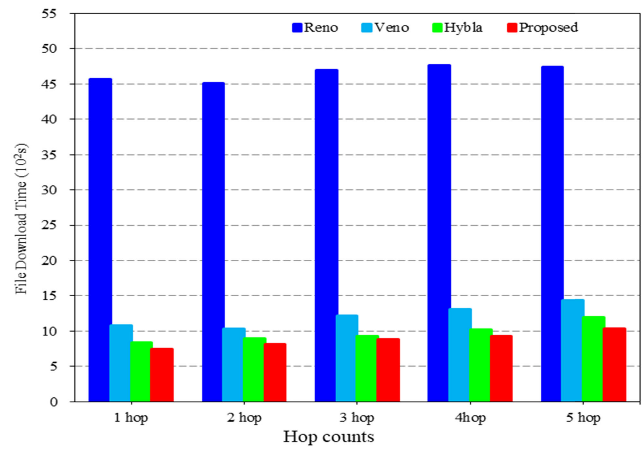

Fig. 8. File download time when the BER is 10^{-6}.

network composed of a satellite network and the industrial IoT, increasing the amount of data transmission is better than distinguishing the data loss to improve the transmission rate of the link. The proposed scheme has the highest transmission rate of the link among the four schemes due to the consideration of the respective characteristics of the satellite network and the industrial IoT.

B. File Download Time

In the experimental simulation, the file download time of different nodes in the IoT is compared with four schemes: TCP Reno, TCP Veno, TCP Hybla, and the proposed scheme. The FTP application is chosen for personalized service in the terrestrial network to facilitate comparison with the simulation results of the link transmission rate. One hop node to five hop nodes in the IoT completes the download of a 12.5 Mbyte file. An experimental simulation was conducted to test the file download time of each node in the industrial IoT. This parameter can reflect the performance of industrial IoT transmission within the heterogeneous network on a micro-level. Fig. 7 shows the file download time from one hop node to five hop nodes for a BER of 10^{-8} on the satellite link.

As shown in the figure, on the whole, all four schemes increase the file download time to varying degrees as the number of node hops within the IoT increases. The file download time of TCP Reno increases from 46.51×10^2 to 46.82×10^2 s. This scheme also encounters the same problem of link transmission rate, that is, the transmission performance of TCP Reno is extremely low when it cannot identify the kind of data loss and keeps the slow start linearly increasing, and its file download time is substantial.

The TCP Veno has a significant reduction in file download time compared to TCP Reno. From one to three hops, the file download time of TCP Veno decreases by approximately 4.47 times compared to TCP Reno. At four hops and five hops, the file download time also decreases by 3.59 times and 2.79 times, respectively, which is generally consistent with the link transmission rate.

Relative to the TCP Veno scheme, the file download time of TCP Hybla decreases from one hop to two hops to three hops by 6.92%, 4.83%, and 5.43%, while at four hops and five hops, it decreases by 11.08% and 13.74%, respectively. As the number of hops increases, even if there is more competition for data access among the nodes within the IoT, increasing the amount of data transmission can further reduce the file download time compared with differentiating the kinds of data loss.

The proposed scheme is not only more accurate in distinguishing data loss but also capable of increasing the data transfer amount. The scheme has the lowest file download time in different nodes among the four schemes. Moreover, compared to the TCP Veno scheme, the file download time of the proposed scheme decreases by 15.43% and 15.73% from one hop to two hops, respectively, and by 17.29% and 17.81% at three hops and four hops, respectively. At five hops, the decrease reaches 25.72%. The decrease in the proposed scheme is further increased with additional node hops within the industrial IoT compared to the case of the TCP Veno scheme.

Fig. 8 shows the file download time of different nodes within the industrial IoT in a heterogeneous network when the BER of the satellite link is 10^{-6}. Compared with Fig. 7, the file download time of TCP Reno has a slight fluctuation from 45.08 $\times$ 10^2 to 47.69 $\times$ 10^2 s, which shows that the larger BER of the satellite link not only increases the file download time of the nodes but also causes fluctuations in the data of different nodes. The other three schemes also have different degrees of increase in file download time. Compared to TCP Reno, the file download time of all three schemes is significantly reduced. Benefiting from the increased amount of data transmitted, TCP Hybla has an advantage over TCP Veno in that the file download time decreases by 22.44% and 13.61% from one hop to two hops, respectively, and by 23.48% and 22.07% from three hops to four hops, respectively. The drop at five hops is also 16.16%. The proposed scheme further increases its decrease in file download time at different multihop nodes with respect to TCP Veno.

In a heterogeneous network composed of satellite networks and the industrial IoT, considering that the node data of the latter will increase dramatically with the expansion of the industrial production scale, the problem of medium access competition will seriously restrict the transmission performance of the heterogeneous network. Thus, the transmission scheme should consider not only the impact of the satellite network of bottleneck links but also the random data loss caused by multihop nodes in the industrial IoT.

VI. Conclusion

In Industry 5.0, if the infrastructure of postdisaster communication is damaged, to provide seamless communication to the multihop network of the factory, this heterogeneous network of satellite and multihop networks can meet the demand of all-weather production and provide continuous and stable production for intelligent production systems. Considering the heterogeneous convergence of different networks under Industry 5.0 (wireless LANs, mobile communication networks 5G, wireless sensor networks, etc.), the performance of their transmission will also be influenced by an increasing number of factors. In this article, we propose a simple and easy-to-implement end-to-end transmission scheme based on the characteristics of multihop nodes within the industrial IoT and satellite networks. The scheme aims to increase the amount of data transmission while distinguishing among different types of data loss. The experimental simulation shows that the proposed scheme can considerably improve the transmission rate of the link and reduce the file download times of the nodes compared with the results of the three other transmission schemes. In the era of Industry 5.0, the number of nodes in the industrial IoT will increase dramatically, posing new challenges to the transmission performance of heterogeneous networks. The proposed scheme provides a useful reference for the development of new transmission protocol standards.

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