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Analysis of the Effect of the Reliability of the NB-Iot Network on the Intelligent System

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ABSTRACT With the rapid development of the Internet of Things (IoT) in recent years, the popularization of different segments of IoT has emerged. The IoT technology is slowly evolving toward intelligence, convenience, low power consumption, large connectivity, and wide coverage. This evolution is significantly attributed to the emergence of Narrowband of Internet of Thing (NB-IoT). NB-IoT is an emerging technology with wide-coverage, large-connection, low-power consumption, and low-costs. The intelligent system based on NB-IoT, an important branch of the IoT field, has various functions and is widely used. However, the intelligent system based on NB-IoT also generates reliability problems, caused by hardware, software, and networks. Therefore, this study deeply evaluates the impact of the NB-IoT network on the reliability of IoT intelligent systems. We simulated the real-world scenario by using the ns-3 simulator, and then carried out several data transmission experiments and recorded the relevant data of transmission performance indicators, finally calculated and analyzed the reliability results by using quantitative reliability indicators. The three main experiments respectively change the transmission distance of the NB-IoT signal, increase the access amount of the NB-IoT signal in the system, and increase the obstacles in the transmission path. The experimental results are represented by the signal-to-interference ratio (SINR), throughput rate, packet loss rate, and correct rate of the received data block and loss. Finally, we verify the impact of the NB-IoT network on system reliability on the basis of the experimental results.

INDEX TERMS Reliability, NB-IoT, intelligent system, Ns-3 simulation.

I. INTRODUCTION

With the steady growth of the Internet of Things (IoT) market, the scale and diversity of IoT data have expanded, the industry ecosystem has gradually improved, and innovations in segmentation areas have emerged. The popularity differentiation of IoT segment areas is a feature of the recent development of the IoT [1]. Specifically, technological evolution drives application products in the direction of intelligence, convenience, low power consumption, large connectivity, and wide coverage [2]. The development of IoT is mainly attributed to the role of the NB-IoT technology. For instance, an intelligent meter reading system under smart home, an intelligent street lamp system under smart city, and a smart parking system under car network as examples, the distinctive performance of the NB-IoT network is fully utilized by these IoT intelligent systems [3]. NB-IoT is an emerging technology proposed by 3rd Generation Partnership Project (3GPP) to support cellular data connections for low-power devices over a wide area network. With its important role in the IoT field considered, NB-IoT has been highly sought after because it provides various advantages with respect to performance [4]. With respect to signal coverage, NB-IoT has a 20 dB improvement over Long-Term Evolution (LTE) and General Packet Radio Services (GPRS) [5]. Given this advantage, the NB-IoT signal can cover underground garages, basements, underground pipes, and other areas where general communication signals are difficult to reach. With respect to terminal connection, NB-IoT can support massive connections [6]. For instance, NB-IoT can support 100,000 connections in only one sector,

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suggesting its significance in realizing the Internet of Everything. With respect to power consumption, NB-IoT uses simplified protocols and introduces new low-power operating states, providing the NB-IoT terminal module a standby time of up to 10 years [7]. With respect to cost, a single connected NB-IoT module costs no more than $5, allowing high-volume purchase and use. NB-IoT focuses on the IoT market with the aforementioned advantages, and various intelligent systems based on NB-IoT have developed [8].

The intelligent system based on NB-IoT is an important branch of the IoT intelligent system. The IoT system itself is a complex system, including the perception layer, control layer, network layer, and application layer, among others [9]. Each layer consists of several sub-layers that play different roles and involve different technical fields. The complex architecture of the system places stringent requirements on system reliability [10]. The uses of the IoT intelligent system vary widely from indoor to outdoor, underwater to high mountains, and urban to rural areas [11]. Differences in application also place demands on system reliability. Compared with that of traditional systems, the reliability of IoT systems is more complex. It is systematic, end-to-end, and all-encompassing. Thus, the reliability of the IoT intelligent system deserves further study and exploration. The reliability of the IoT system refers to the ability of IoT to continuously meet user service requirements under the conditions of coexisting influencing factors and change in business volume [12]. The ability of IoT system to satisfy users' service needs is reflected by the performance indicators of the system. Generally speaking, the better the performance indicators of the system, the more likely it is to achieve 100% of the required functions. The reliability of IoT system is a complex system evaluation problem under the condition of multi-factors, which has the characteristics of universality, dynamics and complexity. System reliability generally includes hardware reliability, software reliability, and network reliability [13]. This study mainly analyzes the effect of the NB-IoT network on the reliability of intelligent systems.

The reliability of the intelligent IoT system based on NB-IoT is analyzed, and the effect of the NB-IoT network on the system is evaluated. This study summarizes the architecture model on the basis of the NB-IoT running scenario and then performs experimental simulation in the ns-3 simulator. Three experimental scenarios for simulation are presented: the first scenario is the analysis of the effect of the NB-IoT network on system reliability by continuously changing the transmission distance of the NB-IoT signal; the second is the analysis of the effect of NB-IoT by continuously changing the number of NB-IoT signals; the third is the analysis of the effect of NB-IoT by adding building barriers to the transmission path. All reliability analyses are based on quantitative data determined from various indicators [14]. The quantitative indicators include the signal-to-interference-plus-noise ratio (SINR), throughput rate, packet loss rate, and correct rate of received data block and loss. All the indicators data are obtained by calling the operation function every time, and then by careful calculation, which has a certain degree of authenticity and reliability. SINR is specifically the ratio of the signal power (useful signal) to the unwanted noise power [15]. This approach measures the quality of wireless connections. The throughput rate, which represents the amount of data transmitted over the network per unit of time, measures system performance. The packet loss rate, which is the ratio of the number of lost packets to the total number of packets sent in per unit time, reflects the transmission quality of the network [16]. The correct rate of received data block represents the average probability of successfully accepting the data after the retransmission mechanism [17]; the higher the correct rate, the more accurate the system transmission. Loss refers to the value of the lost signal energy; the smaller the lost signal energy, the better the data quality and the farther the transmission [18]. These indicators also reflect the results of the experiment.

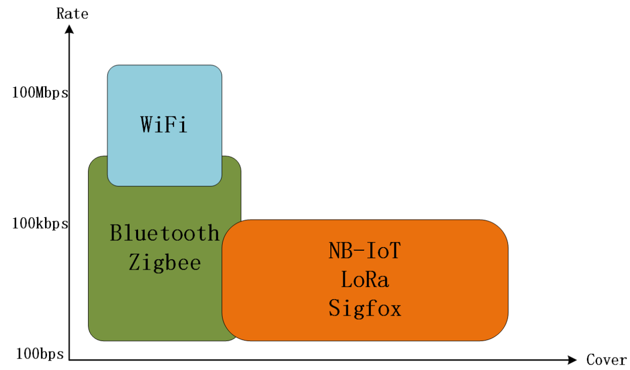

FIGURE 1. Performance comparison of communication technologies.

II. RELATED WORKS

NB-IoT has become an important branch of the Internet of Everything. Built on a cellular network, NB-IoT consumes only about 180 KHz of bandwidth and can be deployed directly on Global System For Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), or Long Term Evolution (LTE) networks to reduce deployment costs and achieve smooth upgrades. Analysis of all aspects of NB-IoT—coverage, data transmission, connection capacity, delay, and power consumption, among others—has recently attracted increased attention. The performance comparison diagram of the related communication technology is shown in the Fig. 1. Detailed assessment of NB-IoT coverage performance by Adhikary et al. indicated that it achieved coverage enhancements of up to 20 dB relative to existing LTE technologies [19]. Oh et al. proposed a scheme to enable a device in an idle state to send small data packets without the establishment procedure of a radio resource control connection [20]. This strategy can improve the maximum number of devices that can be supported in the NB-IoT system. Compared with the conventional scheme, the proposed scheme can increase the maximum number of supported devices by about 60%, as determined from the numerical results of the study. Li et al. comprehensively surveyed NB-IoT and Long Range (LoRa) and found that unlicensed LoRa provides advantages in battery life, capacity, and cost [21]. The licensed NB-IoT also has advantages in QoS, delay, reliability, and transmission range. In their study of small cell-assisted traffic offloading of the NB-IoT system driven by high-throughput and low-power tasks, Sinha et al. used joint traffic scheduling and power allocation to minimize the total power consumption of smart devices [22]. Yang et al. analyzed the data of SigFox, LoRa, General Packet Radio Service (GPRS), and NB-IoT deployed at 8,000km^2 of real sites in the northern part of Denmark [23]. The results indicated that all technologies provided a 95% uplink failure rate of less than 5% for outdoor users; however, only NB-IoT provides uplink and downlink connections with a failure rate of less than 5% for indoor users. Using rigorous mathematical analysis, Lauridsen et al. evaluated the use of NB-IoT in vehicle relays, including transmission delay and communication energy efficiency [24]. Petrov et al. proposed that the expectation maximization-successive interference cancellation (EM-SIC) time-of-arrival (ToA) detector can effectively resist the damage introduced by inter-cell interference, fading channel, and residual frequency-offset (FO); they also used the Observed Time Difference of Arrival for device location [25]. Hu et al. found that potential techniques to compensate for high path loss and high interference can provide knowledge management of NB-IoT partial deployment [26].

With the growing volume of studies on complex networks, research on the reliability of various communication network systems has drawn interest. Jia et al. applied Inter-Personal Area Network (Inter-PAN) concepts and algorithms to implement ZigBee fault detection and reconstruction functions, improving the reliability of ZigBee network data transmission [27]. Mangalvedhe et al. extensively studied the reliability of LoRa and focused on the influence of physical layer settings on the effective data rate and energy efficiency of communications [28]. Simultaneously, they evaluated the effects of environmental factors on LoRa performance, and showed that elevated temperatures significantly reduce the received signal strength and can largely affect packet reception. Song et al. performed an experimental evaluation of LoRa reliability under changing temperatures. Experimental results indicate that an increase in temperature can sufficiently convert a perfect LoRa link into an almost useless link, and that different Port Physical Layer (PHY) settings of LoRa exert different effects on temperature fluctuations [29]. Cattani et al. reduced the size of packet fragments to improve the reliability of communications in duty-limited networks [30]. The reliability of communication is reflected by the energy consumption, throughput, and end-to-end delay. Jia et al. used a top-down approach to characterize the reliability of wireless local area network (WLAN)/Worldwide Interoperability for Microwave Access (WiMAX) Radio Frequency (RF) front-end architecture by using Behavioral Description Language (VerilogA) [31]. Martinez et al. analyzed the reliability of WLANs and discussed the effects of factors such as space, time, environment, hardware, and human presence [32]. Weingrtner et al. analyzed the reliability of the LTE-based wide-area monitoring system, derived reliability expressions from the model framework, and analyzed the effects of various Random Access Channel (RACH) and Access Class Barring (ACB) parameters and monitoring traffic configuration [33].

On the basis of the aforementioned studies, no research have thus far been conducted regarding the effect of the NB-IoT network on the reliability of the IoT system. In the current study, we conducted three simulation experiments to reflect the performance changes of the NB-IoT system under different scenarios and then used quantitative data indicators to reflect the reliability of the NB-IoT system. The results are expected to provide a reference for system builders and developers.

III. MOTIVATION & INDICATORS

A. MOTIVATION

The development of communication technology and sensor technology has significantly accelerated knowledge update and application iteration in the industry. The development of the NB-IoT communication network has led to the advancement of the IoT intelligent system. Accordingly, part of the IoT intelligent system consists of various intelligent systems based on NB-IoT.

The intelligent parking guidance system based on the NB-IoT technology can interconnect the limited resources of traditional parking lots, manage and conduct big data analysis in the cloud center, and obtain idle parking space resources and optimal paths [34]. The cloud pushes the acquired information in real time via the (over-the-top) OTT method, searches for parking lots on off-site, and guides parking and fast search on the court in accordance with the berth information. The system efficiently links the owner and the parking lot, alleviating traffic congestion [35]. However, countless vehicles exist outside the parking lot in a city. If the number of vehicles inside and outside the parking lot connected to the system is increased, and the frequency change of each vehicle is increased [36], the question on whether the system can maintain its operations arises. This question raises concerns on system reliability [37], [38]. Whether a considerable increase in access volume influences the reliability of the entire management system presents a problem that deserves further study in the long-term development of the industry [41], [42].

The intelligent street lamp management system based on NB-IoT promotes the development of urban smart lighting and solves inadequacies in traditional urban lighting management, such as simplicity, high energy consumption, and high costs. The system interconnects original isolated street lights via the NB-IoT network, and combines cloud computing, big data, and GIS technology to form an urban lighting network. This system achieves comprehensive sensing and precise control of each street lamp. However, urban streetlights are widely distributed, from the city center to the outer suburbs of the city. The distance between street lights and the signal collection station induces interest to study the effect of highly distant NB-IoT signal transmission paths on system reliability.

NB-IoT-based forest fire prevention wireless monitoring systems use high-technology inspection and supervision techniques to eliminate the threat in its early stages. Forests are generally located in a remote high mountain area, with deep roads and thousands of trees. This challenge cannot be easily solved by traditional manpower inspection and maintenance. The system monitors the forest area 24/7 by using a camera and various sensors. Monitoring data are transmitted to the management platform for analysis via the NB-IoT network. Once the fire is confirmed, the system notifies the management personnel at the first time. However, the terminal equipment of the system is remote, and the transmission path has numerous obstacles, thus reducing signal energy and transmission quality. Therefore, whether the obstacles on the transmission path can affect system reliability deserves further study [46]–[48].

In addition to the aforementioned examples, many NB-IoT-based intelligent systems encounter reliability issues. Therefore, considering the factors affecting the reliability of the aforementioned systems, we propose an analysis of the reliability of the NB-IoT-based intelligent system in this research. This paper provides a visual representation of reliability performance through quantitative data. Specifically, this study simulates three experimental scenarios to analyze the influence of the NB-IoT communication network on system reliability.

B. INDICATORS

In this study, the evaluation of system reliability is represented by the quantification of indicators. These indicators directly or indirectly reflect the size and change of system reliability. Each reliability indicator is described in the subsections below.

1) SINR

SINR represents the signal-to-interference-plus-noise ratio. Generally, SINR denotes the ratio of the signal (useful signal) power to the unwanted noise power [43]. Unwanted noise includes all external interference noise and internally generated noise. The SINR indicator is often used as a measure of the quality of wireless connections in wireless communications [35]. The higher the SINR, the better the mediated signal; the better the channel environment, the higher the transmission rate. The formula for SINR is expressed as follows:

$$SINR = \frac{Power_{use}}{Power_{interfering} + Power_{noise}} \tag{1}$$

$$Power_{interfering} = \sum_{i=1}^{i \neq n} Power_{interfering\_n} \tag{2}$$

where $Power_{use}$ represents the power of the received useful signal; $Power_{interfering}$ represents the sum of power from all adjacent interfering signals, and it is composed of the sum of n $Power_{interfering\_n}$; and $Power_{noise}$ represents the sum of noise power generated by itself. In accordance with the definition of the aforementioned formula, SINR is a unitless constant, and has no dimension.

2) THROUGHPUT RATE

The throughput rate represents the amount of data transmitted over the network per unit of time [44], [45]. It is an important indicator of network performance. The higher the throughput, the greater the amount of transmission per unit of time. The unit of throughput rate is kbps. The formula for throughput rate is expressed as follows:

$$Throughput\_rate = \frac{Sum_{bytes}}{t} \tag{3}$$

where $Throughput\_rate$ denotes the throughput rate, Sum_{bytes} represents the total transmission in bytes, and t is the total transmission time in seconds.

3) PACKET LOSS RATE

The packet loss rate is the ratio of the number of lost packets to the total number of packets sent in unit time. This ratio indicates whether the data is lost when transmitted, and how much of the total transmission comprises lost data. The packet loss rate indicator reflects the quality of network connectivity and integrity of data transmission. The lower the packet loss rate, the higher the quality of the network connectivity, and the faster and more complete the data transmission. The packet loss rate is expressed as follows:

$$P\_loss\_rate = \frac{Num_{lost}}{Num_{sent}} \tag{4}$$

$$Num_{lost} = Num_{sent} - Num_{receive} \tag{5}$$

where P_loss_rate is the packet loss rate; Num_{lost} indicates the number of lost packets, that is, the difference between the transmitted packet and the received packet; Num_{sent} denotes the number of sent packets; and $Num_{receive}$ represents the number of received packets.

4) CORRECTNESS OF TB

Correctness of TB is the correct rate of received data block. The correct rate of received data block represents the average probability of successfully accepting the data after the retransmission mechanism. The higher the correctness of TB, the more efficient the data transmission, and the more effective the retransmission mechanism. Therefore, the indicator of the correctness of TB reflects the data transmission performance of the system. The correctness of TB is expressed as follows:

$$Correct = \frac{Correct_{succ}^{1} + Correct_{succ}^{2} + \cdots Correct_{succ}^{n}}{n} \tag{6}$$

where *Correct* denotes the correctness of TB, and $Correct^n_{succ}$ indicates the correct rate of successful data reception at the nth retransmission.

5) LOSS

Loss refers to the value of the lost signal energy [39]. The amount of loss in this study refers to the loss caused by building obstacles on the transmission path. The greater the amount of loss, the greater the effect of the building on signal transmission. The loss indicator reflects the attenuation of the signal energy, and excessive signal attenuation affects the transmission length of the signal. Loss is expressed as follows:

$$Loss = Loss_{build} - Loss_{nonbuild} \tag{7}$$

$$Loss_{build} = Energy_{sent} - Energy_{build-recep} \tag{8}$$

$$Loss_{nonbuild} = Energy_{sent} - Energy_{nonbuild-recep} \tag{9}$$

where *Loss* represents loss; $Loss_{build}$ indicates the total loss of signal transmission on the transmission path with building obstacles; and $Loss_{nonbuild}$ is the total loss of signal transmission on the transmission path without building obstacles. $Energy_{sent}$ refers to the energy of the signal sent; $Energy_{nonbuild-recep}$ denotes the remaining energy that the signal transmits to the reception node on the path without the building; and $Energy_{build-recep}$ is the remaining energy that the signal transmits to the reception node on the path with the building.

IV. MODEL ESTABLISHMENT

This section mainly describes the overall structure of the experimental model, including the basic components of the experiment and the running procedure. We describe the basic common model of the three experiments, followed by the enhancements of the three experiments under the common model [40]. Figure 2 presents the basic architecture of the experimental model. When using ns-3 for network simulation, the experimental study is mainly divided into two parts. The first part is the selection of development of the corresponding module, and the second part is the generation of a network simulation script. The combination of the two can form a simple network model. We can select the corresponding simulation module according to the actual simulation object and scenario, including the network module, protocol module, network device module, application layer module, and so on. If the existing modules cannot meet the requirements, users can also design and develop simulation modules. The ns-3 simulation script supports two languages: C++ and Python, which have the same API interfaces. Users can choose the scripting language according to their needs. The basic components of the experimental model in this study are the nodes, network devices, channels, applications, and protocol stacks. The node in ns-3 is an abstract concept, which is equivalent to an empty computer shell. The software and hardware required for the network need to be installed in the node, such as the network card, application, protocol stack, and so on. NodeContainer provides a simple way to create, manage, and use any node object. When a large number of similar nodes exist in the simulation system, the user can immediately operate multiple nodes by using NodeContainer. However, NodeContainer has a limited capacity, and the number of nodes installed cannot be increased infinitely. The node needs to configure the network device. The abstract concept of network devices is equivalent to the sum of hardware devices and software drivers. The network device is installed on the node so that the node can communicate with other nodes via the transmission path. Similar to an actual computer, a node can be connected to multiple transmission paths simultaneously via multiple network devices. Network devices are described by the C++ NetDevice class in ns-3. The NetDevice class provides various ways to manage connections to other nodes and transport paths. In addition, it allows developers to define them in an object-oriented way. Different types of network devices are connected to different transmission paths. The transmission path is abstracted into a channel in ns-3. That is, different types of network devices can be operated on different channels. The channel is an abstract concept of the transmission medium, described in the C++ channel class. We can artificially set the channel delay and other attributes. The channel class provides methods for managing channel objects as well as connecting nodes and channels. The channel and the network device correspond to each other in ns-3. For instance, the WIFI network device corresponds to the WIFI channel; similarly, the LTE network device corresponds to the LTE channel. However, Ethernet devices and wireless channels cannot be used together because they do not correspond to each other. The NB-IoT network can be deployed directly on the LTE network to reduce deployment costs and achieve smooth upgrades. Thus, this experiment is based on the LTE module to develop and generate the NB-IoT module, so that NB-IoT has its own dedicated network equipment and channel. Application part represents an abstraction of a server-side application. The aforementioned concept enables the network node to implement a physical connection, but to achieve communication, software support—that is, a protocol—is required. The protocol specifies the method by which data is transmitted throughout the network. The node transfers the data

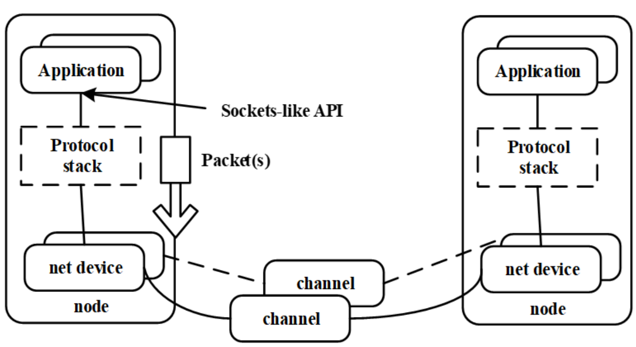

FIGURE 2. Basic architecture of model.

layer by layer from bottom to top, converts the media signal into a binary signal, converts the binary signal into a data frame, converts the data frame into a data packet, and finally transfers it to the corresponding process (application) via the port number. If the application generates data, socket-like programming is used to implement the downward transfer of the data packet. The data packet is then passed down to the network device according to the protocol stack. The network device includes a MAC layer and a physical layer protocol, allowing the data packet to be converted into a binary stream by the data frame as in the real network, and finally becomes a signal transmitted to the destination node. At this point, complete data transfer is ended and is similar to a real network.

After the ns-3 basic model is established, additional modules are added to meet all experimental requirements. Three models of this experiment are based on the previously mentioned basic model for incremental adjustments. Model 1 describes changing the transmission distance of the NB-IoT signal to analyze the effect of the NB-IoT network on system reliability. The model introduces a fixed position model under the mobile module, arranges the initial position distribution of the node, and adjusts the distance between the NB-IoT nodes and the receiving nodes. All NB-IoT nodes are similarly located to eliminate the influence of the NB-IoT node location on reliability. A different transmission distance was used in each experiment, and the corresponding experimental results are recorded. Further analysis of the experimental results determines whether the transmission distance of the NB-IoT signal affects system reliability.

The second model of the experiment describes changing the number of NB-IoT nodes to analyze system reliability. The model also applies the fixed position model under the mobile module to arrange the position distribution of the nodes. To eliminate the influence of positional factors, we place all NB-IoT nodes in the same position during the simulation. Simultaneously, the received node is fixed, and the distance between the received nodes and the NB-IoT sent nodes remains unchanged during the experiment. We continue to add nodes to NodeContainer during the experiment until the total number of nodes is close to the NodeContainer capacity limit. We analyze the different performance results caused by the different number of nodes in NodeContainer, and thus determine the effect of the NB-IoT network on system reliability.

The third model of the experiment describes the effect of building obstacles on the transmission path on system reliability. The model uses the mobile model and energy model. Similar to the previous model, the fixed position model under the mobile model determines the location of all nodes, and no change in position occurs throughout the experiment. This experiment, which also refers to the energy model to record the energy of the node at the sender and the receiver, is a set of comparative experiments. First, experiments are performed on the transmission path without buildings, and the energy at the transmitting end and the receiving end are

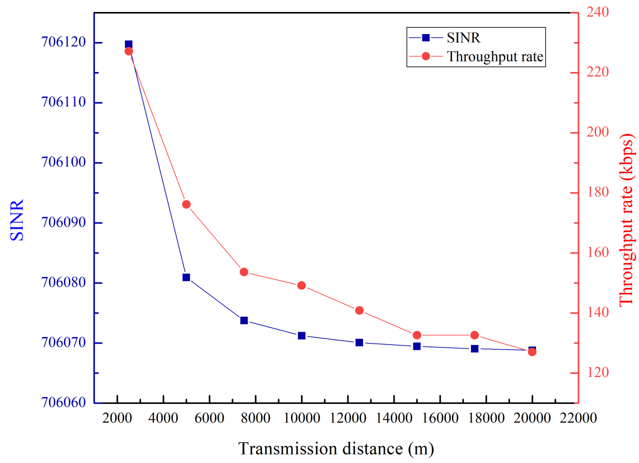

FIGURE 3. SINR and throughput rate at different transmission distance.

recorded. Second, buildings are added to the transmission path, and the energy of the sender and that of the receiver are recoded. By comparison of the two sets of experimental results, we study whether building obstacles can lead to losses, and affect system reliability. In addition, we increase the building material and floor factors to determine whether system reliability is influenced by building materials and floor factors.

V. RESULTS EVALUATION

This section mainly evaluates the experimental results of three simulation experiments. In the study, the ns-3 emulator is installed on the Centos7 platform, running compilers for gcc 4.9 and Python 2.7. During simulation, we used C++ to write the experimental script and run the experiment multiple times in order to achieve accuracy of the experimental results and provide a large amount of data support for reliability analysis.

A. EXPERIMENT 1: EFFECT OF THE TRANSMISSION DISTANCE OF THE NB-IOT SIGNAL ON RELIABILITY

Figures 3 and 4 illustrate the effect of the NB-IoT signal transmission distance of on system reliability. System reliability is represented by four parameters: SINR, throughput rate, packet loss rate, and correctness of TB. As the transmission distance increases, SINR, the throughput rate, and the packet loss rate decrease, whereas the correctness of TB remains basically unchanged. SINR represents the ratio of the strength of the received useful signal to the strength of the interference signal and noise signal. Generally, the higher the SINR, the stronger the mediated signal; the better the channel environment, the higher the transmission rate. When the amount of transmitted data is constant, an increase in transmission distance indices increases in the noise and interference received by the system and ultimately affects the value of SINR. Thus, SINR is decreased. The throughput rate is the amount of data transmitted over the network per unit of time and is an important indicator of network performance.

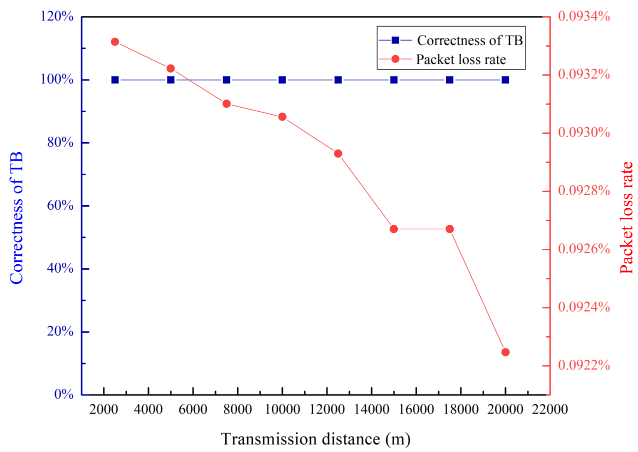

FIGURE 4. Correctness of TB and packet loss rate at different transmission distance.

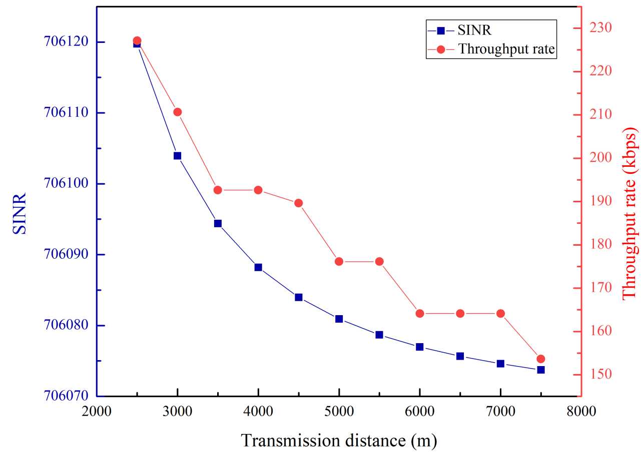

FIGURE 5. SINR and throughput rate at short transmission distance.

Generally, the higher the throughput rate, the better the network performance. As the transmission distance increases, data blocks require a longer time for transmission, thereby decreasing the amount of data blocks received by the node in unit time. Ultimately, the throughput rate of the entire system is reduced, ranging from 227.125 Kbps to 127 Kbps. The general trend in Figure 3 indicates that, when the transmission distance is 2500-7500m, the downward trend of SINR and the throughput rate becomes evident. When the transmission distance is too short, the transmission performance of NB-IoT is unstable and the transmission performance fluctuates. As presented in Figure 5, further experiments shows that rapid decreases in SINR and the throughput rate occur at the initial 2500-3500m. When transmission distance reaches 3500m, SINR and the throughput rate change relatively slowly. The reason is that NB-IoT is a long-distance transmission technique, and the distance corresponding to the rapidly decreasing segment of the curve in the figure is considerably short. Along that segment, the NB-IoT transmission remained in its initial stages, the performance was unstable, and the curve trend caused relatively large fluctuations. The packet loss rate is the ratio of the number of lost packets to the transmitted data packets. A considerably high packet loss rate affects the system operation. As the transmission distance increases, the longer the data transmission time, the more frequent the NB-IoT retransmission mechanism is triggered by the system. Ultimately, the loss of data and the packet loss rate are reduced. The packet loss rate of the entire system ranges from 0.00093314 to 0.000922469. Thus, the retransmission mechanism of NB-IoT alleviates the problem of system data packet loss to a certain extent. The general trend of the packet loss rate curve suggests that, at a transmission distance of 15000-20000m, the packet loss rate of the system is relatively abnormal. The reason is that the distance is relatively long and does not exceed the theoretical transmission distance of the NB-IoT. When the signal transmission distance is too far, or even near the theoretical transmission distance of NB-IoT, the transmission performance of NB-IoT fluctuates unsteadily, and the packet loss rate of NB-IoT decreases. Finally, the retransmission mechanism of NB-IoT can be fully used within the distance, so that the packet loss rate in the segment is relatively minimal. As shown in Figure 4, the packet loss rate remains relatively stable at a distance of 15000-17500m, and the variation is small. However, at a distance beyond 17500m, the packet loss rate markedly decreased. As depicted in Figure 6, the results of further experiments show a significant downward trend of the packet loss rate at a distance of 17500-18000m. However, at a distance exceeding 18000m, the difference in the packet loss rate remains small and almost remains unchanged. The experiment continued to determine the variation in the distance segment ranging from 17500m to 18000m. Figure 7 illustrates that the more accurate decreasing segment lies in the 17850-17950m range. The correctness of TB indicates the correct rate of the data block received by the node. Owing to the retransmission mechanism, although the transmission distance increases, the data block content is relatively complete and correct. Thus, the correctness of TB remains substantially unchanged. The aforementioned data shows that the transmission distance of the NB-IoT signal affects system reliability, but this effect is relatively small.

B. EXPERIMENT 2: EFFECT OF THE NUMBER OF NB-IOT NODES ON RELIABILITY

Figures 8 and 10 show the effect of the number of NB-IoT nodes on system reliability. The experimental results indicates system reliability are reflected by SINR, the throughput rate, the packet loss rate and the correctness of TB. As depicted in Figure 8, as the number of NB-IoT nodes increases, SINR remains basically the same, but the throughput rate continues to increase. The number of the NB-IoT signal in the system increases. However, the transmission path and the transmission environment remain unchanged. The internal and external factors that generate noise signals

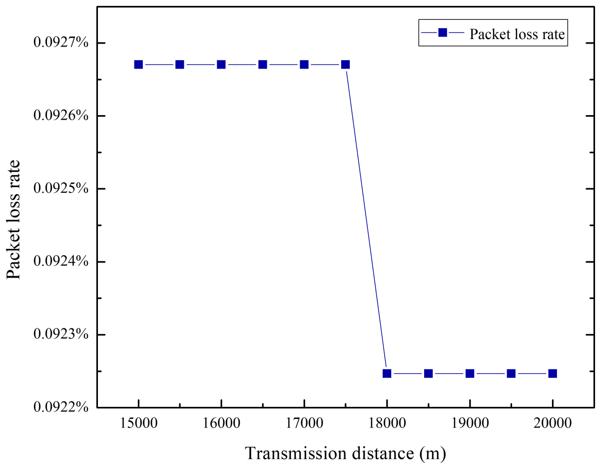

FIGURE 6. Packet loss rate at long transmission distance.

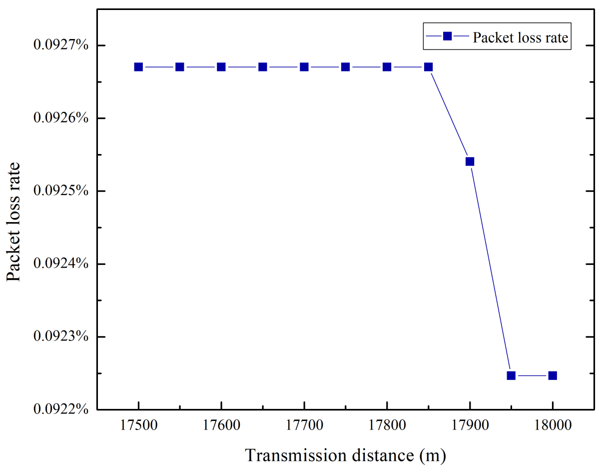

FIGURE 7. Packet loss rate at long transmission distance.

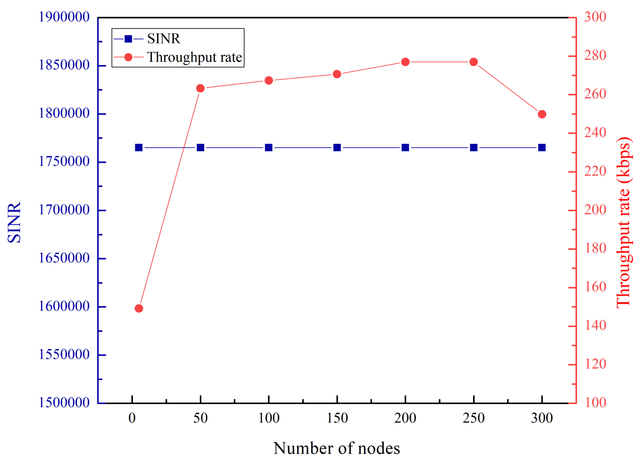

FIGURE 8. SINR and throughput rate at different number of nodes.

and interference signals do not change substantially; thus, SINR remains basically unchanged. As the number of nodes increases, the amount of data increases, thereby increasing the throughput rate of the entire system. The curve of the

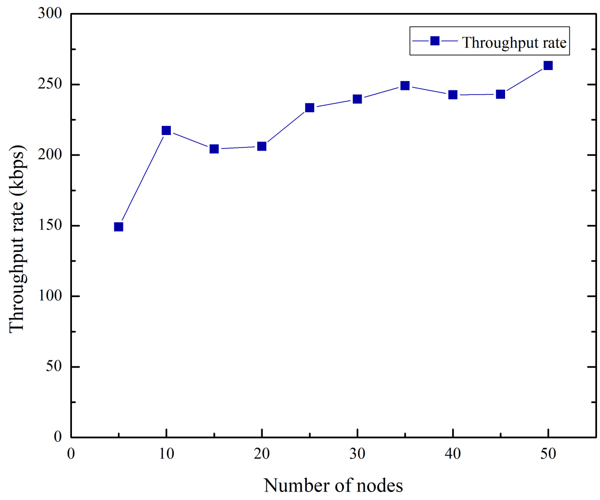

FIGURE 9. Throughput rate at small number of nodes.

throughput rate in Figure 8 shows that when the number of NB-IoT devices ranges from 5 to 50, the throughput rate of the system increases rapidly. When the number of nodes increases, the transmission volume per unit time increases and the overall transmission rate increases. However, when the number of devices ranges from 250 to 300, the throughput rate of the system declines. The throughput rate of the system reaches 177 Kbps with a minimum of 149.125 Kbps. The reduced throughput rate is related to the ns-3 simulation system when the number of devices ranges from 250 to 300. In the ns-3 simulation, the NB-IoT nodes are managed by node containers, which are limited in capacity. 300 nodes is close to the maximum capacity of one container. Thus, when the number is close to 300, the related performance of the throughput rate fluctuates. Figure 9 shows that when the NB-IoT node ranges from 5 to 50, the overall trend of the throughput rate is still increasing. When the number of NB-IoT nodes has only started to increase, the node container resources and other system resources become highly excessive, which can fully provide the increased resource requirements of the node. Thus, the increase in throughput rate is relatively fast. As the number increases, the system resources remain sufficient. The throughput rate continues to increase, but the growth rate decreases. This situation differs from when the number has just increased. Figure 10 shows the trend of the packet loss rate and the correctness of TB. As the number of nodes increases, the packet loss rate increases, and this upward trend is relatively stable. Meanwhile the correctness of TB exhibits a downward trend. The area segments with different numbers of nodes exhibit different decreasing effects. The packet loss rate of the entire system changes from 0.00081 to 0.0096085530, and the correctness of TB changes from 1 to 0.929781082. As the number of NB-IoT nodes increases, the transmission capacity of the system increases, and the probability of system data loss or damage increases. Accordingly, the system packet loss rate increases to a certain extent, and the correct rate of data block decreases. Although

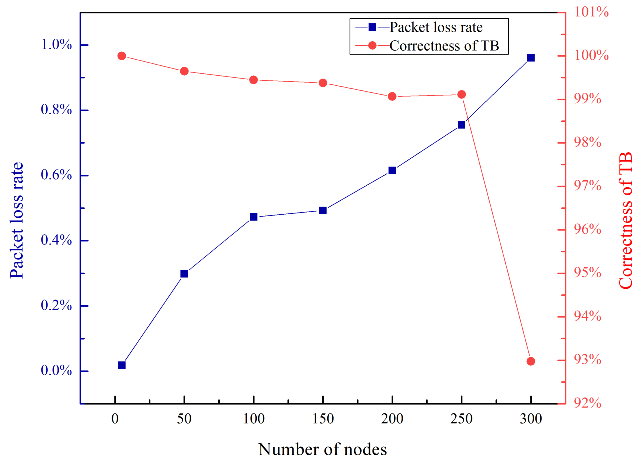

FIGURE 10. **Correctness of TB and packet loss rate at different number of nodes.**

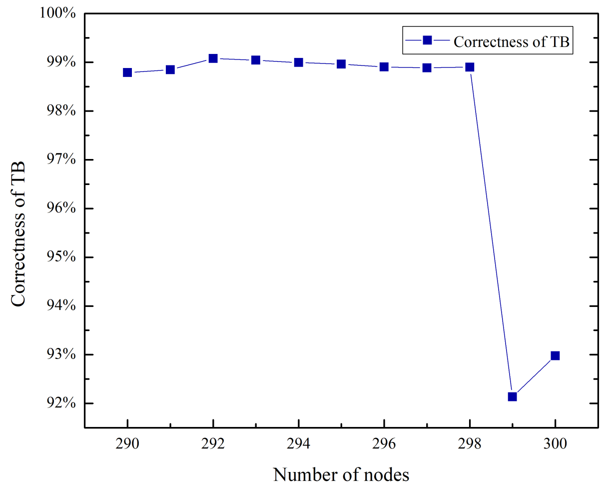

FIGURE 12. **Correctness of TB at large number of nodes.**

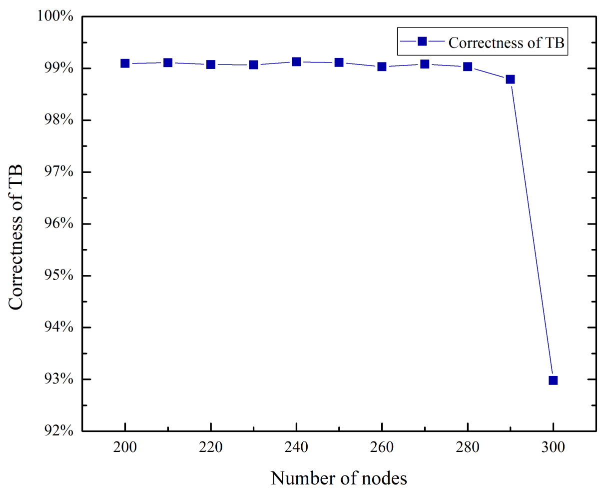

FIGURE 11. **Correctness of TB at large number of nodes.**

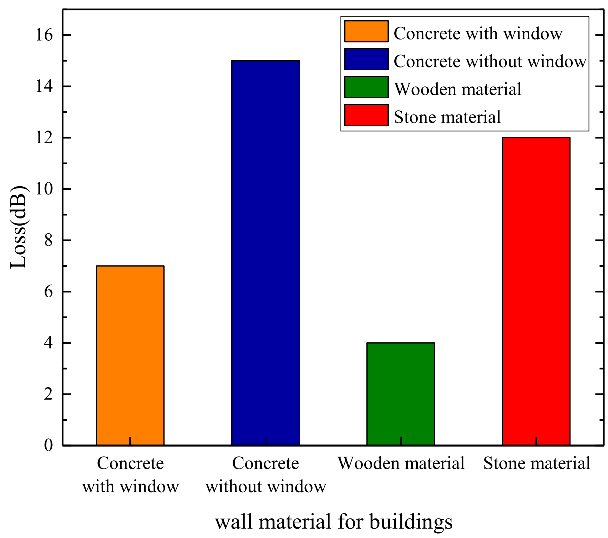

FIGURE 13. **Loss under different material buildings.**

the system has a retransmission mechanism, with a large increase in the amount of data, data retransmission alone within a short time cannot completely recover data loss or damage. When the number of NB-IoT nodes ranges from 250 to 300, the reduction in the correct rate of data block increases significantly. According to a further study, when the number of nodes exceeds 298, the correct rate of data block abruptly changes, as depicted in Figures 11 and 12. However, only a small increase is observed even after 299. The number of nodes is close to the load limit of the node containers, exhibiting a performance mutation. The aforementioned data shows that system reliability is indeed influenced by the number of NB-IoT nodes, but this effect is relatively small.

C. EXPERIMENT 3: EFFECT OF BUILDING BARRIERS ON RELIABILITY

Experiment 3 describes the effect of obstacles on energy consumption through the transmission path and analyzes changes in system reliability. The experiment aims to increase the presence of buildings on the transmission path of the NB-IoT signal, provide signal transmission obstacles, and analyze the energy loss caused by building obstacles. Thus, system reliability in this experiment is represented by parameter loss. The experiment corresponding to Figure 13 intends to add buildings with different types of materials to the transmission path and then analyze the loss of the system. The building materials are concrete with windows, concrete without windows, wooden materials, and stone materials. The experimental results demonstrate that the building exerts an effect on system loss, and that buildings with different materials can lead to various losses. That is, the amount of system loss is related to the building materials of the obstacle. Simultaneously, the experimental results indicate that the buildings causing the maximum loss consist of concrete buildings without windows, buildings of stone materials, concrete buildings with windows, and buildings of wooden

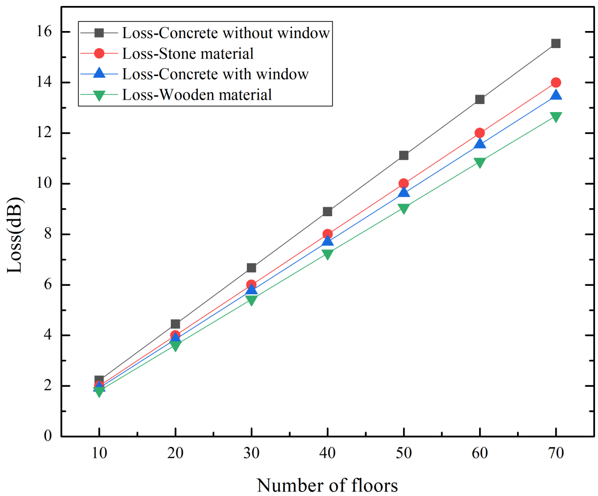

FIGURE 14. Loss under different number of floors.

materials. The corresponding link losses are 14.9996 dB, 11.9996 dB, 6.9996 dB, and 3.9996 dB. Figure 14 reflects the change in system loss caused by floor variations in buildings constructed using different building materials. The experimental results indicate that, regardless of the material the building is made of, the loss of the system increases while the building floor increases. With the same number of floors remaining the same, the building materials made of concrete without windows incur the largest loss, followed by stone buildings, concrete buildings with windows, and wooden buildings. This result indicates that the number of floors in the building also affects system loss. The reliability of the system is also affected by the material and number of floors of the building barrier.

VI. CONCLUSION

This study mainly investigates the effect of the NB-IoT network on system reliability. The effect is specifically reflected by the quantitative indicators of the simulation. The simulation is an abstraction of three specific running scenarios. Experiment 1 describes the impact of the NB-IoT network on the reliability of the entire intelligent system by continuously changing the transmission distance of the NB-IoT signal. Experiment 2 analyzes the effect of NB-IoT network on the reliability of the intelligent system by continuously increasing the signal nodes of the NB-IoT network. Experiment 3 describes the effects of the transmission path building obstacles on signal loss, and analyzes the effect on system reliability through the loss of the network. The quantitative indicators of the experiment are SINR, the throughput rate, the packet loss rate, the correctness of TB, and loss. Simulation experiments 1 and 2 mainly reflect the influence based on the four indicators. The results of experiment 1 indicate that the transmission distance of the NB-IoT signal influences system reliability. The specific quantized data indicates SINR and throughput rate will decrease with the increase of transmission distance. But the correctness of TB remains basically the same, and the packet loss rate reduces small changes of less than 1%. The results of experiment 2 show that the nodes of the NB-IoT network can affect system reliability. Specifically, as the amount of access increases, the packet loss rate of the system increases, and the correctness of TB decreases. However, the overall packet loss rate remains lower than 1%, and the average correct rate of all received data blocks exceeds 98.5%. The results of experiment 3 show that the building barrier on the transmission path influences system reliability. In addition, the material and floor changes of the building exert different effects. Overall, the NB-IoT network exerts an effect on system reliability, but such effect is small and causes no significant performance fluctuations in the overall operation of the system. In addition, for the actual application deployment, all aforementioned quantitative indicator data can support this finding. Attention should be directed toward the change in the NB-IoT network performance, and performance advantage of NB-IoT should be maximized.

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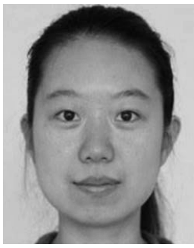

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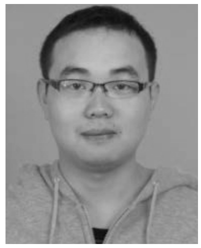

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