Research on Distributed Access Simulation of Large-Scale Multi-Source Terminals for 5G

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Abstract

Large-scale machine communication scenarios are faced with the characteristics of a large number of terminal devices, small communication packets and frequent transmissions. Traditional multiple access technology can't fully apply to these characteristics, so it needs to be improved and designed. In order to further improve the effect of distributed access strategy formulation of large-scale multi-source terminal for 5G, this paper proposes a distributed access technology for large-scale multi-source terminals for 5G. For distributed access scenarios, antenna units in the distributed system are scattered in the system, and each antenna unit keeps communication with the surrounding terminal equipment, which can expand the number of terminal devices randomly accessed in the same time slot. Then, taking advantage of this inherent advantage and the advantage of time-shifted pilot, this paper proposes a distributed random access scheme based on time-shifted pilot.

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Finally, through analysis and simulation, this paper proves that this scheme can effectively reduce the pilot collision probability of each antenna element and the average access delay in the system, which provides a technical reference for the subsequent distributed access of large-scale multi-source terminals.

Keywords: 5G, multi-source terminal, distributed, access.

1 Introduction

The access network is the "gate" for users to access the mobile communication network. As the core facility of the access network, the research and development and design of base stations will greatly affect the performance of the access network and the deployment and operation and maintenance costs of operators. The main components of the base station include the base band processing unit (BBU), the remote radio unit (RRU), and the antenna. In traditional networks, the access network adopts a distributed radio access network (D-RAN) architecture in which BBU and RRU are separated. Under the D-RAN architecture, the BBU of each base station is deployed in a distributed way, and operators still need to build or rent a large number of computer rooms to place BBU and related supporting facilities such as air conditioners and power supplies. Therefore, operators still need to spend high costs on site construction and operation and maintenance. With the increasingly fierce competition among operators, the cost of construction and operation and maintenance of access network has increased significantly. Under this background, cloud radio access network (C-RAN) came into being.

Energy-efficient resource allocation requires scheduling and allocating different types of resources in different problem models. Specifically, these resources include frequency domain resources, time domain resources, spatial domain resources, power resources, computing resources, and cache resources. Among them, the allocation of frequency domain resources and airspace resources has no impact on system energy consumption. Therefore, the allocation of these two resources mainly maximizes energy efficiency by increasing system capacity. However, the allocation of time domain resources, power resources, computing resources and cache resources will affect the system energy consumption. Therefore, the allocation of these four resources can not only optimize the energy consumption for the purpose of energy conservation and emission reduction, but also consider their impact on system capacity to achieve resource allocation that maximizes energy efficiency.

The purpose of massive MIMO (multiple-in multiple out) is to serve a small number of users with a large number of antennas, thus improving system performance. In traditional communication scenarios, because there are fewer users in the cell, the base station can allocate dedicated pilot sequences for all access users to transmit data without pilot collision. Moreover, the base station can use the orthogonality of the pilot to obtain the CSI (channel state information) of each user to recover the data information transmitted by the user. However, in 5G application scenarios, more and more terminal devices need to be connected to the network, and the number of devices has far exceeded the number of available pilots. The shortage of spectrum resources will inevitably lead to the phenomenon that multiple terminals preempt the same pilot, which is called pilot collision (PC). Once a pilot collision occurs, the base station will not be able to correctly estimate the CSI of all terminals selecting the pilot.

Distributed access scheme is a more efficient random access scheme. The biggest difference from the centralized access scheme is that the pilot collision is solved centrally by the base station side in the centralized access scheme, and the pilot collision is solved by the user in the distributed random access scheme. Compared with centralized schemes, this kind of scheme can better leverage the performance advantages of massive MIMO. Specifically, all active users send their own pilot information to the base station. After receiving the pilot information, the base station broadcasts a piece of information to the user. Then, users receive this information and judge whether they have a pilot collision according to certain criteria. For the collision users, some effective conflict resolution strategy is adopted to reduce the impact of pilot collision.

Realize full signal coverage within the system through antenna units distributed throughout the community. Applying distributed systems in large-scale machine communication scenarios can achieve full signal coverage of terminal devices and shorten the communication distance between terminal devices at the edge of the system. Compared with centralized systems, the characteristic of distributed systems is that antenna units are dispersed in different locations within the system and connected to the central processing base station through optical fibers or coaxial cables. The antenna units are only responsible for receiving signals from terminal devices and do not operate on the signals. Instead, they transmit the signals to the central processing base station for signal processing and other operations.

This paper proposes a distributed access technology for large-scale multi-source terminals for 5G. For distributed access scenarios, antenna units in the distributed system are scattered in the system, and each antenna unit keeps communication with the surrounding terminal equipment, which can expand the number of terminal devices randomly accessed in the same time slot. Then, taking advantage of this inherent advantage and the advantage of time-shifted pilot, this paper proposes a distributed random access scheme based on time-shifted pilot.

The main purpose of this article is to improve the multiple access effect in large-scale machine class communication scenarios, reduce the probability of pilot collision within the cell, effectively reduce the average access delay, and enhance the multi terminal access effect and response speed in the 5G era.

The innovation of this article lies in conducting relevant research on multiple access technology in large-scale machine class communication scenarios, with a focus on analyzing the active user detection and channel estimation problems of signal free multiple access technology in the presence of asynchrony, as well as how to improve traditional random multiple access schemes, alleviate the impact of pilot conflicts, and reduce system access latency.

2 Related Work

In terms of cache resources, reference [1] proposes a cache resource allocation algorithm to minimize the energy consumption of user terminals, and provides an approximate expression for system energy efficiency in heterogeneous cellular networks equipped with edge cache resources. Through simulation, it is pointed out that edge cache can more effectively improve system energy efficiency in situations where the return link rate is severely limited, interference strength is low, and user request content is concentrated. Moreover, compared to introducing edge cache at macro cellular base stations, introducing edge cache at small cellular base stations is more conducive to improving system energy efficiency. Reference [2] derived the expression of system energy efficiency using high-dimensional random matrix theory in the C-RAN scenario using forward link compression technology, and based on this, obtained the edge cache capacity value at the maximum energy efficiency. Reference [3] studied the scenario where edge caching is equipped at the RRU in C-RAN, and the results showed that edge caching can reduce communication overhead on the return and forward links, thereby reducing system energy consumption. Based on the scenario of the same edge caching, downlink multicast and unicast schemes considering user association, RRU activation, rate allocation, and signal precoding were studied. Simulation results showed that edge caching can simultaneously improve the spectral efficiency and energy efficiency of the system in both schemes.

In terms of time-domain resources, in order to reduce the energy consumption of the baseband resource pool and RRU, reference [4] discusses the sleep strategy of processors in the baseband resource pool. Reference [5] jointly considers beamforming and sleep strategies, where beamforming is used for energy saving of RRUs, while sleep strategies reduce the energy consumption of the baseband resource pool. Reference [6] studied the RRU sleep strategy based on carrier aggregation in CRAN. Reference [7] first estimated the resource utilization rate of the baseband resource pool in C-RAN, and then studied the sleep strategy of BBUs based on this. Through reasonable task merging, the number of sleeping BBUs was maximized while ensuring QoS. Literature [8] combined with MIMO technology, studied the fine-grained sleep strategy in CRAN, and proposed a traffic shaping strategy, which centrally schedules users in several timeslots, so that RRU can sleep in more timeslots, thus improving energy efficiency. Reference [9] also conducted research on fine-grained sleep strategy in C-RAN, which combines transmission optimization and utilizes group sparsity promotion technology to enable more RRUs to enter sleep while meeting user QoS requirements.

In terms of spatial resources, reference [10] analyzed large-scale MIMO systems from the perspective of circuit power consumption and proposed a system energy consumption and efficiency model directly related to the circuit model. Reference [11] is based on heterogeneous networks using massive MIMO, and designs corresponding beamforming algorithms for weak, medium, and strong cross layer interference environments, optimizing system energy efficiency under QoS and power constraints. Reference [12] proposes an energy-efficient beamforming algorithm based on heterogeneous networks using massive MIMO, in scenarios where the channel state information is non ideal. The algorithm minimizes the total power consumption of the system while ensuring QoS constraints and QoS interruption probability below a certain threshold. Reference [13] studied the scenario of multi cell massive MIMO and proposed an improved zero forcing algorithm to optimize system energy efficiency under the premise of multipath fading and non ideal channel information. Reference [14] combines antenna selection and power allocation in the scenario of massive MIMO uplink, by jointly considering transmission efficiency and circuit and antenna energy consumption, and achieving the goal of minimizing energy consumption under QoS constraints.

In terms of power resources, reference [15] jointly considers power allocation and resource block allocation in C-RAN, and uses genetic algorithm to obtain the most energy-efficient resource allocation. Reference [16] proposes a two-stage scheme for C-RAN scenarios that jointly considers power allocation and RRU selection to optimize energy efficiency. In the first stage, a greedy algorithm is used to select RRUs and corresponding user sets for collaborative multi-point transmission. In the second stage, the inlier method is used for power allocation. This article shows through simulation results that transmission power, RRU density, and the number of served users are the main factors affecting system energy efficiency in this scenario. Reference [17] studied the energy efficiency issue of MIMO downlink in C-RAN and proposed an iterative algorithm based on Lagrange function for power allocation to maximize system energy efficiency.

Reference [18] studied resource allocation based on C-RAN and D2D (Device to Device), and achieved maximum system rate and energy efficiency by jointly considering the uplink power allocation of C-RAN and D2D and the quantization compression strategy of the forward link. Reference [19] studied resource allocation in a scenario where multiple service providers share the same ultra dense deployment of C-RAN. Through uplink power allocation, this paper achieves energy efficiency optimization while ensuring QoS for service providers. Reference [20] jointly considers beamforming and power allocation to improve energy efficiency based on dynamic TDD in C-RAN scenarios. In terms of computing resources, reference [21] models the amount of computing resources required for C-RAN downlink transmission and analyzes the required computing resources under different user densities. Simulation results show that the amount of computing resources increases nonlinearly with the increase of user density. Reference [22] is based on the C-RAN scenario and dynamically allocates computing resources in the baseband resource pool according to the traffic volume. In addition, the article adopts a technology similar to base station sleep, which puts the corresponding BBU into sleep or activation based on the usage of computing resources to achieve energy saving. Reference [23] jointly considers computation offloading selection, wireless resource allocation, and computation resource allocation in MEC, and models a mixed integer nonlinear programming problem to minimize energy consumption. Subsequently, a heuristic greedy algorithm based on Gini coefficient is proposed to solve the problem. In the scenario of reference [24], the amount of computing resources and the required amount of computing tasks for different user terminals are not the same. This paper uses a proportional fairness approach to schedule MEC server resources to different users, and achieves energy efficiency optimization by optimizing the user's computation offloading amount and offloading transmission time. Reference [25] also studied the problem of multi-user computing task offloading. In the scenario of introducing edge caching, this paper designed and derived a single shot function for users to match transmission power and computing resources. By jointly optimizing the allocation ratio of MEC server's computing resources and terminal device's transmission power, the system energy efficiency was optimized. To further improve the efficiency of computation offloading, reference [26] adopts a finer grained computation offloading scheme and uses edge clouds to perform centralized offloading and caching decisions for multiple users.

Traditional random access technology can achieve good performance in traditional IoT systems. Compared to fixed allocation, on-demand allocation, and other methods, random access technology can improve resource utilization. However, during the random access process, different users may simultaneously request access. If the system allocates the same wireless resources to these users or the number of wireless resources cannot meet the simultaneous access requirements of these users, conflicts may occur. When a conflict occurs, conflict resolution methods such as conflict decomposition are needed to ensure that users have access to unique wireless resources. If the conflict resolution fails, the user will perform random access again and compete for resources again. As the number of users in machine communication scenarios increases, the probability of conflicts occurring will also increase, and the success rate of conflict resolution will also decrease, which can easily lead to signaling storms and serious access delays.

3 System Model

3.1 Access Optimization of Large-Scale Multi-Source Terminal

The centralized large-scale machine communication scenario shown in Figure 1 is considered. There is a base station in the center of a cell, which is equipped with M antennas. There are a total of N single-antenna terminal devices (users) in the cell, which are evenly distributed in the cell, and the cell radius is R. When the terminal device receives the broadcast instruction sent by the base station, the terminal device requiring communication randomly selects a pilot in the pilot pool for random access.

In current IoT technology, Time Division Duplex (TDD) mode is commonly used for communication. Both uplink and downlink transmissions are transmitted through the same channel, and the transmitter and receiver do not operate simultaneously. One time slot is used for transmitting data while another time slot is used for receiving data, so there is no interference between the transmitter and receiver. Due to the short channel coherence time of TDD systems, the length of pilot sequences that can be used during random access is relatively short, and the number of pilots that can be allocated to terminal devices in the cell is also limited. In a centralized large-scale machine scenario, a large number of terminal devices will send access requests to the base station at the same time. When the number of terminal devices that need to communicate in the same time slot exceeds the available number of pilots, it will cause many different terminal devices to choose the same pilot sequence, so they will communicate on the same wireless resources. This situation can lead to mutual interference between terminal devices, making it impossible for the base station to estimate the channel through the received signal, causing serious interference to the downlink from the base station to the terminal devices. In addition, pilot conflicts can also reduce the system's throughput and access latency.

In order to access more terminal devices, it is generally considered to use pilot multiplexing for information transmission. At present, there are two main methods for pilot multiplexing. One is to divide the cell into several types of users, use the same pilot in each type of user, and use different pilots between different types of users; Another approach is to divide the small area into different concentric circles, where users within the same concentric circle use the same set of pilots, and users in different concentric circles use different pilot sequences.

With the application of massive MIMO technology, rich spatial freedom can be provided. Thus, the cell is divided into K sectors, each of which is equal in area and contains several terminal devices, as shown in Figure 1.

This kind of processing can use the antenna array of massive MIMO technology, which makes the resolution method of terminal equipment add one dimension in space, and is more conducive to the discrimination of terminal equipment. Accordingly, the base station can detect the uplink angle of arrival (AOA) of the terminal device, thereby determining the sector position in which the terminal device is located. In this way, even if the terminal devices of different sectors use the same pilot, the sector in which the corresponding terminal devices are located can be distinguished by the

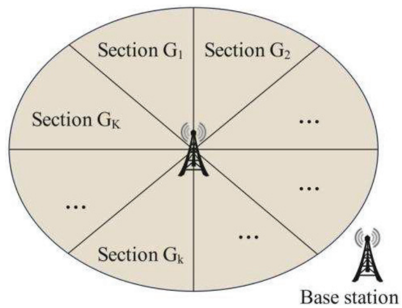

Figure 1 Schematic diagram of sector division in a cell.

angle of arrival, which helps to expand the number of terminal devices that can be randomly accessed in the same time slot.

The k-th sector is marked as G_k, and the probability g_k that the terminal device i is located in sector k is:

$$g_k = \Pr(i \in G_k) = \frac{1}{K} \tag{1}$$

Generally, in a large-scale machine-like communication network, once a terminal device is deployed, its position is almost unchanged, so it can be considered that the sector index number and the angle of arrival information of each terminal device remain stable and unchanged. It is assumed that when the terminal device is deployed, it will store its fixed sector index number and angle of arrival information for use in the random access process.

In order to facilitate the fast detection of the base station and have very good autocorrelation and cross correlation, Zadoff-Chu (ZC) sequence can be used as the pilot sequence of the random access procedure. In large-scale machine communication scenarios, the number of terminal devices that can be supported by ZC sequence with length L is $O(L^2)$, and the generation of ZC sequence is also very fast. Any sequence is uniquely determined by length L and root r, and its sequence set is $Z_L = \{z_L^r | r \in R_L\}$, where $R_L = \{1, 2, \ldots, L\}$. For a certain ZC sequence z_L^r, the expression of its k-th element k is:

$$z_L^r(k) = \exp\left\{-j\pi \frac{rk(k+1)}{L}\right\} (n = 0, 1, \ldots, L-1) \tag{2}$$

Therefore, the pilot sequence pool of the random access process is composed of the ZC sequence cyclic shifting *P* times, and the expression $s_m(k)$

of the *m*-th pilot is:

$$s_m(k) = z_L^r[(k + m \cdot P)_{mod} L](m = 0, 1, \ldots, W - 1) \tag{3}$$

Among them, $W = [L/P]$ is the number of available pilot sequences.

Time-shifted Pilot is proposed to solve the problem of intra-cell and inter-cell pilot pollution, and at the same time, it can achieve significant signal interference gain in massive MIMO. The main idea is to stagger the pilot transmission time of different users and transmit pilots in different time slots, so that even if the pilots transmitted in the same frame are the same, pilot pollution can be avoided because of the sequence of transmission time.

The flow of ERA-TSP scheme is similar to the traditional random access process, and is mainly divided into four steps:

The first step is time-shifted pilot sequence transmission. Firstly, the base station sends a broadcast instruction containing the ERA-TSP scheme. After receiving the broadcast instruction, the terminal equipment needing communication at the current moment randomly selects a pilot sequence from W random access pilot sequences as its own random access pilot. Then, each terminal equipment determines its own pilot time shift length according to the distribution function of time shift length β_i formulated by the broadcast instruction to generate the time shift pilot $s_{m,i}(k)$. Here, the pilot selection between different terminal devices does not interfere with each other, and the pilot time shift length is also independent of each other.

Therefore, the expression of the time-shifted pilot $s_{m,i}(k)$ generated by the terminal device i selecting the m-th random pilot is:

$$s_{m,i}(k) = s_m[(k + \beta_i)_{mod} L] = z_L^r[(k + m \cdot P + \beta_i)_{mod} L] \quad (i = 1, 2, \ldots, N) \tag{4}$$

Among them, β_i is the pilot time shift length of the terminal device i. This means that the time-shifted pilot sequence of the terminal device i is again added with the cyclic shift of β_i on the basis of the aforementioned random access pilot sequence.

Since the ZC sequence is detected by detecting the power delay profile (PDP) of the sequence, the PDP of the pilot sequence detected by the base station changes accordingly β_i due to the different time shift lengths β_i of the pilots generated by different terminal devices. After selecting and generating the time-shifted pilot, the terminal device sends the time-shifted pilot generated by itself to the base station.

The second step is angle of arrival detection and random access response. After receiving the time-shifted pilots sent by active terminal devices, the base station extracts the arrival angles θ of all terminal devices, distinguishes the sectors corresponding to the terminal devices, detects the pilots of each sector respectively, detects the PDPs of all pilots in sequence, and obtains the time TI (Timing Index) $\Delta = \{\delta_m\}(m = 1, 2, \ldots, M)$ at which the PDP of each pilot reaches the peak value. Among them, δ_m is the time TI at which the PDP of the *m*-th pilot reaches the peak value. Then, the base station directionally feeds back to the corresponding sector according to the detected angle of arrival, and simultaneously transmits a random access response RAR including the pilot index m, the corresponding δ_m, the angle of arrival θ_m, and the uplink access grant.

The third step is conflict decomposition. After receiving the RAR transmitted by the base station, each terminal device compares its own angle of arrival and TI corresponding to the transmitted pilot with the angle of arrival and TI information included in the received RAR. Only when the angle of arrival and the TI exactly match, the terminal device will send the information to be sent.

The fourth step is conflict decomposition feedback. If the base station receives information from the terminal device within the preset collision resolution time, the base station sends feedback to the terminal device, indicating that the random access procedure is successful. However, if the base station cannot receive information from the terminal device, or the terminal device does not receive feedback from the base station, it indicates that this random access is unsuccessful, and the terminal device needs to attempt the next random access.

The base station is located in the center of the cell, and there are a total of M antennas to form an array. There are N terminal devices with single antennas in the cell, which are evenly distributed in the cell. If the area of the cell is divided into K sectors, each sector has N/K terminal devices, and the active probability is $\lambda \leq 1$. If it is assumed that in a random access time slot, the terminal equipment that needs communication in each sector randomly selects a pilot sequence from W random access pilot sequences as its own random access pilot, and the set Ω_m contains the index number of the terminal equipment that selects the m-th pilot, then Ω_m represents the number of terminal equipment that selects the m-th pilot, which obeys the distribution:

$$|\Omega_m| \sim \left(\frac{N}{K}, \frac{\lambda}{W}\right) \tag{5}$$

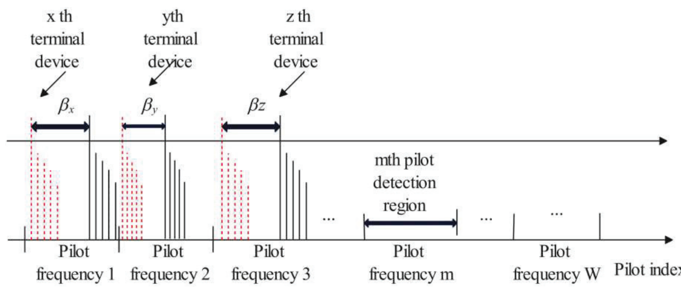

Figure 2 Schematic diagram of pilot detection of ERA-TSP scheme.

Therefore, the signal received by the base station is expressed as:

$$Y = \sum_{m \in N} \sqrt{\rho_m} h_m s_m^T + W \tag{6}$$

Among them, $s_m \in \mathbb{C}^L$ represents the selected m-th pilot, which has been time-shifted, and $W \in \mathbb{C}^{M \times L}$ represents white Gaussian noise.

When the base station receives the uplink information, it detects the received signal. In order to distinguish the sector position in which the terminal device is located, the angle of arrival is estimated, and the estimated angle $\widehat{\theta}_m = (i-1)\pi/K(i = 1, 2, \ldots, K)$ of arrival value of each signal is obtained. At the same time, PDP detection is performed on the pilot received by each sector to determine the time TI of each peak. The specific detection method is shown in Figure 2.

It can be seen that in each sector, the time TI at which the PDP of different pilots reach the peak corresponds to the time shift generated by the terminal device selecting the corresponding pilot. In this way, the detection time of the pilot transmitted by different terminal devices is delayed by different delays, and the collision probability of each terminal device can be reduced.

At the same time, if there are different peaks in the same pilot during detection, the base station performs random access response RAR on these peaks respectively, as shown in Figure 3.

After receiving the RAR transmitted by the base station, the terminal device analyzes the information corresponding to the pilot sequence transmitted by itself, including the pilot index number, the angle of arrival, the peak time TI, etc. When the information completely matches, the terminal device considers that the base station allows itself to access randomly, so the terminal device continues to use the pilot for information transmission. Otherwise, if the terminal device considers that the base station does not allow

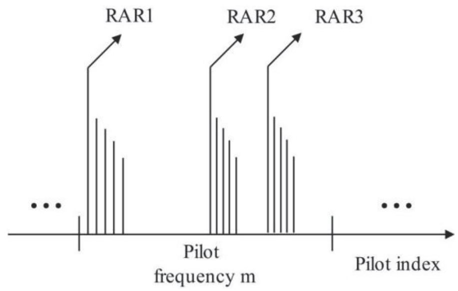

Figure 3 Schematic diagram of processing multiple peaks of the same pilot.

random access, the terminal device will abandon the current access request and initiate the access request in the next random access procedure.

3.2 Performance Analysis

The related performance of the proposed scheme is analyzed, mainly including the probability of pilot collision, average collision probability and average access delay of terminal equipment in ERA-TSP scheme, so as to verify the progressiveness of the model in this paper compared with the traditional model.

According to traditional random access, when two or more terminal devices in the same sector use the same pilot sequence, pilot collision will occur. In the ERA-TSP scheme, the time delay is added to the pilot of each terminal device. At this time, the collision is reflected in the fact that two or more terminal devices in the same sector use the same pilot sequence, and their time delays are equal to each other.

As previously analyzed, in each sector, the number of terminal devices selecting the m-th pilot obeys a binomial distribution, so that there are N_a active terminal devices in each sector, and for a particular pilot, a pilot collision occurs when the pilot is selected for use by two or more terminal devices. The probability that the pilot is not used is:

$$p_{no\_use} = \left(1 - \frac{1}{W}\right)^{N_a} \tag{7}$$

The probability that the pilot is selected for use by only one terminal device is

$$p_{1\_use} = C_{N_a}^{1} \frac{1}{W}\left(1 - \frac{1}{W}\right)^{N_a - 1} = N_a \frac{1}{W}\left(1 - \frac{1}{W}\right)^{N_a - 1} \tag{8}$$

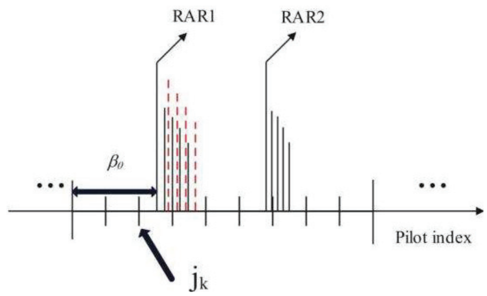

Figure 4 Schematic diagram of pilot collision.

Therefore, the probability of generating a pilot collision is

$$p_{con} = 1 - p_{no\_usen} - p_{1use} = 1 - \left(1 - \frac{1}{W}\right)^{N_a} - N_a \frac{1}{W}\left(1 - \frac{1}{W}\right)^{N_a - 1} \tag{9}$$

This is also the collision probability of traditional random access technology.

Therefore, the average collision probability of traditional random access techniques is

$$Avg\_p_{con} = \sum_{k=1}^{K} g_k \cdot p_{con} \tag{10}$$

For the convenience of analysis, we divide each pilot detection area into J equal parts. Then, for a terminal device whose time delay is β_0, the detection area where its time delay is located is j_k, and the case of collision at this time is that the time delay of other terminal devices is located in the region j_k where β_0 is located, as shown in Figure 4. In this way, the base station does not generate a random access response RAR for the second peak in the same area. When the division region is small enough, more peaks can be distinguished.

Therefore, if we assume that the probability that the pilot peak value of the terminal device is in the region j_k is p_k, the probability that the pilot collision occurs is

$$p_{pro} = 1 - p_{no\_use} - p_{1\_use} = 1 - \left(1 - \frac{p_k}{W}\right)^{N_a} - \frac{N_a p_k}{W}\left(1 - \frac{p_k}{W}\right)^{N_a - 1} \tag{11}$$

Therefore, the pilot average collision probability of the ERA-TSP scheme is:

$$Avg\_p_{pro} = \sum_{k=1}^{K} g_k \cdot p_{pro} \tag{12}$$

Access delay is defined as the duration from the generation of data packets to the successful completion of random access by the terminal device. If $\bar{T}_k$ represents the average access delay of the terminal equipment in sector G_k, the average access delay in the sector is:

$$\bar{T}_k = \bar{T}_q + \bar{T}_r + \bar{T}_s \tag{13}$$

Among them, $\bar{T}_q$ represents the average waiting time after the data packet is generated, and its value is $\bar{T}_q = T_{RACH}/2$, and T_{RACH} represents the random pilot transmission time. $\bar{T}_r$ represents the average time for the terminal device to re-attempt random access, and $\bar{T}_s$ represents the average time for packet transmission after random access is allowed.

The expression of $\bar{T}_r$ is

$$\bar{T}_r = \left[\left(\sum_{i=1}^{\max T_i} i \cdot (1 - p_{pro}) \cdot p_{pro}^{i-1} \right) - 1 \right] \cdot \bar{T}_{re} \tag{14}$$

Among them, $\max T_i$ represents the maximum number of random access reattempts, $\bar{T}_{re}$ represents the average time to retry a random access, and $(\sum_{i=1}^{\max T_i} i \cdot (1 - p_{pro}) \cdot p_{pro}^{i-1}) - 1$ represents the number of random access attempts before successfully completing the random access, that is, the average number of pilot collisions. The average access delay analysis of traditional random access technology is similar to this.

3.3 Distributed Access Model

In the distributed system considered, the cell structure of the centralized system is retained.

In order to access more terminal devices, it is generally considered to use pilot multiplexing for information transmission. At present, there are two main methods for pilot multiplexing. One is to divide the cell into several types of users, use the same pilot in each type of user, and use different pilots between different types of users; Another approach is to divide the small area into different concentric circles, where users within the same concentric circle use the same set of pilots, and users in different concentric circles use different pilot sequences.

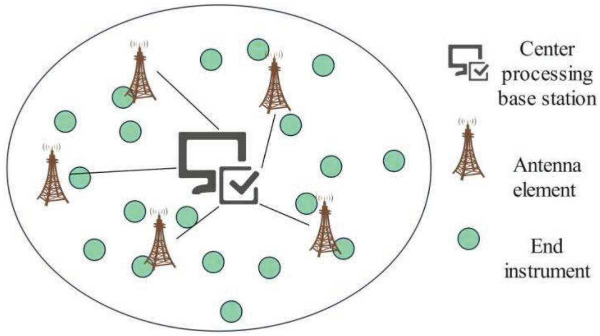

Figure 5 Distributed large-scale machine-like communication system model.

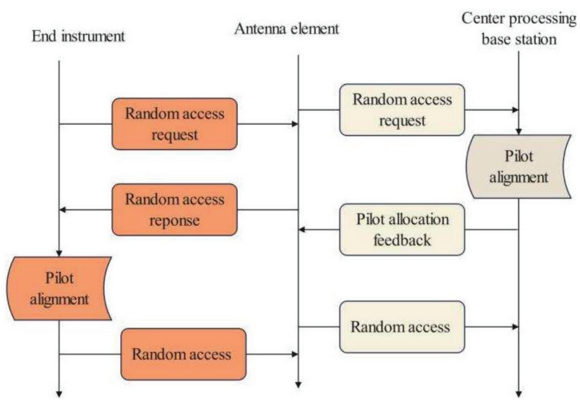

Figure 6 D-ERA-TSP scheme flow chart.

As shown in Figure 5, a total of M antenna units are distributed in the cell, and a total of N terminal devices are evenly distributed in the cell. The antenna unit is connected to the central processing base station through optical fiber or coaxial cable. The antenna unit is only responsible for receiving data sent by the terminal equipment and transmitting it to the base station. The base station side completes data analysis, processing and other operations, and transmits operation instructions and other information to the antenna unit.

The D-ERA-TSP scheme uses antenna units at different positions to receive access requests from terminal devices, and when pilot frequencies collide, through allocation of pilot frequencies and allocation of antenna units, the purpose of accessing more terminal devices in the same time slot is achieved, and the access success rate is improved. The D-ERA-TSP scheme mainly has the following steps, as shown in Figure 6.

The first step is to randomly access the request. The antenna unit broadcasts the instruction to allow random access according to the requirements of the base station;

Step two, pilot allocation feedback. The central processing base station will provide feedback on the allocated random access results to each antenna unit. After receiving the feedback information, each antenna unit will send its received feedback information and random access response RAR;

The third step is conflict resolution. After receiving the information sent by the antenna, each terminal device compares the time shift length of the pilot it sends with the TI of the corresponding pilot in the received RAR, as well as the antenna identifier it requests to access and the received antenna identifier.

Step four, randomly access feedback. If the base station receives information from the terminal device within the pre-set conflict resolution time, the base station sends feedback to the terminal device; If the base station fails to receive information from the terminal device, it indicates that the random access was unsuccessful.

If a total M antenna elements are evenly distributed within the cell and a total N terminal devices are evenly distributed within the cell, the number of possible connected terminal devices around each antenna element is N/M, and its active probability is $\lambda \leq 1$.

If it is assumed that in a random access time slot, the terminal equipment needing communication around each antenna unit randomly selects a pilot sequence from W random access pilot sequences as its own random access pilot, and the set Ω_m contains the index number of the terminal equipment selecting the m-th pilot, then $|\Omega_m|$ represents the number of terminal equipment selecting the m-th pilot, which obeys the distribution:

$$|\Omega_m| \sim \left(\frac{N}{M}, \frac{\lambda}{W}\right) \tag{15}$$

After receiving the uplink information, the base station detects the received signal on each antenna unit to determine the peak time TI of each pilot. The detection method is shown in Figure 7.

When the central processing base station detects the pilot frequency on each antenna element, the pilot frequency allocation is performed to each antenna element respectively, and if the same pilot frequency of each antenna element has a plurality of peaks, the random access response is performed to the peaks respectively. After receiving the pilot allocation information transmitted by the central processing base station, the antenna unit transmits

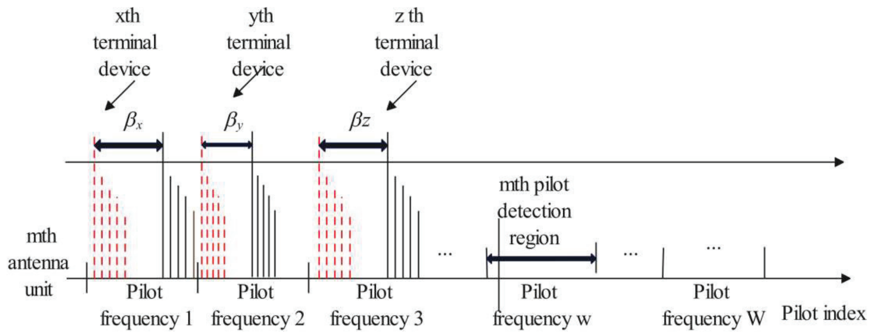

Figure 7 Schematic diagram of pilot detection method.

a random access response to the terminal device, including an antenna unit identifier, a pilot index, and a corresponding peak time TI for which access is allowed. Then, the terminal equipment matches the information of the random access response with the information sent by itself. Only when the antenna unit identifier, the pilot index and the peak time TI completely match, the terminal equipment will think that the central processing base station allows itself to access randomly, and then the terminal equipment sends random access information. Otherwise, the terminal device considers that this random access fails, and initiates an access request in the next random access procedure.

4 Simulation Test

4.1 Simulation Environment

This paper analyzes the simulation results of D-ERA-TSP (Distributed Enhanced Random Access with Time-shifted Pilot) scheme in distributed large-scale machine communication scenarios, mainly including pilot collision probability, average collision probability and average access delay of each antenna element. The scenario shown in Figure 7 is considered.

The collision probability of the proposed D-ERA-TSP scheme in distributed large-scale machine communication scenario and the traditional RA scheme in each antenna element is compared. Among them, the number of evenly distributed antenna units in the cell is 16, and the number of terminal devices in the entire scene is 11,000, and they are evenly distributed in the cell. The simulation parameter settings are shown in Table 1.

Table 1 Simulation parameters

Parameter	Value
Total terminal equipment	5000∼11000
Number of antenna units	10∼100
Active user probability	0.09
Distribution range of terminal equipment	[0 km, 2.2 km]
ZC sequence length	830
Number of cyclic shifts of random pilot	25
Number of random pilots	62
Random pilot transmission time	10 ms
Maximum number of retransmissions	6
Average time to reattempt a random access	8 ms
Average time to send messages	22 ms
Average processing time of the central processing base station	8 ms

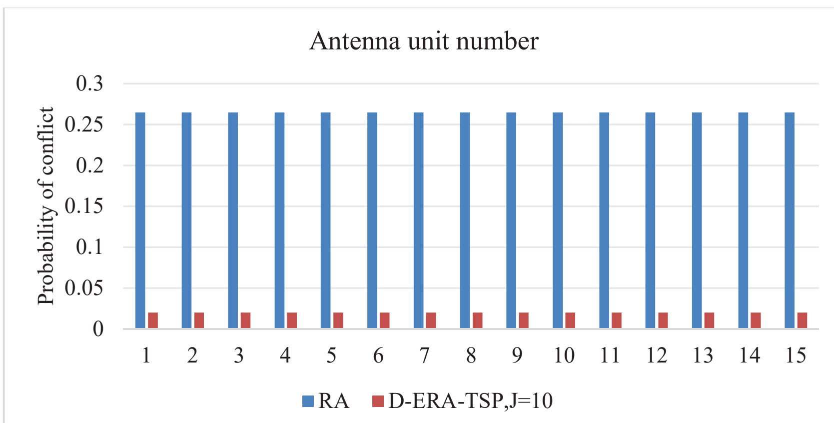

Figure 8 Simulation diagram of pilot collision probability of each antenna element.

4.2 Results

Figure 8 shows the pilot collision probabilities of each antenna element of the distributed RA (Random Access) scheme and the D-ERA-TSP scheme.

Figure 9 shows the relationship between the average collision probability of the two schemes and the number of terminal devices, and the number of antenna units in the cell is set to 60.

Figure 10 shows the relationship between the average collision probability of the two schemes and the number of antenna elements.

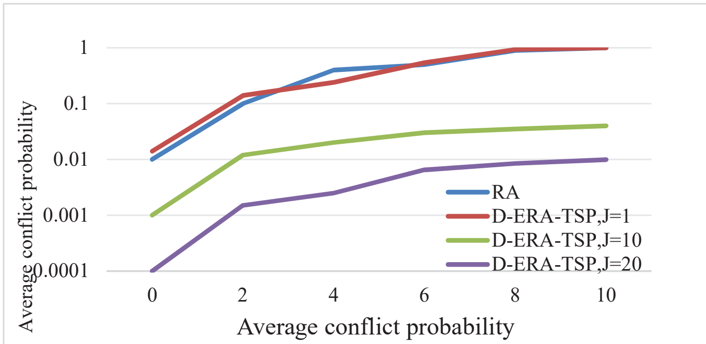

Figure 9 Relationship between average collision probability and number of terminal devices (M = 60).

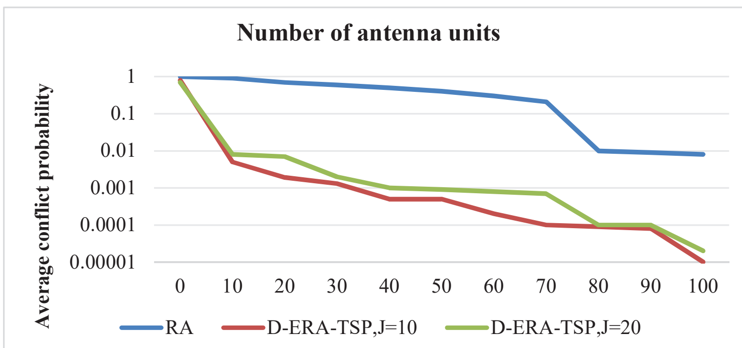

Figure 10 Relationship between average collision probability and number of antenna elements (N = 11000).

Figure 11 shows the relationship between the average access delay and the number of terminal devices of the two schemes.

4.3 Analysis and Discussion

As can be seen from Figure 8, the pilot collision probability of the traditional RA scheme is still very high. However, when the detection area is divided during pilot detection, it is seen that the pilot collision probability of each antenna unit is greatly reduced. At the same time, considering that the terminal devices around each antenna element are uniformly distributed, the pilot collision probability of each antenna element is the same. This shows that the random access scheme based on time-shifted pilot can also be applied to distributed large-scale machine communication scenarios.

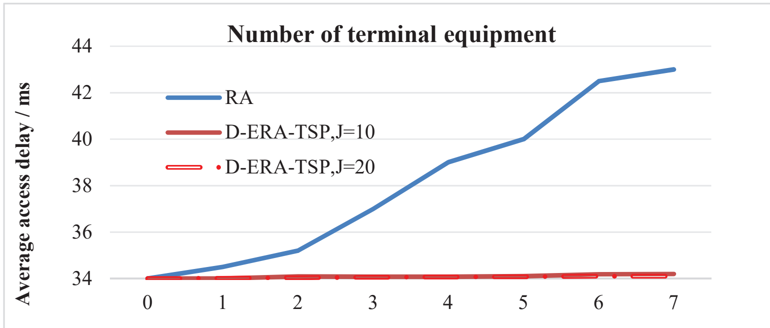

Figure 11 Relationship between average access delay and number of terminal devices (number of antenna units M = 60).

It can be seen from Figure 9 that with the increase of the number of terminal devices, the average collision probability of both schemes increases, but the average collision probability of the proposed model scheme in this paper is lower than that of the traditional RA scheme, and this curve is also consistent with the pilot collision probability in Figure 8. When J = 1, it means that each pilot can only be used by one terminal device, so the average collision probability of the two schemes is consistent. At the same time, it can be noted that in the distributed system, due to the large number of antenna units, the number of terminal devices that each antenna unit communicates with each other is dispersed, so even when the number of terminal devices reaches 100,000, the average collision probability of the traditional RA scheme does not reach 1. It can be seen that the model scheme in this paper can keep the average conflict probability below 0.1. Therefore, the model scheme in this paper can effectively reduce the probability of pilot collision in random access process in distributed large-scale machine communication scenarios.

It can be seen from Figure 10 that with the increase of the number of antenna elements, the average collision probability of both schemes will decrease, and the average collision probability of the model scheme proposed in this paper is lower than that of the traditional RA scheme. At the same time, the curves of both schemes show a trend of first rapid decline and then slow decline.

As can be seen from Figures 9 and 10, the division of pilot detection area will also affect the average pilot collision probability of the model scheme in this paper. When the pilot detection area is divided finer, that is, the smaller J is, the number of terminal devices that each pilot can be allowed to access is larger, and the average collision probability of the pilots is lower. However, the finer the pilot detection area is divided, the higher the processing capacity requirements of the central processing base station will be. Therefore, in practical applications, the division of pilot detection area should be reasonably considered to avoid putting too high requirements on the base station and cannot be realized.

As can be seen from Figure 11, with the increase of terminal equipment, the average access delay of the traditional RA scheme will increase sharply. Even if a large number of antenna units can undertake more terminal equipment access, the RA scheme has a high probability of collision, and the number of collisions of terminal equipment will increase, resulting in too long access attempts or waiting time. Therefore, the average access delay is very high, which will lead to too fast energy consumption of terminal equipment and cannot be applied in distributed large-scale machine communication scenarios. However, the average access delay of the model scheme proposed in this paper is lower than that of the RA scheme, and the average access delay increases slowly with the increase of the number of terminal devices. On the other hand, it can be seen that the division of pilot detection area does not significantly reduce the access delay, and remains basically unchanged. Therefore, the model scheme in this paper can effectively reduce the average access delay of distributed large-scale machine communication scenarios, and will not change drastically with the number of terminal devices. From the above analysis, it can be seen that for distributed large-scale machine communication scenarios, the model scheme proposed in this paper can reduce the pilot collision probability and the average access delay of terminal equipment in the random access process.

Overall, the model proposed in this paper has certain advantages over traditional models in terms of conflict probability and reducing system latency. It can be seen that the proposed model can improve the fusion effect of large-scale multi-source terminal access in 5G to a certain extent, and has a certain promoting effect on terminal access in the 5G era.

5 Conclusion

With the development of communication technology, large-scale machine communication will become an important field of future communication, among which the research of multiple access technology is a very important direction. Large-scale machine communication scenarios are faced with the characteristics of large number of terminal devices, small communication data packets, frequent transmission, etc. Traditional multiple access technology can't fully apply to these characteristics, so it needs to be improved and designed.

In order to solve the problem of pilot collision in large-scale machine communication scenarios when traditional random multiple access technology is applied, this paper proposes an improved random multiple access scheme based on time-shifted pilot for centralized scenarios and distributed scenarios respectively. The research shows that compared with the traditional random access scheme, the proposed scheme can effectively reduce the probability of pilot collision in the cell and the average access delay of terminal equipment. From the above analysis, it can be seen that the proposed scheme based on time-shifted pilot can reduce the pilot collision probability and access time in both centralized and distributed scenarios.

This paper considers that the terminal equipment in the cell will not change in multiple access technology, and this model is the simplest system model. Therefore, we will consider adding the movement of terminal equipment, geographical environment and other factors into the model in the follow-up, and the two schemes proposed in this paper will be improved to make them more perfect and can be applied to real life.

Due to the complex experimental environment and limited laboratory conditions in large-scale machine communication scenarios, it is currently impossible to verify through large-scale experiments. In future research, specific scenarios can be combined for verification.

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