A novel MAC protocol with independent double-pilot scheme and NOMA for MTC in IoT networks

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Abstract. With the rapid growth of IoT devices, machine communication is becoming more and more popular in 5G wireless communication systems. This paper proposes a novel MAC protocol for the Internet of Things (IoT) in a scenario with a gateway and multiple IoT devices. The IoT devices with packets (active IoT devices) send independent double-pilot(IDP). The gateway takes the number and ID of IoT devices and allocates appropriate power to IoT devices. These IoT devices adjust the power and transmit packets using the Power domain Non-Orthogonal Multiple Access Protocol (PD-NOMA). Compared with the traditional single pilot scheme (TSP), the independent double-pilot can dramatically reduce the pilot collision probability, although it will probably bring a moderate increase in detection workload. Furthermore, the IDP-NOMA protocol proposed in this paper dramatically improves the system throughput and the probability of transmission success.

1. Introduction

With the rapid development of the Internet of Everything, more and more physical devices hope to connect to the communication network through wired/wireless channels [1]. Nowadays, millions of new devices are added to the communication system every month. According to Cisco’s recent annual report on the Internet, there will be nearly 30 billion networked devices in the world by 2023. Among them, the number of Machine Type Communication (MTC) devices is expected to reach 14.7 billion. It accounts for 50% of the world’s connected devices [2].

The dramatic increase in the number of IoT devices and the expected amount of data related to IoT applications increases the popularity of communication between 5G wireless communication systems [3]. Non-human intervention MTC forms an important part of the IoT and may require a rethinking of the MAC layer. Furthermore, a lot of IoT devices that are low-complexity can transmit data to the gateway in MTC. Therefore, a novel MAC protocol with a flexible structure and stable high throughput is needed. This paper improves the MAC protocol proposed by [4]-[6].

In [7], TSP scheme was proposed for blind multi-user detection(MUD). Each user independently selects a pilot sequence, but multiple users may choose the same pilot sequence. Such pilot collision probability is high, which will seriously reduce the system performance [8], [9]. [4]-[6] proposed that all active IoT devices use the roughly same power to send the training sequence of length L (gateway
is known) to the gateway for blind MUD. The detection efficiency is roughly the same as the scheme proposed in [7]. Therefore, the protocol proposed in [4]-[6] is called TSP-NOMA protocol here. [10] proposed that more pilot sequences can reduce the probability of pilot collision, but the length of pilot sequences needs to be increased because of the increase of orthogonal pilot sequences. It can reduce transmission efficiency and dramatically increases the complexity of MUD. [11] proposed an independent multi-pilot scheme, in which the users can independently select multiple pilot sequences. Although the probability of pilot collision will decrease, the accuracy of channel estimation will be dramatically reduced as the total pilot energy remains unchanged, and the detection workload of the receiver will be dramatically increased. In [12], a series orthogonal pilot scheme is proposed to mitigate the pilot collision. This scheme takes advantage of the quasi-orthogonality of the user channel, but the receiver needs to be equipped with a certain number of antennas because the user's spatial channels are interrelated.

In this paper, IDP-NOMA protocol is proposed. Based on the TSP-NOMA protocol, IDP scheme is used in the MUD. Each IoT device selects two independent orthogonal pilot sequences from the predetermined pilot pool, each length of which is 1/2 of the pilot sequences in the TSP scheme. The identification of the two pilot sequences is placed in the data payload so that the two pilot sequences selected by the IoT device can be identified once the IoT device's data is decoded. In this scheme, the total length of pilot sequence does not change, but the probability of pilot collision decreases obviously. Moreover, the IDP scheme does not require any spatial correlation and is suitable for more general situations. The disadvantage of the gateway is that the detection workload of the receiver will increase slightly, and the accuracy of the channel estimation will decrease slightly. Nevertheless, by using IDP scheme and PD-NOMA in combination with the improved MAC protocol, the throughput performance of the system has been dramatically improved, and the transmission latency has also been dramatically reduced.

The contributions of this paper include: firstly, IDP scheme is proposed and two pilot sequences are identified in the data payload part, which can improve the detection efficiency of the gateway receiver. Secondly, this scheme is combined with PD-NOMA. The original TSP-NOMA protocol is improved and IDP-NOMA protocol is proposed. Finally, the numerical results show that the novel protocol has been dramatically improved in terms of throughput, transmission success probability, transmission delay and stability.

2. System Model
The scenario in this paper assumes a single antenna gateway and multiple single antenna IoT device.

2.1. Traditional Single Pilot Scheme
The framework structure is shown in Figure 1(a). The active IoT device selects a pilot from the predefined pilot pool and sends the pilot and data that needs to be transmitted to the gateway. The pilot pool has a fixed size. If two or more IoT devices choose the same pilot, it will create a pilot collision and the receiver will identify these IoT devices as the same IoT device. Thus error detection is performed, reducing the accuracy of channel estimation.

![Diagram](a)

![Diagram](b)

Figure 1. The frame structure of TSP scheme and IDP scheme. (a) TSP scheme, (b) IDP scheme
2.2. Independent Double-Pilot Scheme

We propose an IDP scheme and the framework structure as shown in Figure 1 (b), which can dramatically mitigate pilot collisions and has no special requirements on the channel correlation of the IoT device and the number of antennas equipped by the gateway. The length or sequence type of the pilot is not necessarily the same, but two pilots of the same length and type make the IDP scheme more convenient. Assume that the pilot pool size of TSP scheme is $N_{TSP}$. The pilot length is $N_{TSP}$. The pilot pool size of IDP scheme is $N_{IDP} = N_{TSP}/2$. The length of a single independent pilot is $N_{TSP}/2$.

Assume that $N_{IDP} = 2^m$. The $m$ bits in the data division can be used to identify one pilot sequence, and the $2^m$ bits in the data division can be used to identify two independent pilot sequences. So, once the data of one IoT device has been decoded, the two pilot sequences can be determined by identification.

In the TSP scheme, the pilot collision probability is $P_{TSP} = 1/N_{TSP}$. In IDP scheme, the pilot collision probability is $P_{IDP} = (1/N_{IDP})^2 = 4/(N_{TSP})^2$. If $N_{TSP} > 4$, $P_{IDP} < P_{TSP}$ and $P_{TSP} - P_{IDP}$ will increase rapidly as $N_{TSP}$ increases.

2.3. Receiver Design

The receiver at the gateway mainly consists of MUD and IC because the gateway IoT device and the number of each IoT equipment selection of two pilot sequences is unknown. So, the receiver must perform a series of steps as shown in Figure 2. By eliminating the data symbols and pilot signals successfully decoded, the gateway reconstructs the received signals and iteratively executes MUD and IC.

In the IDP scheme, MUD and IC are first executed on one pilot and then MUD and IC are executed on the other as shown in Figure 3. Meanwhile, all decoded transmission symbols can continue to play the role of "pilot". Decode $2^m$ bits in the data section to better determine the two pilot sequences selected by IoT devices. Therefore, better channel estimation can be performed. This method is called data assisted channel estimation. This helps ease pilot competition.

![Figure 2. The receiver at the gateway](image-url)
Figure 3. MUD and IC of IDP scheme

3. Multi-user Detection and Interference Cancellation

3.1. Multi-user Detection

Assume the orthogonal pilot resource pool defined by IDP scheme is $Z = \{z_1, z_2, z_3, \ldots, z_{IDP}\}$, receive on the i-th pilot symbol can be denoted as:

$$y_i = \sum_{k=1}^{K} h_{i,k} z_{n,i,k} + n_i, \quad i = 1, 2$$

Where $z_{n,i,k}$ represents that the pilot sequence $z_n (z_n \in Z)$ on the i-th pilot chosen at random by the k-th IoT device, $h_{i,k}$ is the channel coefficient of the k-th IoT device on the i-th pilot, $n_i$ is additive white Gaussian noise. A flat fading channel is assumed here.

Hypothesis testing is performed on all pilot sequences, pilot sequences of active IoT devices are detected, which can be denoted as:

$$y_i = \sum_{k=1}^{K} h_{x,i,k} z_{n,x,k} + z_{n,x}^H n_x, \quad x = 1, \ldots, N_{IDP}$$

where $H$ is the Hermitian transpose operation.

When $x \neq n$, $z_n^H z_n = 0 \quad x, n = \{1, 2, 3, \ldots, N_{IDP}\}$, the following can be derived for the k-th IoT device:

$$z_n^H y_j = \sum_{k=1}^{K} h_{i,k} z_{n,i,k} + z_{n,i}^H n_i$$

The normalized detection result is obtained:

$$\hat{h}_{i,k} = \frac{z_n^H y_j}{z_n^H z_n} = h_{i,k} + \frac{z_{n,i}^H n_i}{z_n^H z_n}$$

Seek a balance between false alarms and error detection and set this value to the threshold. Then, through the standardized test results, the i-th pilot can be used for the detection of active IoT devices.

Based on channel estimation, the MMSE equalization can be used to obtain the data symbols detected by the active IoT devices, and then the data bits sent by the active IoT devices can be obtained by the
3.2. Interference Cancellation

The data payload carries two pilot sequence identifiers and the IoT device ID. Based on the correctly decoded data bits, two pilot identifiers for an active IoT device can be determined, facilitating IC elimination. Assuming that the pilot and data of the Q-th IoT device have been successfully decoded, the detection process as shown in Figure 3 is utilized. The IC of pilot and data can be denoted as:

$$y_p' = y_p - \sum_{k=1}^{Q} \tilde{h}_{i,k} z_{v,p,k}, \quad p = 1, 2$$

$$y_d' = y_d - \sum_{q=1}^{Q} \tilde{h}_{i,k} d_{k}$$

where $z_{v,p,k}$ is the pilot $z_v$ ($z_v \in Z$) belongs to the k-th IoT device on p-th pilot. $\tilde{h}_{i,k}$ represents the filtered channel estimation on the i-th pilot, $\tilde{h}_{i,k}$ will be used for the IC of pilot and data parts. $d_{k}$ is the reconstructed modulation data symbol for the k-th IoT device. According to $y_p'$ and $y_d'$, the subsequent round of MUD can be carried out. This procedure will execute iteratively until all active IoT devices have been identified or the all new IoT devices have been decoded.

In order to make the IC more accurate, all the pilot sequences and data decoded from the active animal IoT devices can be used for subsequent decoding, and more accurate channel estimation is made by using the least square method [13]. It can be denoted as:

$$\hat{h} = (D^\top D)^{-1}D^\top y$$

Where $y$ represents a vector which is made up of all the received signals, $D = [D_1, D_2, \cdots, D_Q]$ represents a matrix of refactoring transport symbols for all Q IoT devices that have been decoded up to this round, $\hat{h} = [\hat{h}_1, \hat{h}_2, \cdots, \hat{h}_Q]^\top$ is a vector which is more accurate channel estimates.

As more and more IoT devices are successfully decoded, the results obtained using data-assisted channel estimation will become more accurate. In addition, data-assisted channel estimation can improve the probability of successful detection because the possibility of the parts of data sent by different IoT devices being unrelated is close to 100%.

3.3. Existing Problems

3.3.1. Accuracy of channel estimation. Since the total cost and power of IDP scheme and TSP scheme are the same, IDP scheme has two pilots, which is twice the number of pilots of TSP scheme. As a result, each pilot has only half the energy of the original single pilot, reducing the accuracy of the channel estimate by 3dB. Therefore, in order to improve the accuracy of channel estimation, we can enhance the transmission power.

3.3.2. Receiver complexity. MUD is required for each pilot. As the number of IoT devices increases, the interference elimination time will also increase, and the complexity of the whole system will also increase. The detection program is shown in Figure 3, which uses MUD and IC for each pilot. It can avoid repeated decoding, thus reducing complexity.

3.3.3. Number of independent pilots. The number of independent pilots is a very important value. It is evident that increasing the number of independent pilots reduces the probability of collisions. However, the decline of the accuracy of channel estimation and the increase of the complexity of the
receiver at the gateway are inevitable. So, we tried to find a balance and we found that the best performance was to use two independent pilots.

4. IDP-NOMA Protocol
The proposed framework structure is periodic, meaning that the process will be repeated continuously, basically composed of five stages.

1) The gateway sends the beacon signal first.
2) The active IoT device sends a double-pilot sequence and a data part. The data part includes the identification of the two pilot sequences and the ID of the IoT device, etc. All active IoT devices sent to the gateway at the same frequency using the ALOHA protocol. The gateway estimates the number of IoT devices per cycle through multiple hypothesis testing. The receiver at the gateway mainly consists of MUD and IC. Everything is unknown to the gateway receiver, so the receiver must go through a series of steps to obtain the number of active IoT devices and the selected pilot sequences.
3) According to the channel estimation, the gateway can obtain each device’s channel status and ranking. Then, the gateway selects the appropriate power level for each IoT device to broadcast to the IoT device. Each power level has a digital identification, and each IoT device correctly adjusts its transmitted power to the corresponding level. This also means that each IoT device needs to have a different power level. IoT devices that do not detect their ID indicate that a pilot collision may have occurred and that they retreat to the next cycle, where they can also increase their transmission power slightly.
4) All IoT devices transmit their packets to the gateway, and this phase can be thought of as the NOMA of the pure power domain.
5) The gateway sends an ACK packet containing the IoT device ID corresponding to the packet is successfully decoded so that each IoT device can detect whether its packet was successfully received. This framework remains the same as the number of IoT devices changes, does not cause large network fluctuations, and provides greater flexibility. Although the first three phases and ACK may reduce the system's throughput, they have much shorter payloads than the fourth phase.

5. Numerical Results and Analysis
This paper assumes a gateway and 50 IoT devices, M=50. The active IoT device randomly selects two pilots from a predefined pilot pool to transmit the data. If the IoT device failed to transfer, retreat to the next cycle and reinitiate the transfer request. They assume that the number of pilots in the pilot pool of the traditional scheme $N_{TSP} = 8$, the number of pilots in the pilot pool of the proposed scheme $N_{IDP} = 4$, the identification bit of one pilot sequence $m=2$, and the identification bit of two pilot sequences $2^m=4$. The simulation parameters are listed in Table 1.

| Parameter                        | Value     |
|----------------------------------|-----------|
| Number of gateways               | 1         |
| Number of IoT devices            | 50        |
| Carrier frequency                | 0.7 GHz   |
| Number of pilots for TSP scheme  | 8         |
| Number of pilots for IDP scheme  | 4         |
| Modulation and Coding            | QPSK, LDPC|
| Transport block                  | 160 bits  |
| Length of CRC                    | 16 bits   |
| Channel model                    | TDL-A     |
| Delay spread                     | 30ns      |
| Receiver algorithm               | MMSE-IC   |
6. Discussion

Figure 4 shows the comparison of throughput changes between TSP and IDP schemes with different values of \( P_t \). \( P_t \) is the average probability that each IoT device has packets to transmit, and throughput is the number of IoT devices that are successfully transmitted per cycle. As expected, it can be observed that the throughput increases as \( P_t \) increases, first to the optimal state and then decreases due to a large number of collisions. More importantly, it can be seen that the throughput of IDP scheme is always higher than that of TSP scheme, and when the throughput of IDP scheme and TSP scheme reaches the maximum, the \( P_t \) of IDP scheme is higher than that of TSP scheme, so using IDP scheme can greatly improve the throughput of the system.

Figure 5 shows the comparison of the probability of successful transmission \( P_s \) between TSP and IDP schemes under the condition that \( P_t \) takes different values. \( P_s \) is the ratio of the number of IoT devices successfully transferred to the total number of IoT devices initiating transfer requests in a period. It can be observed that \( P_s \) of both TSP scheme and IDP scheme decreases with the increase of \( P_t \), but \( P_s \) in IDP scheme is always higher than that in IDP scheme, and the decline rate is slower. So, the use of IDP scheme can greatly improve the probability of a successful transmission system.

Figure 6 shows the comparison of the changes of the number of average cycle \( N \) of IoT devices in TSP scheme and IDP scheme under the condition that \( P_t \) is set to different values. \( N \) is the average number of cycles per successful transfer for a single IoT device. It can be observed that the \( N \) of both TSP and IDP schemes increases with the increase of \( P_t \), but the \( N \) of TSP scheme is always higher than that of IDP scheme, and the growth rate is much faster than that of IDP scheme. So, using the IDP scheme can greatly reduce the number of times that the IoT device reinitiates a transfer request.

Figure 7 shows how the system throughput changes after 100 cycles over a period at \( P_t = 0.05 \). It can be observed that the throughput of TSP scheme and IDP scheme is basically the same. Because \( P_t \) is small at this time, the probability of pilot collision in the system is small, and the system is relatively stable.

Figure 8 shows how the system throughput changes throughout 100 cycles at \( P_t = 0.06 \). A slow throughput decline in the TSP scheme can be observed as the IoT device that has pilot collisions re-requests the transmission in the next cycle, resulting in more collisions and reducing the throughput of the system. In IDP scheme, the system throughput is relatively stable, because the probability of pilot collision is small. Figure 8 also shows the saturation of the two schemes, that is, the throughput is close to zero due to too many collisions. When both are at \( P_t = 0.10 \), the TSP scheme can accommodate 50 IoT devices, while the IDP scheme can accommodate 100 IoT devices. Therefore, IDP scheme has stronger stability and can accommodate more IoT devices.
Figure 4. Comparison of throughput with different probability of transmission of IoT devices

Figure 5. Comparison of probability of successful transmission with different probability of transmission of IoT devices
Figure 6. Comparison of the number of average cycle per successful transfer with different probability of transmission of IoT devices

Figure 7. Comparison of changes in system throughput with different probability of transmission of IoT devices at $P_t=0.05$
Figure 8. Comparison of changes in system throughput with different probability of transmission of IoT devices at $P_t=0.06$ and $P_t=0.10$.

7. Conclusion
This paper proposes an independent double-pilot scheme and the double-pilot sequences identified in the data payload part. Compared with the traditional single pilot scheme, the probability of pilot collision is dramatically reduced. The original TSP-NOMA protocol is improved, and a new IDP-NOMA protocol is proposed. This protocol is flexible, energy saving, extensible and easy to implement. Simulation results show that compared with the original protocol using training sequence and single pilot, IDP-NOMA protocol dramatically improves the system's performance in terms of throughput, transmission success probability, transmission delay and stability. However, since the number of pilots is increased and the total overhead and energy remain unchanged, the accuracy of channel estimation will decrease and the detection complexity of the receiver will increase. Therefore, the transmission power of IoT devices can be improved as the cost. This protocol has great potential and has a good application prospect in the future.

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