Activation Detection Algorithms for Pattern Division Multiple Access Uplink Grant-free Transmission

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Abstract. As a key technology of 5G, non orthogonal multiple access (NOMA) technology can significantly improve the spectrum efficiency compared with the traditional orthogonal multiple access technology. In addition, grant-free transmission technology can further reduce the transmission delay of the system and effectively improve the number of service users in the cell. In this paper, the pattern division multiple access (PDMA) technology (a typical NOMA technology) is taken as an example, PDMA technology based on Grant-free transmission (GF-PDMA) is studied, the uplink GF-PDMA pilot’s structure is designed and a user activation detection algorithms based on the received pilot’s power is proposed. The simulation results reviews that the algorithm proposed in this paper can fully meet the detection requirements of PDMA.

1. Introduction
In order to solve the increasing shortage of spectrum resources, non orthogonal multiple access (NOMA) technology is proposed as a key technology of 5G. Compared with the traditional orthogonal multiple access technology, NOMA allows multiple users to transmit information on the same system resources (such as time, frequency, power, etc.), which can significantly improve the spectral efficiency. In addition, in order to meet the requirements of 5G massive machine-type communication (mMTC) scenario and further reduce the system transmission delay, grant-free transmission technology needs to be further studied.

In the existing 4G LTE uplink, its data transmission mainly includes two mechanisms based on orthogonal multiple access (OMA): dynamic scheduling (DS) and semi-static scheduling (SS) schedules. There are some problems in DS and SS, such as time delay, high signaling overhead and limited number of users to OMA resources. These problems have become bottlenecks in the application of 5G system in mobile internet of things (IoT) scenarios. In order to resolve these problems, Grant-free transmission mechanism has been heatedly discussed in the 3GPP conference. At the 3GPP RAN1 #85 meeting, several companies recommended the use of Grant-free transmission scheme [1-4] in uplink packet services. At the subsequent RAN1 86# conference, Grant-free transmission has been further discussed: on the one hand, the technical points needed to be studied for uplink Grant-free applications were proposed, including pilot design, activation detection and channel
estimation, hybrid automatic repeat request (HARQ), link adaptation and power control, etc. [5] On the other hand, the application availability of Grant-free in uplink mMTC scenarios was analyzed. [6] What’s more, if only orthogonal transmission is supported, time and frequency resources need to be allocated to each user independently. For burst services such as mMTC, the system efficiency is not high, which is not conducive to supporting massive user connections. Based on previous research on serial interference cancel amenable multiple access (SAMA)[7], pattern division multiple access (PDMA) technology is proposed by China Academy of Telecommunications Technology (CATT)[8], which allow multiple users to share the same time-frequency resources, so as to support massive user connections more effectively.

At the RAN1 #86bits conference, more proposals were put forward on the combination of Grant-free and non-orthogonal multiple access. For example, LG proposed that the basic unit of multiple access physical resources [9] should be considered in scheduling-free multiple access. Huawei gave a comparative analysis of Grant-based (GB) and scheduling-free for packet services [10]; Samsung made pilot collision analysis [11]; Intel proposes that a user identification mechanism suitable for Grant-free non-orthogonal multiple access needs to be studied [12].

In summary, the existing uplink scheduling mechanisms in 4G systems cannot meet the requirements of high-performance indicators such as massive connection, low delay and high reliability under 5G mobile IoT scenarios. When the number of connections of the system reaches a certain level, a large amount of control signaling overhead makes the number of users that can be scheduled seriously bound by the limited control channel resources. Therefore, dynamic scheduling and semi-static scheduling based on orthogonal multiple access cannot meet the requirements of 5G. At this time, it is necessary to study a transmission scheme which can reduce both the delay and the instruction overhead of control channel. Grant-free transmission scheme is an effective way to solve the above problems. In Grant-free transmission scheme, how to effectively detect the active users is one key problem. In this paper we focus on this issue and propose the corresponding solution. The primary contributions of this paper are summarized as follows:

1) Based on the characteristics of basic transmission unit, the pilot of GF-PDMA is designed.
2) The activation detection algorithm based on the received power of pilot signal is proposed, which shows a good performance on missing detection probability with lower antenna configuration (e.g. 1Tx2Tx).

The remainder of this paper is organized as follows: Section II provides the system basic transmission unit model for UL GF-PDMA. Design on the pilot of GF-PDMA is illuminated in Section III. The user activation detection algorithms based on the received pilot’s power are proposed in Section IV. Numerical results are presented in Section V. Finally, Section VI concludes this paper.

2. System Basic Transmission Unit Model

For PDMA uplink Grant-free transmission, several users may share the same patterns on the same RE. Because of the random selection, these users may also transmit data at the same time. As long as the channel or pilot sequence or the modulation reference signal (DMRS) of these users are different, the multisuser detection algorithm can be used to detect these data at the receiving end to distinguish different users. The reuse of patterns can increase the load of the system and achieve links with a larger number of users.

For simplicity, we take a typical PDMA pattern matrix

\[
G_{\text{PDMA}}^{[2,3]} = \begin{bmatrix} g_1, g_2, g_3 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{21} & 0 \\ g_{12} & 0 & g_{32} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix},
\]

as an example, where, \( G_{\text{PDMA}}^{[2,3]} \) denotes the data from three users are superimposed on two resource elements (REs) and the system overload is 150%. The design of basic transmission unit (BTU) in GF-PDMA is shown in Fig.1.[13] One BTU is composed of time-frequency block, PDMA pattern and pilot sequence. An example of carrying three independent PDMA patterns on two time-frequency blocks is given in Fig. 29, in which each pattern has four pilot sequences. The allocation of pattern matrix and
pilot sequence resources is as follows: BTU 0, 1, 2; 3, 4, 5; 6, 7, 8 and 9, 10, 11 have the same pilot from left to right horizontally; BTU 0, 3, 6, 9 have different pilot sequences from bottom to top vertically, but have the same PDMA pattern $g_1 = [1 \ 1]^T$, similar, the pattern for BTU 1, 4, 7 and 10 is $g_2 = [1 \ 0]^T$ and the pattern for BTU 2, 5, 8 and 11 is $g_3 = [0 \ 1]^T$.

![Figure 1. GF-PDMA basic transmission unit](image)

### 3. Uplink GF-PDMA Pilot Design

Assuming that the user uses a single transmitting antenna, the total number of online users supported in the Grant-free basic transmission unit is $M$, the actual set of users sent by the service is $K$, and the length of the pilot sequence is $L$, the pilot received signal on the base station side can be expressed as

$$p = \sum_{k \in M} i_k h_k b_k + n = H_b B + n \quad (2)$$

where, $p$ is the received pilot signal vector with dimension $ML \times 1$,

$$H_b = IH = \begin{bmatrix} i_1 h_1 & 0 & \cdots & 0 \\ 0 & i_2 h_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & i_M h_M \end{bmatrix} \quad (3)$$

is the equivalent channel estimation matrix with dimension $ML \times ML$, where, $i_k$ and $h_k$ are diagonal matrix with dimension $L \times L$ ($k = 1, 2, L, M$), the elements on the diagonal line of $h_k$ represent the channel coefficients of pilot subcarriers. all the elements on the diagonal line of $i_k$ are 1 or 0, when the user $k$ has data to transmit, the value of all the elements is 1, otherwise, the value is 0. $I$ and $H$ are diagonal matrix and channel coefficient matrix of all user indicative functions, and they are respectively defined as follows:

$$I = \begin{bmatrix} i_1 & 0 & L & 0 \\ 0 & i_2 & L & 0 \\ L & L & O & L \\ 0 & 0 & L & i_M \end{bmatrix} \quad (4)$$

and
\[ H = \begin{bmatrix} h_1 & 0 & \cdots & 0 \\ 0 & h_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_M \end{bmatrix} \]

\[ B = [b_1 \ b_2 \ \cdots \ b_M]^T \]

is a column vector with dimension \(ML \times 1\), which is composed of all \(M\) users’ pilot sequences, where \(b_k\) is a column vector with dimension \(L \times 1\); \(n\) is the interference noise vector with dimension \(ML \times 1\), which includes neighboring cell interference and thermal noise in the cell.

From the above analysis, the goal of user activation detection is to determine which diagonal elements are all 0 and which diagonal elements are all 1 in the vector \(i_k (k = 1, 2, \ldots, M)\) of the detection matrix \(I\). The value 0 indicates that the user has data to transmit, and the value 1 indicates that the user has no data to transmit. Therefore, the user activation detection problem based on the received pilot signal is transformed into to estimate whether the Grant-free unit has data transmission or not. The next section will focus on the pilot activation detection algorithm.

### 4. Activation Detection Algorithm

In this section, we propose one user activation detection algorithm based on pilot signal receiving power.

Suppose \(H_{k,n}(n_{sub})\) is the channel estimates of the user \(k\) on the \(n_{sub}\) subcarrier and the receiving antenna \(n\), for the user without data transmission, the average power on all antennas is

\[ \frac{1}{N_R} \sum_{n=1}^{N_R} |H_{k,n}(n_{sub})|^2 \rightarrow \sigma^2, \tag{6} \]

and for the user with data transmission, we have

\[ \frac{1}{N_R} \sum_{n=1}^{N_R} |H_{k,n}(n_{sub})|^2 \rightarrow P_i \]

where \(\sigma^2\) is the thermal noise power and \(P_i\) is the average received signal power on the uplink unit subcarrier. Therefore, we can use the traditional channel estimation algorithm to complete the channel estimation of the pilot resources corresponding to the basic PDMA transmission units occupied by all online users, and then use the above formula to determine which users of the PDMA basic transmission units are sending data. The specific algorithm is implemented as follows:

**Step 1:** Calculate the pilot of PDMA Grant-free unit in frequency domain to estimate the channel by Least Square (LS) method, and get the LS channel estimation in frequency domain.

**Step 2:** The frequency domain LS channel estimation is transformed into time domain by inverse discrete Fourier transform (IDFT), and the time domain channel estimation is obtained.

**Step 3:** Calculate detection statistics \(\Lambda\), decision threshold and interference noise power.

**Step 3.1:** Selecting the target user's time-domain signal window and calculating the received power of pilot in the signal window as detection statistics \(\Lambda\):

\[ \Lambda = \frac{1}{N_{sub}} \sum_{n_{sub}=1}^{N_{sub}} P_R(n_{sub}) = \frac{1}{N_{sub}} \sum_{n_{sub}=1}^{N_{sub}} \sum_{n=1}^{N_R} |h_{k,n}(n_{sub})|^2 \]  \tag{7} \]

Where \(k\) represents the user number, \(N_R\) is the number of antennas for received signals, \(N_{sub}\) denotes subcarrier index, \(N_{sub}\) is the total number of subcarriers,

**Step 3.2:** Define the decision threshold as \(Th = \beta \sigma^2\), where \(\sigma^2\) interference noise power, \(\beta\) can be selected according to the current false alarm probability, such as \(\beta = 3\), there are two methods for calculating the power of interference noise:

**Method 1:** When pilots are allocated, at least one idle window is reserved, and the average power of all
time-domain paths in the idle window is calculated as interference noise power $\sigma^2$.

Method 2: All the time-domain paths except the user signal window of the target cell are taken as the candidate interference noise windows, and all the time-domain paths in the interference noise window are sorted from small to large according to the power value. The average value is calculated by choosing the first $1/N$ values as the interference noise power $\sigma^2$, where $N$ is an integer whose value is greater than or equal to 2.

Step 4: To determine whether there is a prior probability information of user pilot feedback from data joint detection and decoding module, if not enter Step 4.1, otherwise enter Step 4.2.

Step 4.1: Judgment in accordance with the following formula:

\[
\begin{cases}
\Lambda \geq Th_k, \text{ user } k \text{ has data to send} \\
\Lambda < Th_k, \text{ user } k \text{ has no data to send}
\end{cases}
\]  \hspace{1cm} (8)

Step 4.2: Judgment in accordance with the following formula:

\[
\left(\Lambda_k \geq Th_k \right) \cap \left( P_{\text{prior},k} \geq Th_{\text{prior}} \right),
\begin{cases}
\text{user } k \text{ has data to send} \\
\text{Otherwise, user } k \text{ has data to send}
\end{cases}
\]  \hspace{1cm} (9)

where “$\cap$” represents intersection operation, $P_{\text{prior},k}$ represents the pilot prior existence probability of the user feedback from the data joint detection and decoding module, $Th_{\text{prior}}$ is the pilot prior existence threshold value. $P_{\text{prior},k}$ can be obtained by calculating the average of the absolute value of the LLR of the user $k$ bit sequence.

5. Numerical Simulation Results

This section will evaluate the performance of the activation detection algorithm designed in the previous section. Based on PDMA reference link, Least Square Inverse Discrete Fourier Transform (LS-IDFT) is used to detect and estimate the pilot receiving power and noise power based on time window. Cumulative probability distribution of false alarm probability threshold under different SNR is given. The false alarm probability under CDF curve and 1% false alarm probability threshold is measured on the basis of the false alarm probability CDF.

The assumptions for LLS simulation are shown as Table 1.

| Basic parameter                      | Value                        |
|--------------------------------------|------------------------------|
| Carrier a                            | 2 GHz                        |
| System Bandwidth                     | 10 MHz                       |
| Channel model                        | UMA-NLOS                     |
| Number of PRB                        | 6;                           |
| Users’ velocity                      | 3km/h                        |
| Modulation & coding rate             | QPSK 1/2; LTE Turbo          |
| Antenna configuration and type       | 1Tx1Rx; 1Tx2Rx; ULA           |
| User angle interval                  | 180/用户数                   |
| Channel Estimation                   | Ideal for LLS; LS-IDFT for UAD |
| HARQ                                 | No                           |

Fig. 2 shows the false alarm threshold and missed detection probability curve of the active detection algorithm based on the received power of pilot signal when the antenna is configured as 1Tx1Rx.
According to the CDF curve of the false alarm threshold in Fig. 2 (a), the corresponding SNR of 99% CFD (corresponding to 1% false alarm threshold at this time) is 10.33 dB; for the 1% false alarm probability, the corresponding SNR of 1% false alarm probability is about 0.2 dB from Fig. 2 (b).

Fig. 3 shows the false alarm threshold and missed detection probability curve of the activation detection algorithm based on the received power of pilot signal when the antenna is configured as 1Tx2Rx. From Fig. 3 (a), it can be seen that when the antenna configuration of the activation detection algorithm is 1Tx2Rx, the false alarm threshold SNR = 10.22dB; as shown in Fig. 3 (b), for the 1% false alarm probability threshold, the SNR working point is 0.2dB under the 1% missed detection probability.
Comparing Fig. 2 and Fig. 3, it can be seen that the results of 1Tx1Rx and 1Tx2Rx are basically the same for the activation detection algorithm based on the received power of pilot signal. That is to say, the algorithm has no gain for multiple antennas. At the same time, for the threshold of 1% false alarm probability, the SNR working point of 1% missed detection probability is about 0.2dB, because the overload rate of PDMA is 150%, 200%, 300% and above 0.2dB (corresponding block error rate BLER = 1%)[8], which can fully meet the detection requirements of PDMA.

6. Conclusions
In this paper, we take a typical NOMA technology, PDMA, as an example to introduce the transmission scheme in PDMA system based on Grant-free. At first, the uplink GF-PDMA pilot’s structure is designed. secondly, a user activation detection algorithm based on the received pilot’s power is proposed. Lastly, The numerical simulations of the proposed algorithm with different antenna configuration are conducted. The simulation results reviews that the algorithm proposed in this paper has no gain for multiple antennas and can meet the detection requirements of PDMA (The SNR working point of 1% missed detection probability is about 0.2db).

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