Resource Management for Non-Orthogonal Multiple Access based Machine Type Communications

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***Abstract*—With the rapid development extensive application of the Internet of Things, the number of machine-type communications (MTC) devices has been increasing dramatically. But due to limited spectrum resources, the number of MTC devices connected is restricted by traditional orthogonal multiple access (OMA) scheme. In this paper, we formulate a joint sub-carrier and power allocation problem to maximize the number of MTC devices with non-orthogonal multiple access (NOMA) in NB-IoT, considering different requirements of both massive machine-type communications (mMTC) and ultra-reliable low latency communications (uRLLC). The capacity of small packet transmission is considered in the allocation. Furthermore, two MTC devices application scenarios in NB-IoT are analyzed in which both uRLLC devices and mMTC devices are involved and mMTC devices are involved only. Simulation results demonstrate that the proposed algorithm outperforms the traditional OMA scheme in the connectivity of MTC devices.**

I. Introduction

The rapid development of the Internet of Things (IoT) and wireless sensor networks (WSN) has brought many challenges to 5G communication technologies, such as low latency, high reliability, massive connectivity, and green communications [1]. Machine-type communications (MTC), including massive MTC (mMTC) and ultra-reliable low latency communications (uRLLC), plays an important role for in development of IoT [2]. uRLLC communications are mainly used in applications with strict delay constaint and high reliability requirement, such as electronic medical, autonomous control, and intelligent transportation system. In contrast, mMTC communications do not require strict delay constraints, but require massive connections and high energy efficiency such as wireless sensor networks and wearable devices [3]. In addition, another important feature of MTC is the transmission of small data packets, such as periodic monitoring data in smart grids and smart homes. To support MTC communications in the cellular networksn narrowband IoT (NB-IoT) is proposed by the Third Generation Partnership Project (3GPP) [4].

To alleviate the collisions of the network and support multiple devices to access the network simultaneously, non-orthogonal multiple access (NOMA), as a key technology of 5G, allows multiple users to access the network in a non-orthogonal manner in power domain or code domain [5]. Different users can simultaneously transmit on the same time-frequency resource, which improves spectrum utilization, increases the number of device connections, and reduces the access delay [6]. For receiver, various multi-user detection methods are applied to cancel interference between multiple users in the same channel, such as successive interference cancellation (SIC)[7]. However, SIC receivers introduce more processing delay than OMA receivers. With the rapid development of modern integrated circuit chips, the delay introduced by SIC is negligible compared to the user's access delay [8].

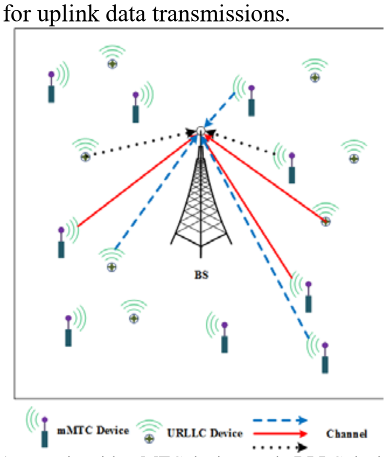
Currently, most of the research work of NOMA technology mainly focus on the system throughput enhancement in the enhanced mobile broadband scenario. Only limited works have investigated NOMA scheme in MTC. In [9], a random NOMA scheme under the mMTC scenario has been presented, which significantly reduce the signaling load required for device access, and improve the system's packet reception probability. In [10], a NOMA-based dense vehicular communication network solution has been proposed. The solution adopts a novel rotation-matching algorithm, and BS centrally controls time-frequency resource allocation to meet the ultra-reliable and low latency requirements of the vehicle-to-everything communications. In [11], a NOMA scheme in which the mMTC devices and uRLLC devices coexist in the NB-IoT system has been proposed. This scheme improves the number of accesses by multiplexing in the power domain. However, only two devices can be allocated on the same subcarrier, which limit the increase in the number of access, and small packet data transmission for MTC devices is not considered.

In this paper, the connectivity of MTC devices in NB-IoT is maximized by power and subcarrier allocation. The main contributions of our work are listed below. Power-domain NOMA scheme is explored for MTC, including mMTC and uRLLC, to allow multiple MTC devices to access the same sub-carrier to increase the number of connections. The resource allocation problem for mMTC and uRLLC is formulated as a connection density maximization problem, and a novel resource allocation scheme is proposed in which the allocation of subcarriers for uRLLC devices is implemented first if the uRLLC devices exist.

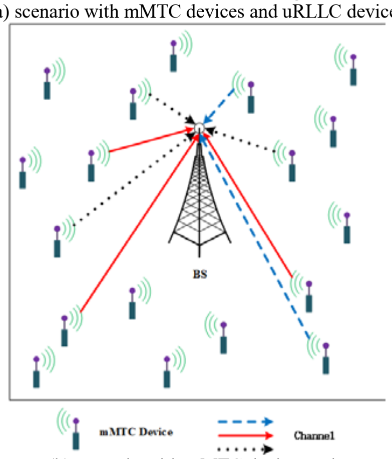
II. System Model and Problem Formulation

A. System Model

We consider a single-cell cellular system with a base station (BS) and multiple MTC devices. MTC devices are uniformly distributed under the cellular network. We consider two MTC Scenarios: only mMTC devices and coexistence of mMTC devices and uRLLC devices as shown in Fig. 1. All MTC devices follow NB-IoT standard and share the system bandwidth for uplink data transmissions.



(a) scenario with mMTC devices and uRLLC devices



(b) scenario with mMTC devices only

Figure 1 Two scenarios for NB-IoT

Scenario I: In the coexistence scenario with mMTC devices and uRLLC devices, the set of M mMTC devices and the set of U uRLLC devices are denoted by $M=\{m_1,\ldots,m_M\}$ and $U=\{u_1,\ldots,u_U\}$, respectively. mMTC devices and uRLLC devices can share the same subcarrier. Supposing uRLLC device u and mMTC device m transmit x_u and x_m over the same sub-carrier with the transmission power p_u and p_m, respectively, the received signal of BS with additive noise σ can then be presented by

$$y=\sum_{u\in U}\sqrt{p_u}h_u x_u+\sum_{m\in M}\sqrt{p_m}h_m x_m+\sigma, \tag{1}$$

where h_m and h_u are the channel gains of the mMTC device m and the uRLLC device u to the BS, respectively. Multiple mMTC devices and uRLLC devices are allocated the same subcarrier. Due to the high reliability requirement of the uRLLC devices, we assume that the received signals power of the uRLLC devices on the same carrier are greater than the received signals power of the mMTC devices. According to successive interference cancelation (SIC), the BS first decodes x_u and then subtract it from the received signal y. The signal-to-interference-plus-noise ratio (SINR) of the uRLLC device u can be expressed by

$$\gamma_u=\frac{|h_u|^2 p_u}{N_0 B+\sum_{m\in M}|h_m|^2 p_m+\sum_{u'\in U'}|h_{u'}|^2 p_{u'}}, \tag{2}$$

where N_0 is the noise power spectral density The interference from all mMTC devices and the uRLLC devices with higher channel gains on the same subcarrier can be presented as

$$\sum_{m\in M}|h_m|^2 p_m+\sum_{u'\in U'}|h_{u'}|^2 p_{u'}, \tag{3}$$

where U' denotes the set of uRLLC devices with higher channel gains on the same subcarrier. The SINR of the mMTC devices after subtracted all uRLLC devices' signals from the received signal y can be written as

$$\gamma_{\mathrm{m}}=\frac{|h_{\mathrm{m}}|^2 p_{\mathrm{m}}}{N_0 B+\sum_{m'\in M'}|h_{m'}|^2 p_{m'}}. \tag{4}$$

Scenario II: In the scenario with mMTC devices only, multiple mMTC devices can share the same subcarrier. The received signal y' can be formulated by

$$y'=\sum_{m\in M}\sqrt{p_m}h_m x_m+\sigma, \tag{5}$$

where p_m denotes the transmission power of mMTC device m. The decoding process is same as that in the first scenario and the SINR is same as formula (4).

In NB-IoT, the total bandwidth of 180kHz is divided into single-tone mode of 48 sub carriers or multi-tone mode of 12 sub carriers [12]. In single-tone mode, the system bandwidth is divided into 48 sub carriers, and the bandwidth of each sub carrier is 3.75kHz. The single-tone mode stipulates that each device can only occupy one subcarrier. If the traditional OMA scheme is used, each subcarrier can be used only by one MTC device, and the system supports 48 devices at the same time. In multi-tone mode, the system bandwidth is divided into 12 subcarriers, each subcarrier is 15kHz, and the multi-tone mode specifies that each device can occupy 1, 3, 6, 12 subcarriers. When the OMA scheme is used, the system supports up to 12 devices at the same time. With the increasing number of MTC devices, the access number of MTC devices is limited by the OMA mode, and the access time limit will increase the access delay, resulting in the uRLLC device cannot meet the requirements of low delay. Therefore, we propose a NOMA based connectivity maximization algorithm for NB-IoT, allowing multiple MTC devices to share the same subcarrier and improve the connectivity of MTC devices.

B. QoS and Power Constraints

In the first scenario, BS first decodes x_u. According to the Shannon formula, the data rate achieved by the uRLLC device u on S_u subcarriers is given by

$$r_u=\sum_{s=1}^{S_u}B_u\log_2\left(1+\frac{|h_u|^2 p_u}{N_0 B_u+I_{u,s}}\right),\forall u\in U, \tag{6}$$

where B_u is the subcarrier bandwidth occupied by the uRLLC device u, $I_{u,s}$ is the interference caused by all mMTC devices and the uRLLC devices with higher channel gains on the subcarrier s.

Since the uRLLC devices require high reliability, the transmission power of all uRLLC devices is set to the maximum transmission power, i.e., $p_u=P_u$, P_u denotes the maximum transmission power limited by the system. Besides, the achievable data rate of the uRLLC device u is greater than the lowest data rate threshold , R_u, so that the BS can successfully decodes x_u, i.e.,

$$r_u \geq R_u, \forall u \in U . \tag{7}$$

Second, In NB-IoT systems, MTC devices typically transmit small packets of the order of 10 Bytes. According to information theory, Shannon's capacity is not an accurate approximation of the achievable data rate since the transmission only involves a small amount of bits. Therefore, the achievable data rate of the mMTC devices with finite bits is formulated as [13]

$$r_m^s = \sum_{s=1}^{S_m} B_m \log_2(1+\frac{|h_m|^2 p_m}{N_0 B_m + I_{m',s}}) - \sqrt{\frac{V}{L}} f_Q^{-1}(\varepsilon_t), \forall m \in M , \tag{8}$$

where B_m is the subcarrier bandwidth occupied by the mMTC device m, and $I_{m',s}$ is the interference caused by the mMTC devices with higher channel gains on the subcarrier s, ε_t is the transmission error probability, L is the number of symbols for transmitting one packet, and

$$V = 1 - \frac{1}{(1+\frac{|h_m|^2 p_m}{N_0 B_m + I_{m',s}})^2} , \tag{9}$$

The first term in formula (9) is Shannon's capacity. When L is large, the achievable data rate in formula (9) approaches Shannon's capacity.

Similar to the uRLLC devices, the achievable data rate r_m of the mMTC device m is greater than the lowest data rate threshold, R_m, so that the BS can successfully decodes x_m, i.e.,

$$r_m \geq R_m, \forall m \in M . \tag{10}$$

In addition, the transmit power p_m of the mMTC device m cannot exceed the maximum transmit power P_m, We have

$$0 \leq p_m < P_m, \forall m \in M . \tag{11}$$

C. Resource Scheduling Constraints

To serve mMTC devices, the total system bandwidth is divided into S_M subcarriers, and the bandwidth of each subcarrier is B_M. Similarly, to serve uRLLC devices, the total system bandwidth is divided into S_U subcarriers. And the bandwidth of each subcarrier is B_U. The values of B_M and B_U are 3.75 kHz or 15 kHz. The number of subcarriers occupied by mMTC and uRLLC devices which successfully connect cannot exceed the total number of subcarriers, i.e.

$$\sum_{m \in M} S_m \leq S_M , \tag{12}$$

$$\sum_{u \in U} S_u \leq S_U . \tag{13}$$

To better depict subcarrier allocation, we introduce the $M \times S_M$ matrix J in which $J_{m,s}$=1 indicates that device m is assigned to subcarrier s, otherwise, $J_{m,s}$=0. Similarly, we introduce the $U \times S_U$ matrix K in which $k_{u,s}$=1 indicates that u is assigned by s, otherwise, $k_{u,s}$=0. Due to the high reliability and low latency of uRLLC devices and the complexity of SIC decoding. We define that the allocation of subcarriers is subject to two constraints. First, one subcarrier is allocated to one uRLLC device and up to Q mMTC devices, and constraints can be expressed as

$$\sum_{m \in M} j_{m,s} \leq Q, s = 1, \ldots, S_M , \tag{14}$$

$$\sum_{u \in U} k_{u,s} \leq 1, s = 1, \ldots, S_U . \tag{15}$$

Second, each MTC device occupies one or several consecutive subcarriers. In formula (5) and (7), the number of subcarriers occupied by mMTC devices and uRLLC devices can be expressed as

$$S_m = \sum_{s=1}^{S_M} j_{m,s}, \forall m \in M , \tag{16}$$

$$S_u = \sum_{s=1}^{S_U} k_{u,s}, \forall u \in U . \tag{17}$$

The subcarriers have different bandwidths, namely 3.75 kHz and 15 kHz, and the subcarriers allocated to the MTC device are different. When the sub-carrier bandwidth is 3.75 kHz, each MTC device $d \in M \bigcup U$ can only occupy one sub-carrier, i.e. $S_d \in \{1\}$, and constraints can be expressed by

$$\sum_{s=1}^{S_M} j_{m,s} \leq 1, \forall m \in M , \tag{18}$$

$$\sum_{s=1}^{S_U} k_{u,s} \leq 1, \forall u \in U . \tag{19}$$

When the sub-carrier bandwidth is 15 kHz, each MTC device $d \in M \bigcup U$ can occupy 1, 3, 6, and 12 sub-carriers, i.e. $S_d \in \{1,3,6,12\}$. When S_d=1, there are 12 combinations in total. When S_d=3, there are 4 combinations in total. When S_d=6, there are 2 combinations in total. For S_d=12 is satisfied, and there is one combination. Overall, there are totally 19 combinations.

In addition, binary variable $v_{d,c}$ is defined in which $v_{d,c}$=1 indicates that MTC device d occupies subcarrier c, otherwise, $v_{d,c}$=0. We have

$$\sum_{c=1}^{C} v_{d,c} \leq 1, \forall d \in M \bigcup U . \tag{20}$$

For $u \in U$ and c=1, 2,…, C, we define the variable $v_{u,c}$ about $k_{u,s}$ as follows,

$$v_{u,1} = k_{u,1}, \ldots v_{u,12} = k_{u,12}, v_{u,13} = \prod_{s=1}^{3} k_{u,s}, \ldots, v_{u,16} = \prod_{s=10}^{12} k_{u,s} , \tag{21}$$

$$v_{u,17} = \prod_{s=1}^{6} k_{u,s}, v_{u,18} = \prod_{s=7}^{12} k_{u,s}, v_{u,19} = \prod_{s=1}^{12} k_{u,s} .$$

Similarly, for $m \in M$, we define the variable $v_{m,c}$=1 about $j_{m,s}$=1,

$$v_{m,1} = j_{m,1}, v_{m,2} = j_{m,2}, \ldots, v_{m,19} = \prod_{s=1}^{12} j_{m,s} . \quad (22)$$

D. Problem Formulation

Resource management in NOMA networks for NB-IoT is to maximize the number of MTC devices connected in the network, while ensuring the reliability and transmit power of MTC devices. Define vector $Z_M = (z_{m_1}, \ldots, z_{m_M})$, $Z_U = (z_{u_1}, \ldots, z_{u_U})$, where z_m=1 reflects that $r_m \geq R_m$ and $p_m \leq P_m$, otherwise, z_m=0; similarly, z_u=1 reflects that $r_u \geq R_u$, otherwise, z_u=0. The problem in the scenario where mMTC devices and uRLLC devices are coexist can be formulated as follows

$$\max_{P_M, J, B_M, S_M, K, S_U} \| Z_u \|_0 + \| Z_M \|_0 , \quad (23a)$$

$$\text{Subject to } r_d \geq z_d R_d , \forall d \in M \cup U , \quad (23b)$$

$$0 \leq z_m p_m \leq P_m , \forall m \in M , \quad (23c)$$

$$B_M \in B , \quad (23d)$$

Constraints (6) / (8), (12) – (17), (21),

Constraints (18), *if* $B_M = 3.75kHz$,

Constraints (20), (22), *if* $B_M = 15kHz$.

where P_M is the transmit power vector for all mMTC devices. For the Constraint (6), (8), due to the small packet transmission characteristics of the mMTC devices, the achievable data rate of the mMTC devices is calculated by the small packet transmission rate expression.

The problem in the scenario with only mMTC devices are can be formulated as follows

$$\max_{P_M, J, B_M, S_M} \| Z_M \|_0 , \quad (24a)$$

$$\text{st. } r_m \geq z_m R_m , \forall m \in M , \quad (24b)$$

$$0 \leq z_m p_m \leq P_m , \forall m \in M , \quad (24c)$$

$$B_M \in B , \quad (24d)$$

Constraints (6) / (8), (12), (14), (16),

Constraints (18), *if* $B_M = 3.75kHz$,

Constraints (20), (22), *if* $B_M = 15kHz$,

The optimization problems (23), (24) require huge amount of computation through exhaustive search. The following new allocation algorithms are proposed to solve the optimization problems in two scenarios.

III. NOMA-Based Resource Management

A. Scenario with mMTC devices only

In the scenario with mMTC devices only, the subcarrier bandwidths of 3.75 kHz and 15 kHz are considered separately to support different mMTC devices. Due to the characteristics of small packet transmission in the NB-IoT system, the achievable data rate of the mMTC devices is calculated by the small packet transmission rate.

When there are multiple superimposed signals on the same subcarrier, the signals of devices who have higher channel gains are treated as noise. To meet the QoS performance requirements of the mMTC devices in (10), based on the small packet data rate expression (8), the minimum transmission power of the mMTC devices can be represented as

$$p_{m,S_m}^{s} = (2^{\frac{R_m+G}{S_m B_M}} - 1) \frac{N_0 B_M + I_{s'}}{|h_m|^2}, s' = 1, \ldots, S_M . \quad (25)$$

where $I_{s'}$ is the interference caused by the signals of mMTC devices with higher channel gains on the same subcarriers, G represents the reduction of achievable data rate caused by small packet transmission ,

$$I_{s'} = \sum_{m \in M'} j_{m,s} |h_m|^2 p_m , \quad (26)$$

$$G = \sqrt{\frac{V}{L}} f_Q^{-1}(\varepsilon_t) , \quad (27)$$

For the mMTC device whose signal is decoded as the last one, the interference value satisfies $I_{s'}$=0. The transmit power can be calculated by the formula (25). The signal can only be superimposed when the minimum power of the mMTC devices is less than the peak power of the system. With the increase of superimposed signals, the minimum transmission power gradually increases until exceeding the system peak power. The specific algorithm is as follows

Connection maximization algorithm for mMTC devices
1) Input: B_M, S_M, h_m, P_m, R_m, if B_M=3.75*kHz*, $S_m \in \{1\}$; if B_M=15*kHz*, $S_m \in \{1,3,6,12\}$;
2) Initialization: $j_{m,s}$=0, Z_m=0, $\forall m \in M, s = 1, \ldots, S_M$;
3) Calculate the minimum transmit power of unassigned mMTC devices by (25) and sort mMTC devices in a ascending order of power;
4) Select mMTC devices that constraint (9) is satisfied, and allocated selected devices on subcarriers, and Z_m=1, $j_{m,s}$=1;
5) Calculate interference by formula (26);
6) Repeat (3)-(5), until all mMTC devices are assigned;
7) Output: Z_m, *J*.

B. Scenario with mMTC devices and uRLLC devices

Here, a two-step algorithm is proposed to tackle problem (23). First, as many uRLLC devices as possible can be accessed preferentially under the QoS requirement. Secondly, as many mMTC devices as possible can be accessed under the constraint of QoS and power. The solution to two sub-problems decomposed provide (23) with a feasible solution.

In the first step, due to the high reliability and low latency requirement of the uRLLC devices, a higher data rate should be provided for uRLLC devices. Therefore, the subcarrier bandwidth B_U of the uRLLC devices equals 15 kHz. Besides, the maximum interference I on per subcarrier can be obtained. In the second step, due to the low QoS performance requirement of mMTC devices, considering the two subcarrier bandwidths of 3.75 kHz and 15 kHz to access different types of mMTC devices, respectively, and more mMTC devices can be accessed by reasonably allocating frequency and transmission power.

1) Resource allocation for uRLLC devices

The subcarrier bandwidth B_U of the uRLLC devices equals 15 kHz, the problem is modeled as

$$\max_{K,S_u} \quad \| Z_u \|_0 + \| I \|_1 , \tag{28a}$$

$$s.t.\ r_u = S_u B_U \log_2 (1 + \frac{| h_u |^2 P_u}{I_{u,S_u} + N_0 B_U}), \forall u \in U , \tag{28b}$$

$$I \geq 0 , \tag{28c}$$

Constraints (12),(15),(17),(20)-(21)

where $I = (I_1 \ldots I_s \ldots I_{S_U})$, and I_s is the maximum allowable interference for uRLLC device u. In this problem, maximizing $\|Z_u\|_0$ is to access more uRLLC devices. When the $\|Z_u\|_0$ value is the same, maximizing $\|I\|_1$ is to access more mMTC devices. With the increase of I, the mMTC devices have more sufficient power to meet the QoS constraint.

The achievable data rate of the uRLLC devices can be obtained by the formula (28b), where $I_{u,Su}$ is the interference for the uRLLC devices u from all mMTC devices on the same subcarrier on the S_u subcarriers . Assuming that the achievable data rate r_u equals the minimum value R_u, the bandwidth allocated to the uRLLC device u equals $S_u B_U$, and $I_{u,Su}$ can be calculated by

$$I_{u,S_u} = \frac{| h_u |^2 P_u}{2^{\frac{Ru}{S_u B_U}} - 1} - N_0 B_U . \tag{29}$$

where the achievable data rate r_u of the uRLLC device is the minimum threshold R_u, the interference value $I_{u,Su}$ is the maximum.

2) Resource allocation for mMTC devices

The resource allocation for mMTC devices is mainly subjected by the transmission power and QoS requirement. Where S_M=S_U, the upper constraint of the transmission power of mMTC device m can be as follows

$$\sum_{m \in M} j_{m,s} | h_m |^2 p_m \leq I_s , s = 1, \ldots, S_M . \tag{30}$$

Second, when $S_M \geq S_U$, the allowable interference of the uRLLC device u on one subcarrier extends to S_M / S_U subcarriers. For example, S_M=48, S_U=12, so $I = (I_1, \ldots, I_{12})$ obtained in the first step is treated as $I = (I_1, I_1, I_1, I_1 \ldots, I_{12}, I_{12}, I_{12}, I_{12})$ in the second step. The resource allocation problem of the mMTC devices can be formulated as:

$$\max_{P_M, J, Z_M} imize \quad \| Z_M \|_0 , \tag{35}$$

s.t. (8), (10), (12), (14), (16), (25)-(27), (30)
Constraints (18), *if* B_M=3.75*kHz*,
Constraints (20), (22), *if* B_M=15*kHz*.

Similar to the scenario with mMTC devices only, the mMTC devices with the lowest power are preferentially selected. As the number of superposed signals increases, the interference value gradually increases until the minimum transmission power exceeds the peak power.

3) The Resource allocation algorithm for mMTC devices and uRLLC devices

Compared with the scenario with the mMTC devices only, in the scenario with uRLLC devices and mMTC devices, resource allocation of mMTC devices need to meet two constraints: first, signals can be decoded successfully under interference from the same carrier; second, when mMTC devices are superimposed on subcarriers, the interference caused by all mMTC devices must satisfy the constraint condition (30). The uRLLC devices that occupy less subcarriers are allocated subcarriers preferentially to maximize the connectivity of uRLLC devices. The specific algorithm is as follows

Connection maximization algorithm for mMTC devices and uRLLC devices
1) Input: B_U, S_U, h_u, P_u, R_u, $\forall u \in U$, B_M, S_M, h_m, P_m, R_m, $\forall m \in M$, if B_M=3.75*kHz*, $S_m \in \{1\}$; if B_M=15*kHz*, $S_m \in \{1,3,6,12\}$;
2) Initialization: $j_{m,s}$=0, Z_m=0, $\forall m \in M$, $s = 1, \ldots, S_M$, Z_u=0, $k_{u,s}$=0, $\forall u \in U, s = 1, \ldots, S_U$, B_U=15*kHz*, $S_u \in \{1,3,6,12\}$;
3) Calculate the interference caused by mMTC devices according to formula (26), and select u that satisfies the limit (38c) and S_u is the smallest to constitute set U';
4) The set U' is sorted in ascending order of S_u. When S_u is the same, it is sorted in order of allowable interference descending;
5) Select as many devices as possible from the set U' and construct a new set U'' and then sort the set U'' in a descending order of S_u, if $\forall u \in U''$, S_u=1, and assign subcarriers to u in set U'' according to S_u to constitute set K;
6) expand I according to the bandwidth relation, and calculate the minimum transmit power of unassigned subcarrier users by (25) and sort mMTC devices in a ascending order of power;
7) Select mMTC devices that constraints (10) and (30) in satisfied, and superimpose devices on subcarriers, and Z_m=1, $j_{m,s}$=1;
8) Calculate the interference by (26); repeat (3)-(5), until all mMTC devices are assigned;
9) Output: Z_u, K, Z_m, J.

IV. Simulation Results

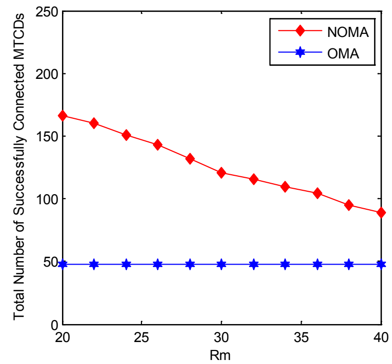
In this section, the performance of the proposed resource allocation scheme is simulated and compared with the OMA mode. Assume that the uRLLC devices and the mMTC devices are uniformly distributed as shown in Fig. 1, where a total of 50 uRLLC devices and 300 mMTC devices. Since the bandwidth of the NB-IoT system is only 180 kHz, the channel fading is set to flat Rayleigh fading, and the carrier frequency of the system is 900 MHz. The Gaussian white noise has a power spectral density of 174dBm/Hz. The highest transmission power satisfies P_d=23dBm, $\forall d \in M \bigcup U$. The bandwidth value B_M, B_U of NOMA and OMA is selected from set B. Compared to the NOMA scheme, in the OMA scheme, subcarriers are not primarily assign to the uRLLC devices.

Fig. 2 shows the number of connections when the subcarrier bandwidth is 3.75 kHz in the scenario with the mMTC devices only. Fig. 2(a) shows the variation of the connections number with the R_m. The coverage range is 1000m, and the bit error rate satisfies ε=0.01 ; Fig. 2(b) shows the number of connections with coverage, and R_m=20kbps and the bit error rate satisfies ε=0.01. In Fig. 2, the number of connections in the OMA scheme equals 48 and does not change with R_m or communication range; the number of connections in the NOMA scheme is significantly higher than that in the OMA scheme, but as R_m or communication range increases, the number of connections in the NOMA scheme will decrease significantly. With the increase of R_m or communication range, the minimum transmission power of the mMTC devices increases, and the interference to other mMTC devices on the same carrier also increases. The constraint (10) is more difficult to satisfy, and the number of superpositions on the same subcarrier then drops.

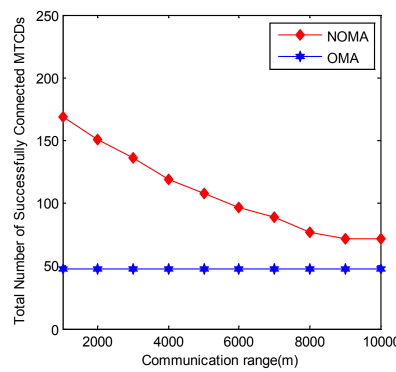
The subcarrier bandwidth is 15 kHz as shown in Fig. 3, and other parameters are the same as in Fig. 2. Similar to Fig. 2, as the data rate or coverage of the mMTC devices increases, the number of connections of the mMTC devices gradually decreases. Compared with Fig. 2, when the bandwidth is 15 kHz, the growth rate of NOMA access is significantly reduced. Because when the bandwidth is 15 kHz, both the data rate and the bandwidth increase, and the rate of increase of the data rate is greater, and higher transmission power is required to meet the data rate requirement of the mMTC devices. In Fig. 3(b), as the communication range increases, the number of connections decreases rapidly. When the coverage area exceeds 7000m, the number of connections to both connection modes is less than the number of bandwidths, i.e., some mMTC devices may occupy 3, 6, and 12 subcarriers.

Comparing Fig. 2 with Fig. 3, it can be concluded that when the bandwidth is 3.75 kHz, NOMA scheme can support more device; while when the bandwidth is 15 kHz, the system can achieve a higher peak rate. Therefore, a bandwidth of 3.75 kHz is suitable for mMTC devices with low data rates. And a bandwidth of 15 kHz is suitable for devices with higher data rate requirements. This conclusion is consistent with the NB-IoT standard.

Fig. 4 shows the number of connections with different R_u and communication range in the scenario with both mMTC devices and uRLLC devices. Fig. 4(a) shows total number of connected mMTC/uRLLC devices with the R_u, where the coverage is 1000m, the bandwidth of the uRLLC devices and mMTC devices is 15kHz and 3.75 kHz respectively and the data rate of the mMTC devices is 20kbps. In Fig. 4(b), the uRLLC devices have a bandwidth of 15 kHz and a data rate of 160 kbps. The mMTC device has a bandwidth of 3.75 kHz and a data rate of 20 kbps. The connectivity of mMTC devices in the NOMA scheme is much larger than the OMA scheme due to the power domain multiplexing, but the connectivity of uRLLC devices is slightly smaller than the OMA scheme because of small packet transmission rate in the NOMA scheme.

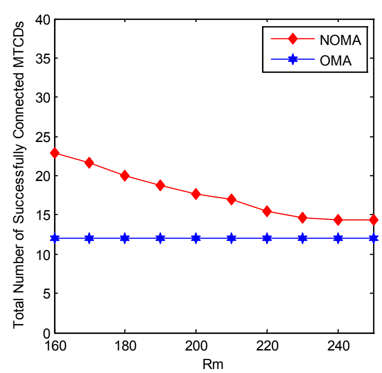


(a) Changes with R_m

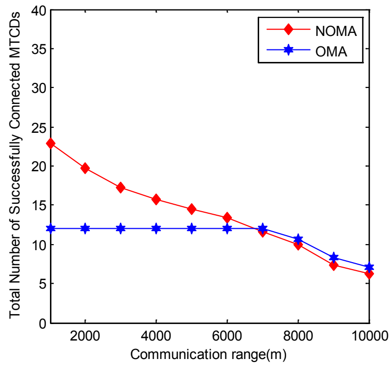


(b) Changes with communication range

Figure 2 The number of devices connected with a bandwidth of 3.75 kHz

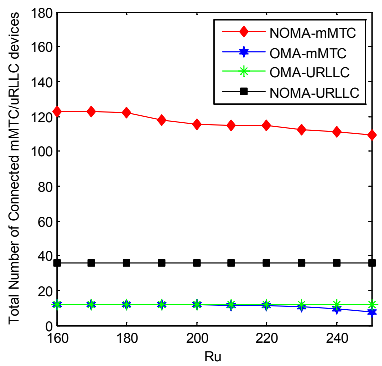


(a) Changes with R_m

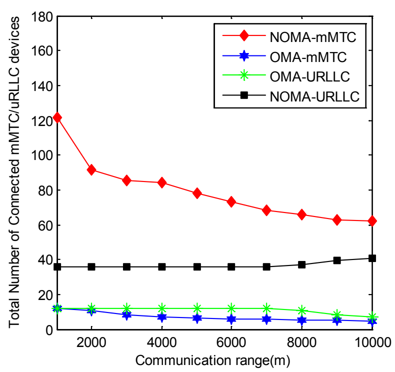


(b) Changes with communication range

Figure 3 The number of devices connections with a bandwidth of 15 kHz



(a) Changes with *Ru*



(b) Changes with communication range

Figure 4 The number of mMTC/uRLLC devices connections

V. CONCLUSIONS

In this paper, we presented a NOMA-based resource optimization algorithm for MTC, considering the two application scenarios with only mMTC devices and with both mMTC devices and uRLLC devices respectively. The achievable data rate of the mMTC devices is calculated by the small packet transmission rate expression. The simulation results show that the NOMA has a significant increase for connectivity of MTC devices compared to the OMA. Also, the number of connected devices is constrained by the minimum rate requirement of each devices.

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