Semi-granted Sparse Code Multiple Access (SCMA) for 5G Networks (Invited Paper)

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Abstract. Sparse Code Multiple Access (SCMA) is a promising non-orthogonal multiple access technology for 5G radio access networks. It improves the connectivity and capacity. However, the two multiple access methods of SCMA: granted and grant-free cannot dynamically match the real-time demands since the resources allocated for the granted method and grant-free method are clearly separated with each other. This further deteriorates the system performance. This article proposes a semi-granted SCMA method, by enabling the granted demands and grant-free demands to share the same resources. Simulation results confirm that semi-granted SCMA matches the dynamically fluent demands and significantly improve the throughput of SCMA 5G system.

Keywords: Sparse code multiple access · SCMA
Non-orthogonal multiple access · Multiple access · Grant-free · 5G

1 Introduction

Since mobile Internet deeply penetrates most aspects of human life, the wireless connectivity and traffic are being proliferating in recent years [1]. The traditional wireless networks can hardly keep pace with these increasing demands. Therefore, the fifth generation (5G) mobile communication system is required to support massive connectivity, super-large capacity, and diverse services.

To improve the connectivity and capacity, sparse code multiple access (SCMA) [2], a promising non-orthogonal multiple access technology [3] for 5G, attracts increasingly attentions from both the academic and industrial communities in recent years. Directly mapping different coded bitstreams into multi-dimensional complex domain codewords generated by predefined codebooks, SCMA enables multiple users' information to be overload in the frequency domain but multiplexed in the code domain. The non-orthogonality achieves the overloading gain and diversity gain, while the sparsity guarantees the simplicity and feasibility of multi-user detection in receiver. Therefore, SCMA significantly improves the connectivity and capacity.

Y.-B. Lin et al. (Eds.): IoTaaS 2017, LNICST 246, pp. 381–388, 2018.
https://doi.org/10.1007/978-3-030-00410-1_44

The increasingly diverse services pose a series of intractable challenges for wireless access network. For example, some Internet of things (IoT) services require ultra low access latency, while service with massive packets but small size aggravates the signalling storm problem, *and etc.* These diverse services ask for multiple access adaptation of wireless networks. Some existing studies introducing SCMA for the IoT system [4]. SCMA introduces two multiple access types: scheduling based multiple access (granted) and contention based multiple access (grant-free). Scheduling based multiple, all access opportunities are scheduled by the base station (BS), is the traditional access method of cellular network. In contrast, contention based multiple access method allows user equipments (UEs) to directly contend the spectrum resources without apply-and-grant [5,6], reducing both the access latency and signalling. Therefore, these two methods obtain the multiple access adaptation for SCMA.

However, the related studies assume that the time-frequency resources allocated for the granted method and that for the grant-free method are clearly separated with each other. This causes the mismatch between resources and real-time demands. The wireless demands continuously vary with time, thus it is quite difficult to “draw the borderline” of granted resources and grant-free resources dynamically. It means the resources allocated for granted and grant-free can hardly match the real-time demands. When the requirements of granted demands are less than the allocated resources and the grant-free demands sharply increase, there is no choice but waste the extra resources allocated for the granted method. Consequently, the collision grows and throughput decreases, and vice versa. Therefore, this mismatch actually leads to a stalemate: the system needs to know the real-time granted and grant-free demands in order to dynamically determine the appropriate resource allocation results, while the granted and grant-free demands are related to the resource allocation since different allocation results result different performance such as collision probability and throughput. Therefore, the clear division between granted resources and grant-free resources affects the system performance and decreases gain achieved by SCMA.

To break the stalemate and obtain further gain of SCMA, we propose semi-granted sparse code multiple access for 5G networks. Breaking the clear separation, semi-granted SCMA enables the granted demands and the grant-free demands share the same resources. In another word, each resource block (RB) can serve both the granted demands and the grant-free demand. In this case, like soft water filling in the hard stones, after scheduling proper resources to the granted demands, the BS indicates the grant-free demands contend all the remaining SCMA layers which are overloaded with the resources occupied by the granted demands. Thus, the resources can efficiently support the real-time demands. Simulation results confirm the flexibility and efficiency of our proposed semi-granted SCMA, and show that semi-granted SCMA significantly outperform the separation method in the system throughput.

The contributions of this article can be summarized as follows:

– To the best of our knowledge, this is the first work to introduce the semi-granted SCMA concept enabling the granted and grant-free sharing the same

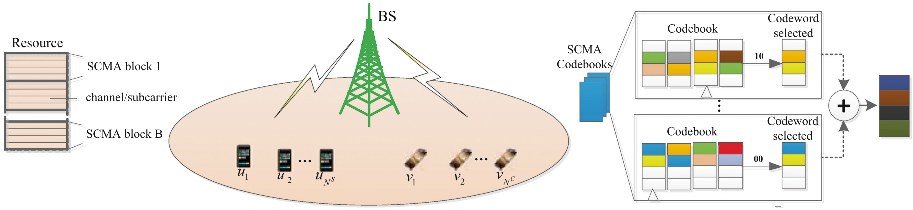


Fig. 1. System model.

resources. It guarantees the resource allocation to dynamically match the varying demands.
- A specific media access control (MAC) frame is proposed for the semi-granted SCMA.

2 System Model

2.1 Network Topology

As Fig. 1 shows, the BS is located at the center of the cell. UEs are distributed randomly in the coverage area surrounding the BS. For simplicity, we divide UEs into two group:

(1) The granted UEs, denoted as $\{u_1, u_2, \cdots, u_{N^S}\}$, where N^S indicates the number of granted UEs. The granted UEs are applicable to the granted access method.
(2) The grant-free UEs, denoted as $\{v_1, v_2, \cdots, v_{N^F}\}$, where N^F indicates the number of grant-free UEs. The grant-free UEs adopt grant-free multiple access method.

2.2 Resources

There are X sub-carriers/sub-channels in the frequency domain. Every K sub-channels are aggregated as a SCMA block. Thus, the total number of SCMA blocks is:

$$m = \lceil X/K \rceil, \tag{1}$$

where $\lceil * \rceil$ denotes the minimum integer that is greater than or equal to $*$.

2.3 SCMA Model

Assuming that the system possesses K subchannels. The codebook set as denoted as $\mathbf{C} = \{c_1, c_2, \cdots, c_J\}$, where J indicates the number of SCMA layers. The size of each SCMA codebook is $K * M$, denoted as $c_i^{K\times M}, i = 1, 2, \cdots, J$. The row in c_i indicates the subchannel i and the column indicates the information incoming bits. It means the SCMA encoder maps every $\log_2 M$ incoming bits into one complex constellation point. For example, when $M = 4$, the incoming bits 00, 01, 10, 11 correspond to the first, second, third and fourth column respectively. Every column is call as a codeword. This means every UE may transmit the same information in several subchannels. Therefore, SCMA can achieve the shaping gain of high dimensional modulation.

Since every UE transmits its signal in several subchannels, multiple UEs' signal overlaps in the shared spectrum. J SCMA layer can support J UEs to transmit concurrently. Thus, the overload factor is $J/K > 1$. These multiple UEs' signals multiplex in the wireless channels. And then the signal received in base station can be described as [4]:

$$\mathbf{y} = \sum_{j=1}^{J} diag(\mathbf{h}_j)\mathbf{x}_j + \mathbf{n}, \tag{2}$$

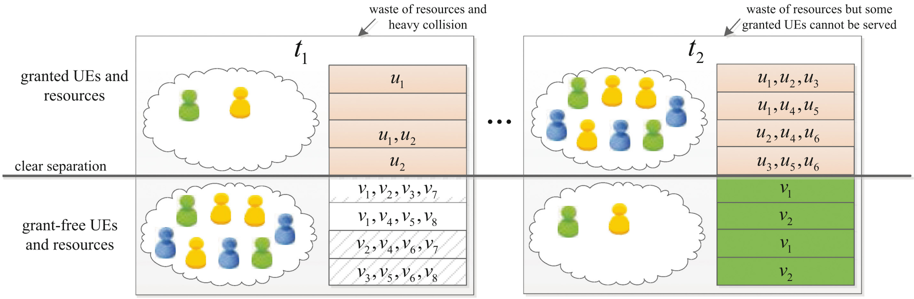
where $\mathbf{x}_j = (x_{1j}, \cdots, x_{Kj})^T$ is the codeword of layer j (UE j). $\mathbf{n}$ is the additive white gaussian noise vector. $\mathbf{y}$ represents the K-dimensional multiplexed receiving signal vector at the receiver. Diagonal matrix $diag(\mathbf{h}_j)$ represents the channel. $\mathbf{h}_j = (h_{1j}, \cdots, h_{Kj})^T$ is layer j's channel vector, and h_{1j} corresponds to the jth subchannel.

SCMA introduces the spares feature, which means every codeword has several, always more than a half, zero elements. Such sparse feature significantly simplifies the computational complex in receiver. Therefore, the receiver may use low complexity multi-user detection algorithms such as message passing algorithm (MPA).

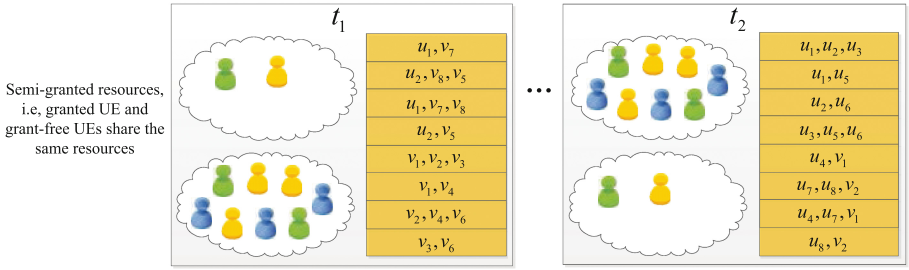
3 Key Idea of Semi-granted SCMA

To easily and clearly introduce the key idea of semi-granted SCMA, an example is presents in Fig. 2. There are two SCMA blocks, each of which consists of four sub-channels. Each SCMA block possesses six layers, thus the overloading factor is $6/4 = 1.5$.

Figure 2(a) illustrates the multiple access method that the resources of granted and grant-free are clearly separated proposed by the existing studies. In this method, the granted UEs cannot use the grant-free resource even if the granted resources are not enough and the grant-free resources are quite vacant. The demands are continuously varying with time. In the time t_1, two granted UEs and eight grant-free UEs want to transmit uplink data. In this case, obviously, the granted resources are seriously wasted because only two granted UEs share the resources. The grant-free UEs collide with each other because in each sub-channel there are four UEs try to contend, which is larger than the max supportable UE number: three. Thus, the throughput in t_1 is low. Similarly, in the time t_2, eight granted UEs and two grant-free UEs want to transmit uplink data. Consequently, two granted UEs cannot be served because the granted resource can support six users at most. Although there are plenty of available grant-free



(a) SCMA with granted/grant-free separation.



(b) Semi-granted SCMA.

Fig. 2. Key idea of semi-granted SCMA.

resources, the two granted UEs have no choice but wait for the scheduling in the future. Thus, the throughput in t_2 is suppressed and the access latency of some UEs is increased.

Figure 2(a) shows the semi-granted SCMA method. In this method, we break the resource separation by enabling both the granted UEs and grant-free UEs share the same resources. Two SCMA blocks can support twelve UEs in total. In the time t_1 and t_2, there are ten UEs want to transmit uplink data. Thus, it is conspicuous that all the UEs can be serviced successfully. Therefore, we highlight that the proposed semi-granted SCMA method naturally matches the time-varying demands, and significantly improves the throughput and QoS.

4 MAC Frame for Semi-granted SCMA

Since every multiple access method needs a corresponding MAC protocol, we propose a MAC frame for the semi-granted SCMA, as Fig. 3 shown. For compatibility, we design the MAC frame based on TD-LTE. The wireless frame, 10 ms, is the basic unit of semi-granted SCMA. Each wireless frame is divided into ten sub-frame, and each sub-frame (SF) occupies 1 ms. Moreover, each sub-frame is composed of two time slot, then each time slot is 0.5 ms. Before each wireless frame, the BS configures the time slot allocation according to the uplink and downlink traffic. The sub-frame 0 (SF0) is configured as downlink, while the SF1

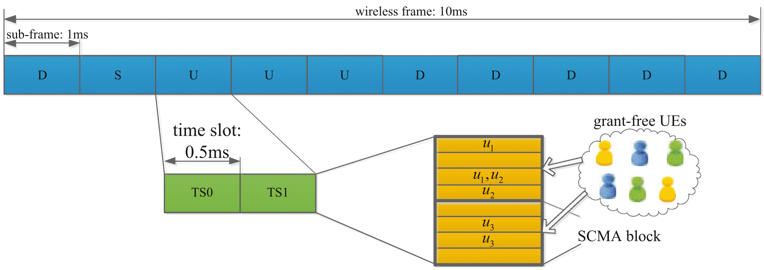


Fig. 3. MAC frame for semi-granted SCMA.

is a special sub-frame similar as TD-LTE. Other sub-frames can be configured as uplink or downlink flexibly.

To support semi-granted SCMA, in each uplink sub-frame, the BS firstly allocates the resources for the granted demands. After that, the remaining resources are available for the grant-free demands. The BS needs to indicates the resource allocation results in the start of each sub-frame. Then, the granted UEs just need to transmit data in the allocated resources, while the grant-free UEs contend for the remaining resources through p-persistent or the backoff mean. The specific contention mean is out of the scope of this article. If the number of granted UEs are large, the BS may reserve some resources for the grant-free UEs. Similarly, if the number of grant-free UEs are large, the BS may adjust the access probability or contention window (CW) for the grant-free UEs. Therefore, this MAC frame is a general frame. It supports not only the semi-granted SCMA, but the specific access means and scheduling algorithms.

5 Performance Evaluation

The system has 10 SCMA-block in total. During each timeslot, 0.5 ms, 1,000 bits are transmitted by each UE. LDPC is adopted for channel coding. Figure 4 shows the throughput verses the granted UE number. For the granted/grant-free separation scheme, 4 SCMA-blocks are fixed as the granted resources and 6 SCMA-blocks as the grant-free resources. When the granted UE number is unsaturated (less than 24), both two schemes achieve the same performance for granted UEs, but the proposed semi-granted scheme outperforms the separation scheme in throughput for grant-free UEs. Further, When the granted UE number is saturated (more than 24), both schemes almost share the same performance for grant-free UEs, but semi-granted outperforms the separation scheme in throughput for granted UEs.

In Fig. 5, the granted UE number is fixed as 24 and we change the ratio of granted SCMA-block. Obviously, 0 means no resources are allocated for the granted UEs, and 1 means all the resources are allocated for the granted UEs. We achieve the similar results from Fig. 5 that semi-granted scheme outperforms the separation scheme before and after saturation (ratio = 0.4).

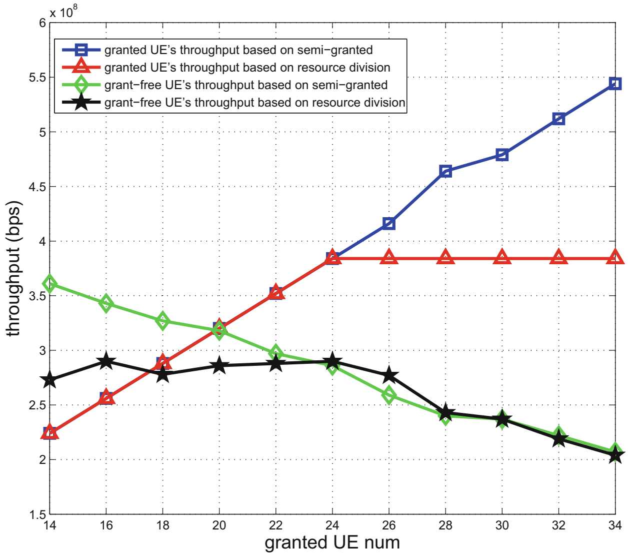


Fig. 4. Performance with granted UE number changing

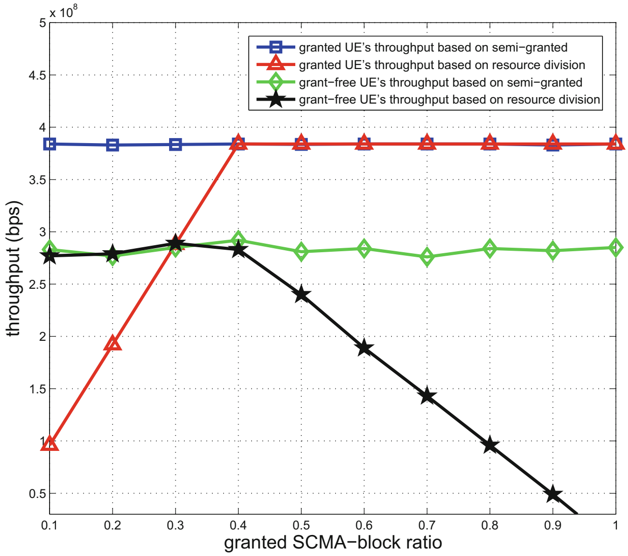


Fig. 5. Performance with granted SCMA block ratio changing.

Thus, we can obtain that semi-granted scheme matches the dynamically feature of user demands and achieve higher throughput and spectrum efficiency.

6 Conclusion

Sparse Code Multiple Access (SCMA) is a promising non-orthogonal multiple access technology for 5G radio access networks. Although SCMA improves the connectivity and capacity, there is still some intractable challenge to be addressed. Existing studies show that SCMA possesses two multiple access method: granted and grant-free, but these two methods can hardly match the real-time demands dynamically since the resources allocated for the two methods are clearly separated with each other. In this article, we propose a multiple access method for the SCMA named semi-granted SCMA, which enables the granted demands and grant-free demands to share the same resources. Simulation results confirm that semi-granted SCMA matches the dynamically fluent demands and significantly improve the throughput of SCMA 5G system.

Acknowledgment. This work was supported in part by the National Natural Science Foundations of CHINA (Grant No. 61271279, and No. 61501373), the National Science and Technology Major Project (Grant No. 2016ZX03001018-004), and the Fundamental Research Funds for the Central Universities (Grant No. 3102017ZY018).

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