Sparse Code Multiple Access for 5G Radio Transmission

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Sparse Code Multiple Access for 5G Radio Transmission

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***Abstract*—Non-orthogonal multiple access has been extensively discussed in New Radio (NR), the study item working on 5G air interface in 3GPP. Sparse code multiple access (SCMA) is one of the proposed MA schemes. In this paper, the basic concept of SCMA is introduced, including codebook mapping, multiple access procedure, and advanced receivers. Then, link-level simulations are applied to verify the design of SCMA, which show that SCMA has many excellent properties: shaping and diversity gain by sparse codebooks, resilient to inter-user interference, and robust to codebook collision, thus it is a promising candidate MA scheme for 5G.**

I. Introduction

New Radio (NR) is a newly approved study item in 3GPP [1], focusing on the design of next generation (5G) air interface. The 5G air interface is targeted to have higher transmission rates, faster access, support of larger user density, and better user experience. Meanwhile, it connects to new vertical industries and new devices, creating new application scenarios such as mMTC and URLLC services by supporting massive number of devices and enabling mission critical transmissions with ultra high reliability and ultra low latency requirement, respectively.

In NR, Non-orthogonal multiple access (NoMA) is one of the most popular topics, with 15 different NoMA schemes proposed [2]. Generally, NoMA can efficiently support higher capacity with greater flexibility and robustness, as well as adaptability towards large number of connections. These properties contribute towards a better user experience for variant kinds of services. Sparse code multiple access (SCMA) is one of the proposed schemes [3]. SCMA can be regarded as a code division multiple access scheme, which is characterized by sparse codebooks. The codebooks are built based on multi-dimensional constellations [4], and the shaping gain help it outperform the traditional spread code based schemes. In SCMA, multiple users will transmit on the same resource blocks with different codebooks. With sparse codebooks, the collision between users is reduced, thus SCMA is resilient to inter-user interference. The sparsity is also benefit for the receiver complexity, and message passing algorithm can be applied to achieve near optimal performance [5].

The rest of the paper is organized as follows. Section II introduces the basic concept of SCMA, including codebook mapping, multiple access procedure and advanced receivers. In Section III, the link-level simulation results with agreed parameters in NR are presented to verify the design of SCMA, and Section IV concludes the paper.

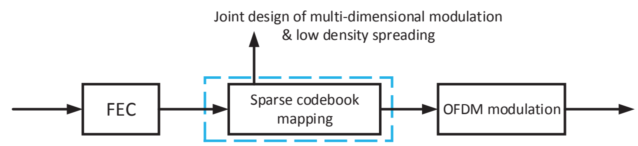


Fig. 1: Basic system model of SCMA.

II. Basic concept of SCMA

Figure 1 illustrates a basic system model of SCMA [6], where the coded bits of a data stream are directly mapped to a codeword from a codebook built based on a multi-dimensional constellation. As can be seen in Figure 1, the basic structure of SCMA implementation would be similar to LTE transmission model, with a key difference of joint design of modulation and spreading. SCMA utilizes low density spreading, which has been used in the LDS (low density signature) technique in CDMA and hereafter referred to as sparse spreading [7]. The model shown in Figure 1 can be used for both uplink and downlink. In this paper, we focus on the uplink.

A. Codebook mapping

SCMA would have layer mapping similar to LTE, i.e. one or multiple SCMA layers can be assigned to a user/data stream. A difference is at each SCMA layer, the SCMA would also do mapping from information bits to codewords, i.e. the SCMA modulator maps input bits to a complex multi-dimensional codeword selected from a layer-specific SCMA codebook. SCMA codewords are sparse, i.e. only few of their entries are non-zero and the rest are zero. All SCMA codewords corresponding to a SCMA layer have a unique location of non-zero entries, referred to as sparsity pattern for simplicity.

Figure 2 shows an example of a codebook set containing 6 codebooks for transmitting 6 data layers. As can be seen, each of the codebook has 8 multi-dimensional complex codewords that correspond to 8 points of constellation, respectively. The length of each codeword is 4, which is the same as the spreading length. Upon transmission, the codeword of each layer is selected based on the input bit sequence. In the downlink, as shown in Figure 2, the codewords from

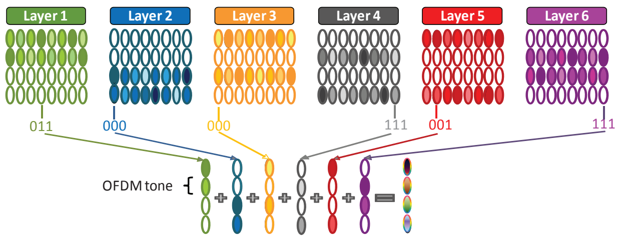


Fig. 2: SCMA codebook bit-to-codeword mapping.

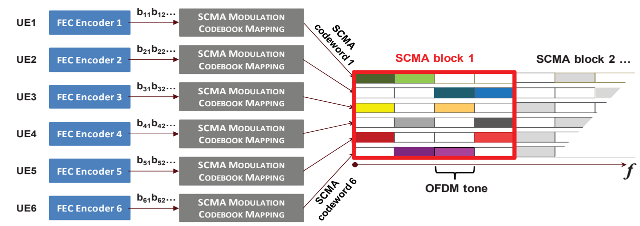


Fig. 4: Multiple Access with SCMA.

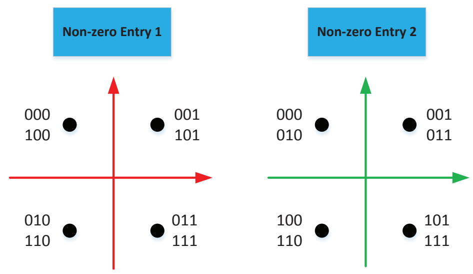


Fig. 3: Example of SCMA 8-point codebook.

different layers are combined before the OFDM modulator. In the uplink, for a single layer UE transmission, each SCMA codeword is first fed into the OFDM modulator resulting in multiple independent SCMA layers over the air transmissions from different users.

The design of SCMA codebook is based on joint optimization of the sparse spreading pattern design and the multi-dimensional modulation design [8]. In general, the aim of the codebook design is to provide good distance properties (Euclidean and/or Product) among the points in the overall multi-dimensional constellation to maximize the coding/shaping gain. Another feature of SCMA codebooks is the possibility of having lower number of projection points over each resource element. This is due to the multi-dimensional nature of the codebooks which allows two constellation points to collide over some of the non-zero components, as they can still be separated over the other non-zero components. An example is shown in Figure 3 below in which the constellation points corresponding to 100 and 000 collide over the first tone, but are separated over the second tone, making the number of projection points equal to 4 instead of 8.

B. Multiple access procedure

Figure 4 shows an example of multiple access of 6 users with the SCMA layer-specific codebooks illustrated in Figure 2. Each user is assigned with one SCMA codebook (in the example, user i takes codebook for layer i, $i = 1, 2, ..., 6$). After FEC encoder (e.g., LDPC encoder), each user's coded bits are then mapped to the SCMA codeword according to its assigned codebook. The SCMA codewords are further combined over OFDM tones and symbols are transmitted in terms of SCMA blocks, similar to resource block concept in LTE.

The main characteristics of multiple access with SCMA can be summarized as follow:

- *Code domain non-orthogonal signal superposition:* It allows superposition of multiple symbols from different users on each resource element (RE). For example, in Figure 4, on RE 1, symbols from UE1, 3, and 5 are overlapped with each other. The superposition pattern on each RE can be statically configured or semi-statically.
- *Sparse spreading:* SCMA uses sparse spreading to reduce the number of symbol collisions. For example, in Figure 4, there are 3 symbols from different UEs are colliding over each RE, instead of 6 (in the case of non-sparse spreading).
- *Multi-dimensional modulation:* SCMA uses multi-dimensional modulation instead of linear spreading as in CDMA. For example, in Figure 3, 4-D constellation is applied instead of 2-D QAM in normal.

Enabled by all these characteristics, SCMA can benefit 5G new radio transmission by high capacity, massive connectivity, low overhead and etc. For example, in Figure 4, 6 data layers can be supported by spreading length 4, resulting in an overloading factor of 150%. The sparseness in the code domain spreading further reduces inter-layer interference so that more symbol collisions can be tolerated with reasonable receiver complexity. In addition, multi-dimension modulation provides more energy-efficient transmission with further complexity reduction, by using SCMA codebooks with low number of projection points. This makes SCMA an important component for supporting low-latency and low-overhead grant-free transmissions for small and sporadic arriving packets.

C. Advanced Receivers

Different advanced receivers can be applied to SCMA, refer to [9] for details. Among all the candidates, the simplest is the SIC receiver (symbol-level or codeword-level) that decodes users/data layers one after another. It works well when the received SNR among users/data layers are quite different from each other. However, it suffers when the SNR difference is not obvious between users/data layers, in which case error propagation happens. Moreover, when there is correlation

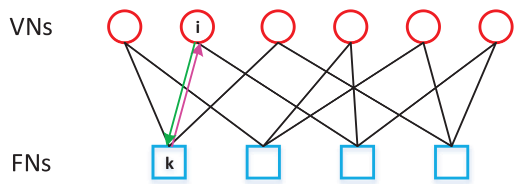


Fig. 5: Example of message passing between FNs and VNs.

between user channels, the performance of SIC receiver also degrades.

On the other extreme of the candidates is the full MPA receiver that jointly decodes all users/data layers. Thanks to the sparseness in the codebook design of SCMA, we can use MPA receiver to achieve close to joint ML detection performance, while the complexity of MPA receiver compared with the original ML receiver is greatly reduced. The MPA receiver can be represented by a factor graph. As shown in Figure 5, the variable nodes (VNs) represent the SCMA layers, the function nodes (FNs) represent the REs, and the complexity of MPA receiver is to the order of M^{d_f}, where M is the modulation order and d_f is the maximum degree of function node (FN). Moreover, it does not have constraint of SNR difference at the receiver, and is more robust to channel correlations between users, as compared with SIC receiver. However, the complexity of full MPA receiver is higher than pure SIC receiver.

To strike a good balance between link performance (close to ML detection and robust to channel imperfection) and implementation complexity (the complexity of the receiver), we could actually combine the features of SIC with MPA to have SIC-MPA receiver. More specifically, MPA is first applied to a limited number of layers, so that the number of colliding layers over each RE does not exceed a given threshold value d_f, which are referred to as MPA layers. Then, the successfully decoded MPA layers are removed by SIC and the procedure continues until all layers are successfully decoded or no new layer gets successfully decoded by MPA. Due to the fact that MPA is used for a very limited number of layers instead of all the layers, the decoding complexity is greatly reduced.

Expectation propagation algorithm (EPA) is another option of low complexity receiver besides SIC-MPA, which has linear complexity w.r.t. the modulation order as well as the maximum degree of FNs. EPA is an approximate Bayesian inference method in machine learning for estimating sophisticated posterior distributions with simple distributions through distribution projection [10]. Mathematically, the projection of a particular distribution p into some distribution set Φ is defined as

$$\mathrm{Proj}_{\Phi}(p) = \arg\min_{q\in\Phi} D(p||q), \qquad (1)$$

where $D(p||q)$ denotes the Kullback-Leibler (KL) divergence. To reduce the computational complexity, choosing the projection set Φ as the complex Gaussian distribution, the message passing then reduces to mean and variance parameter update. Simulation results show that the EPA receiver has nearly the same BLER performance as MPA receiver [11].

TABLE I: Complexity Comparison of Different Receivers

Receivers	Complexity Order
MMSE-SIC	O($S^3 N_{Rx}^3 N_{UE}$)
Full MPA	O($N_{Rx} N_{iter} \sum_{i=1}^{S} M_p^{d(i)}$)
SIC-MPA	O($S N_{Rx} N_{iter} M_p^{d'_f}$)
EPA	O($S N_{Rx} N_{iter} M_p d_f$)

The complexity analysis of different types of SCMA receiver is summarized in Table I, where S is the spreading length of a spreading block, N_{Rx} is the number of receive antennas, N_{iter} is the number of iterations, N_{UE} is the number of users/layers, M_p is the number of projection points on each RE with $M_p \leq M$, $d(i)$ is the degree of FN i, d'_f is the maximum degree of FNs of SIC-MPA.

III. Performance Evaluation

In this section, the link-level simulations results are presented, which show the performance of SCMA under typical scenarios, and compare it with other MA schemes.

A. Simulation Setting

TABLE II: Simulation Settings

Parameters	Value or assumptions
Carrier Frequency	2 GHz
Waveform	OFDM
Transmission Bandwidth	4 or 12 PRB
Target Spectrum Efficiency	[0.01, 0.5] bps/Hz per UE
Channel Coding	LTE Turbo
BS Antenna Configuration	2/4 Rx
UE Antenna Configuration	1 Tx
SNR distribution	Equal SNR
Number of UEs	4, 6, 8, 12
Propagation Channel	TDL-A(DS=30ns), or TDL-C(DS=300ns)
Number of HARQ	1

The evaluation parameters for the link-level simulation are listed in Table II. The BS antenna configuration can be 2 Rx or 4 Rx. The number of UEs can be 4, 6, 8, or 12, depend on the overloading scenario. To simplify the simulation, the long-term average SNR of UEs is assumed to be the same. The channel models can be TDL-A with DS=30ns, or TDL-C with DS=300ns, and the UE velocity is 3 km/h [12]. For ease of presentation, the triple (TDL-A, 30ns, 1T2R) means the system configuration that the channel model is TDL-A, the delay spread is 30ns, and the antenna configuration is 2Rx.

In the simulation, the total transmit bandwidth can be 4RB or 12RB. As we focus on scenarios with multiple UEs, the way of subcarrier allocation needs to be specified. For SCMA, each UE will occupy the whole bandwidth, i.e., all the subcarriers. For OFDMA, there are two ways of subcarrier allocation. One is localized subcarrier allocation, which means allocated subcarriers to each UE are continuous. The other is distributed subcarrier allocation, which means allocated subcarriers are distributed over the whole bandwidth.

In the simulation, different MA schemes are compared under the same target spectrum efficiency. The spectrum efficiency is defined as the total number of information bits over the total number of REs for data transmission. For different MA schemes, each UE may occupy different amount of bandwidth. Thus, the spectrum efficiency is defined by considering the total transmit bandwidth. In the simulation, the range of target transmit block size (TBS) per UE is bytes and the CRC bits are not included in the calculation of TBS.

B. Overloading Scenario

In this section, the performance of SCMA under different overloading scenarios is investigated. In the simulation, the total bandwidth is 12 RB, the target TBS is 54 bytes per UE, the antenna configuration can be 1T2R or 1T4R, and the channel models can be TDL-A with delay spread DS=30ns. To compare per UE performance under different scenarios, the SNR is defined as received signal power per UE over noise power. As shown in Figure 6, SCMA works well in the high overloading scenario, and the link-level performance can approach the single user bound even for when the overloading factor is 300%. If compare the performance of 12 UE with that of 4 UE at BLER=0.1, the performance loss is less than 0.5 dB under 1T2R, and less than 0.1 dB under 1T4R. The performance loss is less than 0.1 dB at BLER=0.01 for all the cases.

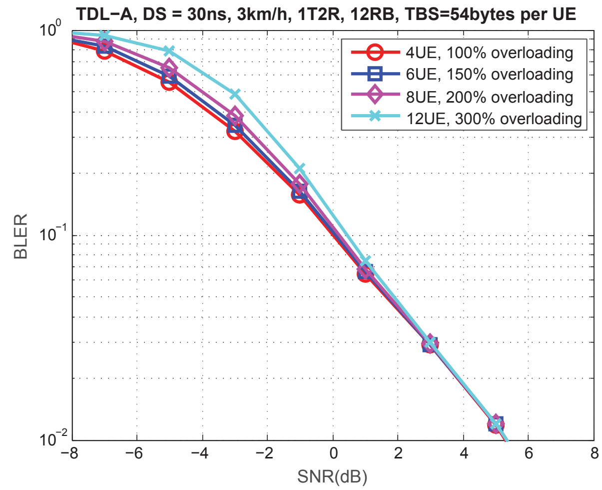
When the supported number of UEs increases, the inter-UE interference will increase due to the non-orthogonal user multiplexing. The codebook design of SCMA makes it feasible for efficient interference cancellation even in the high overloading scenario, thus the performance of SCMA can approach to the single user bound and is stable to different overloading scenarios. When there are more receiver antennas, the capability of interference cancellation will be higher and the performance is closer to the single user bound.

C. Codebook Collision

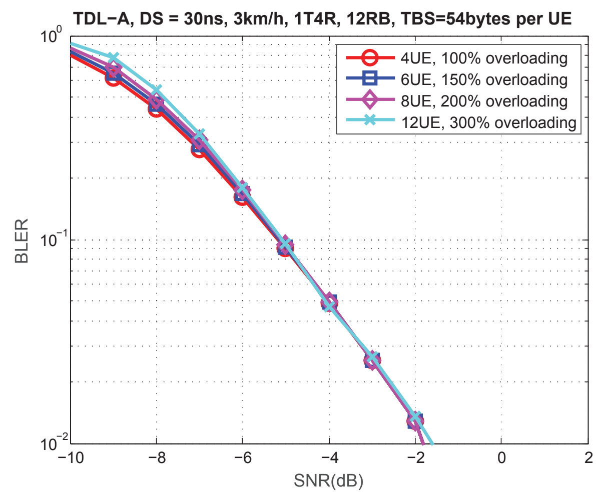
In grant-free scenarios, UEs may choose the SCMA codebooks on their own. When there are multiple active UEs, codebook collision may happen, i.e., multiple UEs transmit with the same codebook. Assume there are 6 active UEs. When there is no collision between the UEs and the signature matrix of codebooks is given by

$$\mathbf{M}_{6,4} = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix} \tag{2}$$

If the UEs choose the codebook on their own, collision may happen. For example, UE1 and UE2 choose the first codebook, UE3 and UE4 choose the third codebook, UE5 and UE6 choose the fifth codebook, then the signature matrix is given by



(a) 1T2R, TDL-A, DS=30ns

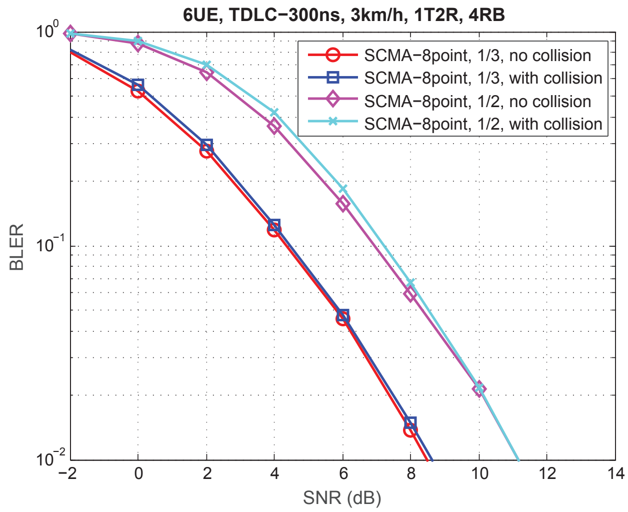


(b) 1T4R, TDL-A, DS=30ns

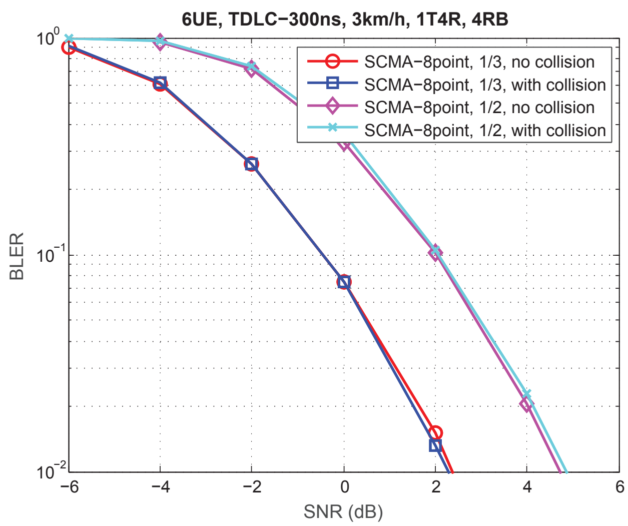
Fig. 6: BLER curves of SCMA under different overloading scenarios.

$$\mathbf{M}^{c}_{6,4} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{3}$$

In the simulation, the total bandwidth is 12 RB, the number of active UEs is fixed to be 6, and the target TBS is 54 bytes or 81 bytes per UE. For SCMA with codebook collision, the UEs are assumed to randomly choose the codebook. For SCMA without codebook collision, the UEs are allocated with different codebooks. As shown in the Figure 7, the performance loss due to codebook collision is less than 0.2 dB for all the cases. This means with the codebook design and MPA-type receiver, SCMA is robust to codebook collision, thus enables grant-free transmission.

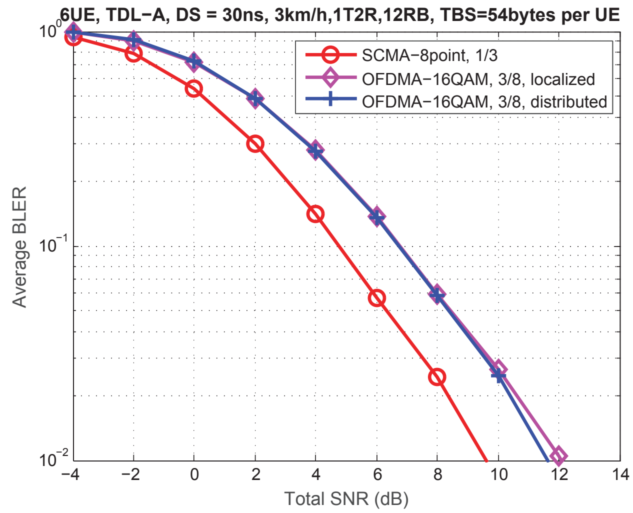


(a) 1T2R, TDL-C, DS=300ns

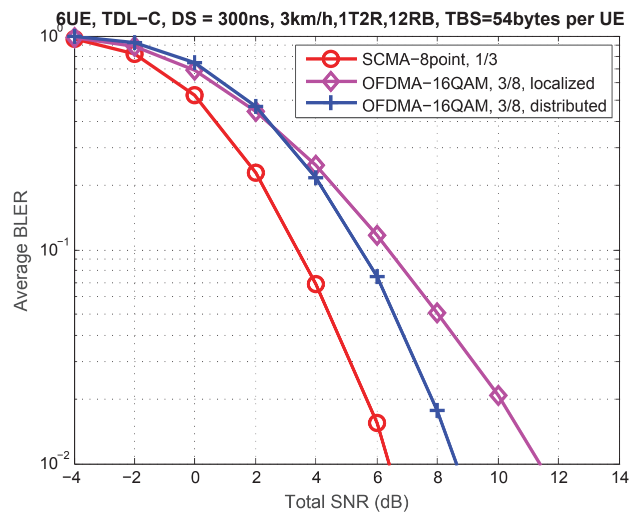


(b) 1T4R, TDL-C, DS=300ns

Fig. 7: BLER curves with and without collision.



(a) 1T2R, TDL-A, DS=30ns



(b) 1T2R, TDL-C, DS=300ns

Fig. 8: BLER curves of SCMA and OFDMA.

D. MA Schemes Comparison

In this paper, different uplink non-orthogonal MA schemes (including SCMA) are compared with the baseline orthogonal scheme of OFDMA with distributed subcarrier allocation. In the simulation, the MMSE receiver is applied for OFDMA. Except for SCMA and OFDMA, the other non-orthogonal MA schemes evaluated are:

- Low Density Spreading OFDMA (LDS-OFDMA), with the same 6-by-4 sparse signature matrix as SCMA. In the simulation, the SIC-MPA receiver introduced is applied for LDS-OFDMA.
- Multicarrier CDMA (MC-CDMA) with complex spreading sequences. Many MA schemes proposed for NR can be regarded as MC-CDMA, e.g. [13] [14] [15]. In this paper, the spreading sequences of MC-CDMA are generated as in [13], which means the real and imaginary parts of the complex elements in the spreading sequence are drawn from -1, 0, 1 with uniform distribution. The MMSE-SIC receiver is applied for MC-CDMA.

With the above assumption, the BLER curves of SCMA and OFDMA are shown in Figure 8. In Figure 8(a), when the channel model is TDL-A with DS=30ns and the antenna configuration is 1T2R, SCMA is 1.9 dB better than OFDMA with either localized or distributed subcarrier allocation. In Figure 8(b), when the channel model is TDL-C with DS=300ns and the antenna configuration is 1T2R, SCMA is 2.0 dB better than OFDMA with distributed subcarrier allocation, and 2.9 dB better than OFDMA with localized subcarrier allocation. For both channel models, SCMA is around 2.0 dB better than OFDMA with distributed subcarrier allocation, which is due to the codebook design and non-orthogonal user multiplexing.

When the configuration is (TDL-A, 30ns, 1T2R), the curves of sum throughput are presented in Figure 9. Figure 9(a) to Figure 9(c) show the results under 4, 6, and 8 UEs, respectively. When per UE spectral efficiency is less than 0.05 bps/Hz, all the MA schemes perform close to each other. In this case, the system is power-limited, and the power efficiency of different MA schemes is the same. When per UE spectral efficiency is higher than 0.05 bps/Hz and the number of UEs is larger than 4, the non-orthogonal MA schemes SCMA, LDS-OFDMA and MC-CDMA have higher throughput than the orthogonal MA scheme OFDMA. This is because the non-orthogonal MA schemes have larger transmit bandwidth than orthogonal MA scheme, thus the bandwidth efficiency is higher. The results also show that among the non-orthogonal MA schemes, SCMA is better than LDS-OFDMA and MC-CDMA.

IV. Conclusion

This paper presented basic concept of SCMA, including the codebook mapping with multi-dimensional modulation, multiple access procedure to support overloading scenario, advanced receivers with low complexity and good performance. Then, link-level simulation was applied to evaluate the performance of SCMA under high overloading and codebook collision scenarios. The results showed that SCMA is resilient to inter-user interference, and robust to codebook collision. Furthermore, SCMA is also better than OFDMA and the other proposed non-orthogonal MA schemes in terms of BLER or sum throughput, which makes it a promising candidate MA scheme for 5G.

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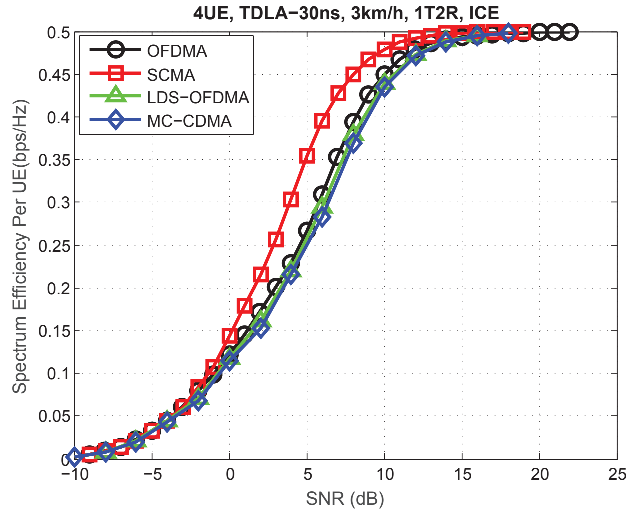
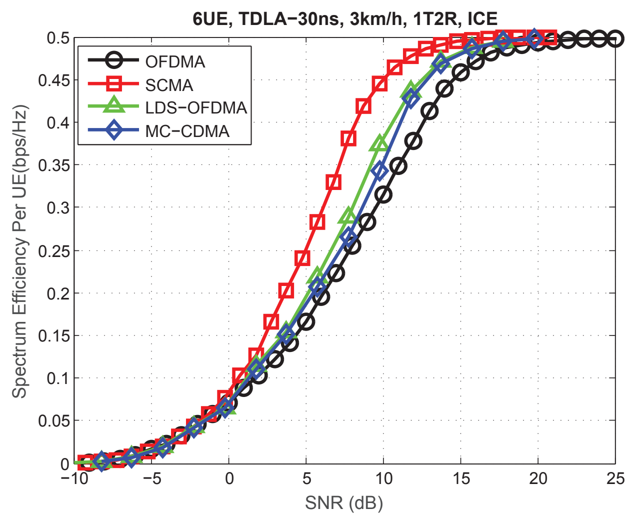
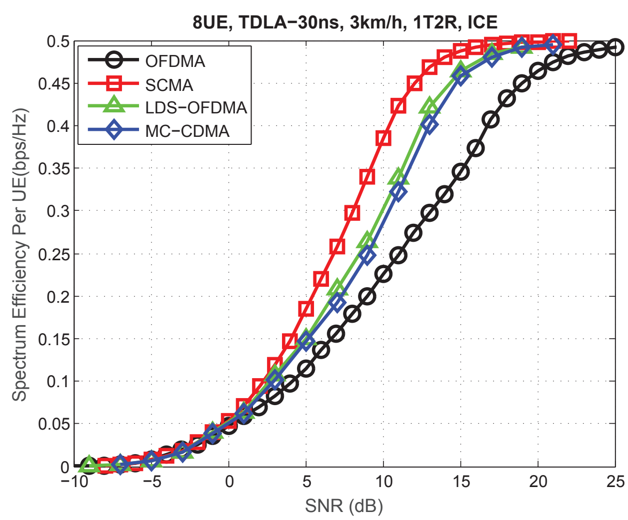


(a) 4UE, 1T2R, TDL-A, DS=30ns



(b) 6UE, 1T2R, TDL-A, DS=30ns



(c) 8UE, 1T2R, TDL-A, DS=30ns

Fig. 9: Normalized sum throughput of MA schemes.