CHAPTER III

NON ORTHOGONAL MULTIPLE ACCESS

Multiple Access (MA) is a basic function in wireless cellular systems. MA techniques can be classified into orthogonal and non-orthogonal approaches. In orthogonal approaches, signals from different users are orthogonal to each other, i.e., their cross correlation is zero, which can be achieved by time division multiple access (TDMA), frequency division multiple access (FDMA) and orthogonal-frequency division multiple-access (OFDMA). Non-orthogonal schemes allow non-zero cross correlation among the signals from different users, such as in random waveform code division multiple access (CDMA) [34], trellis-coded multiple-access (TCMA) [35] and interleave-division multiple-access (IDMA) [36].

First and second generation cellular systems are dominated by orthogonal MA approaches. The main advantage of these approaches is the avoidance of intra-cell interference. However, careful cell planning is necessary in these systems to curtail cross-cell interference. In particular, sufficient distance must exist between re-used channels, resulting in reduced cellular spectral efficiency.

Non-orthogonal CDMA techniques have been adopted in second and third generation cellular systems i.e., CDMA2000. Compared with its orthogonal counterparts, CDMA is more robust against fading and cross-cell interference, but is prone to intracell interference. Due to its spread-spectrum nature, CDMA is inconvenient for data services (e.g., wireless local area networks (WLANs) and high speed uplink/downlink packet access (HSUPA/HSDPA)) that require high single-user rates.

In the 4th generation (4G) mobile communication systems such as LTE and LTE-Advanced adopt orthogonal multiple access based on orthogonal frequency multiple access (OFDMA) in the downlink and signal carrier SC-FDMA in the uplink. It is a reasonable choice for achieving good system-level throughput performance to orthogonal access in packet-domain services. However, considering the future radio access in the 2020s, further enhancement to achieve significant system throughput and user fairness has become one of the key issues in handling this explosive data traffic increase in 5th generation (5G) mobile communication systems and need for enhanced delay-sensitive high-volume services, overview of key radio access technology parameters are given in table 3.1 [37], [38].

To accommodate such requirements, non-orthogonal access can again be a promising candidate as a downlink wireless access scheme for systems beyond those mentioned above. To make non-orthogonal access promising, it should be used with advanced transmission/ reception techniques such as dirty paper coding (DPC) or using a successive interference canceller (SIC) [39], which is different from the 3rd generation mobile communication system.

An attractive feature of non-orthogonal access with advanced transmission/reception techniques is to improve the tradeoff between the total user throughput and user fairness with regard to the achievable user throughput of the respective user. This is because all users can use the overall transmission bandwidth irrespective of the channel conditions in non-orthogonal access, while orthogonal access must restrict the bandwidth assignment to the users under poor channel conditions in order to achieve a sufficiently high total user throughput.

Non Orthogonal Multiple Access (NOMA) with successive interference cancellation (SIC) is considered to be a promising technology that could improve the sum throughput. Because the communication resources (time and frequency) in a NOMA system are shared by all the users, the sum throughput can be enhanced over what is possible, compared with orthogonal multiple access.

Table 3.1 Overview of key radio access technology parameters [38]

Method	2G	3G	4G	5G
Specification	GSM release 7	HSPA+ release 8	LTE release 11	Beyond rel.12
Duplex	FDD, HD	FDD, FD (some TDD exist)	FDD, FD (some TDD exist)	TDD (need synchronization)
Multiple access	TDMA/FDMA	CDMA	OFDMA	OFDMA
Bandwidth	200 kHz	5 MHz	1.4-20 MHz	10-200 MHz
Frame/subframe	4.615 ms	10 ms / 2 ms	10 ms / 1 ms	0.25 ms
Equalizer	Time	Time	Frequency	Frequency
Frequency reuse	3 (varying)	1	1	1
DL/ UL modulation	GMSK, 8PSK, 16QAM, 32QAM	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM	Like LTE

3.1 NOMA CONCEPT

In FRA, we expect that non-orthogonal user multiplexing (NOMA) can be a promising candidate as a multiple access scheme according to the following motivations [40]:

- Evolution of device processing capabilities

To make NOMA promising, it should be used with advanced transmission/reception techniques such as dirty paper coding (DPC) or a SIC receiver, which is different from the CDMA in 3G systems. The fact that NOMA requires a SIC receiver may be a drawback in terms of receiver complexity. This is because the SIC receiver requires demodulation and decoding for other sets of user equipment (UEs) in addition to those for its own UE, which may increase the processing delay. Thus, the feasibility of the NOMA will highly depend on the evolution of device processing capabilities expected in the 2020s.

- Utilization of additional domain for user multiplexing

For FRA, good properties of 3.9/4G, i.e., LTE/LTE-Advanced, should be maintained as much as possible such as robustness against multipath interference, good affinity to MIMO technologies, and supportability for one-cell frequency reuse. Thus, we assume that the basic signal waveform for NOMA could be based on OFDM or DFT spread OFDM as well as LTE radio access. However, different from the current LTE radio access scheme (until Release 11), NOMA superposes multiple users in the power domain (forming a superposition coding) so that its user separation is achieved through SIC and capacity-achieving channel codes such as the Turbo code and low-density parity check (LDPC) code. In this sense, NOMA is a scheme that utilizes an additional new domain, i.e., the power domain, which is not sufficiently utilized in 3.9/4G systems.

In fact, user demultiplexing is ensured via the allocation of large power difference between paired UEs and the application of SIC in power domain. The UE with high channel gain is allocated less power and the UE with low channel gain is allocated more power. Such large power difference facilitates the successful decoding (with high probability) and thus the successful cancellation of the signal designated to UE (being allocated high power) at another UE [40].

- Robust performance gain in practical wide area deployments

In LTE/LTE-Advanced, many technologies are adopted to enhance the system performance. Among them, there are some basic technologies such as OFDM, hybrid automatic repeat request (HARQ), Turbo coding, and open-loop MIMO, which can provide a robust performance gain irrespective of the UE mobility or feedback/processing latency. In other words, these basic technologies do not rely so much on the transmitter knowledge of instantaneous frequency-selective fading channels such as the frequency selective channel quality indicator (CQI) or channel state information (CSI) that require fine feedback signaling from the UE. In practical cellular deployments, often UE feedback signaling cannot follow the variation in frequency-selective instantaneous fading due to mobility, feedback/processing latency, limited implementation capability of the base station (BS) scheduler, uplink coverage limitation for UE feedback, and so on. This becomes more challenging in higher/wider frequency bands. In this sense, it is preferable for NOMA to take a receiver cancellation approach and to specify the basic cancellation mechanism so that NOMA with a SIC receiver can be a basic technology that provides a robust performance gain in practical wide area deployments.

3.2 NOMA TRANSMITTER

The basic concept of NOMA downlink as the eNB select two users with different channel gain and send two signals to each users but in different power allocation on the same bandwidth. Figure 3.1 illustrate NOMA transmitter side where total power for any multiplexed two users is the same. User whose channel gain is better condition than the another user is allocated less power, so power allocated to each user and selecting two pair users affect not only to user throughput but also other user due to inter-user interference.

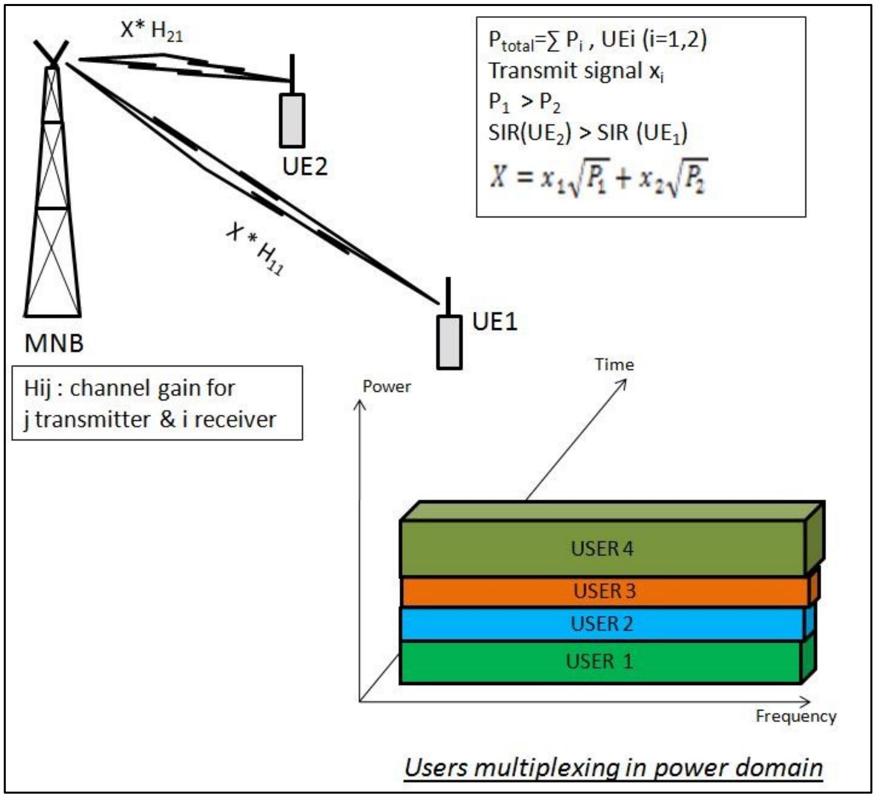

Figure 3.1 Illustration of NOMA transmission side

In NOMA, x_1, x_2 are superposition coded as

$$x = \sqrt{P_1}x_1 + \sqrt{P_2}x_2 \tag{3.1}$$

The received signal at UE_i is represented as:

$$y_i = h_i x + w_i \tag{3.2}$$

Where h_i is complex channel coefficient between UE_i and the base station. Term w_i denotes the receiver Gaussian noise including inter cell interference. The power density of w_i is $N_{0,i}$.

3.3 NOMA RECEIVER

In downlink NOMA, the SIC process is implemented at the UE receiver. The optimal order for decoding is in the order of decreasing channel gain normalized by noise and inter-cell interference power,$|h_i|^2/N_{0,i}$ (called simply channel gain). Based on this order, we assume that any user can correctly decode the signals of other users whose decoding order comes before the corresponding user. Thus, UE_i can remove the inter-user interference from the j^{th} user whose $|h_j|^2/N_{0,j}$ is lower than $|h_i|^2/N_{0,i}$. In a two users case, assuming that $|h_2|^2/N_{0,2} > |h_1|^2/N_{0,1}$, Using superposition coding scheme [41], [42]; user 1 treats signal of user 2 as noise and decodes its data from y_1. User 2 first decodes x_1 (treats its data as interference) and subtracts its component from received signal y_2, and then next, it decodes x_2 without interference from x_1[43].

Assuming successful decoding and no error propagation, the following throughput of two users as [43]:

$$R_1 = \log_2(1 + \frac{P_1|h_1|^2}{P_2|h_1|^2 + N_{0,1}}) \quad (3.3)$$

$$R_2 = \log_2(1 + \frac{P_2|h_2|^2}{N_{0,2}}) \quad (3.4)$$

Where P_1 and P_2 are transmitted power for users i=1,2, h_1 and h_2 are channel gain for two users, N is power of additive white Gaussian noise, R_1 and R_2 are throughput for two users. Figure 3.2 illustrates the structure of Successive Interference Cancellation (SIC) receiver for the case of 2 UEs [44].

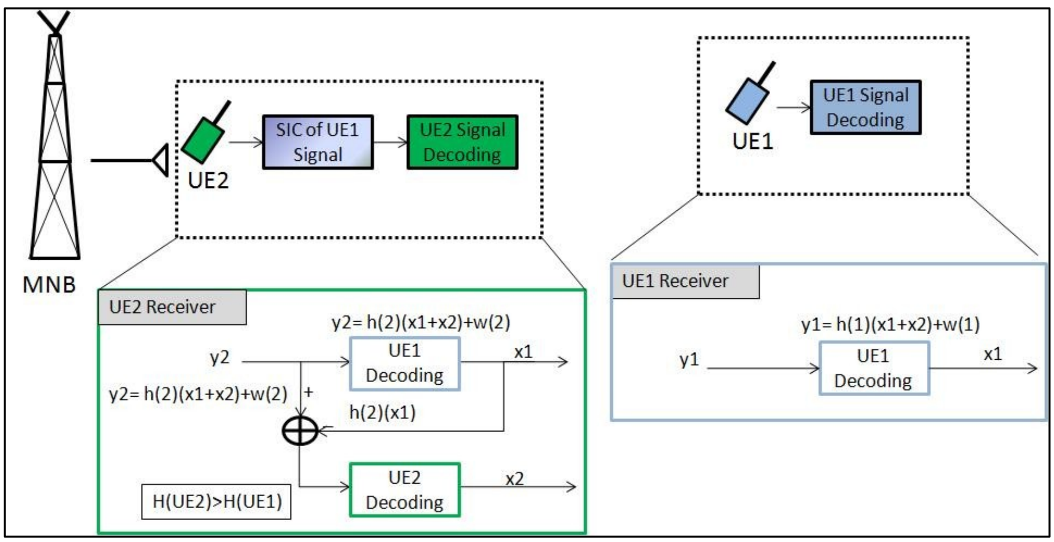

Figure 3.2 Structure of SIC receiver (case of 2-UE) [44]

3.4 COMPARISON WITH OMA

For simplicity, we assume in this section the case of single transmit and receive antennas. The overall system transmission bandwidth is assumed to be 1 Hz. For OMA as orthogonal user multiplexing, the bandwidth of α (0 < α < 1) Hz is assigned to UE 1 and the remaining bandwidth, (1−α) Hz, is assigned to UE 2. The throughput of UE_i, R_i, is represented as [43]:

$$R_1 = \alpha \log_2(1 + \frac{P_1|h_1|^2}{\alpha N_{0,1}}) \quad (3.5)$$

$$R_2 = (1-\alpha)\log_2(1 + \frac{P_2|h_2|^2}{(1-\alpha) N_{0,2}}) \quad (3.6)$$

In NOMA, the performance gain compared to OMA increases when the difference in channel gains, e.g., path loss between UEs, is large. For example, as shown in figure 3.3, we assume a 2-UE case where $|h_1|^2/N_{0,1}$ and $|h_2|^2/N_{0,2}$ are set to 0 and 20 dB, respectively. For OMA with equal bandwidth and equal transmission power are allocated to each UE (α = 0.5, P1 = P2= 1/2P), the user rates are calculated according to (3.5, 3.6) as R1 = 0.5 and R2 = 3.33 bps/Hz, respectively. On the other hand, in NOMA, when the power allocation is conducted as P1 = 1/5P and P2 = 4/5P, the user rates are calculated according to (3.3, 3.4) as R1 = 0.74 and R2 = 4.39 bps/Hz, respectively. The corresponding gains of NOMA over OMA are 48% and 32% for UE 1 and UE 2, respectively. According to the above simple example of 2-UE, NOMA provides higher sum rate than OMA. As later shown in the simulation results, this can indeed be generalized to the case of multiple users with sophisticated multiuser proportional fairness scheduling being used [43].

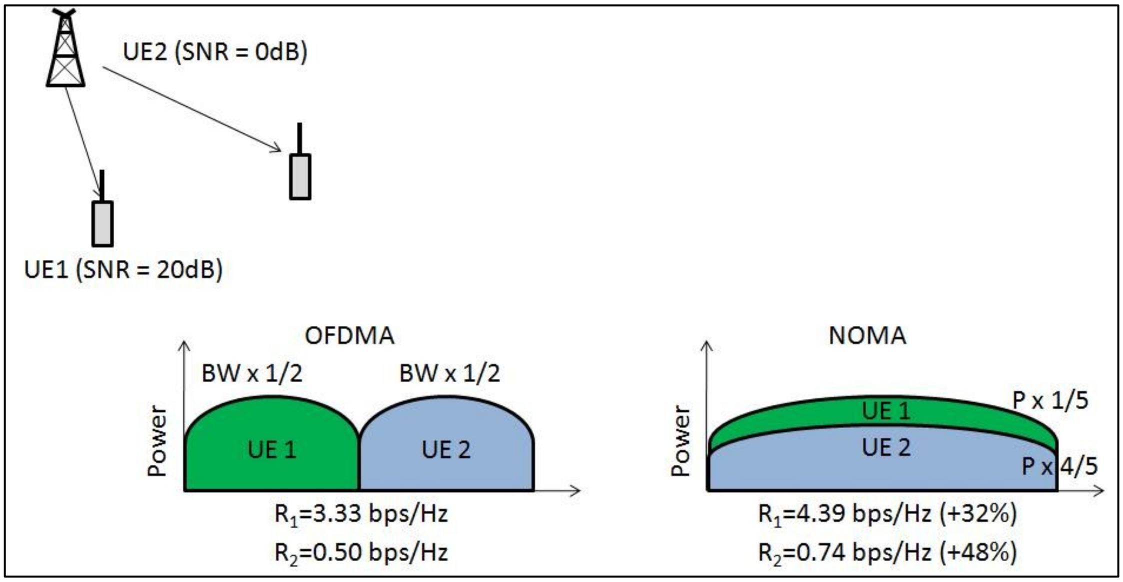

Figure 3.3 Simple comparison example of NOMA and OMA [43]

3.5 IMPERFECT SUCCESIVE INTERFERNCE CANCELLATION

In fact not all interference power is removed under cancellation; the parameter ε → [0, 1] gives the residual power of user after cancellation [45]. In the presence of imperfect interference cancellation, the equation (3.3) will be updated and the user throughput using NOMA after considering imperfect interference cancellation will be:

$$R_1 = \log_2\left(1 + \frac{P_1|h_1|^2}{\varepsilon P_2|h_1|^2 + N_{0,1}}\right) \tag{3.7}$$

$$R_2 = \log_2\left(1 + \frac{P_2|h_2|^2}{N_{0,2}}\right) \tag{3.8}$$

Where ε is imperfect interference cancellation, ε =0 for perfect interference cancellation.

3.6 TRANSMIT POWER ALLOCATION

Due to power domain multi user multiplexing, the transmit power allocation (TPA) is important consideration in NOMA downlink; it affects the achievable throughput of not only that user but also other users due to inter-user interference. The best performance of NOMA can be achieved by exhaustive full search of user pairs and transmit power allocations. In case of full search power allocation (FSPA), all possible combinations of power allocations are considered for each candidate user set. FSPA remains computationally complex. Also, with dynamic TPA, the signaling overhead associated with SIC decoding order and power assignment ratios increases. In NOMA, users with the largest channel gain difference (e.g., the largest path-loss difference) are paired with high probability [40].

3.7 RESULTS OF PREVIOUS WORK ON NOMA

This section presents some results of previous work on NOMA. A Non Orthogonal Multiple Access (NOMA) for future radio access (FRA) is presented in [40]. Different from current LTE radio access scheme, NOMA superposes multiple users in the power domain although its basic signal waveform could be based on the orthogonal frequency division multiple access (OFDMA) or the discrete Fourier transform (DFT)-spread OFDM as well as the LTE baseline. NOMA adopts a SIC receiver as a baseline receiver scheme for robust multiple access, with the expected evolution of device processing capabilities in the future. Figure 3.5 shows the CDF of the user throughput for OFDMA and NOMA with SIC. The figure shows that the user throughput performance of NOMA is improved compared to that of OFDMA.

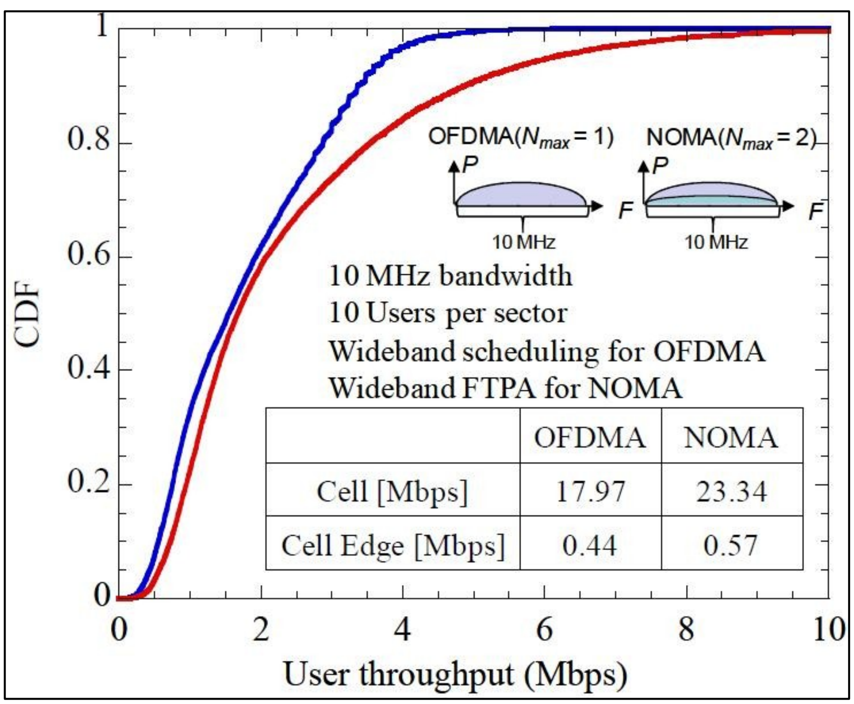

Figure 3.4 System level evaluation of OFDMA and NOMA [40]

In [40-41], Authors proposed NOMA/ MIMO scheme in the downlink. In this scheme, the BS transmitter generates multiple beams like a multiuser – MIMO, and superposes multiple UEs within each beam. In the UE receiver side, two interference cancellation approaches, i.e., SIC and Interference Rejection Combining (IRC) [46], are jointly used as follows.

- ✓ SIC is used for intra-beam user multiplexing, i.e., interference cancellation among the UEs belonging to a group applying the same precoding weights. The multiple access scheme within the group is basically the same as basic NOMA with SIC.
- ✓ IRC is used for inter-beam user multiplexing, i.e., interference suppression among the UE groups applying different precoding weights.

Figure 3.5 shows on form of combining downlink NOMA with MIMO using random beamforming

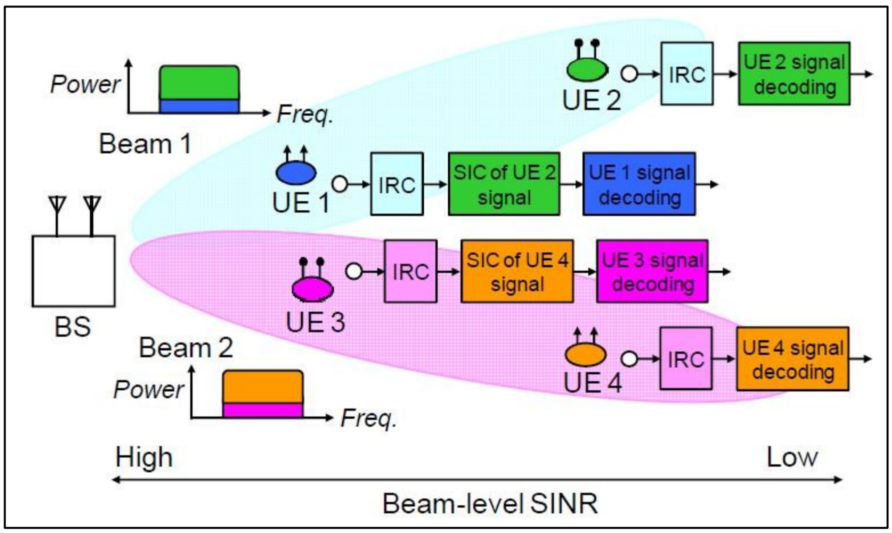

Figure 3.5 NOMA/MIMO scheme applying with IRC-SIC receivers [47]

Figure 3.6 shows the total user rate, R_{sum}, as a function of the number of UEs per cell, obtained via the system-level simulations for the proposed NOMA/MIMO scheme using random beamforming at the BS transmitter side and IRC-SIC receiver at the UE side in the downlink.

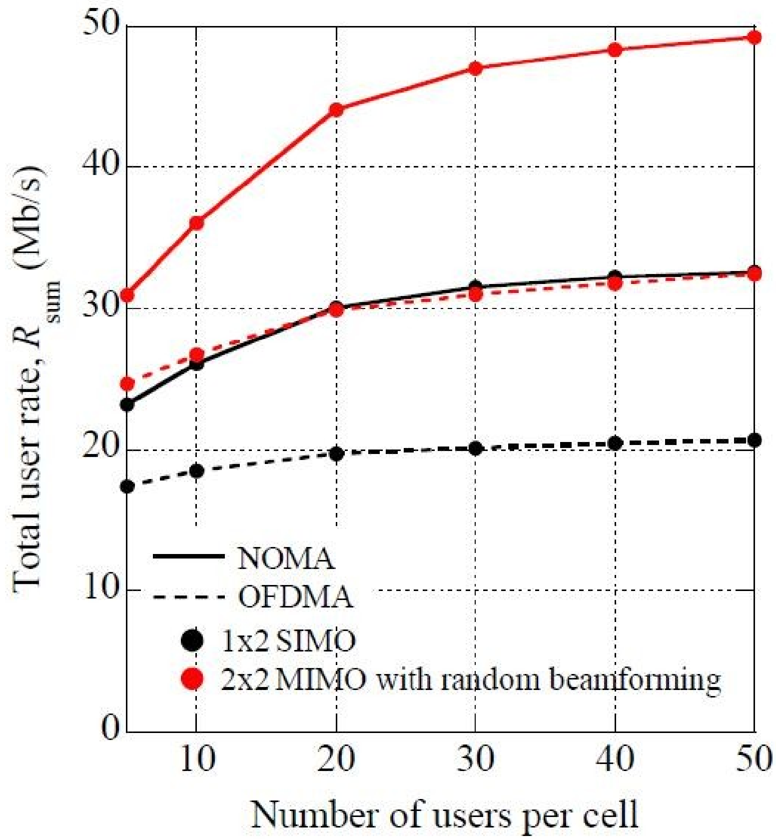

Figure 3.6 System level evaluation for NOMA/MIMO scheme [43]

Figure 3.7 shows the shows the cumulative distributions of the user throughput. The N_{max} values of one, two, and four are shown. The values of M and B are number of antennas and beams, respectively. Term U is number of users per cell. This figure clearly shows that non-orthogonal access with a SIC (thus $N_{max} > 1$) achieves better throughput than orthogonal access for the entire region of the cumulative distribution. This is because the user throughput of the orthogonal access is severely limited by the orthogonal bandwidth allocation, which reduces the bandwidth for the respective users. Non-orthogonal access with a SIC allows for wider bandwidth usage of all users irrespective of the channel conditions. Allocating high power to the power-limited cell-edge users associated with the SIC process, which is applied to the bandwidth-limited cell-interior users, enhances the throughput of the users under a wide range of channel conditions. The impact of the transmission bandwidth limitation on orthogonal access is especially clear in the high cumulative distribution probability region, where the users are under bandwidth-limited conditions. The gain by further increasing N_{max} from two to four is relatively small. This indicates that it is sufficient to multiplex non-orthogonally a moderate number of users to obtain the most from the potential gain using non-orthogonal access with a SIC. It should be noted that the overhead required for the transmission of a downlink reference signal for the proposed non-orthogonal access using intra-beam superposition coding and a SIC is the same as that for the orthogonal access irrespective of the N_{max} value. In the following, the user throughput value at the cumulative probability of 5% is denoted as the cell-edge user throughput [5, 48].

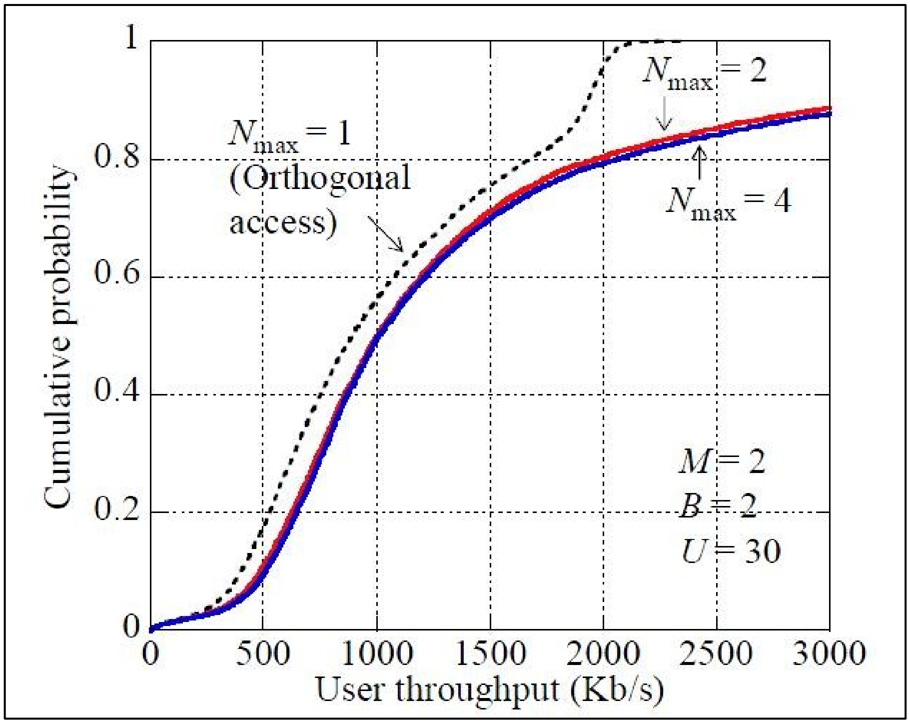

Figure 3.7 Cumulative distribution of user throughput [47]

Authors in [44] extend previously proposed non orthogonal multiple access (NOMA) scheme to the base station (BS) cooperative multiple-input multiple-output (MIMO) cellular downlink for future radio access. The proposed NOMA scheme employs intra-beam superposition coding of a multiuser signal at the transmitter and the spatial filtering of inter-beam interference followed by the intra-beam successive interference canceller (SIC) at the user terminal receiver. The intra-beam SIC cancels out the inter-user interference within a beam. This configuration achieves reduced overhead for the downlink reference signaling for channel estimation at the user terminal in the case of non-orthogonal user multiplexing and also achieves the applicability of the SIC receiver in MIMO downlink. The transmitter beamforming (precoding) matrix is controlled based on open loop-type random beamforming using a block-diagonalized beamforming matrix, which is very efficient in terms of the amount of feedback information from the user terminal. Simulation results in this paper show that the proposed NOMA scheme with block-diagonalized random beamforming in BS cooperative multiuser MIMO and the intra-beam SIC achieves better system-level throughput compared to orthogonal multiple access (OMA), which is assumed in LTE-Advanced. We also show that BS cooperative operation along with the proposed NOMA in particular achieves a high cell-edge user throughput gain which implies better user fairness and universal connectivity.

Figures 3.8 and 3.9 show the sum user throughput per cell and cell edge user throughput as a function of the number of users per cell, U, respectively. Also they tested the cases of N_{max} of one and two. From figure 4, NOMA using N_{max} =2 significantly increases the sum user throughput per cell compared to OMA for wide range of U.

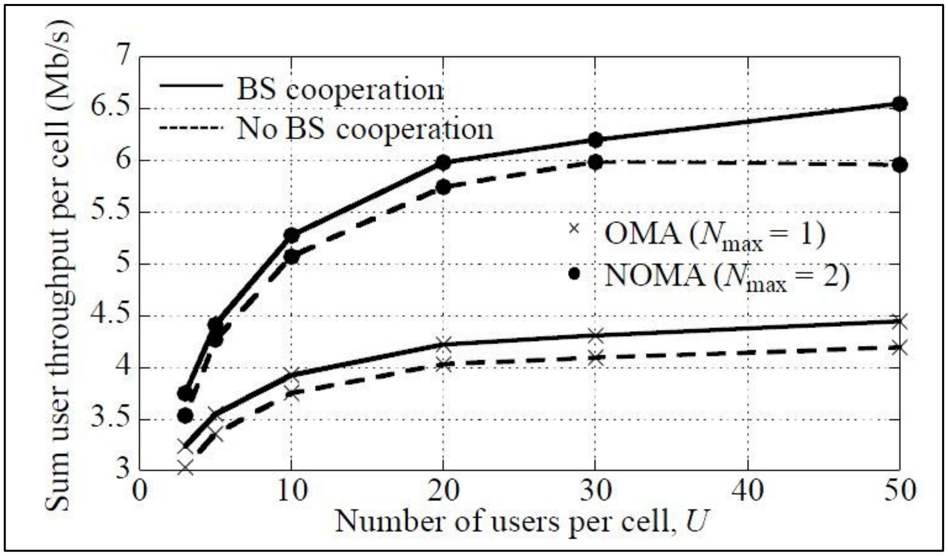

Figure 3.8 Sum user throughput per cell as a function of U [44]

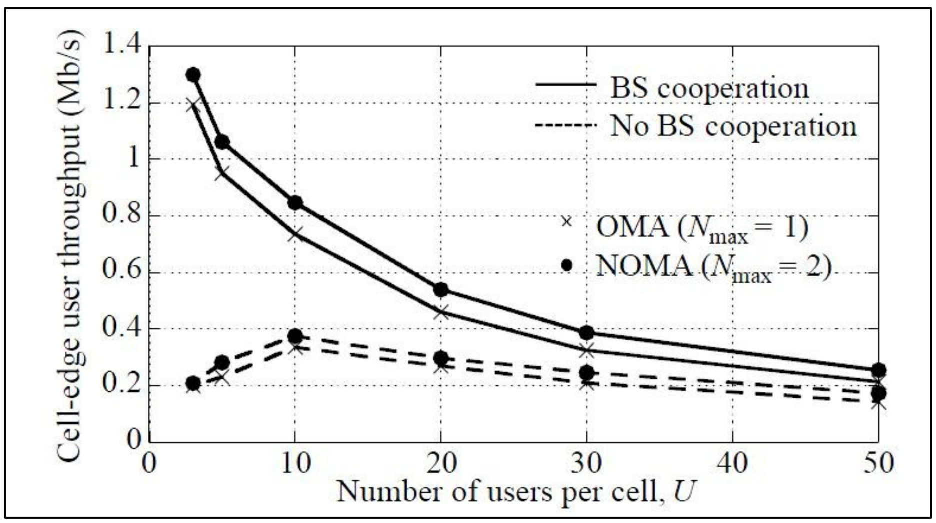

Figure 3.9 Cell edge user throughput per cell as a function of U [44]

Figure 3.10 shows the user throughput gain when using the proposed NOMA under various conditions regarding BS cooperation for the respective user coverage positions (0 indicates the cell edge and 1 indicates the vicinity of the BS). The number of users per cell, U, is set to 30. The throughput gain is always higher than one. This means that the proposed NOMA improves the system performance regardless of the user position. We see that the cell-edge user throughput gain is especially significant, which means improvement in the user fairness.

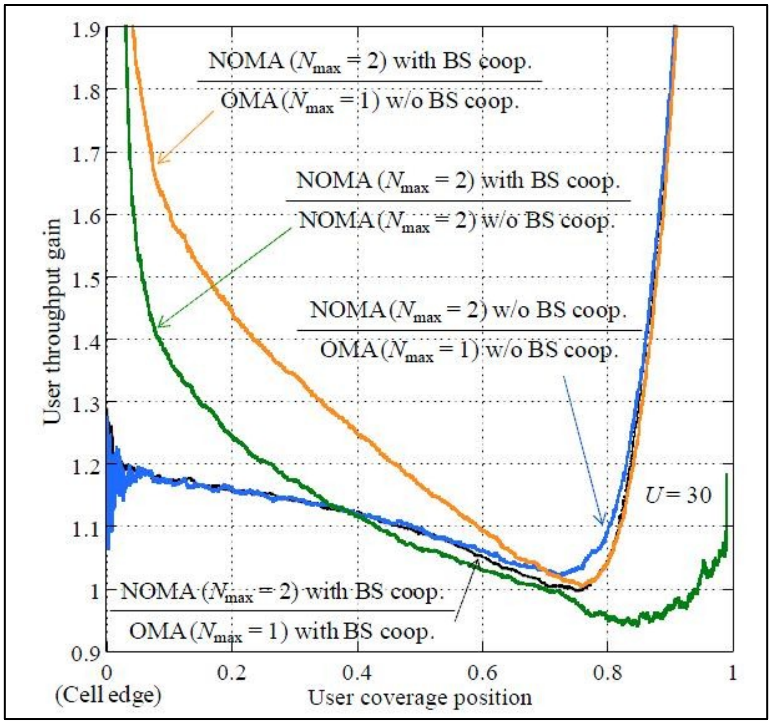

Figure 3.10 User throughput gain [44]