Concept and Practical Considerations of Non-orthogonal Multiple Access (NOMA) for Future Radio Access

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***Abstract*— As a promising downlink multiple access scheme for future radio access (FRA), this paper discusses the concept and practical considerations of non-orthogonal multiple access (NOMA) with a successive interference canceller (SIC) at the receiver side. The goal is to clarify the benefits of NOMA over orthogonal multiple access (OMA) such as OFDMA adopted by Long-Term Evolution (LTE). Practical considerations of NOMA, such as multi-user power allocation, signalling overhead, SIC error propagation, performance in high mobility scenarios, and combination with multiple input multiple output (MIMO) are discussed. Using computer simulations, we provide system-level performance of NOMA taking into account practical aspects of the cellular system and some of the key parameters and functionalities of the LTE radio interface such as adaptive modulation and coding (AMC) and frequency-domain scheduling. We show under multiple configurations that the system-level performance achieved by NOMA is higher by more than 30% compared to OMA.**

Keywords* – *non-orthogonal multiple access, future radio access, power-domain, successive interference canceller

I. INTRODUCTION

In order to continue to ensure the sustainability of mobile communication services over the coming decade, new technology solutions that can respond to future challenges must be identified and developed [1]. For future radio access (FRA) in the 2020s-era, significant gains in capacity and quality of user experience (QoE) are required in view of the anticipated exponential increase in the volume of mobile traffic, e.g., beyond a 500 fold increase in the next decade. In cellular mobile communications, the design of radio access technology (RAT) is one important aspect in improving system capacity in a cost-effective manner. Radio access technologies are typically characterized by multiple access schemes, e.g., frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and OFDMA, which provide the means for multiple users to access and share the system resources simultaneously. In the 3.9 and 4th generation (4G) mobile communication systems such as Long-Term Evolution (LTE) [2] and LTE-Advanced [3], standardized by the 3rd Generation Partnership Project (3GPP), orthogonal multiple access (OMA) based on OFDMA or single carrier (SC)-FDMA is adopted. Orthogonal multiple access is a reasonable choice for achieving good system-level throughput performance in packet-domain services with a simplified receiver design. However, in order to boost further the spectrum efficiency in the future, more advanced receiver designs are required in order to mitigate intra-cell and/or inter-cell interference. As a candidate multiple access scheme for FRA, we proposed a downlink non-orthogonal multiple access (NOMA) scheme where multiple users are multiplexed in the power-domain on the transmitter side and multi-user signal separation on the receiver side is conducted based on successive interference cancellation (SIC) [4-12]. From an information-theoretic perspective, it is well-known that non-orthogonal user multiplexing using superposition coding at the transmitter and SIC at the receiver not only outperforms orthogonal multiplexing, but also is optimal in the sense of achieving the capacity region of the downlink broadcast channel [4]. Note that NOMA can also be applied to uplink (multiple access channel) with SIC applied at the BS side [4,6]. In previous works [6-12], system-level gains of NOMA were investigated in both downlink and uplink.

In this paper, our focus is on downlink NOMA (broadcast channel). Our goal is two-fold: The first is to clarify the basic concept, the benefits, and motivations behind downlink NOMA as a potential candidate multiple access for FRA; and the second is to discuss practical aspects of NOMA, such as multi-user power allocation, signalling overhead, SIC error propagation, performance in high mobility scenarios, and combination with multiple input multiple output (MIMO). Using computer simulations and taking into account practical aspects of the cellular system and some of the key parameters and functionalities of the LTE radio interface such as adaptive modulation and coding (AMC) and frequency-domain scheduling, we provide the system-level performance of downlink NOMA and discuss its related practical considerations. We show under multiple configurations that the cell throughput achieved by NOMA is higher by more than 30% compared to OMA. The remainder of this paper is organized as follows. Section II describes the concept and benefits of NOMA. Section III, discusses practical considerations of NOMA based on the simulation results of its system-level performance. Finally, Section IV concludes the paper.

II. NOMA CONCEPT

In this section, we explain the concept and benefits of NOMA as a potential downlink multiple access for FRA.

A. *Principle*

Fig. 1 illustrates downlink NOMA for the case of one BS and two-UE.

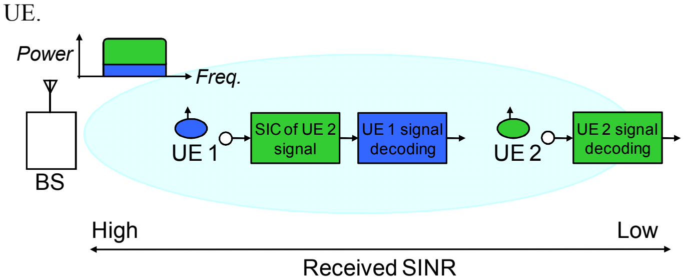

Fig. 1. Downlink NOMA with SIC applied at UE receiver.

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. The base station transmits a signal for UE-i (i = 1, 2), x_i, where $E[|x_i|^2] = 1$, with transmit power P_i and the sum of P_i is equal to P. In NOMA, x_1 and x_2 are superposed as follows:

$$x = \sqrt{P_1}x_1 + \sqrt{P_2}x_2 . \quad (1)$$

Thus, the received signal at UE-i is represented as

$$y_i = h_i x + w_i , \quad (2)$$

where h_i is the complex channel coefficient between UE-i and the BS. Term w_i denotes additive white Gaussian noise (AWGN) including inter-cell interference. The power spectral density of w_i is $N_{0,i}$.

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 in the remaining). 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 2-UE case, assuming that $|h_1|^2/N_{0,1} > |h_2|^2/N_{0,2}$, UE-2 does not perform interference cancellation since it comes first in the decoding order. UE-1 first decodes x_2 and subtracts its component from received signal y_1, then next, it decodes x_1 without interference from x_2. Assuming successful decoding and no error propagation, the throughput of UE-i, R_i, is represented as

$$R_1 = \log_2\left(1+\frac{P_1|h_1|^2}{N_{0,1}}\right), R_2 = \log_2\left(1+\frac{P_2|h_2|^2}{P_1|h_2|^2+N_{0,2}}\right). \quad (3)$$

From (3), it can be seen that power allocation for each UE greatly affects the user throughput performance and thus the modulation and coding scheme (MCS) used for data transmission of each UE. By adjusting the power allocation ratio, P_1/P_2, the BS can flexibly control the throughput of each UE. Clearly, the overall cell throughput, cell-edge throughput, and user fairness are closely related to the power allocation scheme adopted.

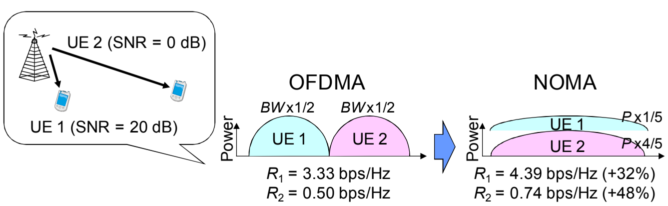

Fig. 2. Simple comparison example of NOMA and OMA (OFDMA).

B. Comparison with OMA

For OMA as orthogonal user multiplexing, the bandwidth of α ($0 < \alpha < 1$) Hz is assigned to UE 1 and the remaining bandwidth, $1-\alpha$ Hz, is assigned to UE 2. The throughput of UE-i, R_i, is represented as

$$R_1 = \alpha\log_2\left(1+\frac{P_1|h_1|^2}{\alpha N_{0,1}}\right), R_2 = (1-\alpha)\log_2\left(1+\frac{P_2|h_2|^2}{(1-\alpha)N_{0,2}}\right). \quad (4)$$

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 Fig. 2, we assume a 2-UE case with a cell-interior UE and a cell-edge UE, where $|h_1|^2/N_{0,1}$ and $|h_2|^2/N_{0,2}$ are set to 20 and 0 dB, respectively. For OMA with equal bandwidth and equal transmission power are allocated to each UE ($\alpha = 0.5$, $P_1 = P_2 = 1/2P$), the user rates are calculated according to (4) as $R_1 = 3.33$ and $R_2 = 0.50$ bps, respectively. On the other hand, in NOMA, when the power allocation is conducted as $P_1 = 1/5P$ and $P_2 = 4/5P$, the user rates are calculated according to (3) as $R_1 = 4.39$ and $R_2 = 0.74$ bps, respectively. The corresponding gains of NOMA over OMA are 32% and 48% 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 multi-user proportional fairness scheduling being used.

C. Motivations and benefits of NOMA

We envisage NOMA as a promising candidate multiple access scheme in the future for the following motivations and benefits.

- *Exploitation of channel gain difference among users*

Unlike OMA (OFDMA) where channel gain difference is translated into multi-user diversity gains via frequency-domain scheduling, in NOMA the channel gain difference is translated into multiplexing gains by superposing in the power-domain the transmit signals of multiple users of different channel gains. As shown in Fig. 2, exploiting the channel gain difference in NOMA, both UEs of high and low channel gains are in a win-win setup. Indeed, UEs with high channel gain (bandwidth-limited UEs) lose a little by being allocated less power, but gain much more by being allocated more bandwidth, while UEs with low channel gain (power-limited UEs) also lose only a little by being allocated little less power and "effective" bandwidth (because of being interfered by the signal designated to the other UEs with high channel gain) but gain much more by being allocated more bandwidth. This win-win situation is also the main reason why NOMA gains over OMA increase when the difference in channel gains between NOMA paired UEs become larger [11].

- *Intentional non-orthogonality via power-domain user multiplexing and advanced receiver processing*

NOMA is a mutliplexing scheme that utilizes an additional new domain, i.e., the power domain, which is not sufficiently utilized in previous systems. Non-orthogonality is intentionally introduced via power-domain user multiplexing; however, interestingly, quasi-orthogonality still can be achieved. 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 (e.g., UE1 in Figs. 1, 2) is allocated less power and the UE with low channel gain (e.g., UE2 in Figs. 1, 2) 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 UE2 (being allocated high power) at UE1 receiver. In addition, at UE2 receiver, the signal designated to UE2 is decoded directly by treating the interference from the signal designated to UE1 (being allocated low power) as noise.

On another hand, NOMA captures well the evolution of device processing capabilities, generally following Moore's law, by relying on more advanced receiver processing such as SIC. In this same spirit, but for the purpose of inter-cell interference mitigation, network-assisted interference cancellation and suppression (NAICS), including SIC, is being discussed in LTE Release 12 [13]. Thus, NOMA can be one good direction to extend the work in 3GPP on NAICS in LTE Release 13 and beyond, as it should be much easier to apply SIC to deal with intra-cell interference than inter-cell interference. The issue of the increased downlink overhead (common to both intra-cell and inter-cell SIC) owing to the signalling of the information related to the demodulation and decoding of other UEs in addition to those for its own UE is discussed in Section III.

- *Robust performance gain in practical wide area deployments*

NOMA user multiplexing does not rely that much on the knowledge of the transmitter of the instantaneous frequency-selective fading channels such as the frequency-selective channel quality indicator (CQI) or channel state information (CSI), which require fine feedback signalling from the UE side. In NOMA, CSI is used at the receiver for user demultiplexing and at the transmitter mainly to decide on user pairing and multi-user power allocation. Thus, a robust performance gain in practical wide area deployments can be expected irrespective of UE mobility or CSI feedback latency.

III. Practical Considerations

We discuss some practical considerations regarding NOMA, such as multi-user power allocation, signalling overhead, SIC error propagation, performance in high mobility scenarios, and combination with MIMO. Evaluation results of the performance of NOMA in a multi-cell system-level simulation [14] are also presented. The major simulation parameters assumed are based on existing LTE/LTE-Advanced specifications [15]. We employed a 19-hexagonal macrocell model with 3 sectors per cell. The system bandwidth is 10MHz (48RBs) and the cell radius is set to 289 meters (inter-site distance of 500 meters). The locations of the UEs are assigned randomly with a uniform distribution. In the propagation model, we take into account distance-dependent path loss with the decay factor of 3.76, lognormal shadowing with the standard deviation of 8 dB and instantaneous multipath fading. The shadowing correlation between the cells (sectors) is set to 0.5 (1.0). The 6-ray typical urban (TU) channel model is assumed. The baseline maximum Doppler frequency, f_D, is set to 5.55 Hz, which corresponds to 3 km/h at the carrier frequency of 2 GHz. The transmission power of the macrocells is 46 dBm. The antenna gain at the macrocell and UE is 14 dBi and 0 dBi, respectively. One-antenna transmission and two-antenna reception (1x2 SIMO) and maximal ratio combining (MRC) at the UE side are assumed as baseline antenna configuration and receiver. Full buffer traffic model is used and the feedback delay is modeled such that the CQI is not available for scheduling until 4 subframes after the periodic report with a 2-ms interval. Hybrid Automatic Repeat reQuest (HARQ) is not assumed. In NOMA, the multi-user scheduler maximizes multi-user proportional fairness metric [16,17] and selects the best UE set among all possible UE sets. Full search power allocation and exhaustive user pairing described in [12] are assumed as baseline. Also, for NOMA, dynamic switching to OMA is assumed with the maximum number of simultaneously paired UEs, m, is set to 2 (m=2).

A. NOMA signalling overhead

■ *Wideband vs. Subband scheduling*

We explore NOMA performance gains with subband scheduling and subband MCS and compare it to NOMA with wideband scheduling and wideband MCS selection. For the case of subband (wideband) scheduling, the system bandwidth is divided into 8 (1) subbands with 6RBs (48RBs) per subband. In Fig. 3, the cell throughput and cell-edge throughput gains for NOMA over OMA are approximately 40% and 39% for wideband scheduling, and 37% and 32% for subband scheduling, respectively. Thus, similar gains can be maintained for NOMA even with larger number of subbands and thus larger frequency-domain scheduling gains. Also note that the performance of all cases is increased according to the number of UEs per cell (10UEs, 20UEs) because of the multi-user diversity gain.

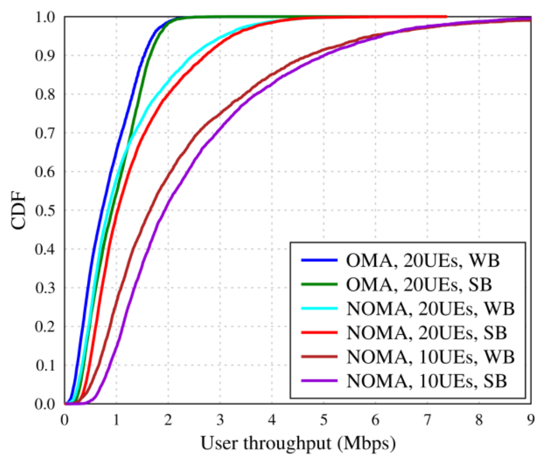

Fig. 3. CDF of user throughput for OMA (m = 1) and NOMA (m = 2) with subband and wideband scheduling (w/o error propagation).

In the case of NOMA with subband scheduling, signalling overhead increases linearly with the number of subbands. To reduce signalling overhead, joint encoding of modulation, coding and power set (MCPS) would be beneficial or some signallings could be widedband or long-term while others can remain subband or short-term. In LTE for example, even when subband scheduling is applied, the same channel coding rate (including rate matching) and data modulation scheme are assumed over all the subbands allocated to each single user, as the average SINR over all the subbands is used for MCS selection. However, for NOMA, such a mismatch between MCS adaptation granularity (e.g., wideband) and power allocation granularity (e.g., subband) might not allow the full exploitation of NOMA gains with subband scheduling [11]. Thus, considerations from this aspect need to be also taken into account.

■ *Multi-user power allocation*

Because of the power-domain user multiplexing of NOMA, the transmit power allocation (TPA) to one user affects the achievable throughput of not only that user but also the throughput of other users. The best performance of NOMA can obviously be achieved by exhaustive full search of user pairs and dynamic 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, however, computationally complex. Also, with such dynamic TPA, the signalling overhead associated with SIC decoding order and power assignment ratios increases significantly.

In order to reduce the signalling overhead associated with multi-user transmit power allocation of NOMA and clarify the degree of impact of user pairing on the performance of NOMA, both exhaustive and simplified user pairing and power allocation schemes are explored [12]. In NOMA, users with large channel gain difference (e.g., large path-loss difference) are paired with high probability; thus, considering practical implementations, user pairing and TPA, could be simplified by using pre-defined user grouping and fixed per-group power allocation (FPA), where users are divided into multiple user groups according to the magnitude of their channel gains using pre-defined thresholds [12].

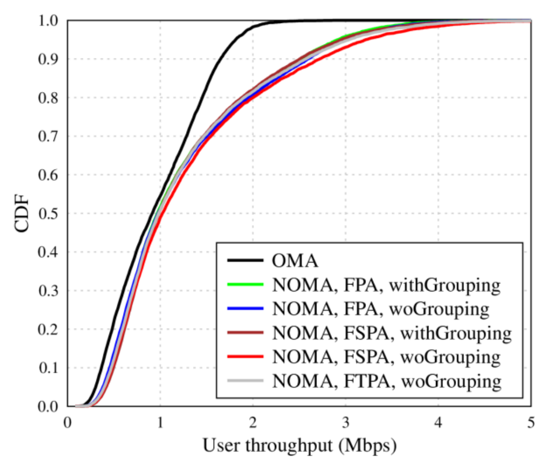

Fig. 4. CDF of user throughput for OMA (m = 1) and NOMA (m = 2) with various power allocation and user grouping schemes (subband scheduling, 20UEs, w/o error propagation).

Figure 4 shows the performance comparison between OMA and NOMA with different power allocation schemes, with and without user grouping. Here, three power allocation schemes are simulated: FSPA, fractional transmit power allocation (FTPA) similar to LTE uplink power control (α_{FTPA}=0.4) [9], and FPA. With grouping, two user groups were assumed where the threshold for user grouping is 8 dB and power allocations in FPA are fixed to (0.2P, 0.8P). The performance gains in the overall cell throughput for NOMA are, FSPA w/o grouping: 37%; FTPA w/o grouping: 31%; FPA w/o grouping: 30%; FSPA w/ grouping: 30%; and FPA w/ grouping: 28%. Thus, even with simplified TPA schemes such as FPA and pre-defined user grouping, a large portion of NOMA gains can be maintained. Taking into account the potential saving in signalling overhead, pre-defined user grouping and fixed TPA can be promising in practical usage. For example, the order of successive interference cancellation (SIC) and information on power assignment do not need to be transmitted in every subframe but rather on a longer time scale.

B. Impact of SIC error propagation

In practice, the impact of SIC error propagation on NOMA performance remains as one concern. To emulate this effect in the system-level simulations of NOMA, we adopt a worst-case model [12]. The worst-case model assumes that at the receiver of UE1, where SIC is applied, the decoding of UE2 is performed first at stage 1. Based on the knowledge of the MCS assigned to UE2 and its received SINR at UE1, the BLER of the user decoded first (UE2) is obtained and decoding is attempted. Then, its replica signal is generated and subtracted from the received signal before the decoding of UE1 at stage 2. Depending on the decoding result of UE2 (successful or not) at stage 1, the signal used for the decoding of UE1 at stage 2 differs, which make the link-to-system mapping difficult. In the worst-case model we assume that the decoding of UE1 at stage 2 is always unsuccessful whenever the decoding of UE2 at stage 1 of the UE1 receiver is unsuccessful. Such a worst-case model is simple but provides us with a simple tool to evaluate the impact of error propagation on NOMA performance without the need for NOMA specific link-to-system mapping.

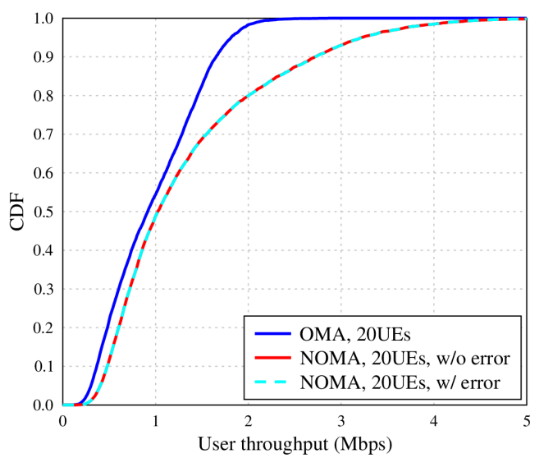

Fig. 5. CDF of user throughput for OMA (m = 1) and NOMA (m = 2) with and without error propagation (subband scheduling, 20UEs).

Figure 5 shows the impact of error propagation on performance of NOMA using the explained worst-case model. It can be seen that error propagation has almost no impact on NOMA performance. The reason is that in most cases NOMA scheduler pairs a UE with bad channel gain with a UE with good channel gain. Because MCS for the UE with bad channel gain is selected with a targeted BLER<=0.1, the decoding failure of a data packet designated to the UE with bad channel gain at the receiver of the UE with good channel is very small, i.e. the BLER is usually much less than 0.01. This again confirms the quasi-orthogonality of NOMA achieved by multi-user power allocation and SIC as mentioned earlier in Section II.

C. Performance in low and high mobility scenarios

Next, we investigate NOMA gain with various UE speeds. Figure 6 shows the cell throughput gain and cell-edge throughput gain of NOMA over OMA for wideband and subband scheduling with different user velocities. The number of users per cell is 10 and FTPA with α_{FTPA}=0.5 is used for NOMA power allocation. It can be seen that the cell throughput gains of NOMA over OMA are observed over a wide range of UE speeds for both wideband and subband scheduling and with and without error propagation. Specifically, NOMA is shown to maintain good gains compared to OMA in particular with wideband scheduling. Thus, NOMA can be a promising multiple access to provide a good robustness to mobility as it relies mainly on receiver side CSI and signal processing.

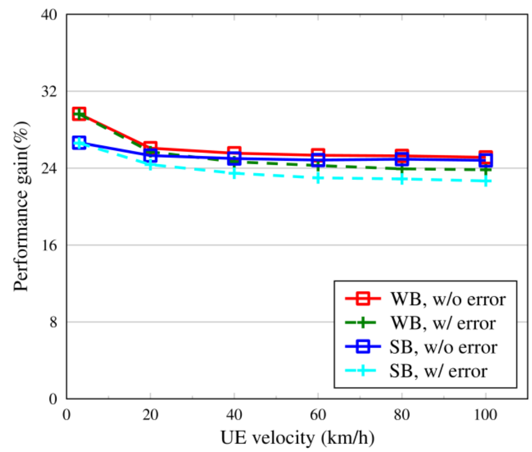

Fig. 6. NOMA cell throughput gains with various UE speeds (wideband and subband scheduling, with and without error propagation, 10UEs).

D. Combination of NOMA and MIMO

Figure 7 shows one form of combining downlink NOMA with MIMO using random (opportunistic) beamforming [17, 18]. In this form, the BS transmitter generates multiple beams similarly to multi-user (MU)-MIMO, and superposes multiple UEs within each beam [8]. In the UE receiver side, two interference cancellation approaches, non-linear SIC and linear interference suppression by interference rejection combining (IRC) [19], are jointly used as follows.

- ✓ SIC is used for intra-beam user demultiplexing, i.e., interference cancellation among the UEs belonging to a group with the same precoding weights applied. The multiple access scheme within each beam (group) is the same as NOMA.
- ✓ IRC is used for inter-beam interference suppression, i.e., interference suppression among UE groups with different precoding weights applied. Interference from other beams is simply suppressed by combining the signals received at the receive antennas of the UE. A key benefit of IRC is that it does not require the decoding of other UE groups in other beams.

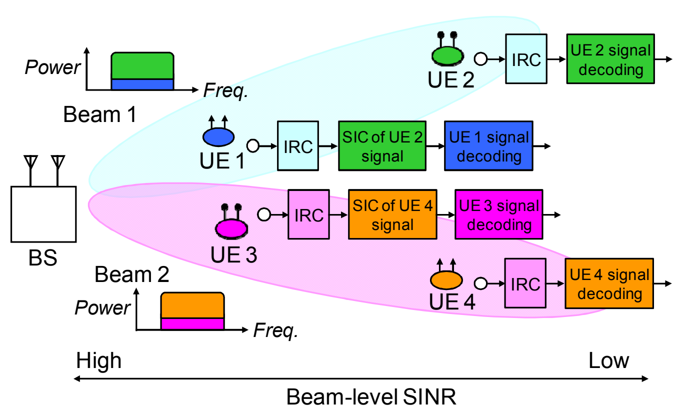

Fig. 7. NOMA/MIMO scheme applying with IRC-SIC receivers.

Figure 8 shows the CDF of the user throughput for NOMA and OMA for 1x2 SIMO (as in previous evaluations), and for 2x2 MIMO using random beamforming at the BS transmitter side and IRC-SIC receiver at the UE side. Differently from previous evaluations in Section III, we apply a 19-hexagonal macrocell model without sectorization. For the case of OMA with 2x2 MIMO, a single-stream transmission is applied per transmit beam. Figure 8 shows that NOMA gains can be maintained almost at the same level irrespective of the antenna configuration, i.e., 1x2 SIMO or 2x2 MIMO with random beamforming. One interesting thing observed here is that the performance of NOMA with 1x2 SIMO is very similar to that of OMA with 2x2 MIMO using opportunistic beamforming (OBF). This implies that the NOMA with SIC has a similar effect to spatial multiplexing using random beamforming, and NOMA can achieve a competitive level of performance to random beamforming with a smaller number of transmit antennas at the BS. However, the proposed NOMA/MIMO scheme requires a relatively large number of UEs to obtain a sufficient throughput gain for random (opportunistic) beamforming [17, 18]. When the number of UEs per cell is small, it may be better to apply a closed-loop precoding or single-user (SU)-MIMO approach rather than the random beamforming approach. Therefore, the support for multiple MIMO modes, e.g., closed-loop and open-loop, SU-MIMO and MU-MIMO and so on, needs to be investigated for NOMA.

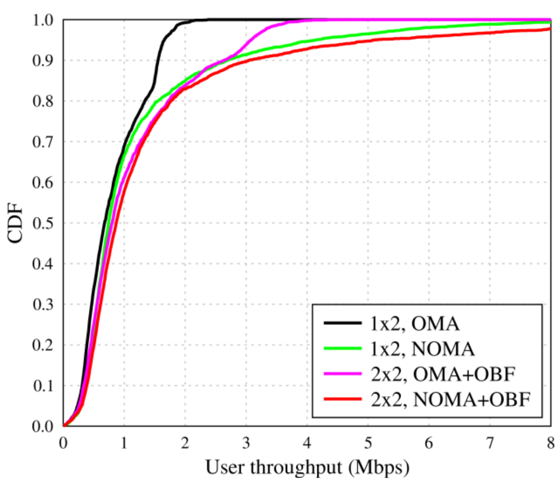

Fig. 8. System-level evaluation of downlink NOMA combined with MIMO using random beamforming (20UEs).

IV. Conclusion

This paper presented our NOMA concept for FRA toward the 2020s-era. Different from the current LTE radio access scheme, NOMA superposes mutliple users in the power-domain, exploits the channel gain difference between multiplexed UEs. Although NOMA adopts an SIC receiver as a baseline receiver, we believe this is becoming more and more viable with the expected evolution of device processing capabilities in the future. In addition, we discussed the practical considerations and the gains of NOMA under practical considerations, such as, multi-user power allocation, signalling overhead, SIC error propagation, and performance in high mobility scenarios. Furthermore, we discussed the combination of NOMA with MIMO by applying random beamforming to transform the MIMO channel to a SIMO channel where SIC receiver is used for intra-beam interference mitigation and IRC for inter-beam interference mitigation. Under multiple configurations and setups, the achievable gains are shown promising, in the order of 30%, even when practical considerations were taken into account.

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