Abstract—We investigate on large-scale deployment of non-orthogonal multiple access (NOMA) for improved spectral and power efficiency in cellular networks to provide massive wireless connectivity (e.g. for machine-type communication [mMTC]). First, we describe the basics of single-antenna NOMA technology and its extension to co-located multiple-antenna NOMA as well as coordinated multipoint transmission (CoMP)-enabled NOMA technologies. Then we discuss some of the practical challenges of large-scale deployment of NOMA such as the inter-NOMA-interference (INI), inter-cell interference, and hardware implementation complexity. To this end, we present one key enabling technique to overcome the challenges of large-scale deployment of NOMA. Generally speaking, for a feasible large-scale NOMA implementation, sophisticated diversity enhancing techniques can be used to compensate for the degradation in coding gain and increase level of required successive interference cancellation (SIC). Furthermore, to massively extend NOMA over the network coverage area, NOMA transmitters have to cooperate in a generalized manner to serve all nearby users simultaneously.

Index Terms—Massive machine-type communication (mMTC), non-orthogonal multiple access (NOMA), successive interference cancellation (SIC), diversity enhancing techniques.

I. INTRODUCTION

Supporting a massive numbers of wireless-connected devices that communicate with each other simultaneously will be an inherent property of the fifth generation (5G) and beyond 5G (B5G) systems. Massive-scale connectivity between various communication devices (e.g. vehicles, sensors, mobiles, etc.) will enable us to form the internet of everything (IoE) that bridges the gap between the ‘Cyber’ and the ‘physical’ worlds. For this so called massive machine-type communication (mMTC), efficient, reliable, and fast communication methods will be required to enhance and control data flows among these devices. As an example, autonomous driving and intelligent transportation systems require that hundreds of machines be coordinating and communicating simultaneously within a certain geographical area. Communications among these machines must be reliable and fast in order to provide a safe driving environment. This can be achieved by increasing the capacity of wireless systems to support significantly higher data rates and/or number of devices. It may also be used to reduce power consumption on mMTC distributed devices.

The capacity of wireless systems however is limited by the availability of spectrum resources. To improve the capacity under limited spectrum resources, sophisticated designs for wireless access and resource allocation will be required. In this context, non-orthogonal multiple-access (NOMA) has emerged as a potential technology to tackle the problem of improving wireless network capacity under spectrum scarcity [1]. The main concept of NOMA (in uplink and downlink) is: in a certain frequency sub-band, signals for multiple users are superimposed in the power domain such that the resultant received signal has a distinct power levels for every user. At the receiver side, successive interference cancellation (SIC) is used to filter out the undesired signals. Generally, SIC can be conducted at the codeword level, symbol level or using reduced complexity-maximum likelihood detection (R-ML). However, codeword and symbol levels SIC are preferable methods due to their ability to suppress interference from adjacent devices and their relatively low complexity [2].

Theoretically, NOMA has been observed to outperform orthogonal multiple access (OMA) schemes such as OFDMA, CDMA and TDMA, in terms of spectral efficiency. Additionally, under the low-rate requirements of mMTC terminal devices, large-scale NOMA can achieve a significantly higher power efficiency when a similar bandwidth as that of OMA system is utilized. However, two major drawbacks of NOMA on its simplest form (single antenna and single base station at transmitter(s) and receiver(s)) limit its usage in a large-scale regime. The first drawback is the increased level of inter-NOMA-interference (INI), which is the interference caused by other users using the same NOMA cluster. When the number of NOMA users in a certain NOMA cluster increases, those users with lower link quality will have to deal with larger number of unfiltered INI signals. The second drawback is the hardware complexity of SIC that increases significantly with the number of users per NOMA cluster [3].

We investigate on a number of enabling techniques that may be used to overcome the challenges of large-scale NOMA (e.g. high INI and high hardware complexity requirements). NOMA can be deployed either in the uplink or the downlink of a wireless system. In this article, we focus on downlink NOMA as discussions can be easily applied to uplink NOMA. The rest of this article is organized as follows. Section II describes the basics of single-antenna, multi-antenna, and CoMP-enabled NOMA technologies. The hardware requirements for large-scale NOMA are discussed in Section III. Section IV outlines a key enabling technique that can support implementation of NOMA.

1In this article, large-scale NOMA refers to the use of relatively high number of users per single NOMA cluster throughout a single frequency sub-band.

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large-scale NOMA. We conclude the article in Section V.

II. NOMA TECHNIQUES

This section describes several enabling technologies the NOMA scheme can be integrated with.

A. Single-Input Single-Output (SISO)-NOMA

In an $m$-user SISO-NOMA cluster, the transmitted signal is given by $x = \sum_{i=1}^{m} \sqrt{p_i} s_i$ such that $\sum_{i=1}^{m} p_i \leq p_t$, where $p_i$ is the transmitted power assigned to the $i$-th NOMA user, $s_i$ is the signal to be sent to the $i$-th NOMA user, and $p_t$ is the power budget of NOMA transmitter per sub-band. Accordingly, the received signal at the $i$-th user end is given by

$$y_i = h_i x + w_i, \quad \forall \ i = 1, \ldots, m,$$

(1)

where $h_i$ is the complex channel gain of the $i$-th user and $w_i$ is the noise plus interference for the $i$-th user. For NOMA, the magnitudes of channel gains between the NOMA transmitter and receivers are first ordered such that $|h_1| \geq \ldots \geq |h_m|$. Thereafter, power fractions are assigned to every superimposed signal such that $p_1 \leq \ldots \leq p_m$. This is done under the condition that the received signals’ power at the $i$-th NOMA user must be separated from other signals’ powers by a minimum SIC hardware sensitivity value $\epsilon$. Following this power allocation mechanism, the $i$-th user will be able to remove all signals with higher power weights than its desired signal through multi-level SIC techniques [2]. Therefore, the achievable throughput at the $i$-th user is given by

$$R_i = B \log_2 \left(1 + \frac{p_i \gamma_i}{\sum_{j=1}^{m-1} p_j \gamma_j + 1}\right),$$

(2)

where $B$ is the allocated bandwidth per NOMA cluster and $\gamma_i = \frac{|h_i|^2}{I_i + N_i}$, in which $I_i$ and $N_i$ are the inter-cluster interference (ICI) power and the noise power at the receiver input of the $i$-th user, respectively. To compare the performance of large-scale SISO-NOMA with that of OMA, Fig. 1 shows a graphical approximation of the $\epsilon$-outage capacity for SISO-NOMA with different cluster sizes ($m$). Here, $\epsilon$ is the maximum allowable outage to achieve a capacity of $C_\epsilon$. In order to investigate SISO-NOMA at the large scale regime, we have used constant transmission power scheme that complies with NOMA protocol and does not affect the insights extracted from the provided results [3]. It can be noticed that increasing the number of users per NOMA cluster causes a significant degradation on the system coding gain (i.e. the performance curve shifts to the right).

In mMTC networks, communicating devices may be significantly small in sizes and distributed within remote areas which makes it difficult to guarantee a permanent power sources for all devices at all times. Accordingly, power consumption plays a critical rule in the design of mMTC networks and devices.

By using NOMA at the large-scale regime, higher spectral efficiency and/or lower power consumption can be achieved. As an example, under the same minimum rate requirements for OMA and NOMA, the required NOMA transmission power per cluster can be significantly reduced when the entire OMA bandwidth is utilized. In general, spectrum-efficiency and energy-efficiency trade-offs can be exploited when deploying large-scale NOMA in mMTC networks.

B. MIMO-Enabled NOMA

The extension of NOMA scheme to multiple-input-multiple-output (MIMO) systems can be considered as the first intuitive solution to integrate NOMA with more sophisticated wireless technologies. There are quite a number of papers in the literature that discussed the merging between MIMO systems and NOMA scheme with different layouts. In this section we present, as an example, a clustering algorithms proposed by [5] to find the best utilization of MIMO-enabled NOMA system. Fig. 2 shows the proposed clustering model for MIMO-enabled downlink NOMA in which a transmitter with a group of antennas transmits to a set of users simultaneously using the same transmission sub-band. Generally, every transmitting an-

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2Optimal transmission power allocation scheme for an $m$-user SISO-NOMA system was presented in [3].
allocate every cluster a share of the overall transmission power budget [4].

For large-scale MIMO-enabled NOMA systems, every cluster should have an order of tens of NOMA users (or even hundreds in the case of massive in-band NOMA scheme) that share the same in-band beam (same cluster). This increase in cluster size will result in an increase in the required transmission power per MIMO beam in order to guarantee a minimum rate per user (especially in presence of high inter-cluster interference). However, MIMO-enabled NOMA adds some degrees of freedom to achieve spectrum-power trade-off designs that comply with the notion of mMTC communication for which a significantly large spectrum efficiency and low power consumption are crucial. Accordingly, using the same OMA resources (i.e. available spectrum and power budget), with the appropriate design, MIMO-enabled NOMA may achieve similar performance with relatively lower power consumption.

C. CoMP-Enabled NOMA

In the last two subsection, we have discussed the NOMA scheme under one transmitter that has a single power budget to be allocated to different NOMA layouts (SISO and MIMO). In this section, we briefly discuss the integration of NOMA with the so called coordinated multi-point (CoMP) transmission. Specifically, we focus on joint transmission-CoMP (JT-CoMP) scheme in which multiple geographically distributed BSs serve different users using the same sub-band. All of the existing literature that focused on CoMP-enabled NOMA considered dividing users into cell-edge users and cell-centre users. Accordingly, every NOMA cluster is assumed to consist of one or multiple of the cell edge users and a one or multiple of cell-centre users.

Generally, under the JT-CoMP system, the received signal at the i-th user can be expressed as

\[ y_i = \sum_{m \in \mathcal{S}_{c,i}} h_{i,m}^{} x_m^{} + \sum_{j \in \mathcal{S}_{nc,i}} h_{i,j}^{} x_j^{} + w_i, \quad (3) \]

where \( h_{i,m} \) is the complex channel gain between the i-th user and m-th BS, \( \mathcal{S}_{c,m}(\mathcal{S}_{nc,m}) \) is the set containing the indices of BSs serving (not-serving) the i-th user through a single sub-band. If the i-th user is identified as a cell-edge user, then more than one BS should transmit the same signal to that user. Fig. 3 shows a possible scenario of CoMP-enabled NOMA scheme. Using this scheme, the achievable throughput at the cell-edge user (denoted UE\(_i\)) and at the j-th user served by the i-th BS (denoted UE\(_{i,j}\)) are expressed, respectively, as

\[ R_1 = \log_2 \left( 1 + \frac{\sum_{i=1}^{2} p_{i,1}^{} \gamma_{i,1}^{} + \sum_{i=1}^{3} p_{i,2}^{} \gamma_{i,1}^{} + \sum_{i=3}^{4} p_{i,3}^{} \gamma_{i,1}^{} + I_{inter}^{} + 1}{\sum_{i=1}^{4} p_{i,4}^{} \gamma_{i,1}^{} + I_{inter}^{} + 1} \right), \]

\[ R_{i,j} = \log_2 \left( 1 + \frac{p_{i,j}^{} \gamma_{i,j}^{} + I_{inter}^{} + 1}{\sum_{k=j+1}^{4} p_{i,k}^{} \gamma_{i,j}^{} + I_{inter}^{} + 1} \right), \]

where \( I_{inter} = \sum_{m=1}^{2} \sum_{n=1}^{2} p_{m,n}^{} \gamma_{i,j}^{} \) is the inter-cluster interference (ICI) caused by joint utilization of the same sub-band by two NOMA clusters. It can be noticed from Eq. 5 that being a cell-centre NOMA user will add an additional burden in the form of ICI \( (I_{inter}) \). In that regard, for large-scale NOMA, we have found that user performance is very sensitive to any further interfering components (in addition to INI component) even in the existence of sophisticated power allocation algorithms. This increases the difficulty of deploying a large-scale NOMA clusters under the conventional CoMP system. Nevertheless, CoMP-enabled NOMA with small cluster sizes was shown to significantly enhance average performance per user [6] Fig. 3.

III. LIMITATIONS AND REQUIREMENTS FOR LARGE-SCALE NOMA

We discuss the limitations and requirements of NOMA deployment with large cluster sizes noting that studies on in-band large-scale NOMA is scanty in the existing literature.

A. High Interference Levels

Generally, there are two main interference components that affect the performance of NOMA receiver namely; the INI and the ICI. Based on NOMA protocol, users with lower channel quality will have to deal with interference due to those with higher channel quality. Accordingly, as the number of NOMA users per cluster \( m \) increases (see Eq. 2), users with low channel quality may suffer due to increased level of unfiltered INI components. Besides, ICI will occur due to the utilization of the same sub-band by more than one NOMA clusters. This can be done either within the same cell (such as MIMO-NOMA) or within different geographically separated cells (such as CoMP and multi-cell networks with a reuse factor greater than or equal to one [7]). It was found that under large-scale NOMA, user performance becomes very sensitive to small values of ICI. Therefore, sophisticated SIC mitigation technologies will be required to implement NOMA with a large cluster sizes.
B. Hardware Requirements for Large-Scale NOMA

The main idea of NOMA is based on the ability of the receiver to cancel a significant component of INI throughout SIC unit. Generally, due to the randomness of channel gains and the mobility of NOMA wireless receivers, a certain NOMA receiver should be able to cancel up to \( m - 1 \) signals at any arbitrary time slot (where \( m \) is the in-band NOMA cluster size). Accordingly, any design for large-scale NOMA receiver must take care of the following concerns:

(a) For large-scale NOMA, SIC must be achieved quickly and efficiently since NOMA is supposed to be operating at the time slot level.
(b) The increase of NOMA receiver sensitivity to different values of ICI at large cluster sizes.
(c) At large NOMA cluster sizes, differences among the received signals’ power components at a certain NOMA receiver becomes smaller, especially for limited power budget. This will negatively affect the performance of SIC unit in decoding the highest weight signal. Accordingly, more complicated receiver designs will be required.
(d) Larger in-band NOMA cluster sizes means a larger number of required SIC operations which results in higher power consumption.

IV. AN ENABLING TECHNIQUE FOR MASSIVE-NOMA

When NOMA signal is enhanced such that the level of the desired power at every NOMA receiver is increased, the amount of interference is decreased and complexity of SIC is reduced, then the deployment of large-scale NOMA will become feasible. Traditional diversity enhancing techniques such as MIMO and CoMP could be a good candidate for large-scale NOMA scheme if the ICI component is mitigated efficiently. Here, we propose a novel cooperative NOMA scheme that enables the deployment of large-scale NOMA. Fig. 4 shows an example of the proposed scheme at which three BSs are cooperating to serve one large-sized NOMA cluster. Using this layout and with a proper network planing, the ICI components may be significantly reduced. Additionally, using this system setup, the amount of desired signal at every NOMA receiver will be increased from more than one transmitter. Such an increase will result in larger power gaps (enhanced receiver sensitivity) and add more degrees of freedom on the required level of SIC for every NOMA receiver. Fig. 5 shows a simulation example of the proposed scheme. The variable \( K(M) \) denotes the number of cooperating NOMA transmitters (receivers). It can be noticed that even under significantly large \( M \), increasing the number of cooperating transmitters enhances the system diversity gain significantly (increase in the slope of the performance curves).

V. CONCLUSION

NOMA can provide the required spectrum-energy efficiency trade-off required for mMTC networks. We have discussed several enabling technologies for NOMA (e.g. SISO-NOMA, MIMO-NOMA, CoMP-NOMA) and practical aspects of the deployment of large-scale NOMA (i.e. NOMA with large cluster sizes). To enable large-scale NOMA for massive mMTC, sophisticated diversity enhancing techniques need to be used to compensate for the severe degradation in coding gain and also to decrease the complexity of required successive interference cancellation (SIC).

REFERENCES

[1] P. Wang, J. Xiao, and L. P. “Comparison of orthogonal and non-orthogonal approaches to future wireless cellular systems,” IEEE Veh. Technol. Mag., vol. 1, no. 3, pp. 4–11, Sep. 2006.
[2] R4-131791, “Receiver structure feasibility for LTE Rel–12,” in 3GPP TSGRAN WG4 Meeting, 15–19 Apr. 2013.
[3] H. Haci, H. Zhu, and J. Wang, “Performance of non-orthogonal multiple access with a novel asynchronous interference cancellation technique,” IEEE Trans. on Wireless Commun., vol. 65, no. 3, pp. 1319–1335, March 2017.
[4] M. S. Ali, H. Tabassum, and E. Hossain, “Dynamic user clustering and power allocation for uplink and downlink non-orthogonal multiple access (noma) systems,” IEEE Access, vol. 4, pp. 6325–6343, 2016.
[5] M. S. Ali, E. Hossain, and D. I. Kim, “Coordinated multipoint transmission in downlink multi-cell noma systems: Models and spectral efficiency performance,” IEEE Wireless Commun., vol. 25, pp. 24–31, April 2018.
[6] M. S. Ali, E. Hossain, A. Al-Dweik, and D. I. Kim, “Downlink power allocation for comp-noma in multi-cell networks,” IEEE Trans. on Wireless Commun., vol. 66, no. 9, pp. 3982–3998, Sep. 2018.
[7] H. Tabassum, E. Hossain, and J. Hossain, “Modeling and analysis of uplink non-orthogonal multiple access in large-scale cellular networks using poisson cluster processes,” IEEE Trans. on Wireless Commun., vol. 65, no. 8, pp. 3555–3570, Aug 2017.
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