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# 14. NOMA – AIDED CELL-FREE MASSIVE MIMO – A REVIEW

## 14.1. Introduction

According to CISCO Annual Internet Report (2018-2023) white paper, over 70% of the global population will have mobile connectivity by 2023 with global mobile devices growing from 8.8 billion to 13.1 billion by 2023 and the number of Internet-enabled devices will have increased to 29.3 billion, with 1.4 billion of those will be Fifth Generation (5G) capable[3]. It further reiterates that the fastest-growing mobile device category is Machine-to-Machine (M2M), which is a key enabler in Smart Cities (SCs).

SC will require a suitable wireless communications system that will provide high data rates, reliability, flexibility, low-latency, massive connectivity, security and among other adaptive functionalities[4]. This growth and demand will eventually overwhelm the network capabilities of the Fourth Generation (4G) and 5G wireless networks. Therefore, there is a need for new targets in terms of network performances for the next generation of wireless networks, also known as Sixth Generation (6G) especially in smart cities (SCs). SC operations can be made possible by faster adoption of strategies brought by the expanded scope of 6G core technologies.

6G networks is expected to have network performance such as increasing the peak data rate to 1 terabit per second, increasing the experienced rate for highly mobile users

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[3] Cisco: Cisco Annual Internet Report (2018–2023) White Paper, Mar 2020. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paperc 11-741490.html.
[4] Al Amin A., Hong J., Bui V.H., Su W.: Emerging 6G/B6G Wireless Communication for the Power Infrastructure in Smart Cities: Innovations, Challenges, and Future Perspectives. Algorithms, 16(10) 2023, p. 474.

to 1 Gbps, increasing connection density to $10^7$ devices/km$^2$, decreasing air latency to 0.1 ms, and improving network reliability to $10^{-7}$ [5].

To achieve the above-mentioned stringent targets, 6G wireless communications networks will require advanced physical layer solutions, new advanced modulation schemes, advanced multiple access techniques, energy harvesting, edge computing, new spectral bands, integration of terrestrial and non-terrestrial communications, cell-free massive Multiple Input Multiple Output (MIMO), blockchain and quantum technologies and adoption of artificial intelligence and machine learning techniques[6].

In conventional mobile networks, a coverage area is divided into cells, with each cell served by one Base Station (BS). One of the key limitations of cellular networks is intercell interference. In addition, users at the cell boundaries perform badly due to strong inter-cell interference limiting the performance of the whole network. Cell-Free Massive MIMO first appeared in 2015[7]. It was proposed to overcome the inter-cell interference in cellular networks[8]. Cell-Free Massive MIMO (CF-mMIMO) has attracted a lot of interest as a potential enabling technology for the envisioned 6G network[9]. In addition, it suggests[10] a cell-free and mesh connectivity as possible 6G architectures. Cell-free massive MIMO (CF-mMIMO) systems and integration between terrestrial and non-terrestrial communications are effective techniques to increasing connectivity and providing full coverage. CF-mMIMO solution is a suitable technique for the next generation indoor and outdoor scenarios. In cell-free systems, the users are surrounded by Access Points (APs) eliminating cell-edges and the traditional notion of edge user suffering the worst performance. Importantly, CF-mMIMO reaps all the benefits of

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[5] You X., Wang C.X., Huang J. et al.: Towards 6G wireless communication networks: vision, enabling technologies, and new paradigm shifts. Sci. China Inf. Sci. 64, 2021, 110301. https://doi.org/10.1007/s11432-020-2955-6; Saghezchi F.B., Rodriguez J., Vujicic Z., Nascimento A., Huq K.M.S., Gil-Castiñeira F.: Drive Towards 6G. [In:] Rodriguez J., Verikoukis C., Vardakas J.S., Passas N. (eds): Enabling 6G Mobile Networks. Springer, Cham 2022. https://doi.org/10.1007/978-3-030-74648-3_1.

[6] Alsabah M. et al.: 6G Wireless Communications Networks: A Comprehensive Survey, in IEEE Access, Vol. 9, 2021, pp. 148191–148243, DOI: 10.1109/ACCESS.2021.3124812.

[7] Ngo H.Q., Ashikhmin A., Yang H., Larsson E.G., Marzetta T.L.: Cell-Free Massive MIMO: Uniformly great service for everyone, 2015 IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2015, pp. 201-205, DOI: 10.1109/SPAWC.2015.7227028; Nayebi E., Ashikhmin A., Marzetta T.L. Yang H.: Cell-Free Massive MIMO systems, 2015 49th Asilomar Conference on Signals, Systems and Computers, 2015, pp. 695–699, DOI: 10.1109/ACSSC.2015.7421222.

[8] Ngo H.Q., Ashikhmin A., Yang H., Larsson E.G., Marzetta T.L.: Cell-Free Massive MIMO: Uniformly great service for everyone, 2015 IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2015, pp. 201–205, DOI: 10.1109/SPAWC.2015.7227028.

[9] Akyildiz I.F., Kak A., Nie S.: 6G and Beyond: The Future of Wireless Communications Systems, in IEEE Access, Vol. 8, pp. 133995–134030, 2020, DOI: 10.1109/ACCESS.2020.3010896; Tataria H., Shafi M., Molisch A.F., Dohler M. Sjöland H., Tufvesson F.: 6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities, in Proceedings of the IEEE, Vol. 109, no. 7, pp. 1166–1199, July 2021, DOI: 10.1109/JPROC.2021.3061701.

[10] Viswanathan H., Mogensen P.E.: Communications in the 6G Era, in IEEE Access, Vol. 8, pp. 57063-57074, 2020, DOI: 10.1109/ACCESS.2020.2981745; Ziegler V., Viswanathan H., Flinck H., Hoffmann M., Räisänen V., Hätönen K.: 6G Architecture to Connect the Worlds, in IEEE Access, Vol. 8, pp. 173508-173520, 2020, DOI: 10.1109/ACCESS.2020.3025032.

network MIMO solutions and key properties of massive MIMO can be beneficially exploited for supporting scalable implementations. In addition to these, further improvements on the system performance in-terms of achievable data-rates, reliability, security among others can be achieved to ensure path to target requirements of 6G networks by integrating CF-mMIMO systems with emerging technologies, such as non-orthogonal multiple-access (NOMA), reconfigurable intelligent surfaces, radio stripes, machine learning, and many others.

On the other hand, NOMA, also as an emerging technology, is a promising one in the next generations wireless communications. While orthogonal multiple access schemes have number of served users limited by the available orthogonal resources, NOMA enables serving of more users than the available resources at the expense of increasing complexity of the receivers. NOMA benefits include massive connectivity, low latency, improved spectral performance and relaxed channel feedback[11].

Given the distinctive benefits of Cell-free massive MIMO and NOMA, the integration of these two techniques is worth investigating to inherit the important advantages of both in order to achieve the stringent demands of 6G and SCs. However, the coexistence of the two technologies remains an issue worth researching especially as key technology applications for 6G wireless communication in SCs.

In the next section, we provide literature of Cell-free massive MIMO and NOMA. In addition, we analyze the state-of-art and provide a simple system model of NOMA-aided Cell-Free massive MIMO.

## 14.2. Literature review

### 14.2.1. Cell-Free Massive MIMO Fundamentals

CF-mMIMO networks consist of many distributed Access Points (APs) connected to a central processing unit (CPU) and they jointly serve all the user equipment (UEs)

[11] Shin W., Vaezi M., Lee B., Love D.J., Lee J., Poor H.V.: Non-Orthogonal Multiple Access in Multi-Cell Networks: Theory, Performance, and Practical Challenges, in IEEE Communications Magazine, Vol. 55, no. 10, pp. 176–183, Oct. 2017, DOI: 10.1109/MCOM.2017.1601065; Saito Y., Kishiyama Y., Benjebbour A., Nakamura T., Li A., Higuchi K.: Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access, 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), 2013, pp. 1–5, DOI: 10.1109/VTCSpring.2013.6692652; Dai L., Wang B., Ding Z., Wang Z., Chen S. Hanzo L.: A Survey of Non-Orthogonal Multiple Access for 5G, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 3, pp. 2294–2323, thirdquarter 2018, DOI: 10.1109/COMST.2018.2835558; Cai Y. , Qin Z., Cui F., Li G.Y., McCann J.A.: Modulation and Multiple Access for 5G Networks, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 1, pp. 629–646, Firstquarter 2018, DOI: 10.1109/COMST.2017.2766698.

within the network simultaneously[12]. Each AP is connected via a fronthaul link to a CPU which is responsible for AP cooperation. The Cell-Free network can be divided into an edge or a core. The edge is comprised of the APs, CPUs, and the fronthaul links, while the core network facilitates all the services requested by UE. The connections between core and edge are called backhaul links. Thence the CPU communicates with the core network via backhaul links. The figure below shows a simple CF-mMIMO network architecture[13].

The word "Cell-Free" means that there are no cell boundaries that exist from a UE perspective during uplink and downlink transmission since all APs that affect a UE will take part in the communication[14]. CF-mMIMO can be viewed as an overarching concept focused on CF networks but which contains convectional massive MIMO, convectional coordinated multipoint (COMP), and convectional ultra-dense networks as three special cases.

[12] Ngo H.Q., Ashikhmin A., Yang H., Larsson E.G., Marzetta T.L.: Cell-Free Massive MIMO Versus Small Cells, in IEEE Transactions on Wireless Communications, Vol. 16, no. 3, pp. 1834–1850, March 2017, DOI: 10.1109/TWC.2017.2655515; He H., Yu X., Zhang J., Song S.H., Letaief K.B.: Cell-Free Massive MIMO for 6G Wireless Communication Networks. arXiv 2021 preprint arXiv:2110.07309; Shaik Z.H., Björnson E., Larsson E.G.: Cell-Free Massive MIMO with Radio Stripes and Sequential Uplink Processing, 2020 IEEE International Conference on Communications Workshops (ICC Workshops), 2020, pp. 1–6, DOI: 10.1109/ICCWorkshops49005.2020.9145164; Yang H., Marzetta T.L.: Energy Efficiency of Massive MIMO: Cell-Free vs. Cellular, 2018 IEEE 87th Vehicular Technology Conference (VTC Spring), 2018, pp. 1–5, DOI: 10.1109/VTCSpring.2018.8417645; Interdonato G., Björnson E., Ngo H.Q., Frenger P., Larsson E.G.: Ubiquitous cell-free massive MIMO communications. EURASIP Journal on Wireless Communications and Networking, 2019(1), 1–13; Ngo H.Q., Tran L., Duong T.Q., Matthaiou M., Larsson E.G.: On the Total Energy Efficiency of Cell-Free Massive MIMO, in IEEE Transactions on Green Communications and Networking, Vol. 2, no. 1, pp. 25–39, March 2018, DOI: 10.1109/TGCN.2017.2770215; Demir Ö.T., Björnson E., Sanguinetti L.: Foundations of User-Centric Cell-Free Massive MIMO, Foundations and Trends in Signal Processing: Vol. 14, No. 3–4, 2021, pp. 162–472. DOI: 10.1561/2000000109; Zhang J., Chen S., Lin Y., Zheng J., Ai B., Hanzo L.: Cell-Free Massive MIMO: A New Next-Generation Paradigm, in IEEE Access, Vol. 7, 2019, pp. 99878–99888, DOI: 10.1109/ACCESS.2019.2930208; Elhoushy S., Ibrahim M. Hamouda W.: Cell-Free Massive MIMO: A Survey, in IEEE Communications Surveys & Tutorials, DOI: 10.1109/COMST.2021.3123267.

[13] Interdonato G., Björnson E., Ngo H.Q., Frenger P., Larsson E.G.: Ubiquitous cell-free massive MIMO communications. EURASIP Journal on Wireless Communications and Networking, 2019(1), 1–13; Zhang J., Chen S., Lin Y., Zheng J., Ai B., Hanzo L.: Cell-Free Massive MIMO: A New Next-Generation Paradigm, in IEEE Access, Vol. 7, 2019, pp. 99878–99888, DOI: 10.1109/ACCESS.2019.2930208.

[14] Demir Ö. T., Björnson E., Sanguinetti L.: Foundations of User-Centric Cell-Free Massive MIMO, Foundations and Trends in Signal Processing: Vol. 14, No. 3–4, 2021, pp. 162–472. DOI: 10.1561/2000000109.

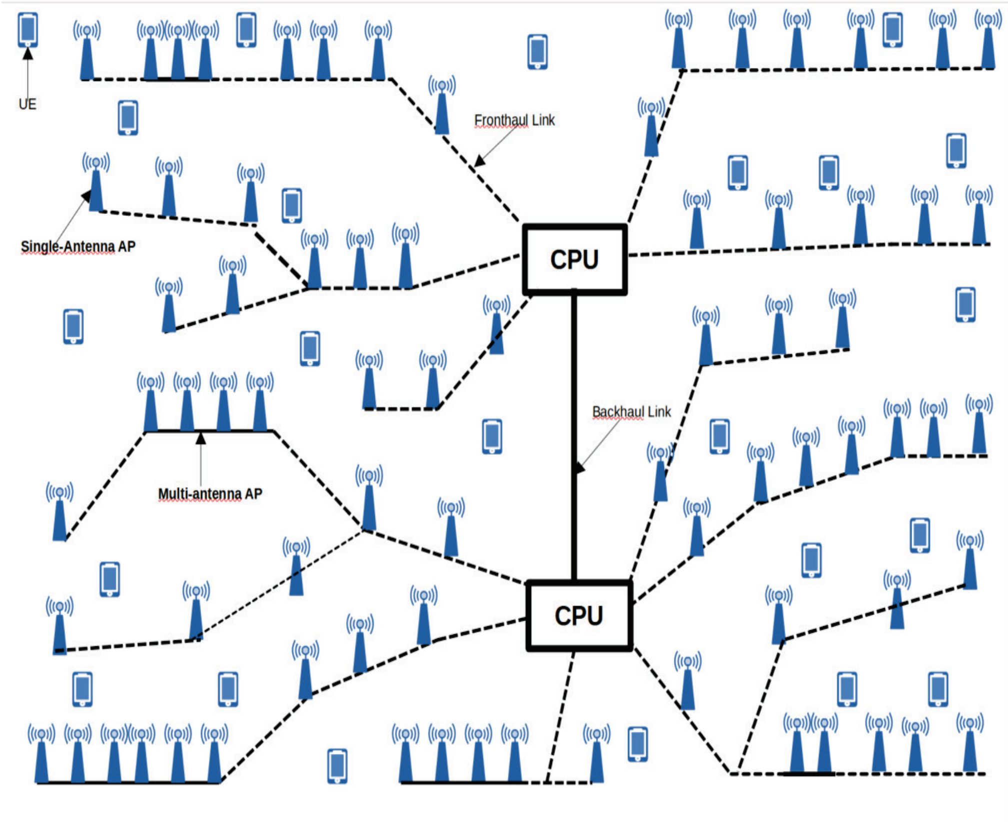


Fig. 14.1. Cell-Free Massive MIMO network
Rys. 14.1. Masywna sieć MIMO bez komórek
Source: based on Interdonato G., Björnson E., Ngo H.Q., Frenger P., Larsson E.G.: Ubiquitous cell--free massive MIMO communications. EURASIP Journal on Wireless Communications and Networking, 2019(1), 1–13; Zhang J., Chen S., Lin Y., Zheng J., Ai B., Hanzo L.: Cell-Free Massive MIMO: A New Next-Generation Paradigm, in IEEE Access, Vol. 7, 2019, pp. 99878–99888, DOI: 10.1109/ACCESS.2019.2930208.

The distinguishing features of Cell-Free architecture are: firstly, Time Division Duplex (TDD) protocol used to exploit channel reciprocity on the uplink and downlink. Secondly, uplink channels estimate computed locally at each AP based on the pilot signals transmitted from users and exploited locally, so that they are not sent on the backhaul link. Third, the beamformers used at the APs, computed locally and not at the CPU. Lastly, the backhaul is used to send data symbols on the downlink and sufficient statistics on the uplink to perform centralized uplink data decisions.

**Communication Protocol: TDD Operation**

As in convectional mMIMO, in CF-mMIMO, TDD operation is preferred because the channel estimation overhead in TDD operation is independent of the number of APs. It only depends on the number of users. This makes CF-mMIMO scalable since adding more APs will not affect the operation of the channel estimation and is always beneficial for increased data rate. Through reciprocity principle, the uplink channel estimates are treated as the downlink channels thus the uplink channels can be used for detection in the uplink and for processing the transmit signals in the downlink. The TDD transmission protocol is shown in Figure 14.2.

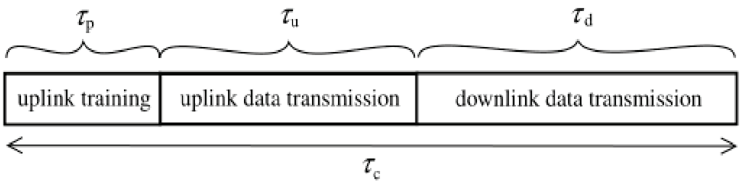


Fig. 14.2. TDD Transmission protocol
Rys. 14.2. Protokół transmisji TDD

The coherence interval which its length is denoted by $\tau_c$ has three activities: uplink training ($\tau_p$ symbols), uplink data transmission ($\tau_u$ symbols) and downlink data transmission ($\tau_d$).

In uplink training phase, all users first send their pilot sequences of length $\tau_p$ symbols to the APs. Then each AP estimates all its channels to the users for the received pilot signals. As in[15], we denote by $\phi_k \in C^{N_{UE}\times\tau_p}$ the pilot sequence sent by the $k$-th UE, and the rows of $\phi_k$ are assumed to be orthogonal, i.e., $\phi_\kappa\phi_\kappa^D = I_S$. Since more than one UE might be assigned to each pilot sequence, we denote the index of pilot assigned to UE $k$ as $t_k \in \{1, \dots, \tau_p\}$. The received signal at AP 1 during the entire pilot transmission is denoted as $y_l^{PILOT} \epsilon^{N\times\tau_p}$ and is given by:

$$Y_l^{PILOT} = \sum_{i=1}^{K} \sqrt{\eta_i} h_{il} \phi_{t_i}^T + N_l \tag{2.1}$$

where $N_l \in \mathbb{C}^{N\times\tau_p}$ is the receiver noise with i.i.d elements distributed as $N_C(0, \sigma_{UL}^2)$. The received uplink signal is the observation that AP $l$ can use to estimate the channel. The estimation can either be carried out directly at AP $l$ or be delegated to the CPU where the AP acts as the relay and sends the received pilot signals to the CPU via the fronthaul link.

To estimate the channel, $h_{kl}$ (either at AP or at the CPU), based on the received pilot signal $Y_l^{PILOT}$ , we remove the interference from UEs using orthogonal pilots by

[15] Akyildiz I.F., Kak A., Nie S.: 6G and Beyond: The Future of Wireless Communications Systems, in IEEE Access, Vol. 8, pp. 133995-134030, 2020, DOI: 10.1109/ACCESS.2020.3010896.

multiplying the received signal $y_l^{PILOT}$ with the normalized conjugate of the associated pilot $\phi_{tk}$ yielding:

$$y_{t_k l}^{PILOT} = y_l^{PILOT}\phi_{t_k}^H = \sqrt{\eta_k \tau_p} h_{k_l} + \sum_{i \in P_k/\{K\}} \sqrt{\eta_i \tau_p} h_{il} + n_{t_k l} \quad (2.2)$$

where the first term is the desired part, the second is interference and the third is the noise. Usually, linear minimum mean-square error estimation (MMSE) technique is used. It exploits channel statistics to obtain good estimates. When the coherence interval is large, compared to the number of users, then we choose $\tau_p > K$, and the pilot sequence can then be assigned for the $K$ users' pair wisely orthogonally. Or else, nonorthogonal pilot sequences must be used throughout the network. The channel estimates of a given user will then be contaminated by pilot signals transmitted from other users, degrading the system performance even if the number of APs is very large. This effect is called the Pilot Contamination.

In the uplink payload data transmission, all users simultaneously send their signals to the APs. The data bearing signal $x_{u,k} \in \mathbb{C}$ with $\mathbb{E}\left\{\left|x_{u,k}\right|^2\right\} = 1$ is sent by the $k$-th user and is mutually independent, and independent of noise and channel coefficients. The normalized transmit power is denoted by $\rho_u$. The received signal at the $m$-th AP is:

$$y_{u,m} = \sqrt{\rho_u} \sum_{k=1}^{K} g_{mk} \sqrt{\eta_k} x_{u,k} + n_{u,m} \quad (2.3)$$

where $n_{u,m} \sim \mathcal{CN}(0,1)$ is additive noise. Each AP uses its local channel estimates to process the received signals and sends the processed signals to the CPU. The APs $m$ multiplies $y_{u,m}$ by $\hat{g}_{mk}^*$ (conjugate beamforming/matched filtering). The CPU then detects all signals transmitted from all $M$ APs the signal of the k-th user as:

$$r_{u,k} = \sum_{m=1}^{M} \hat{g}_{mk}^* y_{u,m} = \sqrt{\rho_u} \sum_{k'=1}^{K} \sum_{m=1}^{M} \hat{g}_{mk}^* g_{mk'} x_{u,k'} + \sum_{m=1}^{M} \hat{g}_{mk}^* n_{u,m} \quad (2.4)$$

Simple linear processing like maximum ratio processing is recommended at each AP. Also, signal processing can be done at the CPUs. The APs need to forward their channel estimates and record data to the CPU for signal detection.

Finally, in the downlink payload data transmission, the APs use their local channel estimates to precode the symbols intended for all $K$ users and broadcast the precoded versions to the users. The data symbol is $x_{d,k} \in \mathbb{C}$ with $\mathbb{E}\left\{\left|x_{d,k}\right|^2\right\} = 1$ . The m-th AP sends the data-bearing signal for all $K$ users as:

$$y_{dm} = \sqrt{\rho_d} \sum_{\kappa=1}^{K} \hat{g}_{mk}^{*} x_{d,k} \tag{2.5}$$

Each user then detects the desired symbol from the received signals. Linear processing such as maximum ratio/conjugate beamforming can be use at each AP. The received signal is given by:

$$r_{dk} = \sum_{m=1}^{M} g_{mk} y_{d,m} + n_{d,k} = \sqrt{\rho_d} \sum_{m=1}^{M} \sum_{k^{+}=1}^{K} g_{mk} \hat{g}_{mk'}^{*} x_{dk'} + n_{d,k} \tag{2.6}$$

CF-mMIMO is expected to bring important benefits such as huge data throughput, ultra-low latency, ultra-high reliability, high energy efficiency and uniform coverage, flexible and cost-efficient deployment, channel hardening and favorable propagation conditions and appealing uniform quality of service[16].

Despite the benefits, CF-mMIMO still faces some challenges and limitations. First, they are practical implementations in which the system requires huge backhaul connections, especially when the number of APs is very large hence suitable transmission approaches are required. User-centric approach is a possible solution, though the performance can't outperform traditional CF-mMIMO in overloaded cases, where the number of UEs is larger than APs. Also, multiple CPUs can be used. Secondly, synchronization of the system is needed so that all APs can coherently serve all the users. Finally, CF-mMIMO is susceptible to pilot contamination which significantly degrades the system performance.

Suggestions have been made to further improve the performance of CF-mMIMO in-terms of achievable data rates, reliability, security, and connection density by integrating CF-mMIMO systems with emerging technologies[17]. These technologies include Non-Orthogonal Multiple Access (NOMA) – our focus, Physical Layer Security

[16] Interdonato G., Björnson E., Ngo H.Q., Frenger P., Larsson E.G.: Ubiquitous cell-free massive MIMO communications. EURASIP Journal on Wireless Communications and Networking, 2019(1), 1–13; Zhang J., Chen S., Lin Y., Zheng J., Ai B., Hanzo L.: Cell-Free Massive MIMO: A New Next-Generation Paradigm, in IEEE Access, Vol. 7, 2019, pp. 99878–99888, DOI: 10.1109/ACCESS.2019.2930208.

[17] He H., Yu X., Zhang J., Song S.H., Letaief K.B.: Cell-Free Massive MIMO for 6G Wireless Communication Networks. arXiv 2021 preprint arXiv:2110.07309; Elhoushy S., Ibrahim M. Hamouda W.: Cell-Free Massive MIMO: A Survey, in IEEE Communications Surveys & Tutorials, DOI: 10.1109/COMST.2021.3123267.

(PLS), Reconfigurable Intelligent Surfaces (RIS), Radio Stripes system, Federated Learning, Machine Learning and Unmanned Aerial Vehicle (UAV).

### Features of CF-mMIMO

CF-mMIMO inherits the benefits and features of mMIMO and provides more features than mMIMO. In addition to channel hardening and favourable propagation that it inherits from mMIMO, it has macro diversity and signal spatial sparsity as two more distinctive features than mMIMO.

- Channel Hardening – it is the effect of small-scale fading which is averaged out, and devices' channels behave a deterministic like wired channel as the number of antennas approaches infinity.
- Favourable Propagation – it is the channel of different devices become orthogonal as number of antennas approaches infinity, which makes different devices distinguishable in space.
- Macro Diversity – it is a signal combination method that combines multiple copies of the same signal into one powerful signal. Macro diversity gain is increased as APs are geographically distributed with several neighbouring APs each surrounding each device other. This leads to a reduced distance from device to any nearest AP as compared to mMIMO.
- Signal Spatial Sparsity – the signal of a device to different APs undergoes different levels of large-scale fading with neighbouring APs in the vicinity of a device usually capture more significant signal energy than other APs. This results in only neighbouring APs within a communication range of a device have non-negligible channel gains due to macro diversity leading to signal spatial sparsity.

### 13.2.2. NOMA Fundamentals

Multiple Access Schemes are used to allow mobile users to share simultaneously a finite amount radio spectrum to achieve high capacity by simultaneously allocating available bandwidth to multiple users. This should be done without degradation in the performance of the system.

Generally, Multiple Access Schemes can be broadly categorized into orthogonal and non-orthogonal approaches. Different multiple access schemes are discussed in [18].

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[18] Dai L., Wang B., Ding Z., Wang Z., Chen S. Hanzo L.: A Survey of Non-Orthogonal Multiple Access for 5G, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 3, pp. 2294–2323, thirdquarter 2018, DOI: 10.1109/COMST.2018.2835558; Cai Y., Qin Z., Cui F., Li G.Y., McCann J.A.: Modulation and Multiple Access

In Orthogonal Multiple Access (OMA) system, orthogonal resource allocation is used among users to avoid intra-cell (inter-user) interference. The number of users that can be supported in then limited by the number of orthogonal resources available.

Non-Orthogonal Multiple Access (NOMA) can support multiple users within a single resource and thus can improve user and overall system throughput at the expense of increased receiver complexity which is required for separating the non-orthogonal signal[19]. The Figure 14.3 shows a simple comparison between basic downlink NOMA and OMA (OFDMA).

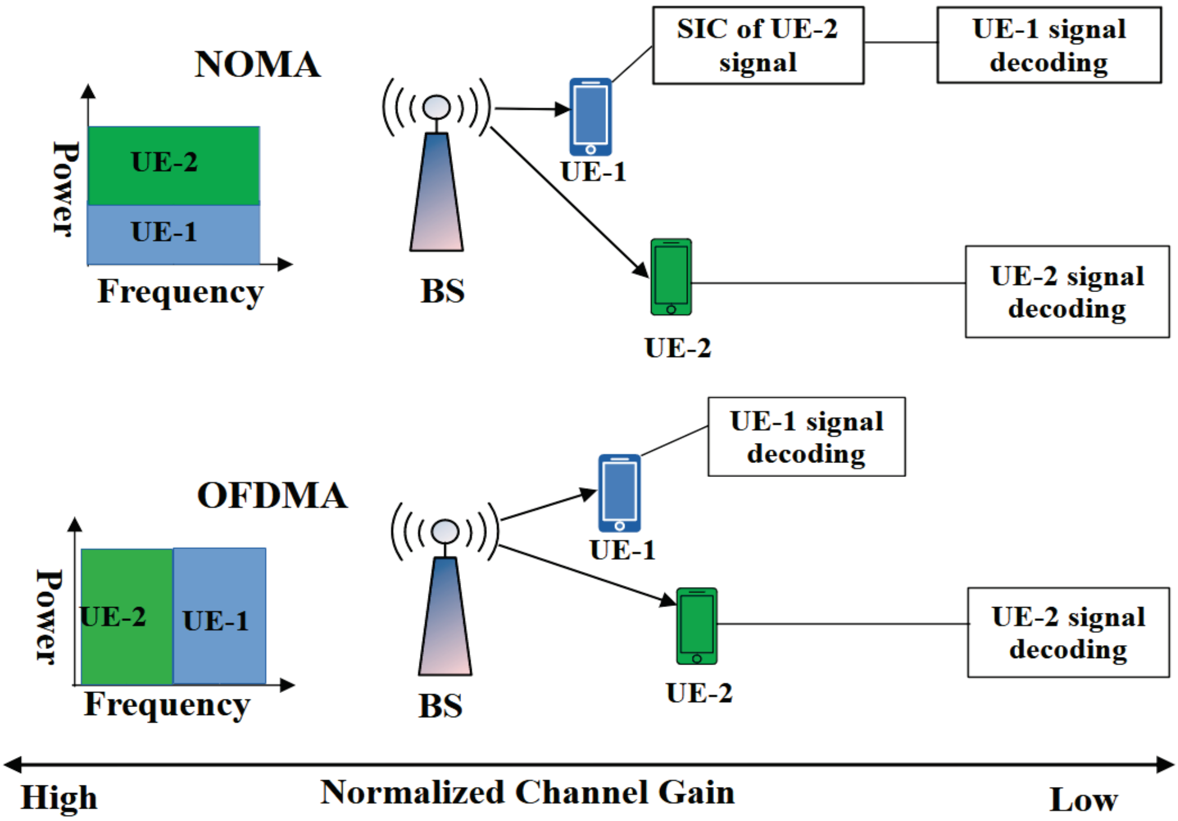


Fig. 14.3. Simple comparison between basic downlink NOMA and OMA (OFDMA)
Rys. 14.3. Proste porównanie pomiędzy NOMA I OMA

for 5G Networks, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 1, pp. 629–646, Firstquarter 2018, DOI: 10.1109/COMST.2017.2766698; He H., Yu X., Zhang J., Song S.H., Letaief K.B.: Cell-Free Massive MIMO for 6G Wireless Communication Networks. arXiv 2021 preprint arXiv:2110.07309.

[19] Dai L., Wang B., Ding Z., Wang Z., Chen S. Hanzo L.: A Survey of Non-Orthogonal Multiple Access for 5G, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 3, pp. 2294–2323, thirdquarter 2018, DOI: 10.1109/COMST.2018.2835558.

Some of the possible benefits of NOMA are[20]:

- Massive connectivity – unlimited number of users.
- Low latency – NOMA can support flexible scheduling and grant-free transmission.
- Improved spectral efficiency – Every NOMA user can utilize the entire bandwidth; the data rates of properly grouped users can be increased.
- Relaxed channel feedback – perfect uplink CSI is not required at the BS.
- Instead, only the received signal strength needs to be included in the channel feedback.

The NOMA cellular system components are: Multi-user grouping, Resource Allocation (power, code, etc.) and Successive Interference Cancellation (SIC) or Multi--user detection (MUD) techniques to remove the controlled NOMA additions.

The following definitions and viewpoints are used to define non-orthogonality in NOMA:

a) *Superposition Coding (SC) and Successive Interference Cancellation (SIC)*

Downlink NOMA employs superposition coding at the transmitter and successive interference cancellation at the receiver making it possible to utilize the same spectrum for all users[21]. SIC is also mentioned in uplink transmission[22].

The objective of SC is to communicate two messages simultaneously by encoding them into a single signal in two layers. In SC, the source node creates two different messages, namely the basic message and the superposed message. For example, assuming a BS is communicating with two end users in a downlink communication, the messages are broadcasted to two receivers, the receiver with the strongest channel can decode both the messages while the receiver with the worse channel can only decode the basic message[23].

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[20] Shin W., Vaezi M., Lee B., Love D.J., Lee J., Poor H.V.: Non-Orthogonal Multiple Access in Multi-Cell Networks: Theory, Performance, and Practical Challenges, in IEEE Communications Magazine, Vol. 55, no. 10, pp. 176–183, Oct. 2017, DOI: 10.1109/MCOM.2017.1601065; Saito Y., Kishiyama Y., Benjebbour A., Nakamura T., Li A., Higuchi K.: Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access, 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), 2013, pp. 1–5, DOI: 10.1109/VTCSpring.2013.6692652; Dai L., Wang B., Ding Z., Wang Z., Chen S. Hanzo L.: A Survey of Non-Orthogonal Multiple Access for 5G, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 3, pp. 2294–2323, thirdquarter 2018, DOI: 10.1109/COMST.2018.2835558; Cai Y. , Qin Z., Cui F., Li G.Y., McCann J.A.: Modulation and Multiple Access for 5G Networks, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 1, pp. 629–646, Firstquarter 2018, DOI: 10.1109/COMST.2017.2766698.

[21] Kizilirmak R.C., Hossein K.B.: Non-orthogonal multiple access (NOMA) for 5G networks. Towards 5G Wireless Networks-A Physical Layer Perspective 83, 2016, pp. 83–98; Liu Y., Qin Z., Elkashlan M., Ding Z., Nallanathan A., Hanzo, L.:Nonorthogonal multiple access for 5G and beyond. Proceedings of the IEEE, 2017.

[22] Liu Y., Qin Z., Elkashlan M., Ding Z., Nallanathan A., Hanzo, L.:Nonorthogonal multiple access for 5G and beyond. Proceedings of the IEEE, 2017.

[23] Liu Y., Qin Z., Elkashlan M., Ding Z., Nallanathan A., Hanzo, L.:Nonorthogonal multiple access for 5G and beyond. Proceedings of the IEEE, 2017; Wang L., Şaşoğlu E., Bandemer B., Kim Y.: A comparison of superposition coding schemes, 2013 IEEE International Symposium on Information Theory, 2013, pp. 2970–2974, DOI: 10.1109/ISIT.2013.6620770;

On the other hand, SIC is a physical technique with a capability that allows a receiver to decode packets that arrive simultaneously. It is the ability of a receiver to receive two or more signal concurrently. SIC is possible because the receiver may be able to decode the stronger signal, subtract (cancel) it from combined signal and extract the weaker one from residue[24]. The method of NOMA that employ SC and SIC is known as Power Domain NOMA (PD-NOMA). The PD-NOMA has been proposed to 3GPP LTE[25].

b) *Overloading*

In this context, NOMA can support multiple transmission within the same time, frequency resource block by assigning different codes to different users, adopt unique user specific spreading sequence[26]. This concept is inspired by the classic CDMA systems. Examples of NOMA schemes developed with this view are Low-density spreading (LDS) CDMA, LDS-OFDM, Sparse Code Multiple Access (SCMA), and Multi-user shared access (MUSA) which are collectively known as Code Domain NOMA.

c) *Linear Transform Decoding*

This involves definition of NOMA based on the complexity of multi-user detection. In this view, in an OMA scheme, the signals of different users can be separated in orthogonal subspaces using linear transform. Then any scheme that does meet this definition can be categorized as NOMA.

d) *Information-theoretical view*

In this, NOMA may refer to any technique in which concurrent transmission is allowed over the same resources in time/frequency/code/space, achieving a better rate region when compared to orthogonalization of one or some of the resources. This includes SC and SIC, rate-splitting (RS) and dirty paper coding (DPC)[27].

From the different definitions and points of view above, we have so many kinds of NOMA. Different kinds of NOMA have been investigated. Basically, there two

[24] Liu Y., Qin Z., Elkashlan M., Ding Z., Nallanathan A., Hanzo, L.:Nonorthogonal multiple access for 5G and beyond. Proceedings of the IEEE, 2017; Sen S., Santhapuri N., Choudhury R.R., Nelakuditi S.:Successive interference cancellation: a back-of-the-envelope perspective. In Proceedings of the 9th ACM SIGCOMM Workshop on Hot Topics in Networks ( Hotnets-IX). Association for Computing Machinery, New York, NY, USA, Article 17, 2010, pp. 1–6. DOI: https://doi.org/10.1145/1868447.1868464.

[25] Liu Y., Qin Z., Elkashlan M., Ding Z., Nallanathan A., Hanzo, L.:Nonorthogonal multiple access for 5G and beyond. Proceedings of the IEEE, 2017.

[26] Dai L., Wang B., Ding Z., Wang Z., Chen S. Hanzo L.: A Survey of Non-Orthogonal Multiple Access for 5G, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 3, pp. 2294–2323, thirdquarter 2018, DOI: 10.1109/COMST.2018.2835558; Cai Y., Qin Z., Cui F., Li G.Y., McCann J.A.: Modulation and Multiple Access for 5G Networks, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 1, pp. 629–646, Firstquarter 2018, doi: 10.1109/COMST.2017.2766698.

[27] Liu Y., Qin Z., Elkashlan M., Ding Z., Nallanathan A., Hanzo, L.:Nonorthogonal multiple access for 5G and beyond. Proceedings of the IEEE, 2017.

dominating categories of NOMA namely: – Power Domain NOMA and Code Domain NOMA[28]. The Figure 14.4 shows a simple category of NOMA techniques.

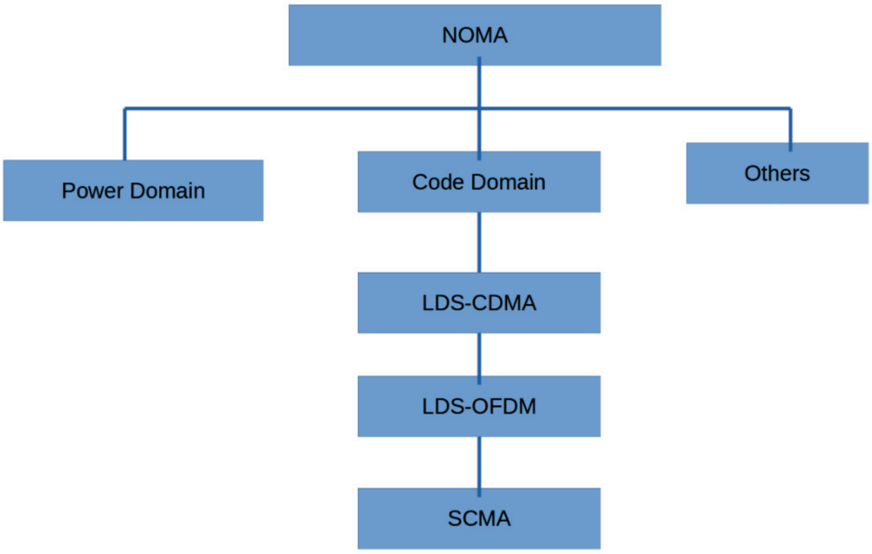


Fig. 14.4. A simple category of NOMA techniques
Rys. 14.4. Kategoria technik NOMA

- To understand NOMA with SIC, let us consider Figure 14.4 that illustrates the basic NOMA scheme applying SIC for UE receivers in the cellular downlink. The overall system transmission bandwidth is assumed to be 1 Hz. The base station transmits a signal for user 1 and user 2, $x_i$ (i = 1,2), where E[|$x_i$|2] = 1, with transmission power $P_i$. The sum of $P_i$ is restricted to P at maximum[29]. The transmitted signal is represented, $x_1$ and $x_2$ are superposition coded as:

$$x = \sqrt{P_1}x_1 + \sqrt{P_2}x_2 \tag{2.7}$$

The received signal at UE-*I* is represented as

$$y_i = h_i x + w_i \tag{2.8}$$

where hi is the complex channel coefficient between UE-i and the base station. $w_i$ denotes the receiver Gaussian noise including inter-cell interference. The power density of $w_i$ is $N_{o,I}$.

[28] Dai L., Wang B., Ding Z., Wang Z., Chen S. Hanzo L.: A Survey of Non-Orthogonal Multiple Access for 5G, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 3, pp. 2294–2323, thirdquarter 2018, DOI: 10.1109/COMST.2018.2835558.
[29] Interdonato G., Björnson E., Ngo H.Q., Frenger P., Larsson E.G.: Ubiquitous cell-free massive MIMO communications. EURASIP Journal on Wireless Communications and Networking, 2019(1), 1–13.

In the NOMA downlink, the SIC process is implemented at the UE receiver. The optimal order for decoding is in the order of the increasing channel gain normalized by the noise and the inter-cell interference power, $|h_i|^2/ N_{o,i}$. Based on this order, any user can correctly decode the signals of the other users whose decoding order comes before that user for interference cancellation. Thus, UE-$i$ can remove the inter-user interference from the $j$-th user whose $|h_j|^2/ N_{o,j}$ is lower than $|h_i|^2/ N_{o,I}$. In UE-2 case, it does not perform interference cancellation since it comes first in the decoding order $h_1|^2/N_{0,1} > |h_2|^2/ N_{o,2}$. UE-2 first decodes $x_2$ and subtracts its component from the received signal $y_1$. Then, UE-1 can decode $x_1$ without interference from $x_2$. Assuming error-free detection of $x_2$ at UE-1, the throughput of UE-$i$, $R_i$, is represented as

$$
\begin{aligned}
R_1 &= \log_2\left[1 + \frac{P_1|h_1|^2}{N_{0,1}}\right] \\
R_2 &= \log_2\left[1 + \frac{P_2|h_2|^2}{P_1|h_2|^2 + N_{0,2}}\right]
\end{aligned}
\tag{2.9}
$$

In comparison with OFDMA, when we assume OFDMA with orthogonal user multiplexing, where the bandwidth of $\alpha$ $(0 < \alpha < 1)$ Hz is assigned to UE 1 and the remaining bandwidth, $1 - \alpha$ Hz, is assigned to UE 2, $R_i$ is represented as:

$$
\begin{aligned}
R_1 &= \alpha \log_2\left[1 + \frac{P_1|h_1|^2}{\alpha N_{0,1}}\right] \\
R_2 &= (1 - \alpha) \log_2\left[1 + \frac{P_2|h_2|^2}{(1-\alpha) N_{0,2}}\right]
\end{aligned}
\tag{2.10}
$$

In NOMA, the performance gain compared to OFDMA increases when there is difference in channel gains. It can be shown in Fig. 14.5 that this NOMA scheme can achieve higher rates than OFDMA. A UE-2 case with a cell-interior UE and a cell-edge UE are assumed, where $P_1|h_1|^2/N_{0,1}$ and $P_2|h_2|^2/N_{0,2}$ is set to 20 and 0 dB respectively. At the same time, this NOMA scheme makes full use of the natural difference of channel gains among users, implying that the near far effect is effectively harnessed to achieve higher spectral efficiency. Consequently, both the attainable sum capacity and the cell--edge user rate can be improved.

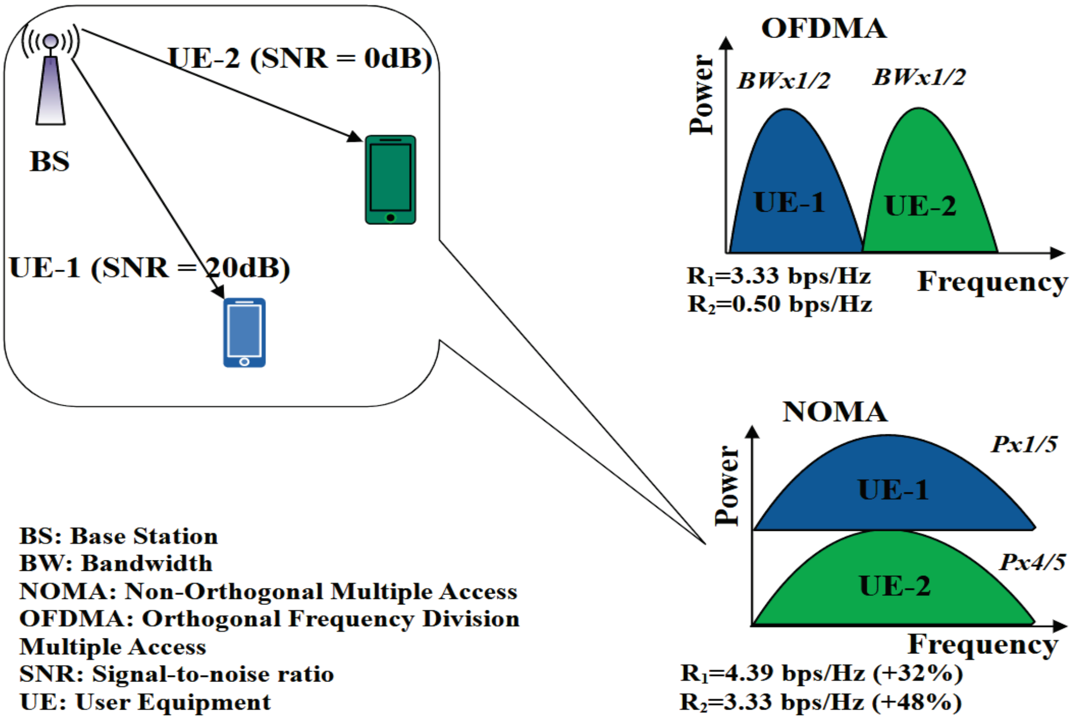


Fig. 14.5. OFDMA vs NOMA (Simple example)
Rys. 14.5. Przykład porównujący OFDMA i NOMA
Source: based on Saito Y., Kishiyama Y., Benjebbour A., Nakamura T., Li A., Higuchi K.: Non--Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access, 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), 2013, pp. 1–5, DOI: 10.1109/VTCSpring.2013.6692652

From Tse et al. (2005)[30], the boundaries of the rate regions achievable with superposition coding and optimal orthogonal schemes for asymmetric, downlink AWGN channel (with SNR1 = 0dB and SNR2 = 20bB) is compared as shown in figure below. We observe that the results of the superposition coding outperform that of the orthogonal signals.

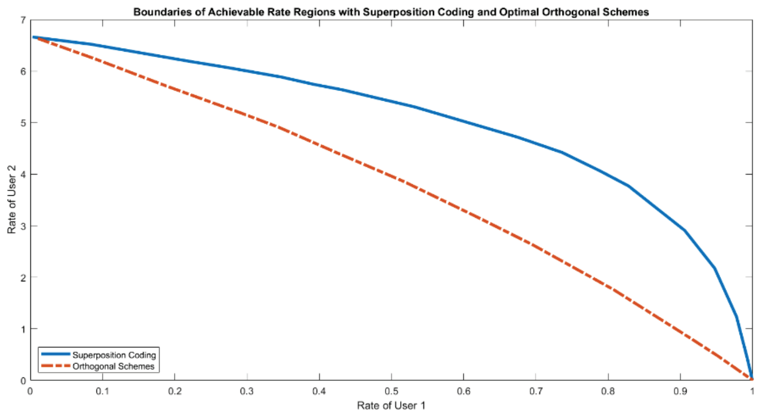


Fig. 14.6. Two user downlink asymmetric AWGN rates achievable by superposition coding (solid line) and orthogonal schemes (dashed line)
Rys. 14.6. Asymetryczne szybkości AWGN w łączu w dół dla dwóch użytkowników osiągalne dzięki kodowaniu superpozycji (linia ciągła) i schematom ortogonalnym (linia przerywana)

[30] D. Tse, P. Viswanath, Fundamentals of Wireless Communication. Cambridge University Press, 2005.

In investigation of performance gain of NOMA in practical assumptions[31], conducts a multi-cell system-level simulation. The performance gain of NOMA using wideband scheduling and power allocation is evaluated. The wideband case is evaluated since the system performance not relying on the frequency-selective channel information is important for practical wide area deployments. To further illustrate this, Figure 14.7 shows the CDF of the user throughput for OFDMA and NOMA with SIC. From the figure we can conclude that the user throughput performance of NOMA is improved compared to that of OFDMA and an approximate gain of 27% for NOMA in is obtained both the cell throughput and cell-edge user throughput.

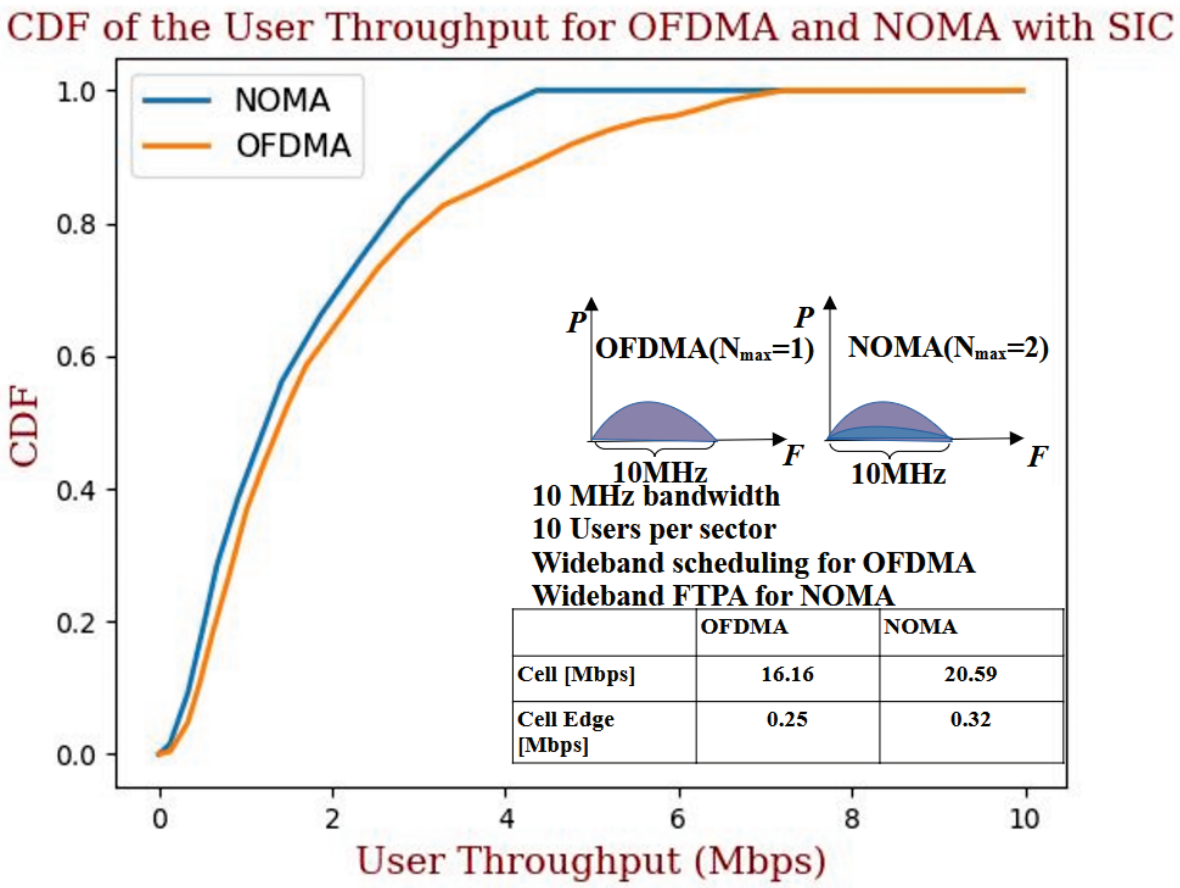


Fig. 14.7. System-level evaluation for OFDMA and NOMA when using wideband scheduling and power allocation

Rys. 14.7. Ocena na poziomie systemu dla OFDMA i NOMA przy użyciu szerokopasmowego harmonogramu i alokacji mocy

Source: based on Dai L., Wang B., Ding Z., Wang Z., Chen S., Hanzo L.: A Survey of Non--Orthogonal Multiple Access for 5G, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 3, pp. 2294–2323, thirdquarter 2018, DOI: 10.1109/COMST.2018.2835558.

[31] Dai L., Wang B., Ding Z., Wang Z., Chen S. Hanzo L.: A Survey of Non-Orthogonal Multiple Access for 5G, in IEEE Communications Surveys & Tutorials, Vol. 20, no. 3, pp. 2294–2323, thirdquarter 2018, DOI: 10.1109/COMST.2018.2835558.

## 14.3. NOMA-Aided Cell-Free Massive MIMO

### 14.3.1. State-of-Art

Despite its advantages and potential, there are only a few works on NOMA in Cell-Free Massive MIMO systems in literature. In this section, we survey the integration of NOMA with cell-free massive MIMO systems.

The first research work on CF-mMIMO-NOMA was done in (Li Y. et al. 2018)[32], where a closed-form achievable sum-rate of PD-NOMA is derived under consideration of the effects of intra-cluster pilot contamination, inter-cluster interference, and imperfect SIC. The system model used consist of a downlink communication with single antenna APs and single antenna users, operating in TDD protocol, and the APs employ conjugate beamforming. Numerical results showed the superior performance of NOMA compared to OMA. The authors in Zhang Y. et al. (2019) [33] were the first to investigate the uplink scenario in CF-mMIMO-NOMA and derived closed-form expression of spectral efficiency for conjugate beamforming considering the effect of intra-cluster pilot contamination, inter-cluster interference and imperfect SIC, and power optimization. It maximizes the SE through an iterative Geometric programming (GP) algorithm based on Sequential Convex Approximation (SCA). The simulation results demonstrated that CF-mMIMO-NOMA can utilize the scarce spectrum more efficiently. In Zhang X. et al. (2020)[34], an optimal backhaul combining process is suggested which maximizes the uplink SINR.

In terms of communication protocol, all the recent works have been based on TDD protocol. None has focused on FDD as a transmission protocol. Just as CF-mMIMO, CF-mMIMO-NOMA system consists of $M$ single/multiple antenna(s) APs and $K$ users. While most literature focuses on single antenna AP[35], present multi-antenna APs.

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[32] Li Y., Baduge G.A.A.: NOMA-Aided Cell-Free Massive MIMO Systems, in IEEE Wireless Communications Letters, Vol. 7, no. 6, pp. 950–953, Dec. 2018, DOI: 10.1109/LWC.2018.2841375.

[33] Zhang Y., Cao H., Zhou M., Yang L.: Spectral Efficiency Maximization for Uplink Cell-Free Massive MIMO-NOMA Networks, 2019 IEEE International Conference on Communications Workshops (ICC Workshops), 2019, pp. 1–6, DOI: 10.1109/ICCW.2019.8756881.

[34] Zhang X., Wang J., Poor H.V.: Statistical QoS Provisioning Over Cell-Free M-MIMO-NOMA Based 5G+ Mobile Wireless Networks in the Non-Asymptotic Regime, 2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2020, pp. 1–5, DOI: 10.1109/SPAWC48557.2020.9154222.

[35] Zhang Y., Cao H., Zhou M., Yang L.: Non-orthogonal multiple access in cell-free massive MIMO networks, in China Communications, Vol. 17, no. 8, pp. 81–94, Aug. 2020, DOI: 10.23919/JCC.2020.08.007; Rezaei F., Heidarpour A.R., Tellambura C., Tadaion A.: Underlaid Spectrum Sharing for Cell-Free Massive MIMO-NOMA, in IEEE Communications Letters, Vol. 24, no. 4, pp. 907–911, April 2020, DOI: 10.1109/LCOMM.2020.2966195; Rezaei F., Tellambura C., Tadaion A.A., Heidarpour A.R.: Rate Analysis of Cell-Free Massive MIMO-NOMA With Three Linear Precoders, in IEEE Transactions on Communications, 2020, Vol. 68, no. 6, pp. 3480-3494, doi: 10.1109/TCOMM.2020.2978189;Zhang J., Fan J., Ai B., Ng D.W.K.: NOMA-Based Cell-Free Massive MIMO Over Spatially Correlated Rician Fading Channels, ICC 2020 – 2020

The channel between users and APs is modelled by most as a Rayleigh fading channel assuming non-line-of-sight (NLOS) links between users and APs. The majority of the work focuses on Rayleigh fading channel, only models[36] the channel using Rician fading channel. Specifically Zhang J. et al. (2020)[37] focuses on a system with multi-antenna APs and single-antenna UEs over spatially correlated Rician fading channels.

While most works use conjugate beamforming precoders at Aps[38], employ Maximum ratio transmission (MRT) precoders employ full-pilot zero-forcing (fpZF) precoders[39] and compares the performance of the three practical linear decoders[40]. Specifically, Rezaei F. et al. (2020)[41], comprehensively evaluates the system performance with MRT, fpZF and modified regularized ZF (mRZF) and derives a closed-form sum-rate expression while considering Rayleigh fading channel, the effects of intra-cluster pilot contamination, inter-cluster interference and imperfect SIC. From the analytical results, mRZF and fpZF significantly outperform MRT with perfect SIC despite having the same fronthauling overhead. mRZF achieved the highest rates compared to fpZF and MRT in perfect SIC, because it tries to balance the inter-cluster interference mitigation and intra-cluster power enhancement. However, with the very large number of users, MRT outperforms fpZF. In addition, Bashar M. et al. (2020)[42] derives a closed-form SINR using both conjugate beamforming and normalized conjugate beamforming taking into consideration the effects of pilot contamination and imperfect SIC with an objective of

IEEE International Conference on Communications (ICC), 2020, pp. 1–6, DOI: 10.1109/ICC40277.2020.9148861.

[36] Zhang X., Wang J., Poor H.V.: Statistical QoS Provisioning Over Cell-Free M-MIMO-NOMA Based 5G+ Mobile Wireless Networks in the Non-Asymptotic Regime, 2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2020, pp. 1–5, DOI: 10.1109/SPAWC48557.2020.9154222; Zhang J., Fan J., Ai B., Ng D.W.K.: NOMA-Based Cell-Free Massive MIMO Over Spatially Correlated Rician Fading Channels, ICC 2020 - 2020 IEEE International Conference on Communications (ICC), 2020, pp. 1–6, DOI: 10.1109/ICC40277.2020.9148861.

[37] Zhang J., Fan J., Ai B., Ng D.W.K.: NOMA-Based Cell-Free Massive MIMO Over Spatially Correlated Rician Fading Channels, ICC 2020 – 2020 IEEE International Conference on Communications (ICC), 2020, pp. 1-6, DOI: 10.1109/ICC40277.2020.9148861.

[38] Rezaei F., Heidarpour A.R., Tellambura C., Tadaion A.: Underlaid Spectrum Sharing for Cell-Free Massive MIMO-NOMA, in IEEE Communications Letters, Vol. 24, no. 4, pp. 907–911, April 2020, DOI: 10.1109/LCOMM.2020.2966195; Nguyen T.K., Nguyen H.H., Tuan H.D.: Max-Min QoS Power Control in Generalized Cell-Free Massive MIMO-NOMA With Optimal Backhaul Combining, in IEEE Transactions on Vehicular Technology, 2020, Vol. 69, no. 10, pp. 10949–10964, DOI: 10.1109/TVT.2020.3006054.

[39] Le Q., Nguyen V.-D., Dobre O.A., Nguyen P.N., Zhao R., Chatzinotas S.: Learning-Assisted User Clustering in Cell-Free Massive MIMO-NOMA Networks, in IEEE Transactions on Vehicular Technology, DOI: 10.1109/TVT.2021.3121217.

[40] Rezaei F., Tellambura C., Tadaion A.A., Heidarpour A.R.: Rate Analysis of Cell-Free Massive MIMO--NOMA With Three Linear Precoders, in IEEE Transactions on Communications, 2020, Vol. 68, no. 6, pp. 3480-3494, DOI: 10.1109/TCOMM.2020.2978189.

[41] Rezaei F., Tellambura C., Tadaion A.A., Heidarpour A.R.: Rate Analysis of Cell-Free Massive MIMO--NOMA With Three Linear Precoders, in IEEE Transactions on Communications, 2020, Vol. 68, no. 6, pp. 3480–3494, DOI: 10.1109/TCOMM.2020.2978189.

[42] Bashar M., Cumanan K., Burr A.G., Ngo H.Q., Hanzo L., Xiao P.: On the Performance of Cell-Free Massive MIMO Relying on Adaptive NOMA/OMA Mode-Switching, in IEEE Transactions on Communications, 2020, Vol. 68, no. 2, pp. 792–810, DOI: 10.1109/TCOMM.2019.2952574.

maximizing the bandwidth efficiency. The results show that the performance of conjugate beamforming is superior to that of normalized conjugate beamforming.

While most authors consider static APs and users, Kusaladharma S. et al. (2019)[43] consider random APs and users. Categorically, they investigate how to improve achievable rates of CF-mMIMO-NOMA systems under random AP/user deployments using stochastic geometry-based modelling to obtain an accurate network-wide characterization of performance. They consider a Poisson point process (PPP) of APs and users along Rayleigh fading and log-distance path loss. Some major observations are that the rate gain of NOMA diminishes as density of APs become smaller and for higher path loss exponents, NOMA provides reduced latency at the cost of reduced overall rate.

One of the major challenges in NOMA are user clustering (UC) and user ordering. As studied in NOMA theory, user clustering is a key technique in NOMA systems, in that it facilitates the implementation of NOMA for many users by reducing the complexity of SIC[44]. In typical NOMA works form the literature, the user clustering schemes have opted to group two users per cluster with random pairing[45]. In Bashar M. et al. (2020)[46], three paring schemes, far-, near-, and random paring, are implemented with two users in each cluster. In Rezaei F. et al. (2020)[47], the authors use the Jaccard coefficient to calculate the similarity between each user's large scale fading profile with a predetermined centroid. The users having strong similarity are assigned into different groups. This is user clustering with low complexity optimal method. Nguyen T.K. et al. (2020)[48] propose an iterative user location algorithm that requires the large-scale fading correlation coefficients and the large-scale fading profiles of two users within

[43] Kusaladharma S., Zhu W.-P., Ajib W., Amarasuriya G.: Achievable Rate Analysis of NOMA in Cell-Free Massive MIMO: A Stochastic Geometry Approach, ICC 2019–2019 IEEE International Conference on Communications (ICC), 2019, pp. 1–6, DOI: 10.1109/ICC.2019.8761506; Kusaladharma S., Zhu W.-P., Ajib W., Baduge G.A.A.: Achievable Rate Characterization of NOMA-Aided Cell-Free Massive MIMO With Imperfect Successive Interference Cancellation, in IEEE Transactions on Communications, Vol. 69, no. 5, pp. 3054–3066, May 2021, DOI: 10.1109/TCOMM.2021.3053613.

[44] Bashar M., Cumanan K., Burr A. G., Ngo H. Q., Hanzo L., Xiao P.: On the Performance of Cell-Free Massive MIMO Relying on Adaptive NOMA/OMA Mode-Switching, in IEEE Transactions on Communications, 2020, Vol. 68, no. 2, pp. 792–810, DOI: 10.1109/TCOMM.2019.2952574.

[45] Bashar M., Cumanan K., Burr A.G., Ngo H.Q., Hanzo L., Xiao P.: On the Performance of Cell-Free Massive MIMO Relying on Adaptive NOMA/OMA Mode-Switching, in IEEE Transactions on Communications, 2020, Vol. 68, no. 2, pp. 792–810, DOI: 10.1109/TCOMM.2019.2952574; Bashar M., Cumanan K., Burr A.G., Ngo H.Q., HanzoL., Xiao P.: NOMA/OMA Mode Selection-Based Cell-Free Massive MIMO, ICC 2019–2019 IEEE International Conference on Communications (ICC), 2019, pp. 1–6, DOI: 10.1109/ICC.2019.8761072.

[46] Bashar M., Cumanan K., Burr A.G., Ngo H.Q., Hanzo L., Xiao P.: On the Performance of Cell-Free Massive MIMO Relying on Adaptive NOMA/OMA Mode-Switching, in IEEE Transactions on Communications, 2020, Vol. 68, no. 2, pp. 792–810, DOI: 10.1109/TCOMM.2019.2952574.

[47] Rezaei F., Heidarpour A.R., Tellambura C., Tadaion A.: Underlaid Spectrum Sharing for Cell-Free Massive MIMO-NOMA, in IEEE Communications Letters, Vol. 24, no. 4, pp. 907–911, April 2020, DOI: 10.1109/LCOMM.2020.2966195.

[48] Nguyen T.K., Nguyen H.H., Tuan H.D.: Max-Min QoS Power Control in Generalized Cell-Free Massive MIMO-NOMA With Optimal Backhaul Combining, in IEEE Transactions on Vehicular Technology, 2020, Vol. 69, no. 10, pp. 10949–10964, DOI: 10.1109/TVT.2020.3006054.

a group is minimized. At the same time, Rezaei F. et al. (2020)[49] propose a User-location aware clustering algorithm where each AP needs to only know the user's location and according to the location CPU puts each two nearest users in a common cluster, so that the path-loss between them is significantly reduced. In Wang Z. et al. (2020)[50], a novel user clustering algorithm using cooperative links between users that does not require complex optimization is studied. It guarantees the existence of reliable channels among the users within the same NOMA cluster. However, all the above clustering schemes don't consider any learning features and random user clustering certainly results in a suboptimal solution while an exhaustive search method comes at a cost of high complexity. Le Q. et al. (2021)[51], proposes the use of unsupervised machine learning based UC algorithms, namely K-means++ and improved k-means++ to effectively cluster users into disjoint clusters. The provided numerical results confirm the effectiveness of the UC algorithms over far-, near-, and random pairing schemes and Jaccard-based UC scheme.

Different power optimization techniques are used in CF-mMIMO NOMA. For instance, whereas Zhang Y. et al. (2019)[52] aims at maximizing the uplink spectral efficiency using an iterative geometric programming (GP) algorithm based on sequential convex approximation (SCA), in[53] SCA is used to maximize sum SE subject to each AP power constraint and SIC power constraint. Apart from the max-min power method in Nguyen T.K. et al. (2020 and 2021)[54], the authors consider a max-min algorithm with adaptive SIC while Galappaththige D.L. et al. (2020)[55] proposes a max-min transmit

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[49] Rezaei F., Heidarpour A.R., Tellambura C., Tadaion A.: Underlaid Spectrum Sharing for Cell-Free Massive MIMO-NOMA, in IEEE Communications Letters, Vol. 24, no. 4, pp. 907–911, April 2020, DOI: 10.1109/LCOMM.2020.2966195.

[50] Wang Z., Zhang D., Xu K., Xie W., Xv J., Li X.: NOMA in Cell-Free mMIMO Systems with AP Selection, 2020 International Conference on Wireless Communications and Signal Processing (WCSP), 2020, pp. 430–435, DOI: 10.1109/WCSP49889.2020.9299790.

[51] Le Q., Nguyen V.-D., Dobre O.A., Nguyen P.N., Zhao R., Chatzinotas S.: Learning-Assisted User Clustering in Cell-Free Massive MIMO-NOMA Networks, in IEEE Transactions on Vehicular Technology, DOI: 10.1109/TVT.2021.3121217.

[52] Zhang Y., Cao H., Zhou M., Yang L.: Spectral Efficiency Maximization for Uplink Cell-Free Massive MIMO--NOMA Networks, 2019 IEEE International Conference on Communications Workshops (ICC Workshops), 2019, pp. 1–6, DOI: 10.1109/ICCW.2019.8756881.

[53] Zhang Y., Cao H., Zhou M., Yang L.: Non-orthogonal multiple access in cell-free massive MIMO networks, in China Communications, Vol. 17, no. 8, pp. 81–94, Aug. 2020, DOI: 10.23919/JCC.2020.08.007.

[54] Nguyen T.K., Nguyen H.H., Tuan H.D.: Max-Min QoS Power Control in Generalized Cell-Free Massive MIMO-NOMA With Optimal Backhaul Combining, in IEEE Transactions on Vehicular Technology, 2020, Vol. 69, no. 10, pp. 10949–10964, DOI: 10.1109/TVT.2020.3006054; Nguyen T.K., Nguyen H. ., TuanH. D.: Cell-Free Massive MIMO-NOMA with Optimal Backhaul Combining, 2020 IEEE Eighth International Conference on Communications and Electronics (ICCE), 2021, pp. 455–460, DOI: 10.1109/ ICCE48956.2021.9352089; Nguyen T.K. , Nguyen H.H., Tuan H.D.: Adaptive Successive Interference Cancellation in Cell-free Massive MIMO-NOMA, 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), 2020, pp. 1–5, DOI: 10.1109/VTC2020-Fall49728.2020.9348505.

[55] Galappaththige D.L., Amarasuriya G.: NOMA-Aided Cell-Free Massive MIMO with Underlay Spectrum--Sharing, ICC 2020–2020 IEEE International Conference on Communications (ICC), 2020, pp. 1–6, DOI: 10.1109/ICC40277.2020.9149105.

power control problem that is a quasi-concave problem, and the optimal solution is found by bisection method. In Le Q. et al. (2021)[56], to maximize the sum spectral efficiency, it uses an inner approximation (IA) based iterative algorithm to solve the optimization problem, whose aim is to optimize the normalized transmit power to maximize the sum spectral efficiency under the constrains of the transmit power budget at the APs, SIC conditions, and all minimum required SE at UEs. Bashar M. et al. (2019, 2020)[57] formulate a max-min problem BE optimization problem under per-AP power constraints. Specifically, in[58], a bisection scheme is conceived for optimally solving the optimization problem. The power minimization problem of conjugate beamforming is solved using second order cone programming (SOCP), whereas for normalized conjugate beamforming standard semidefinite programming (SDP) is utilized. To further enhance the performance, the authors propose a mode switching technique based on the average BE. In Bashar M. et al. (2020)[59], a dynamic intra-cluster power allocation method which leads to dynamic power coefficients with different AP is considered. Investigates Sayyari R. et al. (2021)[60] an adaptive switching algorithm between OMA, non--cooperative NOMA, and cooperative NOMA modes to maximize the achievable sum rate and energy efficiency of the system. The system which initially operates in OMA mode, utilizes all the benefits of the different modes at different scenarios that suits each mode. Hua M. et al. (2021)[61]utilizes a Dinkelbach's method-based algorithm to solve its non-convex optimization to obtain an optimal solution with an aim of maximizing the EE. The algorithm is two layered with the bottom layer aiming to solve the power control optimization. It is based on the difference of convex functions programming. The Authors further expounds on the complexity of the algorithms. Finally, Wang Z. et al.

[56] Le Q., Nguyen V.-D., Dobre O.A., Nguyen P.N., Zhao R., Chatzinotas S.: Learning-Assisted User Clustering in Cell-Free Massive MIMO-NOMA Networks, in IEEE Transactions on Vehicular Technology, DOI: 10.1109/TVT.2021.3121217.

[57] Bashar M., Cumanan K., Burr A.G., Ngo H.Q., Hanzo L., Xiao P.: On the Performance of Cell-Free Massive MIMO Relying on Adaptive NOMA/OMA Mode-Switching, in IEEE Transactions on Communications, 2020, Vol. 68, no. 2, pp. 792–810, DOI: 10.1109/TCOMM.2019.2952574; Bashar M., Cumanan K., Burr A.G., Ngo H.Q., HanzoL., Xiao P.: NOMA/OMA Mode Selection-Based Cell-Free Massive MIMO, ICC 2019–2019 IEEE International Conference on Communications (ICC), 2019, pp. 1–6, DOI: 10.1109/ICC.2019.8761072.

[58] Bashar M., Cumanan K., Burr A.G., Ngo H.Q., HanzoL., Xiao P.: NOMA/OMA Mode Selection-Based Cell--Free Massive MIMO, ICC 2019–2019 IEEE International Conference on Communications (ICC), 2019, pp. 1–6, DOI: 10.1109/ICC.2019.8761072.

[59] Zhang J., Fan J., Ai B., Ng D.W.K.: NOMA-Based Cell-Free Massive MIMO Over Spatially Correlated Rician Fading Channels, ICC 2020–2020 IEEE International Conference on Communications (ICC), 2020, pp. 1–6, DOI: 10.1109/ICC40277.2020.9148861.

[60] Sayyari R., Pourrostam J., Niya M.J.M.: Cell-Free Massive MIMO System With an Adaptive Switching Algorithm Between Cooperative NOMA, Non-Cooperative NOMA, and OMA Modes, in IEEE Access, Vol. 9, pp. 149227–149239, 2021, DOI: 10.1109/ACCESS.2021.3124816.

[61] Hua M., Ni W., Tian H., Nie G.: Energy-Efficient Uplink Power Control in NOMA Enhanced Cell-Free Massive MIMO Networks, 2021 IEEE/CIC International Conference on Communications in China (ICCC Workshops), 2021, pp. 7–12, DOI: 10.1109/ICCCWorkshops52231.2021.9538877.

(2020)[62] consider a power optimization technique for user-centric based CF-mMIMO--NOMA. Specifically, while Zhang X. et al. (2020)[63] uses particle swarm algorithm to distribute transmit power for the APs. In Wang Z. et a. (2020)[64], a joint power optimization technique is adopted in the AP-tiered AP selection-based CF-mMIMO--NOMA in which when the APs in the same group performing SC to derive their own superimposed signals, they use the same power allocation firstly to enable CPU to only optimize the power allocation strategy of each AP group and the amount of calculation for joint power optimization can be reduced.

### 14.3.2. System, Channel and Signal Models

*System and Channel Model*

In this model we shall consider a downlink transmission of a NOMA-aided Cell-Free massive MIMO system in which $M$ single antenna APs serve $KN$ single antenna users spatially distributed in $N$ clusters under Time Division Duplexing (TDD) protocol at the same time-frequency resource block. Each cluster consists of $K$ users. APs are connected to a central processing unit (CPU) via a perfect and error free fronthaul network with unlimited capacity. Figure 14.8 below shows a NOMA-Aided Cell-Free Massive MIMO network with two users in each cluster.

[62] Wang Z., Zhang D., Xu K., Xie W., Xv J., Li X.: NOMA in Cell-Free mMIMO Systems with AP Selection, 2020 International Conference on Wireless Communications and Signal Processing (WCSP), 2020, pp. 430–435, DOI: 10.1109/WCSP49889.2020.9299790; Zhang X., Zhu Q.: NOMA and User-Centric Based Cell-Free Massive MIMO Over 6G Big-Data Mobile Wireless Networks, GLOBECOM 2020–2020 IEEE Global Communications Conference, 2020, pp. 1–6, DOI: 10.1109/GLOBECOM42002.2020.9322423.
[63] Zhang X., Zhu Q.: NOMA and User-Centric Based Cell-Free Massive MIMO Over 6G Big-Data Mobile Wireless Networks, GLOBECOM 2020 - 2020 IEEE Global Communications Conference, 2020, pp. 1–6, DOI: 10.1109/GLOBECOM42002.2020.9322423.
[64] Wang Z., Zhang D., Xu K., Xie W., Xv J., Li X.: NOMA in Cell-Free mMIMO Systems with AP Selection, 2020 International Conference on Wireless Communications and Signal Processing (WCSP), 2020, pp. 430–435, DOI: 10.1109/WCSP49889.2020.9299790.

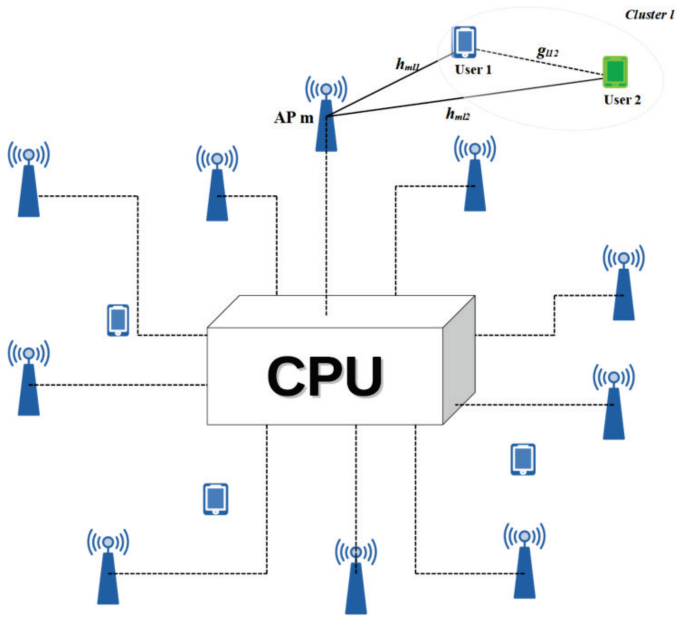


Fig. 14.8. NOMA-Aided Cell-Free Massive MIMO network with two users in each cluster
Rys. 14.8. Masywna sieć MIMO bez komórek wspomagana przez NOMA z dwoma użytkownikami w każdym klastrze
Source: based on Sayyari R., Pourrostam J., Niya M.J.M.: Cell-Free Massive MIMO System With an Adaptive Switching Algorithm Between Cooperative NOMA, Non-Cooperative NOMA, and OMA Modes, in IEEE Access, Vol. 9, pp. 149227–149239, 2021, DOI: 10.1109/ACCESS.2021.3124816.

The downlink channel between the *m*-th AP and the *k*-th user in the *n*-th cluster, where $m \in \{1, \cdots M\}$, $k \in \{1, \cdots K\}$ and $n \in \{1, \cdots N\}$ can be modeled as:

$$h_{mnk} = \zeta_{mnk}^{1/2} \tilde{h}_{mnk} \tag{3.1}$$

where $\zeta_{mnk}$ captures the large-scale fading, which is assumed to be known a priori as it changes very slowly and hence needs to be estimated once about every 40 coherence time intervals and $\tilde{h}_{mnk} \sim \mathcal{CN}(0,1)$ is circularly symmetric Gaussian distributed with zero mean unit variance and accounts for quasi-static Rayleigh fading[65]. Thus, $h_{mnk} \sim \mathcal{CN}(0, \tilde{h}_{mnk})$ is a complex normal random distribution variable with zero mean and covariance $\zeta_{mnk}$[66].

[65] Li Y., Baduge G.A.A.: NOMA-Aided Cell-Free Massive MIMO Systems, in IEEE Wireless Communications Letters, Vol. 7, no. 6, pp. 950–953, Dec. 2018, DOI: 10.1109/LWC.2018.2841375.
[66] Sayyari R., Pourrostam J., Niya M.J.M.: Cell-Free Massive MIMO System With an Adaptive Switching Algorithm Between Cooperative NOMA, Non-Cooperative NOMA, and OMA Modes, in IEEE Access, Vol. 9, pp. 149227–149239, 2021, DOI: 10.1109/ACCESS.2021.3124816.

Also, users within the same NOMA cluster are arranged according to their channel conditions:

$$\sum_{m=1}^{M} |h_{mn1}|^2 \geq \sum_{m=1}^{M} |h_{mn2}|^2 : 1 \leq n \leq N \tag{3.2}$$

The location of users and APs can be modeled with homogenous PPP[67]. The following equation shows the probability of having $M$ APs with a density of $\lambda$ within an area of $B$:

$$[z(B) = M] = \frac{(\lambda_B)^M e^{-\lambda_B}}{M!} \tag{3.3}$$

If $\lambda_u$ is the density of users and $\lambda_a$is the density of APs, then $\lambda_a \geq \lambda_u$ . $K$ is the total number of users within the same NOMA cluster.

Notably, the estimation of the DL channel can be performed by uplink pilots and channel reciprocity assumption in the Time Division Duplexing (TDD) Protocol. Hence the first part of each coherence block is allocated to uplink pilots and the remaining part is used for data transmission. [68] shows that the assumption of channel reciprocity doesn't put into consideration the hardware mismatches at AP and UE side, which are not reciprocal but impacts the system performance.

*Channel State Information Acquisition/ Uplink Pilot Training*

The APs estimate uplink channels via the pilots transmitted by the users and thereby, the downlink channels are obtained by exploiting TDD channel reciprocity. The users within the same cluster are allocated the same pilot sequence with $\tau$ symbols in length to minimize the channel estimation overhead. The $N$ pilot sequences allocated for $N$ clusters are mutually orthogonal hence $\tau \geq N$. The pilot sequence allocated for $K$ users in the n-th cluster is denoted as $\phi_n \in \mathbb{C}^{\tau \times 1}$ satisfying $||\phi_n||^2 = 1$ and $\phi_n^H \phi_l = 0$ for $n \neq l$. The pilot signal received at the m-th AP during the UL channel estimation can be written as:

$$y_m^P = \sqrt{\tau p_p} \ \sum_{n=1}^{N} \sum_{k=1}^{K} h_{mnk} \phi_n + n_m \tag{3.4}$$

[67] Sayyari R., Pourrostam J., Niya M.J.M.: Cell-Free Massive MIMO System With an Adaptive Switching Algorithm Between Cooperative NOMA, Non-Cooperative NOMA, and OMA Modes, in IEEE Access, Vol. 9, pp. 149227–149239, 2021, DOI: 10.1109/ACCESS.2021.3124816.

[68] Ohashi A.A. et al.: Cell-Free Massive MIMO-NOMA Systems With Imperfect SIC and Non-Reciprocal Channels, in IEEE Wireless Communications Letters, 2021, Vol. 10, no. 6, pp. 1329–1333, DOI: 10.1109/LWC.2021.3066042.

where: $p_p$ is the pilot transmit power (UL normalized SNR), $n_m \sim \mathcal{C}N_{\tau\times1}(O_{\tau\times1}, I_i)$ represents the Additive White Gaussian Noise (AWGN) vector at the m-th AP.

In order to estimate the channel $h_{mnk}$, the received pilot signal at the m-th AP ($y_m^P$) is projected onto $\phi_n$ as:

$$\tilde{y}_{mn}^P = \phi_n^H y_m^P = \sqrt{\tau p_p} \sum_{k=1}^K h_{mnk} + \phi_n^H n_m \tag{3.5}$$

In the case that any two pilot sequences are either identical or orthogonal, $\tilde{y}_{mn}^P$ becomes a sufficient statistic. Thence, the Minimum Mean Square Sequence Error (MMSE) estimate $h_{mnk}$ given $\tilde{y}_{mn}^P$ can be given as:

$$\tilde{h}_{mnk} = \frac{\mathbb{E}\left[\tilde{y}_{mn}^{P*} h_{mnk}\right]}{\mathbb{E}\left[\left|\tilde{y}_{mn}^P\right|^2\right]} \tilde{y}_{mn}^P = \frac{\sqrt{\tau p_p}\ \zeta_{mnk}}{1+\tau p_p \sum_{k=1}^K \zeta_{mnk}} \tilde{y}_{mn}^P \tag{3.6}$$

By using the fact that $\tilde{y}_{mn}^P$ is Gaussian distributed, $\hat{h}_{mnk}$ can be written as

$$\tilde{h}_{mnk} = \sqrt{\eta_{mnk}} v_{mn} \tag{3.7}$$

where $v_{mn} \sim \mathcal{CN}(0,1)$, and $\eta_{mnk}$ is defined as:

$$\eta_{mnk} = E\left[\left|\hat{h}_{mnk}\right|^2\right] = \frac{\tau p_p \zeta_{mnk}^2}{1+\tau p_p \sum_{k=1}^K \zeta_{mnk}} \tag{3.8}$$

The channel estimation error is defined as $\varepsilon_{mnk} = h_{mnk} - \hat{h}_{mnk}$ where $\varepsilon_{mnk}$ and $\hat{h}_{mnk}$ are statistically independent. Moreover, $\mathbb{E}[|\varepsilon_{mnk}|^2] = \zeta_{mnk} - \eta_{mnk}$. $\eta_{mnk}$ is the power control coefficient for each AP to serve each user in each cluster. They are determined by CPU and will be delivered to the APs through the fronthaul networks.

*Signal Model*

In the downlink data transmission, the APs employ a conjugate beamformer designed based on the locally estimated CSI, which is acquired via a channel reciprocity and uplink MMSE channel estimation.

The data signal intended for the $K$ users in the n-th cluster is superposition coded as:

$$x_n = \sum_{k=1}^{K} \sqrt{P_{nk}} x_{nk} \tag{3.9}$$

where $x_{nk}$ and $P_{nk}$ are data signal and transmit power allocated for the k-th user in the n-th cluster for $n \in \{1, \cdots N\}$ and $k \in \{1, \cdots K\}$. Furthermore, $x_{nk}$ and $x_{ml}$ for $m, n \in \{1, \cdots N\}$ and $k, l \in \{1, \cdots K\}$ satisfy

$$\mathbb{E}\{x_{nk} x_{ml}\} = \begin{cases} 1, & if \;\; n = m \, and \, k = l \\ 0\,, & otherwise \end{cases} \tag{3.10}$$

Therefore, $\mathbb{E}[|x_n|^2] = \sum_{k=1}^{K} P_{nk} = P_n$, where $P_n$ accounts for the total signal power allocated for the n-th cluster.

The transmitted signal at the m-th AP can be written as

$$t_m = \sum_{n=1}^{N} \frac{\hat{h}_{mnk}^*}{|\hat{h}_{mnk}|} x_n = \sum_{n=1}^{N} \frac{v_{mn}^*}{|v_{mn}|} x_n \tag{3.11}$$

where a short-term power constraint (STPC) is used in the conjugate beamformer design. The total average transmit power at the m-th AP for all $N$ clusters can be written as $P_{tm} = E[|t_m|^2] = \sum_{n=1}^{N} P_n$.

The $KN$ users in $N$ cluster are served simultaneously by $M$ APs, hence the signal at the k-th user in the n-th cluster can be written as:

$$y_{nk} = \Sigma_{m=1}^{M} h_{mnk} + n_{nk} \tag{3.12}$$

$$= \sqrt{P_{nk}} c_{nk} x_{nk} + c_{nk} \sum_{k'=1, K \neq 14}^{K} \sqrt{P_{nk'}} x_{nk'} + \sum_{n^1=1, n' \neq n}^{N} c_{n'k} x_{n'} + n_{nk}$$

where $c_{nk} = \sum_{k=1}^{K} h_{mnk} \frac{v_{mn}^*}{|v_{mn}|}$, $\quad c_{n'k} = \sum_{k=1}^{K} h_{mnk} \frac{v_{mn}^*}{|v_{mn'}|}$ and $n_{nk} \sim \mathcal{CN}(0,1)$.

In power domain NOMA, higher powers are allocated for the users with lower channel strengths yielding $P_{n1} \leq \cdots P_{nk} \leq \cdots \leq P_{nk}$. Hence, within the n-th cluster, the k-th user is always able to decode the signal intended for the l-th user for $\forall l \geq k$ provided that the k-th user can decode its own signal. Thus, the k-th user can successively cancel the intra-cluster interference from the l-th user before decoding its own signal for $\forall l \geq k$. The k-th user treats the signal from users for $\forall l \geq k$ as interference. The optimal power allocation and optimal user-clustering are as open problem for sake of brevity.

It is important to note that in TDD CF-mMIMO, the instantaneous CSI is not available at the user nodes. However, as the number of APs grows sufficiently large, the underlaying channels harden. Hence $\mathbb{E}[c_{nk}]$ can be used as the effective channel gain for decoding $x_n$ at the k-th user in the n-th cluster. The acquisition of $\mathbb{E}[c_{nk}]$ is not practically difficult because it depends only on the statistical properties of the channels and remains fixed for several coherence intervals. Again, due to intra-cluster pilot contamination, channel estimation errors and statistical CSI knowledge at the users, perfect SIC is not perfectly viable. Hence post-processed signal at the k-th user node in the n-th cluster after the imperfect SIC can be written as:

$$\tilde{y}_{nk} = \sqrt{P_{nk}} c_{nk} x_{nk} + C_{nk} \sum_{k'=1}^{k-1} \sqrt{P_{nk'}} x_{nk'} + \sum_{n'=1,n'\neq n}^{N} c'_{n'k} x_{n'} + \sum_{k''=k+1}^{K} \sqrt{P_{nk''}} [c_{nk''} x_{nk''} - \mathbb{E}[C_{nk}] \hat{x}_{nk''}] + n_{nk} \tag{3.13}$$

where $\hat{x}_{nk}$ is an estimate of $x_{nk}$ for $\forall_{n,k}$, $x_{nk}$ is assumed to be drawn from a Gaussian distribution with zero-mean and unit variance. Hence, $\hat{x}_{nk}$ and $x_{nk}$ are assumed to be jointly Gaussian distributed with a normalized correlation coefficient $\rho_{nk}$ as:

$$x_{nk} = \rho_{nk} \hat{x}_{nk} + e_{nk} \tag{3.14}$$

where $x_{nk} \sim \mathcal{CN}(0,1)$ , $e_{nk} \sim \mathcal{CN}(0, \sigma^2_{e_{nk}} / [1 + \sigma^2_{e_{nk}}])$ and $\rho_{nk} = 1 / \sqrt{1 + \sigma^2_{e_{nk}}}$. Furthermore, $x_{nk}$ and $e_{nk}$ are statistically independent.

The upper bound ergodic sum rate is given by[69]:

$$\tilde{R} < \bar{R} = \phi \sum_{n=1}^{N} \sum_{k=1}^{K} \mathbb{E}[\log(1 + \gamma_{nk})] \tag{3.15}$$

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[69] Li Y., Baduge G.A.A.: NOMA-Aided Cell-Free Massive MIMO Systems, in IEEE Wireless Communications Letters, Vol. 7, no. 6, pp. 950–953, Dec. 2018, DOI: 10.1109/LWC.2018.2841375.

where the $\tilde{\tilde{R}}$ is the achievable sum rate given of NOMA-aided Cell-Free Massive MIMO and written as:

$$\tilde{R} = \sum_{n=1}^{N} \sum_{k=1}^{K} \tilde{R}_{n,k} \tag{3.16}$$

Plotting the achievable sum rate compared to OMA counterpart as shown in figure below, we find that NOMA offers a better performance in cell-free massive MIMO.

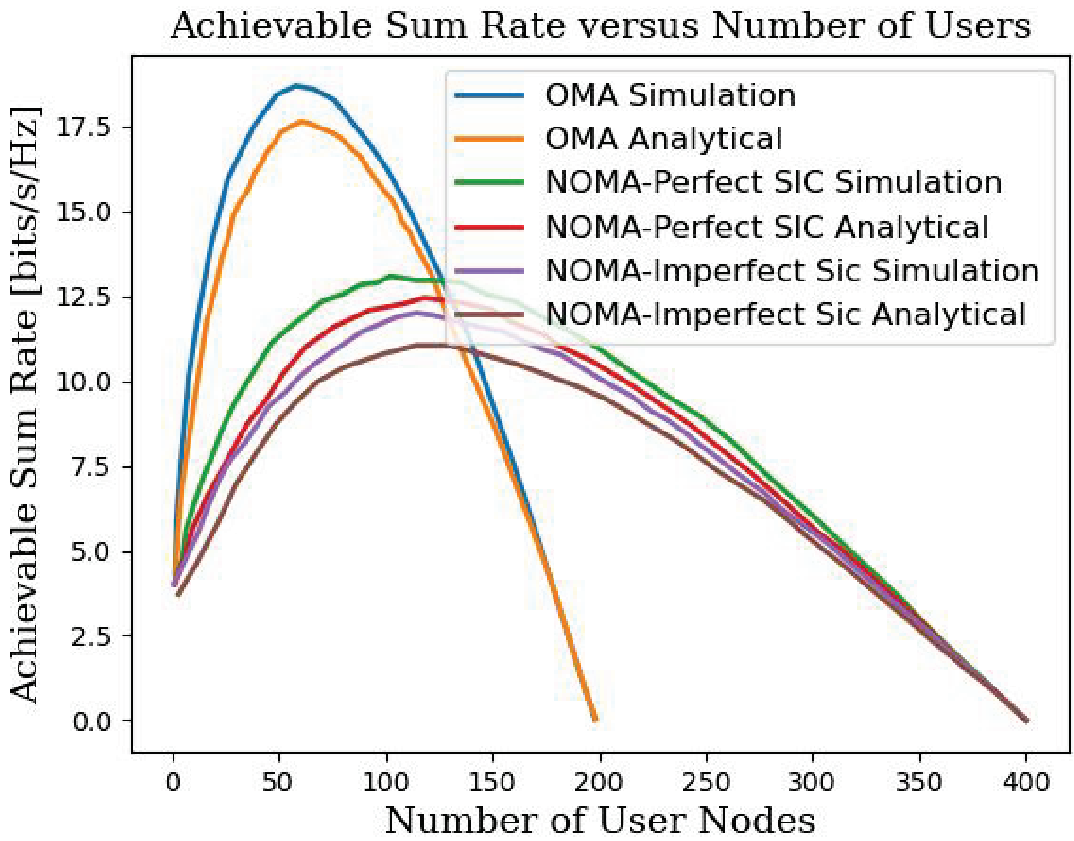


Fig. 14.9. The achievable sum rate versus the number of users
Rys. 14.9. Suma szybkości w zależności od liczby użytkowników
Source: based on Li Y., Baduge G.A.A.: NOMA-Aided Cell-Free Massive MIMO Systems, in IEEE Wireless Communications Letters, Vol. 7, no. 6, pp. 950–953, Dec. 2018, DOI: 10.1109/LWC.2018.2841375.

## 14.4. Conclusion

This chapter provides first a literature review of Cell-free massive MIMO and NOMA. Then we review the state-of-art of available literature on integrating the two. Finally, we study a simple system channel and signals and the achievable rate of NOMA-

-Aided Cell-free massive MIMO. NOMA is prioritized as one of the possible next-generation Multiple Access, while Cell-free massive MIMO should solve the current problems of cellular communications while ensuring broader coverage. In conclusion, integration of the two would reap the benefits of both and would satisfy the stringent requirements of the subsequent mobile wireless communications and would likely to solve various connectivity problems that are encountered by existing and future smart city systems.