Analyzing Energy Efficiency and Capacity in NOMA and OFDMA System

WeiChih Chen 251390109

***Abstract*—Energy efficiency (EE) is a key performance indicator of future wireless networks and has become an important research field in communication networks. In this paper, we consider non-orthogonal multiple access (NOMA) and Orthogonal Frequency-Division Multiple Access (OFDMA) networks and investigate the EE and capacity problem, showing how NOMA address the 5G requirements and standardize effort for NOMA and OFDMA. We have also demonstrated improvements in the throughput of users in NOMA compared with OFDMA in MATLAB simulations.** **Keywords—Non-Orthogonal Multiple access, Orthogonal Frequency Division Multiple Access, Energy- efficiency, Capacity**

I. INTRODUCTION

The rapid development of wireless networks from the first generation (1G) to the fourth generation (4G) is driven by the demand for higher communication capacity and the explosive growth in the number of users.

OFDMA (Orthogonal Frequency Division Multiple Access) is mainly used in fourth generation (4G) technologies such as LTE and LTE-Advance to achieve higher data rate [1]. In this generation, we develop lots of techniques for the increasing need for an amount of traffic volume [2] and massive MIMO [3]. NOMA (non-orthogonal multiple access) are the key technologies that are proposed for 5G communication.

NOMA allows multiple users to share the same frequency band at the same time but separate them by power level [4], and allocate power based on user channel conditions strategically, thereby increasing system performance and user experience [5]. In the NOMA framework, user scheduling is crucial as it determines which users are allowed to access the network at any given time. It is essential to develop an effective scheduling strategy to ensure fair access and to maximize the performance of the overall system. The NOMA approach requires the use of sophisticated signal processing techniques, which adds complexity to NOMA systems. This increased complexity has significant implications for the practical implementation and deployment of NOMA technology [6]

This research explores a particular aspect of performance evaluation in Non-Orthogonal Multiple Access (NOMA) systems, specifically focusing on energy efficiency and user sum rate. Energy efficiency has become an essential factor in modern communication technologies, driven by the global push towards sustainability and efficient resource use. In NOMA systems, how power is distributed among users based on their channel conditions is crucial for achieving energy-efficient operations. By carefully adjusting power levels, NOMA seeks to improve both the system's throughput and its energy consumption. This approach of tailoring power resources to meet user needs leads to better energy efficiency compared to traditional orthogonal access methods. Nonetheless, optimizing energy efficiency in NOMA presents complex challenges. Precise channel estimation is crucial; inaccuracies can result in poor power distribution, reducing the system's energy efficiency.

NOMA effectively maximizes the use of available resources by creating a power hierarchy where stronger users receive more power than weaker ones. This approach allows stronger users to achieve higher data rates, while still maintaining capacity for weaker users. Enhanced user sum rates are achieved using advanced signal processing techniques, such as superposition coding and successive interference cancellation. Evaluating and improving capacity and energy efficiency in NOMA has significant effects on both network capacity and user satisfaction. By addressing the challenges related to interference and resource management, NOMA enhances user experiences by facilitating higher data rates and more efficient utilization of the available spectrum in contemporary wireless communications.

II. IN-DEPTH TECHNICAL ANALYSIS

A. IN-DEPTH TECHNIQUE

NOMA techniques can be categorized into two domains: code and power. The power domain is predominantly used, where less power is allocated to users with higher channel gain and more power to those with weaker channel conditions, allowing NOMA to provide communication links to multiple users simultaneously [7]. This approach ensures a balanced experience across users. The use of the successive interference cancellation (SIC) technique is critical for distinguishing between user signals. While cooperative NOMA can improve performance for users with poorer channel conditions, it requires additional time slots, adding overhead to the system [8-10]. To circumvent this issue, implementing full-duplex (FD) relay strategies has been proposed. SIC is not only pivotal in research advancements but also essential for enhancing spectral efficiency in 5G networks, doubling it compared to half-duplex communications [11-13]. Achieving high data rates remains a primary goal for future communication systems .

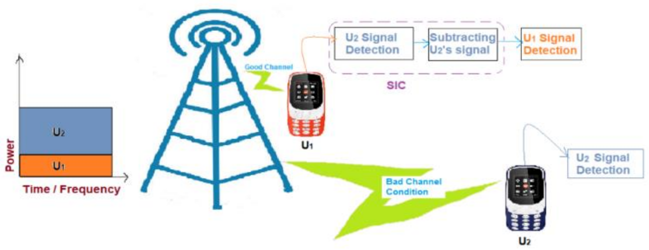

Fig.1 Illustration of downlink power domain NOMA

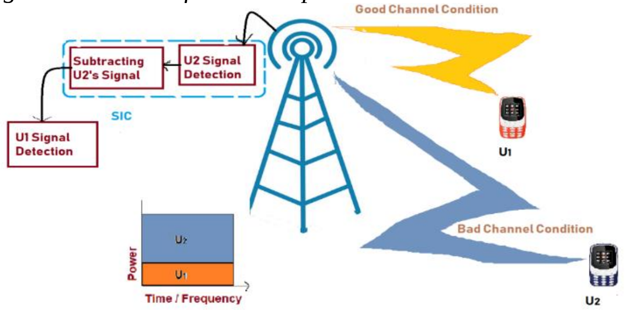

Fig.2 Illustration of uplink power domain NOMA

Referencing Figure 1, it's evident that the transmission power is shared between user 1 and user 2. The division of power is a delicate process, crucial for enhancing the detection precision of each user's signal at the receiver end. Consequently, user 1, who has superior channel state information (CSI), receives less power, while user 2, with subpar CSI, is allotted more power. This allocation strategy minimizes the interference for the user with the weaker CSI. Successive Interference Cancellation (SIC) is utilized to single out and decode user 1's signal distinctly. SIC's application is exclusive to user 1's signal due to its lower power level compared to user 2's signal, which is more robust and can be decoded directly without the necessity of eliminating user 1's signal. In contrast, user 2's signal is not susceptible to interference from user 1's signal due to its higher power level. However, for SIC to function correctly on the receiving end, there must be a significant power differential between the two signals.

B. SYSTEM MODEL

In a NOMA downlink scenario, a single base station (BS) serves N users. The channel gains from the base station to each user are represented as h1, h2, ..., hN, and the noise power by N0. The power distributed to each user is labeled as P1, P2, ..., PN, with Ptotal being the total power available for distribution. Users are organized into groups identified by K (ranging from K=1 to K=k). The system's total bandwidth, B (in Hz), is segmented into a set number of distinct subchannels, N (from N=1 to N=n), with each subchannel's bandwidth determined according to equation (1). Each subchannel, accommodating the highest number of multiplexed users, operates under NOMA principles.

$$B_s = {}^{B}/_{N} \tag{1}$$

In each subchannel of a NOMA downlink scenario, a SISO (Single Input Single Output) Gaussian broadcast channel is utilized for simulation purposes. The base station generates the broadcast signal for each subchannel as specified in equation (2). The signal received by the users is characterized by equation (3).

$$x^n = \sum_{k \in K_n} \sqrt{p_k^n}\, s_k^n \tag{2}$$

$$y_k^n = \sqrt{p_k^n g_k^n s_k^n} + \sum_{k \in K_n} \sqrt{p_i^n}\, s_i^n g_k^n + z_k^n \tag{3}$$

In this context, "g" represents the channel gain, "z" is the AWGN (Additive White Gaussian Noise), and "p" and "s" are the power and input symbols respectively for each user. For any user within group K to decode their intended signal on sub-channel n, the SNR (Signal-to-Noise Ratio) is defined as shown in equation (4). The sequence in which the signals are decoded is detailed in equation (5).

$$\gamma_{k,i}^n = \frac{p_k^n h_i^n}{\sum_{j \in K_n,\, h_j^n > h_k^n} p_j^n h_i^n + 1} \tag{4}$$

$$h_k^n = {}^{|g_k^n|^2}/_{\sigma_k^n} \tag{5}$$

The achievable rate for user k (where k is within the set Kn) on sub-channel n (where n is within the set N) after successful implementation of Successive Interference Cancellation (SIC) is expressed in equation (6).

$$R_k^n(p^n) = \min_{\substack{i \in K_n \\ h_j^n > h_k^n}} \left\{ W_s \log_2\left(1 + \gamma_{k,i}^n(p^n)\right) \right\} \tag{6}$$

Where "p to the power of n" represents the distribution of allocated power among all users, as detailed in equations (7) and (8). Consequently, for every "p to the power of n", the potential rate for each user k (where k belongs to the set Kn) on sub-channel n corresponds to the channel capacity, which is outlined in equation (9).

$$p^n = [p_k^n]_{1 \times K} \tag{7}$$

$$p = [p_k^n]_{N \times K} \tag{8}$$

$$R_k^n(p^n) = W_s \log_2\left(1 + \gamma_{k,i}^n(p^n)\right) \tag{9}$$

The attainable proportion [14-15] of user k (k ∈ Kn) can be found by using (10).

$$R_k(p) = \sum_{n \in N_k} R_k^n(p^n) \tag{10}$$

The energy efficiency (EE) for user k is defined as the ratio of the achievable rate (Rk) to the power consumed (Pk), and this relationship is expressed in equation (11).

$$EE_k = \frac{R_k}{P_k} \tag{11}$$

III. SIMULATION DESIGN

The Our simulation is to prove that NOMA fulfills the requirement of 5G better than OFDMA, we used MATLAB to implement it, the simulation case consists of a circular cell with a radio of 1 km, in each attempt, the users are randomly located inside the cell, the cell divided into five sectors. The frequency used in this simulation is 3.6GHz which is mainly frequency used for 5G in Europe.

In our simulations, OFDMA is simplified because each user transmits the same power and is assigned a specific bandwidth, which is not shared within the sector. When using NOMA, each user is allowed to use all the available bandwidth. The power coefficients in NOMA are assigned to achieve a specific signal interference ratio (SIR)

The capacity of each user is calculated according to Shannon's law (C = W * log2(1 + SINR)). The total capacity of each technology is the sum of the capacity of all users in the cell. For the signals received by each user, we considered only the losses due to free space propagation, which depend on the distance to the base station.

IV. SIMULATION RESULT

MATLAB was employed as a computational resource to conduct a thorough analysis of how minimum rate requirements and user count affect average user capacity and energy efficiency. These assessments were based on the simulation parameters detailed in Table 1. To simulate the network environment, a topology featuring k users was created, with the base station's communication range extending up to 1000 meters, as depicted in Fig. 3.

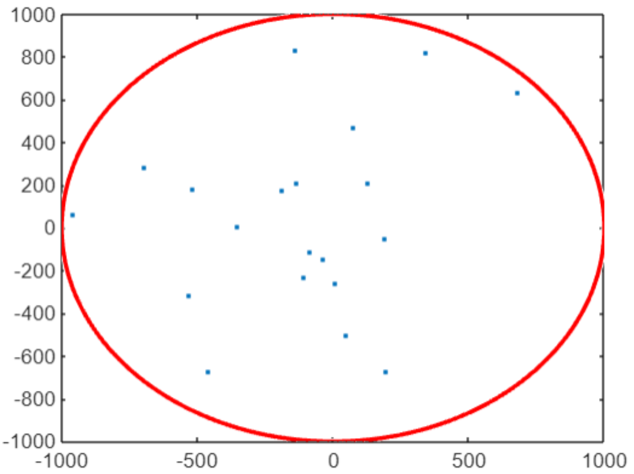

Fig.3 Network topology

In Fig.4, The experiment by changing the parameters, and integrated the experimental data and results into a table.

Power	Users	BW	NOMA(capacity) (bit/s)	OFDMA(capacity) (bit/s)	NOMA(EE) (bit/J)	OFDMA(EE) (bit/J)	Improvement (NOMA-OFDMA EE)
20	5	20	2.928e9	2.908e9	2.44e7	2.423e7	0.7%
20	10	20	3.136e9	3.046e9	2.61e7	2.53e7	3%
20	20	20	3.914e9	3.618e9	3.262e7	3.01e7	8.3%
20	35	20	4.016e9	3.65e9	3.347e7	3.049e7	9.7%
20	20	1.4	2.718e8	2.764e8	2.26e6	2.3e6	-1.7%
20	20	10	1.96e9	1.84e9	1.58e7	1.537e7	2.79%
20	20	20	4.006e9	3.67e9	3.33e7	3.06e7	8.8%
20	20	50	9.78e9	8.67e9	8.15e7	7.229e7	12.7%
1	20	20	3.51e9	3.2e9	3.47e7	3.169e7	9.4%
10	20	20	3.83e9	3.52e9	3.49e7	3.2e7	9%
50	20	20	4.144e9	3.844e9	2.76e7	2.56e7	7.8%
100	20	20	4.22e9	3.917e9	2.11e7	1.958e7	7.7%

Fig.4 Experiment result

The graphs below show the experiment parameters compared with Capacity and Energy Efficiency

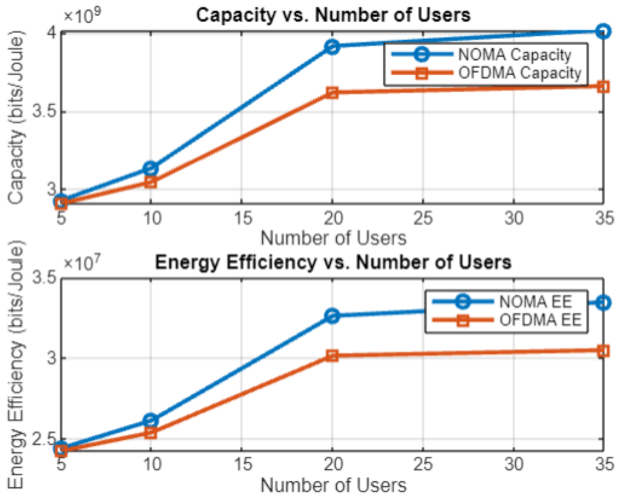

Fig.5 Experiment result (number of users)

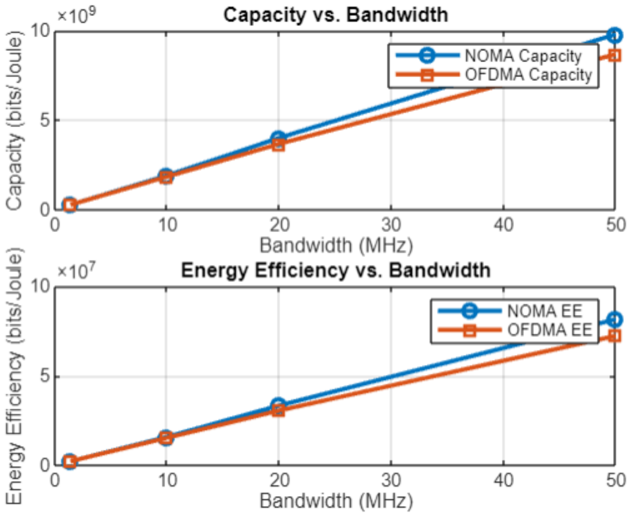

Fig.6 Experiment result (Bandwidth)

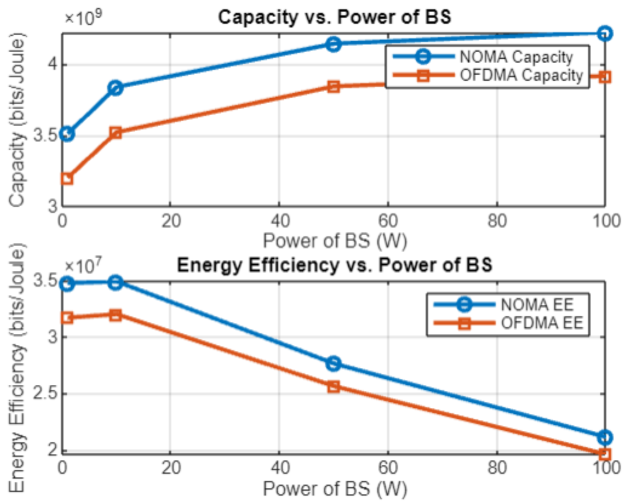

Fig.7 Experiment result (Power of base station)

As illustrated in Figures 5, 6, and the accompanying charts, there is a demonstrable trend where NOMA outperforms OFDMA as both the bandwidth and the number of users increase. This suggests that NOMA is better suited for scenarios with growing user bases and expanding bandwidth requirements, showcasing greater scalability and adaptability in more demanding network environments. The graphs also suggest that NOMA maintains higher energy efficiency across these varying conditions, indicating that it could be a more sustainable option for future wireless networks that need to manage resources more efficiently while accommodating a larger number of connections. Additionally, when examining the impact of the base station's power as shown in Fig.7, NOMA's capacity and energy efficiency metrics continue to showcase its advantage over OFDMA, which could translate into more robust performance in practical deployment scenarios.

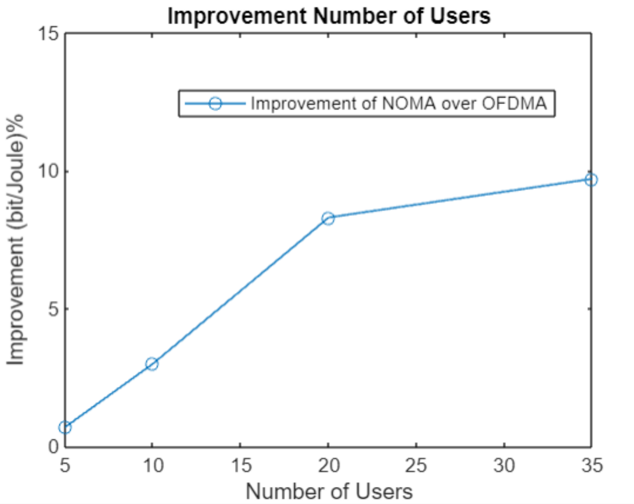

Fig.8 Improvement Number of users

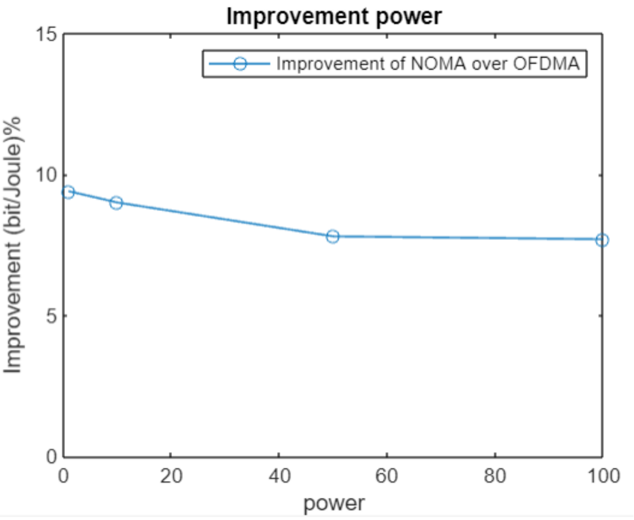

Fig.9 Improvement Power of Base station

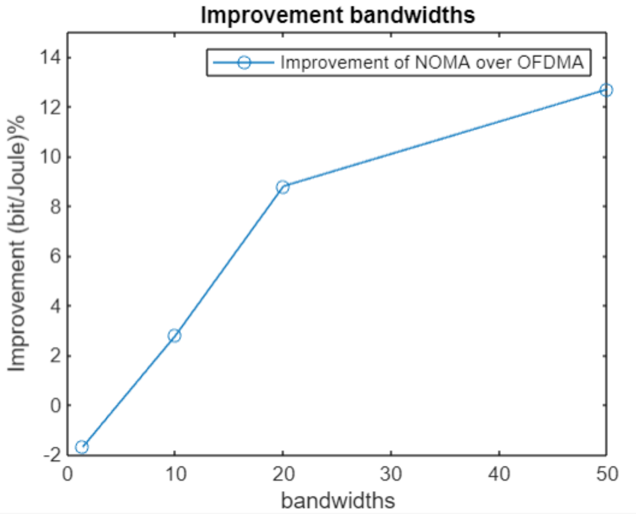

Fig.10 Improvement Bandwidths

Figures 8, 9, and 10 depict that as the number of users, the base station power, and the bandwidth increase, NOMA consistently exhibits superior performance over OFDMA. The improvement is quantified in percentage gains, illustrating NOMA's more effective use of resources. Specifically, with a growing number of users, NOMA shows a steep improvement in efficiency. Concerning power, the gains appear relatively stable across different power levels, while the enhancement in efficiency becomes particularly pronounced as bandwidth expands, underscoring NOMA's potential in high-capacity scenarios. These trends affirm NOMA's strengths in delivering higher data rates and energy efficiency, critical metrics for advancing communication systems.

V. FUTURE WORK

A. OFDMA

In our investigation, detailed in reference [16], we explore forward-looking concepts for enhancing OFDMA. We are developing algorithms for the dynamic allocation of subcarriers and power to improve spectral efficiency and reduce system interference—advancements essential for supporting the increased complexity and user demand in contemporary OFDMA systems. Additionally, we are adapting OFDMA for optimal performance in the sub-6 GHz and mmWave bands, crucial for 5G networks, and exploring its application within the ambit of 6G, which will necessitate greater integration and superior performance metrics. Another area of focus is the refinement of error correction techniques to ensure that rising data rate demands and the quest for lower latency do not compromise communication speeds. These enhancements are geared towards bolstering the OFDMA framework to meet the evolving requirements of modern wireless communication systems.

B. Hybrid NOMA Systems:

By combining NOMA with traditional methods like OFDMA, we can create hybrid systems that excel in resource allocation, ensure fairness among users, and provide higher throughput. This symbiotic approach can take advantage of the strengths of both technologies—OFDMA's orthogonality properties and NOMA's superposition coding—to optimize network performance.[16]

C. IoT Applications:

As the Internet of Things (IoT) continues to grow, applying NOMA principles can significantly elevate signal efficiency and minimize latency, which are pivotal for the massive connectivity demands of IoT ecosystems. The ability of NOMA to serve multiple users concurrently makes it particularly well-suited for the dense and varied communication needs of IoT devices.[17]

D. Integration with Advanced Technologies:

Incorporating NOMA into Massive MIMO systems could dramatically increase spectral efficiency and network capacity by enabling spatial multiplexing of multiple users.

NOMA can complement the high-speed capabilities of mmWave frequencies in 5G networks, helping to mitigate path loss and ensure robust signal coverage.

Utilizing machine learning algorithms can optimize NOMA systems for dynamic network conditions, improving resource allocation, user clustering, and power distribution[18,19]

VI. CHALLENGE

In paper [20], we detail the challenges of implementing NOMA, focusing on its dependence on sophisticated signal processing techniques like Successive Interference Cancellation (SIC). This complexity increases the computational load and power consumption significantly. Additionally, NOMA allows multiple users to share the same frequency band, leading to inter-user interference, a problem that intensifies with the addition of more users. Moreover, determining the optimal strategy for user pairing and dynamic power allocation to maximize throughput while ensuring fairness remains a complex and crucial task.

Both NOMA and OFDMA face the overarching challenge of adapting to the rapidly evolving landscape of wireless networks, which includes meeting the high throughput and low latency needs of burgeoning technologies like the Internet of Things (IoT), Massive MIMO, and machine learning-based network optimization. Balancing complexity, power consumption, and performance will be key in addressing these challenges. There is significant potential in developing hybrid systems that combine NOMA and OFDMA to exploit the benefits of both, thereby achieving greater network efficiency and capacity. However, such integration presents its own set of challenges and necessitates further investigation and innovation.

VII. CONCULSION

In our study's conclusion, it became clear that NOMA systems consistently outperform OFDMA in terms of capacity and energy efficiency under varying conditions of bandwidth, base station power, and user load. Our findings suggest that as the number of users and the bandwidth increase, NOMA systems offer a more scalable solution, showing significant improvements in capacity, which is crucial for handling the burgeoning demand in wireless networks. Moreover, NOMA's ability to maintain higher energy efficiency with an increased number of users positions it as a sustainable choice for future network expansions. The stability of energy efficiency gains in NOMA across different levels of base station power further indicates its robustness in diverse operational conditions. This adaptability is especially pertinent in the face of rapidly evolving network requirements and the push toward green communication technologies.

In light of these observations, NOMA stands out as a potent technology for next-generation networks that require high throughput and efficient energy consumption. However, the implementation of NOMA comes with its own set of challenges, including the need for sophisticated interference management and the complexities of power allocation. These areas present opportunities for further research and development to fully harness the potential of NOMA in practical scenarios.

VIII. REFERANCES

[1] K. Yang, S. Martin, D. Quadri, J. Wu, and G. Feng, " Energy-efficient downlink resource allocation in heterogeneous OFDMA networks," IEEE Trans. Veh. Technol., vol. 66, no. 6, pp. 5086-5098, Jun. 2017.

[2] J. G. Andrews et al., "What will 5G be?" IEEE J. Sel. Areas Commun., vol. 32, no. 6, pp. 1065_1082, Jun. 2014.

[3] Z. Gao, L. Dai, Z. Wang, and S. Chen, " Spatially common sparsity based adaptive channel estimation and feedback for FDD massive MIMO," IEEE Trans. Signal Process., vol. 63, no. 23, pp. 6169-6183, Dec. 2015

[4] Tabassum, H., & Hong, C. S. (2018). "A Survey of Resource Allocation Techniques in NOMA Systems for 5G Networks and Beyond." IEEE Access, 6, 76046-76071.

[5] Sateesh, C., Janardhana Gupta, K., Jayanth, G., Sireesha, C., Dinesh, K., Ramesh Chandra, K. **(2022).** Performance Analysis of Spectrum Sensing in CRN Using an Energy Detector. In: Raj, J.S., Kamel, K., Lafata, P. (eds) Innovative Data Communication Technologies and Application. Lecture Notes on Data Engineering and Communications Technologies, vol 96. Springer, Singapore.

[6] Ravindran, N., Anand, A., & Kumar, N. (2019). "NOMA for Visible Light Communication Networks: A Survey." IEEE Communications Surveys & Tutorials, 21(3), 2484-2510.

[7] . O. Omarov, G. Nauryzbayev, S. Arzykulov, M. S. Hashmi and A. M. Eltawil, "Capacity analysis of wireless powered cooperative NOMA networks over generalized fading," Wireless Communications and Networking Conference (WCNC), pp. 1-6, 2021

[8] Sanjeev Kumar, Krishan Kumar, "Neuro-Fuzzy based Call Admission Control for next Generation Mobile Multimedia Networks", International Journal of Engineering and Advanced Technology (IJEAT), ISSN: 2249 – 8958, Volume-8 Issue-6, August 2019

[9] C. Yu, H. L. Ko, X. Peng and W. Xie, "Secrecy outage performance analysis for cooperative NOMA over nakagami-m channel," IEEE Access, vol. 7, pp. 79866-79876, 2019

[10] V. Aswathi and A. V. Babu, "Non-orthogonal multiple access in fullduplex-based coordinated direct and relay transmission (CDRT) system: performance analysis and optimization," EURASIP Journal on Wireless Communications and Networking, vol. 1, pp. 1-27, 2020.

[11] N. Zaghdoud, A. B. Mnaouer, H. Boujemaa and F. Touati, "Secrecy performance analysis of half/full duplex AF/DF relaying in NOMA systems over κ-μ fading channels," Telecommunication Systems, vol. 70, pp. 1-16, 2021.

[12] X. Yue, Y. Liu, S. Kang, A. Nallanathan and Z. Ding, "Outage performance of full/half-duplex user relaying in NOMA systems," International Conference on Communications (ICC), pp. 1-6, 2017

[13] S. P. Singh and S. Kumar, "Closed form expressions for ABER and capacity over EGK fading channel in presence of CCI," International Journal of Electronics, vol. 104, no. 3, pp. 513-527, 2017.

[14] Ramesh Chandra, K, Borugadda, S. An effective combination of terahertz band NOMA and MIMO system for power efficiency enhancement. Int J Commun Syst. 2022; 35(11).

[15] Gangadhar, Ch. and Chanthirasekaran, K. and Chandra, K. Ramesh and Sharma, Aditi and Thangamani, M. and Kumar, Ponnusamy Siva, An energy efficient NOMA-based spectrum sharing techniques for cellfree

massive MIMO, International Journal of Engineering Systems Modelling and Simulation, 13(4), pp. 284-288, 2022.

[16] Selvam K , Kumar K, Energy and Spectrum Efficiency Trade-off of NonOrthogonal Multiple Access (NOMA) over OFDMA for Machine-to-Machine Communication, 2019 Fifth International Conference on Science Technology Engineering and Mathematics

[17] Taoufik Ben Rejeb, M. G. Bakulin, V. B. Kreyndelin, D. Y. Pankratov, A. E. Smirnov, Performance Analysis of Uplink Non-orthogonal Multiple Access (NOMA), Published in Systems of Signals Generating… 15 March 2022

[18] Moein Aghcheli, Contemporary and future 5 G wireless communication systems : A survey of basic physical layer techniques and performance analysis, Published 2020 Engineering, Computer Science

[19] Yuya Saito*), Yoshihisa Kishiyama*), Anass Benjebbour*), Takehiro Nakamura*), Anxin Li**), and Kenichi Higuchi***), Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access, IEEE Vehicular Technology… 2 June 2013

[20] Moh. Khalid Hasan, M. Shahjalal, Md. Mainul Islam, Md. Morshed Alam, Md. Faisal Ahmed, Y. Jang, The Role of Deep Learning in NOMA for 5G and Beyond Communications, Published in Digital Signal Processing and… 1 February 2020