DEPARTMENT OF ELECTRICAL
AND ELECTRONICS
ENGINEERING

EE492 PROJECT REPORT

Joint Communication and Sensing for NOMA Systems

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TABLE OF CONTENTS

ABBREVIATIONS

NOMA: Non-orthogonal Multiple Access

JCAS: Joint communication and Sensing

SIC: Successive Interference Cancellation

BS: Base Station

TDMA: Time division multiple access

FDMA: Frequency division multiple access

UE: User Equipment

SINR: Signal to Interference Noise Ratio

LIST OF FIGURES

ENGINEERING AND DESIGN CONSTRAINTS

Designing and implementing Non-Orthogonal Multiple Access (NOMA) enabled Joint Communication and Sensing (JCAS) systems requires addressing a number of engineering and design restrictions in order to achieve optimal performance and reliability. These limits apply to different areas of hardware, software, and system-level integration, including spectrum efficiency, power allocation, interference control, and computational complexity.

SPECTRUM EFFICIENCY

One of the key design restrictions is to maximize spectrum efficiency. NOMA does this by enabling numerous users to share the same frequency band using power domain multiplexing. However, this raises the issue of managing interference among users. To overcome this issue, accurate power allocation algorithms must be created to keep the signal-to-interference-plus-noise ratio (SINR) within acceptable ranges for all users. Advanced algorithms are needed to change power levels based on network circumstances in real-time.

POWER ALLOCATION

Effective power allocation is essential in NOMA-JCAS systems. Power domain multiplexing demands careful allocation of power levels to different users, striking a balance between boosting throughput and preserving sensing functionality. The design must take into account the nonlinear nature of power amplification, as well as the possibility of power leakage, which might damage performance. Advanced optimization approaches, such as semi-definite relaxation (SDR) and sequential convex approximation (SCA), are required to handle the non-convex optimization problems inherent in power allocation.

INTERFERNCE MANAGEMENT

Interference management is another key restriction. In a NOMA-JCAS system, signal superimposition might cause increased interference, especially in dense user situations. Effective interference cancellation techniques are necessary to separate distinct users' signals while preserving the integrity of the sensor data. This requires complex signal processing technologies, such as successive interference cancellation (SIC) and beamforming, to isolate and mitigate interference.

COMPUTATIONAL COMPLEXITY

The computational complexity of implementing NOMA in JCAS systems presents a significant barrier. To allow for real-time processing, the algorithms for power allocation, interference management, and resource optimization must be computationally efficient. This necessitates the creation of scalable algorithms capable of handling enormous computing demands while avoiding system delays or bottlenecks. The number of users, the size of the antenna array, and the dynamic nature of the wireless environment all contribute to the complexity of these algorithms.

RELIABILITY AND ROBUSTNESS

Reliability and robustness are crucial for the successful deployment of NOMA-JCAS systems, particularly in applications such as self-driving cars and smart cities where failure is unacceptable. The system must be capable of maintaining good performance under a variety of scenarios, including changing weather, user mobility, and fluctuating levels of network congestion.

In summary, designing and implementing NOMA-enabled JCAS systems requires negotiating a complicated ecosystem of engineering and design limitations. These include maximizing spectrum efficiency, regulating power allocation and interference, resolving computational complexity, overcoming hardware limits, assuring energy efficiency, and maintaining dependability and robustness. Addressing these limits is critical to realizing the full promise of NOMA-JCAS systems for improving wireless communication and sensing capabilities.

Abstract

In this report, we have defined Non-Orthogonal Multiple Access (NOMA) empowered Joint Communication and Sensing (JCAS) systems under the topic of wireless communications, and performed simulations on the capacities of the systems with respect to their communication and sensing performances. As in the article [1], we defined the model in MATLAB by first simulating communication performances. Subsequently, we defined a conventional NOMA implementation and compared the results to improve the model. Finally, using the precodings applied in communication, we defined the sensing model as in [1], which also directed us to [2]. Without optimizing any precodings, we randomly observed the detection performance in the range of the base station between $-\pi/2$ to $\pi/2$.

1 Introduction

As modern technology advances, JCAS systems are being proposed to improve the capabilities of wireless communications by combining sensing and communication functions into a single sim technique.

NOMA-enabled JCAS systems exhibit a significant leap in future wireless communication and radar sensing technology. In contrast to previously defined multiplexing methods such as TDMA and FDMA, NOMA, which has been implemented in this project, multiplexes users in the power domain (optionally, it can also multiplex in frequency or time in the case of more than two users). By superimposing signals and allocating their power share, NOMA improves spectrum efficiency and user connectivity.

The integration of NOMA into JCAS systems provides various advantages. It provides effective resource allocation and interference reduction, which are critical for high-density user situations and complex sensing tasks. JCAS systems that use NOMA can better meet the demands of new applications like autonomous driving and smart cities, which require both communication and sensing.

1.1 Joint Communication and Sensing (JCAS)

Joint Communication and Sensing (JCAS) is a framework that integrates communication and sensing functionalities within a single system. Mathematically, JCAS can be represented as follows:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{1}$$

where:

- $\mathbf{y} \in \mathbb{C}^{M \times 1}$ is the received signal vector,
- $\mathbf{H} \in \mathbb{C}^{M \times N}$ is the channel matrix representing the propagation characteristics between N transmitter-receiver pairs,
- $\mathbf{x} \in \mathbb{C}^{N \times 1}$ is the transmitted signal vector containing symbols intended for N receivers,
- $\mathbf{n} \in \mathbb{C}^{M \times 1}$ is the circullarly symmetric gaussian noise vector with covariance σ^2.

In the JCAS framework, the transmitted symbols $\mathbf{x}$ are designed not only to convey information for communication purposes but also to facilitate sensing tasks. This dual functionality allows for efficient utilization of resources and enhanced system performance.

1.2 Non-Orthogonal Multiple Access (NOMA)

Non-Orthogonal Multiple Access (NOMA) is a multiple access technique that allows multiple users to share the same time-frequency resources by using different power levels and precoding vectors. The key principle of NOMA is to superpose the signals intended for different users in the power domain and apply successive interference cancellation (SIC) at the receivers.

Mathematically, the received signal y at the base station (or user) can be represented as:

$$y = \sum_{i=1}^{K} h_i \mathbf{w}_i \sqrt{P_i} x_i + n, \tag{2}$$

where:

- K is the number of users,
- h_i is the channel gain for user i,
- $\mathbf{w}_i$ is the precoding vector for user i,
- P_i is the transmit power allocated to user i,
- x_i is the transmitted signal from user i with,
- n is the circullarly symmetric gaussian noise and variance σ^2.

The power allocation must satisfy the following constraint:

$$\sum_{i=1}^{K} P_i \leq P_{\text{total}}, \tag{3}$$

where P_{total} is the total available transmit power.

At the receiver, successive interference cancellation (SIC) is employed to decode the signals. The decoding order is typically based on the channel conditions, often starting from the user with the strongest channel gain. Assuming the users are ordered such that $|h_1|^2 \geq |h_2|^2 \geq \ldots \geq |h_K|^2$, the decoding process for user k can be described as:

- Decode and subtract the signals of users $1, 2, \ldots, k-1$,
- Decode the signal of user k,
- Treat the signals of users $k+1, k+2, \ldots, K$ as noise.

The achievable data rate for user k in a NOMA system is given by:

$$R_k = \log_2 \left(1 + \frac{|h_k \mathbf{w}_k|^2 P_k}{\sum_{j=k+1}^{K} |h_k \mathbf{w}_j|^2 P_j + \sigma^2} \right). \tag{4}$$

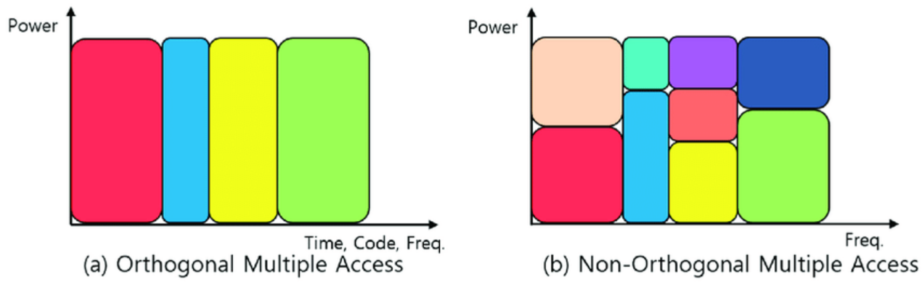

Figure 1: OMA and NOMA Multiplexing Scheme

2 Problem Formulation & System Models

2.1 Referred NOMA Model [1]

A dual-functional base station (BS) with a N-antenna uniform linear array (ULA), K single-antenna users indexed by K = 1,...,K, and M radar targets indexed by M = 1,...,M comprise the proposed NOMA-ISAC system. In contrast to previous research contributions, NOMA is used at the BS in this work to support numerous communication users. In particular, the BS sends the overlaid signals of $\mathbf{w}_i\mathbf{s}_i$ for $\forall i \in \mathcal{K}$ to every user, where precodings $\mathbf{w}_i \in \mathbb{C}^{N\times 1}$ are used to send user i the information symbol $\mathbf{s}_i$. As a result, the signal $\mathbf{y}_k$ that user k received is provided by

$$y_k = \mathbf{h}_k^H \sum_{i\in\mathcal{K}} \mathbf{w}_i s_i + n_k = \sum_{i\in\mathcal{K}} \mathbf{h}_k^H \mathbf{w}_i s_i + n_k, \tag{5}$$

As it was defined in Introduction section parameters hold as channel coefficients and their hermissians (complex conjugate) superimposed signals that includes individual users precoding vectors $\mathbf{w}_i$ multiplied with information symbols $\mathbf{s}_i$, added with the circularly symmetric complex gaussian noise.

In our work $\mathbf{h}_k$ denotes Rayleigh fading channel, we assumed that user's channel strength are in relation to their large scale channel strength, meaning that user K is the strongest user and user 1 is the weakest.

SIC exploited in receiver part of the NOMA is implemented by the following rules, any user k between the interval 1 to K detects and removes the interference from all weaker users with SIC and in order to ensure that SIC carried out rightfully information symbol vector of user k also needed to be decodable at user j's that are stronger than k, yielding the following achievable rate,

$$R_{k\to j} = \log_2\left(1 + \frac{\left|\mathbf{h}_j^H \mathbf{w}_k\right|^2}{\sum_{i\in\mathcal{K}, i>k} \left|\mathbf{h}_j^H \mathbf{w}_i\right|^2 + \sigma_n^2}\right). \tag{6}$$

That will be simulated in MATLAB for this method. When all weaker users are exploited by SIC what remains for user K in terms of data rates are also,

$$R_{k\to j} = \log_2\left(1 + \frac{\left|\mathbf{h}_j^H \mathbf{w}_k\right|^2}{\sigma_n^2}\right). \tag{7}$$

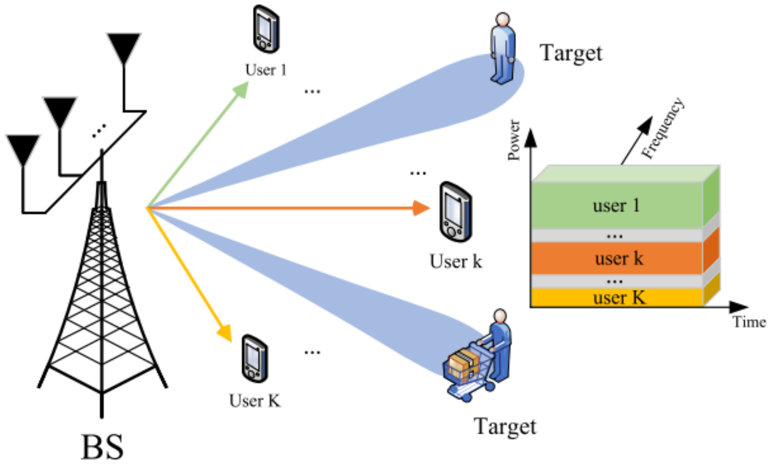

Figure 2: System Model

2.2 Conventional NOMA Model

Having the same structures like in the model referred [1], in this model we introduced the interference to the user that has the strongest channel, user K, and SIC is exploited along the way to the user 1, which results in given communication data rates for the strongest user,

$$R_s = \log_2\left(1 + \frac{|(\mathbf{h}_s^H \mathbf{w}_s)|^2}{|(\mathbf{h}_s^H \mathbf{w}_w)|^2 + \sigma^2}\right) \tag{8}$$

$$R_w = \log_2\left(1 + \frac{|\mathbf{h}_w^H \mathbf{w}_s|^2}{\sigma^2}\right) \tag{9}$$

- $\mathbf{h}_s^H$: Channel coefficients of the strong user.
- $\mathbf{h}_w^H$: Channel coefficients of the weak user.
- $\mathbf{w}_s$: Precoding vector for the strong user.
- $\mathbf{w}_w$: Precoding vector for the weak user.
- σ^2: Variance of the circularly symmetric Gaussian noise.

Equations provided above simulated with the specified system parameters such as two users with individual user equipments (UE) that each has one antennas as receivers and BS is equipped with 4 antennas, users are also to be considered, one far and one close to the base station and the path loss is applied to the users given as in [3],

Also the power allocated equations will be defined as below, power limit has been shared with α's that labelled as 1 and 2 for strong and weak user.

$$R_s = \log_2 \left(1 + \frac{\alpha_1 |(\mathbf{h}_s^H \mathbf{w}_s)|^2}{\alpha_2 |(\mathbf{h}_s^H \mathbf{w}_w)|^2 + \sigma^2} \right) \tag{10}$$

$$R_w = \log_2 \left(1 + \frac{\alpha_2 |\mathbf{h}_w^H \mathbf{w}_s|^2}{\sigma^2} \right) \tag{11}$$

Also the power allocated equations will be defined as above, power limit has been shared with α's that labelled as 1 and 2 for strong and weak user.

$$\mathbf{h}_{\mathrm{ch}} = \frac{1}{\sqrt{2}} \cdot K \cdot (\mathbf{h}_{\mathrm{p}} + j\mathbf{h}_{\mathrm{q}}) \, (\frac{d_{\mathrm{ref}}}{d_{\mathrm{UE}}})^{\gamma}$$

- $\mathbf{h}_{\mathrm{ch}}$: Primary channel coefficients.
- $\mathbf{h}_{\mathrm{p}}$: In phase channel coefficients.
- $\mathbf{h}_{\mathrm{q}}$: Quadrature channel coefficients.
- $\mathbf{d}_{\mathrm{ref}}$: Reference distance.
- $\mathbf{d}_{\mathrm{UE}}$: Distance of user equipment.
- γ: Path loss exponent.
- $\mathbf{K}$: Frequency dependence, antenna gains, and geometry absorbed.

Precoding vector that has been benefited during the simulations is decided to be form from strong user's channel information. By normalizing the hermissian of the channel coefficients we obtain the resultant precoding as the suppressor to the channel both multiplied with the information during the transmission. These vectors effect has been shown in data rate equations as Signal to Interference Noise Ratio (SINR). Reason we use such a simple method to derive precodings was the simplicity of the model since it has only two relative users.

$$w_{s,norm} = \frac{h^H}{||h||}$$

Figure 3: Precoding vector

2.3 Sensing

In a scenario with two users, one base station, and a precoding vector, JCAS uses the covariance matrix and steering vector to improve target identification capabilities. The system's effective sensing capacity is determined by examining the covariance matrix, which contains the spatial features and correlations of the signal. This matrix, together with the steering vector, which provides directionality information, allows for exact target localization and detection. NOMA enables the system to handle several users at the same time by allowing communication signals to overlap at different power levels, hence optimizing spectral efficiency. The incorporation of the precoding vector refines the sent signals, allowing the base station to properly manage power spatial distribution and improve sensing accuracy.

$$R_w = \sum_{i \in K} w_i \cdot w_i^H \qquad\qquad P(\theta) = a^H(\theta_m) \cdot R_w \cdot a(\theta_m)$$

Figure 4: (a) Covariance Matrix , (b) Effective Sensing Power Function .

- $\mathbf{w}_\mathrm{i}$: Precodings.
- $\mathbf{a}$: Steering vector [2].
- θ_m: Angle to the base station.

Overall subject of the study was firstly to simulate communication throughput of two models defined in previous section and select the one that is successful to provide healthier data rates for both users. With the precodings of the model we wanted to measure probability of detection of possible targets that are placed in different radians to the base station. Considering that no optimization aim is satisfied due to time constraints effective sensing power has a linear cumulative probability distribution caused by the randomness benefited in derivation of channel coefficients and precodings as you will see in the results.

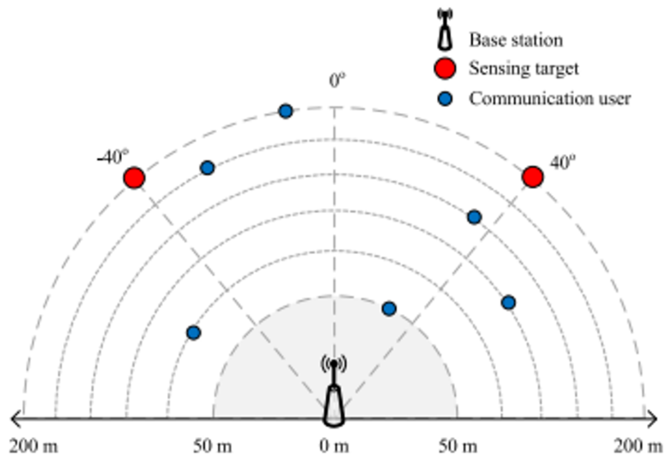

Figure 5: Sensing Model

3 Results and Discussion

3.1 Communication Analysis of Models

We determined the area of possible users as a distance to the BS from 100 meters to 1100 meters for near (strong) user and 500 to 1500 for far (weak) user in order to apply respective path loss. Parameters provided in path loss equation also determined as 1 for constant K and 4 for path loss exponent with reference distance 1 meter.

Resultant communication data rates for each user for each iteration in given distances and overall communication throughput is simulated as below.

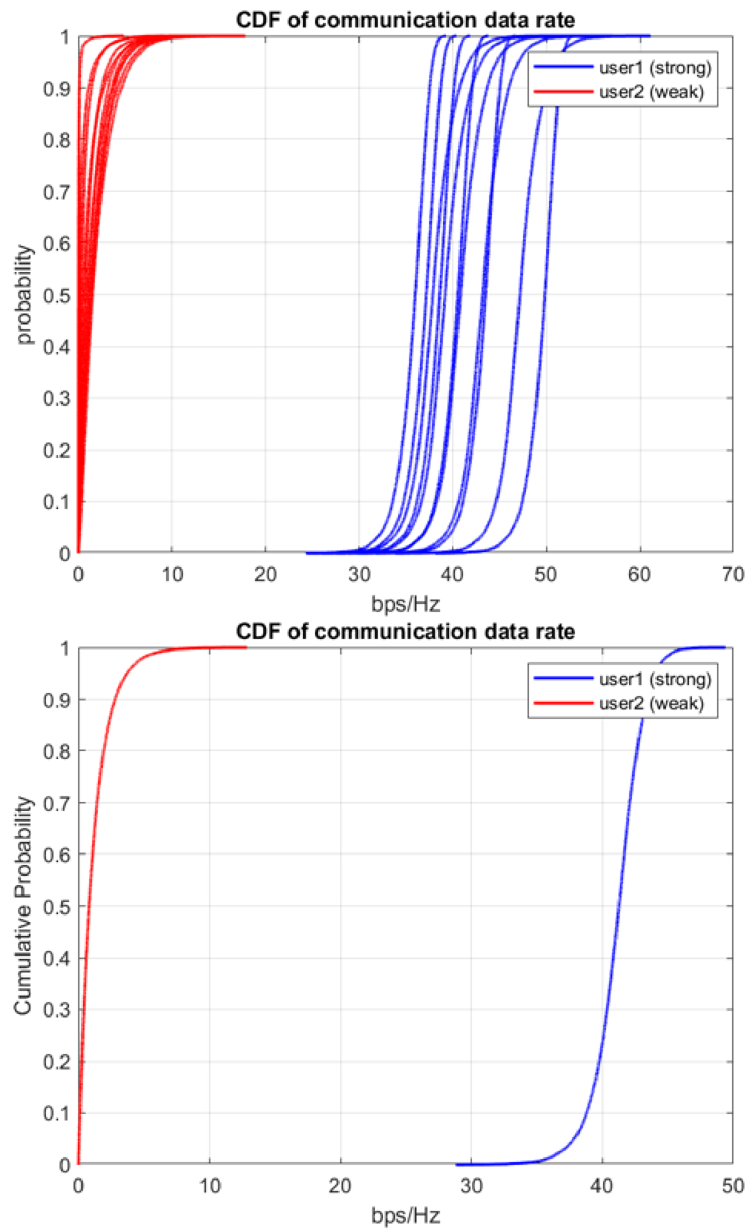

Figure 6: (a) Model simulated with Monte Carlo trials according to the reference [1] with respect to the distances between 100:1100 (strong:green) – 500:1500 (weak:red). (b) Overall communication throughput.

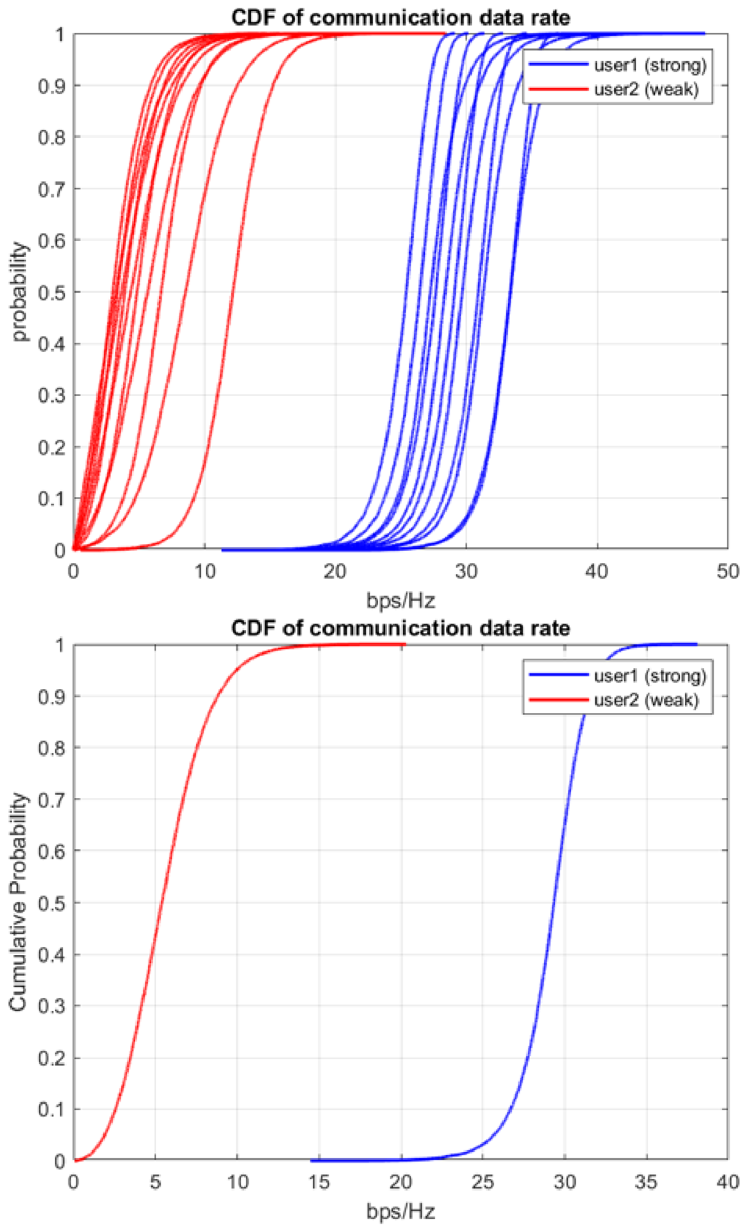

Figure 7: (a) Model simulated with monte carlo trials in conventional NOMA with respect to the distances between 100:1100(strong:green) – 500:1500(weak:red), (b) overall communication throughput.

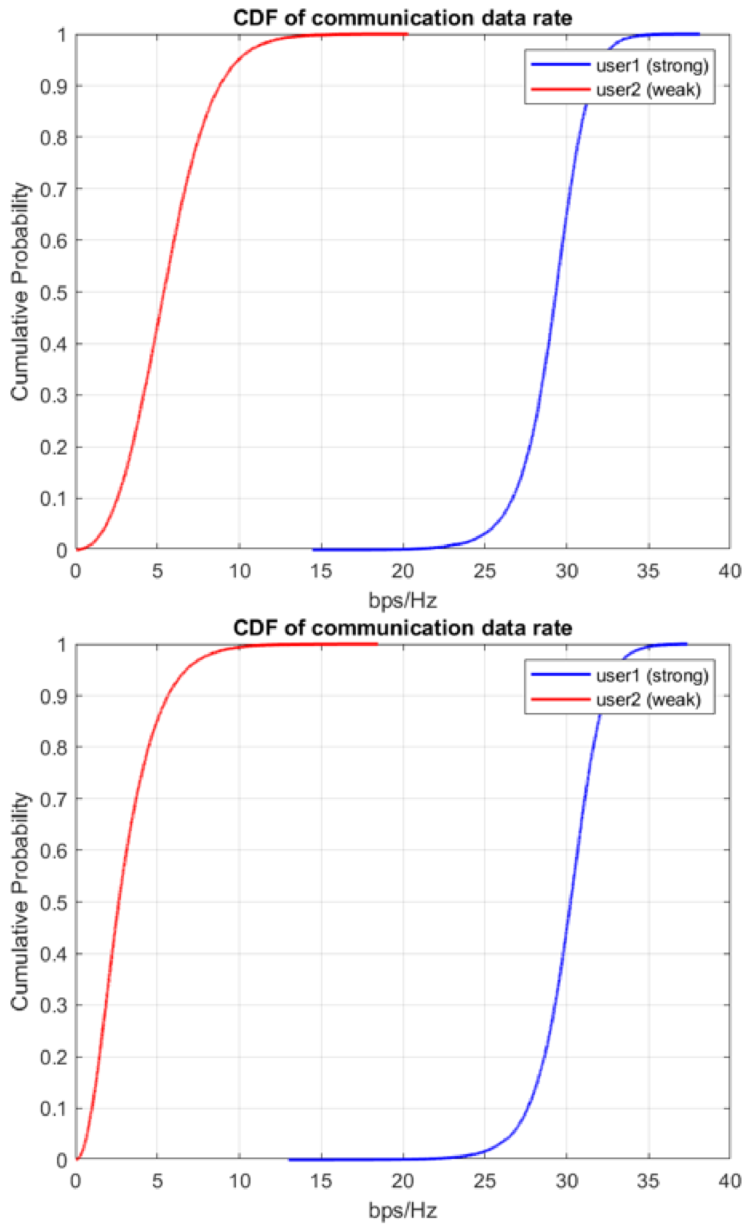

Figure 8: Power allocated results, (a) equally allocated , (b) strong coefficient 0.9, weak coefficient 0.1 .

3.2 Sensing Analysis

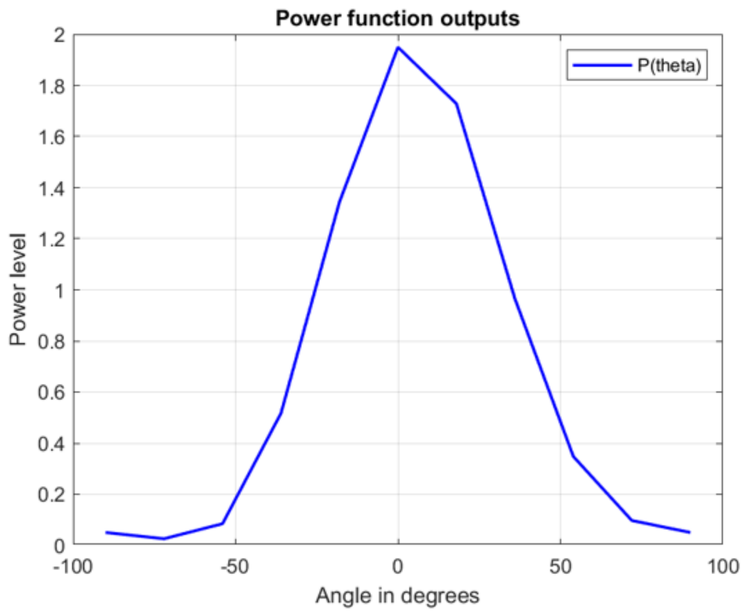

Figure 9: Power function evaluated in different angles, the figure can also be seemed as a map given in Fig. 5

As a result of the simulated communication models best performance is obtained by conventional NOMA model and precodings of the model are used in Sensing part which results are obtained as above.

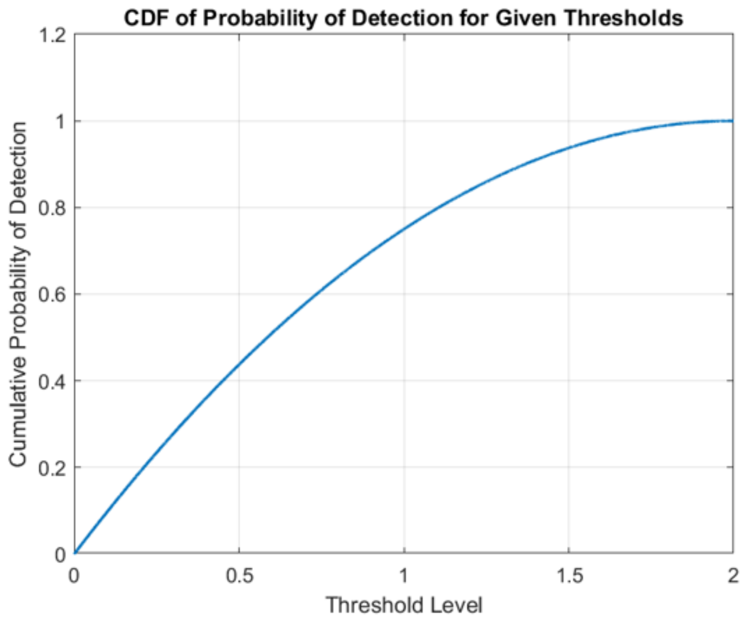

Figure 10: As an output of linear distrubition in power levels, probability of detection distributes similar to a logarithmic function simply indicates that having a large thresholds lower the chance of detection.

In addition to the regional evaluation of effective sensing power, we simulated the cumulative probability distribution with respect to a certain threshold to detect possible targets as,

4 CONCLUSION

In conclusion to our work we successfully performed the simulations in both models and evaluated communication and sensing results.

Simulation results show that NOMA-empowered Joint Communication and Sensing (JCAS) systems boost communication and sensing throughputs significantly. These systems outperform existing multiplexing approaches such as TDMA and FDMA in terms of spectrum efficiency and user connectivity by using NOMA's power domain multiplexing capability. The use of modern signal processing and optimization algorithms improves the performance of NOMA-JCAS systems, ensuring reliable and efficient simultaneous communication and sensing operations. These developments establish NOMA-enabled JCAS systems as a critical technology for future wireless networks, able to meet the complex demands of applications like as autonomous driving and smart cities.

Last but not least this work lacks in optimizing sensing efficiency while preventing optimal values for healthy data rate values to support users caused by time constraints of this work.

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