Statistical Effects of Propagation Environment and Transmit Array Topology on Cell-Edge User Service Quality at mm-Waves

Kreeke, Nicolas Van De; Aslan, Yanki ; Onat, Nehir Berk; Yarovoy, Alexander

DOI
10.23919/EuCAP57121.2023.10133400

Publication date
2023

Document Version
Final published version

Published in
Proceedings of the 2023 17th European Conference on Antennas and Propagation (EuCAP)

Statistical Effects of Propagation Environment and Transmit Array Topology on Cell-Edge User Service Quality at mm-Waves

Nicolas Van de Kreeke[1], Yanki Aslan[2], Nehir Berk Onat[3], Alexander Yarovoy[4]
Microwave Sensing, Signals and Systems Group, Department of Microelectronics,
Faculty of Electrical Engineering, Mathematics, and Computer Science,
Delft University of Technology, Delft, The Netherlands
{[1]*N.VandeKreeke*, [2]*Y.Aslan*, [3]*N.B.Onat*, [4]*A.Yarovoy*}*@tudelft.nl*

***Abstract*—The effects of multipath on the statistical cell-edge user service quality is for the first time investigated for mm-wave multi-user communication systems. The focus is given on setting the user spacing constraints and the transmit array topology via thinning, which can be used to enhance wireless security or decrease analog/digital complexity. A hybrid line-of-sight/non-line-of-sight channel is created by using a statistical model following the communication standards. The multipath signal components are included in the model by using non-coherent or coherent modes of operation. It is shown in simulation that selection, by the medium access control layer, of large angular spacings between the simultaneously served users and application of antenna array thinning at the array edges improves the system performance.**

***Index Terms*—base stations, multibeam antennas, millimeter wave propagation, phased arrays, communication systems.**

I. Introduction

The use of active phased arrays and application of Massive Multiple-Input-Multiple-Output (MIMO) concepts for mobile communications have gained significant attention with the growing use of millimeter-wave (mm-wave) frequencies [1]. Besides, the increasing demand for throughput and capacity has made the multibeam antennas more and more popular in terrestrial networks [2]. However, there is still a missing link between antenna array synthesis and propagation channel modeling, which may cause significant reduction in the optimal design and operation of the communication system [3].

From the system point-of-view, the emerging multi-user communication technologies are facing increased challenges in obtaining reliable yet generic information about the propagation characteristics, which can then be used to decide on the best radio resource management (RRM) and beamforming strategy [4]. Various system-level studies have been presented in the recent mm-wave literature which investigate the user quality-of-service (QoS) based on widely used performance metrics such as Signal-to-Interference Ratio (SINR) or throughput. The impact of increasing the user spacing on the QoS and blind spots in coverage was investigated in [5] by assuming free space propagation. Non-regular array topologies were proposed in [6]–[8] for suppression of side lobes and thus reduction of inter-user interference in free space. Different sector realizations and precoding strategies under free-space propagation assumption were performed in [9], [10]. Performance of multi-lobe and multi-beam arrays on pre-defined multipath environments was studied in [11], [12] based on a given geometrical data and ray tracing simulations.

While the antenna community uses the simplified and deterministic propagation channels, the propagation community considers fully stochastic techniques [13], [14] which did not allow to control transmitter and receiver positions, and did not provide any physical insights into beamforming. To the authors' knowledge, there is still a gap in knowledge about how the QoS performance is "statistically" affected by the propagation environment and array topology when standardized channel models are considered.

In this paper, this gap is reduced by making a novel connection between the channel characteristics, user selection strategies, array topologies and beamforming. To mimic propagation for complex environments in a hybrid (deterministic-stochastic) approach, the software developed at Fraunhofer HHI called QuaDRiGa [15] is used in this paper. The impact of simultaneously served users' distribution on the statistical service quality in different environments (free space and a more realistic hybrid line-of-sight/non-line-of-sight LoS/NLoS channel) is determined. Finally, performance of various antenna topologies are statistically evaluated under different power normalization criteria.

The rest of the paper is organized as follows. Section II presents the system model and its formulation. Section III explains the simulation settings used for demonstration. The simulation results are provided and discussed in Section IV. Section V provides the conclusions.

II. System Model

QuaDRiGa can be used to compute realistic channel matrices (based on the 3rd Generation Partnership Project, 3GPP, standards organization) under various deployment scenarios, propagation conditions, and different MIMO antenna configurations. The QuaDRiGa approach is defined as a "statistical ray-tracing model". Depending on the propagation scenario and antenna positions, it creates statistical/probabilistic

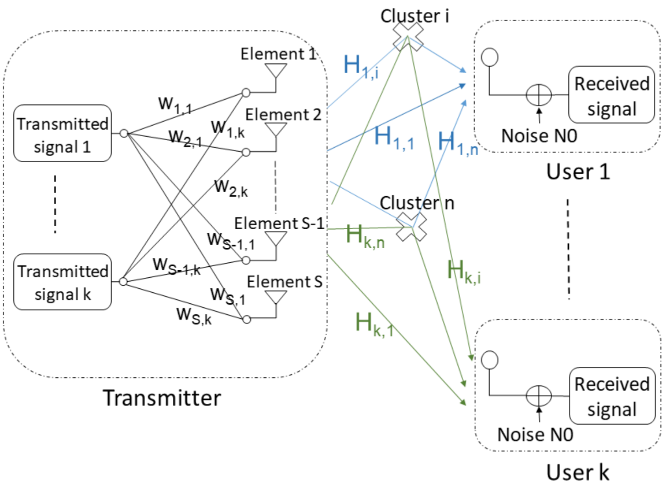


Fig. 1. Communication link between a multibeam transmitter and multiple users in the presence of clusters of scatterers.

environments. Unlike the classical ray tracing approach, QuaDRiGa does not use an exact geometric representation of the environment but distributes the positions of the scattering clusters randomly by following certain statistics [16].

In line with this approach, Fig. 1 visualizes a simplified communication link between a multibeam transmitter phased array and multiple single element users. We consider an isolated cell for simplicity, in which a transmitter with S antenna elements is serving K users simultaneously in the same narrow frequency sub-band using space division multiple access. It is worth to note that for the beam corresponding to the transmitted signal 1 (or transmitted signal k), the channels marked in blue color carry the useful signal (or interfering signal) for User 1, while the channels marked in green carry the interfering signal (or useful signal) for User k.

In this case, the SINR at the k-th receiver for unit transmit symbol energy is defined as [10]:

$$SINR_k = \frac{\Gamma_{r,k,k}}{N_0 + \sum_{i \neq k}^{K} \Gamma_{r,i,k}} \tag{1}$$

where

- $\Gamma_{r,i,k}$ is the total effective channel gain between the transmitter and the k^{th} receiver with the precoding matrix adapted to the i^{th} receiver
- N_0 is the noise at each receiver

Depending on the transmit-receive system architectures in terms of coherent/non-coherent signal addition and time/phase alignment [12], we will consider 3 ways to compute the value of $\Gamma_{r,i,k}$ in the presence of multipath via clusters: (i) non-coherent mode, (ii) coherent mode with time alignment and (iii) coherent mode with time and phase alignment.

In the non-coherent mode, we consider the power that arrive at the receiver k is the sum of the power of each path between the receiver and the transmitter. This method of computation does not take into account the phase of each wave that arrives from different paths. Then, we have:

$$\Gamma_{r,i,k} = \sum_{n=1}^{N} |H_{k,n} \times w_{tx,i}|^2 \tag{2}$$

- $H_{k,n}$ is the H matrix computed by Quadriga of dimension $U \times S$ modeling the n^{th} path between the transmitter and the k^{th} receiver. In the modelling, receivers are single element antennas, so U = 1, then H is of dimension $1 \times S$.
- $w_{tx,i}$ is the precoding matrix at the transmitter which is a column vector of antenna coefficients of dimension $S \times 1$ calculated to maximize the link with the i^{th} receiver.

In the coherent mode with time alignment, we have:

$$\Gamma_{r,i,k} = |\sum_{n=1}^{N} H_{k,n} \times w_{tx,i}|^2 \tag{3}$$

As for the coherent mode with time and phase alignment with the most complicated structure, the formulation becomes:

$$\Gamma_{r,i,k} = (\sum_{n=1}^{N} |H_{k,n} \times w_{tx,i}|)^2 \tag{4}$$

Due to the presence of LoS path in our hybrid LoS/NLoS channel, and by considering its wide application with low complexity and robustness [7], [9], we use the maximum ratio transmission (MRT) precoding in this paper.

III. Simulation Settings

Considering the large number transmitters to be deployed for full-coverage, we selected a relatively conservative 16 element linear multi-beam array in the transmitter generating 3 concurrent beams at 28 GHz. Depending on the multi-beam generation strategy (analog, digital, hybrid), the complexity in terms of analog or digital implementation, heat generation and costs will grow rapidly with increasing number of elements and/or number of beams [2].

We focus on cell-edge users' SINR as they are most prone to additional interference from the nearby cells as compared to the cell-center users [17]. The transmitter is generated following the 3GPP-3D channel model (TR 36.873, v12.5.0,pp.17) [16] as a linear horizontal antenna array composed of 16 elements, vertically polarized. For the 3 receivers in the scene, we choose isotropic antennas. The transmitter is positioned at 10 meters height. The users' height are then fixed at 1 meter (with elevation angle fixed at 2.5 degrees below horizon), and the distance on the ground between transmitter and receivers is equal to 200 meters. Three simultaneous co-frequency users within the azimuthal sector ±60 degrees are selected randomly by the medium access control layer based on a minimal angular spacing criterion [5]. Figure 2 shows as an example in which area the third user can be randomly positioned (green arc) taking into account the other user's positions. Our approach is to start with no restrictive angular interval for the first user and step-by-step reducing intervals where users can be randomly placed (by increasing the minimum angle). The selection of three users is repeated many times for statistical

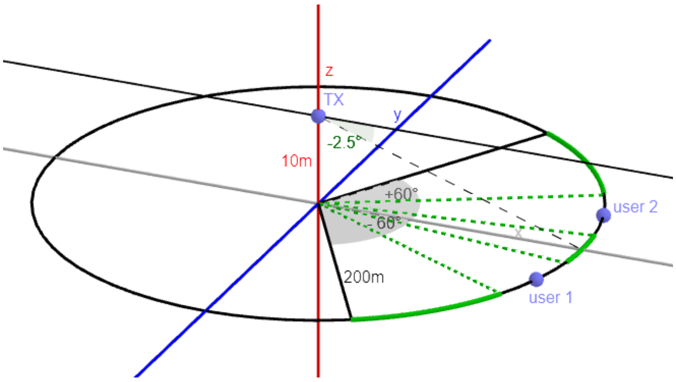
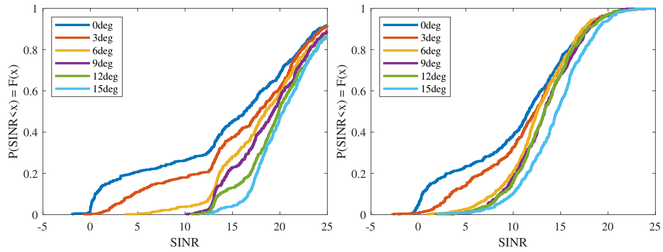


Fig. 2. Random positioning of a third user (in green regions) under certain minimum angular spacing condition between the users.



(a) (b)

Fig. 3. CDF of SINR under different minimum angular user spacing criteria for: (a) free-space, (b) hybrid LoS/NLoS channel in the non-coherent mode.

performance evaluation. In each realization, the three users are served by multiple steerable beams in azimuth via MRT.

Note that in uniformly-distributed ground-user only scenarios with Tx placed at a certain height as we chose, more than 90% of the users are within 2.5 to 10 degrees below horizon [18], which can be effectively covered in elevation within the wide element beam. However, it is useful to mention that the proposed model is flexible in terms of transmit array size, position and number of beams. The number of elements can be increased for improved array resolution, which can be combined with generation of larger number of simultaneous beams in the sector. Array height or cell range can be modified. The individual antenna elements can be replaced by subarrays in the elevation plane providing a fixed and preferably shaped beam for equi-power coverage of the cell [19]. Alternatively, two-dimensional array architectures can be implemented if scanning in elevation is desired. Small single or multi-beam arrays can be used on the receivers as well. In such extensions, propagation simulations must be repeated to obtain the new channel coefficients.

IV. Simulation Results

A. User spacing

Firstly, the impact of smart constraints in random user distribution on the statistical link quality is studied. The main goal is to observe the dependence of the cumulative distribution function (CDF) of SINR in the hybrid LoS/NLoS scenario for different operation modes, and to compare the results with the one from the free-space scenario.

To this end, the minimum spacing constraint is varied from 0 to 15 degrees in 3 degree steps. The results are provided in Fig. 3. A general trend shows that increasing the minimum spacing between the users improves the statistical SINR, which is in line with intuitive understanding of reduced interference due to decay in the side lobe levels with angle. The more realistic hybrid channel causes reduction in the SINRs compared to the free-space channel.

B. Array topology

Next, the effect of transmit array topology on the statistical SINR is studied for two different power normalization approaches. The minimum spacing between the quasi-randomly selected users is selected as 10 degrees and is fixed for each case. In the first part, random array thinning is assumed. In practical systems, this will be used as an antenna layout modulation strategy for secure communications [20]–[22]. To understand the impact of thinning from different portions of the array, the random elements to be turned off are selected either from the central region of the array (defined by 8 elements in the middle) or from the region close to the edges (i.e. the remaining leftmost and rightmost elements). The effect of turning off part the elements is reflected in the total transmit power which will be reduced. Randomized user distributions are repeated for randomized array topologies in order to characterize the full statistical nature of the communication link. The simulations are again given for the free-space propagation scenario as benchmark and for the hybrid LoS/NLoS channel by using the three modes of operation.

The results of the first part are shown in Fig. 4. Among the three modes, the coherent mode with time alignment provides the best performance in terms of SINR, which comes closest to the performance in free-space. This is followed by the non-coherent mode and the coherent mode with time and phase alignment, respectively. It is observed that the negative impact of random array thinning on the SINR is much more significant in the free-space scenario as compared to a more realistic hybrid channel. Thinning from the interior region of the array results in much lower SINR values as compared to applying thinning at the edge elements. This is due to the formation of high side lobes in the resulting aperiodic arrays. Similar to the results in Fig. 3 for the hybrid channel, the coherent mode with time alignment provides the best performance in terms of SINR, which is followed by non-coherent mode and the coherent mode with time and phase alignment, respectively. It is also seen that the non-coherent mode is the most robust among all against the region of thinning. Interestingly, the randomly thinned array could provide very similar (or even better) statistical performance than the fully-populated array in this mode of operation.

In the second part, the statistical performance of particular

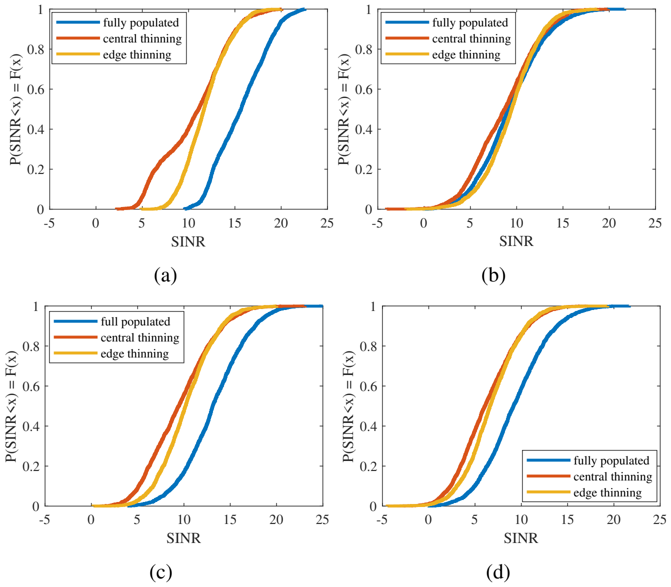


Fig. 4. CDF of SINR in the case of random array thinning for: (a) free-space, (b) hybrid LoS/NLoS channel in the non-coherent mode, (c) hybrid LoS/NLoS channel in the coherent mode with time alignment, (d) hybrid LoS/NLoS channel in the coherent mode with time and phase alignment.

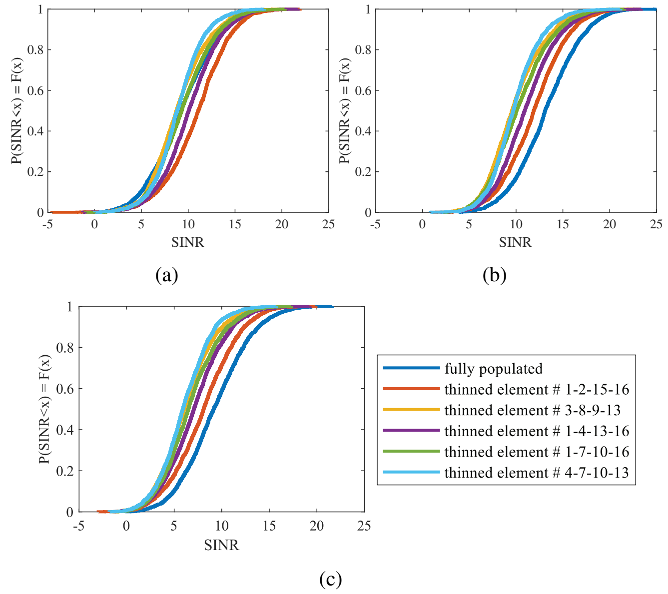


Fig. 5. CDF of SINR for several thinned arrays in the hybrid LoS/NLoS channel for: (a) the non-coherent mode, (b) the coherent mode with time alignment, (c) the coherent mode with time and phase alignment.

thinned arrays are evaluated for the hybrid channel. If selected optimally, such array with a fixed thinned layout can be useful to decrease the number of elements, while keeping a sufficient level of minimum SINR statistically for the users at low cost. For fairness in comparison, the total transmit power is kept the same with the transmit power of the fully populated array in this part. The result of these analyses are shown in Fig. 5 for the three operation modes.

A generic outcome of the study is that despite the increase in the beamwidth, thinning the array from the corner elements and keeping the layout uniform results in the best statistical performance for the selected use case and user distribution criterion. In the non-coherent mode, the SINR performance of all thinned arrays are observed to be similar or better than the fully populated array, which requires further investigation for complete reasoning. In the coherent modes, the fully populated array performs the best, which is followed by the arrays thinned mostly from the edge and from the center and edge, respectively.

V. Conclusion

The statistical effect of multipath on the cell-edge user SINRs is studied for multi-user mm-wave communication systems with spatial multiplexing. The focus is given on the user selection strategy and array thinning. A hybrid LoS/NLoS propagation model is developed and integrated with the transmit array antennas and beamforming by following the 3GPP-3D standards. QuaDRiGa is used to derive the channel matrices in the selected scenario (3 simultaneous co-frequency users at the cell edge, linear array of 16 elements, MRT precoding) for different multiple user selections and transmit array topologies. Performance degradation in more realistic propagation environments than the free-space is quantified, and analyzed for coherent and non-coherent modes of operation for various user spacings. It is shown that under large angular spacing between the users, coherent mode with time alignment of the multipath components arriving at the receiver provides the best and closest performance to the free-space scenario. From the array thinning studies for reduced complexity and/or secure communications, it is inferred that the statistical SINR becomes more stable in the case of multipath and that the thinning should be applied to the array edges when needed.

The future work will focus on expanding the system model to include multi-carrier transmission and NLoS scenarios with optimal precoding schemes at the transmitter and receivers.

Acknowledgment

The research has been performed during the internship of the first author at the Delft University of Technology. The authors would like to thank Prof. Alexandre Chabory from Ecole Nationale De L'Aviation Civile (ENAC) for organization of the internship and EU Erasmus Plus programme for the financial support.

References

[1] W. Hong, Z. H. Jiang, C. Yu, D. Hou, H. Wang, C. Guo, Y. Hu, L. Kuai, Y. Yu, Z. Jiang *et al.*, "The role of millimeter-wave technologies in 5G/6G wireless communications," *IEEE J. Microw.*, vol. 1, no. 1, pp. 101–122, Jan. 2021.

[2] W. Hong, Z. H. Jiang, C. Yu, J. Zhou, P. Chen, Z. Yu, H. Zhang, B. Yang, X. Pang, M. Jiang *et al.*, "Multibeam antenna technologies for 5G wireless communications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6231–6249, Jun. 2017.

[3] G. Oliveri, G. Gottardi, and A. Massa, "A new meta-paradigm for the synthesis of antenna arrays for future wireless communications," *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 3774–3788, Jun. 2019.

[4] P. Angeletti and R. De Gaudenzi, “A pragmatic approach to massive MIMO for broadband communication satellites,” *IEEE Access*, vol. 8, pp. 132 212–132 236, Jul. 2020.
[5] Y. Aslan, A. Roederer, and A. Yarovoy, “System impacts of user scheduling with minimal angular separation constraints in radio resource management for 5G and beyond,” in *Proc. IEEE APMC*, Hong Kong, Dec. 2020, pp. 724–726.
[6] X. Ge, R. Zi, H. Wang, J. Zhang, and M. Jo, “Multi-user massive MIMO communication systems based on irregular antenna arrays,” *IEEE Trans. Wirel. Commun.*, vol. 15, no. 8, pp. 5287–5301, Apr. 2016.
[7] Y. Aslan, S. Salman, J. Puskely, A. Roederer, and A. Yarovoy, “5G multi-user system simulations in line-of-sight with space-tapered cellular base station phased arrays,” in *Proc. 13th EuCAP*, Krakow, Poland, Apr. 2019, pp. 1–5.
[8] N. Amani, R. Maaskant, and W. Van Cappellen, “On the sparsity and aperiodicity of a base station antenna array in a downlink MU-MIMO scenario,” in *Proc. IEEE ISAP*, Busan, South Korea, Oct. 2018, pp. 1–2.
[9] Y. Aslan, A. Roederer, and A. Yarovoy, “System advantages of using large-scale aperiodic array topologies in future mm-wave 5G/6G base stations: an interdisciplinary look,” *IEEE Sys. J.*, Jan. 2021, Early Access.
[10] Y. Aslan, J. Puskely, A. Roederer, and A. Yarovoy, “Trade-offs between the quality of service, computational cost and cooling complexity in interference-dominated multi-user sdma systems,” *IET Comm.*, vol. 14, no. 1, pp. 144–151, Jan. 2020.
[11] V. Degli-Esposti, F. Fuschini, E. M. Vitucci, M. Barbiroli, M. Zoli, L. Tian, X. Yin, D. A. Dupleich, R. Müller, C. Schneider, and R. S. Thomä, “Ray-tracing-based mm-wave beamforming assessment,” *IEEE Access*, vol. 2, pp. 1314–1325, 2014.
[12] Y. Aslan, J. Puskely, A. Roederer, and A. Yarovoy, “Performance comparison of single- and multi-lobe antenna arrays in 5G urban outdoor environments at mm-waves via intelligent ray tracing,” in *Proc. 14th EuCAP*, Copenhagen, Denmark, Mar. 2020, pp. 1–5.
[13] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang, “Overview of millimeter wave communications for fifth-generation (5g) wireless networks—with a focus on propagation models,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6213–6230, 2017.
[14] T. S. Rappaport, S. Sun, and M. Shafi, “Investigation and comparison of 3GPP and NYUSIM channel models for 5G wireless communications,” in *Proc. IEEE 86th VTC-Fall*, Toronto, ON, Canada, Sep. 2017, pp. 1–5.
[15] S. Jaeckel, L. Raschkowski, K. Börner, and L. Thiele, “QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials,” *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3242–3256, 2014.
[16] Fraunhofer HHI, “Quasi deterministic radio channel generator user manual and documentation,” 2017.
[17] M. R. Ramesh Kumar, S. Bhashyam, and D. Jalihal, “Throughput improvement for cell-edge users using selective cooperation in cellular networks,” in *Proc. 5th IFIP WOCN*, Surabaya, Indonesia, May 2008, pp. 1–5.
[18] A. Roederer, J. Puskely, Y. Aslan, and A. Yarovoy, “Shaped elevation patterns for 5G base stations,” in *Proc. IEEE APS/URSI*, Singapore, Singapore, Dec. 2021, pp. 795–796.
[19] J. Puskely, T. Mikulasek, Y. Aslan, A. Roederer, and A. Yarovoy, “5g siw-based phased antenna array with cosecant-squared shaped pattern,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 1, pp. 250–259, 2022.
[20] H. Alves, R. D. Souza, M. Debbah, and M. Bennis, “Performance of transmit antenna selection physical layer security schemes,” *IEEE Signal Process. Lett.*, vol. 19, no. 6, pp. 372–375, Apr. 2012.
[21] X. Chen, D. W. K. Ng, W. H. Gerstacker, and H.-H. Chen, “A survey on multiple-antenna techniques for physical layer security,” *IEEE Commun. Surv. Tutor.*, vol. 19, no. 2, pp. 1027–1053, 2017.
[22] D. Deng, C. Li, L. Fan, X. Liu, and F. Zhou, “Impact of antenna selection on physical-layer security of noma networks,” *Wirel. Commun. Mob. Comput.*, vol. 2018, 2018.