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CONTENT

About the Journal

Journal of Millimeterwave Communication, Optimization and Modelling (JOMCOM) is an international on-line and refereed journal published 2 times a year in English. Journal of Millimeterwave Communication, Optimization and Modelling (JOMCOM) published its first issue in 2021 and has been publishing since 2021. Manuscripts in JOMCOM Journal reviewed of at least 2 referees among the referees who have at least doctorate level in their field.

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Aims & Scope

Communication Technologies: Journal of Millimeter-wave Communication, Optimization and Modelling (JOMCOM) publishes original research and review articles in Communication Technologies, Innovative Technologies, and Systems in the broad field of Information-Communication Technology. Purpose of JOMCOM; To create value in the field by publishing original studies that will contribute to the literature in wireless communication sciences and be a resource for academia and industrial application whole over the world. Besides, JOMCOM aims to bring the valuable work of researchers working in Communication studies to a broader audience at home and abroad. Readership of JOMCOM; valuable representatives of the wireless communication area, especially those who do academic studies in it, and those who do academic studies about modelling and system design and other interested parties. Since JOMCOM will appeal to a broader audience in article submissions, it prioritizes studies prepared in English.

Optimization and Modelling: Journal of Millimeter-wave Communication, Optimization and Modelling (JOMCOM), within the scope of Wireless Communication Sciences, publishes articles on communication theory and techniques, systems and networks, applications, development and regulatory policies, standards, and management techniques. It also reports experiences and experiments, best practices and solutions, lessons learned, and case studies. Additional studies on System Design, Modelling and Optimization. Subject areas of interest covered in the journal include the following but are not limited to:

5G-6G Technologies

Circuits for Optical Communication Systems

Antenna Design

Communication Design Materials

Fiber Optic Communication

Innovative Designs for Communications

Integrated Circuits for Communications

Optimization Methods on Engineering

Realization of Antenna Systems

Realization of Microwave, Radar, and Sonar Systems

RF Circuits

System Design

Visible Light Communication

Wireless Communication

Electrical Smart Grid System (SG)

Received: 26 December 2025; Revised:22 June 2026; Accepted: 29 June 2026 ***Review Article***

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***Abstract*— Smart Grids (SGs) emerge as the cutting-edge power grid system for the future, driven by their resilience, efficiency, reliability, and sustainability. This paper explores the key elements that constitute the smart grid system, management and security, and some advantages of SGs. The components discussed encompass advanced sensors like new sensor-Synchrophasors, renewable energy sources and electric storage, integrated communication systems, distributed power generation, demand response utility rates, and smart meters. Collectively, these components contribute to the evolution and establishment of the SG system. The aim of this paper is to discuss the basic components of Smart Grid (SG) with a focus on the publications between 2018 and 2023.**

Keywords*— *smart grid, microgrid, SG components, management and security, advantages

I. INTRODUCTION

Since the discovery of electricity and up to the present day, the field of energy consumption and distribution has witnessed a profound transformation at the global level, and at the forefront of this development recently comes the concept of smart grids, which will contribute significantly and effectively to the actual field instead of the traditional system. classic energy systems operate on a centralized type which is depicted by large-scale power generation from conventional sources (fossil fuel) and unidirectional distribution carried to the end users. Yet, the limitations of this traditional or existing model, coupled with increasing demands for energy efficiency, flexibility, and sustainability, have led to the discovery or development of the concept of smart grids (SGs).

Smart grids are not just an incremental improvement to existing energy infrastructure; rather, SGs represent a revolutionary reimagining of how electricity is produced, transmitted, and consumed. By using technological devices, such as communications devices and smart meter devices, these technological devices let the system create a dynamic network that can be capable of facing the challenges of the 21st century. According to several sources and perspectives within the field, the term of "smart grids" encompasses a multifaceted array of meanings and interpretations, and the most common definition of SG is tow way communication while the traditional grid is one way communication.

On the other hand, the Microgrid, which plays a crucial role in the development of the smart grid, can also be defined according to [1] as a cluster of interlinked loads and dispersed energy resources operating within well-defined electrical perimeters, microgrids function as a unified and controllable entity in relation to the larger grid.

Smart grids have been developed with the objective of providing sustainable energy by combining energy systems and new developments in communication technologies and data. The main aim of smart grids is to utilize energy efficiently by reducing the rate of loss and leakage and integrating energy produced from renewable energy sources such as solar and wind into the system [2]. The rest of the paper is organized as follows. The Smart Grid Components were presented in Section II. Management and security of SG were presented in Section III. Advantages of SG was presented in Sections IV. Respectively Conclusion was presented in V.

II. SMART GRID COMPONENTS

In the complex framework of smart grids (SGs), a number of components and advanced technologies come together to form the basic elements or components of smart grids. As shown in Table 1. below, these components structure the infrastructure of smart grids.

A. New Sensors-Synchrophasors

Synchrophasors represent intricate grid measurements accessible through devices known as phasor measurement units (PMUs). These units have the capability to report up to 60 measurements per second [4]. The integration of PMUs is pervasive in the functioning of power systems, encompassing tasks such as power system control, monitoring, distribution network control, load shedding control and analysis, and state estimation. This underscores the significance of PMUs in the modern world [5]. PMU and wireless sensors networks have been observed as one of the main monitoring components of power systems in the last few years in the monitoring of the electrical grid. A synchronised phasor measurement system is a substitutional technology obtaining gauge of magnitude, the angle of voltages, and currents at spots terrestrially remote from where the electric power system is located, it also swiftly and accurately records frequencies, harmonics, active and reactive power, speedily, all while maintaining synchronization [6].

TABLE I. BASIC COMPONENTS OF SMART GRID [3]

Smart Grid components	
1	New sensors-Synchrophasors
2	Renewable energy and electric storage
3	Integrated communication systems
4	Distributed power generation
5	Demand response utility rates
6	Smart meters

Figure 1 shows the system of a phasor measurement is basically formed from:

- (PMU) Phasor Measurement Unit.
- (PDC) Phasor Data Concentrator.
- (GPS) Global Positioning System.
- Communication Channels.

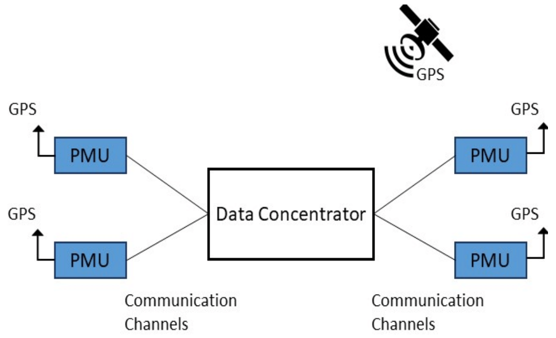

Fig. 1. Synchronized Fasorial Measurement System[6]

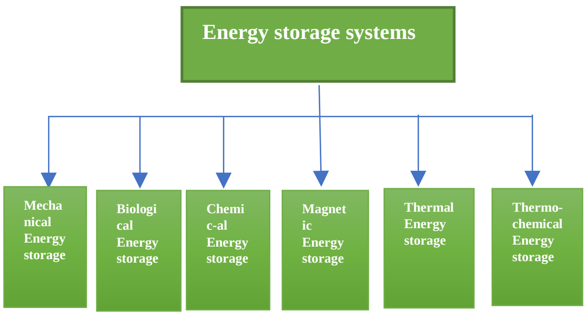

Fig. 2. Categorization of systems for storing energy.

B. Renewable Energy and Electric Storage

Renewable energies such as Photovoltaic (PV) and Wind energy are playing an important role in today's distributed energy resources (DER) and bring challenges to the grid operation, specifically concerning power quality [7] .On the other hand, PV, wind, and storage systems can be remotely controlled providing opportunities for optimizing the utilization of grid resources [7].

The novel rise in the field of renewable energy generation could be able to reduce CO2 and balance consumption. By using the Battery Energy Storage Systems (BESS) optimizing supply and demand, it is more significant than ever before to administer charge control for the interest of the all stakeholders [8]. Various energy storage system technologies can be employed for storing electrical energy. Power and energy density, both in steady-state and transient conditions, are key attributes of energy storage technology, as indicated by multiple studies. Achieving high power and energy density concurrently necessitates the collaboration of multiple energy storage technologies, known as a hybrid energy storage system (HESS) [9]. According to [10], there are different forms of energy storage that can be used, as presented in Fig. 2.

C. Integrated Communication System

For the successful operation of an active distribution network in SG, effective communication infrastructure is essential, incorporating key performance criteria techniques [11]. The communication technology process can be categorized into two primary segments: wired and wireless, in terms of generation, transmission, distribution operations of SG [12]. Wired communications technologies consist of Power Line Communications (PLC), Fiber Optic cables networks and Digital Subscriber Line whilst wireless technologies are generally EDGE/ GPRS/3G/4.5G/5G, Radio Frequency (RF-RF Mesh) Wi-Fi, Wi-Max, Bluetooth, Zigbee, LoRaW [13]. PLC is one of the most popular communication methods by comparison to EDGE/GPRS/3G because it does not need a third-party corporation consequently can eliminate addiction to other partner for communication, and this status is good in terms of cyber security [13], on the other hand using 5G provides infinite bandwidth theoretically and free from regulation also the communication security is guaranteed at physical layer [14]. The choice of communication method should be based on the specific requirements within the application area.

D. Distributed Power Generation

Distributed power generation refers to an electrical power source directly connected to either the distribution network or the customer's meter site, rather than relying solely on centralized power plants that are often far from end-users and remote areas. It includes small-scale decentralized energy sources that can be integrated into local distribution networks so that makes the distribution process easy for all users and they benefit greatly from it [15].

According to [15] distributed generation are classified on three bases: the bases of generation technology, the bases of Connection and the bases of Size.

In SGs, distributed power generation is integrated with advanced communications, control and monitoring technologies this integration let it to make a further reacting and adjustable energy infrastructure. There are some points explain how distributed power generation operates within a smart grid.

- Decentralized Generation: SGs elevate decentralized energy generation, with centering on distributed energy resources (DERs) like small wind turbines, rooftop PV panels, combined heat and power (CHP) systems, and energy storage devices.[16]
- Microgrids (MGs): Power generation is often a key entity for microgrids within smart grids. MGs are small-scale systems related to operating independently or connecting to the main network. It generates energy and supports energy generation at the community level. In a power distribution system with microgrids, habitation who use DERs and interactive devices could react with each other and the grid to exchange power [17].
- Smart Inverters: Smart inverters are devices based on power electronics and play a crucial role in converting DC power generated from renewable energy sources such as solar panels into AC power to be used in the grids. Smart inverters can perform several tasks in the context of the smart grid, such as providing network support functions, voltage regulation, interactive power control, and network synchronization[18].

E. Demand Response Utility Rate

Demand response (DR) stands for group measures to reduce energy demand dynamically at fixed times and in particular places in response to a close shortage in supply [19], in DR there are many security issues could compromise the efficiency of the DR program. Common security requirements in DR are Integrity, availability, authentication and confidentiality [19]. There are two types of programs (Price-based DR and Incentive-based DR [20]) can be used in demand response which uses monetary stimulant to encourage demand participation in balancing the discrepancy between generation and consumers[21].

Price-based DR is a strategy that involves consumers adjusting their electricity consumption patterns in response to price signals. In this approach, changes in electricity prices serve as an incentive for consumers to modify their usage, promoting more efficient and flexible energy consumption [22].

Incentive-based DR refers to a strategy where consumers actively engage with and respond to signals or requests from the grid operator or energy provider to adjust their electricity consumption. This approach involves a two-way communication process, allowing consumers to play a more participatory role in managing their energy use based on real-time information or specific instructions from the grid [23].

F. Smart Meters

In the present day, smart grids encompass various significant systems, including smart meters, distributed renewable energy, energy storage, electric vehicles, and applications for smart cities and homes. Advanced Meter Reading (AMR) stands out as a prominent element within smart grids, offering remote and real-time monitoring of all consumers through their smart meters (SM).[13] [24] also SM's application range covers various benefits, including accurate billing information, user usage information, establish two-way communication and remotely control user devices [25]. AMR can let SGs to have an extensive framework of functions parallel to conventional grid technologies.

As an example of these functions: prediction of the consumption, control of the consumption remotely and the detection of the theft and loss measurements.

In addition to these components the following features should be included in the smart grids systems;

- Intelligence;
- Personalization;
- Digitalization;
- Flexibility;
- Durability; [26]

Intelligence, a cornerstone of contemporary systems, involves the integration of smart technologies within the framework. This entails leveraging sophisticated algorithms, artificial intelligence, and data analytics to optimize operations, enhance decision-making processes, and improve overall efficiency.

Personalization is another necessary part, emphasizing the individual inclusion of customers within the system while ensuring the exclusion of third-party entities. By doing so, the sharing of information and personal data between users and the system becomes not only personalized but also highly secure.

Digitalization plays a fundamental role in transforming the smart grid into a dynamic, responsive platform. The adoption of digital technologies creates a strong foundation, enhancing reliability and facilitating swift and efficient operations. A digital platform ensures that the smart grid system can adapt to the evolving energy landscape and seamlessly integrate emerging technologies.

Flexibility is a key characteristic that underscores the adaptability, adjustability, and expandability of the smart grid (SG). This ensures that the system can accommodate diverse energy resources, respond to fluctuating demand patterns, and readily incorporate technological advancements. The flexibility of the smart grid is essential for meeting the unique needs of different regions, industries, and consumers.

Finally, durability is major in safeguarding the smart grid against potential threats and ensuring its resilience in the face of various challenges. This involves implementing robust cybersecurity measures, fortifying the system against cyber-attacks, and establishing fail-safes to protect against disruptions. A durable smart grid is one that can withstand external pressures and continue to function securely, providing uninterrupted and reliable energy services to the users.

III. Management And Security Of SG

Due to the complexity of the system Smart grid requires advanced sensing and control technologies in order to be well managed and response to the demand response (DR) of the customer. In the rapidly advancing landscape of smart environments (SE), the Internet of Things (IoT) stands out as a pivotal partner in the realm of resource and energy management. As we navigate the complexities of modern energy systems, the integration of IoT technologies has become instrumental. One specific area where this alliance is particularly impactful is in Demand Side Management (DSM) within smart grids (SG). To harness the potential of this synergy, the implementation of a Smart Energy Management System (SEMS) proves to be a strategic move. SEMS, built upon the foundation of advanced meter reading (AMR) and contemporary technologies such as the Internet of Things (IoT), plays a key role in optimizing energy consumption patterns. By leveraging real-time data provided by AMR and the connectivity capabilities of IoT, SEMS transforms into a dynamic and responsive system. The seamless integration of AMR with IoT-based technologies brings about a multifaceted enhancement in the effectiveness of SEMS within smart grids. Not only does it enable accurate and timely monitoring of energy usage, but it also facilitates intelligent decision-making processes. This amalgamation empowers DSM strategies to be more adaptive and finely tuned to the ever-changing demands and conditions of the grid. As we delve further into the era of smart environments, the collaborative interplay between IoT and energy management systems like SEMS becomes increasingly vital. This symbiotic relationship holds the promise of ushering in a new era of efficiency, sustainability, and resilience in our energy infrastructure. [27]. In smart network systems, information comes from the smart metering in the power distribution system is collected by the smart energy management system (SEMS). SEMS can measure, collect, store, analyse, manage, monitor and control the current information of the entire system in real time [25].

The Cyber-demand-side management (DSM) infrastructure combines SG communication protocols and AMR devices to allow the SG system to automatically make decisions such as balancing load requirements or/and network stability improvement requirements. In addition, the DSM platform can bring significant added value to the company by saving customers costs and reducing CO_2 emissions. However, since everything in our lives now depends on the supply of electricity, the unfavourable effects of cyberattacks are becoming increasingly severe[28].

IV. Advantages Of Smart Grids

Smart grids have many advantages compared to traditional electrical grids, and these advantages facilitate the usage of energy in a flexible and simple way in our daily lives by integrating advanced technologies and communications systems into the grid system, some of those advantages are given below.

- Improving the quality and reliability: Smart grids improve the quality and reliability of power distribution by quickly detecting errors or faults and responding directly. Automated systems can isolate and reroute power, reducing downtime and continuously improving overall grid reliability.

- Renewable energy integration: the integration of renewable energy into our energy systems is undergoing a transformative shift with the advent of Smart Grids. These sophisticated infrastructures not only simplify but fundamentally revolutionize the seamless assimilation of renewable sources like photovoltaic (PV) and wind. Smart Grids play a pivotal role in transforming the dynamics of energy production and distribution, going beyond mere simplification. The real-time monitoring and control capabilities inherent in Smart Grids act as a technological backbone, empowering Grid Operators (GO) to effectively navigate the challenges posed by the volatility and unpredictability of renewable energy production. Whether it's the variability in output from photovoltaic systems or the dependence on atmospheric conditions for wind energy, Smart Grids function as intelligent orchestrators, dynamically adjusting and optimizing energy distribution to align with the ever-changing patterns of renewable energy generation. Beyond addressing variability, the integration of renewable energy into the energy mix is a strategic move toward maximizing the utilization of clean and sustainable resources. Smart Grids facilitate the seamless blending of renewable energy, fostering a more environmentally friendly and resilient energy ecosystem. As the world moves towards a future where reliance on renewable energy is paramount, Smart Grids emerge as indispensable catalysts, ensuring that the transition is not just feasible but also efficient. The synergistic relationship between real-time monitoring, adaptive control, and renewable energy integration positions Smart Grids at the forefront of the global pursuit of sustainable and eco-conscious energy solutions. Increased Energy Efficiency: SGs can better manage and optimize energy distribution, minimizing losses during the transmissions and distributions. Increased efficiency helps save energy and lessen overall energy consumption.

- Load Management and Demand Response: SGs revolutionize energy consumption, empowering consumers with tools for active participation. Through advanced demand response programs, consumers actively contribute to grid stability, adjusting energy usage in response to real-time prices and network conditions. This dynamic approach, especially during peak demand, eases strain on the grid. Smart Grids enable informed decisions by allowing consumers to adapt energy consumption based on real-time information, optimizing load distribution for enhanced grid stability and overall energy efficiency. With the integration of renewable sources, Smart Grids seamlessly manage variable outputs, ensuring adaptive load management strategies. Smart Grids turn consumers into active contributors, shaping a sustainable and responsive energy landscape. The synergy of consumer empowerment, real-time data, and efficient load management positions Smart Grids as catalysts for a more sustainable and resilient energy future.

- Self-Healing and Resilience of the Grid: SGs are designed to be more resilient and self-healing. If an outage or failure occurs, the system can automatically detect and isolate affected areas and realign power to reduce impact and restore operations faster.[29][30].

V. Conclusion

To conclude this paper, the main components of smart grids and their important key are explained. the smart grid can be noticed as a digitally improved system of the conventional or existing energy system infrastructure. Operating the smart grids needs clever systems e.g., communication system (wired or wireless), advanced meter reading (AMR), microgrid, management, and security these play a master role in new developments and the realization of the smart grid. and the smart grid's objective is to efficiently, securely, and sustainably deliver electricity from utilities to consumers through the implementation of two-way digital technology.

Statement of Research and Publication Ethics

The author hereby declares that this study has been prepared in strict accordance with the principles of research and publication ethics. All sources of information and literature used in this study have been appropriately cited.

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Validated Predictive Modeling of Antenna Array Directivity,Gain and SNR at 3.6 GHz for 5G Networks

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***Abstract*— Antenna array directivity, vital for RF communication, is explored using 2x2 to 64x64 arrays. Matlab simulations at 3.6 GHz with a 30-degree tilt reveal directivity increases with array size: 6.02 dB (2x2) to 36.12 dB (64x64). SNR also improves, from 125 dB to 155.10 dB. A Random Forest Regressor achieves an R-squared of 0.991, optimizing performance. This study emphasizes the need for directivity optimization in modern wireless antenna designs.**

***Keywords*— antenna directivity; radiation; wireless connection; signal strength**

I. INTRODUCTION

In a range of 3 GHz and 30 GHz, frequency encompasses upper extreme of Super High Frequency (SHF) against the lesser extreme of Ultra High Frequency (UHF) on a considerably limited Fresnel zones and expansive directional gain. SHF is known for its high data flow with finer latency to counterbalance the setback in radiation [1][2].

Antenna is a fundamental tool that sends and accepts electromagnetic waves. As a critical component of telecommunication, it plays the transducing role of interchanging electric signals and radio waves on the corresponding functions of receiving and sending information. This sets its employment across various wireless appliances for the usage of mobile networks, satellite communication, broadcasting, and Wi-Fi [3][4].

Dissimilar antennas possess unalike, yet, integral functions across varying telecommunication domains. On one hand, radiating identical signal encompassing all horizontal directions has made omnidirectional antennas a compatible alternative to multi-directional communications, as seen in applications like Dipole antenna of conventional broadcasting and wireless internet router [5][6]. On the other hand. streamlining radio waves toward a designated direction makes Directional Antennas suitable for minimized disruption across uninvolved directions and increased gain, as seen in Yagi, Parabolic and Patch antennas for signal receiving on television, satellite communication, and other systems with beamforming requirement [7][8][9].

Furthermore, antenna elements can be integrated to form antenna array (AR) such as the multiple-input-multiple-output (MIMO) antennas which has been rudimental to contemporary wireless communication via Wi-Fi, as well as the 4G and 5G networks. Serves as a phased array to computerize the handling of beam directivity, data flow, coverage and reliability are enhanced following an increased number of antennas on both ends of outbound and inbound [10][11].

Parameter surrounding technological configuration of antenna subjects the attention for frequency range in which the designed system operates. Different technological contexts then require distinguished frequency range, as seen from the range of 800 MHz and 3.5 GHz for cellular applications, and 2.4 GHz and 5 GHz for Wi-Fi applications [12][13]. Further preference of directed antenna over isotropic antenna lies on the principal consideration for higher gain from the former's capacity in directing undisrupted wave with minimal interference [14]. System effectiveness as measured in decibels (dBi) on both gain and signal radiation, thus, reflects directivity or specified direction of the antenna in radiation focusing against the considerably less directive setup of omnidirectional alternatives [15][16][17].

This is besides the accounting of electric field orientation or polarization in wave radiation towards improving the magnitude of communicating signal between connected outbound and inbound [18][19]. On the peripheral, sustaining angular width of an antenna's main lobe is important within contemporary technological ground for superior directivity that narrows beam width for elevated operational precision and reliability [20][21][22]. This takes into account the aspects of array factor (AF) and element pattern for the established directivity of uniform linear array (ULA) and uniform rectangular array (URA) [23][24]. Reflected in the layout of a parabolic dish, directivity value is enhanced from a directional design that tremendously narrows the main lobe [25].

This paper pursues the investigation of directivity in antenna configuration from a pre-construed frequency of 3.6 GHz. On a tilt antenna element of 30 degree for observed radiation between the x and y surfaces from boresight as adjacent to the x surface, this study aims to compute the effectiveness of antenna arrays in energy focusing toward a designated direction based on dissimilar designs of 2×2, 4×4, 8×8, 16×16, and 64×64 in rows and columns. The remainder of this papers encompasses related algorithmic equations, acquired findings with explanations of each studied antenna array, and conclusive summarization in the second, third and fourth sections, respectively.

II. MATHEMATICAL MODEL

At each designated direction of , directivity D spherically systemizes the radiation intensity to accord its average ratio. The outcome is manifested by [25]:

$$D(\theta, \varphi) = \frac{U(\theta,\varphi)}{Uavg} \tag{1}$$

where $U(\theta, \varphi)$ represents radiation intensity toward the designated direction, and Uavg represents the average radiation intensity that identifies $P_{rad}/4\pi$ with P_{rad} as the total radiated power.

In this case, radiation intensity affiliates each unit area of radiated power toward the designated direction on the expression of:

$$U(\theta,\varphi) = r^2 . P(\theta,\varphi) \quad (2)$$

where $P(\theta,\varphi)$ represents the power density following spatial gap of r distancing the antenna at the direction of (θ,φ). Constituting the fundamental in radiation intensity across the solid angle in entirety, total power as radiated from the antenna P_{rad} is then manifested by:

$$P_{rad} = \int_0^{2\pi} \int_0^{\pi} U(\theta,\varphi) \sin\theta \, d\theta \, d\varphi. \quad (3)$$

The replacing of Uavg in the Equation (1) with Equation (3) consequentially adapts the expression of directivity as:

$$D(\theta,\varphi) = \frac{4\pi\, U(\theta,\varphi)}{Prad}. \quad (4)$$

Following this, the consideration for maximum directivity is equated by:

$$Dmax = max\left(\frac{4\pi\, U(\theta,\varphi)}{Prad}\right), \quad (5)$$

with approximated directivity of the antenna a specific base number of elements being derived by:

$$D \propto N. \quad (6)$$

Such arrangement fixates the parallel between number of elements and magnitude of directivity through an increasingly precise or narrowed main lobe. The approximation is derived by:

$$D \approx 10 \log_{10}(N) \quad (7)$$

with N represents the total elements of each array. The directivity expression can be exemplified on an 8×8 antenna array with 64 total elements through the derived approximation of:

$$D \approx 10 \log_{10}(64) = 10 \times 1.8 = 18 \text{ dB}. \quad (8)$$

Constructive integration of array factors toward designated direction of the main lobe elevates potency across extensive spatiality with growing focus in the energy radiation. The intention of understanding such proficiency propelled simulated outputs across antenna array designs of 2×2 to 64×64 (2×2, 4×4, 8×8, 16×26 and 64×64) in the Matlab software.

On further note, simulating direction for antenna arrays accounts directionality in propagated signal and data rate on the system's extent for effective information transference. This study specifies the widely adopted element spacing of λ/2 as a fractional incorporation to wavelength λ for decreased disruption and increased manageability of the side lobes. The system's data rate is further gauged on existing affiliation between the specified bandwidth and SNR in Shannon capacity based on the expression of:

$$R = B \cdot \log_2(1+\text{SNR}) \quad (9)$$

where B represents the bandwidth at the specification of 100 MHz. Notably, directivity is influential toward SNR Signal to Noise Ratio due to improvements in signal receiving in the designated direction, lost power and encountered noise from the directional gain. Thereupon, incorporation of machine learning mitigates validity issue of current results on 1,000 samples. System's effectiveness from unseen data is concomitantly appraised on steering angles within the range of -90 and 90 degrees, and the pre-construed frequency of 3.6 GHz between separation of 80% and 20% in training and testing data sets to mitigate the possibility of overfitting. In its entirety, implementation of the model followed fit ensemble function in Matlab software for the training of Random Forest Regressor off 50 decision trees, with further estimations that generate the values for Mean Squared Error (MSE), Mean Absolute Error (MAE), and R-squared metrics [26][27].

Algorithm 1

Input:
Array of actual directivity values (in dB)
Array of predicted directivity values (in dB)
Output:
Scatter plot comparing actual and predicted directivity, with a linear fit line
//Step 1: Import or define the data:
{
Array of actual directivity values (dB)
}actual_directivity←Array of actual directivity values (dB)
{
Array of predicted directivity values (dB)
}predicted_directivity←Array of predicted directivity values (dB)
//Step 2: Initialize the plot:
Create a scatter plot of predicted_directivity{predicted_directivity}predicted_directivity vs. actual_directivity{actual_directivity}actual_directivity using blue circles ('o'\text{'o'}'o').
Overlay a scatter plot of actual_directivity{actual_directivity}actual_directivity vs. itself using red crosses ('x'{'x'}'x').
//Step 3: Add labels and title:
Set the x-axis label as "Actual Directivity (dB)".
Set the y-axis label as "Predicted Directivity (dB)".
Set the title as "Comparison of Actual vs. Predicted Directivity".
//Step 4: Add a legend:
Include labels for:
"Predicted Directivity"\text{"Predicted Directivity"}"Predicted Directivity" (blue circles).
"Actual Directivity"\text{"Actual Directivity"}"Actual Directivity" (red crosses).
//Step 5: Enable gridlines:
Activate gridlines to enhance plot readability.
//Step 6: Add a linear fit line:
Compute regression coefficients:
Use least-squares fitting to derive slope and intercept of the line:
fit_line=m·x+b\text{fit_line} = m \cdot x + bfit_line=m·x+b where m is the slope and b is the intercept.
Generate fitted line values for the range of actual_directivity\text{actual_directivity}actual_directivity.
Add the fit line to the plot:
Plot the fit line as a dashed black line ('–k'\text{'--k'}'–k').
//Step 7: Finalize the plot:
Adjust plot aesthetics for clarity, ensuring all elements are visible and distinguishable.

Algorithmic inclusion elevates the scientific rigor of this study, besides improving the consistency and conformity to a research's best practices. Key benefits enclose clarity, adaptability, and comprehensibility of endorsed method toward improved operation reliability and ability to be validated.

III. Result And Discussion

Current findings visually manifest the 2×2, 4×4, 8×8, 16×16 and 64×64 in antenna array designs to enable independent performance appraisal, while divulging modifiable practices to achieve improved directivity, minimized side lobes, or attaining specific radiation layout pattern. On the onset, Figure 1 and Figure 2 separately illustrate the antenna element array and radiation pattern of a 2 rows by 2 columns (2×2) antenna array design.

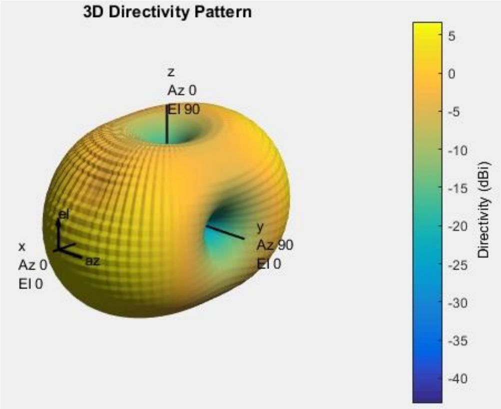

Fig. 1. 2×2 antenna array

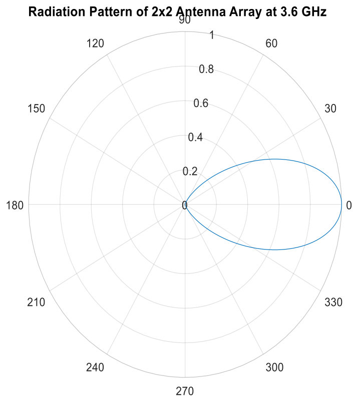

Fig. 2. Radiation Pattern in 2×2 antenna array

The simplistic and cost-effective nature of 2×2 antenna array makes it more preferable for applications in Wi-Fi and other miniature cells. However, it is outperformed by the larger arrays in terms of directivity and capacity, where restricted data stream limits the applications with high data rate requirement. Better performance can be observed from an antenna array design of 4 rows and 4 columns (4×4) as a progressive blueprint through the illustrated elements and radiation pattern in Figure 3 and Figure 4, respectively.

As an improvement in signal quality to the 2×2 antenna array, this design is more reliable. The enhanced data rate, signal quality, and magnitude of wireless network, therefore, idealize the 4×4 antenna array for high usage and operational needs in various urbanized, public and entrepreneurial networks, especially toward the configuration of 4G LTE and 5G NR (New Radio). It is similarly popularized toward numerous complex communication applications such as fixed wireless access and radar systems. Nevertheless, the elements and radiation pattern of a more advanced antenna array design of 8 rows and 8 columns (8×8) can be separately observed in Figure 5 and Figure 6 with an increased antenna directivity.

With a total of 64 elements, the 8×8 antenna array advances other designs with lesser elements on increased gain and directivity, as well as a refinement in spatial multiplexing. Such performance is leveled by its setbacks of increased cost and power usage. However, this is subservient to the 256 elements of the more complex antenna array design of 16 rows and 16 columns (16×16) in Figure 7, following a radiation pattern as observable in Figure 8.

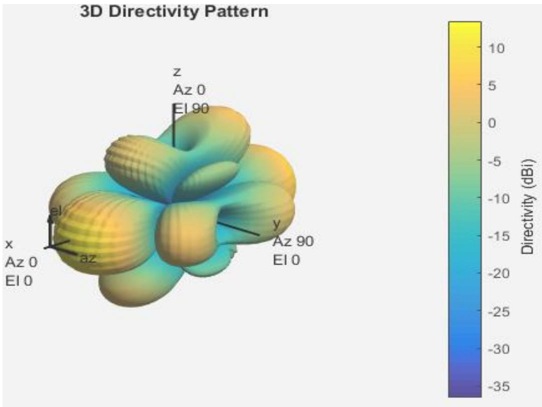

Fig. 3. 4×4 antenna array

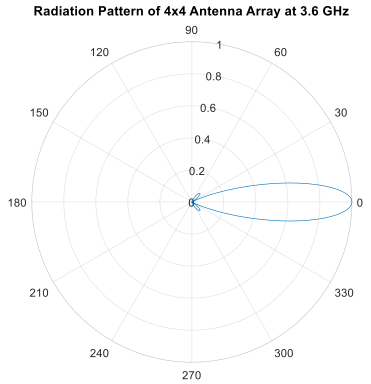

Fig. 4. Radiation Pattern in 4×4 antenna array

This design capitalizes considerable data flow and usage capacity with accurate beamforming to further improve directivity, gain, and spatial resolution in accommodating highly demanding practical applications. Being a critical section of massive MIMO technology in 5G networks, exclusive employment of the 8×8 antenna array on mmWave (millimeter-wave) frequency bands especially exploits the shorter wavelengths to achieve precision in beamforming and increased gain. Practical ability of massive MIMO to concurrently manage heavy traffic and sustain a high data flow, thus, subjects the design's nomination for urbanized and stadium employments on considerable usage capacity. The shortcomings then lie on its increased cost, power consumption, and complexity [10].

Eventually, the most complex design is observed in the 64 rows and 64 columns (64×64) antenna array with a total of 4,096 elements, where the visual configuration and radiation pattern are respectively outlined in Figure 9 and Figure 10.

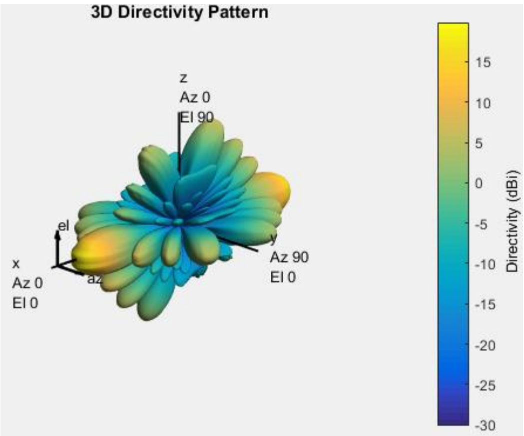

Fig. 5. 8×8 antenna array

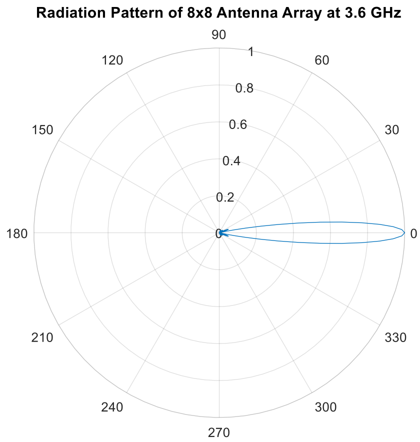

Fig. 6. Radiation Pattern in 8×8 antenna array

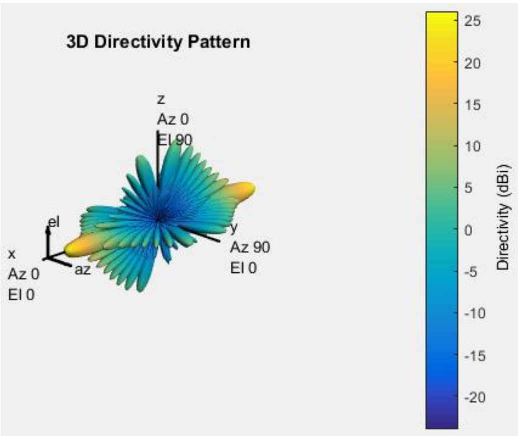

Fig. 7. 16×16 antenna array

As a design that accommodates wireless communications and radar applications with paramount requirement, the design's errorless handling of radiation pattern is idealized for fundamental components of the 5G and the upcoming 6G networks like the ultra-reliable, low-latency communication (URLLC). Additional applications enclose cardinal domains that require timely and reliable information transference such as remote surgery, self-driving automobiles, smart manufacturing, and automated industrialization. However, setbacks remain on the lack of cost effectiveness and operational simplicity [28].

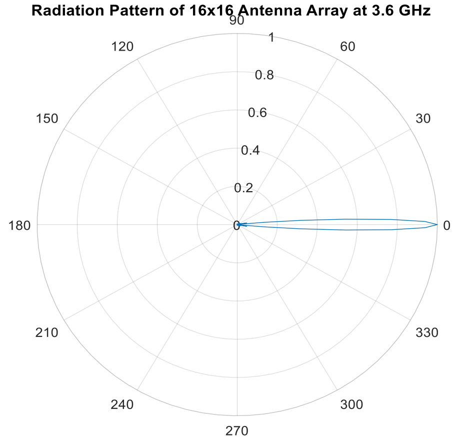

Fig. 8. Radiation Pattern in 16×16 antenna array

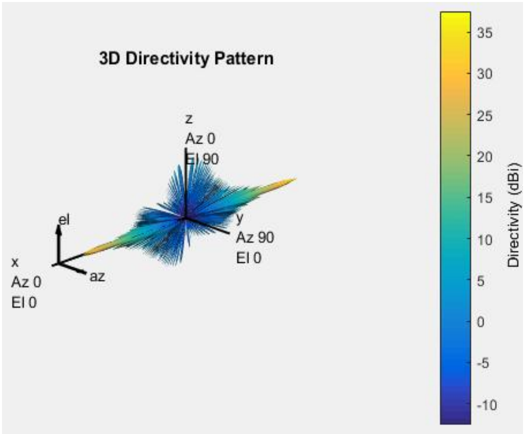

Fig. 9. 64×64 antenna array

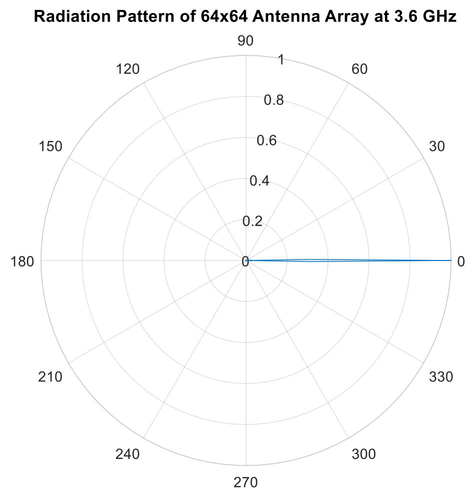

Fig. 10. Radiation Pattern in 64×64 antenna array

TABLE I. ANTENNA ARRAY CALCULATIONS

Antenna array elements	Antenna Directivity in dB	No. of Side Lobes	Achievable SNR in dB
2×2	6.02	0	125.00
4×4	12.04	2	131.02
8×8	18.06	6	137.04
16×16	24.08	14	143.06
64×64	36.12	62	155.10

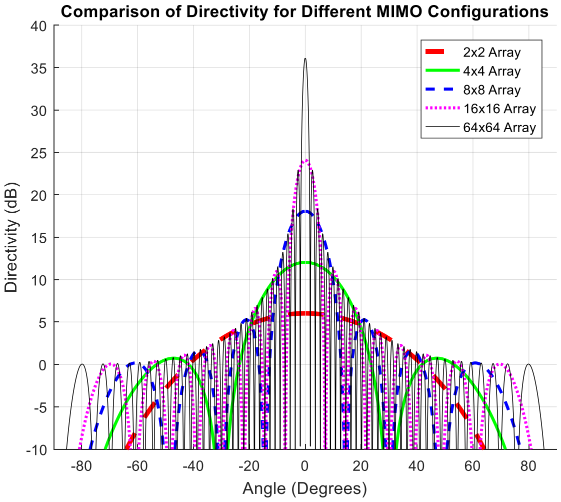

Fig. 11. A comparison directivity for 2×2, 4×4, 8×8, 16×16, and 64×64 antenna arrays

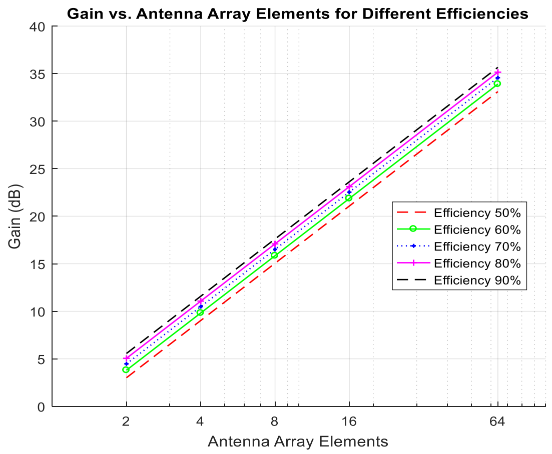

Fig. 12. A comparison gains in dBi for 2×2, 4×4, 8×8, 16×16, and 64×64 antenna arrays

Calculations for the model power rational directivity from the explained antenna array designs are tabulated in Table 1 based on the dBi measurement. Produced results show increased directivity with increasing number of elements. From the absence of side lobe for 2×2 antenna array, it is formed and multiplied on a trend of 2, 6, 14 and 62 for the respective configurations of a 4×4, 8×8, 16×16 and 64×64 rectangular arrays. With pattern of plotted array factors as a reference, the smallest antenna array of 2×2 can be readily used to estimate the total side lobes of larger rectangular N×N (2, 4, 8, 16…) arrays. Progressively, Figure 11 compares the directivities alongside the increasing number of side lobes across the explained antenna array types.

Illustrated comparison based on the explained antenna array designs demonstrates an approximate upward shift of 6 dB in directivity on a factorial increase of 4 in array size. A consistent 6.02 dB in directivity increase is ultimately shown across the intermittent transitions of 2×2, 4×4, 8×8, 16×16, and 64×64 antenna array configurations. Moreover, attainable gain G of each array antenna design with accordance to the respective directivities is outlined in Figure 12.

Gain G is derived from a simplistic formula of $D = G - L$, where D represents the directivity, L represents the lost dBi from the antenna's inefficiency, with consideration for the relationship between efficiency τ and L $(L = 10 \log10(\tau))$. This produces the gain values in dBi from dissimilar efficiency levels, as tabulated in Table 2.

As an extension, the previously mentioned factorial configurations (factorial increase of 4) surmise an intermittent increase of 6 dB in directivity and gain across the antenna array designs. With the ability of antenna directivity system in accommodating an immense usage capacity, the idealization of antenna arrays with higher number of elements to demanding environmental and practical domains is established out of the need for intense data flow. The designs should also mitigate the defiance from emerging usage of mmWave and THz bands on a high directivity, narrowed beam and information transference over distanced locations.

Additionally, performances of each antenna design are contrasted and optimized based on the inclusion of machine learning (ML). Random Forest Regressor was used to appropriate the approach's ensemble learning method with Bagging (Bootstrap Aggregating) as a variation of supervised learning [29][30][31]. The outputs are shown in Figure 13.

An aggregate outlook toward ML estimations and conventional simulations accelerates appraisal to further provide supporting knowledge on the operational compatibility between antenna array designs and the criterion of 3.6 GHz. A significant correlation on estimated to actual directivities can then be concluded on a highly accurate estimation with Mean Squared Error (MSE) of 0.906, Mean Absolute Error (MAE) of 0.756, and R-squared (R2) of 0.991.

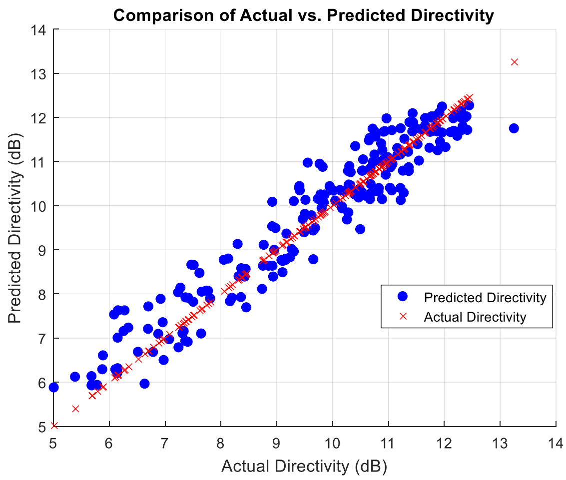

Fig. 13. A comparison between actual and predicted directivity

TABLE II. ANTENNA GAIN CALCULATIONS IN DIFFERENT EFFICIENCIES

Antenna array elements	Efficiency in dB				
	50%	*60%*	*70%*	*80%*	*90%*
2×2	3.01	4.22	5.15	5.95	6.47
4×4	9.03	10.24	11.17	11.97	12.49
8×8	15.05	16.26	17.19	17.99	18.51
16×16	21.07	22.28	23.21	24.01	24.53
64×64	33.11	34.32	35.25	36.05	36.57

IV. Study Validation

Validation is important to a study in confirming the reliability, authenticity and credibility of yielded results. In particular, undertaken statistical and rigorous comparison of current results against previous scholars corroborates increases the integrity merits of the former, while buttressing its scientific contribution. This is contemporaneously done against the results by [32] on the comparable groundworks in elements and frequencies of antenna arrays through the evaluation of antenna directivity and gain. The results for both antenna directivity and gain are separately contrasted in Figure 14 and Figure 15.

On similar parameters, [32] produces the directivities of 7.06 dB, 13.48 dB, 19.71 dB, 25.8 dB, and 38.8 dB for the respective designs of 2×2, 4×4, 8×8, 16×16, and 64×64 in antenna arrays. Whereas, it generates the independent gains of 6.64 dB, 12.67 dB, 18.53 dB, 24.33 dB, and 36.51 dB from these increasing antenna arrays. A between-results validity of 50% to 90%, therefore, confirms exceptional reliability to the findings of this study.

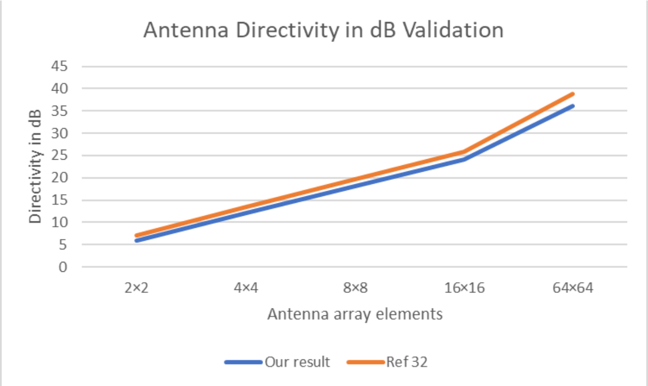

Fig. 14. A comparison between our result and Reference [32] in antenna directivity

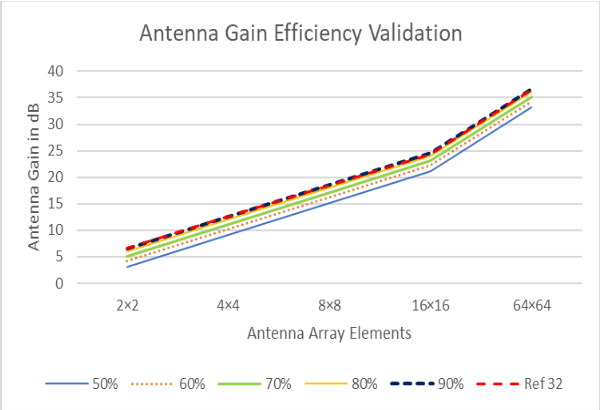

Fig. 15. A comparison between our result and Reference [32] in antenna gain

V. Conclusion

As a centralized tool in telecommunication for the wireless transference and receiving of information throughout different channels, the proliferation of antennas demands contemporary attuning of directivity to a number of communicational requirements such as broadcasted channels and satellite connections that capitalize capacity of the post-5G era. More advanced logarithm from an increased number of antenna array elements could handle the forthcoming challenge of THz bands from a narrowed beam. Findings on a higher number of side lobes and increased directivity from 16×16 and 64×64 antenna array designs over their lesser configurations (2×2 and 4×4) engender precision in beamforming from an increasingly focused radiation pattern for applications like 5G, radar, and satellite systems. Such outcome has been compared against previous scholar on similar grounds, where reliability and validity hold. Upcoming studies can potentially explore the pragmatic optimization of artificial intelligence (AI) algorithms in response to the progressive tapestry.

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