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Design of a Retrodirective Array Antenna for Microwave Power Transmission in Terrestrial Backhaul Links

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Abstract:- A Retrodirective array (RDA) is an array of antennas designed to receive signals from a specific direction and retransmit another signal back in the opposite direction. This property is useful in backhaul networks, where communication links need to be established between base stations. Microwave Power Transmission (MPT) involves the transmission of power wirelessly using microwaves with applications, such as powering remote equipment or sensors. In this work we have redesigned an RDA antenna using CST Studio suite software, allowing for the creation of a system with novel functionalities such as improved antenna performance and signal steering. This antenna design is capable of transmitting power efficiently using the phased array method. This system can be deployed in powering terrestrial backhaul links in cellular networks located in rural areas.

Keywords:- *Retrodirective Array, RDA, Microwave, Metamaterials, Wireless, Transmission, MPT.*

I. INTRODUCTION

In an era defined by relentless expansion of cellular networks, the demand for efficient and reliable backhaul solutions has reached unprecedented heights [1]. Terrestrial backhaul networks serve as the backbone of our modern communication infrastructure, facilitating the seamless flow of data between base stations and the core network [2]. However, as the cellular landscape evolves, so too do the challenges facing these critical networks in terms of electrical power supply.

➢ *Problem Statement*

Retrodirective arrays have shown promise in various applications, however, conventional arrays suffer from low MPT efficiency and alignment sensitivity which affects their adaptation for long distance application. Consequently, there is need to develop innovative technologies that can enhance the performance of these arrays specifically for long-distance MWPT, addressing issues related to power efficiency, alignment precision, and scalability to enable efficient energy transmission over extended distances.

➢ *Terrestrial Backhaul Cellular Networks*

A backhaul of a mobile network connects a cell site to the core network. Mobile Network Operators (MNOs), use fiber-based backhaul and wireless point-to-point backhaul microwave links.

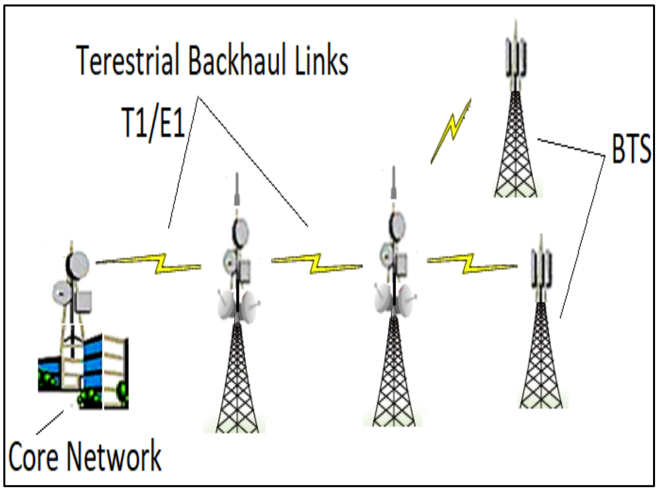

Fig 1 Cellular Backhaul Network [2]

Terrestrial backhaul networks serve as the backbone of our modern communication infrastructure, facilitating the seamless flow of data between base stations and the core network. This research is primarily motivated by the following: (1) The cost of grid extension, particularly in rural areas is a very expensive undertaking [3]. (2) Solar based solutions are prone to fluctuating weather conditions and theft and vandalism of hardware such as solar panels particularly in rural areas. (3) Theft of batteries from solar PV systems and diesel from generators is another rampant crime in BTS [3]. (4) Access to wireless electricity could help close up the digital divide in rural areas, thus creating employment and reducing poverty levels [4].

➢ *Microwave Power Beaming*

Microwave power beaming is a cutting-edge wireless energy transmission technology which is being explored for its potential integration into backhaul networks, the critical backbone of modern wireless communication systems. Microwave power beaming operates on the fundamental principles of electromagnetic wave propagation and energy conversion. Understanding the mathematical foundations of these concepts is pivotal for comprehending the mechanics of this innovative technology.

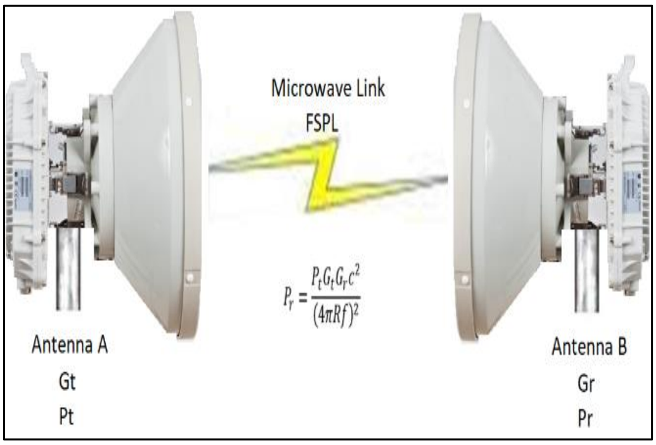

Fig 2 Point-to-Point Microwave Link [5]

The core components include a transmitting antenna, responsible for emitting focused microwave radiation, and a receiving antenna fitted with rectifying circuits, known as rectennas, which convert the microwave energy back into usable direct current (DC) electricity.

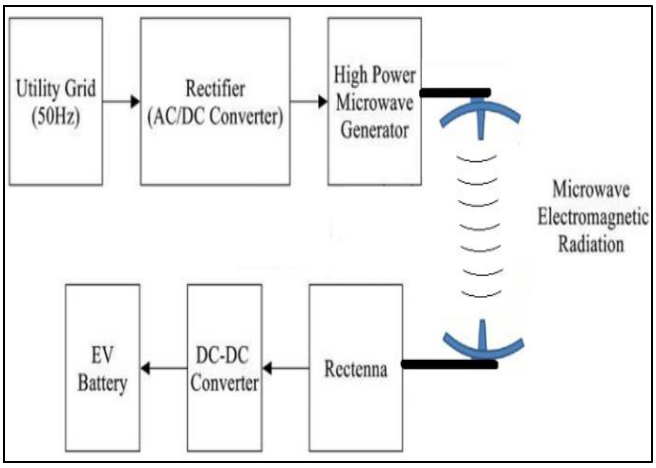

Fig 3 Block Diagram [5]

II. LITERATURE REVIEW

Alexis Zamora's paper on An Overview of Recent Advances in retrodirective Antenna Arrays [6] reviewed recent advances in the field by comparing and contrasting several RDA architectures. He discussed the need to reduce size of antennas whilst optimizing efficiency. Blaine T. Murakami, et.al's paper on Self-Steering Antenna Arrays for Distributed Picosatellite Networks [7], discussed the potential for using self-steering arrays for secure crosslinks in picosatellite networks. The development of two-dimensional, circularly polarized retrodirective arrays optimized for size and power consumption was developed. The zero gravity, free-floating nature of the satellites necessitates 2D tracking and therefore a 2D retrodirective array. To date, very few 2D arrays have been demonstrated. Kin Shing, et.al [88], Developed a Passive Retrodirective Van Atta Array Reflector at X-band. The development of a passive retrodirective Van Atta array reflector was based on microstrip antenna operating at X-band. Van Atta Array was designed for radio signal propagation only and it was not tested on WPT.

III. RESEARCH OBJECTIVES

The objectives of this study would be specific goals and outcomes that guide the research process. These objectives are designed to address the challenges and fulfill the purpose of the study: (1) To develop and optimize the geometric arrangement and properties of the RDAs for efficient MWPT. (2) To define performance metrics and measurement methodologies to evaluate the reliability and performance of the RDAs in terms of MPT.

IV. METHODOLOGY

Several challenges must be addressed for successful implementation of microwave power beaming in backhaul networks. The flow chart of Figure 4 shows the methodology adopted in achieving the intended objectives starting from step 1 with literature review through to step 13.

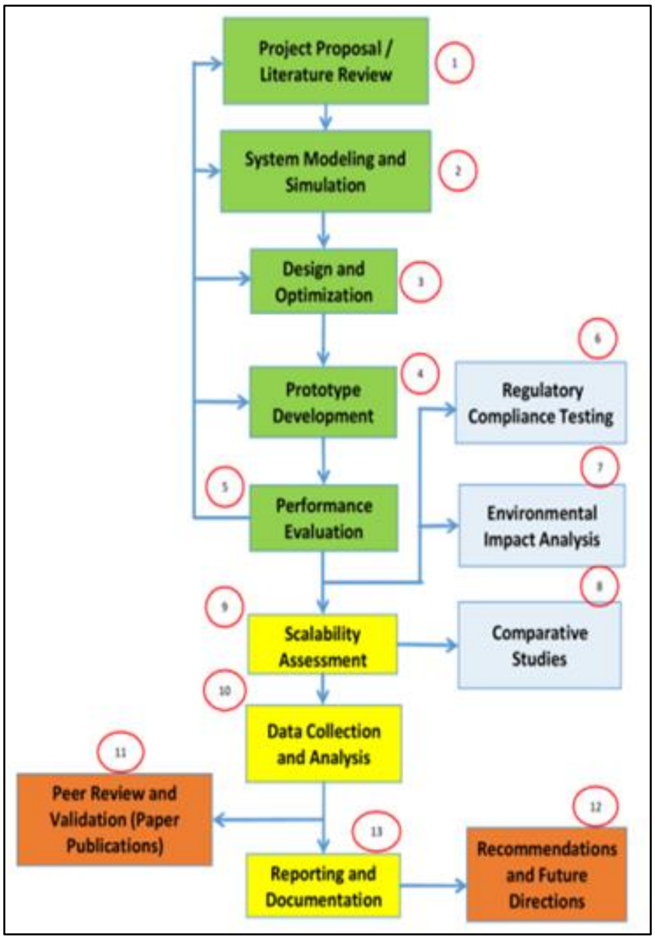

Fig 4 Methodology Flow Chart

A. *Retrodirective Array (RDA)*

A retrodirective antenna (RDA) is an antenna that transmits the signal back in the same direction and location it came from. It's based on the principle of self-phase conjugation of the input signal. Directivity depends on relative phases of signal radiated from different elements. An arrayed antenna consists of multiple, identical radiating elements and retrodirectivity can be achieved entirely passively with the use of a Van Atta Array.

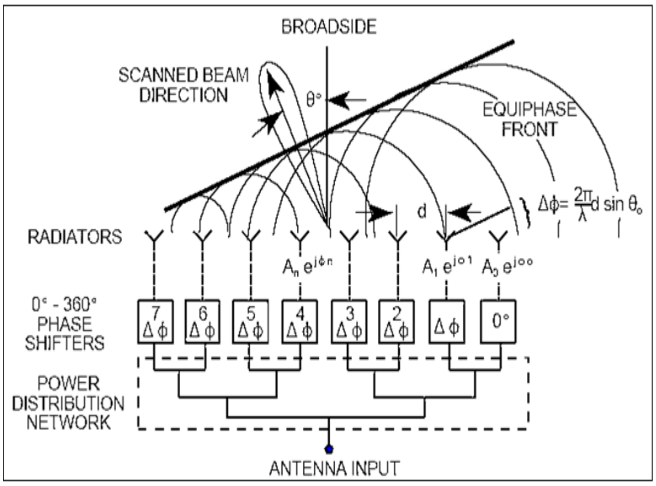

Fig 5 Passive Van Atta antenna RDA [13]

Non-phase conjugating structures carry out wave front retrodirective manipulation by means of symmetrically positioned delay lines placed between array antenna elements [8]. The CST Studio design software for a 4X4 element RDA in Figure 9 was designed based on the parameters of a single patch antenna designed in Figure 1.

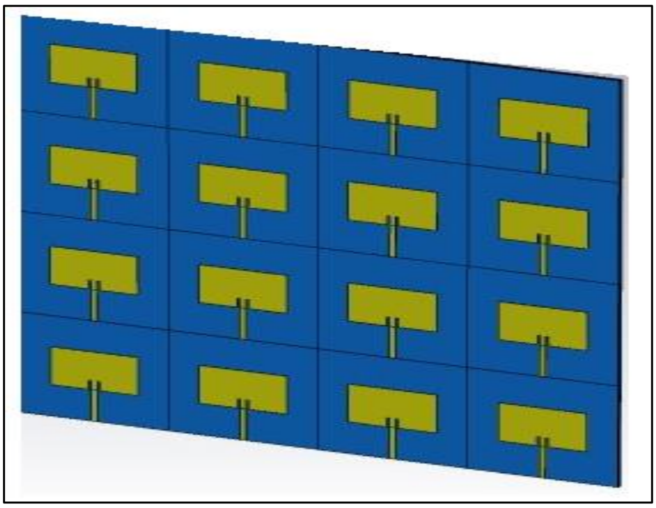
Fig 6 4x4 RDA Antenna

B. Principle of Retrodirectivity

The RDA is made up of the pilot signal source, the power receiver, and the retrodirective array antenna which is the power transmitter [9]. The power receiver and the pilot signal source are located in the same position. The retrodirective array amplifies and returns the phase conjugate signal of received pilot signal Fig.1.12. Suppose that the direction of arrival of the pilot signal is θ_0 and that the phase difference ψ occurs in the signal received by each element [10]. When the phase conjugate signal of the pilot signal is input to each array element, the phase difference of the power transmission signal between elements becomes $-\psi$. The direction of transmission θ_0 is as in equation (1) [10]: The phase difference is given by;

$$\psi = \Delta\phi = \left(\frac{2\pi}{\lambda}\right) d \sin\theta_0 \qquad (1)$$

Where, θ_0 is the direction of arrival of the pilot signal beam and d is the separation between the elements.

The total received signal will be;

$$E_a = E_{1+} E_2 + \dots\dots\dots + E_N \qquad (2)$$

Where, *Ea* is total signal received and E_1, E_2 *to* E_N are individual element received signals of the RDA.

$$E_a = Sin(\omega t + 2\psi) + \sin(\omega t + 3\psi) + \cdots + \sin(\omega t + (N-1)\psi)$$

$$= \sin\omega t + \sin(\omega t + \psi) + \sin(\omega t + 2\psi) + \sin(\omega t + 3\psi) + \dots\dots\dots + \sin(\omega t + [N-1]\psi)$$

Therefore, the total signal is expressed as;

$$E_a = \sin\left(\omega t + (N-1)\frac{\psi}{2}\right)\left[\frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)}\right] \qquad (3)$$

The first term represents the magnitude while the second term is the phase component. In order to determine the radiation pattern of the beam we need to know the magnitude of the received signal.

$$|Ea(t)| = \left|\frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\frac{\psi}{2}}\right| = \left|\frac{\sin\left(\frac{N\pi}{\lambda} d\sin\theta_o\right)}{\sin\left(\frac{\pi}{\lambda} d\sin\theta_o\right)}\right| \qquad (4)$$

Therefore, the radiation pattern $G_a(\theta_o)$ of an RDA is given by the expression;

$$G_a(\theta_o) = \frac{|E_a|^2}{N^2} = \frac{\sin^2\left(\frac{N\pi}{\lambda} d\sin\theta_o\right)}{N^2\sin^2\left(\frac{\pi}{\lambda} d\sin\theta_o\right)} \qquad (5)$$

Where, Ea is the total received signal strength from all the elements (Fig. 1.12). The direction of the microwave power transmission beam will be given by the expression (Fig. 12) [10];

$$Q_t = \sin^{-1}\left\{\frac{\delta_\alpha}{2\pi d}\right\} - \pi = \theta_p - \pi \qquad (6)$$

This means that the power signal beam is directed in the direction of arrival of the pilot signal [multipath].

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C. Designing an RDA at 2.4GHz CST Microwave Studio Software

The parameters that pertain to Microstrip Patch Antenna design are governed by the resonant frequency, f_0; antenna material permittivity, Ɛr; and the material thickness, h [10].

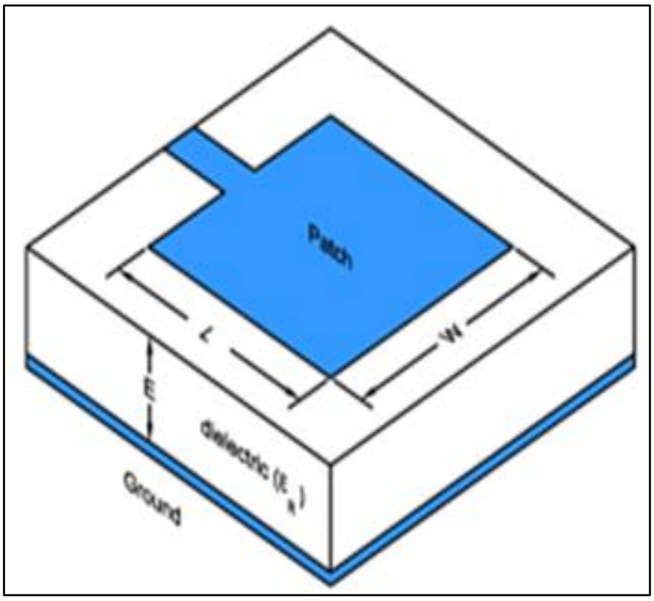

Fig 7 Microstrip Patch Antenna [23]

These parameters are (1) Wavelength, λ; (2) Width, W and (3) Length, L (Fig. 1).

$$\lambda = \frac{C}{f} \quad (7)$$

$$W = \frac{C}{2f}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (8)$$

$$L = L_{eff} - 2\Delta L \quad (9)$$

Where, W = Width of patch; C=velocity of light; F=Resonant frequency; L=length of the patch antenna; Ɛr=Dielectric constant of the substrate

L_{eff}=Effective length which is given by;

$$L_{eff} = \frac{C}{2f\sqrt{\varepsilon_{reff}}} \quad (10)$$

The normalized extension in length is given by;

$$\Delta L = 0.412h \left\{ \frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} + 0.258)\left(\frac{W}{h} + 0.8\right)} \right\} \quad (11)$$

Where, ε_{reff} = Effective refractive index whose equation is given as;

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\sqrt{\left(1 + 12\frac{h}{W}\right)} \quad (12)$$

The length of a ground plane (Lg) and the width of a ground plane (Wg) are calculated using the following equations, 13-15 [14];

$$L_g = L + 6h \quad (13)$$

$$W_g = W + 6h \quad (14)$$

Where, Lg and Wg are length and width substrate and h is given by the expression;

$$h = \frac{0.0606\lambda}{\sqrt{\varepsilon_r}} \quad (15)$$

The width W of the microstrip antenna controls the input impedance. Larger widths can increase the bandwidth. For feeding the microstrip patch antenna, there are different methods for example, feed line method, coaxial probe feeding method etc. But mostly coaxial probe method is used.

V. TEREESSTRIAL MICROWAVE LINK BUDGET

In designing the power transmitter and receiver, the link budget should be analyzed and the system should be designed to maximize the power transmission efficiency. A link budget for a point-to-point radio link accounts for all the gains and losses from the transmitter, through cables, antennas and free space to the receiver (Figure 1.2) [12]. The equation of link budget as follow:

Link Budget = Tx power (dBm) + Tx Antenna Gain (dBi) + Rx Antenna Gain (dBi) – Tx Cable losses (dB) – Rx Cable Losses (dB) –FSPL (16)

Generally, when the distance of the MPT system is increased, the transmission efficiency decreases, and in order to increase the transmission efficiency, the distance should be shortened [12]. The power efficiency of the MPT system may be calculated using equation 16.

VI. RESULTS

Consider a square patch antenna which is insert fed in Figure 1.7. The substrate is a dielectric with a permittivity equal to 4.08, and that L=W=80 mm, so that the patch is to resonate at 4.5 GHz. The simulation in CST software was done with the following parameters; (1) The resonance frequency was selected as 2.4GHz; (2) The patch antenna dimension (L and W) is calculated by using microstrip transmission line formula shown in equations 7-9: (3) The dielectric is calculated with permittivity of 4.08.

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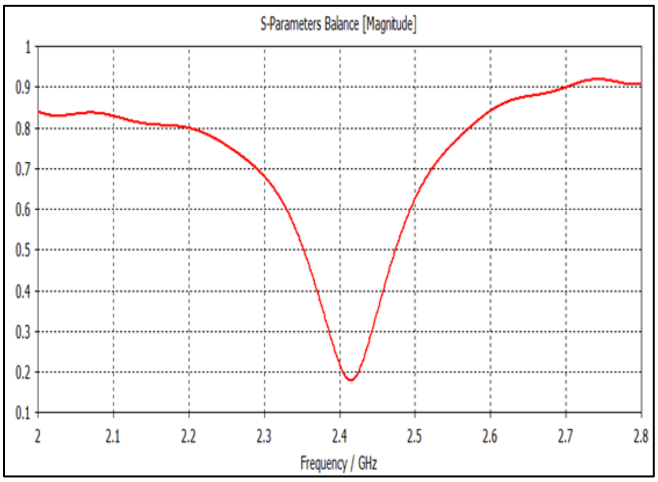

Fig 8 Magnitude of S-Parameter of the Single Patch Antenna

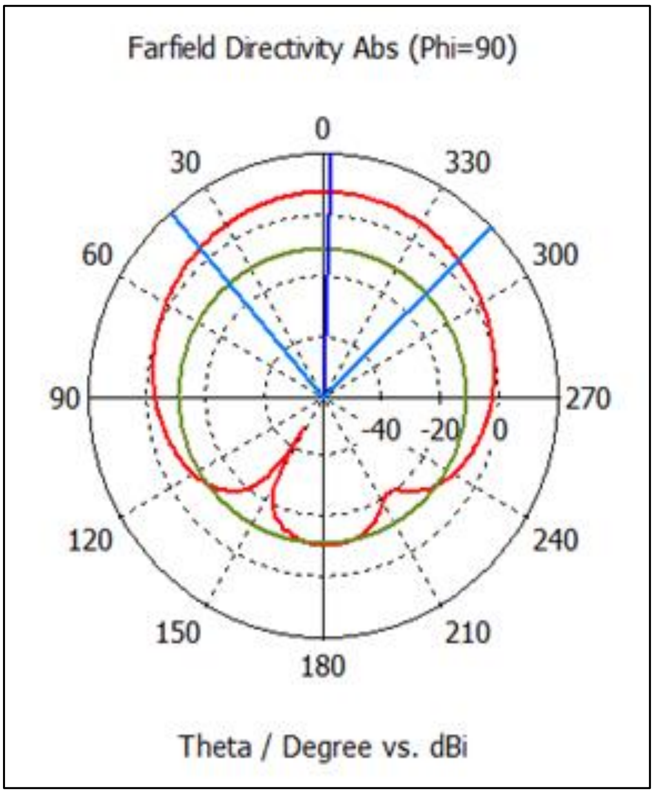

Fig 9 Far-Field Directivity of a Single Patch Antenna

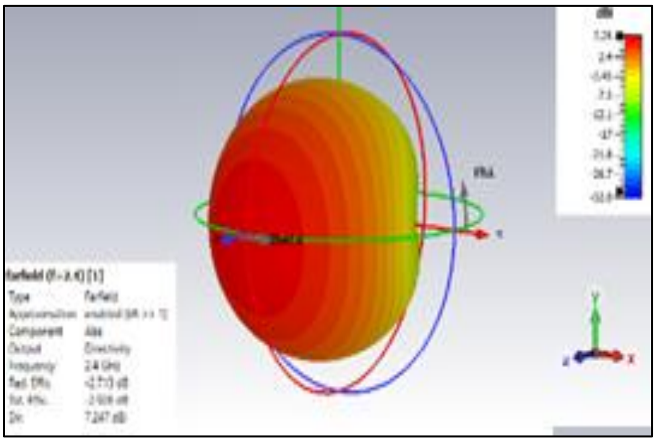

Fig 10 Radiation for Antenna of Single Patch Antenna

VII. CONCLUSIONS

Microwave Power Transfer (MPT) is concept that represents an interdisciplinary approach, combining expertise in antenna design, metamaterials, optimization algorithms, and wireless power transmission. This concept paper aims to present an overview of MPT, its potential applications, benefits, challenges, and the feasibility of its implementation. The practical implementation would require thorough testing, validation, and consideration of real-world factors such as environmental conditions and regulatory constraints.

REFERENCES

[1]. Utilitiesone, 2023, "Splicing Solutions for Reliable Cellular Backhaul Networks" Accessed 02/01/204. Available: https://utilitiesone.com/splicing-solutions-for-reliable-cellular-backhaul-networks

[2]. Peng Wang et. al, 2020, "Convergence of Satellite and Terrestrial Networks: A Comprehensive Survey", https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8946626

[3]. Tim Reber et. al, "Tariff Considerations for Micro-grids in Sub-Saharan Africa", National Renewable Energy Laboratory- Alliance for Sustainable Energy, LLC, under Contract No. DE-AC36-08GO28308 with the U.S. Department of Energy ("DOE"). Available: https://www.nrel.gov/docs/fy18osti/69044.pdf

[4]. Nur Hazwani Hussin et. al, "Encryption Techniques and Wireless Power Transfer Schemes", January 2018Indonesian Journal of Electrical Engineering and Computer Science 9(1):183-190, DOI:10.11591 /ijeecs.v9.i1.pp183-190

[5]. Wireless Excellence Limited , 2020. "Cable Free Microwave Antennas", https://www.cablefree.net/cablefree-microwave/cablefree-microwave-antennas/

[6]. Alexis Zamora "An Overview of Recent Advances in Retrodirective Antenna Arrays" 2010, 978-1-4244-7092-1/10/$26.00 ©2010 IEEE.

[7]. B. T. Murakami, et. al, "Self steering antenna arrays for distributed picosatellite networks," in Proceedings of the 17th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2003

[8]. Yu Chun Guo, "Overview on the Phase Conjugation Techniques of the Retrodirective Array", International journal of antennas and propagation, Volume 2010 | Article ID 564357 | https://doi.org/10.1155/2010/564357, June 2010.

[9]. Vincent Fusco, Neil Buchanan, "Developments in retrodirective array technology", IET Research Library, https://doi.org/10.1049/iet-map.2012.0565, January 2013

[10]. Vikaram Singh et.al, "Wireless Power Transfer Using Microstrip Antenna Assigned with Graded Index Lenses for WSN", International Conference on Advances in Computing. Communications and informatics (ICACCI), 2014.

[11]. https://www.pasternack.com/t-calculator microstrip-ant.aspx
[12]. Anwar H. Ibrahim, "Link Budget Design for RF Line-of-Sight via Theoretical Propagation Prediction", International Journal of Communications, Network and System Sciences, 2019, 12, p11-17, ISSN Online: 1913-3723
[13]. Eli Brookner, 2022 "Phased Array Antennas", Microwave 101 Newsletter. Online Available, www.microwave101.com
[14]. M. H. Jamaluddin et. al, "Microstrip Dipole Antenna Analysis with Different Width and Length at 2.4 GHz", Asia pacific conference on applied electromagnetics, December, 2021.

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