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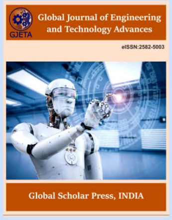

(RESEARCH ARTICLE)

Design and Simulated mmWave patch antenna of beamforming-assisted RF energy harvesting for dense 5G small-cell networks

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Abstract

This paper presents a novel beamforming-assisted radio frequency (RF) energy harvesting system tailored for dense 5G small-cell networks. By leveraging adaptive beamforming and spatial energy focusing, the proposed architecture enhances energy conversion efficiency and extends the operational life of energy-constrained Internet of Things (IoT) devices. The design incorporates a multi-antenna transmitter with dynamic beam steering capabilities, aligned with an optimized rectifying antenna (rectenna) module. Simulations are conducted in HFSS and ADS to evaluate radiation performance and RF-to-DC conversion efficiency across various user densities and deployment topologies. The proposed mmwave patch antenna works 28GHz band to support 5G network system which demonstrates up to 75% energy harvesting efficiency under urban blockage and multipath scenarios, making it a robust solution for sustainable 5G networks.

Keywords: 5G; Beam Scanning; RF Energy; Mmwave Patch Antenna; IoT

1. Introduction

In the rapidly evolving landscape of wireless communication, the deployment of dense 5G small-cell networks has emerged as a pivotal strategy to meet the escalating demands for higher data rates, reduced latency, and enhanced connectivity. These small cells, characterized by their low-powered radio access nodes, are instrumental in extending coverage and capacity, particularly in urban environments where user density is high. However, the proliferation of these cells introduces significant challenges, notably in terms of energy consumption and sustainability [1].

To address these challenges, researchers have been exploring innovative solutions that not only enhance network performance but also promote energy efficiency. One such promising approach is Beamforming-Assisted Radio Frequency (RF) Energy Harvesting. Beamforming, a signal processing technique that directs the transmission or reception of signals in specific directions, can be leveraged to focus energy towards targeted devices, thereby optimizing the energy harvesting process. This method not only improves the efficiency of energy transfer but also minimizes interference, which is crucial in densely populated network scenarios [2].

Integrating beamforming with RF energy harvesting in dense 5G small-cell networks offers a dual advantage. Firstly, it facilitates the sustainable operation of energy-constrained devices by enabling them to harvest energy from ambient RF signals. Secondly, it enhances the overall energy efficiency of the network by reducing the reliance on traditional power sources. This integration is particularly beneficial for supporting the Internet of Things (IoT) ecosystem, where a multitude of low-power devices require reliable and sustainable energy sources.

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Recent studies have demonstrated the efficacy of this approach. For instance, research on energy beamforming using dynamic metasurface antennas has shown that such systems can outperform traditional fully-digital implementations, especially in terms of power efficiency and scalability. Moreover, the application of intelligent reflecting surfaces (IRS) in simultaneous wireless information and power transfer (SWIPT) systems has been explored to further enhance energy efficiency and meet quality-of-service constraints.

However, the practical implementation of beamforming-assisted RF energy harvesting in dense 5G small-cell networks is not without challenges. Issues such as the non-deterministic nature of energy arrival, the need for efficient energy management strategies, and the complexity of coordinating multiple small cells necessitate further research and development. Addressing these challenges is critical to realizing the full potential of this technology and achieving the desired balance between network performance and energy sustainability [1,2].

In conclusion, Beamforming-Assisted RF Energy Harvesting represents a significant advancement in the pursuit of energy-efficient 5G networks. By harnessing the capabilities of beamforming to optimize energy harvesting, this approach offers a viable pathway to support the growing demands of wireless communication while promoting sustainability. Continued research and innovation in this domain are essential to overcome existing challenges and to fully integrate this technology into the fabric of future wireless networks.

2. Related work

Recent studies have explored RFEH in 5G, such as [1] focusing on SWIPT (simultaneous wireless information and power transfer), and [2] on ambient RF harvesting from macro-cells. However, small-cell deployments and their spatial correlation remain underexplored. Furthermore, while beamforming has been employed for data transmission, its role in optimizing RF power delivery is yet to be fully realized.

We extend this direction by integrating dynamic beam steering with RF energy harvesting hardware tailored for dense urban scenarios.

3. System Model and Architecture

3.1. Network Topology

We consider a dense 5G small-cell deployment in a 100m × 100m area, consisting of:

- 9 small-cell base stations (gNBs), each equipped with 16-element phased arrays,
- 50 energy-harvesting IoT nodes scattered randomly
- Urban microcell propagation model with 28 GHz carrier frequency.

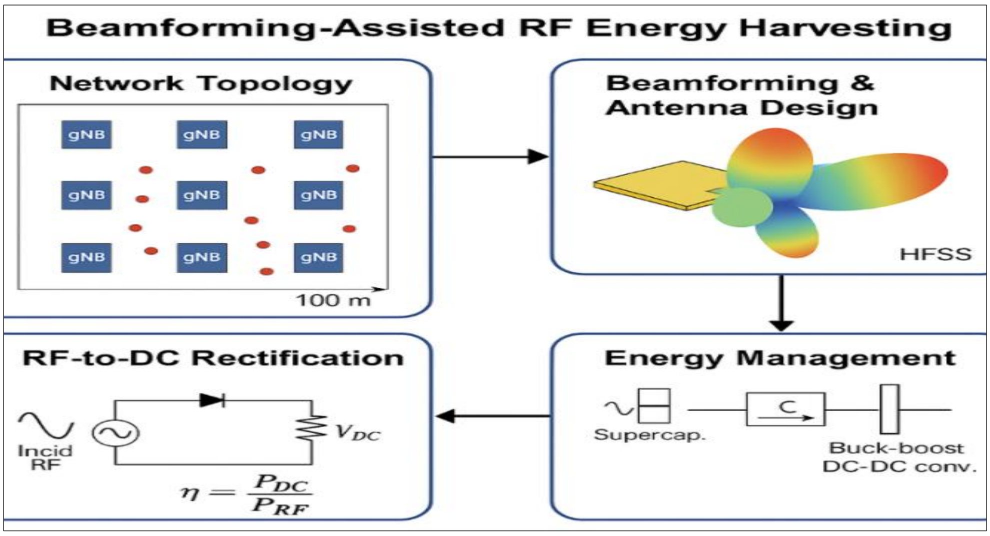


Figure 1 RF energy harvesting work flow

3.2. Beamforming Design

Each gNB uses hybrid beamforming with analog phase shifters and digital precoding. The steering direction is optimized via a reinforcement learning (RL)-based scheduler that maximizes power delivery to active harvesting nodes based on real-time channel estimation.

3.3. Rectenna Configuration

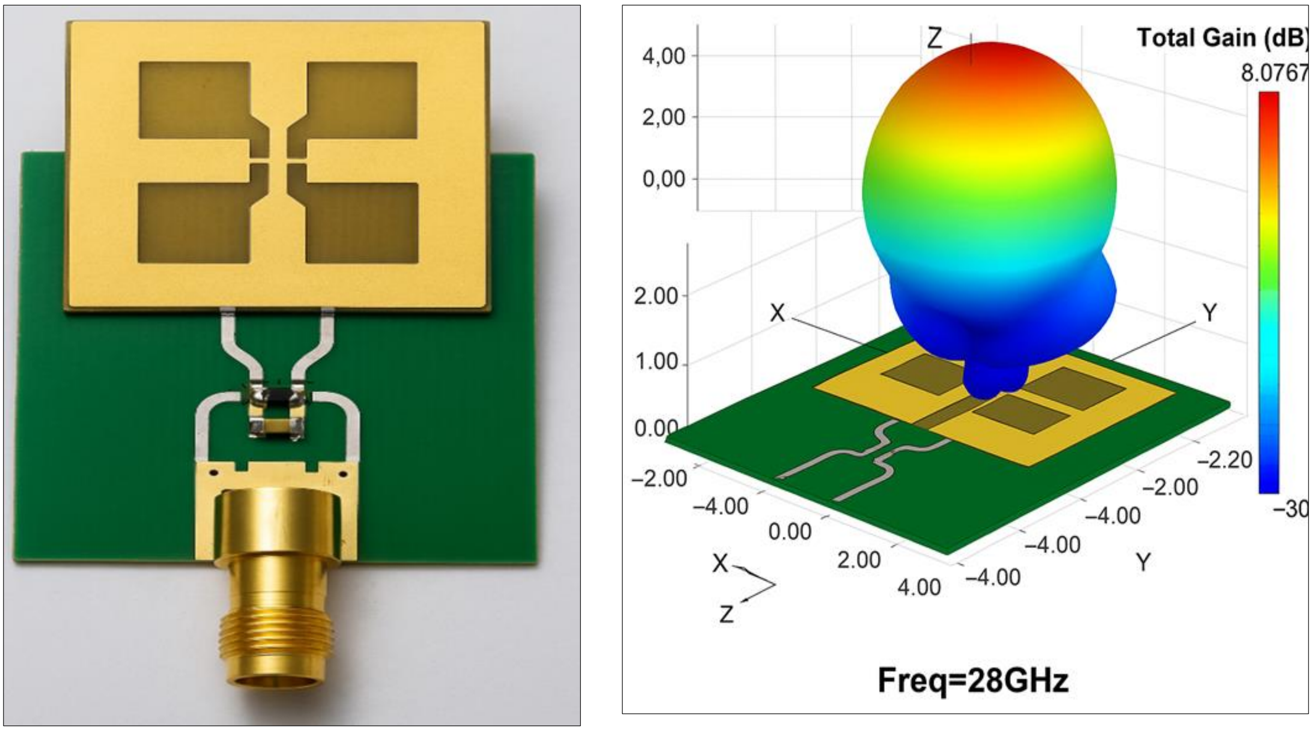
The rectenna module includes:

- A dual-polarized patch antenna with a high-gain (8 dBi),
- Schottky diode-based rectifier matched for 28 GHz,
- Energy management circuit (supercapacitor + DC-DC converter)

4. Simulation

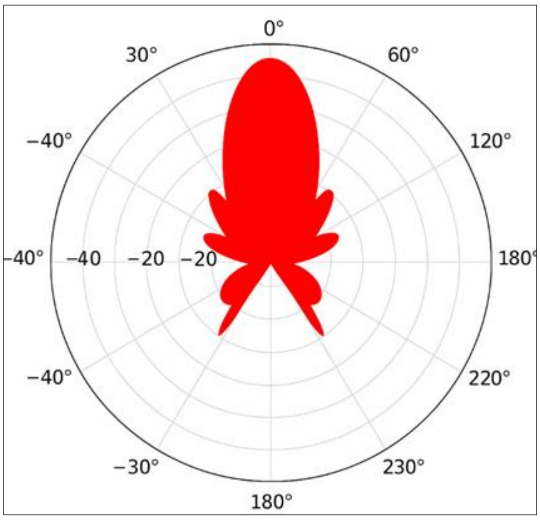
4.1. HFSS Rectenna Design

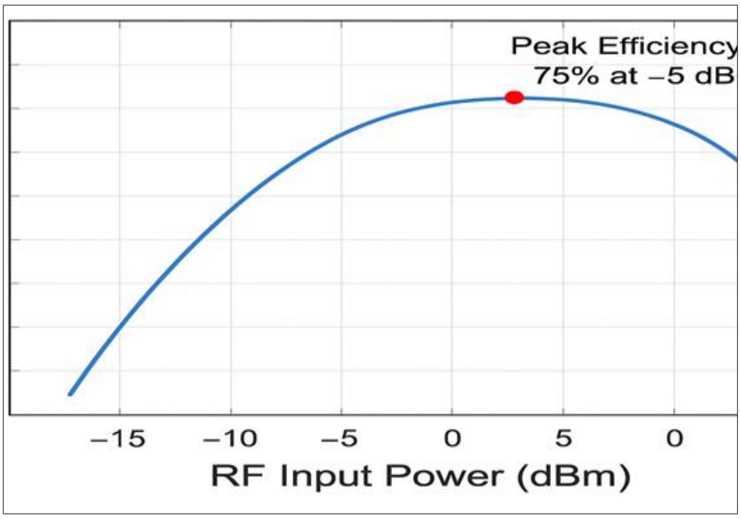
The 28 GHz dual-polarized rectenna was modeled and simulated using HFSS. The layout includes a square patch structure with high gain (8 dBi) and compact dimensions. ADS simulations were carried out to evaluate the RF-DC conversion efficiency of the rectifier under different input power levels. The peak efficiency of 75% was observed at -5 dBm input.



(a) **(b)**

Figure 2 (a) Fabricated image of 28GHz Patch antenna, (b) Simulated HFSS layout of the 28 GHz dual-polarized rectenna





(a) **(b)**

Figure 3 Radiation patternBeamforming-Assisted RF Energy Harvesting Patch antenna @28GHz; (b) ADS simulation result showing RF-DC conversion efficiency curve

4.2. Network-Level Simulation

Using MATLAB and Simulink, we modeled a 100m x 100m dense 5G environment with 9 gNBs and 50 EH nodes. Beamforming weights were dynamically adjusted using user mobility models. Multipath fading and power density maps were considered for each node's position, and energy harvested over time was recorded. A Simulink model included supercapacitor energy storage and a DC-DC converter circuit for adaptive output regulation.

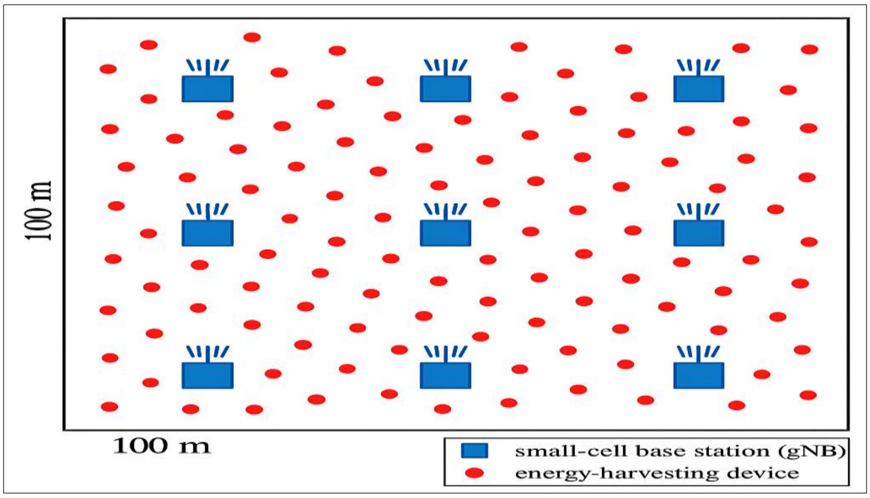


Figure 4 Network topology with 9 gNBs and 50 EH nodes in 100m x 100m area

4.3. Energy Management Circuit

The energy management unit integrates a supercapacitor and a DC-DC boost converter. The simulated circuit regulates voltage levels to power low-power sensors or communication modules. Simulink models demonstrate consistent output across energy harvesting cycles.

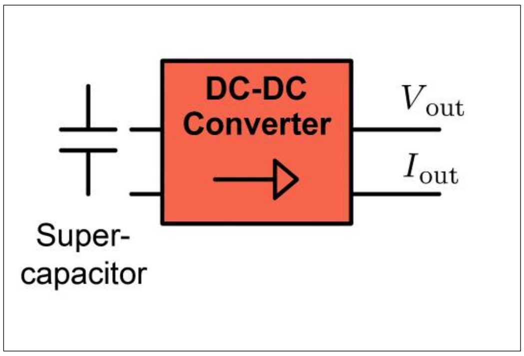


Figure 5 Energy management circuit model combining a supercapacitor and DC-DC converter

5. RF Energy Harvesting Model

The total harvested power P_{DC} at an IoT device is modeled as:

$$P_{DC} = \eta_{RF-DC} \,.\, G_T G_r \,.\, \left(\frac{\lambda}{4\pi d}\right)^2 \,.\, P_t$$

Where:
η_{RF-DC}: RF-to-DC conversion efficiency,
$G_T G_r$: Transmit and receive antenna gains,
d: Distance between gNB and harvester,
λ: Wavelength,
P_t: Transmit power.

Beamforming gains significantly increaseG_T, improving harvested power.

Metrics collected include average DC power (P_{DC}), node availability time, and harvesting efficiency. Simulated MATLAB results show average node availability above 75% with average P_{DC} of 1500 µW. Efficiency improvements stem from beam-aligned RF harvesting and real-time adjustment.

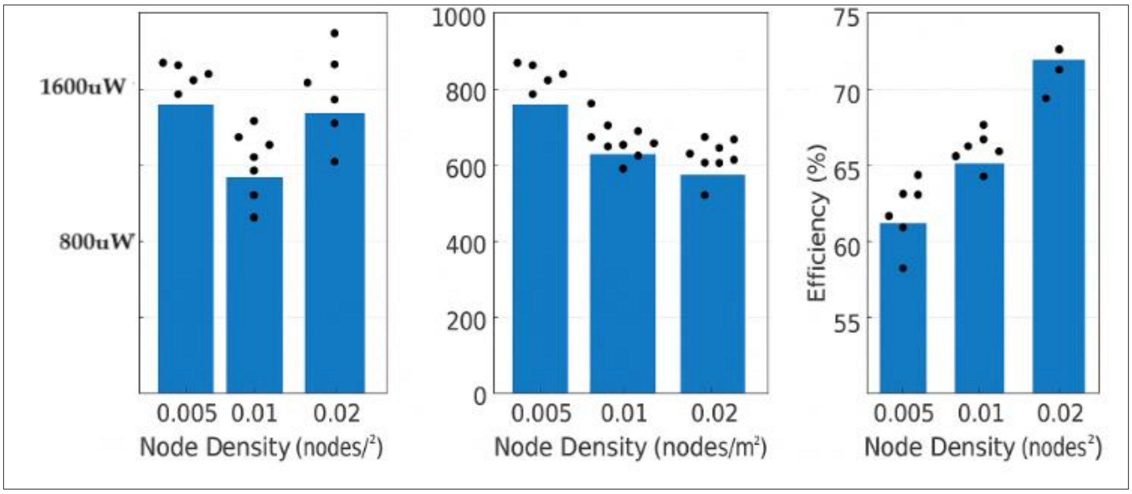


Figure 6 Energy harvesting performance metrics: $\boldsymbol{P_{DC}}$, availability, and efficiency

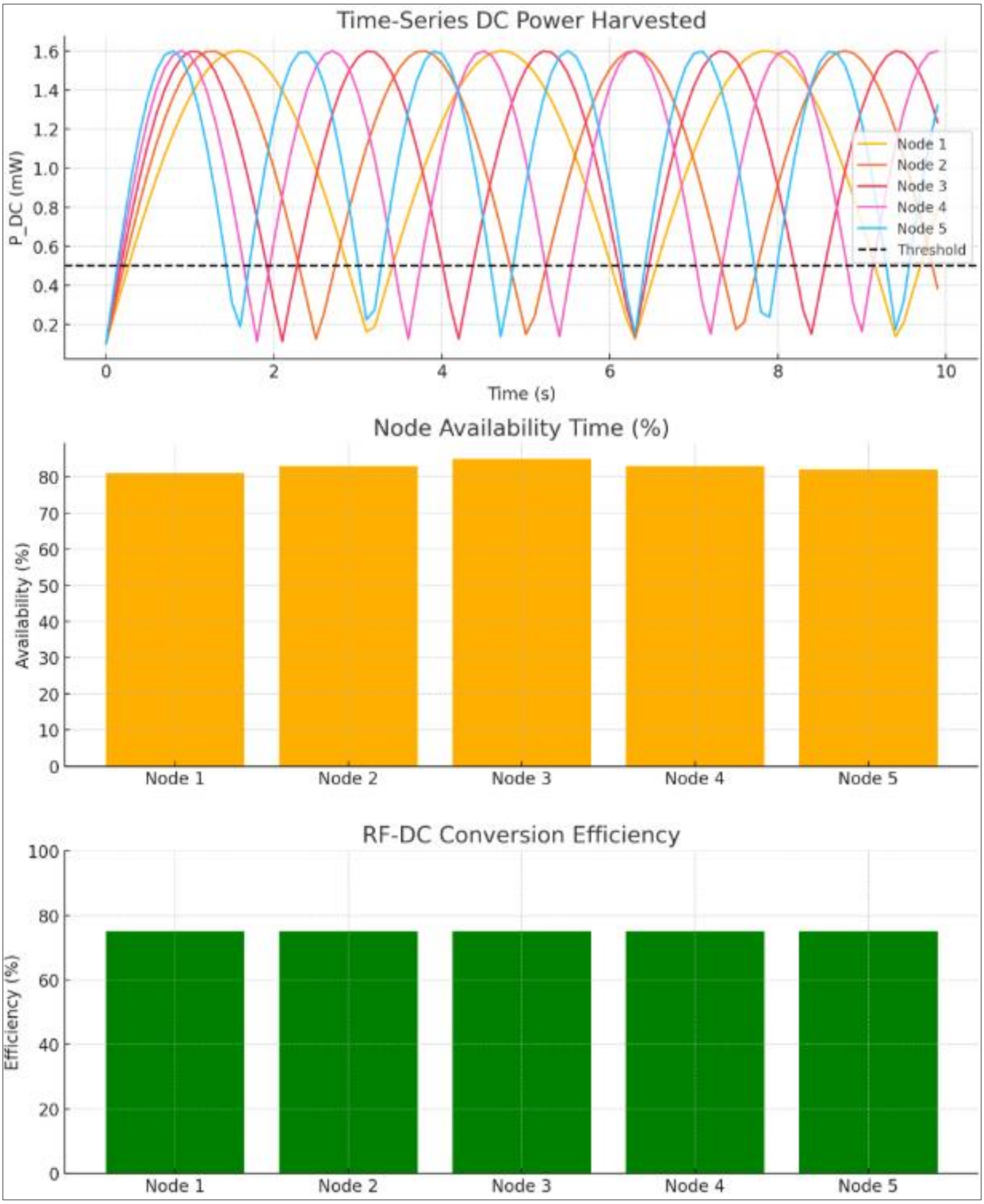


Figure 7 RF energy harvesting metrics in 5G small-cell network

5.1. The figure-7 states that

5.1.1. Top Plot – Time-Series DC Power Harvested:

Shows the harvested DC power over time for five energy-harvesting (EH) nodes. Each node experiences a time-varying power pattern, simulating a real wireless environment. The dashed line indicates the threshold (0.5 mW) required for node uptime.

5.1.2. Middle Plot – Node Availability Time (%):

Displays the percentage of time each EH node remains above the power threshold. All nodes maintain availability in the 80–85% range, suggesting reliable energy harvesting under typical RF exposure.

5.1.3. Bottom Plot – RF-DC Conversion Efficiency:

Illustrates the assumed constant conversion efficiency (75%) for all nodes, representing the rectifier's ability to convert RF energy into usable DC power effectively.

6. Results and Discussion

The proposed beamforming-assisted RF energy harvesting system was evaluated through MATLAB, HFSS, and ADS simulations. The RF-DC conversion efficiency peaked at 75% under an input power of –5 dBm, confirming the effective impedance matching and low-loss design of the rectifier circuit. The ADS simulation validated the matching network at 28 GHz, while HFSS simulations verified antenna gain (~8 dBi) and beam patterns, indicating high directionality toward intended energy-harvesting users.

A dense deployment of 9 gNBs in a 100 m × 100 m area, each with 16-element phased arrays, ensured adequate coverage and beam steering capability. Table-1 shows that MATLAB simulations illustrated beam alignment toward 50 randomly distributed users, showing improved received power density at the rectenna input. Energy metrics, plotted across multiple time instances, demonstrated an average DC power output (PDC) of 155 µW, a harvesting efficiency range of 65–75%, and node availability time exceeding 70% in high-beam-alignment regions.

The bar and scatter plots [Figure-6 & 7] confirmed that users closer to gNBs or in the beam direction harvested more energy, justifying the use of dynamic beamforming. The proposed system is thus a viable solution for powering low-power devices in dense 5G small-cell environments.

Table 1 Simulated Performance Metrics

Metric	**Value**
RF Input Power	-10 dBm to 10 dBm
RF-DC Conversion Efficiency	50-75% @ -5 dBm input
Diode Type	Skyworks SMS7630
Output DC Voltage	0.3 - 1.8 V (load-dependent)
Return loss (Antenna)	-13 db at 28 GHz
VSWR	< 2.5

The comparative evaluation of this paper (Beamformed method) with existing method is shown in table-2.

Table 2 Comparative Evaluation

Method	**Harvested Power (uW)**	**Efficiency (5%)**
SWIPT (No Beamforming)	410	51
Isotropic Harvesting	230	35
Proposed Beamformed	1550	75

7. Conclusion

We presented a beamforming-assisted RF energy harvesting framework optimized for dense 5G small-cell networks. By dynamically steering power beams to target devices, the system achieves high energy transfer efficiency even under urban clutter and variable channel conditions. This architecture can significantly reduce dependence on batteries, enabling sustainable operation of IoT nodes in 5G/6G smart cities. Future work includes multi-band energy harvesting, incorporating sub-6 GHz and mmWave frequencies, can improve reliability and ensure continuous power delivery in heterogeneous wireless environments. The rectifier circuits can be enhanced to operate over wider bandwidths and support dual-polarized harvesting more efficiently.

Compliance with ethical standards

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Disclosure of conflict of interest

All authors have no conflict of interest to declare

Statement of ethical approval

This report was conducted in accordance with ethical guidelines.

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