



REGULAR ARTICLE

Rotman Lens-Based Multibeam Planar Antenna System for UWB IoT Applications

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(Received 03 December 2025; revised manuscript received 15 February 2026; published online 25 February 2026)

This paper presents a cost-effective and portable multibeam planar antenna system designed to enhance connectivity in Internet of Things (IoT) applications. IoT networks face challenges such as high energy consumption, interference, and inefficient coverage, necessitating innovative antenna solutions. To address these issues, we propose a Rotman lens-based beam-steering antenna system operating in the 7-8 GHz ultra-wideband (UWB) range. The system consists of a three-input, six-output Rotman lens for analog beamforming and a six-element UWB antenna array, enabling the generation of three switchable beams. The fabricated prototype, developed on low-cost FR4 substrate with a thickness of 1.6 mm, achieves a peak gain of 8 dBi in the broadside beam configuration. Simulated and measured results demonstrate good agreement, confirming the efficient beam-steering capability and wideband performance of the proposed system. The design ensures low power consumption while maintaining reliable and adaptive connectivity. These characteristics make it well-suited for real-world deployment in dynamic IoT environments. The findings highlight the potential of Rotman lens-based antennas for low-power, high-performance IoT applications, offering an effective solution for smart industrial and wireless sensor networks.

**Keywords:** IoT application, Beam steering antenna, Rotman network.

DOI: [10.21272/jnep.18\(1\).01016](https://doi.org/10.21272/jnep.18(1).01016)

PACS number: 84.40.Ba

1. INTRODUCTION

The advent of 5G enhances connectivity with lower latency, higher capacity, and broader bandwidth [1–3], benefiting IoT but posing challenges like data management and packet collisions in large networks [4]. Retransmissions increase power consumption, making energy-efficient solutions essential. Pattern-reconfigurable antennas address these issues by directing radiation, reducing energy use, latency, and collisions. Switched-beam antennas lower energy consumption by 88% and collisions by 24% compared to omnidirectional designs [5]. For long-range communication, adaptive patterns with maximum azimuthal gain are preferred. Electronic switches, including RF MEMS and PIN diodes, enable reconfigurability, though PIN diodes suffer from high insertion loss. GaAs and CMOS switches are cost-effective options, but GaAs requires additional components and is high-power, while CMOS suits low-Power IoT applications with low insertion loss and minimal current consumption [6, 7]. One potential solution for radiation pattern reconfiguration involves using parasitic antenna arrays. In these configurations, a primary-driven radiator is commonly accompanied by multiple parasitic elements that are activated through

coupling. The radiation pattern is then fine-tuned by regulating variable loads linked to these parasitic elements [8]. This technique requires individual control of each reactance, affected by microcontroller voltage variations. Alternatives use integrated components like PIN diodes [9, 10] and dimmers [11], powered externally. In [12], eight reconfigurable modes are achieved with eight PIN diode switches, while [13] uses twenty PIN diodes for beam agility. Though effective, these designs depend on multiple components, making them impractical for energy-limited IoT nodes.

A Rotman lens provides a simple, cost-effective beam-steering solution using PCB technology for antennas and phase adjusters. It functions as a phase shift network, introducing phase delays at antenna ports by selecting the input port [14]. In [15], introduced a combination of a Rotman network and a Yagi-Uda antenna array on a PCB designed for operation at 28 GHz. However, the study primarily relied on simulated radiation patterns, with measurements limited to  $S_{11}$ . The gains reached approximately 8 dBi for the beams, although the setup did not incorporate a switch network. It's crucial to integrate a switching network into Rotman network design as these networks introduce losses, impacting realized gain. Practical use of a Rotman network

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necessitates the presence of a switching network. In [16], Rotman network designs for the 60 GHz band, including integrated switch networks, showcase promising results, achieves five beams with 7.5 dBi gains, while [17] presents a Rotman network configuration incorporating a solitary switch and four beams, attaining a gain of 4.5 dBi. Nevertheless, these designs have fixed beams perpendicular to the PCB. Exploring a design with beams parallel to the PCB could benefit low-cost base stations, allowing stacking for 2-D beam steering in practical systems. In contrast to beamforming techniques such as the Butler matrix, which manipulate phases across RF channels, Rotman network lens beamforming operates based on the lens geometry, rendering it a true time delay (TTD) beamformer. The size of the lens is directly correlated with operating wavelengths, rendering Rotman network suitable for high-frequency applications such as forthcoming 5G networks and IoT systems.

Despite significant advancements in IoT antenna technology, existing solutions either rely on complex phased-array beamforming, which increases power consumption and cost, or utilize fixed-beam antennas that lack adaptability for dynamic IoT environments. To address this, we propose a cost-effective, low-power Rotman lens-based beam-steering antenna system operating at 7 GHz with ultra-wideband (UWB) characteristics. The proposed design achieves passive beamforming, making it suitable for energy-constrained IoT networks, while offering improved coverage and reduced interference compared to omnidirectional antennas.

2. ANTENNA DESIGN

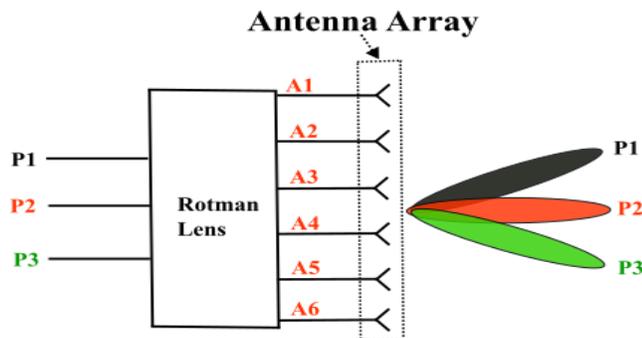


Fig. 1 – Schematic of proposed design

The antenna system consists two primary elements: a Rotman and a UWB array. The Rotman network generates phase excitation depending on the chosen port, and the UWB array functions as the radiating elements.

2.1 Rotman Network

The Rotman network is commonly implemented in either waveguide or microstrip. While the waveguide version can handle more power, the microstrip variant offers a wider bandwidth. The fundamental structure of the Rotman network comprises a beam and array contour, housing beam and array ports, respectively. Phasing/delay

lines extend from the array ports, and the space between the contours is known as the parallel plate region.

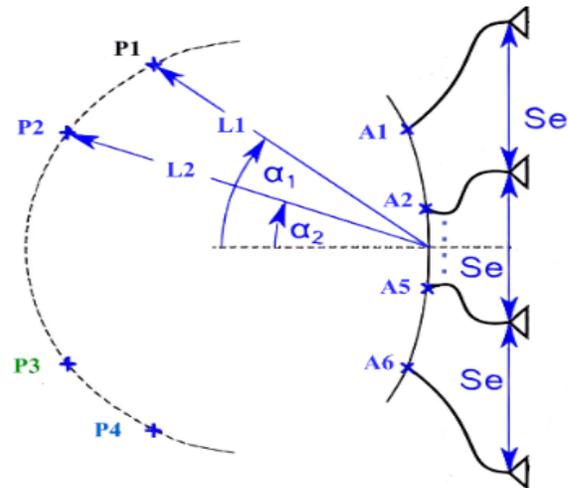


Fig. 2 – Schematic diagram and design parameters of the Rotman network

The lens structure is symmetrically designed around the central axis, with tapered microstrip lines matching the microstrip transmission to the parallel plate region. These lines, meandered for correct phasing, feed the antenna array. The Rotman network functions as a beamformer, introducing phase tapering at output ports. Its contour is precisely designed to minimize inter-focal port phase errors, ensuring signals focus at designated points along the array. Optimized for three focal points, any misaligned beam ports introduce phase errors, which the design mitigates.

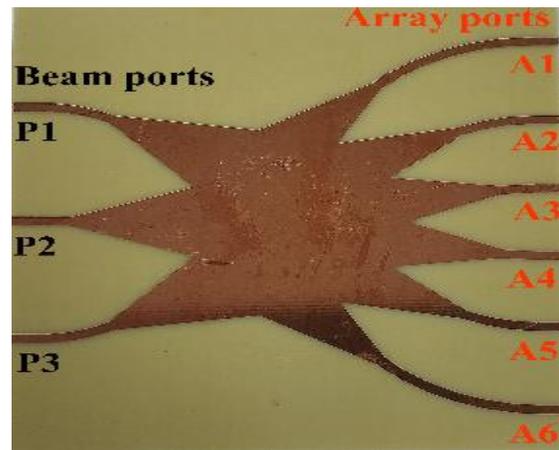


Fig. 3 – Fabricated Rotman network

The Rotman network lens is constructed with 3 beam ports and 6 array ports, as depicted in Figs. 2 and 3. Specifically, the arrangement incorporates three beam openings ( $P_1$ ,  $P_2$ , and  $P_3$ ) situated along the circular focal path, often referred to as the beam contour. The array ports  $A_1$  to  $A_6$  are evenly positioned at a focal angle ( $\alpha$ ) with respect to the origin allowing for a linear

adjustment in phase, which empowers the array to direct the beam towards a scanning angle ( $\psi$ ). Focal ratio ( $\beta$ ) represents the relationship between  $L_2$  and  $L_1$ . Establishing the length of the  $T_x$  line that links the internal and outer array contours adheres to the fundamental principles outlined by Rotman network [18].

Fine-tuning  $\psi$ ,  $\alpha$ , and  $\beta$  customizes the contours and the overall structure to suit the requirements of 7 GHz, with an approximately 125 mm diameter. Key dimensions include  $L_1 = 20.71$  mm,  $L_2 = 14.71$  mm,  $\alpha_1 = 30^\circ$ ,  $\alpha_2 = 0^\circ$ ,  $\psi = 25^\circ$ ,  $S_e = 16.08$  mm. Fabricated using an FR4 ( $\epsilon_r = 4.3$ , height of 1.6 mm). In Fig. 4, the phase relation between the beam port and array ports is depicted, revealing a sequential phase shift is approximately  $30^\circ$  when port 1 is excited.

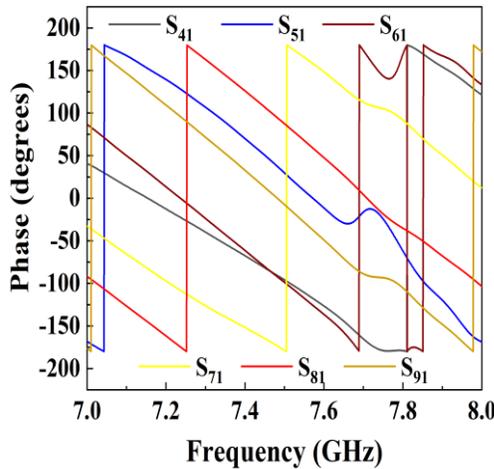


Fig. 4 – S-parameters for the Rotman network

### 2.2 Antenna Design

The individual UWB planar bowtie dipole antenna, as shown in Fig. 5, incorporates a  $50 \Omega$  microstrip feed, a perpendicular coupler section, and a ground plane with a bowtie dipole radiating element and an extending slot on the reverse side. To enhance bandwidth, a microstrip feed line with a perpendicular coupling section utilizes a UWB microstrip to slot line transition. The antenna's wideband performance is optimized through careful design modifications, including an ultra-wideband microstrip to slot line transition for efficient energy transfer. The structure also includes a truncated ground plane serving as a reflector. The optimized geometric parameters for are  $W = 62.22$  mm,  $W_1 = 9.67$  mm,  $W_2 = 1.81$  mm,  $W_3 = 24.8$  mm,  $W_4 = 3.36$  mm,  $W_5 = 1.23$  mm,  $W_6 = 12.69$  mm,  $W_7 = 0.61$  mm,  $L = 91$  mm,  $L_1 = 53.36$  mm,  $L_2 = 10.96$  mm,  $L_3 = 13.78$  mm, and  $L_4 = 8.49$  mm. In this setup, the planar bowtie dipole acts as a unit element, aiming for high gain and low complexity. Positioned on the top side of the substrate are six antenna elements, complemented by a truncated ground plane on the bottom side.

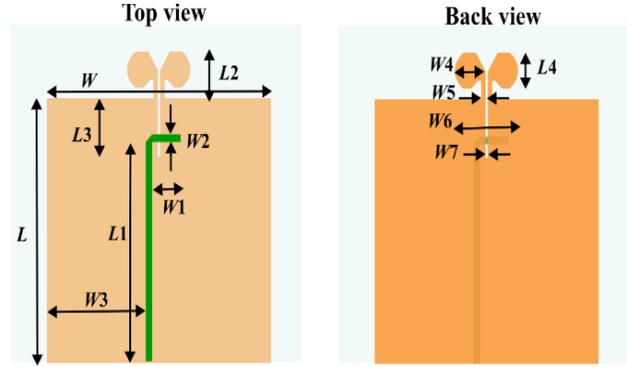


Fig. 5 – Schematic of the proposed UWB antenna element

### 3. RESULTS AND DISCUSSIONS

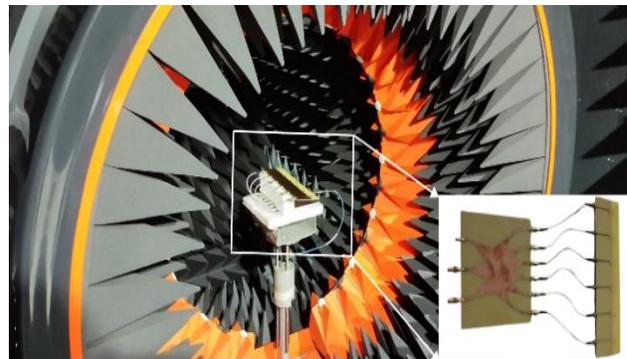


Fig. 6 – Photograph of the fabricated antenna array with the experimental setup

The proposed configuration, as shown in Fig. 6, integrates both a Rotman network and a six-element antenna array. The Rotman network consists of 3 beam ports and 6 array ports, with these ports interconnected with the antenna array. Examining measurements and simulations, the reflection coefficients consistently remain below  $-10$  dB above 7 GHz for all ports, as depicted in Fig. 7.

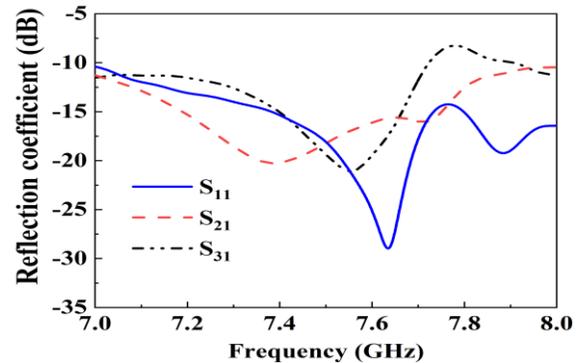


Fig. 7 – Reflection coefficient for the proposed antenna

Exciting the first beam port of the Rotman network and matching the remaining two ports with terminations successfully removes undesired reflections. This

arrangement introduces a 30° phase discrepancy between the output ports, consequently guiding the array to produce a beam at 0° (as shown in Fig. 8). Similarly, when individually exciting the lens beam ports 2 and 3, the antenna array generates beams directed at -38° and -25°, respectively (refer to Fig. 9 and Fig. 10). Changing the excitation of individual port in the Rotman network allows for directional beam control without relying on complex circuits. Fig. 11 shows the gain of the antenna array, revealing a peak gain of 8 dBi at 7 GHz. These results affirm the effective deployment of the beam controlling mechanism through a straightforward planar Rotman network, rendering it well-suited for IoT applications. Small variations between measurement and simulation results could arise due to the fabrication inaccuracies, differences in connector performance, and measurement errors.

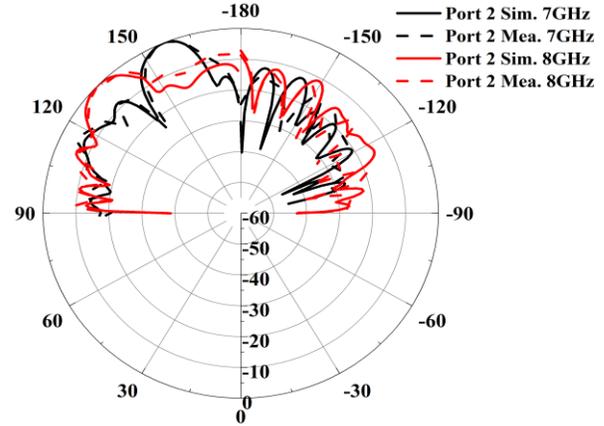


Fig. 10 – Radiation pattern at port 3

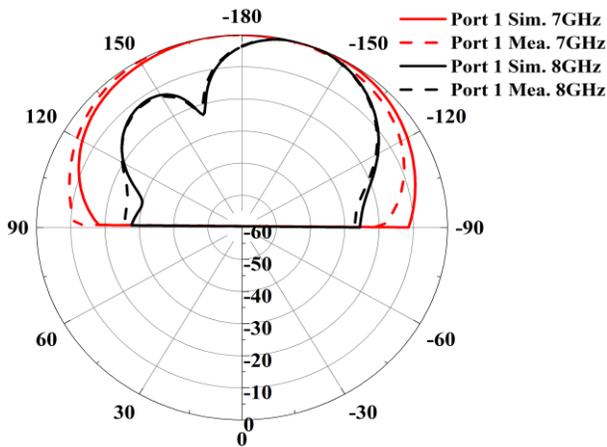


Fig. 8 – Radiation pattern at port 1

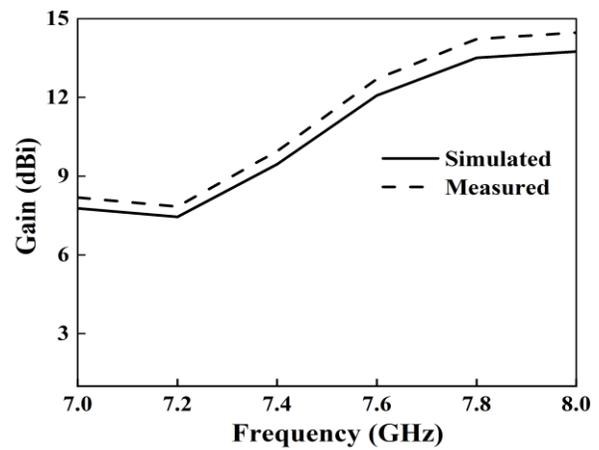


Fig. 11 – Peak gain when port 1 excited

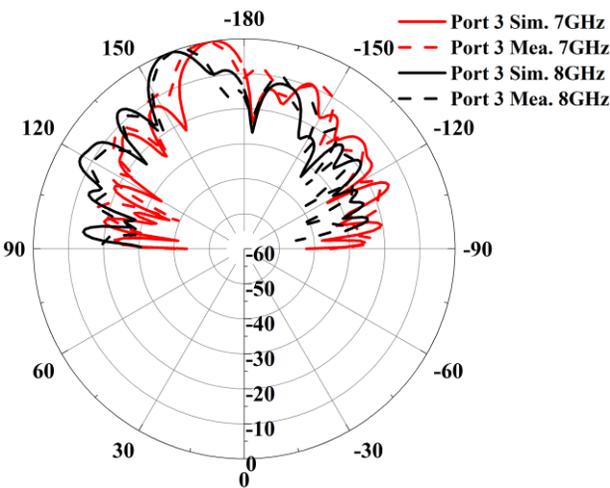


Fig. 9 – Radiation pattern at port 2

#### 4. CONCLUSION

In summary, this paper introduces a beam-steerable UWB antenna array incorporating a Rotman network, specifically designed for internet of things applications operating within the 7-8 GHz frequency spectrum. The integration of the Rotman network lens with the UWB antenna array showcased effective beam steering capabilities, enabling the production of three selectable beams at 0°, -38°, and -25° for flexible beam control. The designed antenna demonstrated a commendable gain of 8 dBi at 7 GHz. CST Studio Suite software was employed for simulation, providing crucial insights into the intricate interactions among various antenna components. This understanding played a pivotal role in overcoming the intricate challenges inherent in the design and manufacturing processes of antennas tailored for internet of things applications. Furthermore, the research introduces economical and effective strategies for industrial antenna manufacturing, highlighting the strategic integration of a Rotman network with UWB antenna array techniques to streamline design and manufacturing procedures while presenting an economically viable approach.

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### Багатопроменева планарна антенна система на основі лінз Ротмана для застосувань UWB IoT

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У цій статті представлено економічно ефективну та портативну багатопроменеву планарну антенну систему, призначену для покращення зв'язку в застосунках Інтернету речей (IoT). Мережі IoT стикаються з такими проблемами, як високе споживання енергії, перешкоди та неефективне покриття, що вимагає інноваційних антенних рішень. Для вирішення цих проблем ми пропонуємо антенну систему з керуванням променем на основі лінзи Ротмана, що працює в надширокосмуговому (UWB) діапазоні 7-8 ГГц. Система складається з лінзи Ротмана з трьома входами та шістьма виходами для аналогового формування променя та шестилінійної UWB антенної решітки, що дозволяє генерувати три перемикані промені. Виготовлений прототип, розроблений на недорогій підкладці FR4 товщиною 1,6 мм, досягає пікового коефіцієнта посилення 8 дБі в конфігурації бічного променя. Моделювані та виміряні результати демонструють хорошу узгодженість, підтверджуючи ефективну здатність керування променем та широкосмугову продуктивність запропонованої системи. Конструкція забезпечує низьке енергоспоживання, зберігаючи при цьому надійне та адаптивне підключення. Ці характеристики роблять її добре придатною для реального розгортання в динамічних середовищах IoT. Отримані дані підкреслюють потенціал антен на основі лінз Ротмана для малопотужних, високопродуктивних застосувань Інтернету речей, пропонуючи ефективне рішення для інтелектуальних промислових та бездротових сенсорних мереж.

**Ключові слова:** Застосування Інтернету речей, Антена з керуванням променем, Мережа Ротмана.