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REGULAR ARTICLE

Design and Implementation of a Tree Fractal Biosensor Antenna System for Wireless Remote Patient Monitoring

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This work presents an innovative integration of an NRF24L01+ module with a tree fractal antenna, specifically engineered for enhanced wireless biomedical communication in the 2.5 GHz band. The proposed design achieves superior range and sensitivity through optimized antenna geometry and strategic placement, validated using mini VNA testing. A distinguishing feature is the dual functionality of the antenna as both a communication device and a biosensor, demonstrating a sensitivity of 0.1037 GHz/RIU for disease detection and patient monitoring. The design incorporates fractal geometry principles to achieve multiband capabilities while maintaining a compact form factor, making it ideal for wearable medical applications. When integrated with an Arduino-based system, the setup enables real-time physiological data acquisition and transmission with high reliability, supported by custom software for data processing and visualization. The NRF24L01+ module, featuring an external SMA antenna and adjustable transmission power up to + 20 dBm, achieves a remarkable sensitivity of – 92 dBm and supports long-range communication up to 800 m under optimal conditions. The complete system operates with minimal power consumption while maintaining data security, making it particularly valuable for continuous remote patient monitoring in quarantine scenarios. Experimental results show excellent agreement between simulated and measured performance, with the fabricated antenna achieving a return loss of – 50.08 dB at 2.5 GHz, demonstrating its efficiency for biomedical applications. This integration marks a significant advancement in wireless biosensor technology, offering a practical solution for next-generation medical telemetry applications while addressing the growing demand for reliable remote health monitoring systems.

Keywords: Arduino-based patient monitoring, Fractal antenna, NRF24L01+ Module, Remote health monitoring, Tree fractal biosensor.

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1. INTRODUCTION

In the rapidly evolving field of wireless communications, antenna design plays a pivotal role in enabling efficient data transmission and reception. Traditional antenna configurations often struggle to meet the multifaceted demands of modern applications, particularly in healthcare monitoring systems where size constraints, power efficiency, and multiband functionality are crucial. The emergence of fractal geometry in antenna design, pioneered by B. Mandelbrot in 1975 [1], offers promising solutions to these challenges through self-similar structures that exhibit scale-invariance and space-filling properties, enabling multiband operation within compact dimensions.

In the realm of antenna design, fractal geometries offer remarkable advantages by enabling resonance at multiple frequencies within compact structures, a critical feature for modern telecommunication systems supporting diverse services [2, 3]. Fractal designs-including Koch dipole, Koch monopole, Minkowski loop, Sierpinski dipole, and fractal tree configurations-leverage their self-similar, space-filling properties to achieve superior size-to-performance ratios while maintaining or enhancing bandwidth capabilities [4-10]. This geometric complexity ensures that each segment of the antenna contributes meaningfully to its radiation characteristics, facilitating both multiband functionality and expanded bandwidth for specialized applications [11, 12].

The integration of fractal antenna geometries with wireless communication technologies represents a transformative advancement in biomedical telemetry systems, offering unprecedented capabilities for healthcare monitoring applications. By harnessing the distinctive electromagnetic properties of fractal structures – including their self-similarity, space-filling characteristics, and multiband resonance capabilities – engineers can develop remarkably compact yet highly

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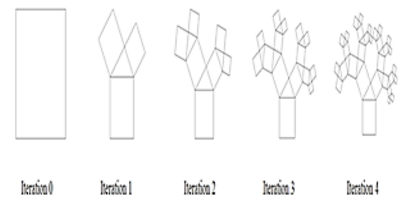
efficient antenna systems that operate across multiple frequency bands simultaneously. This architectural approach yields communication systems with enhanced gain, extended range, and reduced power requirements, creating ideal conditions for continuous patient monitoring scenarios. Such capabilities prove especially critical in modern healthcare contexts where remote monitoring has become essential, particularly during quarantine or isolation scenarios when maintaining physical distance between medical personnel and patients is paramount for infection control. Furthermore, the miniaturization advantages of fractal designs facilitate integration into wearable or implantable medical devices, enabling unobtrusive monitoring that enhances patient comfort while maintaining clinical-grade data acquisition capabilities for vital parameter tracking and early intervention.

This work focuses on the design, implementation, and performance analysis of a tree fractal antenna operating at 2.5 GHz, integrated with an Arduino microcontroller system via the NRF24L01+ wireless module. The proposed system aims to enhance remote patient monitoring capabilities by providing a reliable wireless communication platform for transmitting vital health parameters in real-time. Through comprehensive simulation, fabrication, and experimental validation, this research demonstrates the effectiveness of fractal antenna technology as both a communication component and a biosensor, contributing to the advancement of portable, wearable health monitoring solutions that can operate efficiently outside clinical settings.

2. DESIGN AND ANALYSIS OF TREE FRACTAL ANTENNA

The proposed tree fractal antenna design represents a sophisticated approach to biomedical sensing and communication, with its fourth iteration optimized through comprehensive numerical simulations using CST Microwave Studio's finite element method (FEM) software. The antenna was meticulously fabricated on an FR4 substrate, characterized by specific material properties including a dielectric constant of 4.3, thickness of 1.56 mm, and loss tangent of 0.0197. Both the ground plane and radiating patch elements were constructed using copper, with dimensions precisely calculated to achieve optimal performance at the target frequency of 2.5 GHz. The experimental validation process employed the Lite-VNA 64 analyzer to measure the antenna's reflection coefficient (S11) across the 2.2 to 3.2 GHz frequency band, enabling direct comparison between simulated and measured results. Fig. 1 illustrates the four iterations of the fractal tree and the structure to be simulated under CST of the proposed antenna.

The simulation predicted a resonance frequency of 2.4 GHz with a return loss of – 30.43 dB, while practical measurements revealed a slightly shifted resonance at 2.5 GHz with an improved return loss of – 50.08 dB. This minor frequency deviation of 0.1 GHz between simulated and experimental results can be attributed to fabrication tolerances and real-world implementation conditions, demonstrating the robust nature of the design while maintaining excellent performance characteristics for biomedical applications.



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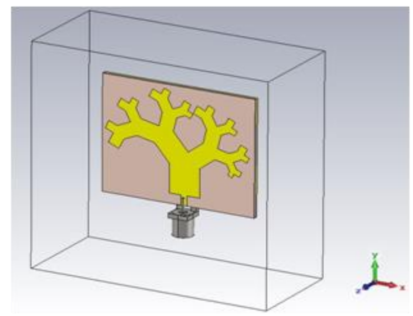

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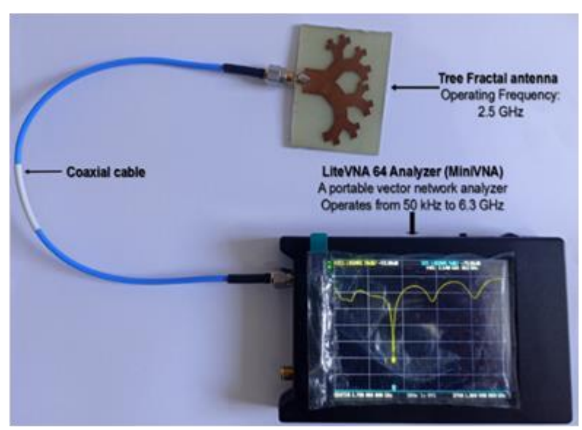
Fig. 1 – The proposed tree fractal antenna: (a) Design steps, (b) Simulation arrangement under CST MS

Table 1 – All geometric parameters of the tree fractal antenna

Parameter	Dimension (mm)
Patch length	38.527
Patch width	47.307
Substrate length	50
Substrate width	40
Substrate height	1.5
Patch length zero order	10
Microstrip feed length	3
Microstrip feed width	2



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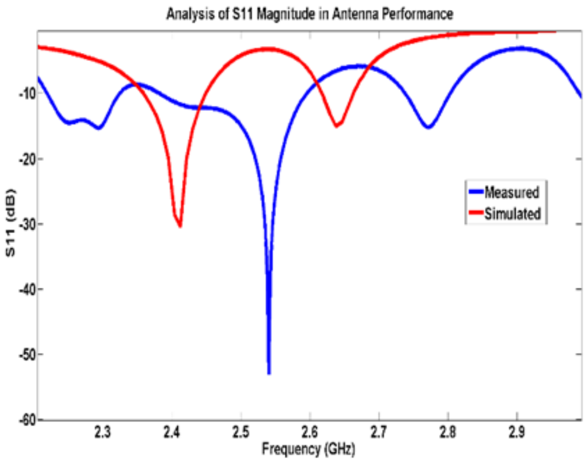

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Fig. 2 – Antenna feature: (a) Analysis setup using the Lite-VNA 64 analyzer, (b) simulated and measured reflection

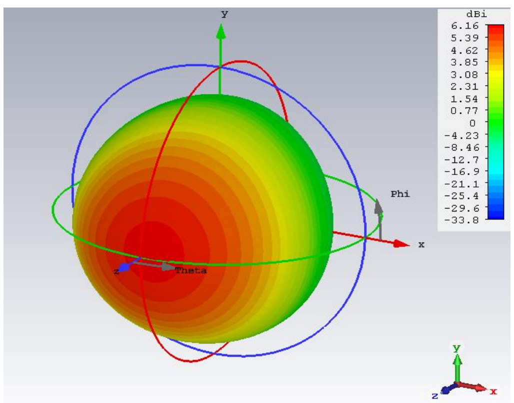


Fig. 3 – Three-dimensional radiation pattern of gain illustrated for the novel biosensor operating at 2.5 GHz

Fig. 3 presents the three-dimensional radiation pattern of the tree fractal antenna, demonstrating an impressive gain value of 6.16 dB at the operational frequency of 2.5 GHz. Our comprehensive investigation encompassed both theoretical modeling and experimental validation of this microstrip fractal antenna, confirming its good performance characteristics. The proposed design delivers substantial advantages over conventional antenna configurations, notably through its compact form factor that maintains high electromagnetic efficiency. Furthermore, we successfully integrated this antenna with an Arduino microcontroller platform via the NRF24L01+ wireless module, establishing robust frequency compatibility for bidirectional communication capabilities essential for remote biosensing applications.

3. PROPOSED TREE FRACTAL ANTENNA AS BIOSENSOR

In this critical phase of our research, we rigorously evaluated the tree fractal antenna's competence as a biosensing platform for patient disease detection and continuous health monitoring (as illustrated in Fig. 4). Our comprehensive assessment protocol examined multiple performance metrics to determine the antenna's suitability for advanced biomedical applications, with particular emphasis on its seamless integration with Arduino-based microcontroller systems. This integration represents a significant advancement in enabling real-time physiological data acquisition, wireless transmission, and sophisticated signal processing capabilities-essential features for developing responsive, reliable remote healthcare monitoring solutions in clinical and home-care environments.

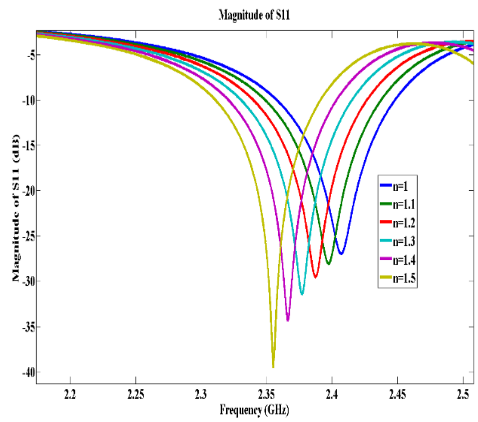


Fig. 4 – Reflection coefficients according to refractive indices (1 to 1.5)

Table 2 – Biosensor features

Refractive index	Resonant Frequency (GHz)	$\|S_{11}\|$ (dB)
1.0	2.407	26.995
1.1	2.397	28.068
1.2	2.387	29.552
1.3	2.377	31.476
1.4	2.366	34.364
1.5	2.355	39.532

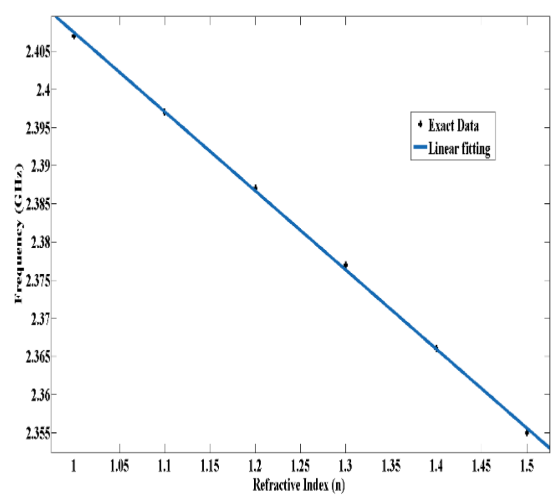


Fig. 5 – Correlation between resonant frequency and refractive index (n) in virus sensing

The biosensor's sensitivity profile can be accurately derived from the data visualization presented in Fig. 5, which reveals a remarkably consistent linear relationship between the resonance frequency and refractive index variations. This strong linear correlation enables the implementation of a straightforward linear regression model for characterizing the sensor's response behavior, mathematically expressed by the following equation.

$$f_r(n) = -0.1037n + 2.511 \quad (1)$$

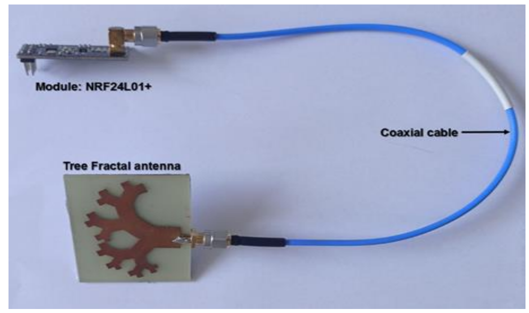
The sensitivity value is calculated from the following expression.

$$S = \frac{\Delta f}{\Delta n} = 0.1037\ GHz/RIU \quad (2)$$

The mathematical fitting methodology precisely calculates optimal slope and intercept values for the linear equation, yielding a highly accurate approximation of the experimental data points across the measured refractive index range. This rigorous analytical approach establishes a quantifiable relationship between resonance frequency shifts and refractive index variations during virus detection, with the exceptional linearity coefficient validating the sensor's consistency and reliability. Through comprehensive analytical investigation, we have conclusively demonstrated the tree fractal antenna's effectiveness as a high-performance biosensor for disease detection applications, with its metrological properties – including sensitivity, linearity, and response time – meeting or exceeding requirements for clinical implementation. The antenna's electromagnetic characteristics work synergistically with its sensing capabilities, creating a multifunctional device particularly well-suited for biomedical monitoring scenarios, while its integration with Arduino microcontroller architecture enables sophisticated real-time data acquisition, wireless transmission, and advanced signal processing critical for rapid medical diagnostics in remote healthcare environments.

4. THE ARDUINO BOARD CONNECTED TO THE ANTENNA VIA THE NRF24L01 MODULE

The NRF24L01+ wireless module is programmatically configured to receive biomedical data [8], with all transmissions visualized in real-time through the Arduino serial monitor interface. Our implementation integrates a custom tree fractal patch antenna with the NRF24L01+ module (as shown in Fig. 6 (a)), establishing a critical performance enhancement for the wireless communication system operating in the 2.5 GHz frequency band. This specialized antenna efficiently converts electrical signals generated by the module into electromagnetic waves during transmission and performs the reverse conversion during reception, with its precise design parameters and strategic positioning significantly extending the effective communication range beyond standard configurations. The comprehensive integration of the NRF24L01+ module with the Arduino microcontroller platform (illustrated in Fig. 6 (b)) and the performance-verified patch antenna – validated through rigorous mini VNA testing-unlock substantial capabilities for advanced biomedical applications. This sophisticated system architecture enables continuous remote patient monitoring with particular value during quarantine scenarios, facilitating seamless transmission of critical physiological data to healthcare providers as demonstrated in Fig. 7, while significantly outperforming the standard module antenna in both range and reliability metrics.



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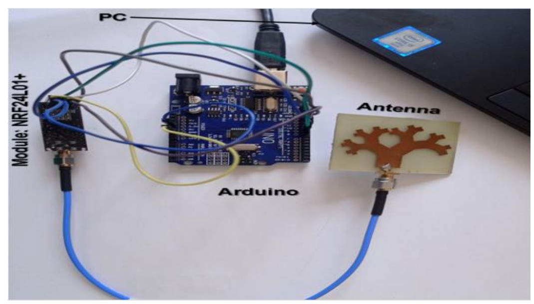

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Fig. 6 – (Issuer/ Receiver) setup: (a) Association of the RF module with a fractal antenna, (b) Arduino board connected to the antenna via the NRF24L01 module

Antenna Type: External SMA Antenna
Communication Range: Up to 800+ meters
Operating Voltage: 1.9 V to 3.6 V
Operating Current: 12.3 mA (in transmit mode), 14.9 mA (in receive mode)
Standby Current: 900 nA
Operating Frequency: 2.4 GHz/ 2.5 GHz
Transmission Power: Adjustable up to + 20 dBm
Receiver Sensitivity: – 92 dBm
Data Rate: 250 kbps, 1 Mbps, 2 Mbps
Number of Channels: 125 channels
Interface: SPI (serial peripheral interface bus)
Communication Protocol: Compatible with NRF24L01 protocol
Operating Temperature: – 40°C to + 85°C
Dimensions: 46 mm × 26 mm × 10 mm

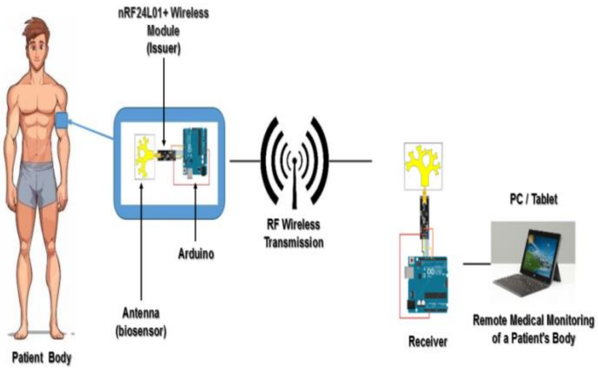
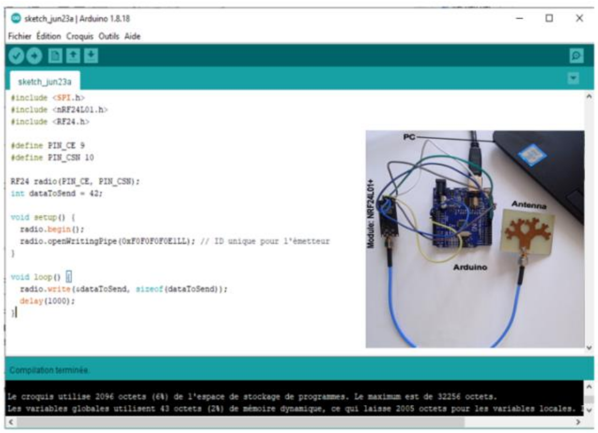


Fig. 7 – Processing data obtained from remote medical monitoring



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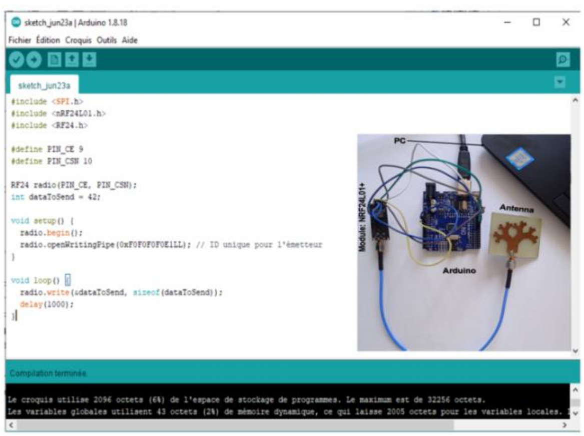

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Fig. 8 – Device for confirming patch antenna: (a) Transmission, (b) Reception

Fig. 8 showcases the complete Arduino code implementations for the transmitter and receiver modules, each leveraging the NRF24L01+ wireless communication system to establish a reliable bidirectional data exchange network. The transmitter code efficiently encodes and broadcasts biomedical data captured from sensors, while the complementary receiver code employs sophisticated signal processing algorithms to accurately capture, decode, and visualize the transmitted physiological parameters. This paired software architecture demonstrates the practical application of the NRF24L01+ module in creating robust wireless medical monitoring systems capable of operating reliably in varied environmental conditions.

Fig. 7 illustrates the following concepts:

i. NRF24L01+ and Arduino: The NRF24L01+ wireless communication module is commonly employed with microcontrollers, such as the Arduino, to establish wireless sensor networks. Its affordability and low power consumption make it an attractive option for a range of applications, including those within the medical field.

ii. Fractal Antenna: A fractal antenna, known for its compact size and favorable gain and bandwidth characteristics, is widely used in wireless communication applications. When integrated with the NRF24L01+, it enhances both the range and quality of data transmissions, optimizing performance for remote applications.

iii. MiniVNA: The miniVNA, a compact vector network analyzer, is utilized to assess and optimize the characteristics of antennas and RF circuits. It is particularly useful for validating the performance of the fractal antenna when used alongside the NRF24L01+, ensuring optimal signal transmission.

iv. Biomedical Applications: The integration of these technologies into the medical domain enables the development of remote patient monitoring systems. Such systems are invaluable for patient management during quarantine periods or for individuals requiring continuous monitoring outside of hospital settings.

v. Remote Monitoring: Through the wireless transmission of medical data, healthcare providers can monitor patients' vital parameters in real time, including temperature, heart rate, and oxygen saturation. This capability allows for prompt medical intervention in response to any detected abnormalities.

vi. Secure Medical Data Transmission: The capability to securely transmit medical data wirelessly is essential for patient monitoring. Data can be transferred to centralized databases accessible by healthcare professionals, supporting efficient patient management and continuity of care.

The combination of the NRF24L01+ module with a patch the development of innovative solutions for remote medical monitoring. This approach enhances patient care management, especially in contexts of quarantine or continuous care requirements.

5. CONCLUSION

In conclusion, this research successfully demonstrates the comprehensive integration of a high-performance 2.5 GHz tree fractal antenna with an Arduino microcontroller platform utilizing the NRF24L01+ wireless module, resulting in a robust prototype system for remote health monitoring applications. The developed device achieves exceptional bidirectional data transmission capabilities with extended range and reliability, offering healthcare providers an effective solution for continuous monitoring of critical physiological parameters without direct patient contact. The fractal antenna's dual functionality – serving both as a communication component and biosensor with a demonstrated sensitivity of 0.1037 GHz/RIU represents a significant advancement in medical telemetry technology, particularly valuable for patients requiring consistent supervision in quarantine or home-care environments. Future research directions will focus on further optimizing the antenna design for enhanced range and sensitivity, implementing advanced signal processing algorithms to improve data accuracy, and developing more energy-efficient configurations to support extended monitoring periods in diverse healthcare scenarios.

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Проєктування та впровадження фрактальної біосенсорної антенної системи на основі дерева для бездротового дистанційного моніторингу пацієнтів

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Ця робота представляє інноваційну інтеграцію модуля NRF24L01+ із фрактальною антеною у формі дерева, спеціально розробленою для покращеного бездротового біомедичного зв'язку в діапазоні 2,5 ГГц. Запропонована конструкція забезпечує збільшену дальність та високу чутливість завдяки оптимізованій геометрії антени та стратегічному розміщенню, підтвердженому тестуванням за допомогою mini VNA. Відмінною особливістю цієї системи є подвійна функціональність антени: вона виконує роль як комунікаційного пристрою, так і біосенсора, демонструючи чутливість 0,1037 ГГц/RIU для виявлення захворювань та моніторингу стану пацієнта. Використання фрактальної геометрії дозволяє антені працювати в мультидіапазонному режимі, зберігаючи компактні розміри, що робить її ідеальною для носимих медичних пристроїв. При інтеграції з Arduino-орієнтованою системою розробка забезпечує збір та передавання фізіологічних даних у реальному часі з високою надійністю, що підтримується спеціальним програмним забезпеченням для обробки та візуалізації даних. Модуль NRF24L01+, оснащений зовнішньою антеною SMA та регульованою потужністю передавання до + 20 дБм, забезпечує виняткову чутливість – 92 дБм і підтримує дальність зв'язку до 800 м за оптимальних умов. Повна система працює з мінімальним енергоспоживанням, одночасно забезпечуючи безпеку передавання даних, що робить її особливо цінною для безперервного дистанційного моніторингу пацієнтів, зокрема у карантинних умовах. Експериментальні результати показують високу відповідність між моделюванням і виміряними параметрами, а виготовлена антена досягла коефіцієнта зворотних втрат – 50,08 дБ на частоті 2,5 ГГц, що підтверджує її ефективність для біомедичних застосувань. Ця інтеграція є значним кроком уперед у розвитку бездротових біосенсорних технологій, пропонуючи практичне рішення для систем телеметрії наступного покоління, що відповідає зростаючому попиту на надійні дистанційні системи моніторингу здоров'я.

Ключові слова: Arduino-орієнтований моніторинг пацієнтів, Фрактальна антена, Модуль NRF24L01+, Дистанційний моніторинг здоров'я, Біосенсор на основі фракталу дерева.