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A Dual-Band Reconfigurable Active Antenna for IoT-Enabled Health Monitoring Systems

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ABSTRACT: In this study, a dual-band active antenna integrated with an IoT healthcare monitoring system for measuring body temperature, heart rate, and SpO_2 is presented. A MAX30100 sensor and NodeMCU ESP32-CAM enable data acquisition and cloud-based monitoring through Ubidots. The antenna, fabricated on a Rogers Duroid RO3003$^{\mathrm{TM}}$ substrate ($37 \times 42 \times 1.52\,\mathrm{mm}^3$), operates at 2.4 GHz and 5.8 GHz using an inverted U-shaped slot and a PIN diode for frequency reconfiguration. Received Signal Strength Indicator (RSSI) measurements showed improved signal strength from -35 to -40 dBm compared to -40 to -45 dBm for the onboard antenna. Experimental evaluation on three volunteers aged 21, 36, and 55 years demonstrated reliable physiological monitoring, with heart rate values of 84–90 BPM and temperature readings of 30–36°C. The results validate the suitability of the proposed antenna for reliable IoT-based healthcare applications.

1. INTRODUCTION

The Internet of Things (IoT) has become a key technology for data acquisition and long-distance wireless communication, offering a framework for connecting sensors, microcontrollers, and cloud platforms [1, 2]. The IoT enables several devices to interact with each other to gather, analyze, and send data for various uses, including smart cities, smart homes, healthcare, agriculture and military systems [3–5]. These applications improve resource utilization, operational efficiency, and decision-making processes. Moreover, progress in wireless communication technologies [6] has further improved the performance and connectivity of IoT devices and networks. Antennas are one of the key components of IoT systems and play a significant role in achieving reliable wireless communication. Thus, the design of small, low-profile, and easy-to-integrate antennas that support multiple frequency bands and functions [7] is gaining interest.

Modern wireless communication systems increasingly require adaptive antennas that can operate efficiently under different conditions. However, existing fixed antennas are not always able to meet these changing needs. This has led to the development of reconfigurable antennas. Reconfigurable antennas can change the operating frequency, radiation characteristics, polarization, or a combination of these parameters based on application demands [8–11]. This is typically achieved using active switching elements, such as PIN diodes, varactor diodes, and radio frequency micro-electromechanical switches (RF MEMSs) [12, 13]. PIN and varactor diodes have low insertion losses and continuous tuning; however, they may be nonlinear. Several miniature frequency reconfigurable antennas have been proposed in the literature. For example, Abdulhusein et al. introduced a monopole antenna that uses two PIN diodes to operate with four frequency bands, 2.4 GHz, 3.5 GHz, 5.2 GHz, and 5.8 GHz [14]. On the other hand, Karthika et al. suggested a miniaturized antenna that operates with three PIN diodes and generates eight resonances with desirable gain, directivity, and voltage standing wave ratio [15]. Likewise, Shah et al. introduced a frequency reconfigurable patch antenna that utilized the LTE and WLAN frequency bands with the help of PIN diodes [16]. Hussain et al presented a flexible frequency reconfigurable antenna based on the RT5880 substrate material with PIN diodes [17].

The adoption of healthcare systems using IoT has been widely recognized because of their capability to ensure continuous monitoring of patients' conditions, offer quality healthcare services, decrease costs, and contribute to the early detection and treatment of diseases [18]. It is also important to monitor vitals to ensure timely medical assistance, avoid serious consequences of poor health conditions, and reduce mortality rates. In most cases, traditional healthcare monitoring requires manual measurements and devices that can complicate the process of real-time observation and burden healthcare practitioners with additional tasks [21, 22]. The use of IoT in healthcare helps overcome such obstacles owing to the introduction of continuous monitoring and availability of physiological information via cloud computing [23]. Elderly people and those who require continuous supervision greatly benefit from such an approach.

Many studies have been conducted on IoT-based monitoring of physiological parameters. Studies have been conducted using Arduino-based monitoring devices for heart rate [24] and body temperature monitoring [25]. The monitoring of heartbeat systems with integration to smartphones [26] and remote servers [27, 28] has also been explored. A portable system for infant body temperature measurement using an LM35 sensor and Espresso Lite V2.0 microcontroller was introduced by Zakaria et al., which sends information to cloud servers through Wi-Fi technology [29]. Similarly, a study has been done by Mohamad Hadis et al. which presents an IoT-based patient moni-

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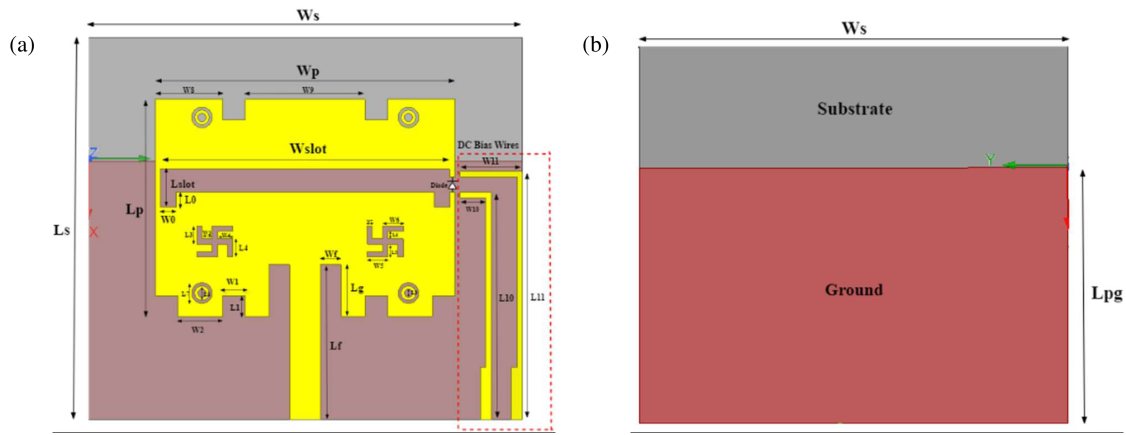

FIGURE 1. Reconfigurable active antenna with PIN diode. (a) Front view and (b) back view.

toring system that measures body temperature and respiration rate through Arduino Mega 2560 and ESP8266 Wi-Fi modules [30].

The proposed healthcare monitoring system using IoT technology is described for the real-time measurement of heart rate, body temperature, and SpO_2 values utilizing a MAX30100 sensor. A small reconfigurable active antenna ($37 \times 42 \times 1.52\,\text{mm}^3$) was designed by applying a PIN diode and Swastik-shaped slots, which operates at 2.4 and 5.8 GHz. The collected data were sent to a Ubidots cloud platform. The suggested antenna provides a gain of 5.7 dB, bandwidth of 0.2 GHz, and radiation efficiency of 99%. The main contributions of this study are as follows:

- Design and fabrication of a compact dual-band reconfigurable active antenna operating at 2.4 and 5.8 GHz Industrial, Scientific, and Medical (ISM) bands using a PIN diode on a Rogers Duroid RO3003$^{\text{TM}}$ substrate.
- The integration of the designed antenna within an IoT-based healthcare monitoring system that transmits heart rate, body temperature, and SpO_2 measurements to the Ubidots cloud server in real time.
- The antenna exhibited excellent performance with a gain of 5.7 dB, bandwidth of 0.2 GHz, and radiation efficiency of 100%.
- The antenna design was successfully validated in experimental tests, where RSSI and physiological parameter values were measured for comparison with the performance of a reference dipole and onboard Wi-Fi antennas.

2. DESIGN AND CONFIGURATION OF ACTIVE ANTENNA

A compact dual-band reconfigurable antenna was designed and analyzed using ANSYS HFSS R2021. The antenna, shown in Fig. 1, incorporates an inset-fed structure, an inverted U-shaped slot, two swastik-shaped slots, four circular grooves, and a partial ground plane to enhance compactness, impedance bandwidth, and dual-band operation. Frequency reconfiguration between the 2.4 and 5.8 GHz ISM bands is achieved using a Skyworks SMP-1321-079LF PIN diode. The antenna was fabricated on a Rogers Duroid RO3003$^{\text{TM}}$ substrate ($\epsilon_r = 3$, $h = 1.52\,\text{mm}$, $\tan\delta = 0.0013$) with overall dimensions of $37 \times 42\,\text{mm}^2$. A microstrip feed line connected through an SMA connector was employed for excitation, whereas the PIN diode enables dynamic switching between the operating bands.

The design equations to calculate the length/width of the patch/feedline are given in Equations (1)–(4), respectively:

$$\text{Length of the Patch, } L_P = L_{\mathit{eff}} - 2\Delta L \tag{1}$$

where, $L_{\mathit{eff}} = \frac{c}{2f_r\sqrt{\epsilon_{\mathit{eff}}}}$, $\epsilon_{\mathit{eff}} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2} \cdot \left(1 + \frac{12h}{w}\right)^{-1/2}$, $\Delta L = 0.412h\frac{(\epsilon_r+0.3)\left(\frac{W}{h}+0.804\right)}{(\epsilon_r-0.258)\left(\frac{W}{h}+0.8\right)}$, h — height of the dielectric substrate, w — width of the microstrip line.

$$\textit{Width of the patch, } W_p = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{2}$$

$$\textit{Length of the feedline, } L_f = \frac{C}{2f_r\sqrt{\varepsilon_r}} \tag{3}$$

$$\textit{Width of the feedline, } W_f = \frac{7.48h}{\exp\left(\sqrt{0.33(\sqrt{\varepsilon_f}+1.41)}\right) - 1.25t} \tag{4}$$

The dimensions of the proposed antenna are listed in Table 1. Fig. 2 shows the equivalent circuit with the biasing circuit of the PIN diode. In the ON state, it exhibits series resistance and inductance, and in the OFF state, and the diode is shunted with resistance and capacitance. The biasing network of the PIN diode consists of an inductor ($L_p = 27\,\text{nH}$) and a capacitor ($C_b = 1800\,\text{pF}$), ensuring impedance matching and DC bias control while preventing RF signal disruption.

3. PERFORMANCE MEASURES OF ACTIVE ANTENNA

The fabricated dual-band reconfigurable antenna integrated with a PIN diode is shown in Fig. 3. The antenna performance was evaluated using a Keysight N5234B Vector Network Analyzer (VNA) for S_{11} measurements, as shown in

TABLE 1. Dimensions of the proposed antenna (in mm).

L_s	W_s	H_s	L_{pg}	L_p	W_p	L_{slot}	W_{slot}	L_f	W_f	W_{part}
37	42	1.52	25	21	29	3.7	28	15	2	2.98
L_g	L_0	L_1	L_2	L_3	L_4	L_5	L_6	L_7 (Outer circle diameter)	L_8 (Middle circle diameter)	L_9 (Inner circle diameter)
5	1.5	2	1.5	1.75	1.75	1.25	0.75	0.5	0.35	0.25
L_{10}	L_{11}	W_0	W_1	W_3	W_4	W_5	W_6	W_7	W_8	W_9
22	24	1.45	2.2	1	1.5	2	2	0.5	3	6

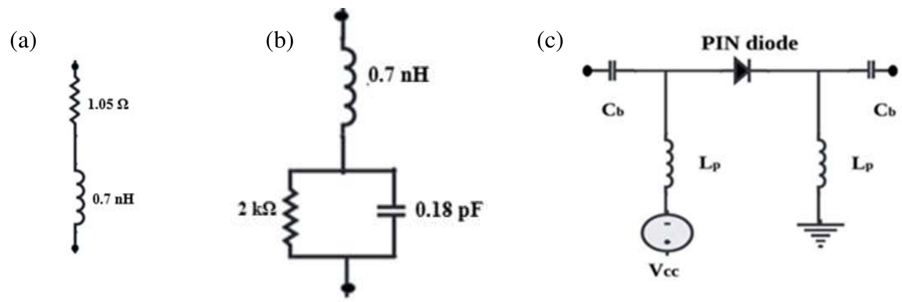

FIGURE 2. Lumped elements of PIN diode. (a) ON state, (b) OFF state, and (c) biasing circuit.

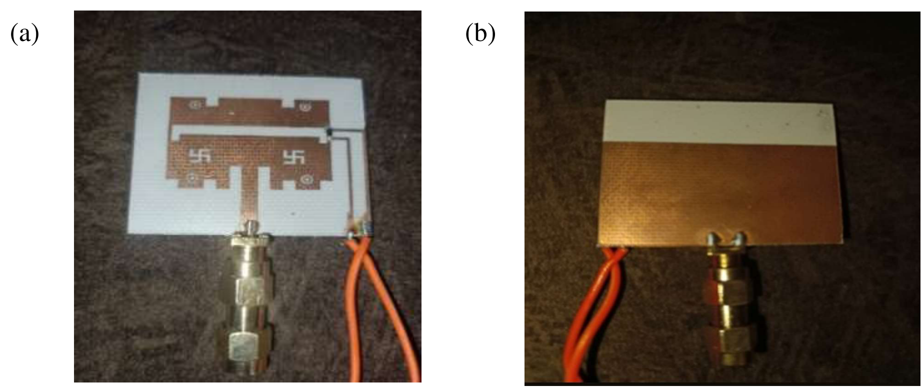

FIGURE 3. Fabricated antenna with PIN diode. (a) Front view and (b) back view with partial ground.

Fig. 4, and the radiation characteristics were measured in an anechoic chamber. The measured results were compared with the simulated ones to validate the antenna performance. Fig. 5 presents the simulated and measured reflection coefficients for both PIN diode states. In the ON state, the antenna operated at 2.38 and 5.54 GHz with measured impedance bandwidths of 71 MHz (2.332–2.403 GHz) and 182 MHz (5.439–5.621 GHz), respectively. In the OFF state, the antenna exhibits single-band operation at 5.44 GHz with a bandwidth of 270 MHz (5.337–5.607 GHz).

The antenna's voltage standing wave ratio (VSWR) characteristics are shown in Fig. 6. In the ON state, measured VSWR values of 1.12 and 1.09 were obtained at 2.38 GHz and 5.54 GHz, respectively. In the OFF state, the antenna achieved a VSWR of 1.26 at 5.44 GHz. These results confirm good impedance matching and efficient power transfer at the operating frequency.

The radiation characteristics of the proposed antenna were evaluated using simulated 2D radiation patterns at the resonant frequencies. As shown in Fig. 7(a), the antenna exhibits a bidirectional E-plane pattern and omnidirectional H-plane pattern at 2.4 GHz in the ON state. At 5.64 GHz, the E-plane becomes directional, whereas the H-plane remains omnidirectional, as shown in Fig. 7(b). In the OFF state, the antenna operated at 5.44 GHz, maintaining a directional E-plane and omnidirectional H-plane radiation pattern, as shown in Fig. 8. The simulated gain characteristics are shown in Fig. 9. In the ON state, gains of 2.12 dB and 5.46 dB are achieved at 2.4 and 5.64 GHz, respectively. In the OFF state, the antenna attained a maximum gain of 5.7 dB at 5.63 GHz.

Surface current analysis was performed to investigate the antenna's frequency reconfiguration behavior. In the ON state, a strong current concentration was observed around the inverted U-shaped slot at 2.4 GHz, indicating its role in gener-

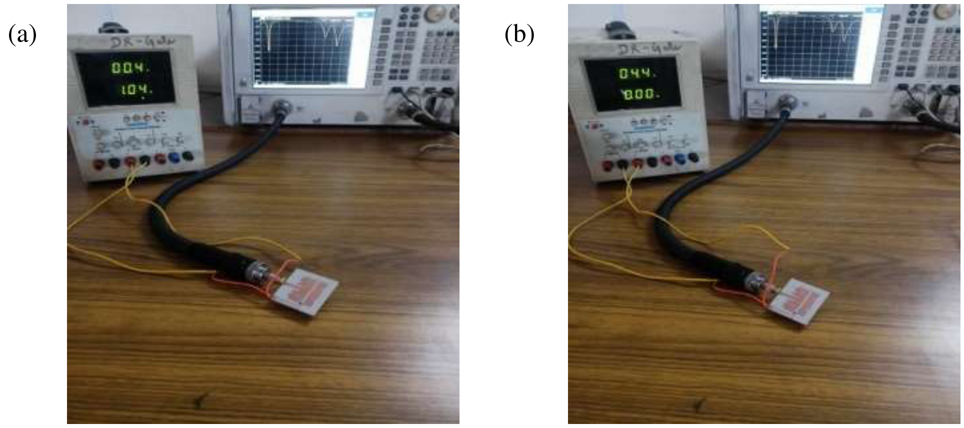

FIGURE 4. S_{11} measurements. (a) Antenna with diode in ON state and (b) antenna with diode in OFF state.

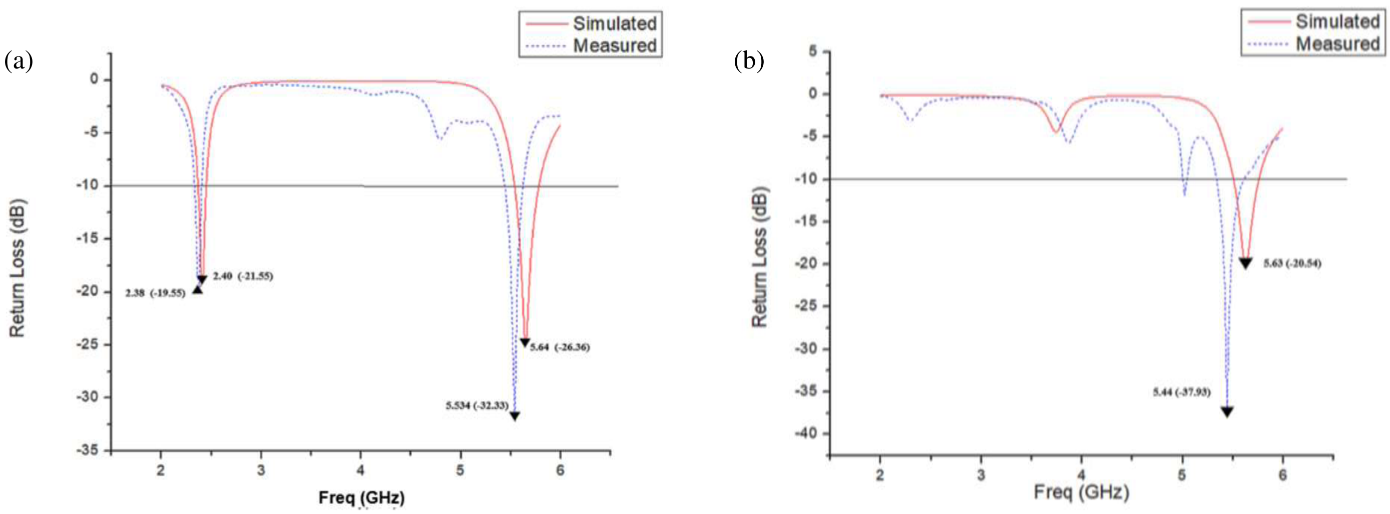

FIGURE 5. S_{11} comparison. (a) Diode in ON state and (b) diode in OFF state.

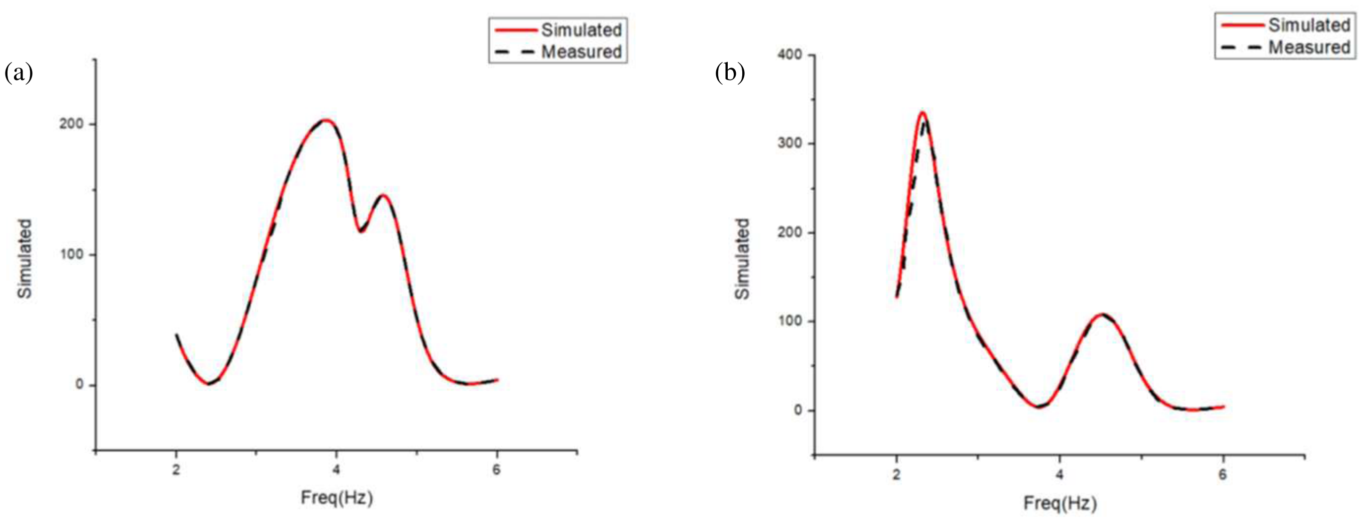

FIGURE 6. VSWR comparison. (a) Diode in ON state and (b) diode in OFF state.

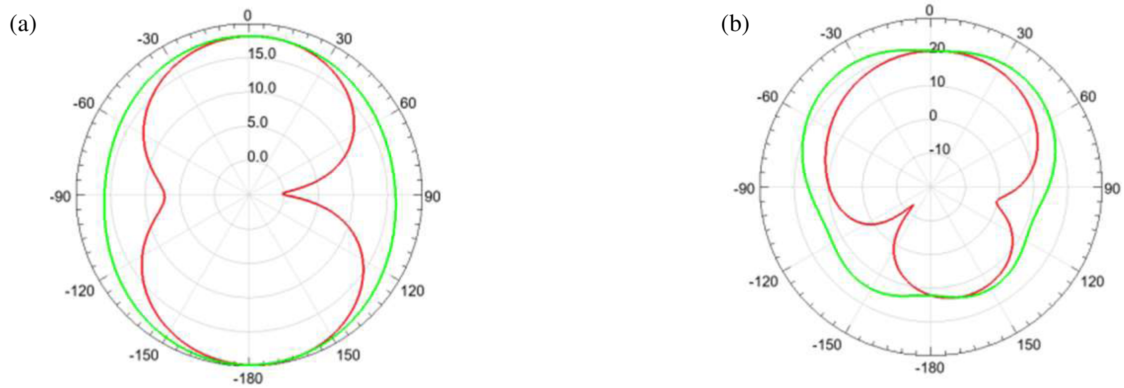

FIGURE 7. Simulated radiation patterns. (a) 2.4 GHz (ON state) and (b) 5.6 GHz (ON state).

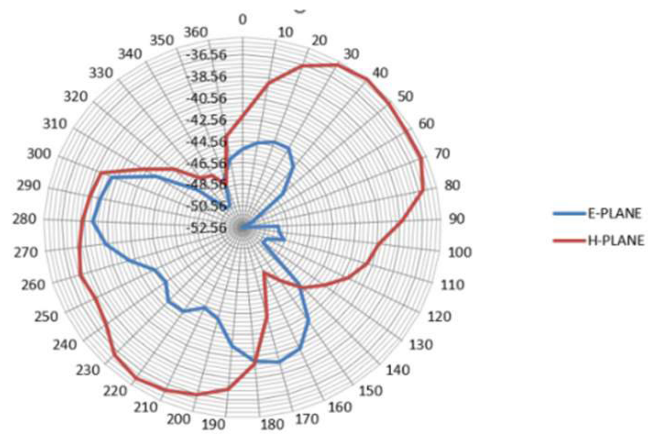

FIGURE 8. Measured radiation pattern at 5.6 GHz (OFF state).

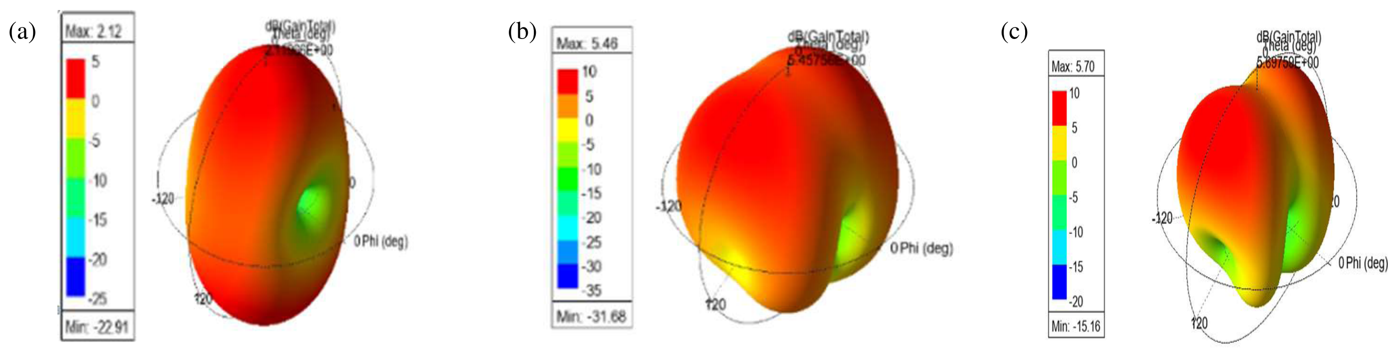

FIGURE 9. Simulated gain. (a) 2.4 GHz (ON state), (b) 5.6 GHz (ON state), and (c) 5.6 GHz (OFF state).

ating a lower-frequency resonance, as shown in Fig. 10(a). At 5.6 GHz, the current is mainly distributed along the edges of the radiating patch, as illustrated in Fig. 10(b). However, there were no traces of the current in the OFF mode at 2.4 GHz, as shown in Fig. 11(a), which means that this resonance was effectively suppressed. There was also a current spread over the radiating patch in the OFF mode at 5.6 GHz as depicted in Fig. 11(b), which ensured single-band operation.

Figure 12 shows the simulated radiation efficiency of the proposed antenna under both PIN diode switching states. In the ON state, the antenna achieves radiation efficiencies of 84.53% at 2.4 GHz and 100% at 5.6 GHz, as shown in Fig. 12(a). When the PIN diode was switched OFF, a radiation efficiency of 99.9% was obtained at 5.6 GHz, as shown in Fig. 12(b). The high efficiency values observed under both operating conditions indicate effective radiation with low power dissipation. The measured antenna characteristics corresponding to these operating states are listed in Table 2.

Table 3 compares the proposed antenna with recently reported reconfigurable antenna designs. The proposed antenna is compact, has high radiation efficiency, and is simple. Compared to other existing antennas, which have multiple PIN diodes mounted on an FR-4 substrate [14, 16, 31], our antenna uses only one PIN diode and a low-loss Rogers Duroid

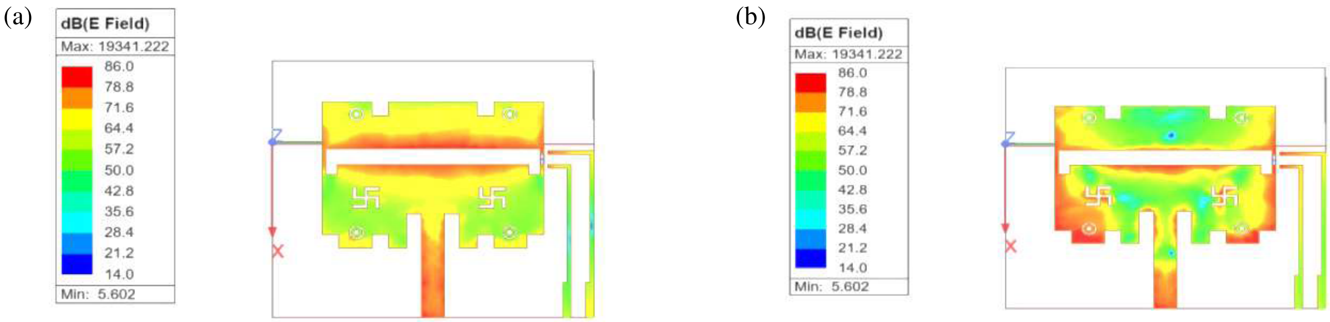

FIGURE 10. Current distribution in the ON state. (a) 2.4 GHz and (b) 5.6 GHz.

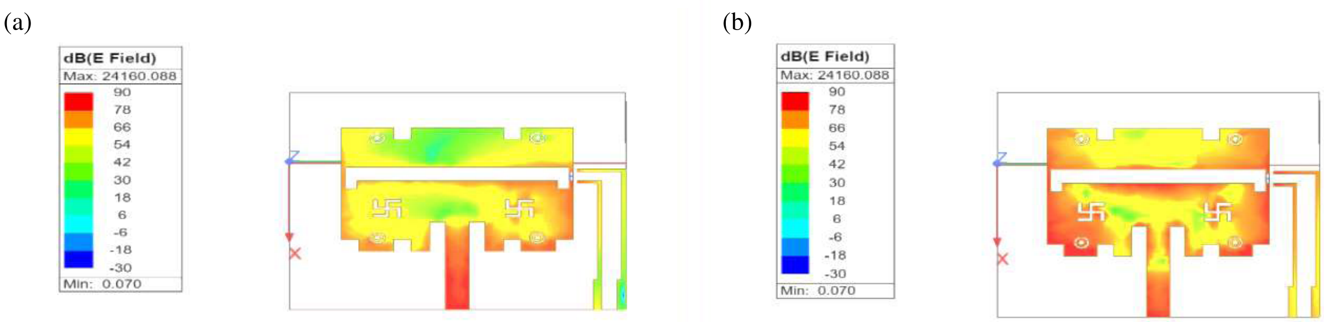

FIGURE 11. Current distribution in the OFF state. (a) 2.4 GHz and (b) 5.6 GHz.

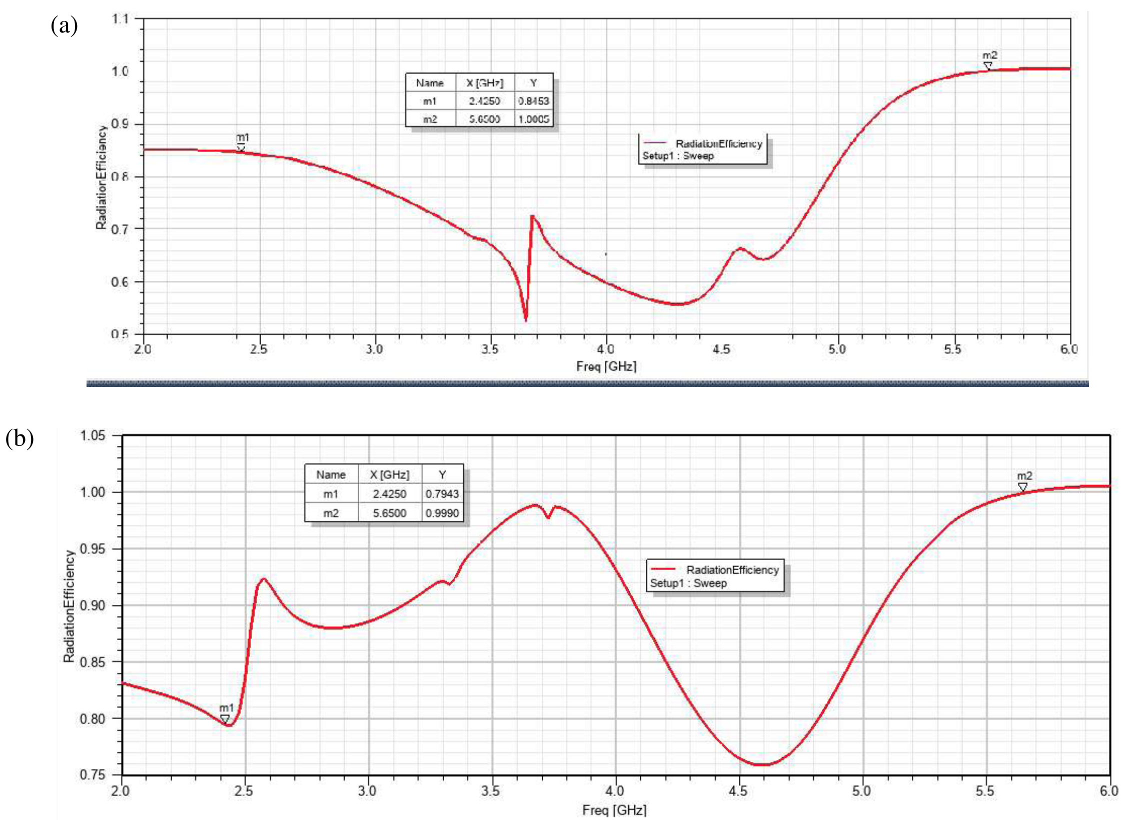

FIGURE 12. Antenna efficiency. (a) Diode in the ON state and (b) diode in the OFF state.

TABLE 2. Measured antenna parameters.

Antenna Parameters	Antenna with diode in ON state		Antenna with diode in OFF state (5.6 GHz)
	(2.4 GHz)	(5.6 GHz)	
S_{11} (dB)	-19.55	-32.33	-37.93
VSWR	1.12	1.09	1.26
Gain (dB)	2.12	5.46	5.7
Efficiency (%)	84.53	100	99.9
Bandwidth	71 MHz	182 MHz	270 MHz

TABLE 3. Performance comparison of the proposed antenna with state-of-the-art works.

Ref.	Size (mm)	Substrate Material	No. of Diodes	Frequency (GHz)	-10 dB BW (GHz)	Radiation Efficiency (%)
[14]	$30 \times 20 \times 1.6$	FR-4	2	2.7, 3.6, 4.6, 4.8	0.18–1.28	80–92
[31]	$35 \times 35 \times 1.6$	FR-4	3	2.4, 3.5, 4.7, 5.8, 6.23	0.30–3.06	73–79
[16]	$50 \times 50 \times 1.6$	FR-4	1	2.68, 5.16, 5.30	0.32–0.98	80-85
[17]	$12 \times 14 \times 0.25$	ROGERS RT5880LZ	2	2.3–5.7, 6.1–10 2.4, 4–6.6	0.53–3.50	77–87
This work	$\mathbf{37 \times 42 \times 1.52}$	**Rogers Duroid RO3003™**	**1**	**2.4, 5.6 (ON state), 5.6 (OFF state)**	**0.07–0.27**	**84–100**

RO3003™ substrate, making the whole design simpler while maintaining good reconfigurability. This antenna has a good radiation efficiency of 84–100%, which is better than that of almost all existing antennas. The antenna operates on two frequency bands: the 2.4 and 5.8 GHz ISM bands, making it suitable for wireless applications, particularly in Wi-Fi networks. Although the bandwidth obtained in this study, i.e., 0.07–0.25 GHz, is quite small, it still suits our purpose very well. The results of this study prove that it is a good and simple antenna design and that it works better than the one described in [16].

4. IOT-BASED HEALTHCARE MONITORING SYSTEM CONFIGURATION

Figure 13 shows the proposed IoT-based healthcare monitoring system. It consists of an ESP32-CAM NodeMCU board connected to a MAX30100 pulse oximeter sensor to monitor heart rate, body temperature, and SpO_2 level. The data collected from the sensors were processed by ESP32-CAM and then sent to the Ubidots cloud platform for monitoring and storage. An SSD1306 OLED was used as a display to visualize the acquired measurements. A rechargeable 18650 Li-ion battery, with the help of a TP4056 charging circuit, powers the complete circuit. To improve the communication link, the system was integrated with a two-band reconfigurable microstrip patch antenna operating at frequencies of 2.4 and 5.6 GHz. The frequency reconfigurability of this antenna was accomplished using PIN diodes. The combination of sensor monitoring, cloud connectivity, and reconfigurable antenna technology enables reliable remote healthcare monitoring. The hardware connections are shown in Figs. 13(b) and 13(c). The ESP32-CAM communicates with both the MAX30100 sensor and the SSD1306 OLED display through the I^2C interface. GPIO15 and GPIO14 were configured as serial data line (SDA) and serial clock line (SCL), respectively, for both devices. The proposed antenna was connected to the ESP32-CAM through an IPEX connector to facilitate wireless data transmission, whereas a rechargeable Li-ion battery supplied power to the entire system. Fig. 14 presents the data transmission performance under different antenna configurations along with the corresponding visualization of physiological parameters on the Ubidots cloud platform.

Table 4 compares the RSSI, heart rate, body temperature, and SpO_2 measurements obtained from the three participants in four antenna configurations with other measuring devices. The proposed antenna with the PIN diode in the ON state consistently achieved the strongest signal strength, with RSSI values ranging from -22 dBm to -25 dBm, followed by the OFF state configuration (-27 dBm to -30 dBm). In contrast, the reference dipole antenna and onboard ESP32-CAM antenna exhibited weaker signal levels, ranging from -35 dBm to -49 dBm.

However, despite differences in RSSI, the physiological signals sensed via the proposed antenna correlated closely with results obtained by measuring the same parameters using the reference dipole antenna. The heart rates detected by the proposed antenna varied between 85.62 and 89.62 BPM, the body temperature between 32.58°C and 34.86°C, and the SpO_2 signal between 90% and 93%. All the differences between the reference and proposed antennas were small enough to stay within acceptable boundaries for health monitoring applications. Hence, the proposed antenna performs significantly better than its reference counterpart in terms of providing higher-quality wireless communication and sensing capabilities.

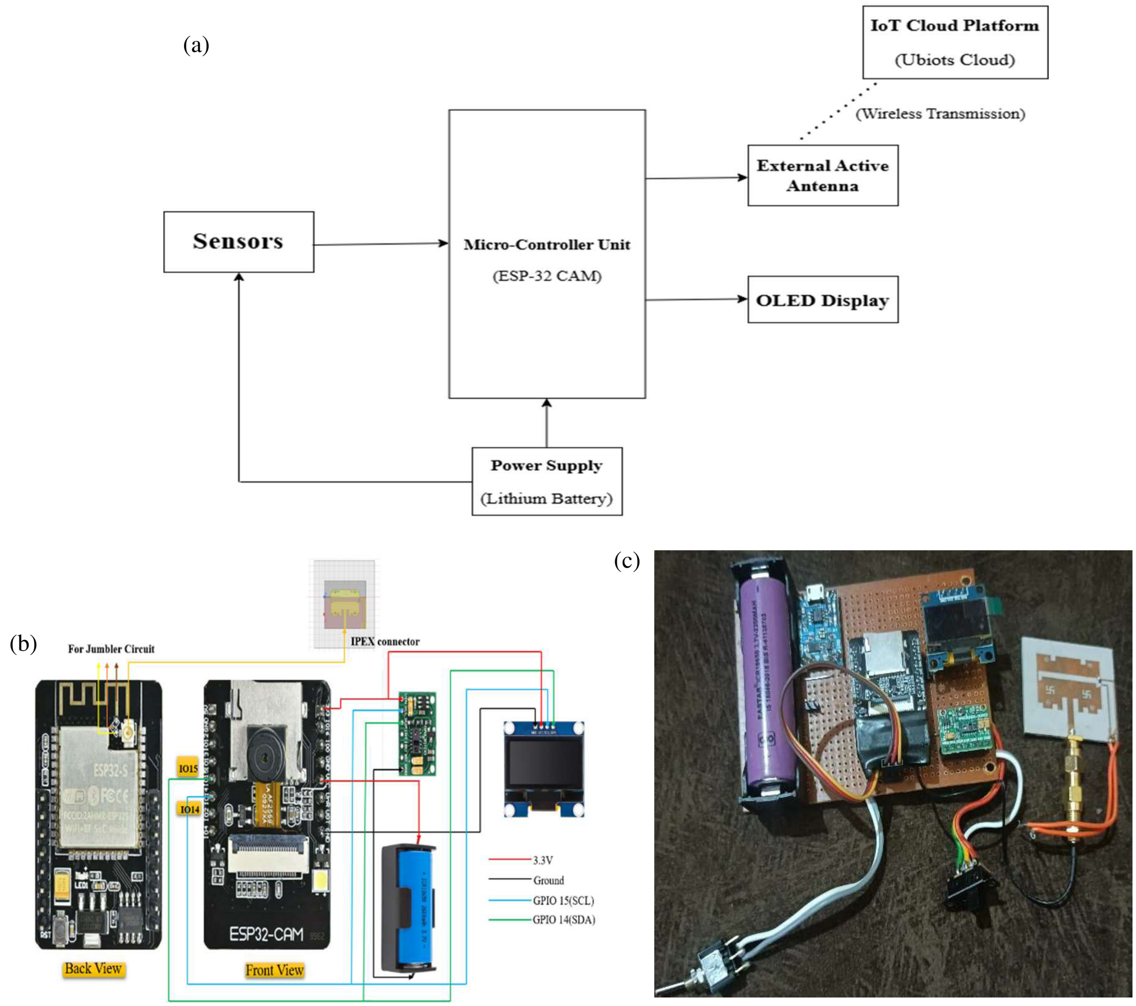

FIGURE 13. Proposed IoT-based health care system. (a) General block diagram, (b) circuit diagram, and (c) hardware implementation.

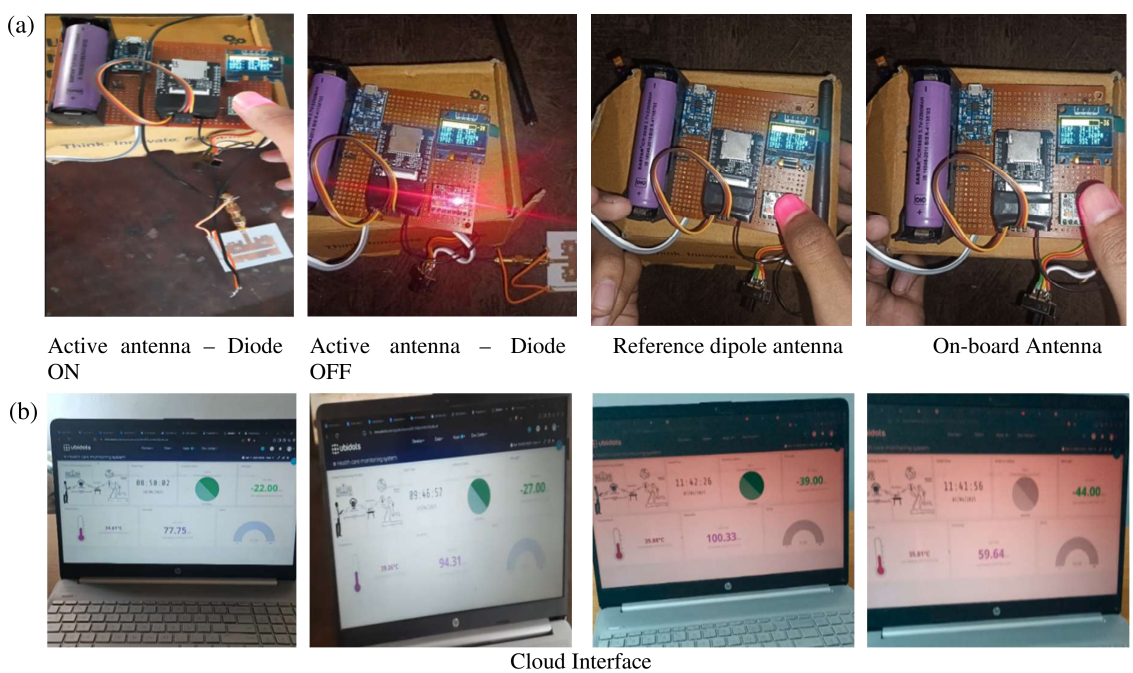

FIGURE 14. Data transmission. (a) Using different antenna conditions and (b) corresponding cloud interface.

TABLE 4. Comparison of the RSSI, heart rate, body temperature, and SpO_2 level of three participants using the proposed healthcare monitoring system (HMS) with four scenarios and other measuring devices.

Participant	Age	Scenario	RSSI Value (dBm)	Heart rate (BPM)		Body Temperature (°C)		SpO_2 level (%)	
				HMS	Heart Rate Monitor	HMS	Digital thermometer	HMS	Pulse oximeter
P1	21	Antenna with PIN diode at ON state	−22	89.62	89.34	34.86	35.2	93	96
		Antenna with PIN diode at OFF state	−27	88.26		33.18		92	
		Dipole Antenna (Reference Antenna)	−37	90.92		35.41		95	
		On-board Antenna of ESP-32 CAM module	−49	92.57		37.43		96	
P2	36	Antenna with PIN diode at ON state	−24	86.74	88.31	34.05	34.8	91	95
		Antenna with PIN diode at OFF state	−29	87.23		33.56		92	
		Dipole Antenna (Reference Antenna)	−36	88.91		35.02		94	
		On-board Antenna of ESP-32 CAM module	−47	90.34		36.44		95	
P3	55	Antenna with PIN diode at ON state	−25	85.62	85.63	32.58	33.6	90	94
		Antenna with PIN diode at OFF state	−30	86.15		33.71		93	
		Dipole Antenna (Reference Antenna)	−35	88.15		36		95	
		On-board Antenna of ESP-32 CAM module	−48	82.58		32.05		89	

5. CONCLUSION

This study describes the design and fabrication of a reconfigurable dual-band frequency microstrip patch antenna for integration into an IoT-based real-time healthcare monitoring system. The dual-band frequencies used are the 2.4 and 5.8 GHz ISM bands. Frequency reconfiguration is made possible by using a PIN diode. The benefits of this reconfiguration include increased flexibility and improved wireless performance. Important antenna characteristics, including return loss, VSWR, gain, radiation pattern, and efficiency, were analyzed through simulations and experiments in the ON and OFF states.

The hardware implementation involved a NodeMCU ESP-32 CAM connected to a MAX30100 pulse oximeter sensor and an SSD1306 OLED screen. The device allows for real-time heart rate, SpO_2, and body temperature measurements to be done in real time. All results can be shown on the local interface, while at the same time being uploaded wirelessly to the Ubidots cloud server through Wi-Fi. The system is powered by a rechargeable lithium-ion battery with TP4056 charging circuitry, which provides portability and low power consumption. RSSI testing revealed that the proposed antenna performed much better in terms of signal strength than the reference dipole antenna and even the built-in ESP32-CAM antenna. Consequently, more efficient data transmission can be achieved. The measured health values corresponded to the reference values obtained using the antenna. Thus, the feasibility of the proposed approach was demonstrated. Owing to its small size, high efficiency, reconfigurable operation, and good IoT connectivity, the proposed antenna is recommended for use in health-monitoring applications.

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