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RESEARCH ARTICLE

Development of a Wearable Wideband Antenna in the Frequency Range of 2.4 GHz and 5.2 GHz

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Abstract

This research focuses on designing and developing a wearable textile antenna made from denim fabric, operating in two primary frequency bands (2.4 GHz and 5.2 GHz). The antenna is designed to meet the needs of modern broadband communication applications, such as in the Industrial, scientific, and Medical (ISM) sectors and Wi-Fi. This study includes a literature review, design, simulation using CST Suite Studio software, antenna fabrication, and performance measurement. The designed antenna is expected to possess superior characteristics such as being lightweight, low-cost, mechanically robust, easy to manufacture, maintenance-free, and easy to install. The antenna's performance is evaluated by measuring parameters such as reflection coefficient, bandwidth, *gain*, and radiation pattern. Additionally, flexibility tests are performed to ensure reliable performance under various user mobility conditions. This antenna supports various Wi-Fi standards, including IEEE 802.11a, 802.11n, 802.11ac, and 802.11ax (Wi-Fi 6). The measurement results from the textile antenna work at frequencies 2.33 GHz - 2.43 GHz and 5.02 GHz - 5.29 GHz with bandwidths of 100 MHz and 270 MHz, respectively. The results of the antenna radiation pattern show the directional pattern and the antenna *gain* of 1.51 dB and 3.39 dB for the 2.4 GHz and 5.2 GHz frequencies; these measurement results agree with the simulation results. Therefore, the proposed antenna can be used as a candidate for wearable Wi-Fi applications. These conditions can be reached in planar conditions.

Keywords: Wearable antenna, Wi-Fi standards (IEEE 802.11a, 802.11n, 802.11ac, 802.11ax), Wideband, Jeans material

1. Introduction

The rapid development, ascending variation, and advancement in the latest wireless and mobile communication technology are due to user demand for multiple services in different frequency bands supported by a single handheld device. Recent research has focused on compact and portable multiband antennas. In the last decade, the design of textile wearable antennas has received much attention. Wearable antennas for modern communication systems are a crucial field of knowledge nowadays. The standard requirements of wearable antennas are lightweight, low cost, inexpensive, mechanically robust, easy to fabricate, free of maintenance, and easy to install. Due to these attractive and efficient features, making the antenna as unobtrusive and conformable as possible is desirable since it can be integrated into the user's clothes. Wearable materials such as polyester, cotton, jeans, and leather are utilized to design flexible textile antennas [1]. Several forms have been proposed for wearable antennas. Among them are planar monopole antennas, integrated Inverted-F antennas (IIFA), planar Inverted-F antennas (PIFA), microstrip patch antennas, magneto-electric dipole antennas, substrate-integrated waveguide (SIW) antennas, EBG-based antennas, dipole antennas, and cavity slot monopoles in the lower frequency bands [2] Currently, the wireless communications technology demands miniaturized planar antennas with wide bandwidth to support wireless devices, such as Industrial Scientific Medical (ISM) and Wireless Local Area Network (WLAN) [3].

Recent research has proposed numerous papers on using jeans substrates for multiband antennas [4]. Various techniques have been utilized and documented in the literature to achieve multiband characteristics in a single patch antenna. The overall performance, such as size, gain, directivity, and efficiency of the antenna, depends on the selection of the substrate material and the design procedure [5].

A microstrip patch antenna is suitable for wearable antenna applications because the substrate can be replaced with textile material. Another advantage is that the structure of the microstrip antenna has a ground plane that can protect body tissue from antenna radiation, so it is safe to be integrated into clothing [6].

Different antennas on various textile/cloth materials have been proposed in recent work to achieve the desired goals. The most famous textile materials used in the design of wearable antennas include leather [7], Teflon [8], polyester [9], wash cotton [10], zelt [11], nylon [12], conducting wire [13], fleece fabric form [14], Nomex [15], liquid crystal polymer (LCP) [16], conducting paint [17], copper-coated fabric [18], insulated wire [19], geotextile [20], polypropylene [21], fabric [22], felt [23], Dacron fabric [24], woven fibreglass fabric [25], polyethene foam [26], silk [27], denim [28], zelt [29], and RT/duroid 5880 [30]. Careful selection of the material is crucial to ensure the efficient performance of the antenna. These antennas support a range of wireless applications.

In this paper, an innovative defective wearable microstrip patch antenna with a rectangle-shaped slot is designed using jeans as a substrate material. Jeans material was chosen as it is readily available at a low cost and has conformable low-loss characteristics [10]. The proposed antenna is capable of operating in frequency bands, i.e., 2.36 GHz – 2.41 GHz band is one of the primary frequency bands used for Wi-Fi, specifically under the IEEE 802.11b/g/n standards, 5.2 GHz band is utilized by several Wi-Fi standards such as IEEE 802.11ac (Wi-Fi 5). The recent 802.11ax (Wi-Fi 6) standards use the 5 GHz band to improve speed and performance over earlier standards. This band includes several channels used under the IEEE 802.11a/n/ac/axe standards, and overall, the standardization is explained. This study proposes a textile-based antenna with an entire ground plane and multiband operation covering the 2.4 GHz and 5.2 GHz Wireless communication bands and the IEEE UWB (Institute of Electrical and Electronics Engineers Ultra-Wideband) high band, respectively. Compared with the previously reported works, the proposed antenna can cover these bands for wearable devices while achieving sound isolation, a smaller size, a directional radiation pattern, and comparatively higher operating gain and efficiency. This is an excellent wearable textile-based antenna with a complete ground plane covering these wireless communication bands and the IEEE UWB high band [11].

2. Antenna Design

The proposed antenna was constructed on a 0.7 mm thick jeans dielectric substrate with a relative permittivity of 1.6 and a tangential loss of 0.02 [31]. Jeans textile substrate was selected due to its thinness, lightness, flexibility, and comfort, making it suitable for wearable applications. Copper was used for the antenna's ground plane and radiating patch.

2.1 Design Evolution I

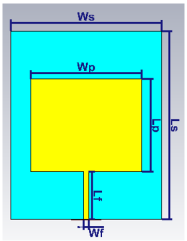


Figure 1. Design antenna evolution I

Table 1. Parameter of antenna

Parameter	Dimension (mm)	Observation
Lp	48.88	Patch length
Wp	58.78	Patch width
Lf	25.56	Transmission line length
Wf	2.6	Feed width
Ws	80	Substrate width
Ls	100	Substrate length

Table 1 shows the dimensions of each antenna parameter. The patch design is rectangular, with port measurements from CST Studio used to determine the width of the feed line to achieve an impedance value close to 50 Ohms. This antenna design utilizes a microstrip patch, where the ground dimensions are the same as the dielectric dimensions.

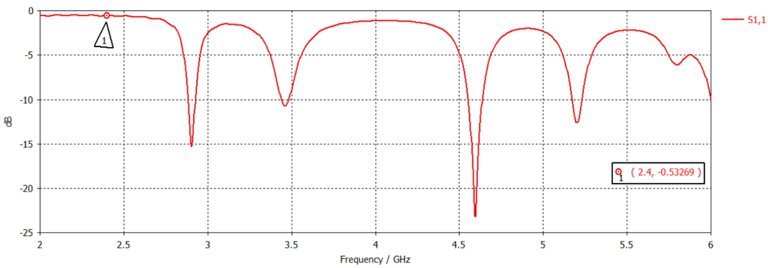


Figure 2. S_{11} parameter for evolution I

Figure 2 shows a frequency of 2.4 GHz with an S11 value of approximately -0.53 dB. This indicates that most of the energy is reflected, meaning the antenna is not operating optimally at this frequency. This article conducted further evolution to achieve a suitable S11 value by adding an inset on the side of the patch transmission line.

2.2 Design Evolution II

After simulating the first design, the antenna exhibited poor performance and did not meet the S11 parameter, which should be below -10 dB. One of the main functions of the inset feed is impedance adjustment. The inset feed helps match the antenna's input impedance with the transmission line impedance, typically 50 Ohms. Matching this impedance minimizes the reflection coefficient (S11), ensuring maximum power transmission efficiency. Figure 3 shows the antenna design with the added inset, where the inset length (Lif) is 8.1 mm, and the inset width (Wif) is 4 mm.

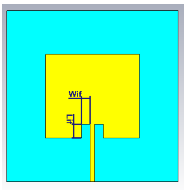


Figure 3. Design antenna Evolution II

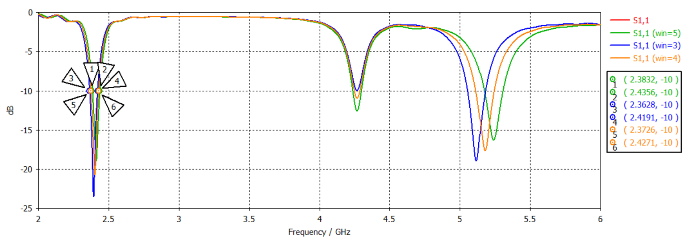
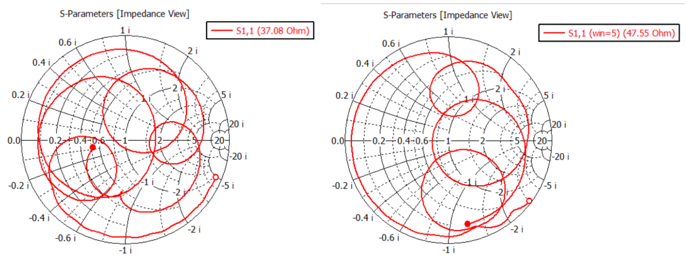


Figure 4. S_{11} parameter of evolution II



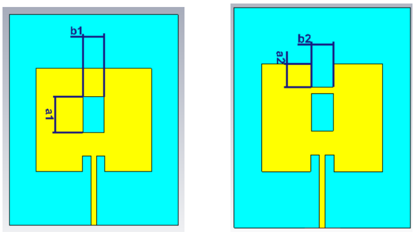
(a) (b)

Figure 5. Smith chart displays (a) before the inset was added and (b) after the inset was added

Adding an inset feed to the microstrip antenna improved the impedance matching from approximately 37.08 Ohms to nearly 47.55 Ohms, as shown in Figure 5, approaching the characteristic impedance of 50 Ohms. Before adding the inset, the reflection path on the Smith chart showed significant movement and was far from the centre, indicating poor impedance matching and high reflection. After adding the inset, the reflection path became more focused and closer to the centre of the Smith chart, indicating better impedance matching with less reflection. This improvement increases the antenna's power transmission efficiency, allowing more power to be radiated and less to be reflected, thus enhancing the overall antenna performance.

2.3 Design Evolution III

In Evolution 3, this article will add slots to the patch antenna to create new resonance frequencies, improve performance, and enhance impedance matching. Adding slots changes the patch's current distribution and electromagnetic field, creating additional resonance modes at specific frequencies. This allows the antenna to operate at multiple frequencies or improve impedance matching at the desired frequency. Slots can help improve impedance matching at additional frequencies, increasing power transmission efficiency. Figure 6 shows the addition of one slot with a length of a1=17mm and a width of b1=10mm and two slots with lengths a2=10.44mm and widths b2=10mm.



(a) (b)

Figure 6. Design antenna evolution III (a) 1 slot added (b) 2 slots added

Figure 7 illustrates the S11 of the two-slot antenna design, while the S11 result for the one-slot design is more significant than -10 dB. At a frequency of 5.2 GHz, a significant decrease in S11 is observed.

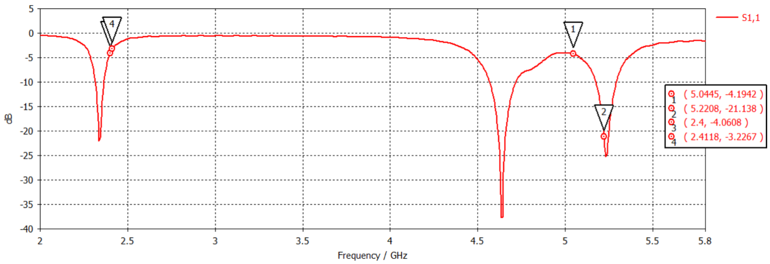


Figure 7. S_{11} parameter of evolution III

2.4 *Design Evolution IV*

This article found that adding slots can create new resonance frequencies from the third evolution design; however, the central frequency experiences a significant increase in S11. This article performs parameter sweeping on the antenna design to achieve lower or higher frequencies. Figure 8 shows the S11 results after modifying the length and width of the antenna patch.

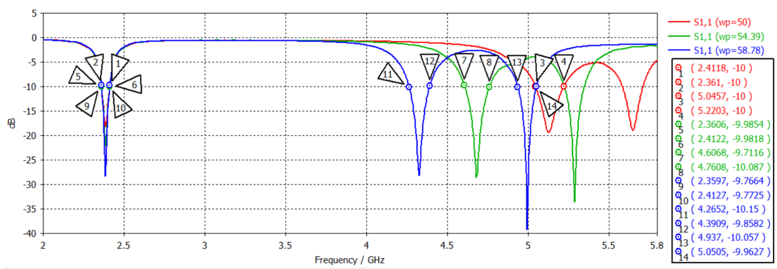


Figure 8. S_{11} parameter of evolution IV

Figure 8 shows the best results with the configuration wp=50, showing three frequency bands that meet the requirements: 2.4 GHz, 5.2 GHz, and 5.6 GHz, as indicated by the red curve. In this thesis, the third frequency band is not utilized due to the absence of permission for Wi-Fi usage based on the Circular Letter of the Director General of Resources and Equipment of Post and Informatics Number 595 of 2018 [32]. The analysis indicates that this configuration has a lower S11 value at several critical frequencies, with a significant decrease at the 2.4 GHz frequency with a 50 MHz bandwidth and at the 5.2 GHz frequency with a 180 MHz bandwidth, achieving S11 values below -10 dB.

Figure 9 illustrates the modification of the antenna patch size to 50 mm x 47.88 mm to enhance antenna performance. This new patch size optimizes resonance at the desired frequencies, improves impedance matching, and reduces power reflection.

Figure 10 shows the radiation pattern and antenna gain in the Farfield 3D at 2.4 GHz and 5.2 GHz frequencies. At 2.4 GHz (Figure a), the antenna gains 1.91 dBi with a radiation efficiency of -6.32 dB and a total efficiency of -6.50 dB. The radiation pattern is uniform, with most energy concentrated around the z-axis. At 5.2 GHz

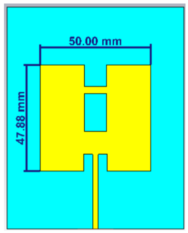
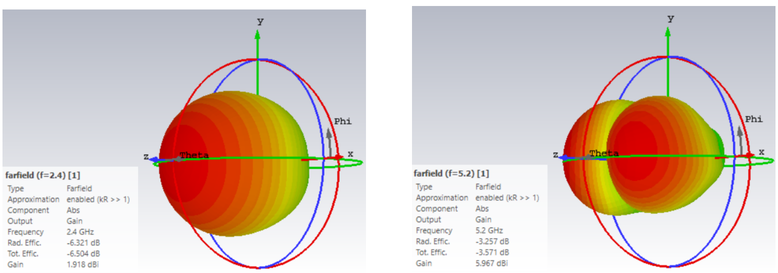


Figure 9. Design antenna Evolution IV



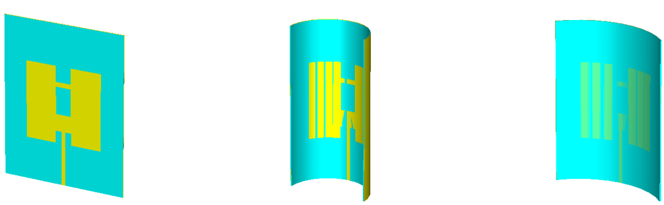
(a) (b)

Figure 10. Antenna gain and radiation pattern in Fairfield 3D view (a) at 2.4 GHz, (b) at 5.2 GHz

(Figure b), the antenna shows a significant gain increase to 5.96 dBi, with a radiation efficiency of -3.25 dB and a total efficiency of -3.57 dB.

Figure 10 illustrates the antenna's radiation pattern at 2.4 GHz and 5.2 GHz. At 2.4 GHz, the antenna exhibits an omnidirectional radiation pattern, with energy distribution evenly around the z-axis and uniform radiation in the horizontal plane (xy-plane), making it suitable for applications like indoor Wi-Fi networks. Conversely, at 5.2 GHz, the antenna demonstrates a directional radiation pattern with more focused energy concentration, emitting signals with higher intensity in a specific direction, ideal for long-distance communication such as point-to-point links or outdoor communication applications.

2.5 Flexibility Test of the Antenna



Planar R=2.5 cm R=5 cm

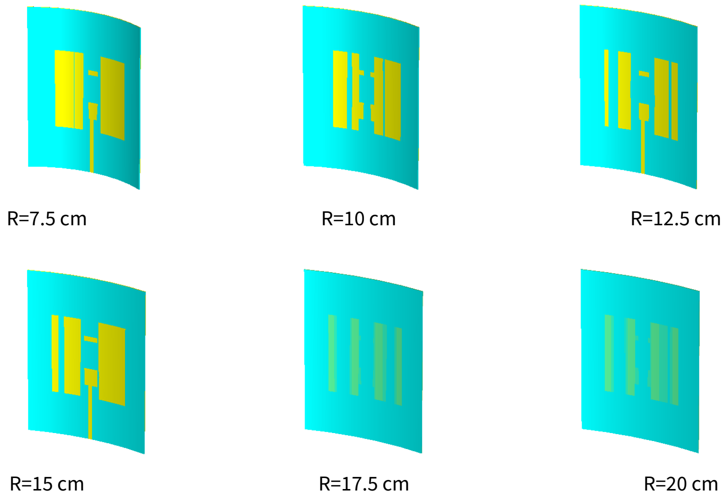


Figure 11. Cylindrical Bending Structure

Both frequencies operate well in planar conditions, with only the 2.4 GHz frequency performing optimally at R=2.5 cm, while the 5.2 GHz frequency does not. However, at R=5 cm to R=20 cm, the antenna's performance is suboptimal. The analysis of this antenna in planar conditions shows that at a radius (R) of 2.5 cm, only the 2.4 GHz frequency is effectively supported. This frequency's wavelength (λ) aligns better with the antenna's physical dimensions, allowing for good resonance and high radiation efficiency.

3. Result and discussion

3.1 Bandwidth Comparison Analysis

Figure 12 below compares the reflection coefficient graphs of the antenna design's simulation results at 2.4 GHz and 5.2 GHz frequencies with the measurement results using a VNA analyzer.

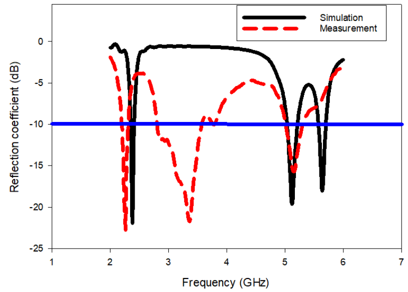
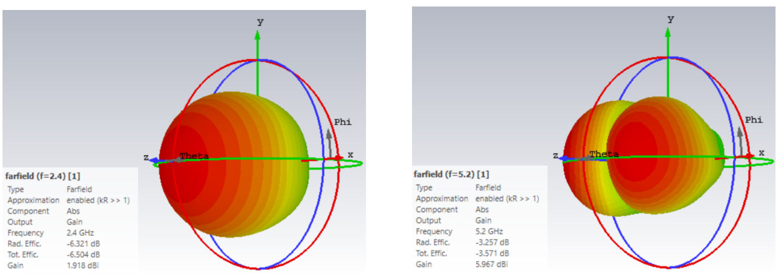


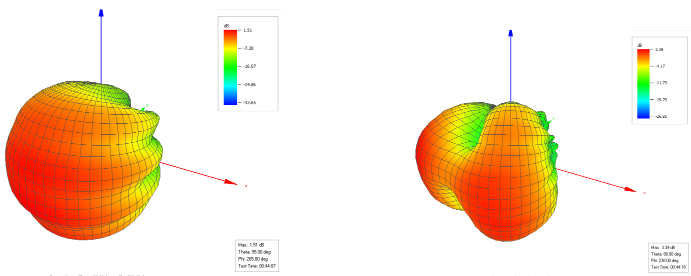
Figure 12. S_{11} of simulation and measurement

Figure 12 shows a frequency shift between the fabricated antenna and the simulation results. The fabricated antenna produced a frequency range (Black line) of 2.33 GHz – 2.43 GHz with a bandwidth of 160 MHz and a frequency range of 5.02 GHz – 5.29 GHz with a bandwidth of 290 MHz. In contrast, the bandwidth in the simulation results was 50 MHz and 169.1 MHz. The difference in bandwidth between the simulation and the measurement is due to the fabricated dimensions not being 100% identical to the simulation results and the dielectric material constant and loss tangent factor of the substrate used for fabrication not being the same as those used in the simulation.

3.2 Gain and Radiation Pattern Comparison Analysis



(a)



(b)

Figure 13. Gain and radiation patterns of the antenna at 2.4 GHz and 5.2 GHz (a) Simulation (b) measurement

Table2 presents the operational frequencies, gains, and radiation patterns to analyze the gain values and radiation patterns between the simulation and measurement results in Figure 13.

Table 2. Comparison of S11, Gain, and Radiation Patterns

Operational frequency (GHz)		Reflection coefficient (dB)		Gain (dB)		Radiation pattern
Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated and measured
2.36 GHz – 2.41 GHz	2.33 GHz – 2.43 GHz	-13.95	-10.31	1.91	1.51	Omnidirectional
5.04 GHz – 5.22 GHz	5.02 GHz – 5.29 GHz	-11.57	-8	5.96	3.39	Directional

Table 2 compares the antenna's simulated and measured operational frequencies, gains, and radiation patterns at 2.4 GHz and 5.2 GHz frequencies, indicating significant differences that require a deep understanding of contributing factors.

At 2.4 GHz, the frequency difference between measurement results (2.33 GHz - 2.43 GHz) and simulation (2.36 GHz - 2.41 GHz) is 0.02 GHz at the lower bound and 0.025 GHz at the upper bound. The measured gain of 1.51 dBi is 0.40 dBi lower than the simulated gain of 1.91 dBi. The omnidirectional radiation pattern shows consistency, although slight differences may exist influenced by environmental conditions and model inaccuracies.

At 5.2 GHz, the frequency difference between measurement results (5.02 GHz - 5.29 GHz) and simulation (5.04 GHz - 5.22 GHz) is 0.01 GHz at the lower bound and 0.07 GHz at the upper bound. The measured gain of 3.39 dBi is 2.57 dBi lower than the simulated gain of 5.96 dBi. This discrepancy may be due to the difference in reflection coefficients; the simulation shows -11.57 dB, whereas the measurement shows -8 dB at 5.2 GHz, affecting the decrease in gain. The directional radiation pattern indicates that the antenna is more focused in simulation than measurement, possibly due to lower radiation efficiency under real-world measurement conditions.

4. Conclusion

This research successfully achieved its primary objectives in designing, developing, and evaluating a wearable textile antenna made from denim fabric. It operates in two main frequency bands: 2.4 GHz - 2.48 GHz and 5.15 GHz - 5.25 GHz. Here are the key conclusions drawn from this study:

1. In simulation results, the antenna exhibited a bandwidth of 50.8 MHz in the first band (2.36 GHz – 2.41 GHz) and 180 MHz in the second band (5.04 GHz – 5.22 GHz). The radiation pattern was directional for both bands, achieving gains of 1.91 dB and 5.96 dB at 2.4 GHz and 5.2 GHz, respectively.
2. Measurement results showed the textile antenna operating at frequencies 2.33 GHz - 2.43 GHz and 5.02 GHz - 5.29 GHz, with respective bandwidths of 100 MHz and 270 MHz. The radiation pattern indicated directional characteristics, with gains of 1.51 dB and 3.39 dB at 2.4 GHz and 5.2 GHz, respectively.
3. Under planar conditions, both frequency bands operated optimally. The antenna with a radius (R) of 2.5 cm effectively supported the 2.4 GHz frequency due

to better wavelength alignment with its physical dimensions, allowing for good resonance and high radiation efficiency. The shorter wavelength of 5.2 GHz was less optimal at this radius due to a mismatch between wavelength and antenna size, resulting in reduced efficiency and increased energy loss.

4. In a good agreement for the proposed frequency bands, the wearable textile antenna exhibited consistent results between simulation and measurement. The simulation showed the antenna operating at 2.36–2.41 GHz with a bandwidth of 50.8 MHz and at 5.04–5.22 GHz with a bandwidth of 180 MHz, achieving gains of 1.91 dB and 5.96 dB, respectively. Measurements indicated operational frequencies of 2.33–2.43 GHz and 5.02–5.29 GHz, with bandwidths of 100 MHz and 270 MHz and gains of 1.51 dB and 3.39 dB.

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