Design and Analysis of Compact Diversity Antenna for Wearable Applications

Anshuman Mishra¹, P Sandeep Kumar¹*, Rikesh Shrestha¹, K Malathi²#, and Kanaparthi V Phani Kumar¹

¹Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamil Nadu, India
²Department of Electronics and Communication Engineering, College of Engineering Guindy, Anna University, Chennai, Tamil Nadu, India
Email: *sandeep@srmist.edu.in, #mala@annauniv.edu

Abstract: A new compact Ultra-Wideband (UWB) antenna is designed for wearable applications using jeans fabric as the substrate. The proposed antenna has an impedance bandwidth from 3.1 to 11.1 GHz. The antenna footprint is of size 18mm x 26 mm, and the thickness of the substrate is 0.8mm. It is based on a simple patch antenna configuration where the radiator consists of a simple rectangular structure and an ellipse added on top. Circular and elliptical notches are removed from the radiator, and rectangular notches are removed from the feed line for bandwidth enhancement. A partial ground plane of size 18mm x 9mm with a square notch is present on the other side of the antenna. Two such antennas are placed side by side as unit cells, one horizontal and the other vertical, to obtain a 2-port diversity set. The unit cells are placed at a distance such that minimal mutual coupling is present between the cells, and the size is also not compromised. The final diversity set so obtained is of size 44mm x 26 mm. The simulation results for reflection coefficients, SAR, and radiation pattern for both unit cell and diversity port are presented. Diversity parameters like ECC and diversity gain are also simulated for diversity antenna. The results obtained by testing the fabricated prototype are found to be matching reasonably with the simulated results. The antenna is also subjected to bending analysis.

Keywords: Wideband antennas, UWB antennas, wearable antennas, MIMO antenna

1. Introduction

Ultra-Wide Band communications have evolved as a topic of interest ever since Federal Communications [1]. Wearable technology has evolved as another revolutionary topic in the field of wireless communication. The concept of using wearable antennas over the UWB range is extremely advantageous because despite operating in the human body's vicinity, the power dissipation will be very low. Hence the concept can be applied in healthcare, navigation, sports, military, etc. [2]. The choice of a substrate remains one of the biggest factors in wearable antenna design. The substrate must be flexible, economic, easily available, and should possess a low dielectric constant. Fabrics can be used as substrates due to their low dielectric constant and the fact that they can be easily integrated into day-to-day clothing. Several textiles are tested for their dielectric constant values in [3], concluding that jeans, polycount, and polyester are better suited for wearable technology use. Many other substrates like Polydimethylsiloxane (PDMS),
Felt, Acrylic, Teslin can also be used as flexible substrates as an alternative to fabrics [4-6]. Antennas can also be mounted on buttons for wearable applications. It can be advantageous compared to the textile and other flexible antennas as it should not be subjected to bending, wrinkling, and washing [7]. The wearable antennas can be a single radiating antenna or used in MIMO configuration or diversity scheme. MIMO can be realized using different radiating elements as in [8] or by exciting a common radiator through separate feeds [8-9]. Although UWB offers many advantages, it eventually succumbs to multipath propagation and fading [10].

In this paper, wearable UWB technology is combined with a diversity scheme concept to design a 2-port diversity antenna on a jeans substrate to operate in the UWB range. The proposed antenna covers a frequency range of 3.1 to 11.1 GHz with negligible mutual coupling and ECC, resulting in a high DG. The unit cell is designed first and tested for its S11 parameters. The same unit cell is replicated twice to obtain a 2-port diversity set exhibiting spatial, polarization, and pattern diversity. CST Microwave Studio- 2019 is used for simulation, while Anritsu MS2037C VNA is used for testing the fabricated prototype. The unit cell and diversity antenna design is discussed in the next section, followed by simulated and measured results and analysis. The final section concludes the paper and also presents an insight into the future scopes of this theme.

2. Antenna Design

The wearable antenna is constructed on Jean's substrate of the relative permittivity ($\varepsilon_r$) 1.6. The bandwidth of the antenna depends upon the radiator and ground configuration. There are many techniques for the enhancement of bandwidth by altering the radiator and ground.

Fractal geometry is used in [11], where the pentagonal slot is circumscribed in a circle for several iterations. The antenna proposed in this literature is made up of simple geometrical shapes added to and subtracted from one another. Another concern remains the ground of the antenna. A full ground plane can be used, but the radiator configuration will have to be complex as the inherently narrowband performances of full ground should be overcome by using slots on the radiator [12-13] or stacked patches. The defected ground plane concept is another technique of modifying the ground by introducing slots into the ground plane and tapering the ground plane if required [14-15]. Our proposed antenna uses a partial ground plane with a slot introduced at the top for bandwidth enhancement.
2.1 Evolution of the unit cell

The monopole antenna is shown in figure 1. It is designed on an 18mm x 26mm sized substrate. The conducting parts are made using 0.08mm copper tape. Figure 2 shows the step-by-step design of the unit cell. Figure 2(a) shows that a simple rectangle of 12mm x 7mm is designed with a ground plane of length 10mm. A feed of length 13mm is used to excite the radiator. The width of the feed is 3mm to satisfy the 50Ω impedance matching. An ellipse of X-radius 6mm and Y-radius 5mm is added on top of the rectangle. The top edge of the rectangle divided the ellipse into two equal parts about the X-axis, as shown in figure 2(b). Two elliptical slots are etched out from the bottom and a circular slot from the top, as in figure 2(c), to increase the electrical length of the antenna. The circle has a radius of 3mm, while the
ellipses have an X-radius of 3mm and a Y-radius of 2mm. In figure 2(d), an alteration is brought into the feed by removing notches of size 1mm x 3mm from both sides. In the final stage of evolution, a notch of square 3mm x 3mm is etched out from the ground, as shown in figure 2(e). The comparison of S_{11} parameters of all five stages is given in figure 3.

![Figure 3: Comparison of five stages of the unit cell](image)

2.2. Diversity Antenna

Two unit cells are arranged to get a 2-port diversity antenna; the diversity scheme makes the antenna more efficient against multipath propagation. The proposed antenna has three types of diversity: spatial, polarization and pattern. The unit cells should be placed close to maintain the compactness but not so close that mutual coupling becomes evident. One unit cell is placed horizontally, and the other one vertically. The diversity antenna's final footprint is 44mm x 26mm, keeping the mutual coupling and compactness. The diversity antenna so obtained can be seen in figure 4. Other diversity parameters such as ECC, DG are also calculated. The S_{11}, S_{22}, and S_{12}, and S_{21} parameters are shown in figure 5.

![Figure 4: 2-port Diversity Antenna](image)
3. Results And Discussions

The designed antenna is fabricated, as seen in figure 6, to affirm the simulated results further. The simulated results are compared to measured results for the unit cell and then for the diversity antenna, and all the measurements are made using Anritsu MS2037C VNA. The bending analysis is also done for the fabricated diversity antenna. The results obtained from the VNA are slightly different from the results obtained during the simulation, which is because of unavoidable real-time conditions like connector losses, error in fabrication, environmental factors, etc. The simulation considers ideal conditions, which are difficult to model in real life.

![Fabricated Diversity Antenna (Front and Back View)](image)

Figure 6: Fabricated Diversity Antenna (Front and Back View)

3.1. Impedance Parameters

The comparison of simulated and measured S-parameters of the unit cell is presented in figure 7. The measured values slightly differ from the simulated values. The bandwidth is increased in the measured values but at the cost of gain as there is a tradeoff between the gain and the bandwidth of the unit cell. The simulated S-parameters of the 2-port diversity antenna are presented in fig. 5. The $S_{11}$ and $S_{22}$ parameters are almost identical. The isolation is also high, i.e., less mutual coupling. The $S_{21}$ and $S_{12}$ are both less than -20dB. The measured mutual coupling is also obtained at less than -15dB, which shows that the unit cells are well isolated to function as a diversity antenna, as shown in figure 8.

![S-parameters of 2-port Diversity Antenna](image)

Figure 5: S-parameters of 2-port Diversity Antenna
3.2. Radiation Characteristics

Figure 7: Comparison between simulated and measured $S_{11}$ for Unit Cell

Figure 8: Comparison between simulated and measured $S_{21}$ parameters

Figure 9: Farfield Radiation Characteristics of Unit Cell
The unit cell's far-field radiation characteristics can be observed in figure 9 at frequencies of 3.5GHz, 7.5GHz, and 10.5GHz. The E-plane (yz-plane) radiation is dumb-bell-shaped, while that in the H-plane (xz-plane) is circular. Figure 10 shows the radiation characteristics of one of the diversity antenna ports at the same reference frequencies. We obtain the same inference as what we obtained in the case of a unit cell. It can be concluded from these inferences that the unit cell operates as an omnidirectional antenna and that the diversity antenna has an omnidirectional radiation pattern.

3.3. Diversity Parameters

This paper's main motive is to design a robust diversity antenna, which leads us to the fact that the antenna should have good diversity parameters. To ensure that the antenna works well for diverse applications, we must make sure that the ECC value is very less; the lesser the ECC, the lesser is the correlation channels. ECC can be calculated from the formula below[8]:

\[
ECC = \frac{|S_{11}S_{12} + S_{21}S_{22}|^2}{(1-|S_{11}|^2)(1-|S_{22}|^2)}
\]  

The graphical representation of the ECC over the entire band of operation can be obtained in figure 11. The value of ECC is obtained to be less than 0.001 throughout the entire band of operation. Another
diversity parameter that can be calculated from ECC is the Diversity Gain (DG) which can be obtained from the relation given below[8]:

\[ DG = 10 \sqrt{1 - (ECC)^2} \]  

(2)

Figure 12: Diversity Gain

DG can also be represented graphically, as in figure 12. The value of diversity gain throughout the UWB band is found to be about 10.

3.4. bending analysis
The fabricated prototype of the diversity antenna is subjected to X-bending analysis over a 20mm cylinder. The S_{11} and S_{12} parameters after bending can be observed in figure 13 and 14.

Figure 13: S_{11} after Bending Analysis

Figure 14: S_{12} after Bending Analysis
Although the $S_{12}$ (mutual coupling) is satisfactory throughout the band, some inconsistencies in the $S_{11}$ parameters are at certain frequencies; the impedance characteristics go above the 10dB line, which leads us to the conclusion that the extremity of X-bending of the antenna is 20mm. Y-bending is not done because this would disturb the position of the port.

3.5. Sar Analysis
The antenna is designed to operate close to the human body, which infers that the SAR value should be within the permissible FCC limits of 1.6 W/kg. A three-layer human tissue model is designed to perform the SAR analysis, and the antenna is placed at a distance of 5mm from the tissue to obtain the desired SAR value. The tissue model is sculpted using the parameters present in Table 1.

| Tissue   | Relative permittivity ($\varepsilon_r$) | Loss Tangent (tanδ) | Thickness (mm) |
|----------|----------------------------------------|---------------------|----------------|
| Skin     | 37.358                                 | 0.2786              | 2              |
| Fat      | 5.2138                                 | 0.152110            | 10             |
| Muscle   | 51.936                                 | 0.24804             | 20             |

The averaged SAR value over the entire operation band is 0.15W/kg for the 1g tissue model, which is well within the prescribed FCC limits. This low SAR is the particularly compact size of the antenna and the lesser area of radiating region concerning the antenna footprint. The SAR value will further develop if the antenna is placed farther from the body [12]. If the proximity with the human body is not compromised, electronic bandgap structures can be introduced for the additional lowering of the SAR [13]. Table 2 shows the comparison of proposed antenna with various references.

| Ref. No. | Antenna Footprint (mm) | Substrate     | Wearable | Diversity |
|----------|------------------------|---------------|----------|-----------|
| [4]      | 80 x 67 x 3           | PDMS          | Yes      | No        |
| [5]      | 80 x 61 x 4.51        | Felt          | Yes      | No        |
| [6]      | 50 x 40 x 1           | Polyamide/Teslin | Yes      | No        |
| [7]      | Diameter 16           | Rogers 5880   | Yes      | No        |
| [8]      | 55 x 35 x 1.5         | Jeans         | Yes      | Yes       |
| [11]     | 32 x 32 x 1.6         | FR-4          | No       | No        |
| Proposed Antenna | 44 x 26 x 0.8 | Jeans         | Yes      | Yes       |

4. Conclusion
A compact 2-port wearable diversity antenna designed to operate in the UWB range is presented in this paper, which has a 10dB bandwidth of 8GHz (3.1 GHz – 11.1 GHz). The antenna exhibits spatial, polarization, and pattern diversity, and the diversity antenna has reasonable diversity parameters with an ECC< 0.001 and DG>9.9, and also the antenna has very high port isolation (>20dB) throughout the band of operation. The antenna also has considerable resistance to bending with an ability to withstand X-bending of about 20mm. The simulated values from the CST model and measured values from the fabricated prototype are identical in all cases. The diversity antenna has a SAR value of 0.15 W/kg. This
antenna can be further developed by increasing the number of ports and making the unit cells more packed to reduce the antenna footprint.

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