Advanced Multiband MIMO Antenna for Soldier Communication in X-band Applications

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Abstract–This paper presents a flexible folded–shorted patch (FSP) antenna designed for wearable applications that possess dual band capabilities. The suggested this paper presents a flexible folded-shorted patch (FSP) antenna designed for wearable applications. That they possess dual band capabilities. The suggested antenna can be regarded as small for the lower. Operational frequency range (0.13λ_0 x 0.13λ_0 x 2.4 GHz) and operates at the frequency 400 MHz and2.4GHz.Since flexible polydimethylsiloxane (PDMS) is strong and reasonably priced for wearable applications, it is chosen as the substrate. A comparative analysis of the fields emitted by the FSP with respect to the TM010 and TM001 modes is also show cased, taking into account the cavity model that is genuinely associated with the two operating bands mentioned. The design leverages compact and lightweight antenna elements, optimized for operation within the X-band frequency range, while maintaining low-profile characteristics suitable for integration into soldier-worn equipment. The equations required to determine the directivity and beam pattern for these modes are also derived, and the outcomes are contrasted with measurements of a wearable PDMS prototype and commercial full-wave simulations. Overall, the presented advanced MIMO antenna system promises to revolutionize soldier communication capabilities, facilitating efficient and resilient communication channels essential for mission success in modern military operations.

Keywords: TM modes, wearable antennas, folded-shorted patch (FSP) antenna, HFSS (high frequency structure simulator).

I. Introduction :

Recent years have seen substantial advancements in wearable antenna technology and research into a wide range of applications. There are various potential industries where this antenna can be useful, including healthcare. Defence retail and transportation. These antennas will also be essential to current and upcoming wearable communication systems. A few textile-based products that are sold commercially are smart vests [3], wearable sensor jackets and badges [1], and sensor T-shirts [2].Other wearable that customers use on a daily basis includes smart watches, health and tracking b/bracelets and smart eyewear.

This study proposes a wearable antenna with dual-band capability that is intended for military search rescue missions and emergency services. An FSP antenna is typically defined by two or more layers in this configuration. The FSP antenna idea was first presented in [11] and then expanded upon in [12] and [13]. A dual-band FSP operating at around 800 MHz and 2.2 GHz was developed in response to these earlier advances [14]. The authors in [15] presented preliminary findings for a straight forward, single layer circularly polarized (cp) patch antenna, in which they finished investigation on the adopted polydimethylsiloxane (PDMS) substrate's resilience and endurance in terms of bending wet, and temperature testing. According to the results .such an antenna is capable of withstanding these operating circumstances without suffering appreciable in impedance matching or antenna losses in impedance matching or antenna gain.

After these advancements, some initial findings for a three-layer. By leveraging the principles of MIMO technology, which exploits spatial diversity and multipath propagation, the proposed antenna system aims to enhance data rates, coverage and reliability while minimizing the physical footprint and power consumption.

The suggested antenna using the cavity model. Applying a traditional patch [18] [10] on a multi-layer FSP. New closed- form equations for calculating the beam pattern and directivity are derived in the upcoming sections. Comparisons the between theory, the full-wave simulation and measurement are used to validate the results.

II. Antenna design overview and motivation

This paper's proposed PDMS antenna takes advantages of the FSP's TM010 and TM001 modes. Which can be reached without the need for slots as in [14] [17], where the FSP antennas using the TM010 and TM030 modes of operation. Antenna engineers may quickly and simply predict the operational frequency, pattern shape ,polarization ,and directivity before beginning any modelling or fabrication work thanks to the developed analysis approach designed exclusively for FSPs. The motivation for an advanced multiband MIMO antenna for soldier communication in X-band applications stems from the need for reliable, high-speed communication in military operations. X- Band frequencies offer advantages such as high data rates and reduced susceptibility to atmospheric interference, making them suitable for military communication systems.

Time spent on design and optimization may be cut down as a result. Wearable antenna should be durable and resilient to such a harsh environment and especially when considering the applications of military and search and rescue operations. It is imperative that wearable antennas exhibit durability and resilience in adverse environments, particularly with regards to their potential applications in military and search and rescue missions.

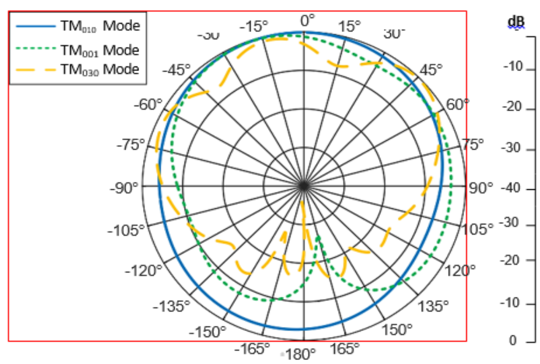


Fig 2: Beam pattern at the TM010, TM001 and TM030 modes for a three –layer FSP antenna.

Copper foil was used for the patch and ground plane of the antenna .Robustness tests such as Bending, temperature and wet proved that the antenna can maintain its performance even after deformation. The CP patch antenna has a broadband performance with a FBW of 21.5%. The proposed FSP antenna in this work is also designed using copper foil and is fully enclosed inside a PDMS substrate to provide robustness to the structure.

III. Substratum wearable Antenna considerations:

It is know that several properties can influence antenna behaviour. For example, the permittivity and substrate thickness of a micro strip antenna primarily dictate its band width and efficiency. Polydimethylsiloxane (PDMS)is one of the possible material that could satisfy the requirements of a wearable antenna.

These properties also prevent changes in the relative dielectric constant and loss tangent. Comparing PDMS to traditional textile materials, it is also better because it is flexible, low cost, waterproof, weatherproof, and easy to fabricate. It also has a low permittivity.

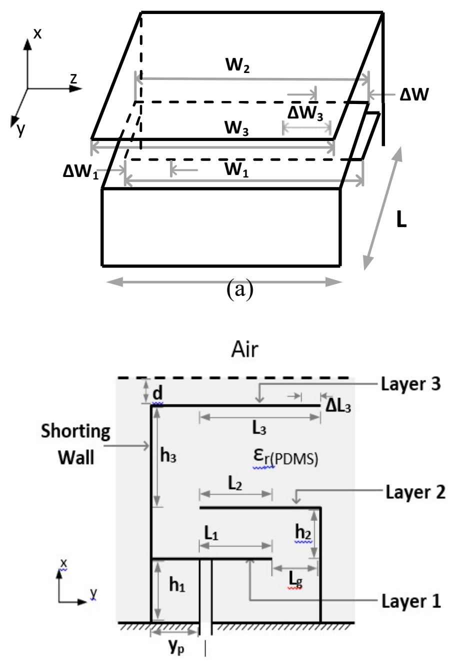
Using copper meshes or perforated metal plates as a conductive part of the antenna [11], embedding high density carbon nanotubes within the polymer to achieve carbon nanotube sheets with high compatibility [13], and combining PDMS with conductive fabric [14],[15], can all help to improve the practical adhesion between metal and such a polymer, i.e. PDMS.

In the past, PDMS has also been used in the applications involving molecular micro channel and bio molecular detection using micro fluidic devices [16], [17].PDMS has also been used recently for flexible antenna as well .In [18], an assessment of PDMS technology was presented with a the use of multiple input multiple output (MIMO) antenna operating at 5.8GHz for WLAN application.

Table 1 : Dimension of the three-layer FSP antenna

Parameter	Value(mm)
L_1	32
L_2	32
L_3	38
W_1=W_2=W_3	40
h_1	5.0
h_2	2.2
h_3	12.7
y_p	5.0
D	1.0
Ground plane	200X200
Ground plane(thickness)	0.1

The use of PDMS substrate for single frequency patch antennas has also been demonstrated in [19], [20].



(a)

(b)

Fig.3 depicts a cross –sectional view of a three-layer FSP with a PDMS substrate. In (a) W1, W2.and W3 denotes the width of the three layers for the FSP. Additionally, in (b), yp represents the distance of the probe from the shorting wall in the y-direction.

IV. Antenna synthesis and analysis:

It is established that a number of characteristics can affect antenna behaviour. The BW and efficiency of a micro strip antenna, for example are mostly influenced by the substrate's thickness and permittivity. One substance that might be able to satisfy the requirements for a wearable antenna is polydimethylsiloxane(PDMS). It should be noted that in-depth research was done to determine whether copper foil and PDMS could coexist.

A. Folded-shorted patch (FSP) antenna geometry:

To design a FSP antenna, the ground plane and shorted patch can be folded twice defining a physical length of λ/12 defining the formation of the three- layered FSP.The three folded layers can have lengths: L1, L2, L3 as described in Fig.3 (a), and the total height of the conducting part of the antenna can be defined as H=h1+h2+h3 where h1, h2, h3 are not equal Lg characterizes the gap between the folded metallic layers and the metallic side wall, whileh3 defines the radiating slot for the dominant TM010 mode.D is the distance between layer 3 and air.Fig.3 (b) shows W1, W2 and W3 which are the width TM010 and TM001 mode comparison of the conventional patch and three-layer FSP antenna. In order to describe the FSP modes, the resonant frequency.

B. Portable antenna substrate important aspects

For the standard patch, formulae like f010~1}4L and f001~1}4W can be utilized, starting with [18], [12].Here, W denotes the radiating element's width, L denotes the radiating element's length, while µ and {stand for the substrate's permittivity and the permeability, respectively.

C.FSP Antenna prototype

For the TM010 modes the field undergo a phase reversal along the length (L) of the patch and the FSP but they are uniform along the width (W).This uniform pattern along W contributes significantly to the radiation.

In order for the antenna to produce a broadside radiation pattern in the far-field, phase reversal along L is crucial [18].

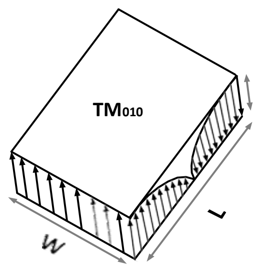


Fig 4 (a)

D.TM010 and TM001 mode comparison of the three-layer FSP Antenna and the conventional patch

This paper proposes a three-layer FSP that operates at the TM010 and TM001 modes, providing broadside radiation and avoiding slot loading in the top aperture, which has been done in [14] and [20].

This loading could potentially change the beam width and cause a beam squint. The electric-field pattern is uniform along L of the patch and the FSP for the higher order TM001 mode, and the fields are in phase reversal along W 6(a-d). In the TM010 mode, the electric field is primarily oriented perpendicular to the surface of the patch.In the TM001 mode,the electric field oriented parallel to the surface of the patch.

1) The TM010 mode emits the following fields: Each slot radiates the same field, which can be modelled as a magnetic dipole with current density Ms= -2n xEa, where n and Ea are the unit normal vector and electric-field at the slots, respectively. This is known from the equivalency principle.

E. Eletric-field distribution

The equivalent magnetic current densities along the two slots, each of width W and height h, are both of the same magnitude and same phase [18].Consequently, a two-element array is formed by these two slots.

A broadside pattern will form in the far-field as a result of the constructive interference of the fields produced by these two sources in a direction normal to the patch and ground plane. Taking into account how the single-layer patch functions in the TM010 mode, the directivity and radiated field by these two slots.

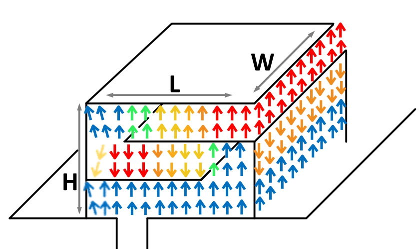


Fig 4 (b)

Fig (a) illustration of the electric field for the TM010 mode of the conventional patch antenna.,(b) sketched vector of electric-field pattern of the TM010 mode of the FSP antenna.

On the other hand, the FSP antenna investigated in this work has three electric and three magnetic walls. As a result, the FSP antenna radiates fields through a single slot.Therefore, the electric-fields radiated by a single slot in the far-fields in the TM010 mode experience a phase reversal along the patch's length (L) and the FSP, but they remain uniform along its width(W). This consistent design along W makes a substantial contribution to the radiation.

For the antenna to produce a broadside radiation pattern in the far-field, the phase reversal along L is crucial [18].

Additionally, the electric-field pattern of the 400 MHz FSP Is comparable to that of the prevalent TM010 mode for the Traditional patch.

One of the key equations related to MIMO (multiple input multiple outputs) communication system, including multiband MIMO antennas, is the channel capacity equation which is given by:

$$C=\log_2\left(1+\frac{SNR}{n}\right) \qquad (1$$

Where:

The bit-per-second (bps) channel capacity is denoted by C.

SNR is the signal to noise ratio

N is the number of antennas.

For MIMO systems, this equation can be extended to include the spatial multiplexing gain, which accounts for the additional capacity gained by using multiple antennas:

$$C=\sum_{i=1}^{N} \quad log2\left(1+\frac{SNRi}{N}\right) \qquad (2)$$

Where:

N is the total number of antennas (transmit and receive).

SNR is the signal –to-noise ratio for the i^{th} antenna.

Directivity

The directivity of a multiband MIMO (multiple input multiple outputs) antenna for soldier communication in X-band application can be calculated using the following equation:

$$D=10\log_{10}\left(\frac{4\pi Ae}{2}\right) \qquad (3)$$

D is the directivity

The antenna's effective aperture is denoted by A_e.

⎣ is the wavelength of the signal.

For a multiband MIMO antenna , need to consider the effective aperture and wavelength for each band of operation within the X-band frequency range.

A. Reflection coefficient of the prototype FSP antenna:

According to the FSP antenna uses two frequencies of operation 400MHz and 2.45GHz.Multi-band operation is possible since the higher order TM001 mode and the dominant TM010 mode both correspond to a favourable matching condition (|S11|<=-10db) at around 2.45GHz and 400MHz,respectively.

Furthermore, the FSP antenna functions as a beacon a t 400MHz and doesn't need a high bandwidth in fact 13MHz of bandwidth is seen at the dominant mode in both simulations and tests. Additionally, the antenna's broad ground plane enhances transmission away from the body and has a 180 degree beam width.

B. Pattern of radiation:

An anechoic chamber was used for the radiation pattern measurement and a key sight vector network analyser (VNA) was utilized they were founded on a far field antenna.

There is a DAUT gap between the horn antenna and the AUT. For the purpose of measuring the polar radiation pattern, the AUT is rotated 360 degrees in a single plane.

Peak cross-polarization levels both simulated and measured are at least 20 dB below the broadside main co-polar maximum.These antenna leverage the principles of beamforming and spatial multiplexing to enhance communication performance.Additionally,the radiation pattern may exhibit polarization diversity to mitigate the effects of multipath fading and improve link reliability.

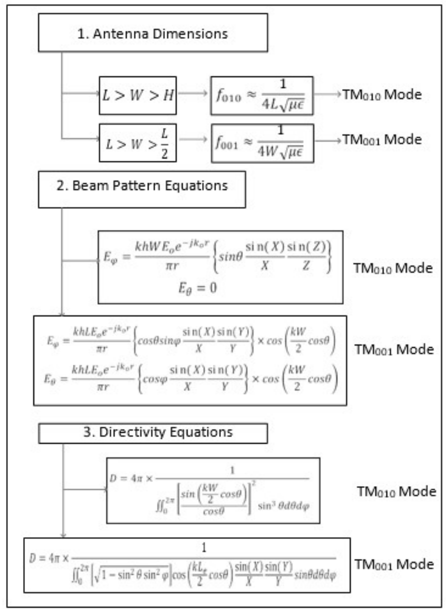


Fig 5: Diagram explains the step by step procedure of Antenna dimension, beam pattern equations and directivity equation.

Typically, this antenna is designed to be compact and light weight to suit the needs of mobile communication devices for soldiers. For the most accurate up to date information on antenna dimension for such applications, you may need to refer to recent research papers, patents, or technical specification provided by antenna manufacturers specializing in military communication system.

The beam pattern includes characteristics such as radiation directionality, beam width and side lobes. In such antennas, designers aim to achieve specific beam patterns to optimize signal coverage, minimize interference, and enhance communication performance for soldier.

V. Antenna methods and conservations

Antenna directivity is influenced by factors like antenna design, geometry, array configuration, and signal processing techniques.

Designers typically use techniques such as array beam forming and pattern shaping to enhance directivity while maintaining compatibility with the multiple frequency bands required for multiband operation.

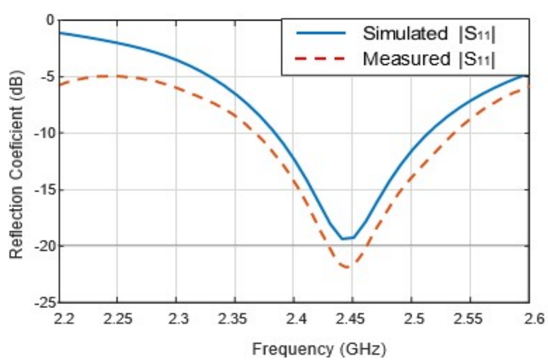
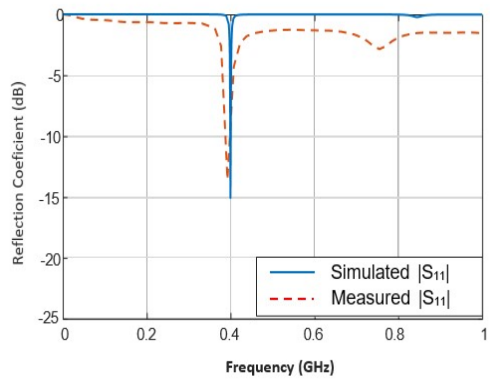


Fig 6 (a)



(b)

Fig 6 (a),(b) describes the reflection coefficient is crucial for efficient energy transfer and maximizing signal strength in communication systems, especially in the x-band frequency range(8-12GHz) commonly used for military applications.

A low reflection coefficient indicates efficient transmission of signals, which is crucial for reliable communication in dynamic battle field environments. Sophisticated design techniques, such as impedance matching and beam forming, are often employed to minimize the reflection coefficient and optimize antenna performance across multiple frequency bands.
The antenna for soldier communication, the reflection coefficient refers to the ratio of the reflected wave amplitude at the interface between the antenna and the transmission medium. The FSP antenna's radiation effectiveness is 50% and 65% while it is on a human body and 54% and 70% respectively when it is in free space at 400MHz and 2.4GHz.

The antenna might be thought to have a low realised gain and efficiency at the dominant mode, but as the FSP is serving as a beacon antenna and the only needs modest data rates, this is not a significant issue.
Similar efficiency was reported for wearable antennas, indicating that the realized gain efficiency reached at 2.4GHz is efficient for Wi-Fi communications.

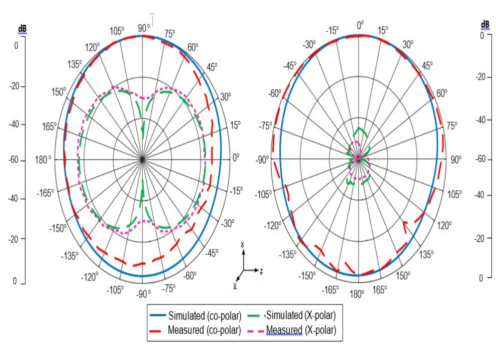


Fig 7 X-Y polar Plot

Process the simulation or measurement data to extract the copular x-y plot information.
This may involve converting raw data into a suitable format for plotting and analysis. Use your preferred plotting tool to generate the copular x-y plot the antenna's radiation pattern in the x-y plane, considering both the horizontal (x) and vertical (y) polarization components.
Analyze the co polar x-y plot to evaluate the antenna's suitability for soldier communication in the X-band. Look for factors such as polarization isolation, beam width and side lobe levels, which can impact communication performance.

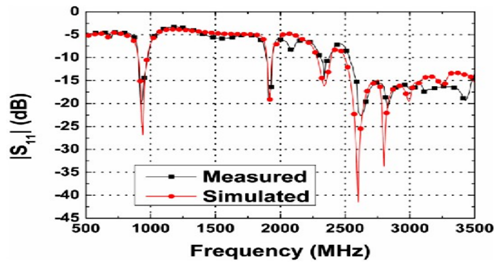


Fig 8: S-parameter helps the how the antenna to performs across different frequency bands within the X-band range.

This includes patrameters such as S11(reflection coefficient),S21 (transmission coefficient) and others, which are crucial for optimizing signal loss,and ensuring efficient communication in various operating conditions.

These parameters describe the behavior of the antenna system in terms of how electromagnetic waves are scattered or transmitted at various ports or connection within the system.

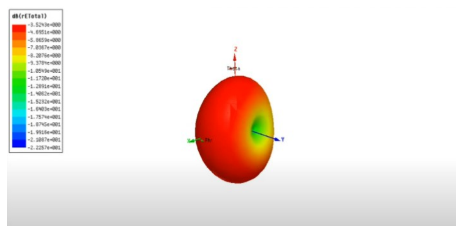


Fig 8: 3D polar plot consider the frequency bands within the X-band range.

The design elements(patches,dipoles,etc) to cover these bands efficiently.After running simulations for various angles,generate a3D polar plot.This plot should illustrate the antenna's radiation pattern across azimuth and elevation angles for each frequency band within the X- band.

Conclusion:

The design, construction and testing of a dual-band, three-layer FSP antenna operating at the TM010 (400 MHz) and TM001 (2.4 GHz) frequencies were given in this work. The various modes were examined and the cavity model was used to numerically calculate the far-field beam patterns. The results are in conformity with values derived from HFSS full-wave simulations. Furthermore, directivity equations have been constructed and proven for both the standard patch and the suggested three-layer FSP, taking into account the TM010 and TM001 modes. The FSP prototypes primary measurements, based on the lower design frequency of 400MHz, are $0.27\lambda_0$ x $0.27\lambda_0$ x $0.025\lambda_0$. Furthermore, there is a general consistency between the simulated outcomes and the reported data. Broadside radiation is seen at 400 MHz and 2.4 GHz.Additionally, the antenna's compact and light weight design aligns with the requirements of military applications, ensuring ease of integration into soldier equipment without comprising mobility or agility. Overall, the deployment of this advanced represents a substantial advancement in soldier communication systems, providing enhanced connectivity, resilience and performance in X-band applications.

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