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THE DEVELOPMENT AND ANALYSIS OF A WEARABLE TEXTILE YAGI-UDA ANTENNA DESIGN FOR SECURITY AND RESCUE PURPOSES

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Abstract: Advancements in technology have generated an escalating demand for robust mobile communication systems, highlighting the importance of wearable applications in diverse sectors such as biomedicine, military, and rescue services. This research underscores the crucial role of wearable antennas in addressing this growing need, with a specific focus on their design and development for applications within the Internet of Things (IoT). The primary objective is to establish resilient communication links capable of operating across various environments and weather conditions. Within this context, the investigation delves into the utilization of microstrip Yagi-Uda antennas renowned for their directivity, lightweight construction, low profile, and cost-effectiveness. The study introduces the simulated and fabricated design of a wearable Microstrip Yagi-Uda antenna optimized for operation at 2.45 GHz, applicable in health and rescue services. The antenna was analyzed by applying jeans textile as a substrate material and reached the return loss of -20.1 dB with an 8.5 dB gain. Jeans material as a substrate showed appropriate results to be applied in a wearable antenna.

Keywords: Yagi-Uda antenna, microstrip patch antenna, body area network, wearable communication.

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ҚҰТҚАРУ ҚЫЗМЕТІ МАҚСАТЫНДА КИІМГЕ ОРНАЛАСТЫРЫЛАТЫН ТЕКСТИЛЬДІ ЯГИ-УДА АНТЕННАСЫНЫҢ ДИЗАЙНЫН ҚҰРУ ЖӘНЕ ТАЛДАУ

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Аннотация: Технологиялық жетістіктер биомедицина, әскери және жедел құтқару қызметтерін қоса алғанда, әртүрлі секторларда киімге орналастырылатын қолданбалардың маңыздылығын көрсете отырып, сенімді ұялы байланыс жүйелеріне сұраныстың артуына әкелді. Бұл зерттеу осы өсіп келе жатқан қажеттілікті қанағаттандыруда киімге орналастырылатын текстилді антенналардың негізгі рөлін атап көрсетеді, олардың дизайны мен заттар интернеті (IoT) қосымшаларын әзірлеуге ерекше назар аударады. Мақсат - осындай антеннаны қолдана отырып, әр түрлі ортада және ауа-райында тұрақты байланыс арналарын құру. Бұл зерттеу жұмысында қарапайым дизайнымен, төмен профилімен және үнемділігімен ерекшеленетін Яги-Уда микрожолақты антеннасы қарастырылған. Жобаланған антенна 2,45 ГГц жиілігінде жұмыс жасауға арналып компьютерлік бағдарламада модельденді және шынайы дизайны құрастырылып, нәтижесі ұсынылды. Антеннаны жобалау кезінде джинса текстилі субстрат материал ретінде зерттеліп, басқа зерттеу жұмыстарымен салыстырылды. Джинса субстратты антеннасын жобалау кезінде 8,3 ДБи күшейту коэффициентімен және 2,45 ГГц жиілікте -20,1 ДБ кері шығынмен жақсы өнімділікке қол жеткізілді.

Түйін сөздер: Яги-Уда антеннасы, микрожолақты антенна, киімге орналастырылатын текстильді антенна.

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РАЗРАБОТКА И АНАЛИЗ ДИЗАЙНА ВСТРАИВАЕМОЙ ТЕКСТИЛЬНОЙ ЯГИ-УДА АНТЕННЫ ДЛЯ ПРИМЕНЕНИЯ В СФЕРЕ СПАСАТЕЛЬНЫХ СЛУЖБ

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Аннотация. Технологические достижения вызвали растущий спрос на надежные системы мобильной связи, подчеркивая важность встраиваемых в одежду приложений в различных секторах, включая биомедицину, военные и спасательные службы. В этом исследовании подчеркивается ключевая роль носимых антенн в удовлетворении этой растущей потребности, особое внимание уделяется их проектированию и разработке для приложений Интернета вещей (IoT). Цель состоит в создании устойчивых каналов связи в различных средах и погодных условиях. В этом исследовании рассматриваются микрополосковые антенны Яги-Уда, известные своей направленностью, легкой конструкцией, низким профилем и экономичностью. В исследовании представлена смоделированная и изготовленная конструкция носимой микрополосковой антенны Яги-Уда, работающей на частоте 2,45 ГГц. При проектировании антенны материалом подложки был выбран джинсовый текстиль и сравнивался с другими исследовательскими работами. При проектировании была достигнута хорошая производительность с коэффициентом усиления 8,3 ДБи и коэффициентом отражения -20,1 ДБ на частоте 2,45 ГГц.

Ключевые слова: Яги-Уда антенна, микрополосковая антенна, встраиваемая текстильная антенна.

Introduction

Technological progress has heightened the need for dependable mobile communication systems, making them essential not only for entertainment but also for safety. Wireless technology, especially in the form of wearable devices, has proven valuable in fields like biomedicine, the military, and rescue operations by enabling efficient monitoring. IoT-enabled wearable devices, which can be worn as accessories, integrated into clothing, implanted in the body, or even tattooed on the skin, have become increasingly popular due to their ability to connect to the internet, gather data, and facilitate the exchange of information, which is crucial for making informed decisions. These wearable IoT applications are generally classified into four categories: healthcare, entertainment, security, and rescue (Dian, et al,2020). Many of these devices operate in the Industrial Scientific Medical (ISM) frequency bands, such as 902-928 MHz, 2.4-2.4835 GHz, and 5.725-5.875 GHz. However, these bands are subject to specific limitations, like short-range operation or low power output, to reduce interference and ensure coexistence in the spectrum (Federal Communications Commission, REPORT AND ORDER AND FURTHER NOTICE OF PROPOSED RULEMAKING.). This paper primarily aims to develop and design a durable and reliable wearable antenna for various IoT applications. The antenna must perform well in different scenarios, including security and rescue operations, and maintain stable communication links in various environments and weather conditions. Additionally, it should be seamlessly integrated into the user's uniform and remain durable under different conditions. The wearable antenna also needs to support multiple communication types and services, such as GPS or satellite communication, which presents challenges regarding interoperability. With the expansion of sensor networks and IoT technologies, many areas remain unexplored. Therefore, given the current research gaps in wearable antennas for IoT applications, there is a pressing need for in-depth studies to unlock the potential contributions in this field. The development of reliable, high-performance wearable antennas for IoT applications could lead to significant advancements in industries such as healthcare, sports, and emergency services.

Literature review

According to a study by T. Islam and S. Ullah, wearable Body Area Networks (BANs) have shown promise in various fields, including healthcare monitoring, sports performance tracking, and entertainment (Islam, et al, 2019). The study emphasizes the importance of developing wearable IoT devices using textile materials that are both comfortable and functional. A recent study introduced a wideband, low-profile, semi-flexible antenna designed for wearable biomedical telemetry applications, offering high gain and efficiency at a 2.4 GHz operational bandwidth. This antenna, constructed from a semi-flexible RT/Duroid 5880 material, measures 17x25x0.787mm and demonstrated a gain of 2.5 dBi with 93% efficiency, making it a strong candidate for compact wearable devices that perform well on the human body (Nazari, et al, 2021). In recent years, significant research and development have been directed toward wearable antennas, which hold great potential for various wireless communication applications, particularly for wearable devices. Textile materials, with their low dielectric constant (around 1 to 2), help reduce surface wave losses and improve antenna bandwidth. A microstrip patch antenna using jeans textile, sized 120x120mm, was designed to operate at 2.45 GHz, achieving a return loss of -32.57 dB and a gain of 7.2 dBi (Purohit, et al). Additionally, antenna parameters were enhanced by doubling the Yagi antenna arrays, resulting in a -20dB return loss at 5.5GHz (Ismail, et al, 2012). However, the antenna designed in (Purohit, et al)is large and susceptible to bending issues. A miniaturized textile antenna would reduce bending, thus providing more stable performance. A flexible Yagi-Uda patch antenna operating at 2.48GHz was evaluated for bending effects, revealing that severe bending degrades performance, though the antenna's matching performance remains relatively robust under such conditions (Jianying, et al, 2016). In reference (DeJean, et al, 2007), a novel microstrip Yagi array antenna is presented, capable of achieving high gain with minimal backside radiation across various applications, including the millimeter-wave frequency spectrum. The antenna's high front-to-back (F/B) ratio, up to 15 dB, is attributed to the constructive interference between the printed Yagi arrays within the design. Researchers have investigated various substrates to maintain antenna efficiency and flexibility, considering factors like thickness and size. The antenna's radiation pattern is also crucial for overcoming electromagnetic absorption by the human body. While numerous antenna models have been proposed for applications in healthcare, rescue, defense, and entertainment, there remains significant room for further research (Hu L, et al, 2019). This literature review underscores the importance of developing efficient wearable antennas suited for body-worn devices by evaluating their performance with different substrate materials. The key challenge is that wearable antenna' performance is significantly impacted by the human body, necessitating designs that maintain efficiency and flexibility. Further research is needed to explore the potential of wearable antennas for healthcare applications and enhance their overall performance. However, one potential drawback of the microstrip Yagi-Uda antenna is its narrow bandwidth and limited radiation compared to other antennas. Additionally, the microstrip antenna may be more sensitive to environmental factors, such as the proximity of the user's body, which can affect its performance. This paper proposes modeling a miniaturized microstrip Yagi-Uda antenna to be embedded in wearable IoT applications for rescue monitoring purposes. The antenna simulation is carried out using CST Microwave Studio at 2.45 GHz.

To achieve this goal, the following tasks are outlined:

- Develop a new wearable microstrip Yagi-Uda antenna design using a jeans textile substrate and simulate it with CST Microwave Studio Simulation Software.

- Achieve appropriate measurement results during antenna fabrication to validate its performance.

- Compare the simulation and fabrication results, evaluating the antenna's performance in terms of its radiation pattern, gain, efficiency, and bandwidth.

Methods and materials

This paper outlines the design process of the microstrip Yagi-Uda antenna, which is divided into three phases: calculating the geometrical parameters, simulating and optimizing the model using CST Studio Suite, and finally fabricating the antenna prototype. The key features of this antenna system include its smaller geometric dimensions compared to traditional Yagi-Uda antennas, ease of manufacturing, and planarity (Losher, et al, 2006: Nurzhaybayeva, 2022). As shown in Figure 1 below, this Yagi-Uda antenna design incorporates both driven and parasitic elements. The driven element is directly connected to the transmission line, receiving power from the source. Parasitic elements, on the other hand, obtain energy through mutual induction with either a driven element or another parasitic element (Daya, et al; Tanti, et al, 2020). When a parasitic element is longer than the driven element, it acts as a reflector, absorbing energy from the driven element and influencing signal strength by reducing it in its direction while increasing it in the opposite direction. In contrast, a parasitic element that is shorter than the driven element functions as a director, typically added to amplify the field strength in its direction while diminishing it in the opposite direction.

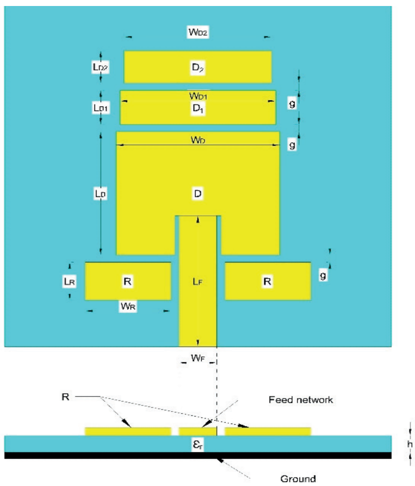

Figure 1 - The geometry of the proposed microstrip Yagi-Uda antenna

Patch of the antenna. Although various types of patches, such as rectangular, circular, and triangular, exist, the rectangular patch was specifically selected for the antenna. This choice was made because the rectangular patch offers a larger physical area, resulting in higher bandwidth and easier fabrication compared to other patch types (Kiourti, et al, 2016). In the construction of the reflector, directors, and driven element, copper is utilized as the manufacturing material. Copper, on the other hand, is employed as the manufacturing material for the ground.

Substrate. Generally, for microstrip antennas the range of substrate's dielectric constants is in the range of $2.2 \leq \varepsilon_r \leq 12$. Here, as a wearable antenna, we have chosen jeans textile, so the dielectric constant will be lower. Characteristics for the jeans fabric are provided in Table 1 below.

Table 1. Non-conductive fabric characteristics

Non-conductive fabric	**The dielectric constant, ε_r**	**Loss tangent**
Jeans	1.6	0.025

The design specifications of the proposed antenna are shown in Table 2 and the geometry is provided in Figure 1. The antenna mainly consists of a driven element, a reflector, and 2 directors aimed to be printed on jeans substrate material.

Table 2. Design specifications of the proposed antenna

Parameter	**Value**
Operating frequency	2.45 GHz
Transmission line	microstrip feed
Material of the patch	copper
The thickness of the patch, h (mm)	0.035 mm
Material of the substrate	jeans
The thickness of the substrate, h (mm)	0.52
Material of the ground	copper
The thickness of the ground, h (mm)	0.035 mm

The textile Yagi-Uda antenna design co-exists, such as rectangular, circular, and triangular prism a driven patch element, and a set of parasitically coupled director and reflector patch elements. The driven element, denoted as D, is excited by a microstrip feedline to achieve a 50 Ohm input impedance. This is achieved by utilizing a small gap between the driven element and the reflector elements, which are considered as a single element with a gap in the middle for feeding purposes. Additionally, two director elements, labeled D1 and D2, are incorporated to establish beam directionality and enhance antenna gain.

Calculation of the Patch dimensions.

The following equations given below (1-5) are used to identify the other parameters of the substrate and patch

The width of the patch is given as:

$$W = \frac{c}{2 * f_0 \sqrt{\frac{(\varepsilon_r + 1)}{2}}} \qquad (1)$$

Where, c is the velocity of light, f_0 is the resonant frequency and is relative dielectric constant.

In order to calculate the length, the effective dielectric constant of the substrate should be determined:

$$\varepsilon_{eff} = \frac{(\varepsilon_r+1)}{2} + \frac{(\varepsilon_r-1)}{2}[1 + 12\frac{h}{W}]^{-\frac{1}{2}} \quad (2)$$

The effective length is:

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \quad (3)$$

The equation of length extension, where the dimensions of the path along its length have been extended on each by a distance, ΔL, which is a function of the effective dielectric constant and the width-to-heigh ratio (W/h):

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \quad (4)$$

Because of the inherent narrow bandwidth of the resonant element, the length is a critical parameter, and the above equations are used to obtain an accurate value for the patch length L. The actual length of the patch is obtained:

$$L = L_{eff} - 2\Delta L \quad (5)$$

Calculation of Microstrip Line Feed

Then, the microstrip synthesis, *H* with characteristic impedance, Z_0 equals to 50 Ohm is generated using:

$$H = \left[\frac{Z_0\sqrt{2(\varepsilon_r+1)}}{119.9}\right] + \frac{1}{2}\left[\frac{\varepsilon_r-1}{\varepsilon_r+1}\right]\left[\ln\left(\frac{\pi}{2}\right) + \frac{1}{\varepsilon_r}\ln\left(\frac{4}{\pi}\right)\right], \quad (6)$$

Based on (6), the width of microstrip line feed, W_f is computed as in the following:

$$W_F = \left[\left(\frac{e^H}{8} - \frac{1}{4e^H}\right)^{-1}\right] * 1.60mm, \quad (7)$$

Moreover, the length of microstrip line feed, L_f is obtained through:

$$L_F = \theta * \frac{\bar{\lambda}_g}{360^o}, \quad (8)$$

where,

$$\lambda_g = \frac{c}{f*\sqrt{\varepsilon_{reff}}}, \quad (9)$$

Calculation of the Antenna ground dimension

The length of the ground plane is calculated using the following:

$$L_g = L + 6h, \quad (10)$$

moreover, the width of the ground plane is computed as shown below:

$$W_g = W + 6h, \quad (11)$$

To achieve optimal gain and favorable return loss, all the values in the design were carefully selected. The spacing between elements, denoted as g, is set at $0.1\lambda_g$. The width of the directors, W_{D1} and W_{D2}, is slightly shorter than the width of the driven element, W_D, by approximately 5% and 10% respectively. Conversely, the width of the reflector, W_R, is 5% longer than the width of the driven element. Through simulation, the length of the reflector and directors are determined to be approximately one-fourth of their total width. These design choices aim to maximize the performance of the antenna in terms of gain, while ensuring efficient signal reflection and transmission properties.

Table 3. Calculated geometry of the microstrip Yagi antenna

Parameter list	**Dimensions (mm)**
W_D	53.7
W_{D1}	51
W_{D2}	48.33
W_R	28.2
W_F	12.45
L_D	45.7
L_{D1}	12.75
L_{D2}	12.08
L_R	14.1
L_F	44.39
g	2.56

After all calculations of the parameters, the design of the wearable microstrip patch antenna is modeled using CST Simulation software.

Results

Designing a microstrip patch antenna requires careful consideration and evaluation of several critical parameters, including bandwidth, S-parameters, VSWR, radiation pattern, and impedance. One of the main challenges in microstrip antenna design is achieving a wide bandwidth and high efficiency. A narrow bandwidth limits the antenna's ability to effectively capture signals, while low efficiency results in poor overall performance. To overcome these challenges, the inset-fed edge technique is utilized, enabling an operating bandwidth greater than 200 MHz. This approach helps to broaden the antenna's bandwidth and enhance its efficiency. Additionally, to further improve efficiency, the antenna is designed with the aim of achieving a return loss (S11) of less than -10.000 dB in both the simulation and fabrication phases. This goal is set to ensure optimal performance and minimize any potential signal loss or degradation.

Figure 2 and 3 below shows the fabricated design of the textile Yagi-Uda antenna with a jeans substrate. The Nano VNA analyzer is used to indicate the return loss of the antenna.

Figure 2 - Fabricated wearable Yagi-Uda antenna.

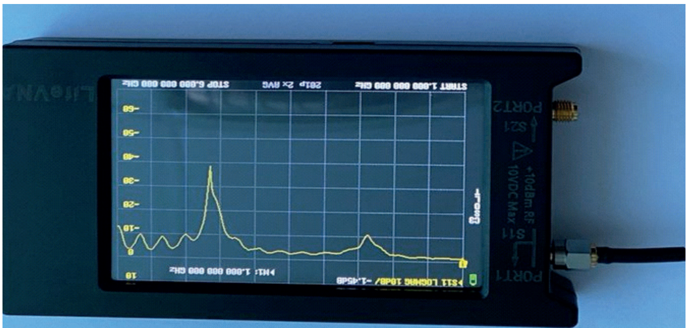

Figure 3 - Fabricated wearable Yagi-Uda antenna result at Nano VNA analyzer

These parameters below are obtained from the simulation results.

Reflection coefficient is also known as S_{11} or return loss. It describes the loss of the power in the signal reflected by a transmission line. Return loss is mainly related to Standing wave ratio. For any microwave devices, the return loss should be very minimum. The return loss must lie below -10dB, then the device yields maximum output.

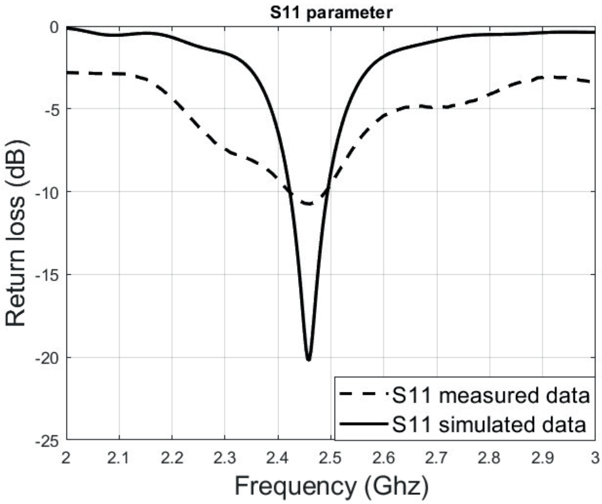

Figure 4 - Simulated and experimental S_{11} parameter results of Yagi-Uda antenna with jeans substrate

From Figure 4, the simulated antenna with jeans substrate reached the return loss of -20.1dB at 2.45 GHz, which is 98% of the power transmitted. In comparison, the S11 parameter of the fabricated antenna is -10.84 dB.

Equation (12) states the relation between ratio of incident and reflected power.

$$RL(dB)=10log_{10}\frac{Pi}{Pr} \quad (12)$$

According to the simulation results of S11 parameter, it can be emphasized that jeans material can be applied in the wearable antenna design and can achieve satisfying results with minimum power loss.

From Figure 4 seen, the S11 parameter are presented in decibels over frequency. A comparison of experimental and CST Microwave Studio full-wave numerical solver results is shown. A slight downshift in frequency is observed for the measured prototypes. This discrepancy is within the tolerance limits for the substrate and foam permittivities.

Voltage standing wave ration (VSWR) is used to describe how well the antenna impedance is matched with the connected transmission line. It specifies the total efficiency of an antenna and how efficient the electromagnetic signals are transmitted / received in a particular frequency band. For better performance, VSWR must lie between 1 and 2. It is a function of reflection coefficient; real and positive number. The VSWR value for jeans substrate is 1.26. VSWR of the antenna is calculated using equations (13) and reflection coefficient was calculated using equation (14). Figure 5 below shows the reflection coefficient of the antenna with jeans substrates. VSWR plays a crucial role in analyzing the performance of an antenna.

$$\mathrm{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|}, \qquad (13)$$

$$|\Gamma| = \frac{S-1}{S+1}, \qquad (14)$$

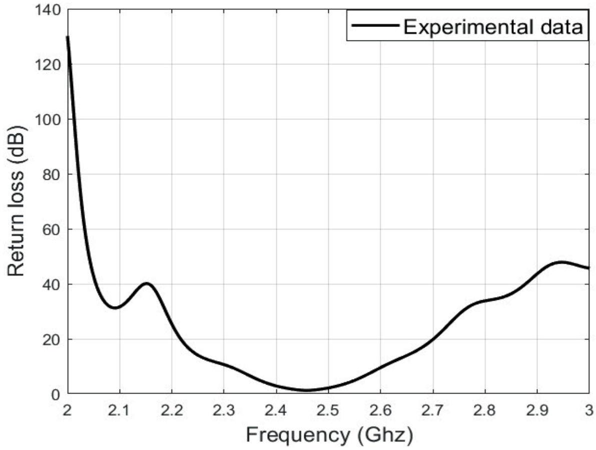

Figure 5 - VSWR of the simulated wearable microstrip Yagi-Uda antenna with jeans substrate.

The sketch drawn to represent the radiation properties of an antenna is called Radiation pattern. It is plotted as a function of angular position and radial distance. It describes the relative strength of the radiated field in multiple directions from the antenna. It includes both reception and transmission patterns. For a wearable antenna, which will embedded in the cloth, it is better to achieve circular polarization in order to cover the human body at 360 degrees.

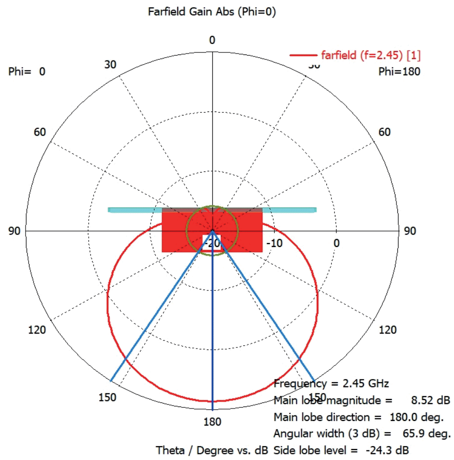

Figure 6 - The simulated two-dimensional radiation pattern of the microstrip Yagi antenna with jeans substrate.

Figure 6 shows farfield diagram from the simulation result for 2.45 GHz.

The antenna gain is calculated both in transmitting and receiving antenna. In transmitting antenna, gain specifies how well the antenna converts input power into waves transmitted in one particular direction. In receiving antenna, the operation is vice versa how well the antenna converts the radio waves into electrical signal. Microstrip Yagi-Uda antenna design with jeans substrate shows a gain of 8.5 dBi.

$$G = \frac{Po}{Pin} * D, \quad (15)$$

where, Po – output power in watts, Pin – input power in watts, D – directivity in dB.

Directivity is one of the antenna parameters which measures the radiation intensity in one particular direction. If the antenna is transmitting in all directions, then it will have zero directivity. The directivity value obtained is 9.1 dB.

Discussion

Compared to the design presented in, where the Yagi-Uda antenna using an FR-4 substrate achieved a return loss of -11.17 dB with a gain of 6.89 dBi, the proposed antenna design with a jeans substrate demonstrated superior performance, achieving a return loss of -20.1 dB and a gain of 8.5 dBi at 2.45 GHz. The jeans-substrate antenna also shows promising results in terms of directivity. As illustrated in Figure 6, the main beam is directed towards approximately 180°, which corresponds to the end-fire direction. This improvement is achieved by adding directors and increasing the ground plane to match the size of the substrate, providing a well-balanced and reasonably sized antenna.

Conclusion

In conclusion, a wearable Yagi-Uda antenna operating at 2.45 GHz for use in healthcare and rescue services has been successfully designed and evaluated. The antenna's performance was assessed using jeans textile as the substrate material. Simulation results showed a return loss of -20.1 dB and a gain of 8.5 dB, indicating that jeans material is a suitable substrate for wearable antennas.

The proposed wearable microstrip Yagi-Uda antenna offers reliability and high performance, which could lead to significant advancements across various industries and applications, including healthcare, sports, and emergency services. However, it is important to note that wearable systems are generally not used on flat surfaces. The study highlighted that bending can alter the resonant length of the antenna, leading to deviations in the resonant frequency. Additionally, factors such as human body movements, material wetness, and specific absorption rate (SAR) are critical and should be the focus of future research to prevent degradation of the antenna's performance.

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CONTENTS

INFORMATICS

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