FLEXIBLE SKIN-CONTACT ANTENNA WITH ARTIFICIAL MAGNETIC CONDUCTOR FOR HEALTH MONITORING APPLICATION

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DEDICATION

To my beloved mom & dad,

Rosadah Abu Bakar & Othman Puteh,

my dearest husband and kids, and my all supportive family members

for their endless love and support

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ABSTRACT

Flexible antenna plays a significant role to ensure efficient wireless communication in wearable devices. The choice of the dielectric substrate material of the antenna is one of the important factors to ensure good antenna performance while being tolerant to mechanical deformation. In addition, the size of the antenna becomes the main issue in designing the antenna for on-body applications. Furthermore, the radiation and transmissions performance of the on-body antenna suffers from performance degradation due to several factors such as dielectric properties of the human body as well as line of sight (LOS) and non line of sight (NLOS) transmission conditions. Therefore, this study presents a flexible Skin-Contact Antenna with Artificial Magnetic Conductor surface (SCA-AMC) made from medical-friendly material. Initially, three different types of medical materials which include transdermal cotton patch, semi-transparent film, and self-adhesive bandage were proposed for investigation as the antenna's dielectric substrate. The dielectric properties of the proposed materials were measured prior to the antenna design. For preliminary design investigation, a conventional bowtie antenna was designed using the proposed medical materials and optimized to operate at frequency of 2.4 GHz. To achieve the objectives, the feasibility of medical material usage for the antenna's substrate was explored based on wetness and repeatability test. The proposed SCA is intended for on-body wireless communication devices where there is a significant limitation on the overall size of the antenna. In order to develop a compact flexible antenna, a meandering technique is applied to the conventional bowtie antenna. By employing the meandering technique, the total length of the antenna can be reduced by 20 %. As the body protection against electromagnetic absorption is important, a dipole-like AMC structure was designed at frequency of 2.4 GHz and integrated with the meandered bowtie antenna. The proposed SCA-AMC is made of flexible material for the substrate and conducting parts, making it suitable for wearable applications. Furthermore, the factors that influence the antenna's radiation and transmission performance have been determined. The experiments have been carried out considering various conditions such as body movements and the presence of either human body or obstacle in between the SCA-AMC transmitter and the receiver. The results indicate that the human body introduces an additional 20 dBm power loss when present between the transmitter and receiver. Also, the presence of the book causes 6 dBm reduction in received power while sweatshirts and cotton polo shirts contribute to a small variation of approximately from 0.5 to 1 dBm. Besides, wetness measurements were also carried out using tap water and sweat-like solution. The sweat-like solution had been developed using a mixture of sodium chloride, sodium bicarbonate, and water. The material characterization of the developed sweat-like solution was then performed. The developed sweat-like solution has a measured permittivity and loss tangent of 75.8 and 0.13, respectively at the frequency of 2.4 GHz. The proposed SCA-AMC was also tested in a real-life situation by merging it with an electrocardiogram (ECG) sensor node. The results obtained show that the wireless ECG pattern is comparable to the ECG pattern measured using a conventional ECG machine. The findings in this research have profound implications for future studies to develop an efficient wireless device, especially for on-body applications.

ABSTRAK

Antena yang fleksibel memainkan peranan yang penting untuk memastikan komunikasi tanpa wayar yang cekap dalam peranti boleh pakai. Pemilihan jenis dielektrik antena adalah salah satu faktor penting untuk memastikan prestasi antena yang baik disamping mempunyai ketahanan terhadap ubah bentuk mekanikal. Saiz antena menjadi isu utama dalam mereka bentuk antena untuk aplikasi di atas badan. Tambahan pula, prestasi sinaran dan penghantaran data antena mengalami kemerosotan prestasi disebabkan oleh beberapa faktor seperti sifat dielektrik badan manusia serta keadaan penghantaran garis penglihatan (LOS) dan bukan garis penglihatan (NLOS). Oleh itu, kajian ini bertujuan untuk menghasilkan antena sentuhan kulit bersama permukaan pengalir magnet buatan (SCA-AMC) yang diperbuat daripada bahan mesra perubatan. Tiga jenis bahan perubatan yang berbeza seperti tampalan kapas transdermal, filem separa lutsinar, dan pembalut lekat sendiri dicadangkan untuk penyiasatan sebagai substrat dielektrik antena. Sifat dielektrik bahan yang dicadangkan diukur sebelum reka bentuk antena. Untuk penyiasatan reka bentuk awal, antena tali leher lazim direka menggunakan bahan perubatan yang dicadangkan dan dioptimumkan untuk beroperasi pada frekuensi 2.4 GHz. Untuk mencapai objektif, kebolehlaksanaan penggunaan bahan perubatan untuk substrat antena diterokai berdasarkan ujian kebasahan dan kebolehulangan. SCA-AMC yang dicadangkan bertujuan untuk peranti komunikasi tanpa wayar pada badan di mana terdapat had yang ketara pada saiz keseluruhan antena. Teknik garis berliku digunakan pada antena tali leher lazim untuk membangunkan antena boleh lentur padat. Dengan menggunakan teknik tersebut, jumlah panjang antena boleh dikurangkan sebanyak 20%. Oleh kerana perlindungan badan daripada penyerapan elektromagnet adalah penting, struktur AMC seperti antena dwikutub direka pada frekuensi 2.4 GHz dan disepadukan dengan antena tali leher garis berliku. SCA-AMC yang dicadangkan diperbuat daripada bahan mudah lentur untuk substrat dan bahagian pengalir, menjadikannya sesuai untuk aplikasi mudah alih. Tambahan pula, faktor yang mempengaruhi sinaran antena dan prestasi penghantaran telah ditentukan. Eksperimen telah dijalankan dengan mengambil kira pelbagai keadaan seperti pergerakan badan dan kehadiran tubuh manusia atau halangan di antara penghantar SCA-AMC dan penerima. Keputusan menunjukkan bahawa tubuh manusia menyebabkan kehilangan kuasa sebanyak 20 dBm apabila berada di antara pemancar dan penerima. Selain itu, kehadiran buku menyebabkan pengurangan sebanyak 6 dBm dalam kuasa yang diterima manakala baju peluh dan baju polo kapas menyumbang kepada variasi kecil iaitu antara 0.5 dBm hingga 1 dBm. Selain itu, pengukuran kebasahan juga telah dijalankan menggunakan air paip dan larutan peluh. Larutan peluh dihasilkan dengan menggunakan campuran natrium klorida, natrium bikarbonat, dan air. Larutan peluh yang dihasilkan mempunyai kebolehpercayaan dan tangen kehilangan yang diukur, masing-masing sebanyak 75.8 and 0.13 pada frekuensi 2.4 GHz. SCA-AMC yang dicadangkan juga diuji dalam situasi kehidupan sebenar dengan menggabungkannya dengan nod penderia elektrokardiogram (ECG). Keputusan menunjukkan bahawa corak ECG tanpa wayar menghampiri dengan corak ECG yang diukur menggunakan mesin ECG lazim. Penemuan dalam penyelidikan ini mempunyai implikasi yang mendalam untuk kajian masa depan untuk membangunkan peranti tanpa wayar yang cekap, terutamanya untuk aplikasi pada badan.

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LIST OF ABBREVIATIONS

LOS	-	Line of sight
NLOS	-	Non line of sight
SCA-AMC		Skin-Contact Antenna with AMC
ECG	-	Electrocardiogram
EEG	-	Electroencephalogram
AMC	-	Artificial Magnetic Conductor
VNI	-	Virtual Networking Index
PET	-	Polyethylene terephthalate
PDMS	-	Polydimethylsiloxane
UWB	-	Ultra-wideband
CPW	-	Coplanar waveguide
PMC	-	Perfect Magnetic Conductor
SAR	-	Specific absorption rate
FCC	-	Federal Communications Commission
ICNIRP	-	International Commission on Non-Ionizing Radiation Protection
AUT	-	Antenna under test
EM	-	Electromagnetic
SAM	-	Specific Anthropomorphic Mannequin

LIST OF SYMBOLS

f_r	-	Resonant frequency
ε_e	-	Effective permittivity
ε_r	-	Relative permittivity
θ	-	Opening angle
μ_0	-	Permeability of free space
ε_0	-	Permittivity of free space
η_o	-	Free space impedance
λ	-	Wavelength
σ	-	Conductivity
ρ	-	Mass density

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CHAPTER 1

INTRODUCTION

1.1 Research Background

With the increasing number of monitoring system either in health care, sports or security sector using a wireless area network technology, intense researches are focusing on the development of wearable electronics. Wearable electronics are getting more attention due to the wide range of healthcare, sports, security, and also military applications. These wearable electronics are leading to the creation of wireless devices that is easier to be carried out by the user. The wearable wireless device is usually being attached to the user body or being carried out in the pocket thus improves the user convenience. This phenomenon indicates a strong potential for the wired-communication network to be replaced with wireless communication. Along with this trend, body-centric wireless communication which refers as human-self and human-human networking has received more exposure especially for continuous monitoring applications in the medical sector.

Conventionally, a medical device for health monitoring such as electrocardiogram (ECG) and electroencephalogram (EEG) use rigid electrodes coupled to the skin via electrolyte gels and affixed with adhesive tapes. Therefore, measuring the bio-signal using the conventional method for everyday life may be tricky due to inconveniences caused by the bulk wire connection of the electrodes and the reliability of the measurement caused by gel drying. Besides, by using the rigid electrodes, the measurement procedure will be limited only to locate the sensor to the flat region of the body such as the forehead or chest. Therefore, flexible antenna comes into play aimed at enhancing the quality of human life by providing comfort during the continuous health monitoring in the medical sector.

1.2 Problem Statements

In the conventional wearable wireless device, a rigid antenna is used to transmit data at 2.4 GHz operating frequency, commonly used for WiFi, Bluetooth, and Zigbee standard. This however limits the positioning of the device on the human body and makes the user uncomfortable for longer usage. Nowadays, there are varieties of wearable antennas made of flexible substrates have been proposed such as fleece, jeans, polymer, and organic paper [1]–[4]. These materials however suffer from serious drawbacks due to high water absorption and pattern distortion due to wrinkles and crumpling. The antenna performance may significantly degrade in wet conditions [5]–[7], experienced poor impedance matching and suffers from a significant reduction of radiation efficiency for up to 26 % due to crumpling effect [8]. In addition, the previously proposed wearable antenna required an additional adhesive element in order to attach to the human body [9]–[11]. The inclusion of additional adhesive elements could change the dielectric properties of the entire substrate material. Thus, affecting the antenna radiation properties. Therefore, suitable flexible materials such as medical patches, bandages, and others that are currently available in the market may be useful for further investigation. This medical-friendly material has proven to be comfort and safe to the user for longer usage. Suitable type of medical-friendly material will be proposed by considering the wet and crumpling effect on the antenna performance. None of these materials has been reported in the literature to be used as the antenna's substrate.

Furthermore, the wearable antenna is required to be located in close proximity to the human body. However, the flexible antenna when operated very close to the human body has been reported to suffer from performance degradation due to the dielectric properties of the body itself [12], [13]. Besides that, electromagnetic power absorption by the human body leads to the tissue heating and present an adverse health effect due to the power absorbed by the body [14]. It is important to evaluate the antenna performance within the human body as well as to minimize the Specific Absorption Rate (SAR). The SAR is the parameter to determine the level of power absorbed by the human body. One of the common technique for reducing the SAR is using a simple ground plane [11], [15]. However, this technique suffers from the out-of-phase reflection property contributing to decrease in the total efficiency [16]. Other method for SAR reduction using metamaterial such as Artificial Magnetic Conductor (AMC) surface as a shield to the wearable antenna have been considered and studied [17]–[20]. With that being used, the antenna's backward radiation is greatly minimized. As a results, the electromagnetic radiation toward the human body is significantly lowered and improved the antenna performance in term of gain and total efficiency [19], [21]. Therefore, it is expected that integrating flexible AMC surface with flexible antenna will further improved the on-body antenna performance and user's convenient. Since a medical-friendly substrate material will be considered and proposed, the same material will be used as the AMC surface in this study. In addition, none of earlier studies have used or considered AMC using this kind of medical-friendly as the substrate dielectric material. Parametric studies and further optimization will be done in order to design an AMC surface. The proposed flexible antenna will be integrated with the AMC surface made of medical-friendly material for further investigation and analysis.

Besides that, previous works show that antenna in wet conditions experienced performance degradation due to the presence of high permittivity water which in turn alters the dielectric properties of the antenna's substrate. Tap water, rainwater, and seawater have been considered while investigating wetness effect on the antenna performance in their research [5], [6], [22]. Another rational situation that should be considered while designing a wearable antenna is the effect of human sweat. The wearable antenna is believed to be worn on the human body. Thus, there is a tendency for the antenna to exposed to sweat during daily activities especially athlete who is in the recovery process or their daily fitness routine. Human sweat contains additional chemicals that are expected to influence the antenna performance further. Limited research has investigated the human sweat effect on antenna performance [23]. Author in [23] tests the effect of artificial sweat solution on the S_{11} magnitude of the wearable antenna made of denim substrate. The research found that, the resonant frequency is shifted by approximately 10 % when the antenna is exposed to the artificial sweat. Up to date, there is no research reported on the effect of sweat on the transmission performance. Hence, the development of sweat-like liquid using the combination of three different chemical substances is proposed in this study. The developed sweat-like liquid is expected to be suitable for laboratory and small scale investigation. In addition, the developed sweat-like liquid can be used to further examine and determine the effect of wetness on the antenna radiation and transmission performance in this study.

Moreover, the propagation characteristics of the wearable antenna are greatly affected by several factors such as the human body movements and changes in body posture [24]–[26]. An animated human movement and realistic measurement have been performed in order to study the effect of the body movement on the antenna transmission and propagation characteristics. Previous studies demonstrate that during some daily activities such as exercise, jumping, or even walking, the body dynamic will cause significant degradation on the antenna radiation and transmission performance [25], [27], [28]. However, in these previous works, the antenna alone is used as the transmitter during the characterization. None of the research is found to further investigate and characterize the factors that affect the propagation characteristics of an antenna with the inclusion of an AMC surface. The inclusion of AMC surface may modify the antenna propagation characteristics depending on the position of transmitter and receiver as well as dynamic body movement. Therefore, propagation characteristics of antenna integrated with AMC surface using the proposed medical-friendly material need to be done considering factors such as different height and angle between the transmitter and receiver. Moreover, the effect of human body movement such as degree of turning and bending are considered in this study too. In addition, the presence of additional obstacles in front of the antenna with AMC are likely to influence the transmission and propagation performance. Previous study shows that, the presence of obstacle such as tree in between the transmitter and receiver contribute to the signal attenuation [29]. However, no further research is found to investigate the effect of common obstacles such as book and sweatshirt on the propagation characteristics. These obstacles are commonly found in real situation and present near to the human body. Therefore, it is worth to further characterize and determine the effect of these obstacles on the propagation characteristics. Furthermore, there are limited research presents measurement in the actual home-monitoring setup. Therefore, real home-monitoring setup will be considered in this study to mimic the real situation of in-house monitoring application considering daily routine and activities of the user.

1.3 Research Objectives

The objectives of the current research are:

i. To propose new substrate material for wearable application
ii. To design and fabricate flexible antenna and flexible AMC surface using medical-friendly material
iii. To develop a sweat-like solution in order to investigate the effect of human sweat on the antenna performance
iv. To examine the off-body transmission and propagation characteristics of the flexible antenna with AMC surface considering the actual home-monitoring environment

1.4 Scope of Research

This study starts with an extensive literature review in order to understand the basic concept of antenna design and the fundamental of AMC working principle. CST Microwave Studio is used as the simulation software to design the antenna with AMC. Antenna performance parameter such as S_{11} magnitude, radiation pattern, gain, and total efficiency are considered in this study. Whilst, the antenna transmission performances are discussed in terms of S_{21} magnitude and received power. The main focuses of this study is to develop a flexible antenna with AMC surface for on-body applications using a medical-friendly material as the dielectric substrate. There are various types of medical materials that are widely available in the market. However, the proposed flexible antenna with AMC surface is targeted for on-body applications where the antenna can be placed directly on the human body. Therefore, this study introduces and investigates the possibilities of three different medical materials (transdermal cotton patch, semi-transparent film, and self-adhesive bandage) to be used as the antenna's substrate. In this study, the flexible antenna and AMC are limited to the operating frequency of 2.4 GHz. Material characterization has been conducted using open-ended probe. Conventional bowtie antenna is designed for the initial investigation using the proposed substrate materials. Wetness test and repeatability test are conducted to explore the possibilities of the proposed medical material to be used as the antenna substrate. Next, the conventional bowtie antenna is miniaturized using meandering technique. Few series of parametric studies have been conducted to obtain an optimized antenna design at 2.4 GHz. In additions, the AMC surface is designed using the selected substrate materials. The antenna performance above the AMC surface is studied by varying the the AMC array size, the position of the antenna above the AMC surface as well as the separation distance between the antenna and the AMC surface. Finally, an optimum flexible antenna with AMC surface is proposed and denoted as Skin-Contact Antenna with AMC (SCA-AMC).

To further quantify the SCA-AMC performance for on-body conditions, various experiments have been conducted. The factors that contribute to the transmission loss are investigated in terms of the presence of the human body and obstacles in between the transmitter and receiver. Line-of-sight and non-line-of-sight conditions between the transmitter and receiver are also taken into consideration during the measurements. Four different body movements are considered in this study in order to mimic the daily situation. The off-body measurements are conducted in an anechoic chamber with a maximum distance of 300 cm between the transmitter and receiver for two different conditions (with and without the human body). In the measurements, the proposed SCA-AMC is used as the transmitter and wideband horn antenna is used as the receiver. The proposed flexible antenna with AMC surface is integrated with the available wireless ECG sensor kit in order to test its reliability for actual applications.

1.5 Thesis Organization

The thesis consists of seven chapters. Chapter 1 briefly introduces the background of the research, problem statement, research objectives, and the scope of the research.

Chapter 2 discusses the background of the flexible antenna and AMC for wearable applications. Works related to the propagation characteristics of wearable antenna are also reviewed in this chapter.

The method used in this thesis is discussed in detail and presented in Chapter 3. The discussions start with the process to characterize and select the best flexible material to be used in the antenna and AMC design. Then, the method to design and optimize the antenna and AMC operate at 2.4 GHz is discussed. The measurement process to explore the off-body transmission and propagation characteristics is also presented in this chapter too.

In Chapter 4, numerical analysis of the antenna and AMC design is presented. The chapter starts with the introduction of three different flexible materials and processes to determine the suitable flexible material to be used as the antenna's and AMC's dielectric substrate. Then, the miniaturization of the bowtie antenna and AMC design are discussed.

In chapter 5, the antenna performance near the human body with and without the AMC surface is explored. Besides that, off-body transmission and propagation characteristics are discussed. The results are presented in terms of S_{21} and received power, P_r. Several conditions that are expected to affect the transmission and propagation characteristics such as body movement, the effect of water and sweat and also the presence of obstacles close to the human body are also considered and tested.

Chapter 6 presents the possibilities of the proposed flexible SCA-AMC to be integrated with the wireless system. The real-time monitoring ECG signal for in-house monitoring by varying the position and distance between the transmitter and receiver are presented in this chapter.

Chapter 7 summarizes some important conclusions obtained from this research as well as the significance of the research finding. Future works are also suggested.

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Appendix A

LIST OF PUBLICATIONS

Journal

[1] N. Othman, N. A. Samsuri, M. K. A. Rahim, K. Kamardin "Low specific absorption rate and gain-enhanced meandered bowtie antenna utilizing flexible dipole-like artificial magnetic conductor for medical application at 2.4 GHz" Microw Opt Technol Lett. pp 1– 9, 2020

[2] N. Othman, N. A. Samsuri, M. K. A. Rahim, N. H. Sulaiman "Water ageing effect on wearable antenna made of medical-friendly and transdermal material at 2.4 GHz" J. Phys.: Conf. Ser. 1502 012011, 2019

[3] N. Othman, N. A. Samsuri, M. K. A. Rahim, K. Kamardin, H. A. Majid "Meander bowtie antenna for wearable application" TELKOMNIKA, Vol.16, No.4, pp. 1522-1526, 2018

[4] N. Othman, N. A. Samsuri, M. K. A. Rahim, K. Kamardin," Design and analysis of flexible bow-tie antenna for medical application" Journal of Electrical Engineering, Vol.16, No.1, pp. 17-21, 2017

Conference & Proceeding

[1] N. Othman, N. A. Samsuri, "Performance of Skin-Contact Meandered Bowtie Antenna with AMC Exposed to Sweat-like Liquid for Health Monitoring" International Conference on UK-China Emerging Technologies (UCET), August 2020, Tele-presentation

[2] N. Othman, N. A. Samsuri, M. K. A. Rahim, K. Kamardin, "Transmission Characteristic of Meandered Bowtie Antenna at 2.4 GHz in proximity to human body" IEEE Asia-Pacific Conference on Antennas and Propagation (APCAP),

August 2018, New Zealand

Awards

[1] Best Student Paper Award - 2020 International Conference on UK-China Emerging Technologies (UCET) with paper titled “Performance of Skin-Contact Meandered Bowtie Antenna with AMC Exposed to Sweat-like Liquid for Health Monitoring”.

[2] Gold Medal - 2020 Industrial Art and Technology Exhibition (INATEX 2020) product title “Skin-Contact Transdermal Patch Antenna for Perpetual Health Monitoring Application”.

Patent

[1] Skin Contact Flexible Antenna Assembly Utilizing Transdermal Patch For Continuous Health Monitoring