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On-Body Performance of a Frequency Reconfigurable Wearable Antenna for 5G Health Monitoring Application

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Abstract: This paper presents the design and simulation of a meandered bowtie frequency reconfigurable wearable antenna for a 5G health monitoring application. The antenna is based on a transdermal patch as the substrate, hence it offers convenience when it is applied on a user as compared to other recent developed wearable antennas. The antenna can cater to various frequencies especially the 5G frequency bands in Malaysia (700MHz, 3.5GHz) and Indonesia (2.3 GHz, 3.4 - 3.6 GHz). Studies on the deployment of the antenna on a body phantom are also presented in this paper as well as several techniques to reduce the on-body effects. Results have shown that the design can be a promising candidate in wearable healthcare monitoring applications as well as a reference for future research and studies.

Keywords: Frequency reconfigurable, healthcare monitoring, on-body effect, pin diode, wearable antenna.

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1. INTRODUCTION

Over the past few years, the wearable antenna has gained plenty of interest from the microwave research community due to its promising applications. Among its application is in healthcare services which specifically can support the healthcare monitoring system [1]-[2]. In parallel the integration of 5G communication and wearable antenna has also been an interest to the researchers, therefore an ideal 5G healthcare monitoring system comprises sensors and an antenna attached to the human body which can send real-time data to healthcare providers [3].

However, many challenges arise when designing a wearable antenna as well as integrating it with the 5G communication. One of the challenges in designing an antenna that can operate in various frequency bands as 5G spectrum from country to country may differ from each other, thus wearable antenna which possess such capability may also support the growing trend of medical tourism which specifically can support the monitoring of patients travelling from country to country [4]. Recent types of frequency reconfigurable antennas have their pros and cons [5]. For instance, optical and MEMS switches require a complex doping process and require high actuation voltage respectively [6]-[7]. In reference [8], the microfluidic switch offers robustness, however, the limited range of liquid dielectric limits the reconfigurability range. Lastly, origami-based antennas are not robust when exposed to water [9].

In addition, it is known that the deployment of the wearable antenna near the vicinity of the human body may lead to the antenna performance deviation because of the radiated fields which interact with the human skin layers. Therefore, this paper presents a frequency reconfigurable wearable antenna design based on the electrical switch and the study of the antenna deployment on and near to the vicinity of the human body.

2. DESIGN CONSIDERATION AND METHODOLOGY

Fig.1 shows the proposed antenna design which was a modified version from [10]. The antenna is composed of PEC as the radiating element, transdermal patch as the substrate having the permittivity of 1.4597, tan δ of 0.0036 and its thickness of 0.25 mm. Several operating frequencies are aimed based on the 5G band of Malaysia (700 MHz and 3.5 GHz) and Indonesia (2.4 GHz, 3.4 GHz and 3.6 GHz). It is to be noted that these frequencies are also commonly used by most early 5G developing countries. To switch between those different frequencies, hence lumped element is used to simulate an ideal switch in the CST simulation where giving resistance value of 0.0001 Ω or close to 0 will simulate an ON state of the switch while giving very high resistance value or close to

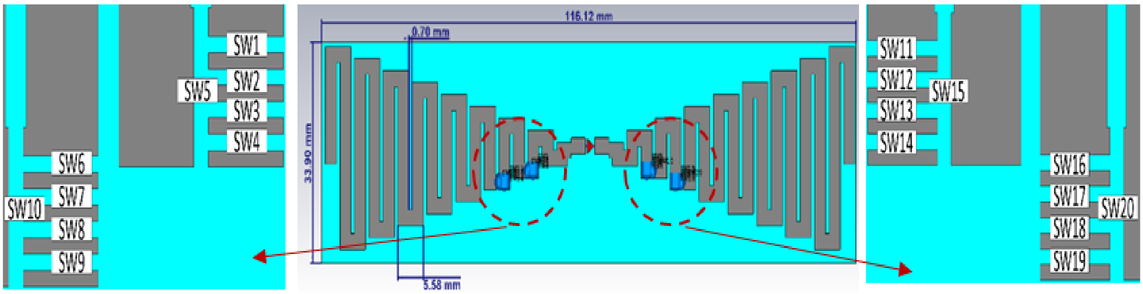

Figure 1. Top view of the proposed frequency reconfigurable wearable antenna with left arm and right arm switches configuration

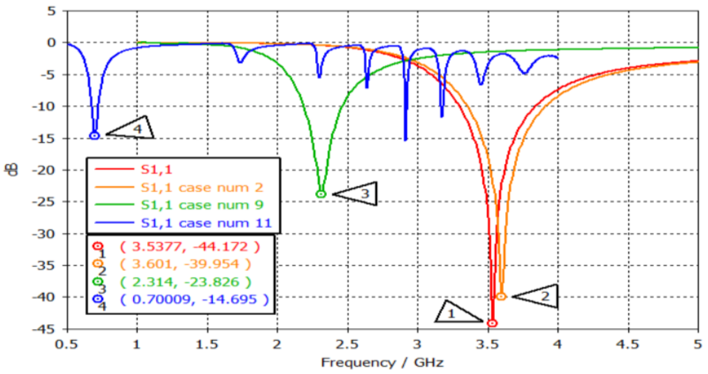

Figure 2. Top view of the proposed frequency reconfigurable wearable antenna with left arm and right arm switches configuration

Table 1. switch configuration states and its operating frequency (ON states ■)

Case	Switches states (left arm)										Switches states (right arm)										Frequency (GHz)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
1																					3.664
2	■										■										3.601
3	■	■									■	■									3.538
4	■	■	■								■	■	■								3.475
5	■	■	■	■							■	■	■	■							3.43
6	■	■	■	■	■						■	■	■	■	■						2.404
7	■	■	■	■	■	■					■	■	■	■	■	■					2.377
8	■	■	■	■	■	■	■				■	■	■	■	■	■	■				2.359
9	■	■	■	■	■	■	■	■			■	■	■	■	■	■	■	■			2.332
10	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■		2.314
11	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	0.7

infinity will simulate an OFF state for the switch.

The switches are added and located in between arms at which the switches created a gap of 0.5mm between each separated radiating element. In detail, the positioning of the switches was based on the process of trial and error by simulating various lengths of the radiating element starting from the shortest length and targeting the highest frequency to the longer length and lower frequencies. In addition, the following equation is used as a guideline to expect the antenna operating frequency based on the radiating element length:

$$L = \frac{c}{2f\sqrt{\varepsilon_{eff}}} - 0.824h\left[\frac{(\varepsilon_{eff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{w}{h}+0.8\right)}\right] \qquad (1)$$

where w is the width of the patch antenna, f is the desired frequency, ε_{eff} is the effective permittivity, h is the height of the substrate, L is the length of the patch antenna. Therefore, based on the equation, by increasing the effective length of the radiating element then a lower operating frequency can be expected. Table 1 shows the frequency response for 11 switching conditions. Based on the simulation it is noticed that there are 4 main switching cases to obtain the targeted frequencies which are switching cases 2, 3, 5, and 11, respectively.

3. Results and Discussion

3.1 Frequency Response for Different Switching Condition

Fig. 2 shows the return loss of each of the switching cases for the desired frequency which are 3.6 GHz, 3.5 GHz, 2.3 GHz and 0.7 GHz, respectively. It is noted that the good return loss is affected by the capacitance and inductance effect between each of the meandering, hence increasing the signal quality. However, despite the ability to cater for the desired frequency, the whole dimension of the antenna is relatively large which has a total area of 116 mm □ 34 mm in which the 700 MHz contribute to the longer radiating element in the design.

3.2 On-Body and Off-Body Comparison

The designed antenna with the switching configuration for 2.3 GHz with the reduced arm length version was then simulated on a phantom body which consists of three layers with each having the area 40.62x12.00mm as shown in Fig. 3. The first layer has a thickness of 1.5 mm skin with a permittivity of 5.3, a conductivity of 0.0981 S/m, and a density of 911 kg/m^3. The second layer is 20 mm fat with a permittivity of 5.3, conductivity of 0.0981 S/m, and a density of 911 kg/m^3. The last layer is the 30 mm muscle layer with a permittivity of 52.9, the conductivity of 1.64 S/m, and the density of 1090 kg/m^3.

Fig. 4 shows indicate that the attachment of the antenna on the body phantom leads to frequency shifting from 2.3 GHz to 6.98 GHz. This is due to the oscillating fields that decay exponentially towards the skin which when body phantom is within the vicinity of the field it can modify the antenna performance as well as shift the resonant frequency.

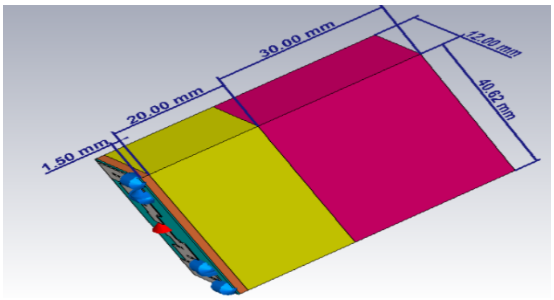

Figure 3. Attaching the designed antenna on 3 layers body phantom

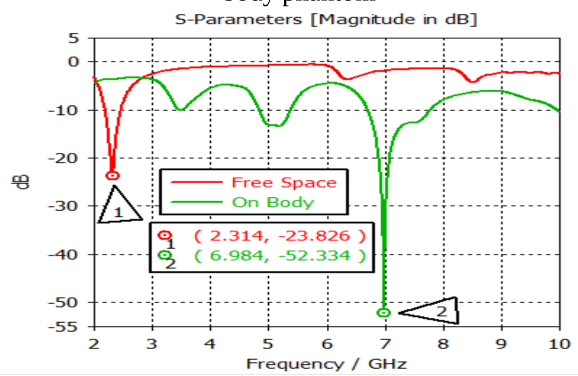

Figure 4. Simulated S11 result for on and off body cases

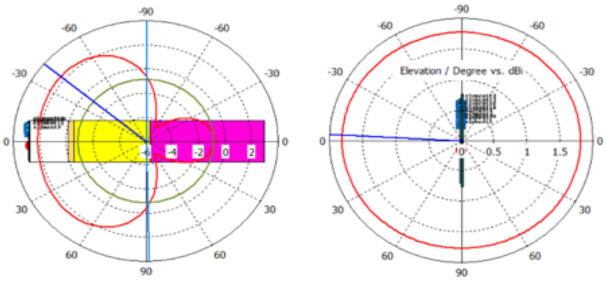

Figure 5. The simulated radiation pattern for on body case (left) and in free space (right)

Fig. 5 shows the radiation pattern in free space and on-body cases with both having the 2.3 GHz switch configuration. For the on-body case, the main lobe magnitude obtained is 2.36 dBi with a side lobe level of -3.2 dB, while an omnidirectional pattern is achieved in the free space case. However, it is noted that the existence of the back lobe indicates there are oscillating fields in which energy decays exponentially towards the skin that lead to coupling effect and energy absorption thus affecting the antenna performance and radiation.

3.3 Airgap Inclusion in Between the Antenna and Body Phantom

Fig. 6 shows the return loss for the variation of the air gap distance between the antenna and body phantom. The introduction of airgap is meant to reduce field exposure by the skin therefore able to reduce the shifting of the resonant frequency.

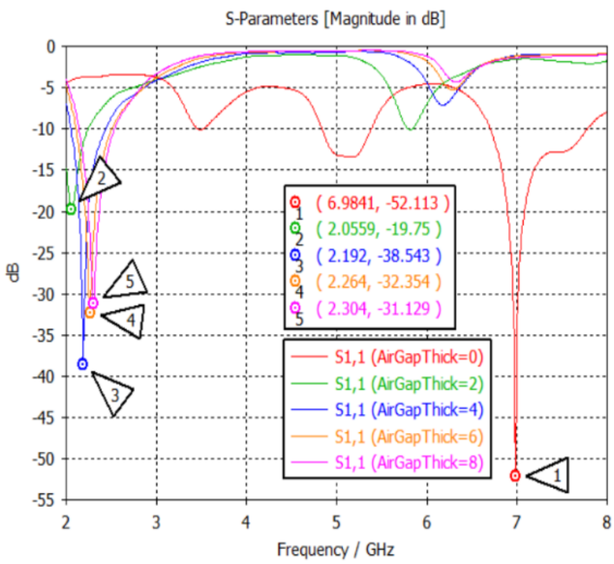

Figure 6. Simulated return loss, S11 for airgap distance variation

3.4 Adding Substrate Thickness

Introducing some distance between the antenna and the human body has proven capable to reduce the field exposure that shifts the resonant frequency. By increasing the substrate thickness, the field is attenuated when it has reached the skin layer, thus the desired frequency can remain as shown in Fig.7. Despite the result having shown a promising offer to reduce frequency shifting, however, the substrate thickness that needs to be introduced is relatively thick of approximately 10 mm.

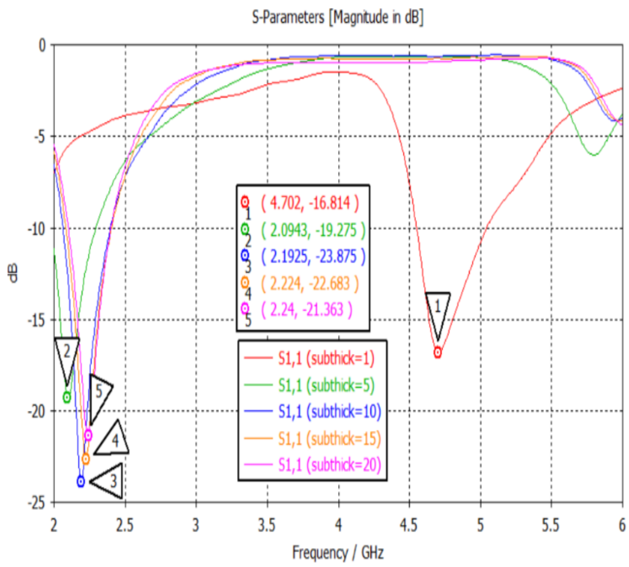

Figure 7. Simulated return loss, S_{11} for variation of substrate thickness

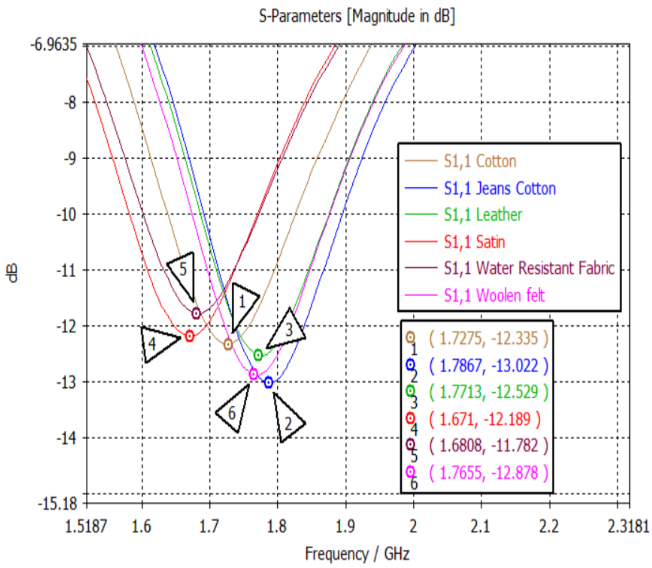

Figure 8. Simulated return loss, S11 for different stacked materials.

3.5 Stacking New Materials Beneath the Antenna

Another simple solution to reduce the on-body effect is by attaching the antenna on clothes or stacking on another fabric layer material as well as reducing the thickness of the whole system. Therefore, several materials as shown in Table II are considered in this study to be stacked between the antenna substrate and the body phantom. The electrical properties of these materials are obtained from previous research on material characterization [11]-[14].

Fig 8. shows the simulated return loss and it can be seen that by comparing the cotton fabric and the woollen felt fabric, therefore, lower permittivity will result in higher operating frequency which also corresponds to the microstrip patch equation where the frequency is inversely proportional to its permittivity. In addition, it is also shown that the jeans cotton can be a promising offer to reduce the on-body effect as well as to reduce the complexity of the system design especially in terms of the required minimum distance between the antenna and the human body. Moreover, the water-resistant fabric may also become a promising material due to its characteristics to resist water or sweat so that less sweat may penetrate to the antenna which can alter the antenna performance.

Table 2. Selected materials with their electrical properties and thickness [11] – [14]

Material	Permittivity	Loss Tangent	Thickness
Cotton	1.6	0.02	0.45
Leather	2.38	0.037	1.3
Woolen felt	1.16	0.02	0.45
Water Resistant Fabric	3.8	0.0010	0.35
Jeans Cotton	1.76	0.034	0.9
Satin	1.75	0.039	0.25

3. CONCLUSION

A frequency reconfigurable wearable antenna based on the meandered bowtie shape has been designed and able to operate within the desired 5G frequency bands of 700 MHz, 2.3 GHz, and 3.4 - 3.6 GHz. In addition, a study on the deployment of the antenna on the phantom body has been conducted which shows the on-body effect may alter the antenna performance. Studies on several promising techniques to reduce the on-body effect have also been done such as the introduction of airgap, adding more substrate layers, and also stacking of other materials beneath the antenna substrate. Last but not least, further research on reducing the antenna on-body effect is expected in future studies to improve the wearable antenna performance.

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