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Design and characterization substrate integrated waveguide antenna for WBANS application

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ABSTRACT

Millimetre-wave frequencies are defined as one of the front-runner contenders for body-centric wireless communication. In this study, low-profile antenna with the substrate integrated waveguide (SIW) has been proposed that operate in the band of the millimetre-wave frequency that has been centred at 60 GHz. The proposed antenna has been implemented with the use of the FR4 substrate with εr and tangent loss of 4.3 and 0.025, respectively. The substrate height and size are 1.5875 mm and 20 mm x 20 mm, respectively. The performance of the antenna is evaluated in off-body (free space) and on-body (human voxel model), through simulation. The proposed antenna has an ultra-wideband (UWB) and a specific absorption rate the maximal (SAR) for (10 g) is 0.0344815 W/kg and for (1 g) is 0.0184723 W/kg. It achieves 74% and 63% efficiency in the off and on-body scenario, respectively. The small antenna with the exceptional matching of impedance, low SAR, broad bandwidth, and good efficiency, a good voltage standing wave ratio good (VSWR), and good front-to-back ratio (FBR). As a result, its characteristics make it one of the best potential candidates for the simultaneous transmission and reception of data at (mm-wave) band for WBAN applications.

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1. INTRODUCTION

The potential health risks of the radio frequency (RF) waves that are radiated from the antennas to the human body had emerged as one of the general concerns. The growing international movement in the field of wireless personal area networks (WPAN) and wireless body area networks (WBAN), had been increasingly gaining interest in the usable antennas that have been designed for the human body [1]. The future improvements of portable wireless will be having a significant impact on the area of wireless communications security and success, indoor constraints and arranging, social protection, and welfare, for example, bio-monitoring [2].

The antennas can be defined as key elements in designing and successfully deploying body-centric networks (BCN). The design of the BCN antennas is one of the highly challenging tasks, because of the multiple requirements for ensuring reliable links, mobility, and robustness. The antennas of the BCNs must have a small size, low profile, lightweight, and have to have high flexibility for offering conformity with the shape of the human body [3]. The low consumption of power is an additional matter which must be taken under consideration [4]. Researh by Cihangir *et al*. [5] for millimeter-waves, the high gain and the wide bandwidth are necessary for the operations to meet the high data rate requirements. In addition to that, the effect of the presence of the human user on these antennas has to be identified as the human body is one of the inherent BCN application parts. The antennas that operate in the human body vicinity have been subjected to electromagnetic distortions as a result of absorptions in loss of human body tissue as well as scattering or reflections from the surface of the body [6]. Therefore, the high efficiency of the BCN systems requires detailed evaluations of interactions between wearable antennas (on body) and free space (off body) for WBANs. In addition to that, the latest telehealth systems and the future scenarios of the 5G/IoT applications are necessitating the interconnectivity between the body-worn access points, body-worn sensors, and units of remote processing [7].

The basic challenges in the optimization of the BCN antennas are the reductions of negative impacts of the electromagnetic interactions (EMs) between the proposed antennas and biological tissues [8] The BCN can be defined as a highly attractive venue for wireless technologies of the next generation because of a wide variety of applications. The body-centric devices offer many different services. Although personal healthcare is a dominant area, its applications are covering tracking and navigation, fitness and sports, localization and detection, smartwatches and infotainment and gaming augmented reality [9]. They are expected as well to be playing a highly significant role in the 5G and IoT [10], [11]. The applicability and popularity of BCNs led to massive annual device shipments of 20 million units in 2015 and by 2020 it is estimated to increase to 187.2 million units [12], [13]. The mm-wave frequencies at 60 GHz lately gained a considerable deal of interest for BCNs as a result of high demands for the increased data rates and network capacity [14]. No licensing requirement and potential adoptions for the technologies of the 5G generations resulted in further adding to the popularity [15]. The low interferences and confidentiality that result from the high atmospheric attenuations is an additional attraction source for 60 GHz BCN [16].

Researchers worldwide exerted many efforts in studying the efficiency of antenna particularly the on\off body cases as it has been currently well-known that the human tissue almost results in achieving high levels of loss over the spectrum of the communication. Moreover, it is a fact that the human tissue has an influence on the efficiency of the antenna through the de-tuning of the frequency and distortion of the pattern of radiation [17], [18]. Despite the lower ranges of the frequency, it can be copied by utilizing embroidered fabric, slot patches, substrate integrated waveguides [19], [20].

Electromagnetic bandgap (EBG) configurations for the reduction of SAR have also been presented in [21]. An 8-element SIR head coil that is combined with a CP patch antenna for the MRIs at 298MHz in which it is concluded that the result in [22]. The ultra-wideband (UWB) antennas of the application of body area network (BAN) have been based upon EM radiations and the limits of the SAR have been suggested in [23]. It is important to mention a 2-turn external loop antenna, without a magnetic core manages to transfer a higher level of power compared to simple loop antennas which result from the uniform and low distribution of SAR. The purpose of understanding the antenna position impacts upon the phone is the manifestation of the value of the SAR [24] which has been compared to the case of reversing the location of phone [25], [26]. The fractal-base dual-band antenna is integrated with square size EBG for portable applications [27]. Furthermore, the whole body of the antenna practically performs the calculation of the mean value of the specific rate of absorption that has been estimated with the use of distributed expositor [28]. Besides, a wide range of wearable antennas was proposed to BAN applications in a monopole antenna form [29]. An inverted-F antenna is designed to manifest the performance on body configurations which were suggested in [30]. However, the inverted-F antenna has not been a compact nor unremarkable impact during the performance of the antenna.

The substrate integrated waveguide with minkowski-sierpinski fractal antenna plane area which was suggested in [31] have low efficiency as a result of important total radiation of the energy in the human body and they have to be located rather separately from the body. In order to get an efficient exploration of built-in and usable antennas for the body-centered system of wireless communications, it has been important for the assessment of interactions between the body and EM wave that has been emitted by the antenna. It is a matter of fact that interactions represent two different types, i.e. the human body impacts antenna efficiency and the effects of the EM waves on the human body. Moreover, to investigate the efficiency of the antenna as well as the effects of the electromagnetic, researchers have to use a human voxel model as one of the tools for validation prior to applying the antenna to the human body. According to the literature, it has been noticed that the majority of researchers have regarded the substrate integrated waveguide SIW with planer antennas as a highly proper candidate for portable applications as a result of the fact that it is easy to integrate, cost-effective and low profile [32], [33].

This paper discusses the comparison performance of SIW antennas between the human voxel model for an on-body environment and in the free space for an off-body. The proposed antenna operates at 60 GHz of the millimeter-wave. The CST microwave software is used to design the proposed structure. The proposed antenna is implemented using the FR-4 substrate, which has a permittivity of 4.3, a loss tangent of 0.025, and a height of 1.5875 mm. Through simulation, the performance of the proposed antenna is suitable for the purpose of attaining simultaneous transmission/reception of the data at (mm-wave) band for the applications of wireless body area network (WBAN).

2. RESEARCH METHOD

The general structure of substrate integrated waveguide SIW is shown in Figure 1. SIW parameters have to be considered. Width between vias may be found by [34].

$$a_R = w - \frac{D^2}{0.85\, S^2} \tag{1}$$

Where a_R represents the width of the waveguide, D represents the diameter of the via, and S represents the spacing between every via.

$$D \leq \frac{\lambda_g}{5} \tag{2}$$

$$S \leq 2D \tag{3}$$

$$a_R = \frac{a}{\sqrt{\varepsilon_r}} \tag{4}$$

Where *a* is the width of the rectangular waveguide standard, and λg is the guided wavelength of the SIW, which can be obtained by using [34]:

$$\lambda_g = \frac{2\pi}{\sqrt{\frac{\varepsilon_r (2\pi f)^2}{c^2} - \left(\frac{\pi}{a}\right)^2}} \tag{5}$$

Where f represents desired frequency, c represents the light speed, and ε_r represents the permittivity of the substrate.

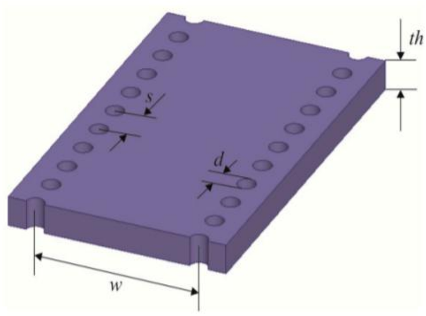
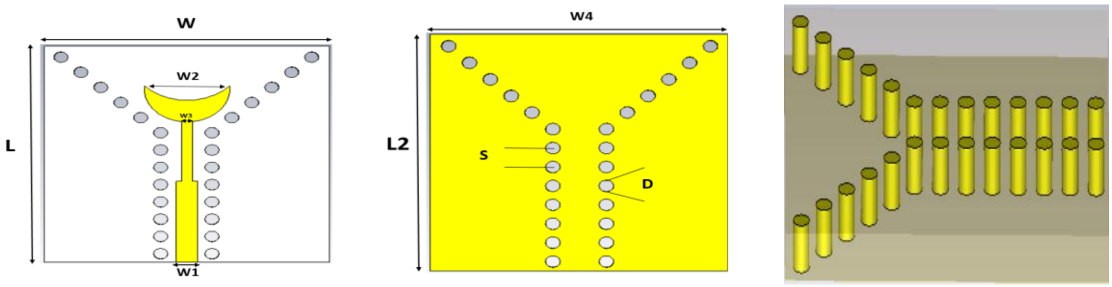


Figure 1. The general structure of a substrate integrated waveguide [34]

The proposed antenna has been has been designed with FR-4 substrate (permitivities, ε_r=4.3 and loss tangent, tan δ=0.025) with a thickness of 1.5875 mm. Figures 2(a) and (b) illustrates low-profile antenna geometrical structures with the SIW at 60 GHz. As show in Figure 2(c), the substrate height is 1.5875 mm, whereas ground and patch use the copper with a thickness, *h*=0.035 mm, the spacing of holes, diameter, and width between the holes may be specified at the 60 GHz desired frequency. Table 1 tabulates the proposed antenna's dimension.

In this study, a simulated performance of the SIW antenna on the body is performed in a human voxel model. Gustav was chosen among the other anatomical models, as observed from Figure 3(a). Gustav represents a normal-weight male that has a resolution of 2.08 mm x 2.08 mm x 2 mm [35]. Voxel models thigh area cross-section, a 3-layer human body model (fat, muscle, and skin) was used for sub-cutaneous on-body antennas. The antenna performances were assessed on-body (human voxel model) with the closest separation distance from the skin layer, roughly estimated 2 mm as shown in Figure 3(b).

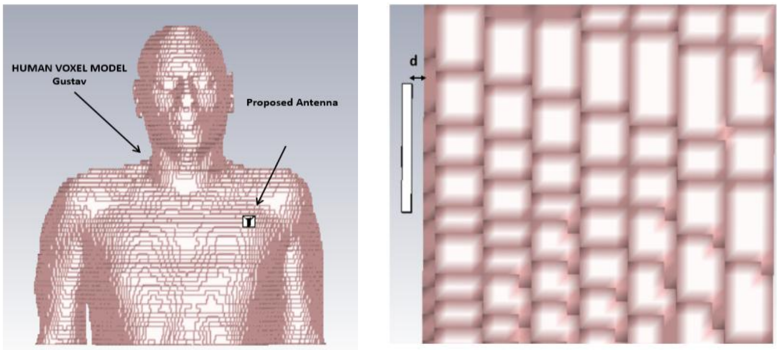


(a) (b) (c)

Figure 2. The proposed structure of SIW antenna (a) top view, (b) bottom view, and (c) SIW with the vias structures

Table 1. Parameters values of the proposed antenna with SIW (all dimensions in mm)

Variable	Patch	Substrate	Ground
W=W4	-	20	20
L=L2	-	20	20
W1	1.50	-	-
W2	5.95	-	-
W3	0.75	-	-
S	2	2	2
D	1	1	1
h	0.035	1.5875	0.035
Material	Copper	FR-4	Copper



(a) (b)

Figure 3. Location of the proposed antenna with (a) the gustav human voxel model and (b) separation distance, d=2 mm from the skin layer

3. RESULTS AND DISCUSSIONS

This section discusses and analyses the proposed low-profile antenna with substrate integrated waveguide SIW performance. Comparison between the off-body (free space) and on-body (human voxel model) has been made using CST based upon the finite different time domains. Both simulated reflection coefficients (S11) for the off-body and on-body of the proposed antenna are depicted in Figure 4. It is proved that both simulated S11 performances cover the whole millimeter-wave frequencies, i.e. from UWB by considering the reflection coefficient lower than -10 dB. The reflection coefficient, S11 at 60 GHz as shown in Figure 4 achieves -42.8 dB and -21.5 dB for off-body (free space) and on-body (human voxel model), respectively. In Figure 5, the voltage standing wave ratio (VSWR) of the proposed antennas is < 2 on/off-body at 60 GHz. Figure 6 depicts the front-to-back ratio (FBR) of 16 dB for off-body (free space) and 14 dB for on-body (human voxel model) at 60 GHz.

Figures 7(a) and 7(b) show the SAR value (10 g) with 0.0344815 W/kg and (1 g) with 0.28 W/kg at 60 GHz, respectively. SAR represents the main parameter for the characterization of power that is consumed by the (human voxel model) under the electromagnetic radiation according to the global standards established, the international commission non-ionizing radiation protection (ICNIRP) guideline 1998 [36]. ICNIRP limit 2.0 W/kg for 10 g mass of tissue as a limit of SAR, while the american national standards institute (ANSI) and federal communications commission (FCC) guidelines and procedures limit 1.6 W/kg for 1 g mass of tissue [36].

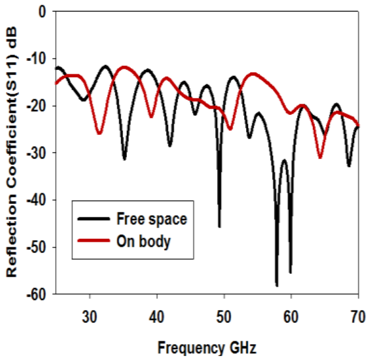


Figure 4. Simulated refection coefficient of the proposed antenna at 60 GHz

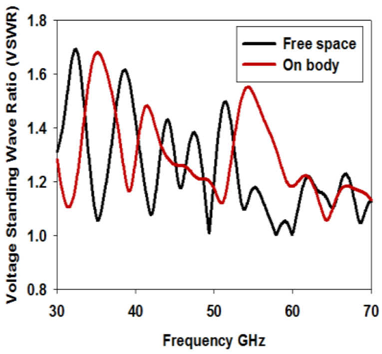


Figure 5. Simulated voltage standing wave ratio of the proposed antenna at 60 GHz

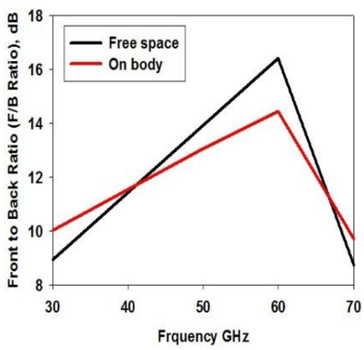
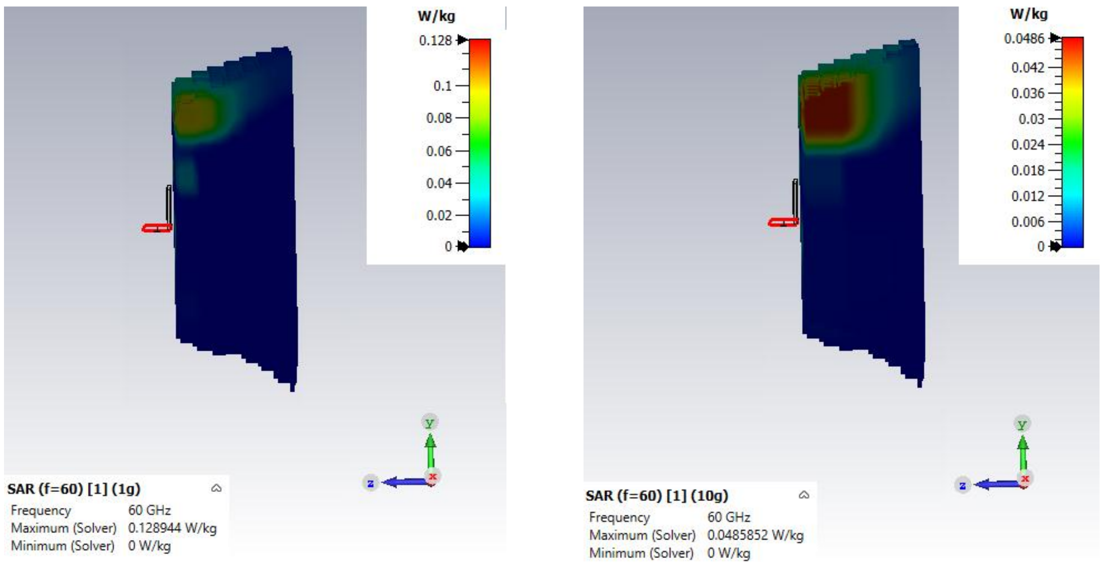


Figure 6. Simulated front-to-back ratio of the proposed antenna at 60 GHz



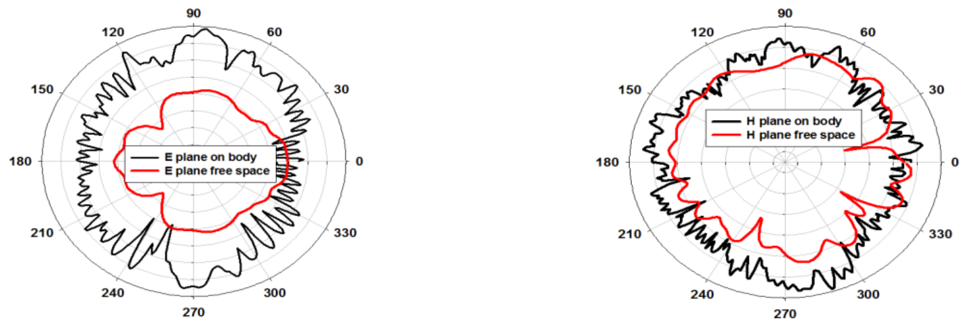
(a) (b)

Figure 7. Simulated specific absorption rate of the proposed antenna at 60 GHz value results (a) on 1 g average tissue, and (b) on 10 g average tissue

The human body's properties have affected the character of the radiation pattern. It is proved in Figure 8 showing the different simulated results between off-body and on-body performance. Table 2 tabulates all the simulated results. The proposed design is compared with recently published articles [37]–[41] which are propagated with 60 GHz as a center frequency for WBAN in terms of structure, size, and radiation characteristics to show its effectiveness. Table 3 illustrates a comparison among [37]–[41]. It is clear that the proposed antenna shows a wide bandwidth than others except for the proposed antenna as in [37]–[41] which has a sophisticated shape. Most importantly, the proposed design works perfectly with on-body techniques. This comparison illustrates the performance of the proposed antenna for BCN applications at 60 GHz.

Table 2. The simulated results of the proposed antenna at 60 GHz

Parameter	Off-body value	On-body value
Reflection coefficient dB	-42.8	-21.5
Specific absorption rate value W/kg	--------	0.28, 0.0344815
Voltage standing wave ratio dB	1.0	1.2
Front-to-back ratio dB	16	14



E- plane **H-plane**

Figure 8. Simulated radiation pattern of the proposed antenna at 60 GHz

Table 3. Comparison between the proposed antenna and state of the art mm-wave antennas

Ref.	Antenna structure	Size (*mm*)	10 dB BW (GHz)	Off-body S11 (dBi)	On-body S11 (dBi)	Off-body FBR (dB)	On-body FBR (dB)	SAR 1g W/kg	SAR 10g W/kg
[37]	End-fire Yagi-Uda array with 18 directors	33×15×0.127	55-60	-22	-18	13	11	N/I *	N/R **
[38]	End-fire textile Yagi-Uda array with 10 directors	26×8×0.2	57-64	-30	N/I *	14	N/I *	N/I *	N/R **
[39]	SIW-fed disc-like antenna with dielectric loading	49.7× 31 ×3.1	59.3-63.4	-20	N/I *	11	N/I *	N/I *	N/R **
[40]	SIW horn with metallic vias and plates	24×17×0.79	56.7-62.5	-23	N/I *	13	N/I *	N/I *	N/R **
[41]	Microstrip-fed four-patch array on 3 mm thick ground	20×8×3.13	59-65	- 33	N/I *	15	13	N/I *	N/R **
This work	low profile antenna with substrate integrated waveguide (SIW)	20×20×1.6	20-70	-42.8	-21.3	`16	14	0.28	0.0344815

* The paper does not investigate human body effects on the antenna
** The authors have not reported this value

4. CONCLUSION

A SIW very low-profile antenna that is useful in the WBAN has been proposed in the present study. The effects of the electromagnetic radiations that have been emitted from the antenna on human bosy (human voxel model) has been investigated. For the purpose of analyzing SAR simulation, the proposed antenna achieved a lower SAR value (10 g) with 0.0344815 W/kg, and (1 g) with 0.2.8 W/kg at 60 GHz. Even though the reduction of the size of the antenna is a distinguishing antenna development topic, the efficiency of the antenna considerably drops for the small antennas. Therefore, the suggested antenna resonates at 60GHz of millimeter-wave frequencies band for the applications of WBAN. The result showing a promising S11 which is below -10 dB for on/off-body and achieved wideband UWB. Additionally, with good impedance matching, low SAR, broad bandwidth, and good efficiency make it one of the suitable candidates for attaining simultaneous transmissions/receptions of the data at (mm-wave) band for the applications of WBAN.

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