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A wearable finger-ring antenna for smart-home Internet of Things

***Abstract**. In this paper, a wearable finger-ring loop antenna is proposed. The antenna is conformal to the finger and fashionable at the same time. The antenna obtained a broad-10 dB bandwidth covering multiple frequency bands which are TD-LTE (B-TrunC) (1.447–1.467 GHz), ISM (902-928 MHz, (2.4-2.5 GHz) LTE42/43 (3.4–3.8 GHz), WiMAX (3.3–3.8 GHz), 5G band n78 (3.4–3.8 GHz). The antenna has obtained gain values of up to -16.1 dBi at 2.45 GHz and robust performance with an up to 3 mm spacing from the finger. In addition, the antenna can work over a distance of onger than 8.6 m indoor which is satisfactory for smart-home IoT applications.*

Streszczenie.** W tym artykule zaproponowano antenę pętlową na palec do noszenia. Antena jest dopasowana do palca i jednocześnie modna. Antena uzyskała szerokie pasmo 10 dB obejmujące wiele pasm częstotliwości, takich jak TD-LTE (B-TrunC) (1,447-1,467 GHz), ISM (902-928 MHz, (2,4-2,5 GHz) LTE42/43 (3,4-3,8 GHz), WiMAX (3,3-3,8 GHz), pasmo 5G n78 (3,4-3,8 GHz). Antena uzyskała wartości zysku do - 16 dBi przy 2,45 GHz i solidną wydajność przy odległości do 3 mm od palca. Ponadto antena może pracować na odległość większą niż 8,6 m wewnątrz pomieszczeń, co jest zadowalające dla aplikacji IoT inteligentnego domu. (**Poręczna antena pierścieniowa do inteligentnego Internetu rzeczy w domu)

Keywords: IoT, ISM, 5G, wearable antenna.
Słowa kluczowe: IoT, ISM, 5G, *antenna di noszenia*

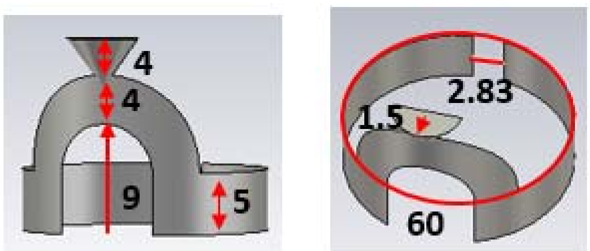
Introduction

Recently, wearable antennas are widely used in different applications including healthcare where different parameters such as pressure and temperature are monitored [1]. In addition, wearables have been recently integrated to smart-home IoT applications in which different activities inside the house are controlled by devices worn on the human body [2]. The wireless control of such devices are mainly enabled by the antenna which transmits and receives data wirelessly. To obtain an efficient connection and to maintain it, the antenna is required to perform well on the human body. The human body absorbs most of the antenna radiation and degrades its performance. This effect can be reduced by isolating the human body effect from the antenna. In addition, the antenna is required to be small in size, conformal to the human body. Wearable antennas for smart home applications are susceptible to larger attenuation losses attributed to the indoor environment [3]. Hence, it should obtain good gain values to overcome such attenuation losses and to build a communication link over a distance far enough to support the intended applications. Several antennas have been recently proposed for different smart IoT wearables. In [4-5], smart watch antennas were proposed. However, these antennas were of dual band only. Another antenna based on Complementary Split Ring Resonators (CSRRs) was proposed in [1] for 5G and IoT applications. That antenna was large in size with a diameter of 39.4 mm and of a complicated structure. A portable wearable antenna was proposed in [6], That antenna was flexible and worked for multiple frequency bands. In [7], a monopole antenna for finger ring has been proposed. That antenna operated in the Ultra Wide Band (UWB) (7.25 GHz–10.25 GHz). Another wearable finger antenna was also proposed in [8]. It worked around 5 GHz. However, it had a typical microstrip structure which is less attractive for wearable rings. Moreover, that antenna was not evaluated around a finger model. In [9], a wearable finger ring antenna array was proposed for 5G/mmWave applications at 28 GHz. That antenna was not accurately modeled on a finger model which may lead to distutbances in the antenna performance after implementation in relaity. Indeed, wearable antennas can be be used on different body parts. However, the werable finger antenna might be less suciptible to the human body losses and attenautaions. In addition the direction of its radiation can be controlled by different movements of the finger and hand. Hence, a wearable finger ring antenna is proposed in this paper. The antenna is of simple and an appealing structure at the same time. This is preferred as the antenna will be an accessory piece. The proposed antenna has a number of appealing features including simpilcity, broad bandwidth and performance robustness at the same time. All of these features are integrated together in the same design to overcome shortcomings of previous designs proposed in literature.

This paper is arranged as follows: First, the design structue is presented. The perfromance is then analyzed and evaluated after that. The paper is finally concluded in the final section.

Design Geometry and Methodology

The proposed antenna has a ring structure which forms a loop when bent around the human finger. It can be seen in the following figure:



(a) (b)

Fig.1. The proposed antenna: (a) oblique side and (b) oblique top structures (dimensions in mm)

The antenna is designed around human finger model as shown in Fig. 2. It has a cylindrical shape, 10 mm in radius and 80 mm in length and an equivalent material of a human skin. Its dielectric properties are summarized in Table 1. It is obvious that the relative permittivity decreases with frequency while the conductivity increases [10]. To expedite the overall design process, simulations are conducted on the human finger model from the beginning. The design is conducted using the Microwave CST software. Hexahedral meshes and time-domain solver are used [11].

The design aims to obtain the following objectives:
- conformity to the human finger.
- broad bandwidth covering the 2.4-2.5 GHz ISM bandwidth at least.
- attractive shape as an accessory piece.

Table 1. Dielectric properties of dry skin at centre frequencies of the bands of interest [10]

Frequency (GHz)	Relative permittivity (ε_r)	Conductivity (S/m)
0.915	41.3	0.872
1.457	39.528	1.056
2.45	38	1.464
3.55	36.96	2.06
3.6 GHz	36.92	2.09

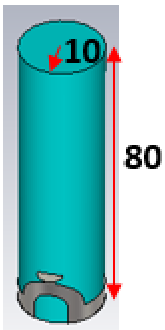


Fig.2. The proposed antenna on the human finger model (dimensions in mm)

To obtain these objectives the design went through the following steps:
Step 1. A simple loop antenna structure is first selected. This structure is typical for rings. It is initially designed as a flexible rectangular strip that can be bent around the finger. Its overall length is 60 mm. It has a width of 5 mm only. The antenna is well matched at this stage at the intended bands. It has obtained a gain value of -21 dBi. The antenna at this step is shown in Fig. 3.
Step 2. The second step aims at making the antenna much more fashionable while obtaining a larger gain at the same time. Hence, the antenna structure has been modified as follows: The flat strip has been bent into a dome-like shape as shown in Fig. 3. This makes the design much more appealing as a finger ring than the normal strip. It also worked to increase the antenna radiation efficiency and gain. This is due to the increase of the magnetic field ($\overline{H}$ (A/m)) at the center of the bent part [12-13].

(1) $$\overline{H} = \frac{I}{2\pi\rho}(\tan\theta + \pi - \theta)\vec{a}_\phi$$

Where I (A) is the input current, ρ (m) is the radius and θ is the angle shown in Fig. 3.
As the bent shape is a circle, θ is 45 degrees. The magnetic field intensity will increase by a factor of 3.356 in comparison with the flat strip of which the magnetic field intensity can be calculated as [13]:

(2) $$\overline{H} = \frac{I}{2\pi\rho}\vec{a}_\phi$$

The near magnetic field plays a major role in controlling the antenna gain for this case and increasing its value increases the gain accordingly [14].
Step 3. Half conical piece has been added on the top of the bent part. For this step, an additional piece on the top has been added. This makes the antenna much more fashionable. It has a radius of 1.5 mm and height of 4 mm. It also has the effect of increasing the gain as the antenna is top-loaded by this conical piece [15].

The simulated reflection coefficient of the three cases can be shown in Fig.4.

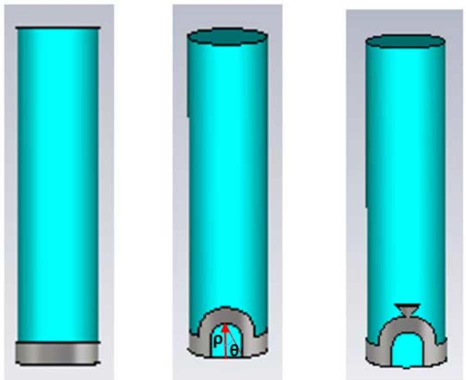


Fig.3. The antenna structures on the finger model of: (a) step 1, (b) step 2 and (c) step 3 of the design process.

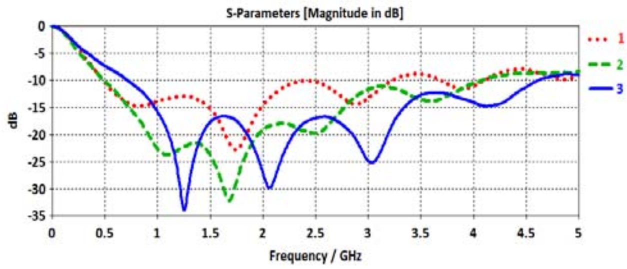


Fig.4. The simulated reflection coefficient S_{11}(dB) for the antenna in: step 1(1), step 2 (2), step 3(3)

The results in the figure indicate that the optimized antenna structure has obtained the deepest matching below -10 dB. The antenna has a deep matching (S11< -10 dB) TD-LTE (B-TrunC) (1.447–1.467 GHz), ISM (902-928 MHz, (2.4-2.5 GHz) LTE42/43 (3.4–3.8 GHz), WiMAX (3.3–3.8 GHz), 5G band n78 (3.4–3.8 GHz) [6].

Performance and Analysis

The simulated antenna gain and radiation efficiency at the centre frequencies of the bands of interest are summarized in Table 2.

Table 2. The simulated max-3D gain and radiation efficiency of the proposed antenna

Frequency (GHz)	Max-3d gain (dBi)	Radiation efficiency (%)
0.915	-28.3	0.11
1.457	-22.1	0.32
2.45	-16.4	1.4
3.55	-16.2	1.5
3.6 GHz	-16.1	1.55

The results indicate that the gain and radiation efficiency increase with frequency despite of the increase in attenuation losses. This is because the antenna is electrically larger.
The radiation pattern of the final antenna at the different frequencies is shown in Fig. 5.

The results indicate that the antenna obtained an omnidirectional radiation pattern almost in the azimuth direction away from the human body direction. Almost the same gain is obtained at both of 3.55 and 3.6 GHz frequencies as they almost have the same values.

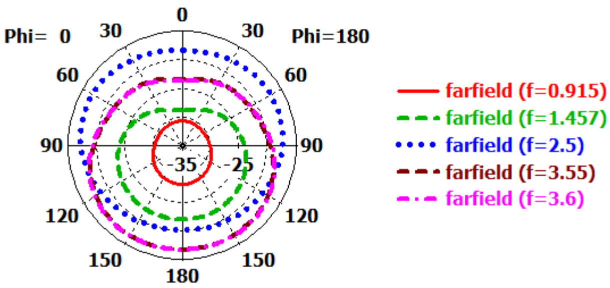


Fig.5. The simulated gain pattern of the proposed antenna (polar plot) at Phi=0 plane (azimuth plane) and at f=0.915, 1.457, 2.45, 3.55 and 3.6 GHz.

One important parameter that the antenna should satisfy is the Specific Absorption Rate (SAR) limitations. The maximum 1-g average SAR should be less than 1.6 W/kg or 2 W/kg [16]. For a strict condition, the design has been evaluated for 1.6 W/kg satisfaction. The simulated max 1-g SAR values at all of the operating frequencies for the proposed antenna are summarized in Table 3.

Table 3. The simulated 1-g average SAR (W/kg) of the proposed antenna

Frequency (GHz)	Max 1-g average SAR (W/kg)
0.915	304.9
1.457	246.9
2.45	271.5
3.55	258.6
3.6 GHz	260.8

The results in the table indicate that the antenna can be provided with up to 5.24 mW (7.193 dBm) while still satisfying the SAR limitations.

Evaluation of Performance Robustness

The wearable ring could not exactly fit around the finger. Hence, its performance with some spacing distance around the finger should be evaluated. The antenna has performed well while keeping a deep matching below the -10 dB for a distance of up to 3 mm. The reflection coefficient of the proposed antenna at different spacing between the finger and antenna is shown in Fig. 6.

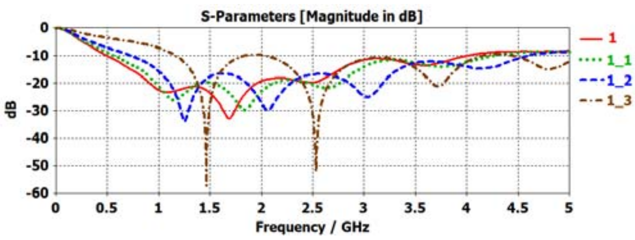


Fig. 6. The simulated reflection coefficient S_{11}(dB) for spacing of: 1: 0, 1_1: 1, 1_2: 2 and 1_3: 3 mm.

The results in the figure indicate that the resonant frequency tends to shift up as the spacing distance between the antenna and finger increases. This is because the effective permittivity around the antenna decreases with the spacing. Nonetheless, the antenna has always obtained deep matching for all the frequency bands of interest at a spacing of up to 3 mm between the antenna and finger. It is worth indicating that 0.4 dBi larger gain is obtained at case of the 3 mm-spacing.

Link budget Calculations

The antenna is intended to work inside home for smart home applications. Hence, it is important to evaluate the distance of communication over which this antenna communicate in an indoor environment. This distance can be calculated using Eqs. 3-4 [17]. The link parameters for this case are summarized in Table 4.

Table 4. Indoor link parameters and calculated distance of communication

Parameter	Symbol	Value	
Input power (dBm)	P_{tx}	0	
Receiver sensitivity (dBm)	P_{rx}	-96	
Path loss exponent	N	3	
Transmitting antenna gain (dBi)	G_{tx}	f=0.915	-28.3
		f=1.457	-22.1
		f=2.45	-16.4
		f=3.55	-16.2
		f=3.6	-16.1
Receiving antenna gain (dBi)	G_{rx}	2.15	
Link Margin (dB)	LM	10	
Calculated distance (m)	D	f=0.915	8.6
		f=1.457	10.6
		f=2.45	11.22
		f=3.55	8.9
		f=3.6	8.89

An input power of 0 dBm is assumed. This still smaller than the maximum input power that can be provided to the antenna which is calculated as 7.193 dBm in the previous section. A receiver sensitivity of -96 dBm is also considered for a receiver of small Bit Error Rate (BER) [18]. The receiving antenna is assumed to be omnidirectional in order to receive signal from the ring in different directions and orientations. A link margin of 10 dB is assumed. This is to take all possible losses from doors, windows and floor reflections into consideration.

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_P - LM \tag{3}$$

Where L_P (dB) is the path loss which can be calculated as:

$$L_P = 10n\log\left(\frac{d}{d_0}\right) + 20\log\left(\frac{4\pi d_0}{\lambda_0}\right) + S \tag{4}$$

Where d_0 (m) is the reference *distan*ce which is taken at 1 m and λ_0 (m) is the free space wavelength. *S* (dB) is the standard deviation which is considered zero in this equation.

Based on the above link parameters and equation, the distance at the above mentioned frequencies are calculated and summarized in Table 4. The antenna communicates over a distance of longer than 8.6 m. This is long enough to support communications inside homes. It is worth pointing that an extra margin of 10 dB (the link margin) is considered which is large enough to take the effect of other losses from floor and walls in considerations.

Comparison with Previous Designs

Table 5 summarizes most recent work proposed for finger wearable antennas. The table indicates that most of previous designs were either for one or dual frequency bands [19] while the proposed antenna supports up to five frequency bands. The gain values reported in literature for some designs such as that in [9], and [22] were relatively larger than that for the antenna proposed in this paper. However, this is because they were in free space and not around the human finger model. Generally speaking, antenna arrays are expected to obtain larger gain values and this justifies the larger gain value obtained for the design in [21]. However, this is usually accompanied with larger power consumption and design complexity. Some designs such as that in [9], [21] and [22] work for relatively high frequencies. Indeed, path losses increase with frequency and hence short ranges of communication are expected for this case.

Moreover, many of the previous antenna structures are not appealing to be worn as a wearable ring. This applies to the designs in [8] and [9].

Overall, the proposed antenna has an appealing structure, it has also a robust performance over longer than 8.6 m. It probably had the largest number of operating frequency bands for wearable finger ring applications.

Table 5. A comparison between previous and proposed work

Ref	Gain (dBi)	Rad eff (%)	Centre freq (GHz)	Structure	range (m)
[19]	-10 -5	---	2.45 0.950	Multi-strip ring	---
[9]	5.14	---	28	Typical planar patch array	---
[20]	---	45%	2.45	Folded dipole	---
[21]	5	---	28	Circular phase array	---
[7]	6.9	44.7	5	Typical patch antenna	
[22]	5.5	---	29	Helical	---
This work	-28.3 -22.1 -16.4 -16.2 -16.1	0.11 0.32 1.4 1.5 1.55	0.915 1.457 2.45 3.55 3.6	Loop with a half-pyramid piece	8.6 10.6 11.22 8.9 8.89

Conclusions

In this paper a wearable finger ring antenna is proposed for smart home IoT applications. The proposed antenna has a broad bandwidth which covers multiple frequency bands. In addition, the proposed antenna can maintain its performance at different spacing up to 3 mm between the ring and finger which guarantees that it can perform well for different people of different finger sizes. Also, the antenna can perform over a distance of longer than 8.6 m which is long enough to support indoor smart home applications. All of these features make this antenna a good candidate for smart home IoT applications.

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