Anupma Gupta[1], Shonak Bansal[2], Ahmed Jamal Abdullah Al-Gburi[3], David I. Forsyth[3], Mohd Muzafar Ismail[3]

[1] Department of Interdisciplinary Courses in Engineering Chitkara University, Punjab
[2]Chandigarh University, Punjab
[3]Center for Telecommunication Research & Innovation (CeTRI), Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Jalan Hang Tuah Jaya, Durian Tunggal, Melaka 76100, Malaysia
ORCID: 1.0000-0001-7614-1756; 2. 0000-0002-6551-6011; 3. 0009-0002-1818-2052; 4. 0000-0002-5305-3937; 5. 0000-0003-3177-997X

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Design of an elliptical arc-shaped antenna at 37 GHz and performance analysis for 5G on-body application

***Abstract**. This paper presents a compact 5G wideband antenna designed for body-centric networks (BCN) operating on the Ka band. The antenna design includes a simple arc-shaped radiator patch with full ground plane and transformer impedance feedline. Computer Simulation Technology (CST) Microwave Studio Suite, a reliable electromagnetic simulation program, is used for the antenna's design and simulation. The antenna was simulated in free-space, and its resonant frequency is found to be 37 GHz, falling within the Ka band and 5G's n260. The proposed antenna has a size of 37.4 mm^3, and it offers a wide impedance bandwidth of over 5.7 GHz (34.3-40 GHz). At the resonant point, the antenna exhibits a gain of 4.48 dBi and unidirectional radiation pattern. Parametric studies demonstrated that by reducing the arc width, the antenna bandwidth can be improved but with destroying impedance matching. The antenna is proposed for use in body area network applications. To evaluate its on-body performance, a muscle equivalent body model is virtually developed. The on-body performance is assessed by placing the antenna in close proximity to body model. The results of the on-body simulations showed that at 37 GHz, the reflection coefficient is 29.5 dB ensuring good impedance matching. The simulated on-body gain is found to be 7.05 dBi. A distance based investigation is conducted to study the impact of the human body's presence on the antenna's behavior. The antenna was positioned at four different distances from the human model to compare the results and assess the effects of distance. The on-body simulations showed consistent results with slight deviations, even when the distance from the human body was varied.*

***Streszczenie**. W artykule przedstawiono kompaktową antenę szerokopasmową 5G przeznaczoną do sieci typu body-centric (BCN) pracujących w paśmie Ka. Konstrukcja anteny obejmuje prosty patch grzejnika w kształcie łuku z pełną płaszczyzną uziemienia i linią zasilającą o impedancji transformatora. Do projektowania i symulacji anteny wykorzystywana jest technologia symulacji komputerowej (CST) Microwave Studio Suite, niezawodny program do symulacji elektromagnetycznej. Antenę symulowano w wolnej przestrzeni, a jej częstotliwość rezonansowa wynosi 37 GHz i mieści się w paśmie Ka oraz n260 5G. Proponowana antena ma rozmiar 37,4 mm^3 i oferuje szerokie pasmo impedancji przekraczające 5,7 GHz (34,3-40 GHz). W punkcie rezonansowym antena wykazuje zysk 4,48 dBi i jednokierunkową charakterystykę promieniowania. Badania parametryczne wykazały, że zmniejszając szerokość łuku, można poprawić szerokość pasma anteny, ale ze zniszczeniem dopasowania impedancji. Antena jest proponowana do stosowania w zastosowaniach sieciowych obejmujących obszar ciała. Aby ocenić jego działanie na ciele, wirtualnie opracowano model ciała równoważny mięśniom. Działanie na ciele ocenia się umieszczając antenę w pobliżu modelu ciała. Wyniki symulacji prowadzonych na ciele wykazały, że przy częstotliwości 37 GHz współczynnik odbicia wynosi 29,5 dB, co zapewnia dobre dopasowanie impedancji. Stwierdzono, że symulowane wzmocnienie na ciele wynosi 7,05 dBi. Przeprowadza się badanie oparte na odległości w celu zbadania wpływu obecności ludzkiego ciała na zachowanie anteny. Antenę umieszczono w czterech różnych odległościach od modelu człowieka, aby porównać wyniki i ocenić wpływ odległości. Symulacje na ciele wykazały spójne wyniki z niewielkimi odchyleniami, nawet przy różnej odległości od ciała ludzkiego. (**Projekt eliptycznej anteny łukowej o częstotliwości 37 GHz i analiza wydajności dla zastosowań 5G na ciele**)*

Keywords: arc-shaped radiator, full ground plane, on-body antenna, 5G communication, body area network.
Słowa kluczowe: grzejnik łukowy, pełna płaszczyzna uziemienia, antena umieszczona na ciele, komunikacja 5G, sieć obszarowa ciała.

Introduction

5G mobile communication has marked a transformative era in telecommunications. It offers a vast range of opportunities with its wide spectrum availability, low latency, enhanced stability, and blazing-fast data transfer rates. With growing demand for wireless communication, next generations facilitate more real-time connections with multiple-devices, providing reliable connections even for high-speed networks, and enabling data rates of multiple gigabits per second. These advancements need highly reliable transceivers to meet the growing demands.

Antennas plays a crucial role in wireless communication, academics are tirelessly working to designed advanced-antennas efficient for 5G technologies. The primary objective of fifth-generation communication is not merely connecting individuals virtually but aiming to connect everything, including home appliances, devices, machines and gadgets. To achieve this goal, 5G NR (New Radio) established the Third-Generation-Partnership-Project (3GPP) [1]. The 39 GHz band, lies from 37.00 GHz to 40.0 GHz, is referred to as 3GPP n260 band. This band fall directly within the „Ka" (K-above) and used in various applications [2–9].

Adapting to technological developments, the wireless-body-centric-network (WBCN) is embracing more innovative equipment, where robust-connections, fast-paced transmission network with high data-rates have become essential. The health-care sector particularly benefits from body-area networks, requiring robust, and low-latency connections for precise observing of vital-signs, real-time patient-supervision, and seamless data synchronization between body area networks (BAN) and base terminals. Future body-centric applications and 5G communication could be integrated facilitate direct exchange of physiological data using internet. Moreover, body-centric networks find applications beyond healthcare facilities, extending to entertainment, military, sports and defense [10–14].

Existing literature

A miniaturized 5G antenna is designed to operate at 33.5 GHz and 60.8 GHz, demonstrating improved on-body efficiency and gain [15]. It experienced a reduction in performance due to the bio-tissue effect. In [16] authors suggested a triple-band multiple slotted antenna. The on-body gain is 8.3 dBi, and efficiency is 54%. In another study, the authors presented an antenna for 58/60/62 GHz frequencies for body-centric networks [17]. A dual-meander-line antenna for 5G BCN, capable of functioning across multiple bands, including 58/44 /34/22 GHz to widen the bandwidth and also expanded the 267hant of resonance-bands [18].

A circularly polarized dual-band 5G antenna shows favorable results for 5G, however, it is not evaluated for on-body phantom [19]. A dual-band monopole-antenna operating at 24/60 GHz using 0.13-micron CMOS technology [20] is designed. Jain et ©. Introduced an antenna operating at 28/38 GHz, featuring a ban notch at 33 GHz. Additionally, a Hexagonal Fractal Antenna Array (HFAA) for next-generation wireless communication was presented in another study [21].

A wearable disk-shaped antenna, based on electromagnetic coupling between feed and radiator is proposed in [22]. A 60 GHz antenna with a substrate-integrated-waveguide-technique for on-body data transmission, recording a gain of 2 dB while maintaining a 5-millimeter gap from the antenna element is designed [23]. A MIMO antenna operating at 24 GHz, utilizing EBG structure is designed in [24]. This MIMO antenna achieved an on-body gain of up to 6 dB [24]. Additionally, a textile antenna operating at 26/ 28 GHz, showcasing gain of 7 dB is presented in [25].

The primary objective of the paper is to design and evaluate a wideband antenna for 5G (at Ka band) wireless body area network. The paper presents an antenna design operating at 37/39 GHz within 5G's n260 under the Ka. The CST Microwave Studio is utilized for antenna design, followed by the examination of the antenna's free-space performance parameters. Subsequently, the on-body performance of the antenna is assessed on muscle tissue. The proposed antenna design is featuring remarkably small size and substantial bandwidth. When placed in close proximity to the human body model, the antenna performs admirably.

Antenna design and configurations

As depicted in Figure 1, the proposed antenna design is based on microstrip patch technology. It consists of modified arc-shaped patch serving as the radiators, a quarter wave transformer impedance strip line and full ground plane. The substrate material FR4 possesses a relatively permittivity of 4.4, with loss tangent of 0.25 and thickness of 0.8. Following design equations are considered to design the basic elliptical patch antenna [26].

$$f_r^{e,o} = \frac{15}{\pi a_{eff}}\sqrt{\frac{q11_{e,o}}{\varepsilon_r}} \qquad (1)$$

$$q11_e = -0.0049e + 3.788e^2 - 0.72783e^3 + 2.314e^4 \qquad (2)$$

$$q11_o = -0.0063e + 3.861e^2 - 1.3151e^3 + 5.229e^4 \qquad (3)$$

$$a_{eff} = a\left[1 + \left(\frac{2h}{a\pi\varepsilon_r}\right)\left\{\log n\left(\frac{a}{2h}\right) + (1.41\varepsilon_r + 177) + \frac{h}{a}\,(0.268\,\varepsilon_r + 1.65)\right\}\right]^{1/2} \qquad (4)$$

Where, a is semi major axis of elliptical radiator, h is the height of substrate, ε_r is the permittivity of substrate material, a_{eff} is the effective semi major axis, and $f_r^{e,o}$ is the resonance frequencies for even and odd modes. Table1 gives the dimensions of proposed antenna where length of major axis is represented by parameter R2. Antenna is miniaturized planar dimensions of 5.5 mm ×8.5 mm, and elliptical patch is modified as arc shaped radiator for wider impedance bandwidth to avoid the narrow bandwidth characteristic of full ground plane.

To analyze the on-body performance of antenna a three-dimensional muscle equivalent phantom of size 80 mm×80 mm×15 mm is designed numerically in CST microwave studio. Antenna is first designed and simulated in free space and then deployed on muscle phantom at the distance of 2 mm as shown in Figure 1. Minimum gap is maintained for the ease of body movement and postures. 2 mm space is filled with foam to insulate the antenna from body tissue. Electric properties of the muscle phantom are taken as given in [27] with electric permittivity of 24.44.

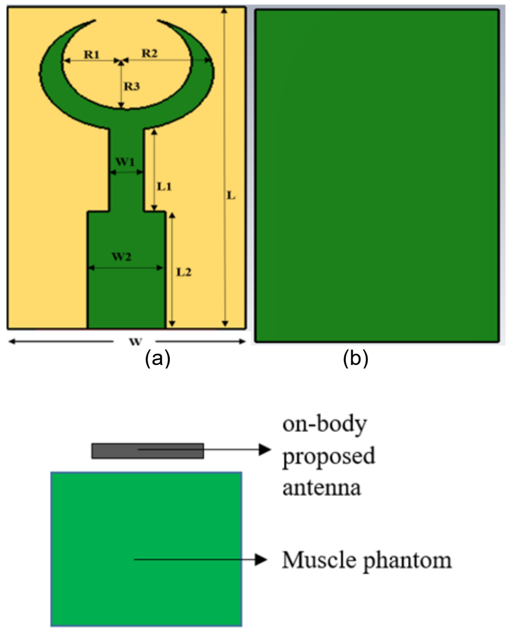

Fig.1. Antenna geometry (a) front view (b) back view (c) on-body simulation setup

Table1 Dimensions of antenna

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
W	5.5	L	8.5	R1	1.5
W1	0.8	L1	2.4	R2	2
W2	1.8	L2	3.1	R3	1.25

Results and discussions

Reflection coefficient, and radiation pattern are the major parameters of antenna performance to evaluate the bandwidth, resonance frequency, impedance matching, gain and orientation of radiation. Plot for reflection coefficient for free space and on-body performance is shown in Figure2. Antenna has overlapping -10 dB impedance bandwidth for both the operating conditions. Bandwidth ranges form 34.3-40 GHz covering 3GPP n260 band effectively. |s11| value of 35 dB in free space and 30 dB in on-body condition is representing the excellent impedance matching. To analyze the effect of antenna structure on frequency, parametric analysis is performed for the arc width (R1). Arc width is varied from 1 mm to 1.75 mm and its effect on reflection coefficient is shown in Figure3. Optimum results are obtained at R1=1.5 mm. On reducing the R1, bandwidth can be broadened towards the lower cut off frequency. It also causing the shifting of |s11| plot upward showing the degradation of imp4edance matching. On increasing the R1, antenna lost its resonance and impedance matching at the desired band.

Human tissue is a complex structure with high permittivity and conductivity. It causes multiple diffraction and reflections at the boundaries of heterogeneous mediums. It interference with the antenna surface current. Thus, for the on-body performance, it is required to evaluate the antenna behavior for varying gap between antenna and body. In practical scenario, it is possibility of varying gap due to body movements. Gap ‘s’ is varied from 2 mm to 8 mm and reflection coefficient plot for the same is shown in Figure4. Antenna has excellent stability of resonance bandwidth for all the distances a negligible shifting of |s11| can be observed. It signifies the robustness and stability of antenna for on-body application.

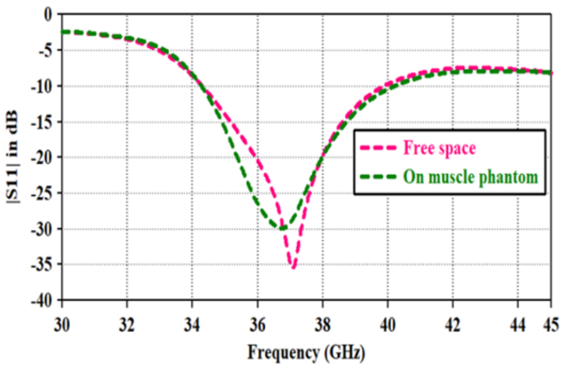

Fig.2. Reflection coefficient for on-body and free space

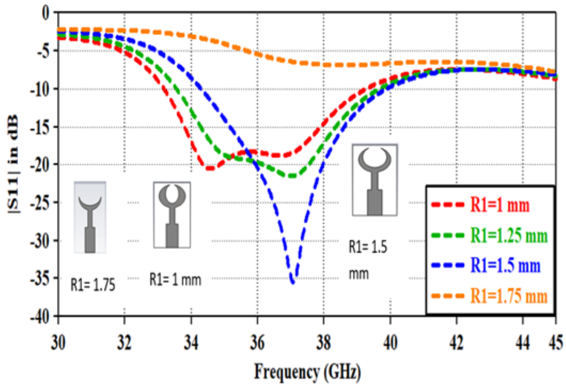

Fig.3. Reflection coefficient for varying arc width

Behavior of antenna radiations in far field, 3-D and 2-D patterns are plotted in Figure 5 for both the operating conditions. 3-D plot shows that antenna gain is 4.48 dBi in free space which is increased t0 7.05 dBi on muscle tissue. High gain is due to the full ground. On muscle tissue radiation pattern becomes unidirectional due to reflections of radiations from the body tissue. It is the desired feature for wireless body area network application. 2-D radiation pattern in free space is bidirectional and unidirectional on body tissue in both the E-plane and H-plane. Unidirectional radiations protect the body tissue from the heating effect and ensures the safety of user.

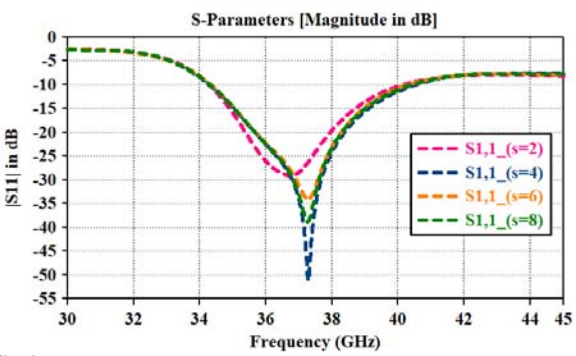

Fig.4. Reflection coefficient for varying antenna and body tissue distance

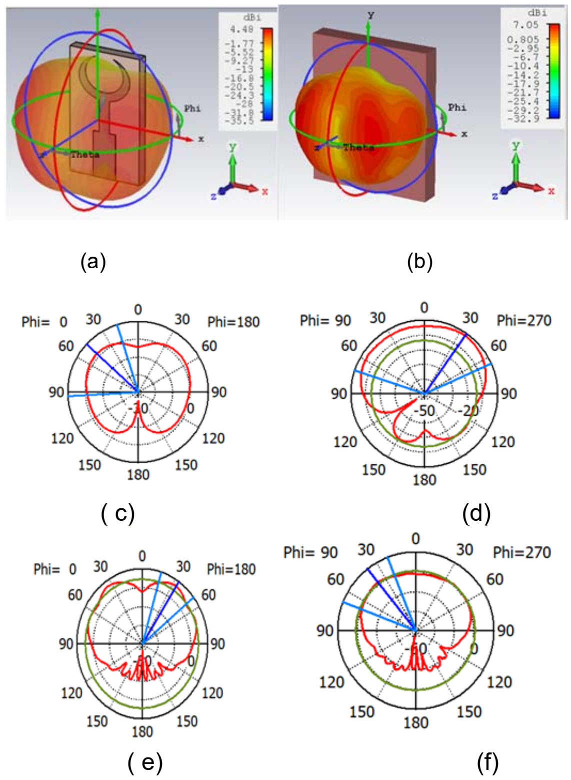

Fig.5. radiation pattern (a) 3-D free space (b) 3-D on-body (c and d) free space E-palne and H-plane (e and f) on-body E-palne and H-plane

Conclusions

A 5G antenna designed for on-body communication, operating at Ka band, is analyzed. The proposed structure exhibited excellent behavior in free-space and also have stable performance when placed on the muscle tissue. On-body simulations further demonstrated the antenna's consistent and reliable performance. The return loss measurements revealed stable antenna performance from the 26 GHz frequency, making it suitable for application in both the 3GPP's n260 band for 5G NR FR2. However, it is observed that the antenna performed even more consistently when positioned at a distance above 2-millimeters from the human body, as close proximity to the body caused some impedance reducing due to the high conductivity of the body and alters the near-field distribution of the antenna. For varying body and antenna distance analysis, antenna has stable results. Even in on-body scenarios, the antenna retained its wider bandwidth, and its gain increased by 2.57 dBi. Overall, the antenna performed satisfactorily in both on-body and off-body applications.

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The correspondence address is: *Ahmed Jamal Abdullah Al.-Gburi, Center for Telecommunication Research & Innovation (CeTRI), Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Jalan Hang Tuah Jaya, Durian Tunggal, Melaka 76100, Malaysia; email: ahmedjamal@ieee.org.*

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