A Wideband Wearable Antenna with AMC Ground Plane for WBAN Applications

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Abstract. *A flexible wearable antenna with wideband characteristics and having a conical radiation pattern which is suitable for ON body application is presented. To realize a compact antenna size, characteristic modal (CM) analysis is performed initially, and the ground plane of the antenna is utilized to generate one of the resonant modes. The quasi- current loop in the feed layer patch is used to generate another resonant mode. Combination of these two modes has resulted in the wideband performance of the antenna from 4.72 to 6.08 GHz. A planar wideband artificial magnetic conductor (AMC) is used beneath the antenna. This AMC surface compensates the undesired coupling taking place due to the ground radiator thereby reducing the specific absorption rate (SAR) to 76.4% and enhancing the gain of the antenna. The performance of the antenna in terms of return loss, gain, efficiency, SAR and bending sensitivity is studied.*

Keywords

Wearable, AMC, SAR, wideband

1. Introduction

The field of wearable body area networks (WBAN) witnessed huge progress in the last decade. With the massive deployment in the field of healthcare, security, entertainment, tracking etc., it has impacted the human life a lot [1]. These wearable devices are distributed over the human body in different positions and work synchronously. In the meantime, it monitors various bio-signals like heart rate, blood pressure, glucose level etc. [2]. Moreover, it can be used to communicate with sensor nodes placed on another person thus establishing an efficient body to body (B to B) communications which can be helpful especially in the battlefields and firefighting like the head-worn antennas [3].

For establishing efficient ON body communications, a conical-like radiation pattern with 360° coverage in the azimuthal plane like that of a monopole antenna is highly desirable [1]. Several techniques were employed using patch and slot antennas in the past to realize conical radiation patterns. These include using higher order modes for different patch antenna configurations like circular patch [4], square patch [5] and slot array antenna [6], [7]. Since the wearable antennas work in proximity with the human body which has got high permittivity and loss tangent, so frequency detuning is a common issue that can be compensated with the application of wideband antennas. Also, for high-resolution data transmission, a large bandwidth is a prerequisite [8].

Moreover, there is always a quest to design compact efficient wearable antennas. A full ground plane is generally preferred to reduce the coupling with the lossy human tissue. Since, the ground is normally larger than the radiator, so a technique of using the ground plane as a radiator to design compact dual-band wearable antenna is proposed recently [9]. However, the efficiency of ground radiating wearable antennas drops sharply when coming closer to the human body [10]. AMC based ground planes are found to be successful in reducing the coupling with the lossy human body and thereby increasing the front to back ratio in addition with gain [11], [12].

In this work, a compact wideband wearable antenna having a conical radiation pattern is proposed. CM analysis is used to study the resonating modes of the ground plane initially. Wideband characteristic is generated by tuning the ground radiating mode and the quasi-current loop mode in the feed layer. Further bandwidth enhancement and improved matching are achieved with a parasitic open-ended slot placed in the ground plane. It may be noted that unlike the ON body antennas designed earlier where higher-order modes or arrays have been utilized, here the patch and ground plane were utilized as individual resonators to realize a wideband performance.

To reduce the undesired coupling with the human body, a planar wideband AMC ground plane is applied beneath the antenna. This AMC surface reduces the SAR value of the standalone antenna which is very important from the safety standard view. Moreover, the antenna is

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flexible in nature which reduces the discomfort caused by rigid substrates.

2. Antenna Design and Characteristics

The topology of the antenna is shown in Fig. 1(a–d). The antenna comprises of a four-way symmetrical feeding network which is co-axially fed at the center, four numbers of asymmetrical pair slots in the ground plane and 4×4 square shaped planar AMC unit cells. The antenna is realized on a felt substrate with $\varepsilon_r = 1.63$, $\tan\delta = 0.044$ and thickness of both the antenna substrate and the substrate used in the AMC plane is 3 mm respectively. Adhesive backed copper sheets of thickness 0.076 mm were used to realize the conductive parts. The detailed dimensions of the antenna are given in Tab. 1.

The design procedure can be categorized into four steps. As a first step CM analysis is performed with the slotted ground plane to study the resonating modes and radiation patterns of different modes. In the next step, a proper feeding network is employed to excite the suitable modes with omnidirectional pattern. In the 3rd step, to widen the bandwidth of the antenna, the resonant mode generated by the quasi-current loop in the feed line is tuned properly to merge with the slot mode. In the meantime, another parasitic slot is etched on the ground beside the main slot. This 2nd slot not only enhances the bandwidth but also improves the matching of the antenna. In the 4th step, a planar wideband AMC ground plane is employed which not only shields the human body from unwanted radiation but also enhances the front to back (F/B) ratio and reduces the SAR of the antenna.

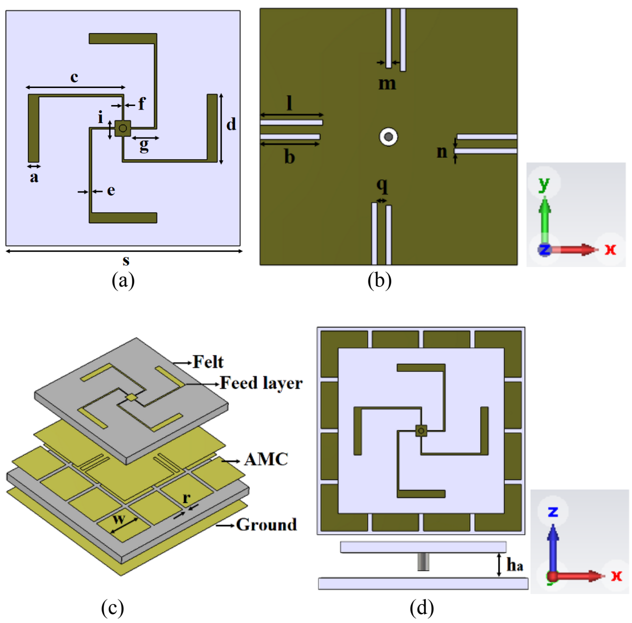


Fig. 1. Proposed antenna views: (a) Top. (b) Bottom. (c) Exploded structure of the antenna. (d) Top and lateral (a = 2, b = 10.5, c = 18.3, d = 13, e = 0.5, f = 0.3, g = 5, i = 3, l = 12, m = n = 1, q = 1.5, r = 1.25, w = 12.75, h_a = 10) (unit: millimeters).

Modal analysis can be used to study the radiation characteristics of arbitrarily shaped radiators. To realize a compact antenna, the ground plane can be utilized to behave as the main radiator. To realize this, CM analysis of the slotted ground plane is performed, and the result is shown in Fig. 2(a). Modal significance (MS) values signify the normalized amplitude of current modes [13] which is given by:

$$MS = \left| \frac{1}{1 + \mathrm{j}\lambda_n} \right| \tag{1}$$

where λ_n is the eigenvalue. For a mode to be resonant properly, *MS* value must be unity. It can be observed that the *MS* value is near unity at 5.8 GHz where the slots (having length of 13.5 mm) behave as quarter wavelength resonators. The corresponding far-field patterns for mode 1, 2 and 3 are shown in Fig. 2(c–e).

Almost omnidirectional field is obtained for mode 1 at 5.8 GHz. Other modes are not suitable as they have a broadside radiation pattern which is not appropriate for ON body applications. To excite the mode properly with omnidirectional radiation pattern, the electric field maximum position is the suitable position. The electric field plot

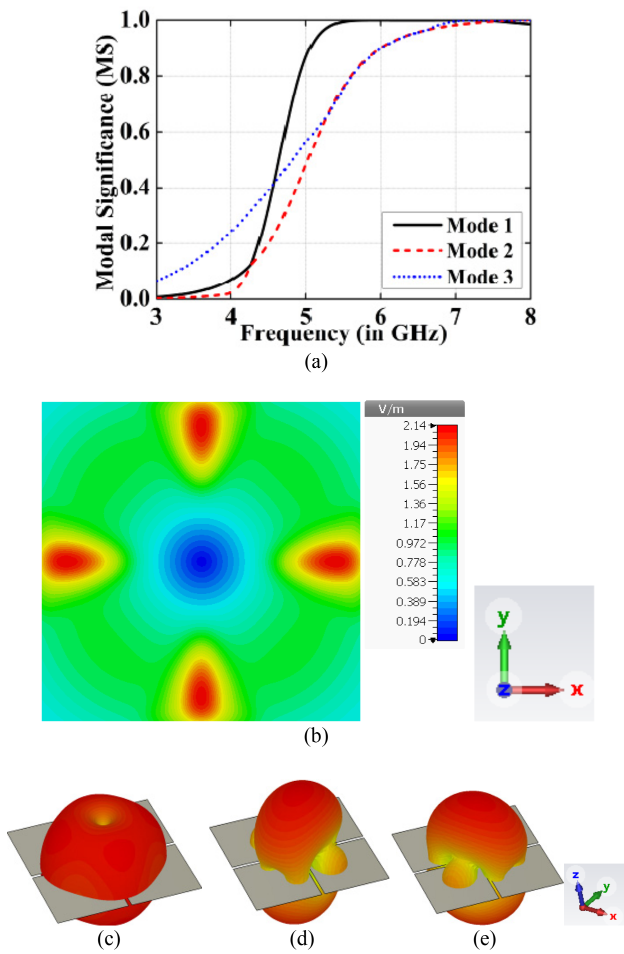


Fig. 2. Simulated results of the ground plane: (a) MS values. (b) Electric field distribution at 5.8 GHz. Far field patterns for (c) Mode 1, (d) Mode 2, (e) Mode 3.

for mode 1 at 5.8 GHz is shown in Fig. 2(b). In accordance with the electric field distribution at 5.8 GHz, a four-way symmetric power divider needs to be applied. Some parametric analyses were performed to find out the factors affecting antenna performance. The S_{11} variation with the width (a) and length (d) of the bent portion in the feed line is shown in Fig. 3(a, b). The width of the bent portion must be maintained amid 1–4 mm to achieve wideband property. More reduction in '*d*' results into the convergence of the two bands into a single one.

The S_{11} result of the antenna with the variation in the length of the 1st and 2nd slot (*b* and *l*) is shown in Fig. 3(c, d). Increasing length of the main slot (*b*) moves the resonant frequency to the lower side. It can be observed that the 2nd slot not only improves the matching of the antenna but also enhances the bandwidth of the antenna. The surface current distribution of the antenna at 4.72 and 5.71 GHz is shown in Fig. 4(a, b).

At 4.7 GHz, current mainly flows in the bend portion of the feed line which corresponds to a quasi-current loop whereas, at 5.7 GHz, the main slot in the ground plane plays a major role. In the next phase of the design, a planar wideband AMC ground is incorporated with the antenna.

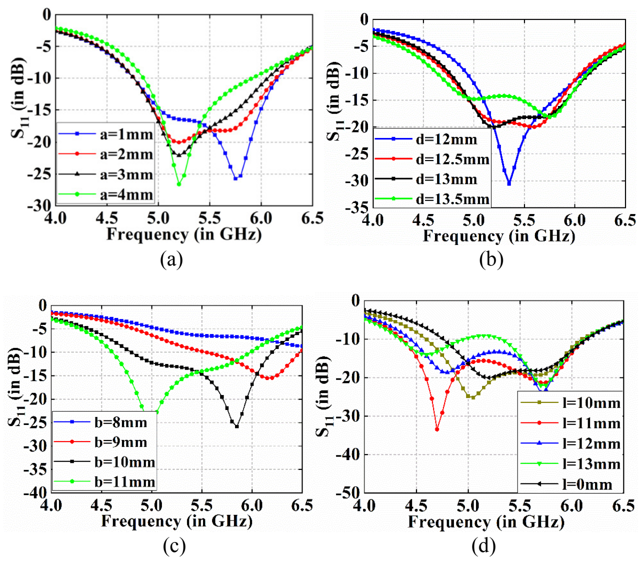


Fig. 3. Parametric results for S_{11} variation with (a) the width of the bend portion, (b) the length of the bend portion, (c) the length of the main slot, (d) the length of the 2nd slot.

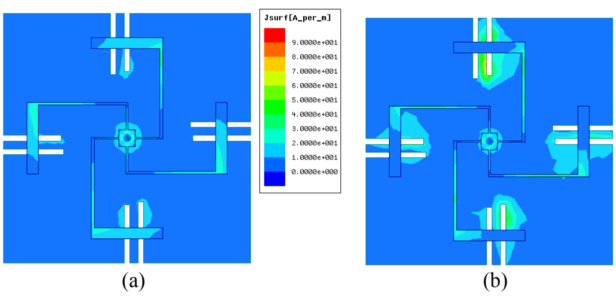


Fig. 4. Surface current distribution of the antenna at: (a) 4.7 GHz, (b) 5.7 GHz.

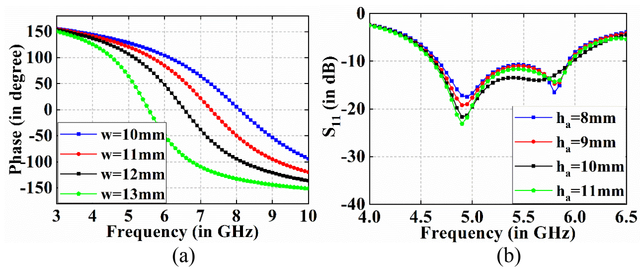


Fig. 5. Simulated results: (a) Reflection phase variation of the AMC unit cell with side length. (b) S_{11} variation of the antenna with AMC gap.

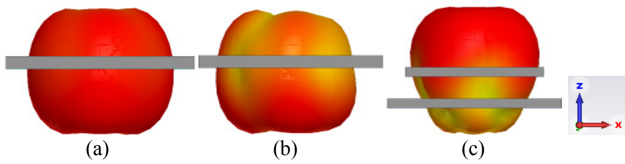


Fig. 6. 3-D radiation pattern plot of the antenna: (a) With a single slot; (b) With single and parasitic slots; (c) With AMC.

An AMC based ground plane can be utilized to act as an in-phase reflector. For this, unit cell analysis of the AMC is performed with proper boundary conditions respectively. The reflection phase variation of the square unit cell with side length (*w*) is shown in Fig. 5(a). For $w = 12.75$ mm, the usable bandwidth i.e., where the reflection phase variation lies within ±90° covers the required impedance bandwidth of the antenna. Within this bandwidth, the reflected and incident waves are more in-phase. The resonant frequency of the AMC unit cell is at 5.56 GHz.

The parametric study of the variation of the gap (h_a) between the AMC ground and antenna is shown in Fig. 5(b). It can be observed that maximum matching occurs when the gap is maintained at 10 mm respectively. The 3D-radiation pattern plot for the antenna with a single major slot, major and parasitic slot and final antenna with AMC is shown in Fig. 6(a–c). It can be observed that though the antennas in the 1st and 2nd cases shows omnidirectional behavior in the horizontal plane, considerable back radiation takes place which enhances the SAR considerably. Finally, with the designed AMC ground plane, the back radiation is minimized to a good extent. The antenna radiation pattern now corresponds to a monopole-like radiation pattern which can be used for ON body applications with reduced coupling from the body.

3. Antenna Performance

The antenna performance and parametric analysis results in free space conditions were discussed in the previous section. For ON body characterization, the antenna is simulated in both single as well as multi-layer phantom models with defined dielectric properties. For a single layer model, dry skin (thickness 15 mm) and for a 3-layers model skin (1 mm), fat (1 mm) and muscle (30 mm) is taken. The antenna with AMC is placed at a height of

2 mm from the phantom model. The simulation model and on phantom measurement model is shown in inset Fig. 7.

The dielectric properties of the phantom i.e. relative permittivity (ε_r) of 35.4 and conductivity (σ) of 3.4 has been achieved according to the standard technique [14]. The phantom is prepared using sucrose, NaCl, de-ionized water, agarose and the dielectric property is measured using Agilent Dielectric Measurement probe kit. The results of the S_{11} analysis on the single, multi-layer phantom model as well as measured results on phantom are shown in Fig. 7. The discrepancy between the measured and simulated results occurred due to manual fabrication process. Since the wearable antennas work near the body so they are prone to bending effects. As a result, the robustivity of the antennas needs to be checked by performing bending sensitivity studies. A cylinder of height 100 mm with the radius of 30 mm is employed to wrap the antenna around it. The simulation and measurement model for the antenna wrapped around the cylinder is shown in inset Fig. 8.

The measured and simulated S_{11} results are shown in Fig. 8 under bending conditions. Frequency detuning and impedance mismatch take place on account of the bending as seen in the measured results. The antenna radiation patterns have been analyzed and the results are shown in Fig. 9 at frequencies of 5, 5.5 and 5.8 GHz, respectively. It can be observed that with the inclusion of AMC ground, the back radiation reduced to a good extent. Maximum radiation is pointed towards elevation angles of 30°–60°, respectively. The measured radiation pattern results are shown in Fig. 10. Almost an omnidirectional pattern is obtained in the horizontal plane (θ = 30°) in all the cases.

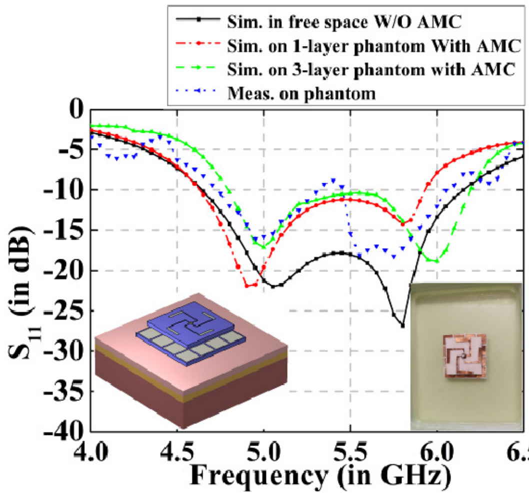


Fig. 7. Simulated and measured S_{11} results.

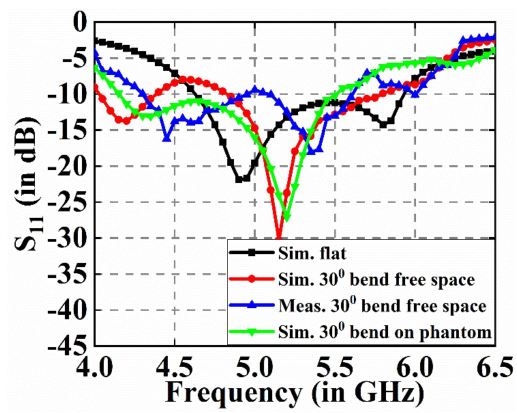


Fig. 8. Simulated and measured S_{11} results of the antenna with bending.

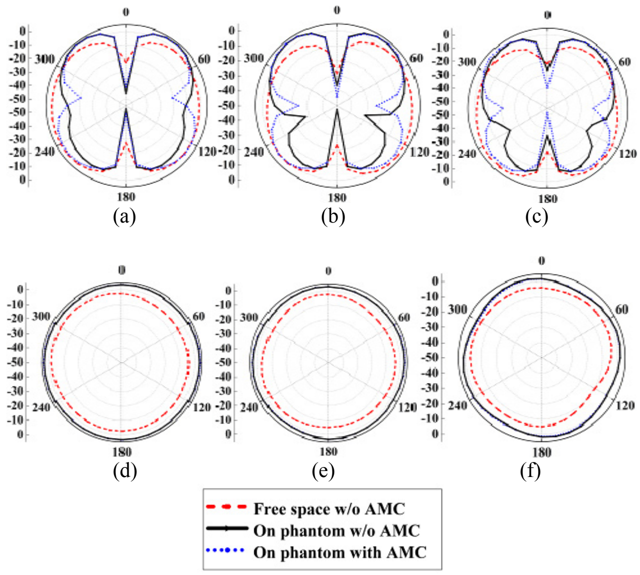


Fig. 9. Radiation patterns for XZ (φ = 0°) plane at (a) 5 GHz, (b) 5.5 GHz, (c) 5.8 GHz and XY (θ = 30°) plane at (d) 5 GHz, (e) 5.5 GHz, (f) 5.8 GHz.

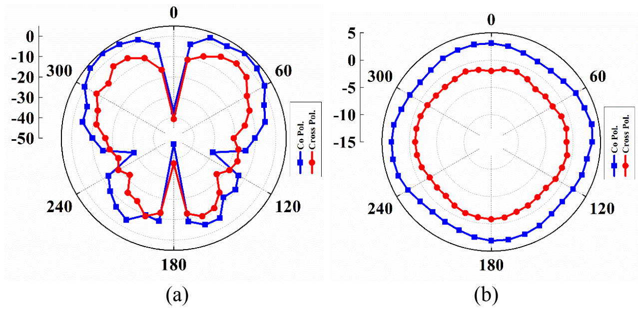


Fig. 10. Radiation patterns for plane at 5.5 GHz: (a) XZ (φ = 0°) plane; (b) XY (θ = 30°) plane.

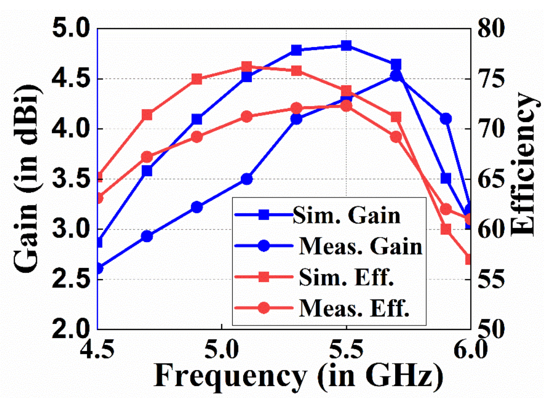
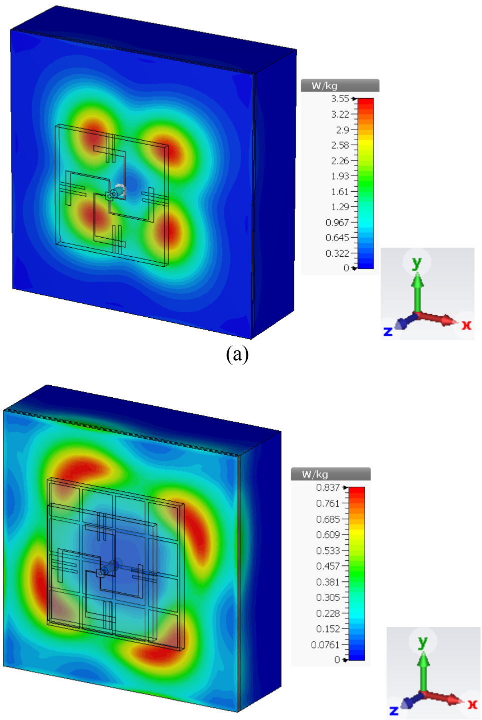


Fig. 11. Simulated and measured gain and efficiency results.



(a)

(b)

Fig. 12. SAR values: (a) Without AMC; (b) With AMC.

Ref.	**Volume**	**Substrate type**	ε_r	**B.W (MHz)**	**Gain (dBi)**
[4]	$\pi \times 20^2 \times 1$	Flexible	1.2	160	–10.7
[5]	50×50×4	Flexible	1.2	150	4.5
[16]	60×65×3.15	Rigid	2.2	18	0.5
Prop.	**56.75×56.75×16**	**Flexible**	**1.63**	**1360**	**4.53**

Tab. 1. Performance comparison with some previous works.

The measured gain and efficiency results are shown in Fig. 11 where a maximum gain and efficiency of the antenna within the band of interest achieved is 4.53 dB and 72.3%, respectively. Also, an enhanced F/B ratio of 5.5 dB is achieved with the AMC based ground plane than without it.

To find out the effect of radiation on human body, the SAR value needs to be computed for safety concerns. A 3-layer phantom model is used to find out the SAR values. The SAR values are shown in Fig. 12(a, b) where without the AMC ground plane, the SAR value is 3.55 W/kg. But with the use of AMC based ground plane, it reduces to 0.84 W/kg for 1 gm average. According to [15], the maximum threshold SAR value for 1 gm average should be less than 1.6 W/kg which is satisfied in the 2nd case only. A comparative study is given in Tab. 1 with previously reported antennas for ON body applications. It can be observed that the proposed work has the advantage of widest bandwidth, enhanced gain in comparison to the reported works along with flexibility for wearable applications.

4. Conclusion

A compact wideband wearable antenna backed with an AMC ground plane is designed for ON body applications. Compactness of the antenna has been maintained by utilizing the ground plane to act like a radiator in addition to the patch. Wideband characteristic is achieved by tuning the resonant modes of the patch and the ground plane respectively. Further, the impact of radiation on the body due to the ground plane which is acting as one of the radiators is lowered with the application of wideband AMC based ground plane. Considering the performance of the antenna in terms of flexible design, small size, wide bandwidth, and low SAR it can be a suitable option for ON body applications.

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