Flexible thin antenna solution for wearable ankle bracelet applications with GNSS and BLE connectivity

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Abstract
A thin antenna structure to operate in GNSS (Global Navigation Satellite System) and BLE (Bluetooth Low Energy) communication standards is proposed. The antenna was built on a flexible and thin Kapton material inserted between 2 layers of bovine leather, suitable for limited weight and slim ankle bracelet designs. Proposed antenna structure consist of 2 opposed planar inverted F antennas modified using matching stubs, sharing the same substrate and ground plane, with total size of 96.8 × 35 × 4.14 mm. The ground plane area of the antenna can be used for electronic circuit and battery placement. The antenna structure operates in the following specific 4 bands: BeiDou (1561 MHz), GPS (1575 MHz), GLONASS (1602 MHz), and BLE (2400 MHz). The antenna exhibited great agreement between electromagnetic simulations in ADS Momentum and measurements performed into 3D anechoic chamber with anthropomorphic leg-foot model from Speag. The antenna peak gain is approximately −1.8 dBi for GNSS bands and −2.0 dBi for BLE.

Keywords
Wearable, GNSS, BLE, Ankle-Bracelet, Thin-Flexible

1 | INTRODUCTION

Ankle bracelet antenna solutions have been created in the last years to effectively design offender tracking systems, house arrest devices, white collar trackers, parole monitoring, and so forth. The ankle monitor sends a radio frequency signal with information like location and other vital signs (blood oxygen level SpO2, heart rate, body temperature, blood alcohol level, etc.) to a receiver. A limited number of articles on wearable antennas have been published.1–3 Flexible and wearable antennas are recognized as one of the most recent trends in the state of the art of today’s world demand. Intensive research has been conducted to miniaturize antennas, especially in the growing sector of the Internet of Things (IoTs). The number for wearable devices connected to the IoT network is now millions, being Fitbit one of the largest provider where wrist worn devices includes Global Navigation Satellite System (GNSS) and Bluetooth Low Energy (BLE) antennas. Typical devices in wearable applications have antennas in WiFi, Bluetooth, GPS, and some in 3G and 4GLTE bands. Can be found in literature some examples related to this work in WiFi and Bluetooth wireless technologies,4,5 or related to cellular communications applications.6

In this article, a combined antenna structure consisting of 2 planar inverted F-antennas to cover a total of 4 bands is presented. The first antenna is designed to operate in 1561 MHz BeiDou band, 1575 MHz for GPS/QZSS/Galileo, and 1602 MHz for Glonass,7 while second antenna is designed to cover the 2400 MHz BLE band.8 Then, a required spectrum to cover the mentioned bands and standards comprises from 1561 to 1606 MHz for BeiDou/GPS/Glonass and 2410 to 2490 MHz for BLE. A planar inverted F antenna (PIFA) topology was selected since this type of structure exhibits good stable response.9 We describe the proposed antenna structure and present theoretical and experimental results such as impedance, VSWR, efficiency, peak gain, average gain (antenna losses) and 3D radiation patterns of the antenna, including simulations using a Leg-Foot model and measurements using a phantom leg-foot inside of an anechoic chamber.

2 | ANTENNA STRUCTURE AND DESIGN

The proposed antenna structure consists of 2 PIFAs modified using matching stubs, designed to cover a total of 4 bands. The first antenna is designed to operate from 1561 to 1606 MHz for GNSS: BeiDou/GPS/Glonass/Galileo/QZSS applications, while second antenna was designed to cover from 2410 to 2490 MHz for BLE. The available area for the antenna design including the ground plane was set to 100 × 40 mm, and have been divided into 3 sections to fabricate...
The whole antenna structure has a rectangular form factor, were the antenna is positioned vertically in the ankle area. SAR analysis and measurements are not into the scope of this research work, since GNSS is just a receiver and BLE is a low power device. Besides, to minimize radiation to the ankle surface of the skin, we are keeping a space of 2 mm with the bovine leather thickness.

The antenna design is described by layers from top to bottom, where at the top of the whole antenna structure is the first 2 mm leather layer having a dielectric constant of 1.5, then a 1 oz copper layer with the antenna shape and ground plane. Following a Kapton layer with a thickness of 0.035 mm and a dielectric constant of 3.8, and finally a bottom 2 mm leather layer are used to complete the construction of the antenna that was measured as shown on Figure 2. The size of the whole effective area of the 2 final antennas including the ground plane is 96.8 × 35 mm. Where the effective area for the GNSS antenna is 8.4 × 35 mm, the effective area of the BLE antenna is 8.4 × 24.3 mm and finally the shared ground plane area is 80 × 35 mm. The GNSS resonator element size is 27 × 2 mm, while for the BLE resonator is 16.3 × 2 mm. For antenna matching purpose is included a small open stub on each antenna with dimensions described in the drawing Figure 1A. In order to perform the electromagnetic simulation of the proposed ankle bracelet antenna, we input the 4 layers mentioned above (bovine leather-cooper-Kapton-bovine leather). To bond the copper tape and Kapton material we used adhesive transfer from 3M 467MP with a layer thickness of 0.06 mm, but this adhesive was not considered during simulations since its effect is negligible.

The proposed antenna structure shown in Figure 1B was analyzed and optimized using Momentum ADS, with data of the substrate layers and dimensions described earlier. The optimization goals were return losses ≤ −10 dB, into the bandwidth of 1561–1602 MHz for the GNSS: BeiDou/GPS/Glonass and 2410–2490 MHz for BLE, taking care of the size limits (100 × 40 mm maximum) for the whole antenna structure.
structure. Harvey N. Mayrovitz et al.\textsuperscript{14} found by measurements on a human forearm the dielectric constant exhibits average values of 28.2 at 300 MHz with conductivity 0.59 S/m. On the other hand the company Speag developed the CTIA approved model number SHO-LFPV2, phantom leg-foot with a dielectric constant of 27.5 at 1575 MHz and conductivity 0.9 S/m, for 2450 MHz dielectric constant is 25.7 and a conductivity 1.32 S/m.\textsuperscript{9} The properties of the material used for electromagnetic simulations of the human ankle model into ADS-Momentum is a dielectric constant of 26.5 and a conductivity 1 S/m and 50 mm thickness.

3 | RESULTS AND DISCUSSION

The proposed antenna shown in Figure 1A was electromagnetically analyzed using Momentum ADS, with dimensions described and including a human ankle model. In Figures 3–8 are presented simulation results of the most relevant antenna parameters, including measurements results. The antenna prototype was measured using two 1.37 mm mini-coax cable with 100 mm length and U.FL connector inside of an ETS-Lindgren model AMS-8900 3D anechoic chamber. The chamber has capabilities to measure antenna losses (average gain), antenna efficiency and 3D radiation pattern properties, using the conical cut antenna method, through the 23 multi-antenna array fixed ring and rotary mast. Chamber as well as phantom parts are CTIA approved; equipment specialized for the M2M, IoT and wireless communications. Chamber calibration has been performed across the bands using high precision sleeve calibration dipoles from 1400 to 6000 MHz. No common mode current effects were observed on the RF cable during measurements, since return loss responses were stable with cable movement, location or orientation. Typically this phenomenon is associated with inefficient and electrically small antennas. Theoretical and experimental results for the antenna impedance are plotted in Figure 3A,B for the GNSS from 1400 to 1800 MHz and BLE band from 2100 to 2800 MHz. We can observe good agreement on the return loss simulation results compared to the measured ones. Since the application is an ankle bracelet

FIGURE 3 Return loss with phantom leg-foot for GNSS (A) and BLE (B) [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 4 Efficiency with phantom leg-foot for GNSS (A) and BLE (B) [Color figure can be viewed at wileyonlinelibrary.com]
the system only works when it is mounted in the human ankle. Due to this, we limited our work for measurements only mounted on the Speag phantom leg-foot, as well the simulation only with presence of the human ankle.

Return losses behavior exceeds the requirements, where for GNSS are $<-10$ dB from 1490 to 1710 MHz for simulated results, and measured ones from 1410 MHz to higher of 1800 MHz as shown in Figure 3A. This antenna fulfill with the required bandwidth from 1561 to 1606 MHz, to cover GNSS: BeiDou, GPS, Glonass, Galileo, and QZSS bands with return losses below $-17$ dB. The impedance measured response in the BLE antenna exceeds requirements comprising from 2210 to higher of 2800 MHz. It can be found that simulation and measurement results cover the 2410–2490 MHz with return losses below $-18$ dB as shown in Figure 3B. Good agreement is found between simulations and measurements, especially for the GNSS antenna. For the BLE antenna there is some difference that can be attributed to the limitation of mesh discretization in high frequency, variation in the dielectric constant of substrates, the approximated model used for the leg-foot, imperfection in the prototype fabrication and coaxial cable assembly used for measurements.

Antenna efficiency is the second most important antenna parameter to qualify, requiring an anechoic chamber with 3D

<table>
<thead>
<tr>
<th>Band</th>
<th>Output Power (dBm)</th>
<th>Average gain Tx (dB)</th>
<th>Expected TRP (dBm)</th>
<th>Received sensitivity (dBm)</th>
<th>Average gain Rx (dB)</th>
<th>Expected TIS (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>$-148$</td>
<td>$-7$</td>
<td>$-141$</td>
</tr>
<tr>
<td>BLE</td>
<td>5</td>
<td>$-7$</td>
<td>$-2$</td>
<td>$-97$</td>
<td>$-7$</td>
<td>$-90$</td>
</tr>
</tbody>
</table>
scanning capabilities, especially for satellite or mobile communications, since there is no control of the antenna position towards the base station. If the communication link is fixed, then the peak gain becomes the second most important parameter, since the control of the propagation direction exists. Efficiency results are shown in Figure 4A,B from 1150 to 1620 MHz for GNSS and from 2390 to 2510 MHz for BLE. The measured efficiency when measured on a phantom leg-foot for the GNSS band (1561–1606 MHz), is around 21% and little higher than the simulated results where values are around 17%. On the other hand, the efficiency responses in the high frequency band BLE (2410–2490 MHz) have better simulation performance as shown in Figure 4B. The measured efficiency on phantom leg-foot for BLE is around 18% while simulation results are approximately 22%. The efficiency agreement between simulations and measurements tends to be very good, having differences around 2%–7%. This was achieved by using high precision calibration sleeve dipoles where the peak gain is within 0.1 dB across the specified height, instead of using horn antennas, since on horn antennas the phase center change with frequency.

Peak gain measurements using a 3D anechoic chamber can be the most difficult parameter to characterize with high accuracy, since this value is the maximum gain at any given angle per frequency. It can be rapidly be affected by calibration, since the calibration procedure assumes an isotropic dipole. During calibration is very important a proper alignment and position of the dipole with respect of the antenna.
The measurement and simulation results of the antenna peak gain are given in Figure 5A from 1150 to 1620 MHz for GNSS and in Figure 5B from 2390 to 2510 MHz for BLE. The measurement peak gain is about $-2$ dBi for GNSS band, while for BLE is between $-1.5$ and $-2.5$ dBi across the frequency band. A very good agreement between theoretical and experimental results with leg-foot models is obtained specially for BLE Band.

The average gain also known as antenna losses, is the representation of the antenna efficiency in dB scale, being an absolute way of measurement to qualify antennas, where the scale is within $-\infty$ to 0 dB (0%-100%), making this measurement independent of size, topology, material, gain and frequency. The measured results of the antenna average gain are shown in Table 1. For the GNSS receiver Ublox NEO-M8P with $148$ dBm of sensitivity,17 the estimated TRP and TIS shown in Table 1. For the GNSS receiver Ublox NEO-M8P with $-148$ dBm of sensitivity,17 the estimated TRP and TIS values when mounted on a Speag phantom leg-foot are shown in Table 1.

Each antenna has been optimized to resonate in the GNSS and BLE frequencies independently, with an isolation better than $-12.5$ dB as can be observed in Figure 7 for simulated results. The measured isolation using the phantom leg-foot is below $-17.5$ dB from 1400 to 2800 MHz, but better than $-20$ dB at the desired GNSS and BLE operation bands.

We have obtained by measurements the 3D radiation patterns of the antenna mounted on a phantom leg-foot into an anechoic chamber with 3D scanning system. Having a 3D chamber can quickly determine the radiation pattern properties, since is obtained immediately the peak gain at all angles. Since the antenna works in multiple bands, we have selected the approximate central frequency of each operation band, showing results for GNSS at 1575 MHz and for BLE at 2450 MHz. Measured 3D radiation patterns with phantom leg-foot and simulated results with leg-foot model are presented in Figure 8A for GNSS at 1575 MHz and in Figure 8B for BLE at 2450 MHz.

4 | CONCLUSIONS

In this work, a new antenna structure based on PIFA for wearable applications on the human ankle location for GNSS and BLE bands is proposed. The antenna has been designed, simulated and optimized using the 2.5D electromagnetic simulator ADS Momentum with antenna mounted on a leg-foot model approximation. The antenna was fabricated on a thin Kapton flexible material, and inserted into 2 thin layers of bovine leather easily adaptable to the shape of the ankle. Proposed antenna is based on PIFAs modified by stubs with final total size of $96.8 \times 35 \times 4.14$ mm. The antenna was measured into a state of art 3D anechoic chamber (ETS-Lindgren) mounted on phantom leg-foot from Speag. The antenna was optimized to achieve the highest performance possible on real electromagnetic environment. Presenting results of return loss, peak gain, and radiation patterns exhibiting good performance. Efficiency and average gain results are included as key parameters needed to design antennas in mobile or satellite geolocation, estimating its TRP and TIS values for better understanding.

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REFERENCES

Dual-band WLAN MIMO antenna with a decoupling element for full-metallic bottom cover tablet computer applications

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Abstract
A MIMO antenna system based on two dual-band loop-slot combination antennas for Wireless Local Area Network (WLAN) applications is proposed. The decoupling element for enhancing the port isolation is based on the neutralization line technique. The bandwidth of operation of the proposed antenna covers both the WLAN 2.4 GHz (2.4–2.484 GHz) and 5 GHz (5.15–5.85 GHz) frequency bands using a −10 dB definition. The isolation between the two close placed antennas is improved to −16 and −23 dB in the WLAN 2.4 and 5 GHz bands, respectively. The size of the proposed antenna is only 60 × 7.5 × 4.5 mm3 with a metal bottom cover underneath and an LCD panel nearby. Good radiation performance, as quantified by the antenna gain and antenna efficiency, is achieved.

1 | INTRODUCTION

High data-rate wireless communication systems have developed greatly in recent years. To meet high data-rate requirements techniques such as Multiple Input Multiple Output (MIMO)1 and diversity are used for enhancing data rate or channel capacity. To the best of our knowledge, the MIMO antenna system is the most effective way of increasing channel capacity without the need for additional transmission power or spectrum.2 However, it requires good isolation between antennas, and as the design space of portable devices is very small in modern devices, achieving isolation is a very important design issue in closely packed devices.

With this in view, several techniques based on the Decoupling Element (DE) method have been developed to enhance the isolation between two strongly coupled antennas. They include the neutralization line technique,3,4 the resonator technique,5–8 techniques that involve the placement of an electromagnetic band-gap (EBG),9,10 the use of lumped circuit decoupling networks,11 and methods that involve adding multiple feeds in the same radiating structure.12