Body-Worn 30:1 Bandwidth Tightly Coupled Dipole Array on Conductive Textiles

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***Abstract*—We present a novel tightly coupled dipole array (TCDA) based on conductive textiles (E-threads) that achieves 30:1 bandwidth across the 60MHz to 2000MHz frequency range (VSWR<4). The proposed antenna occupies 1.4m in length and 0.05m in width, and consists of 3 overlapping dipoles that are fed in phase to ensure uniform current flow. Two fabricated prototypes are presented in this paper. The first is a rigid metallic version using a 1.524mm thick Rogers RO4003 board via conventional printed circuit board fabrication. The other is a fully flexible textile-based prototype 'printed' on organza fabric via automated embroidery of conductive threads (E-threads). In both cases, measurements are in very good agreement with simulations. Specifically, the TCDA is well matched from 500MHz to 2000MHz with VSWR<2.5 and has a realized gain ranging from -16dBi to 6dBi across the entire bandwidth from 60MHz to 2000MHz. The proposed design is intended for on-body operation (e.g., placed along the arms). To assess the performance of this antenna for body mounting, we applied a 2cm-thick ground beef beneath the textile TCDA to represent body tissue. Overall, the proposed TCDA brings forward new opportunities for several ultra-wideband applications.**

***Index Terms*—body-worn, overlapping dipoles, conductive textiles, embroidered antenna, measurements with tissue**

I. Introduction

BODY-WORN wideband antennas are needed for a variety of commercial and governmental applications. A key requirement is for the antenna to be conformal and flexible. Existing technologies for conformal and flexible electronics include conductive tapes [1], screen–printed silver nanowires [2], liquid metal alloys [3], inkjet-printed electronics [4], and conductive threads (E-threads) [5]-[9]. Among these, conductive tape antennas have excellent RF performance as the employed materials behave almost the same as those used for traditional antennas. However, tapes are prone to cracking when flexed multiple times [7]. Inkjet-printed electronics suffer from similar issues, viz. ink surfaces rupture when flexed and stretched. In [2], a stretchable patch antenna based on silver nanowires (AgNWs), embedded in PDMS was presented, but the radiation efficiency was 67.2% at most due to the lower conductivity of the AgNWs nanowires. An antenna based on liquid metal upon a stretchable substrate was presented in [3]. This liquid metal has excellent conductivity and the associated antenna prototypes were fully flexible. However, this approach has fabrication complexity and there are potential challenges due to liquid metal cracking and leakage.

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TABLE I. FREQUENCY BANDS OF INTEREST

Name	Frequency Bands
SINCGARS	30-88 MHz
FM radio	88-108MHz
Air and Marine	116-174 MHz
UHF	225-450 MHz
UHF-Public Safety	450-512 MHz
L-Band	1-2 GHz

With both mechanical and RF performance considered, conductive threads are desired over other approaches. These threads could be knitted, weaved, and embroidered into designed structures for various wearable applications [5]-[6]. Previous work [7] has shown that resolution as high as 0.1mm can be achieved when embroidering such textile surfaces. More importantly, the RF performance of antennas based on conductive E-threads is almost the same as that of copper antennas. Superb mechanical robustness and tolerance, including drastic temperature changes, were also validated for this textile fabrication technology [8]-[9].

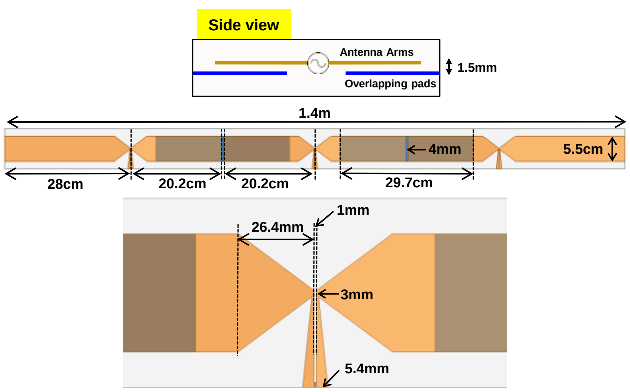
In this paper, we present an ultra-wideband antenna using a sequence of 3 overlapping dipoles to cover the 60MHz to 2000MHz range (30:1 bandwidth). The proposed dipole array covers several important communication bands including SINCGARS, FM radio, Air and Marine, UHF, UHF-Public Safety, and L bands (see Table I). Notably, existing wearable antennas for the above-mentioned frequencies, such as dipoles and dipole arrays [10]-[11] have limited bandwidth (up to 400MHz). Commercial antennas [12]-[13] have reported operation from 60MHz to 2000MHz. But these antennas are reported to exhibit gains on the order of -40dBi to 4dBi across 60MHz to 6000MHz and are designed as vest and backpacks. Our body-worn dipole array is instead designed to be placed across the arms and shoulders. It is shown to have realized gain that ranges from -16dBi to 6dBi across 60MHz to 2000MHz. To our knowledge, this is the first time that a tightly coupled dipole array TCDA is fabricated on textile threads, and this is by far the only conductive textile antenna that exhibits such good performance across a 30:1 bandwidth.

This paper is organized as follows: Section II focuses on antenna design and fabrication. Section III presents measurements of the antenna performance in free-space. Measurements when mounted on tissue to emulate the human body are given in Section IV.

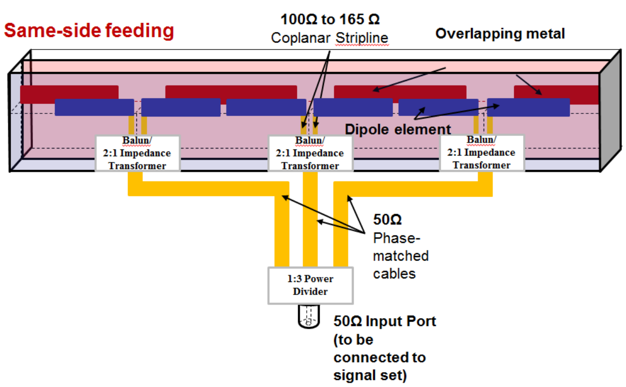
II. Antenna Design and Fabrication

The proposed antenna is a 1.4m in length and 0.05m in width tightly coupled dipole array. The array consists of three elements fed in phase to ensure uniform current distribution. The detailed geometry is depicted in Fig. 1(a).

Notably, the adjacent dipoles overlap by 0.297m by printing them on both sides of the organza as the substrate layer. Conventionally, array elements are placed apart to minimize mutual coupling. However, for our TCDA, coupling is not only desired but also enhanced and adjusted to increase bandwidth. In fact, the strong mutual coupling between array elements effectively emulates a uniform current sheet which results in ultra-wide performance.



(a)



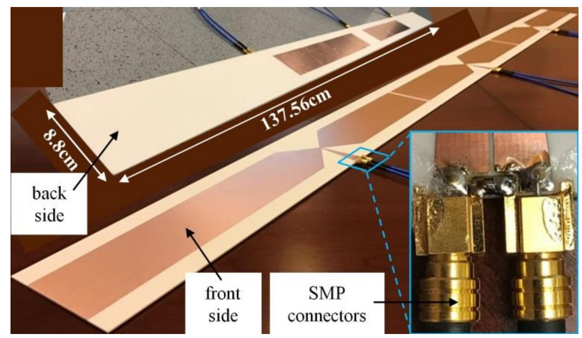
(b)

Fig. 1. Body-worn tightly coupled dipole array structure: (a) detailed dimensions, and (b) feeding network for evaluating antenna bandwidth.

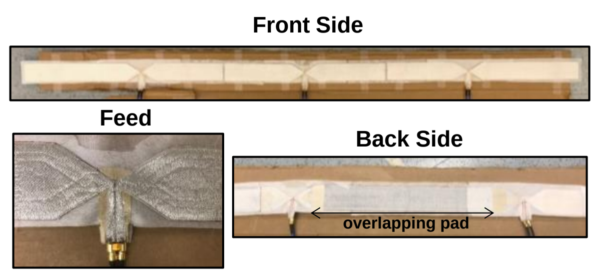
The feed structure of the proposed TCDA is depicted in Fig.1 (b). As noted before, all three dipole elements are fed in phase to ensure uniform current flow. To achieve this, we employed a modified version of the feeding network developed by authors of [14]. Specifically, a 50 Ω 1:3 power divider was employed to provide equal power and phase to each of the 3 dipole elements. Also, a balun together with a 2:1 impedance transformer was used to transform the unbalanced 50Ω microstrip/coplanar/ coaxial line to a balanced 100Ω twin lead line. Subsequently, a tapered line impedance transformer was employed to convert the 100Ω twin lead to 165Ω, for matching to the port impedance of each dipole elements.

Two prototypes were fabricated using this design as shown in Fig. 2. One is based on traditional printed circuit board technology. The other prototype was fabricated using automated textile embroidery process. For this textile antenna, the dipole elements and overlapping pads were weaved using 7-filament silver-plated copper Elektrisola E-threads. For fabrication, the front and back sides were first automated embroidered separately and then manually sewed together.

To simplify the measurement process and get rid of loss introduced by power divider, these array prototypes were fed at the center element, with the other two ports terminated by matched impedance. The balun used in measurements is Marki's BAL003, which is a wideband balun operating from 200KHz to 3GHz.



(a)



(b)

Fig. 2. Fabricated body-worn tightly coupled dipole array: (a) copper array, and (b) textile array.

III. Antenna Performance

The two arrays were measured in an anechoic chamber as depicted in Fig. 3. A large piece of hard paper was attached to the textile antenna to keep the array in shape.

The measured voltage standing wave ratio (VSWR) of the center element for both prototypes is given in Fig. 4, and compared to simulations. As seen in Fig. 4, the measurements of the textile antenna fit with simulation well and are comparable to those of the copper antenna. It is observed that the body-worn TCDA has a VSWR < 2.5 from 500MHz (antenna size=2.5λ) to 2000MHz (antenna size=10λ).

We next examine the gain and antenna patterns for this dipole array. In Fig. 5 we demonstrate the measured maximum realized gain of this array. Due to the limited frequency range of our anechoic chamber, the array was measured from 150MHz to 2GHz. Both measurements of textile array and copper array are presented and compared with simulations across the entire 30:1 bandwidth. Since the dipole array has a nearly omnidirectional pattern in H-plane, Fig. 5 collects the maximum realized gain available in the E-plane (φ = 90º, θ=-180º~180º). As seen, the gain ranges from -16dBi (at 60MHz) to 6dBi which is comparable to existing body-worn antennas at similar frequency range. The maximum gain of the textile antenna is 1 to 4dB lower than that of the copper antenna from 1500MHz and up. This is because of the increased resistive loss of textile surface at higher frequencies.

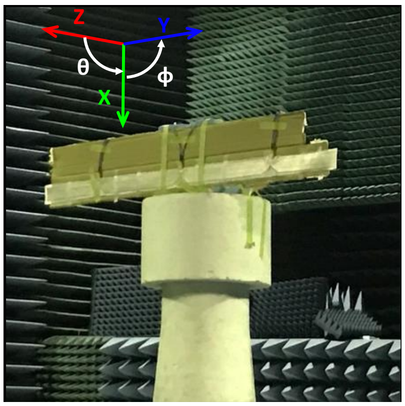


Fig. 3. Measurement of body-worn TCDA in chamber.

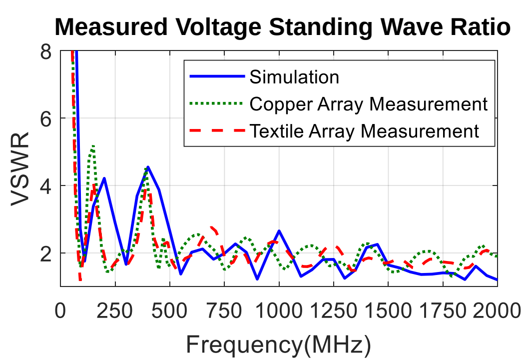


Fig. 4. Simulated and measured VSWR of the designed body-worn TCDA.

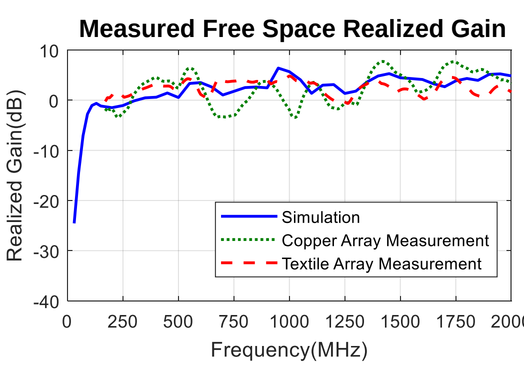


Fig. 5. Simulated and measured maximum realized gain of the designed array in Fig. 2.

Radiation patterns at different frequencies are shown in Fig. 6. As expected, when the frequency increases, multiple beams appear. This is because the array's electrical length is sufficiently large at higher frequencies, up to 10λ at 2GHz. The radiation patterns for the textile and copper dipole arrays are also depicted in Fig. 6. As seen, both copper and textile antenna compare well with simulation patterns.

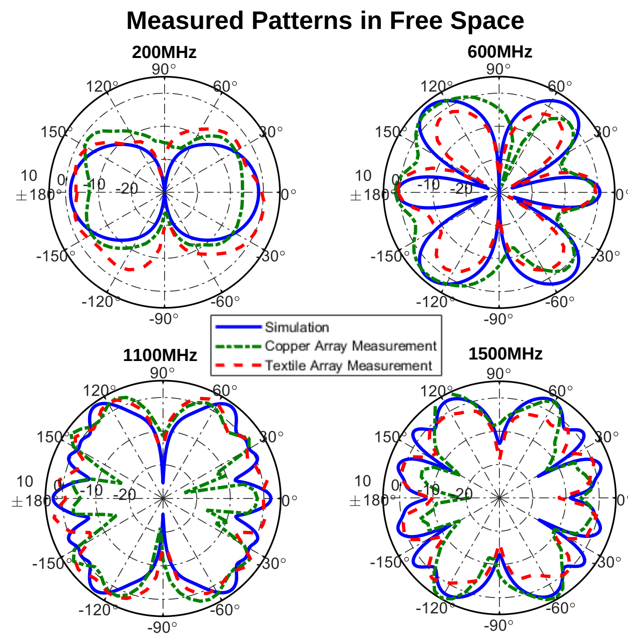
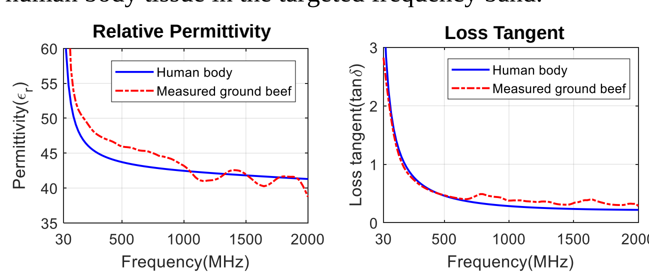


Fig. 6. Simulated and Measured radiation patterns at 200MHz, 600MHz, 1100MHz and 1500MHz of the designed array in Fig. 1.

IV. On-Tissue Simulation and Measurements

The proposed 3-dipole textile array was designed for on-body applications. To test it for this application, we proceeded to place it on a 2cm-thick medium to emulate human body tissue. This thickness corresponds to the half wavelength in tissue at the center operational frequency. The dielectric properties of the human body tissue are given in [15].

Similar to [16], we applied 80% lean and 20% fat ground beef to emulate human body. The measured permittivity and loss tangent of ground beef are demonstrated in Fig.7 and are compared with those of human body tissue. As shown, the measured properties of ground beef are closely matched to human body tissue in the targeted frequency band.



(a) (b)

Fig. 7. Relative Permittivity (a) and loss tangent (b) of ground beef emulating human body tissue.

Simulation and measurement setups are both depicted in Fig.8. In the simulation, the antenna is mounted on top of 1.5mm-thick skin layer and 2cm-thick human body tissue. For measurement setup. In the measurement, the ground beef is

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sealed in plastic bags that were taped beneath the array. The thickness of tissue bags was kept 2cm as in simulation.

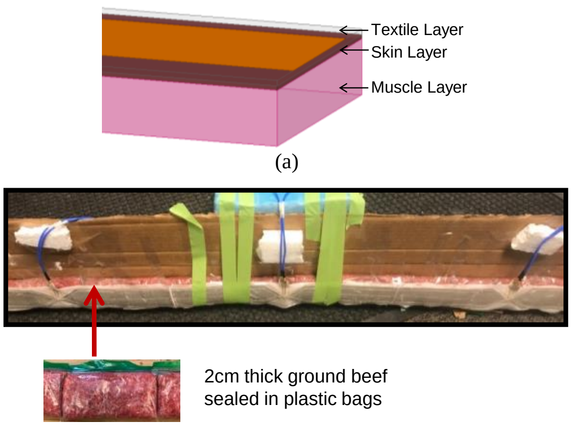

Fig. 8. Body-worn textile TCDA mounted on tissue: (a) simulation setup, and (b) measurement setup.

The measured and simulated maximum realized gain when placed on ground beef are presented in Fig. 9 and compared to free-standing data. Also, we observed that a 10dB gain difference exists between antenna in free space and antenna mounted on ground beef.

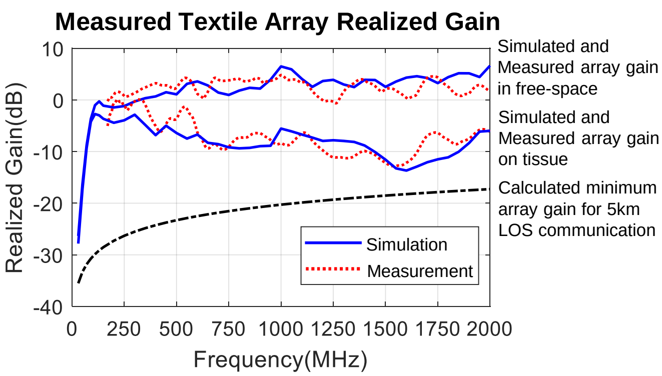

Fig. 9. Maximum realized gain comparison between body-worn TCDA placed in free space and mounted on tissue. Together with minimum required antenna gain for 5km LOS communication.

To demonstrate that the proposed textile array provides reliable performance for body-worn communications, we carried out link budget analysis for line of sight (LOS) connectivity. To do so, we assumed a 5W broadcasting signal and a receiver sensitivity of -110dBm. Further, we assumed a distance of 5km between the transmitter and the on-body receiver with textile antenna. Using Friis transmission formula, the minimum antenna gain for reliable connectivity is given by

$$G = 0.5 * [P_r - P_t + 20\log(\mathrm{D}) + 20\log(f) + 32.44] \qquad (1)$$

and plotted in Fig. 10. As seen, there is at least 6dB margin across the entire frequency band for successful LOS communication over 5km distance. This suggests that the proposed body-worn textile array retains its 30:1 gain bandwidth in free-standing and body-worn deployments.

V. Conclusion

A novel body-worn array of overlapping dipoles was presented and shown to achieve 30:1 bandwidth, from 60MHz to 2000MHz. The entire array is 1.4m long and 0.05m wide, and delivered a gain of -16dBi to 6dBi across the frequency range. Two prototypes were fabricated and tested for this array. One was copper-based and printed on a thin Rogers RO4003 board using conventional printed circuit board fabrication. The other was E-textile-based and was embroidered on organza using an automated embroidery machine. The textile antenna was weaved using Elektrisola E-threads, thin enough to achieve geometrical precision as high as 0.1mm. The antennas were measured to extract the associated VSWR, realized gain and radiation patterns. The antenna's performance was also assessed when mounted on a 2cm thick ground beef substrate to emulate the human body. Measurements and simulation were in good agreement, and suggest that up to a 10dB loss is expected when the antenna is mounted on a substrate emulating the human body. To our knowledge, this is the first tightly coupled dipole array fabricated using textile threads, and delivering a remarkable bandwidth of 30:1.

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