URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Millimeter-Wave Textile-Based Monopole Antenna for Wearable Wireless Power Transmission

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Abstract

With a wide bandwidth and a high potential for antenna miniaturization, the millimeter-wave (mmWave) bands have attracted interest for a range of wearable applications. In this paper, a textile-based end-fire monopole is proposed for wireless power transmission (WPT) applications. The proposed Yagi-inspired antenna bandwidth covers the 24 GHz license-free band. The antenna achieves 73% total efficiency, a 2.5 dB improvement over a microstrip patch on the same textile substrate. The antenna has a peak gain over 4 dBi with a wide 80° half-power beamwidth both in space and on a layered human tissue model. The antenna is experimentally characterized for line-of-sight WPT showing a 7 dB forward transmission improvement compared to 2.45 GHz WPT, for 55 cm separation, between two symmetric antennas with sub-cm^2 area. Given the antenna's 0.4 cm^2 area, it is shown that mmWaves enable high-efficiency WPT to miniaturized antennas in future 5G networks.

1 Introduction

Millimeter-wave (mmWave) bands are increasingly recognized as an enabler of future wireless networks [1]. Body area networks (BANs) operating in the mmWave bands have been investigated for high-speed on and off-body links [2]. Moreover, mmWave energy harvesting has attracted significant interest where high gain transmitting and receiving antennas can improve the end-to-end efficiency in wireless power transmission (WPT) compared to UHF bands [3].

mmWave rectennas and antennas have been widely developed for WPT and energy harvesting in the K/Ka-bands using a variety of implementations. For instance, a cavity-backed circularly polarized array [4], a broadband textile-based antipodal vivaldi antenna [5], flexible and printed microstrip patch arrays [6, 7], and a Rotman lens-fed microstrip array [8] were proposed for mmWave WPT. For mmWave antennas operating on lossy substrates, such as 3D printable flexible packages and textiles, achieving a high radiation efficiency is a significant challenge due to the high dielectric (tanδ) losses.

Textile-based mmWave antennas have been reported with varying radiation efficiencies, typically under 70% due to the lossy textile substrates [9, 10, 11, 5]. End-fire and broadside textile-based antennas have been proposed for 60 GHz on- [10] and off-body [9] communications, respectively, achieving under 50% radiation efficiency. In [5], a reflector-backed antenna was proposed for energy harvesting, achieving around 67% radiation efficiency owing to its thicker substrate and lack of ground-plane backing. Recently, an experimental characterization of on-body UHF and mmWave links have shown that the excess delay can be reduced by a factor of three at 60 GHz compared to 900 MHz, with comparable path-loss when using 60 GHz horn antennas [12].

In this paper, a Yagi-inspired microstrip-fed monopole antenna is proposed for WPT and energy harvesting applications in future 5G bands, achieving a wide bandwidth and a high radiation efficiency. The antenna maintains a wide $S_{11} < -10$ dB bandwidth from 22 to 26 GHz covering the license-free 24 GHz band with a 73% total antenna efficiency, demonstrating a higher efficiency compared to reported textile-based mmWave antennas. The antenna design and simulated parameters are presented in Section 2, Section 3 then presents the experimental validation, as well as WPT measurements between symmetric antennas in a Line-of-Sight (LoS) link.

2 Antenna Design and Simulation

The antenna is designed for the 24 GHz K-band Industrial Scientific and Medical (ISM) band, previously considered for various rectenna implementations [4, 6]. The antenna is designed based on a $\lambda/4$ monopole with an unconnected reflector and 9 director elements, fabricated on a single metal layer. The number of directors was selected as a trade-off between achieving a medium peak gain, a wide beamwidth, and for keeping the antenna compact. Additional directors can be added to increase the antenna's on-body (end-fire) gain.

Figure 1 shows the layout and dimensions of the proposed antenna. The antenna is designed for a 300 μm-thick polyimide-on-woven polyester textile-based substrate. The substrate's dielectric properties were measured using two

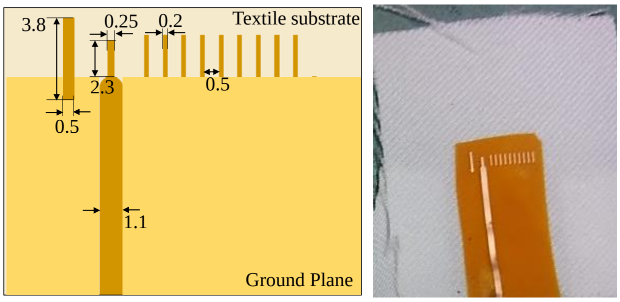

Figure 1. Layout and dimensions (in mm) of the antenna and photograph of the fabricated prototype on textile.

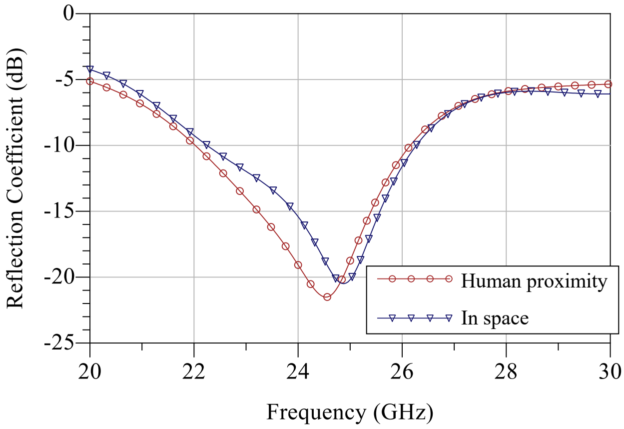

Figure 2. Simulated reflection coefficient (S_{11}) of the proposed antenna.

microstrip lines on the same substrate to be ε_r=1.95 and tanδ=0.02, in line with most woven-textile substrates previously used for wearable antennas [9, 5]. A prolonged microstrip feed was added to match the fabricated prototype, where the prolonged feed reduces the unwanted reflections off the coaxial connector [9, 5], which is significantly larger than the antenna's radiator. The antenna occupies a total area of approximately 10×4 mm, excluding the prolonged microstrip feed.

The antenna was simulated in CST Microwave Studio. As the antenna is intended for wearable applications, a layered tissue model similar to [5], based on the previously reported experimental mmWave dielectric properties of skin [13], was included to observe the human-proximity effects on the antenna's S_{11} and radiation properties. The tissue model was placed at 4 mm from the antenna. Figure 2 shows the simulated S_{11} of the antenna in the presence and absence of the tissue model, demonstrating a stable and wide bandwidth from 22 to 26 GHz, covering the 24 GHz ISM-band. The minimal variation in the simulated S_{11} in human proximity is attributed to the antenna's wide bandwidth and the reflection of the mmWave radiation off-skin.

The radiation patterns of the antenna were simulated in CST, with and without the tissue model. Figure 3 shows the simulated realized gain (inclusive of impedance mismatch)

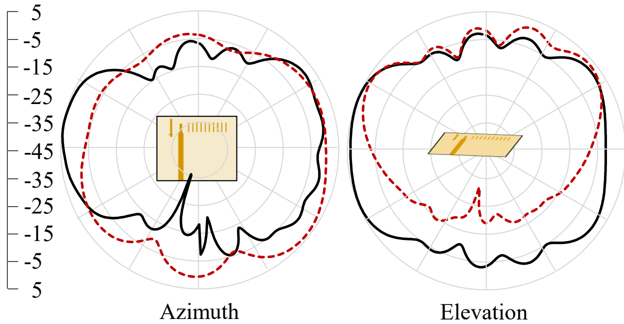

Figure 3. Simulated realized gain patterns (in dBi) of the proposed antenna in space (solid) and in human-proximity (dashed).

over the azimuth and elevation planes. The peak realized gain is 4.8 and 4.6 dBi in absence and presence of the tissue model, respectively.

From the gain patterns, it can be observed that the antenna maintains a wide beam-width over both planes, with over 80° 3 dB beam-width on the azimuth plane. A wide beam was previously found to improve the energy harvesting efficiency from unknown directions [14], and is more generally considered a figure-of-merit in wearable communications [15]. The peak end-fire gain is validated through the WPT measurement in the next section.

A TM_{10} common geometry microstrip patch antenna was simulated on the same textile substrate, to enable evaluation the improvement in the radiation efficiency, achieved by the proposed design. The patch's dimensions are L=4.3 and W=4 mm. Both antennas were fed using a short 3 mm microstrip line to minimize any feed-induced insertion losses, enabling a better evaluation of the antenna's own losses [9]. At 24 GHz, the proposed antenna achieves a 73% efficiency with the 3 mm microstrip feed. On the other hand, the microstrip patch achieves a 40% efficiency, owing to the increased dielectric losses in the tanδ=0.02 substrate. Therefore, the proposed antenna represents around 2.5 dB efficiency improvement over a TM_{10} patch, explaining the higher efficiency over previously-reported textile-based mmWave antennas such as [5, 9, 10].

3 Antenna Measurements

The antenna was fabricated using photolithography on a commercially-available flexible polyimide copper laminate using the method described in [5]. The antenna's traces were then adhered to the woven-polyester textile substrate using a spray-mount adhesive. A low-temperature solder was then used to mount the connector in order to avoid damaging the textile substrate.

The antenna was characterized using an Agilent E8361A 67 GHz PNA Vector Network Analyser (VNA) with a standard SOLT electronic calibration. A solder-terminated connector was used to connect the antenna to the VNA. As

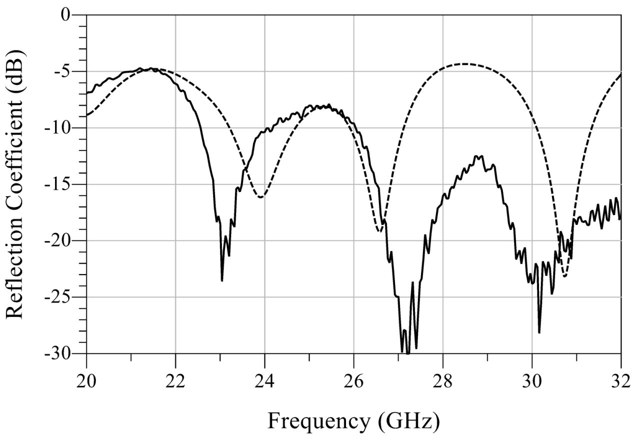

Figure 4. Simulated (dashed) and measured (solid) reflection coefficient of the antenna with a solder-terminated edge connector

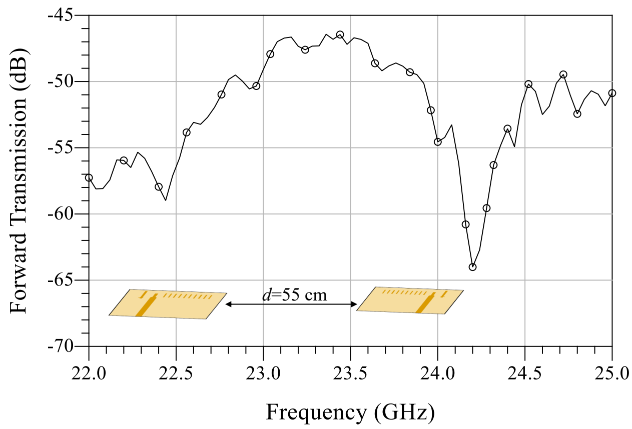

Figure 5. Measured forward transmission between two symmetric antennas at d=55 cm.

the connector's unshielded pin is of comparable size to $\lambda/4$ around 26 GHz, which may alter the impedance (S_{11}) response, the antenna needs to be simulated with the connector [5]. Figure 4 shows the simulated and measured reflection coefficient of the antenna with the mounted connector. Both the simulated and measured demonstrate the antenna maintains an $S_{11} < -10$ dB at 24 GHz. Furthermore, when considering the VSWR<3 ($S_{11} < -6$ dB) bandwidth, it can be observed that the antenna's bandwidth spans the full 5G K/Ka-band spectrum up to 32 GHz.

The next step in characterizing the antenna is investigating its performance in a LoS point-to-point WPT link, demonstrating that a higher WPT efficiency can be achieved at mmWave bands. The power received by an antenna from an incident Poynting vector (RF power density) S is given by

$$P_{RX} = SA_{\text{eff.}}, \tag{1}$$

where A_{eff} is the antenna's effective area. Given that A_{eff} is limited by the aperture efficiency of an aperture antenna (e.g. horn or microstrip patch) [16], (1) can be rewritten as

$$P_{RX} = A_{TX}A_{RX}\eta_{TX}\eta_{RX}\frac{f^2}{c^2d^2} \tag{2}$$

where f is the frequency, c is the speed of light, and η and A are the antennas' aperture efficiency and physical area respectively [3].

From (2), it can be observed that for compact transmitters and receivers of a fixed physical area A, operating at a higher f enables a better forward transmission between the antennas and subsequently a higher end-to-end efficiency in WPT. Two symmetric antennas based on the proposed monopole were connected to a VNA's ports at a fixed distance d=55 cm. The S_{21} was measured from 1 to 40 GHz. Figure 5 shows the measured S_{21} over the antenna's impedance bandwidth.

At 23.5 GHz, where the maximum S_{21}=−47 dB was measured, and for d=55 cm, the free space path-loss is 54.7 dB. Hence the measured gain of the antenna, using the two-antennas method [16], is 3.9 dBi, agreeing with the peak simulated gain presented in Section 3.

The mmWave S_{21} between the compact antennas is compared to that at UHF bands. At 2.45 GHz, and after excluding the impedance mismatch losses, a forward transmission of -55 dB was measured. Given the 35 dB path-loss at 2.45 GHz, the antennas' gain is around -10 dBi in the 2.4 GHz ISM-band, showing that for a wireless power transmitter and receiver restricted to sub-1 cm^2 area, a significantly higher gain and subsequently P_{RX} can be achieved by operating in the 24 GHz band. From a WPT perspective, while the RF to DC efficiency is lower at mmWave bands compared to UHF [3], several recent rectifier implementations have shown efficiencies over 60% up to 35 GHz [17].

4 Conclusion

In this paper, a textile-based microstrip antenna was presented for wearable WPT. The proposed antenna achieves an S_{11} bandwidth covering the 24 GHz ISM-band and over 4 dBi gain with a broad beam in both the presence and absence of human tissue. The antenna's performance for UHF and mmWave WPT has been compared showing over 7 dB forward transmission improvement, for the same separation and antenna physical area, by operating in the 24 GHz band. Finally, the antenna's high radiation efficiency of up to 73% and its small form-factor demonstrate that the proposed antenna is suitable for mmWave WPT applications in future 5G+ networks.

5 Acknowledgements

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/P010164/1.

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