Towards Multi-Mode Millimeter Wave Body Area Networks for Information and Power Transmission: A Co-Existence Study

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***Abstract*—While millimeter-wave (mmWave) technologies are often associated with costly applications using large arrays, several inexpensive implementations promise mmWave connectivity closer to the user in Body Area Networks (BANs) applications. Here, we evaluate the potential for multi-mode mmWave links for information and power transfer applications. The co-existence of off-body radiative and on-body wave-guiding mechanisms is experimentally investigated based on state-of-the-art transmission lines and antennas. First, a body-to-body link with at least −50 dB channel gain is demonstrated based on wide-beam microstrip and reflector-backed broadband antennas. Co-existence is then studied experimentally by measuring the coupling between the off-body communication/power transfer antenna and a wearable Single Wire Transmission Line (SWTL), with an ultra-low on-body attenuation of below −0.8 dB/cm around 28 GHz. Less than −40 dB coupling is demonstrated for clearances as low as 1 cm between the antenna and SWTL. The measured results indicate that co-located textile-based antennas and transmission lines can enable multi-mode high-performance body-centric mmWave networks, and highlight the need for interference-countering mechanisms in future high-density BANs.**

***Index Terms*—Antenna, Body Area Networks (BANs), mutual coupling, Single Wire Transmission Lines (SWTLs), transmission lines, wearables.**

I. Introduction

With 5G networks undergoing commercial deployment, research interest in unobtrusive and wide-scale millimeter-Wave (mmWave) Internet of Everything (IoE) applications has significantly increased, leveraging additive manufacturing [1], and targeting emerging applications such as Wireless Power Transmission (WPT) [2], [3]. From textile-based mmWave antennas [4], [4], inkjet printed flexible components [5], to mmWave flexible and printed energy harvesters [2], [6]–[8], inexpensive, flexible, and conformable mmWave are expected to enable new applications in future 5G+/6G networks.

mmWave Body Area Networks (BANs) are among the applications widely discussed in mmWave antennas literature around the 5G bands and the 60 GHz. Textile antennas for communication at 60 GHz were among the earliest implementations addressing high-sped BANs [4], [9]. Recently, on-body 60 GHz links using aligned horn antennas were demonstrated with comparable channel gain to 900 MHz links using omnidirectional antennas [10]. On the other hand, non-radiative means have been proposed for wearable applications based on surface wave propagation [11], [12], but the reported approaches were narrow-band and limited to sub-6 GHz applications. Recently, a shielded broadband Single Wire Transmission Line (SWTL) has been realized with low loss compared to microstrip lines and wireless up to 50 GHz [13], presenting nearly 4× lower attenuation than a microstrip line on the same substrate.

Nevertheless, the co-existence of multi-mode mmWave devices in the context of wearables has not been investigated experimentally. Furthermore, with many mmWave applications requiring large arrays [14], [15], the undesired coupling between closely-spaced mmWave components in future BANs remains unknown. To add, low-loss on-body links as well as off-body mmWave power transfer may take place at a significantly higher power level than the sensitivity of information transceivers, leading to a high noise level [16].

In this paper, we experimentally investigate the co-existence of on/off-body links in terms of mutual coupling between wearable on/off-body antennas and transmission lines. It is shown that the coupling of tightly coupled antennas and on-body lines could be comparable to the wireless path gain of other off-body devices. This work represents an early step towards the scaling and wider integration of mmWave components and links in future IoT and BAN networks.

II. Multi-Mode mmWave BANs

To realize multi-functional mmWave-enabled BANs, high-efficiency textile-based antennas are required for links with off-body devices. Off-body links can be achieved using broadside antennas such as microstrip patch antennas [15], [17] or reflector-backed broadband antennas [8], previously found have an improved radiation efficiency due to the minimization of the dielectric loss. As shown in Fig. 1, off-body antennas can be used in mmWave energy harvesting arrays [15].

Two high-efficiency textile-based antennas realized using photolithography on inexpensive polyimide copper laminates are considered in this work for realizing and evaluating the

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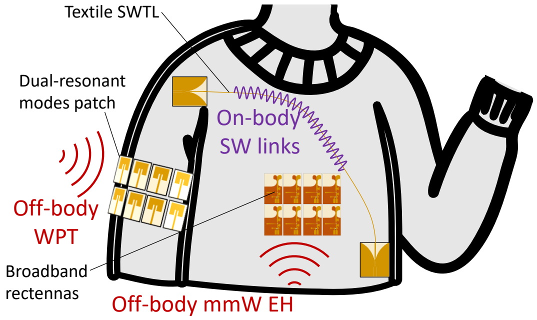

Fig. 1. A multi-mode textile-based mmWave BAN with on and off-body links using radiative and wave-guiding mechanisms.

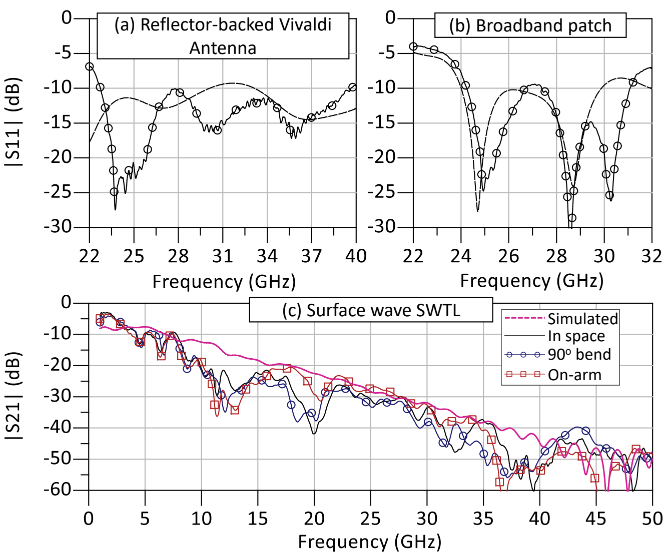

Fig. 2. Simulated (dashed) and measured (solid with markers) s-parameters of the three components of the investigated BAN: (a) broadband AVA [8]; (b) wide-beamwidth microstrip patch [15]; (c) on-body shielded SWTL [13].

off-body radiative mmWave links. The first is a broadband Antipodal Vivaldi Antenna (AVA)-inspired monopole, with a measured 69% total efficiency, whose simulated and measured S_{11} is shown in Fig. 2(a). The second antenna is a higher-order TM mode microstrip patch with a broad beam and a wide bandwidth, maintaining a total efficiency of 60% with a very low profile under 0.4 mm [15]. The microstrip antenna's S_{11} is shown in Fig. 2(b). Both antennas maintain broadside off-body radiation making them suitable for either communication or wireless power reception (when connected to a 50 Ω-matched rectifier) from an off-body gateway [17]. In addition, the antennas can be used to realize mmWave body-to-body links [18].

For high-speed mmWave communication to take place between on-body devices, a low-loss on-body mmWave signalling mechanism is required. A state-of-the-art textile-based SWTL, of approximately 45 cm (inclusive of the coplanar waveguide feed and tapered launchers) is used in this work to realize the on-body mmWave link [13]. While the SWTL is not a wireless transmission mechanism, high-frequency

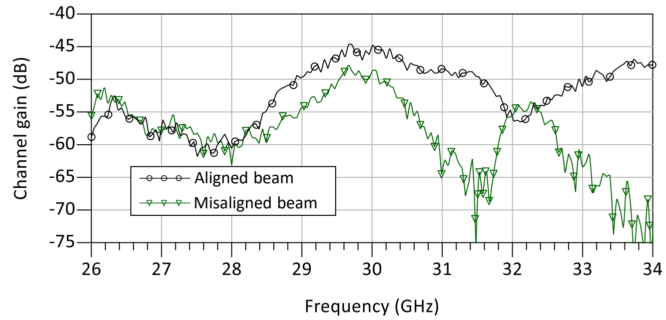

Fig. 3. Measured body-to-body broadside link with and without beam alignment between the Vivaldi-inspired monopole and the broad-beam patch.

wave-guiding mechanisms using slow-wave lines have been reported for a variety of on-body sensing applications without affecting the user's experience [11]. In addition to the low attenuation evident through the high S_{21} in Fig. 2(c), the SWTL maintains a stable and uniform phase response, i.e. group delay, making it suitable for wide-band communication [13]. However, while a relatively low cross-talk between co-located SWTLs was previously observed [13], the interaction between the SWTL and other antennas remains unknown. The coupling between the on-body SWTL-supported on-body link and co-located off-body/body-to-body antennas is reported in the next section.

III. On/Off-Body S-Parameter Characterization

A. Body-to-Body Link

The first mode investigated is body-to-body links, where two off-body antennas communicate with each other in line-of-sight, with an without main-lobe alignment. The performance of a body-to-body link can also be used to broadly evaluate that of an off-body link, where only one antenna is placed on the body. Fig. 3 shows the measured channel (path) gain between the body-to-body antennas for a 60 cm link. The measurements were performed for with the antenna's main lobes aligned, and with a slight misalignment of approximately 30°, based on the previously measured radiation patterns in [8], [15].

Based on a 60 cm link at 30 GHz, the free-space path loss for 0 dBi antennas is 57.6 dB. As in Fig. 3, the 12.6 dB higher measured channel gain indicates a gain of roughly 6.3 dBi per antenna. This is in fair agreement with the peak gain of both antennas which is around 8 dBi, when the full spherical patterns were measured in an anechoic range [8], [15]. The misaligned beam case still exhibits a fairly high channel gain which is suitable for short to medium range links (up to a few meters) based on the two antennas.

B. On-Body SWTL/Antenna Coupling

While the SWTL offers significantly improved confinement over radiative propagation, it still suffers from higher spurious radiation than a conventional microstrip or coplanar waveguide [13], [19]. To understand the impact of closely-spaced antennas and transmission lines in a multi-mode BAN, the

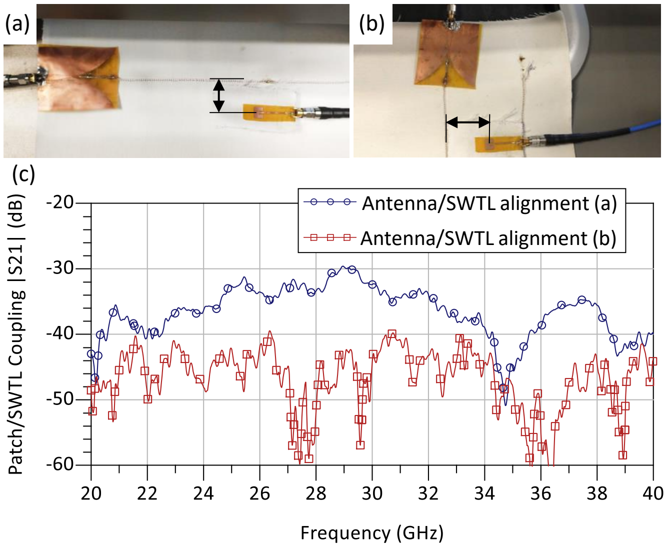

Fig. 4. SWTL-patch mutual coupling: (a) experimental setup with aligned feeds; (b) misaligned microstrip feed/SWTL; (c) measured coupling at 2 cm clearance for the alignments shown in sub-figure (a) and (b).

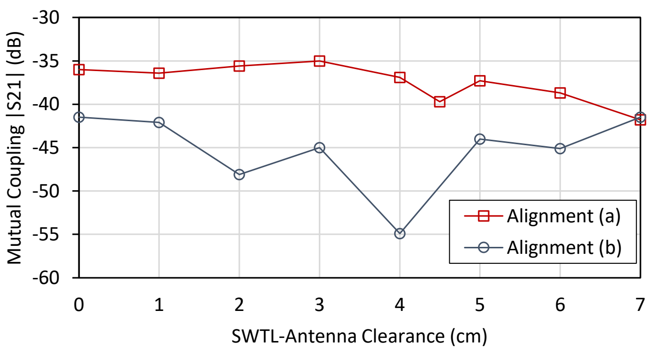

Fig. 5. Measured SWTL-patch coupling for varying clearances at 28 GHz in the positions shown in Fig. 4(a) and (b).

mutual coupling between the SWTL and the microstrip antenna has been experimentally measured in the configuration shown in Fig. 4 (a) and (b).

The measured mutual coupling for both orientations around the antenna's bandwidth is shown in Fig. 4(c), with a maximum coupling around 26–30 GHz, where the antenna's S_{11} is matched, as previously seen in Fig. 2(b). It can also be seen that the coupling is suppressed by at least 5 dB between 26 and 32 GHz. This can be attributed to the misalignment between the antenna's microstrip feed and the SWTL. To explain, while the antenna's polarization will be mostly stable across its main-lobe, the SWTL is in the antenna's near-field, and the polarization at this angle will not be similar to that of the antenna's main-lobe.

To further observe the effect of the SWTL-antenna clearance on the mutual coupling, the separation between the antenna was varied between 0 cm, i.e. the antenna's feed positioned exactly over the SWTL, to 7 cm. Fig. 5 shows the measured coupling as a function of antenna/line separation. Across the measured antenna-SWTL clearances, it can be seen that the misaligned feed suppresses the interference and improves the isolation by nearly 5 dB for the closely-located antenna and line. Nevertheless, comparing the mutual coupling between the misaligned patch and the SWTL at 30 GHz, around −45 dB, to the channel gain over the 60 cm body-to-body link, also around −45, it can be seen that interference mitigation [20] may be required. To explain, if such a closely-packed high-capacity mmWave BAN is to be realized, the signal strength of off-body and body-to-body links exceeding 1 m may be lower than the mutual coupling from co-located wearables using non-radiative transmission mechanisms such as the shielded SWTL.

IV. Conclusion

In this paper, the concept of multi-mode BANs at mmWave frequencies using textile-based antennas and on-body transmission lines was investigated. It is shown that when antennas are co-located within close vicinity to a non-radiative transmission line, the mutual coupling could be comparable to the channel gain of an off-body link. Moreover, it is found that the alignment of on-body devices could directly influence the mutual coupling between antennas and transmission lines at varying clearances. This work highlights the need for on-body shielding mechanisms between the different wearables which may operate in different BAN modes such as off-body, body-to-body, and on-body mmWave links, as well as motivate future work on large-area flexible and textile-based decoupling mechanisms between wearable antennas.

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