Conformable Single-Wire Transmission Lines: From Modelling to mmWave Applications

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Abstract

The Goubau single-wire transmission line (SWTL), guiding conformal surface waves, offers a potential for reduced losses compared to two-conductor transmission lines, as well as free-space propagation. This presentation presents a state-of-the-art flexible single-wire transmission line with a coplanar waveguide feed. The line is implemented using conductive threads for on-body transmission, i.e. operation near a lossy medium, and is shown offering over 20 dB 0.5-4 GHz broadband link improvement over UWB antennas over the same range. In addition, the SWTL exhibits a stable group delay and enables conformable non-line-of-sight links. A shielded SWTL is then proposed for mmWave applications and is shown with 4x lower attenuation than a printed microstrip line on the same substrate at 50 GHz. To simplify the analysis of the line, a phase-accurate loss-less transmission line model is developed for the shielded line, showing an accurate group delay and under 7% phase error compared to measurements and full-wave simulations up to 50 GHz. The sensitivity of the SWTL to moisture and humidity is finally explored and compared to microstrip lines.

1 Introduction

The Goubau-Sommerfeld single-wire transmission line (SWTL) was developed in the 1950s, enabling low-loss long-range links in the UHF spectrum. Such single-conductor lines were later expanded on to include spoof surface plasmons (SSPs) [1], as well as on-chip sub-THz lines [2].

Communication using surface waves in the context of wearable and on-body networks has recently attracted attention [3]. For example, a textile-based body area network was proposed based on spoof surface plasmons (SSPs) [4]. The same structure was later used to overcome NLOS shadowing around the body [5]. Furthermore, SWTLs were proposed for ultra-long-range RFID [6]. Nevertheless, these approaches were either limited in bandwidth, e.g. to the 2.4 GHz band [4], or required bulky launchers based on horn-like radiators [6].

This paper provides an overview of our recent progress in the design of SWTLs using flexible and conformable applications, towards communication in a lossy environment, i.e. on-body links. The paper first introduces the numerical and closed-form analysis of the SWTL up to mmWave frequencies. Selected experimental results which demonstrate the feasibility of using the SWTL in wearable communication, as well as emerging sensing and wireless power transfer applications, are presented.

2 Numerical modelling and field confinement

The first step in evaluating the suitability of an SWTL in wearable applications is through full-wave simulation. A 45 cm over a uniform skin layer is simulated. In Fig. 1(a), the E-field propagating between two UWB monopole antennas is shown, where it can be seen that the E-field received by the second antenna is orders of magnitude lower than the excitation, due to the spherical spreading the absorption in the lossy skin layer. The proposed single-wire transmission line is simulated in Fig. 1(b), where a coplanar waveguide (CPW) to SWTL launcher is observed. The tapered launcher gradually increases the characteristic impedance of the 50 Ω CPW to match the SWTL's [7]. The line is simulated and implemented based on a 40 µm-thick wire, modelled as lossy copper; the launcher's dimensions are detailed in [7].

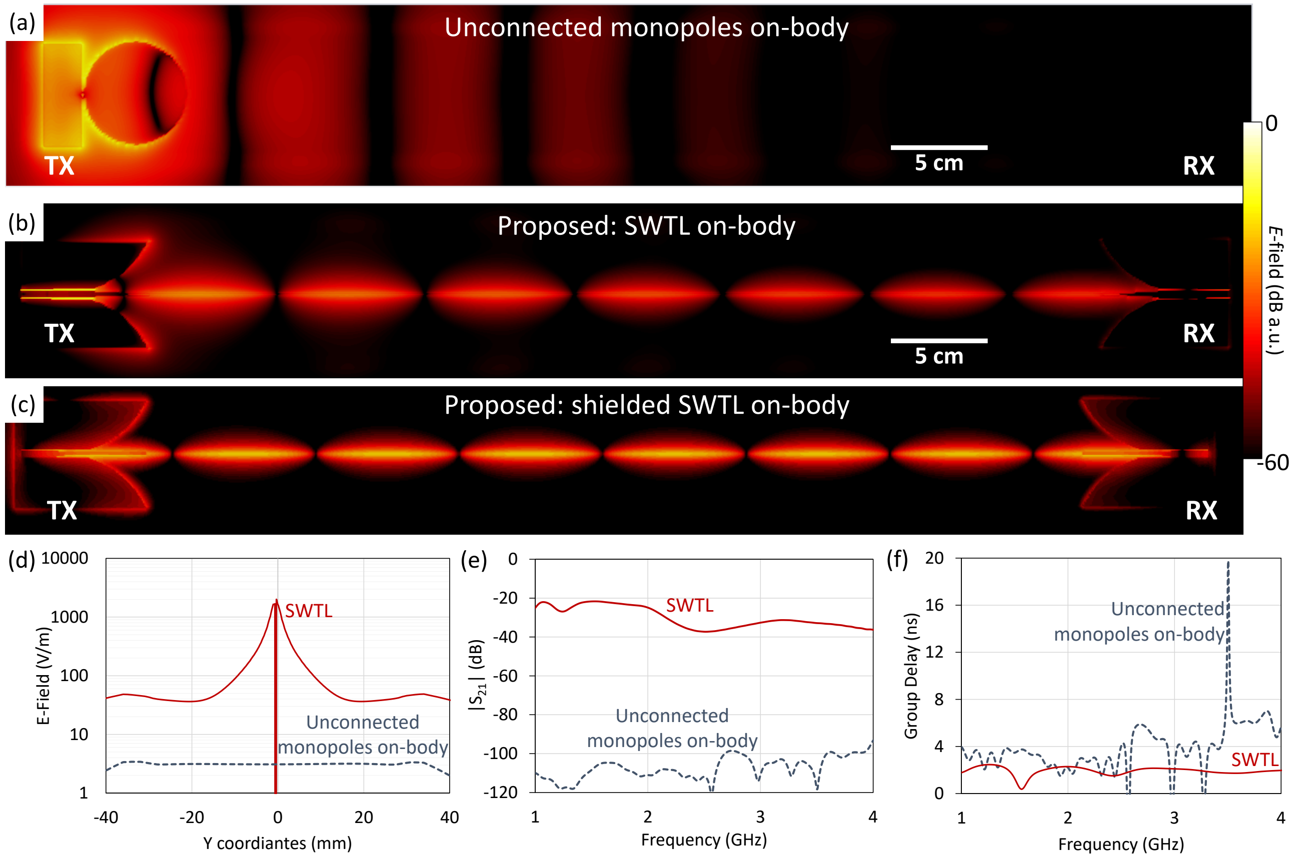

Figure 1: Full-wave analysis of the proposed SWTL: (a) benchmark on-body link using standard broadband antennas; (b) E-field distribution of an SWTL on-body; (c) E-field distribution of a shielded SWTL on-body; (d) 1D plot of the E-field magnitude; (e) S_{21} comparison of the antennas in (a) and the SWTL in (b); (f) group delay comparison showing the phase stability [7].

From the simulated E-fields, it can be clearly seen that the surface wave guide provides an improvement to the received power. However, the absorption challenge still persists. This would limit the maximum power to be transmitted over the SWTL due to the specific absorption rate (SAR) regulations. In order to isolate the line from the surroundings, an unconnected reflector is proposed. Fig. 1(c) shows the E-field distribution around the reflector-backed line. While the reflector is unconnected, it results in the SWTL supporting a hybrid quasi-TEM mode instead of the TM mode for an ideal SWTL. Fig. 1(d) shows the magnitude of the peak E-field across the SWTL and for the two unconnected monopoles case, with Fig. 2(e) and (f) showing the S_{21}'s magnitude and phase, respectively.

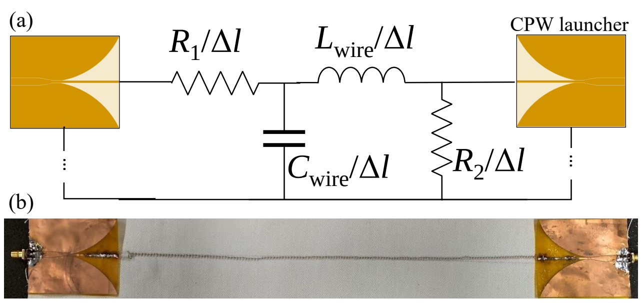

Figure 2: Modelling the SWTL: (a) equivalent circuit model per unit length, not including the CPW launchers; (b) photograph of the implemented textile-based line ©IEEE [8].

Given that the SWTL is best suited to long-range links, an alternative to full-wave simulations is required. To simplify the analysis, the line is modelled based on a simple transmission line equivalent circuit model. The inductance of the line was calculated based on that of a circular wire, with the capacitance modelled as the capacitance between the line and the reflector backing [8]. In previous work where an SSP line was proposed and modelled, the capacitance was calculated based on the capacitance of a single conductor, with the E-fields terminated at infinity [1]. Fig. 2(a) shows the equivalent circuit model per unit length of the proposed line, with Fig. 2(b) showing the fabricated line using textile-based materials for wearable applications.

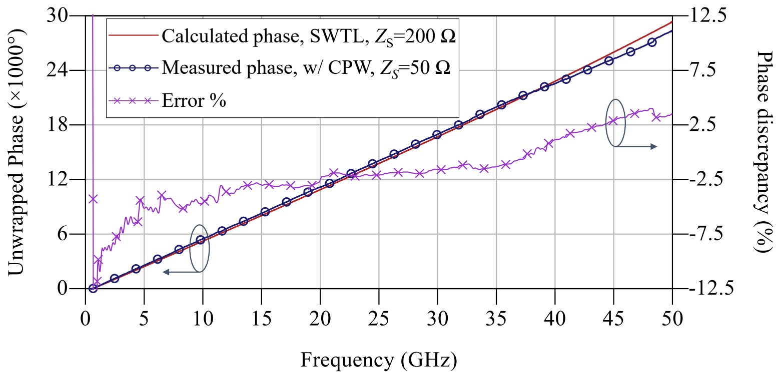

Figure 3: Comparison of the closed form phase response with the experimental phase delay, showing under 7% variation ©IEEE.

To simplify the modelling, the launchers were excluded from the equivalent circuit model, as their length would not vary for different lines. The characteristic impedance of the line was calculated based on the closed-form inductance and capacitance and found to be around 210 Ω, within the $200 < Z_0 < 350\Omega$ range described in Goubau's early work. The inductance and capacitance values per unit length are given in [8]. Fig. 3 shows the measured (setup detailed in the next section) and calculated phase delay based on the equivalent circuit model. The deviation in the unwrapped phase was calculated and is found to be under ± 2.5% between 5 and 50 GHz. As the model was based on Δz=1 mm, each unit cell represents $\lambda/6$; a smaller Δz is therefore required should the line be modelled at higher frequencies.

3 On-Body Operation

3.1 UHF Operation and Comparison with Radiative Antennas

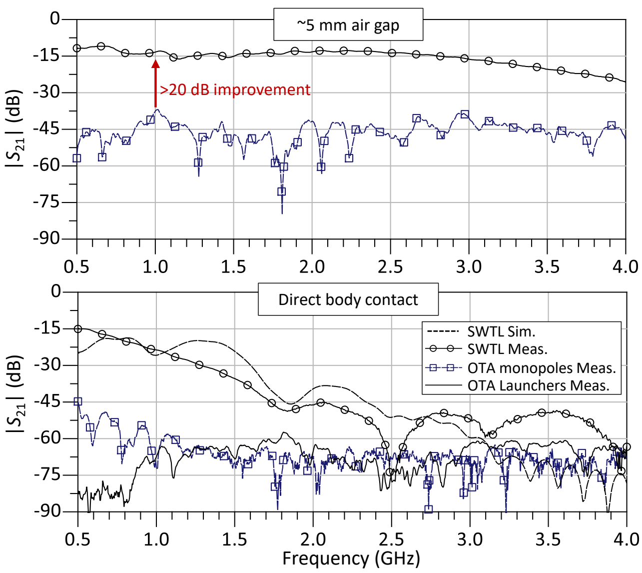

Figure 4: The measured transmission of the SWTL compared to on-body antennas: (a) comparison with unconnected antennas with an air gap; (b) direct body contact and comparison with the simulated response.

The SWTL was experimentally characterised in a variety of on-body links and scenarios including NLOS and direct skin contact [7]. Fig. 4(a) shows an exemplary link on the user's torso using textile-based ultra-wideband (UWB)-inspired disc monpole antennas as well as the proposed SWTL. Both the antennas and the SWTL were attached to baggy clothing leading to around 5 mm of air between the clothing and the body, reducing the absorption by the tissue. In the UHF spectrum, it can be clearly seen that the SWTL improves the link by over 20 dB across all frequencies, as well as improves the stability of the S_{21} enabling wideband signalling.

The second use case shown, in Fig. 4(b), is where the line and the antennas are pressed against the skin with under 0.5 mm of fabric separation. Such setup is representative of epidermal applications such as smart bandages or, beyond wearables, transmission lines used over highly lossy media. While the losses in the SWTL significantly increase over the first case, with an air gap between the line and the lossy medium, the improvement over the unconnected antennas is still significant. Fig. 4(b) also shows a discrepancy between the measured response and the CST Microwave Studio simulations. This is attributed to the homogenous block of tissue used in the CST model, which does not accurately model the human body over all frequencies. Furthermore, the numerical model dealt with a planar line and body model, to reduce the problem size, whereas the measured line conformed to the body. The response seen in Fig. 4(b), particularly where the losses increase dramatically with frequency, motivates moving to the shielded SWTL for applications beyond 4 GHz.

3.2 mmWave Evaluation

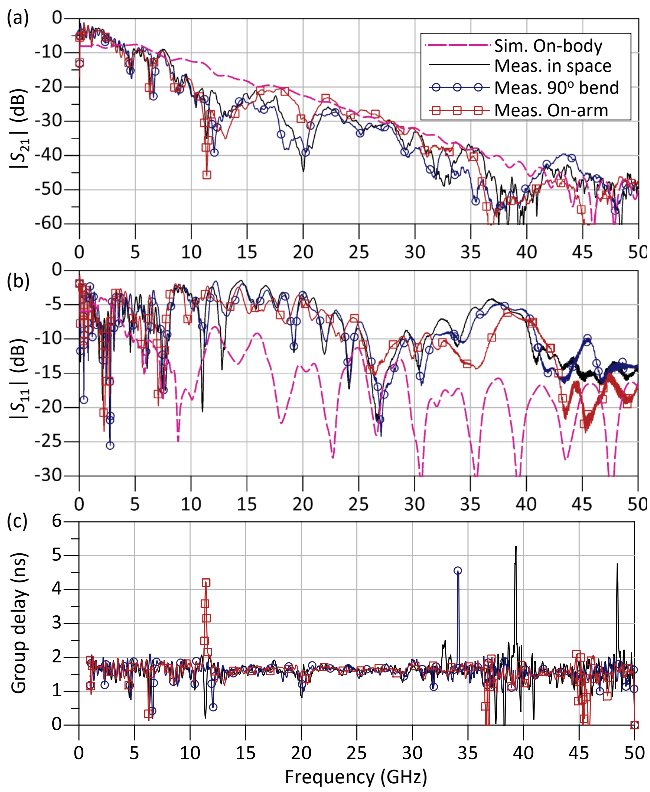

Figure 5: Simulated and measured mmWave response of the SWTL: (a) forward transmission magnitude; (b) reflection coefficient magnitude; (c) group delay [7].

The line's mmWave response was evaluated experimentally to demonstrate its improvement over other printed transmission lines on wearable materials. 2.4 mm coaxial connectors were soldered onto the CPW launchers for measurements up to 50 GHz. An Agilent E8361A PNA, calibrated using a standard SOLT electronic calibration kit, was used to measure the transmission through the line. Fig. 5(a) shows the measured —S_{21}— across the 45 cm-long line in space and on-body, as well as under bending. The simulated response, from CST Microwave Studio, is shown alongside the measured response, in good agreement. The reflection coefficient, on the other hand, in Fig. 5(b) shows noticeable differences due to the difficulty of achieving a uniform transition from the coax to the CPW on the flexible and textile-based substrate, causing additional reflections. However, where the S_{11} is under -10 dBm and in agreement with simulations, the S_{21} response does not exhibit any ripples, and the line's true response can be observed.

The simulated and measured group delay are shown in Fig. 5(c). Apart from limited spikes caused by standing waves along the line, it can be seen that the line maintains a very uniform and broadband group delay. Thus, the proposed SWTL could be used for very high data-rate wideband applications in lossy media, where radiative transmission would rapidly attenuate. Furthermore, the stable S_{21} magnitude and group delay under a 90° bend demonstrate that the proposed SWTL is suitable for NLOS applications. To explain, prior work on 60 GHz on-body links relies on highly directional horn antennas [9], which would not be a feasible option for NLOS on-body links. Furthermore, the proposed SWTL exhibits a comparable S_{21} to the horn-based links in [9] for similar distances, despite being implemented using low-cost all-flexible and textile-based materials.

4 Conclusions

This paper presented an overview of SWTL design, modelling, and fabrication, for mmWave applications in a body-centric connectivity application. It is shown that the SWTL is a suitable candidate for low-loss signalling using very inexpensive and flexible conductors, particularly where a wide bandwidth is required or the signals need to travel near a lossy medium. Future work includes designing improved launchers as well as using the SWTL for simultaneous conformable and radiative communication.

Acknowledgment

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