Wearable 868 MHz LoRa Wireless Sensor Node on a Substrate-Integrated-Waveguide Antenna Platform

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***Abstract*— Nowadays, wireless sensor networks at sub-GHz frequencies are becoming more and more ubiquitous, owing to their impressive link budget. One of the most widespread standards is LoRa, employing Chirp Spread Spectrum modulation to achieve a relatively high data rate at low transmit powers. The latter is ideal for body-centric communication, but the challenge for wearable devices consists in keeping the antenna dimensions sufficiently small. By exploiting substrate-integrated-waveguide technology, a compact wearable 868 MHz LoRa sensor node has been successfully integrated onto a compact textile antenna platform. The wearable LoRa unit operates in a fully autonomous manner, including an integrated battery, transceiver, microprocessor and memory. This paper documents the construction and the radiation patterns of the wearable node, autonomously deployed on the human body and measured in an anechoic chamber. The measurements were performed without any cables attached to the wearable node and, hence, accurately characterize realistic off-body propagation at sub-GHz frequencies. Finally, a body-to-body wireless link is measured between two persons equipped with wearable nodes in the anechoic chamber, considering different body orientations.**

***Keywords*— LoRa, WSN, Textile antennas, SIW Antennas**

I. Introduction

Currently, long-range wireless sensor networks have become very popular, thanks to a number of recently applied coding and modulation schemes. Although these schemes were already known for a long time, their widespread application has only recently been enabled by the introduction of dedicated single-chip transceivers by a number of important semiconductor manufacturers. These long-range data links operate in Industrial Scientific and Medical (ISM) frequency bands on a license-exempt basis and incorporate techniques to mitigate interference experienced in this heavily occupied part of the radio spectrum.

Currently a number of standards dominate the long-range wireless sensor communication market, being LoRa [1], Sigfox [2], DASH7 [3] and Weightless [4]. LoRa transmissions employ Chirp Spread Spectrum (CSS) modulation, whereas DASH7 uses Gaussian Frequency Shift Keying (GFSK). Both transmission modes allow a relatively high data rate, but LoRa combines this with a significantly larger range. The Sigfox and Weightless standards employ narrow-band Bi-Phase Shift Keying (BPSK) and its differential version DBPSK, respectively. A large range is possible but corresponds to a very narrow bandwidth and hence a low data rate. We chose to employ LoRa modulation for the body-centric wireless sensor node because this standard offers the combination of a long range with an acceptable throughput. Additionally, configurable parameters for the LoRa transmission allow flexibility to exchange range for more date rate, if desired.

LoRa transmissions can legally be performed in the 434 and 868 MHz bands, with the latter band allowing the use of compact wearable antennas to exploit the excellent sub-GHz propagation characteristics. The corresponding wavelength is 35 cm and Substrate-Integrated-Waveguide (SIW) technology enables conveniently sized antennas that can be integrated into garment. The 868 MHz and lower bands benefit from significantly better propagation characteristics compared to the commonly used 2.45 GHz ISM band.

Although long-range wireless sensor technology is becoming widespread, only a limited number of scientific publications document their performance. Recent publications about LoRa communication links document Doppler robustness, scalability and coverage in mobile operating conditions [5], [6] as well as long-range fixed links from base station to base station [7]. Channel characterization for a LoRa body-to-base-station link is described in [8]. Recently, a body-worn channel measurement node for the 868 MHz band was presented [9] and a custom garment-integratable LoRa sensor node in [10]. An outdoor base-station-to-body LoRa link range measurement was described in [11]. To our knowledge, body-to-body communication using LoRa nodes has not been documented in literature before.

In this paper, the body-to-body channel characteristics are determined by measurements in an anechoic chamber. First, the free-space antenna radiation patterns are measured for the fully autonomous, battery-powered wireless nodes. Signal levels are extracted by making use of a standard gain horn and a spectrum analyzer, to determine the Effective Radiated Power (ERP). Further, the body-to-body communication channel between two wearable sensor nodes is characterized, for test persons wearing body-centric nodes, oriented at different azimuth angles. Subsequent analysis evaluates the expected range versus outage probability for body-to-body SISO and MIMO communication links. The range defined for 10% outage probability is increased by almost an order of magnitude by employing a 2×2 MIMO link instead of a SISO link.

The paper is further organized as follows. The hardware and measurement setup are described in Section II and the measured characteristics are shown in Section III. These results are used to derive the 10% outage probability range for SISO and MIMO body-to-body links in Section IV. Finally the conclusions are summarized in Section V.

II. Materials and Methods

The wearable wireless sensor node is composed of the textile SIW antenna described in [12], integrated with the custom LoRa measurement node documented in [10] and a PKCELL® low-profile 3.7 V, 1200 mAh lithium-polymer battery. Two different measurements are performed in the anechoic chamber: being the free-space ERP and a realistic body-to-body communication channel between test persons, to determine the received signal power for different orientation angles of both persons.

A. *Free space measurement*

For the free-space measurement, the wireless LoRa node is mounted on the antenna rotor in the anechoic chamber, as shown in Fig. 1. The LoRa transceiver is configured in Continuous Wave (CW) mode to allow power measurements. The power delivered by the transceiver is 10 dBm. The signal is analyzed using a standard gain horn antenna connected to a Rohde & Schwartz FSV40 spectrum analyzer, after which the ERP is calculated.

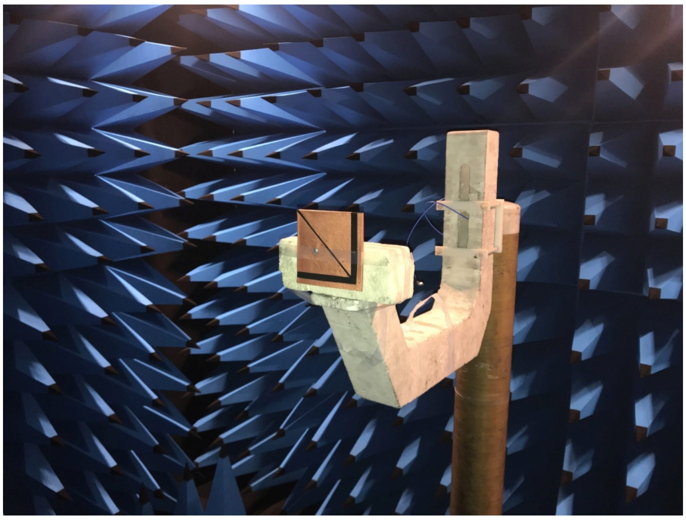

Fig. 1. Textile SIW antenna with integrated LoRa node in the anechoic chamber. Fully autonomous, no cables connected.

B. *Body-centric measurement*

For the body-to-body link, two persons are placed into the anechoic chamber. Each person wears a LoRa node on his front torso. The first person, shown in Fig. 2, is rotated onto the azimuth rotor over 360°, and the signal is measured per degree of rotation. The second person is placed at a distance of 4.3 m. The measurement is performed three times, for the latter person oriented over angles of 0°, 90° and 180°, described as Front, Side and Back orientations. Front means both persons are directed with the wearable nodes pointing toward each other. The received power at different angles is now determined based on the true signals as received by the wearable node. Therefore realistic practical body-to-body link performance is accurately characterized by fully eliminating the effect of measurement equipment.

Fig. 2. Test person wearing the LoRa node in the anechoic chamber. Fully autonomous, no cables connected.

III. Measurement Results

A. *Free space measurement*

The SIW antenna is elliptically polarized [12] and its ERP, displayed in Fig. 3, is measured with a linearly polarized standard gain horn antenna. For the horn antenna horizontally polarized (curve “H”), the maximum ERP corresponds to 5.3 dBm, for the transmitter injecting a power of 10 dBm into the antenna’s feed port. The radiation pattern is directional, but substantial back radiation occurs. The front-to-back ratio is approximately 8 dB. For the horn antenna rotated for vertical polarization (curve “V”), the maximum ERP is 2.5 dBm and front-to-back ratio around 5 dB.

B. *Body-centric measurement*

The body-to-body radiation patterns are displayed in Fig. 4, for the Front, Side and Back orientations of one person, while the person at the other end of the link is rotated over 360°. We now focus on the power received by one wearable node, from the identical integrated elliptically polarized SIW antenna of the other node transmitting. This figure is relevant to the actual performance of the link. The lower limit for successful detection of received packets is specified as −136 dBm.

Reliable detection requires signal levels around -126 dBm [13], a detection level corresponding to a very good sensitivity.

For the measurement at a 4.3 m distance, the highest received signal level corresponds to -46 dBm, when the wearable nodes are pointing toward each other. The front to back ratio is now as high as 30 dB, indicating the important influence of shadowing by the human body. A very sharp notch is visible in the off-body radiation pattern, corresponding to the area that is fully shadowed by the body. Note the front-to-back ratio of the antenna measured in free space was only 8 dB.

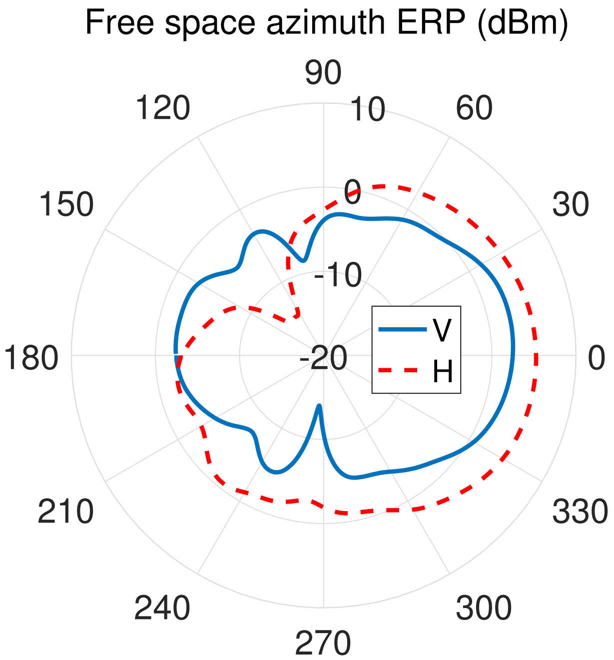

Fig. 3. LoRa node measured in the anechoic chamber, in free-space conditions, at a distance of 4.3 m, for a horizontal (H) and vertical (V) polarization of the transmit antenna. Front side of antenna patch oriented toward 0°

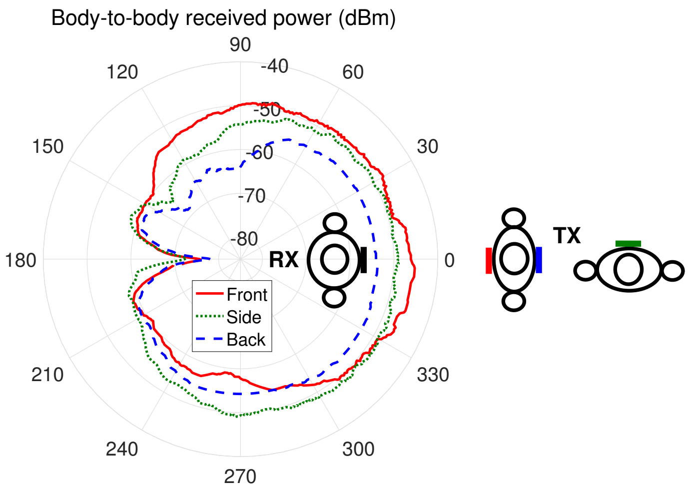

Fig. 4. Body-to-body communication with wearable LoRa nodes on the front torso. Received power by a person rotated 360°. Signal transmitted by the other person oriented with Front, Side and Back towards the rotating person. Distance 4.3 m. Orientation of transmitting person illustrated on the right, wearable node shown in same color as the corresponding curve.

When the person at the other end of the link is rotated by 90° (towards the side) or 180° (towards the back), the received power is generally lower, as expected. However, little difference exists between the side and back orientations, apart from a slight angular shift. The on-body antenna indeed performs excellently for signals covering at least a hemisphere around the body. Note that the second person could not be mechanically rotated in an automated manner. Instead he had to reposition himself, enlarging the error on the desired orientation angle.

IV. Range for SISO and MIMO links

The results from the previous section demonstrate the back radiation from the antenna is severely shadowed by the body, drastically increasing the front-to-back ratio. Therefore, it is interesting to employ the measurement data to evaluate the range for SISO as well as MIMO links in anechoic conditions.

A. Range for SISO body-to-body links

Based on the measured radiation patterns, the range for anechoic conditions is derived by means of the Friis equation. The contour plot in Fig. 5 displays the range for every combination of azimuth orientations for the two persons. This map is calculated as follows. The signal level detected with the test persons oriented front-to-front at 4.3 m distance is taken as a reference for the signal level corresponding to the path loss at this distance. Both persons, equipped with wireless nodes are assumed to have similar radiation patterns, as in the Front curve of Fig. 4. Then, the extra drop in signal level due to increasing path loss and different orientation angles is calculated from the Friis equation and the radiation pattern, respectively. As visible in the map, the range varies from 47.1 km down to values as low as 40 m, due to the extreme shadowing when the two bodies are oriented back to back.

The outage probability is calculated, assuming both persons are oriented randomly with uniform and uncorrelated angle distributions. The range for a 10% outage probability is 1.6 km, meaning at this range the received signal is stronger than -126 dBm for 90% of the time. This value can be significantly improved by employing antenna diversity to counter body shadowing.

B. Range for MIMO body-to-body links

The performance for a 2×2 MIMO configuration with front and back wearable nodes worn by each person is determined in a similar way. Employing Selection Combining, the maximum signal level is determined for each of the four combinations of the front and back antennas. This procedure is performed for every combination of azimuth angles, assuming front and back antennas differ in orientation by 180° .

The result is displayed in Fig. 6, indicating a much better coverage. The minimum range now corresponds to 7.6 km whereas the maximum range remains unaltered at 47.1 km. The range for a 10% outage probability is increased to 13.2 km.

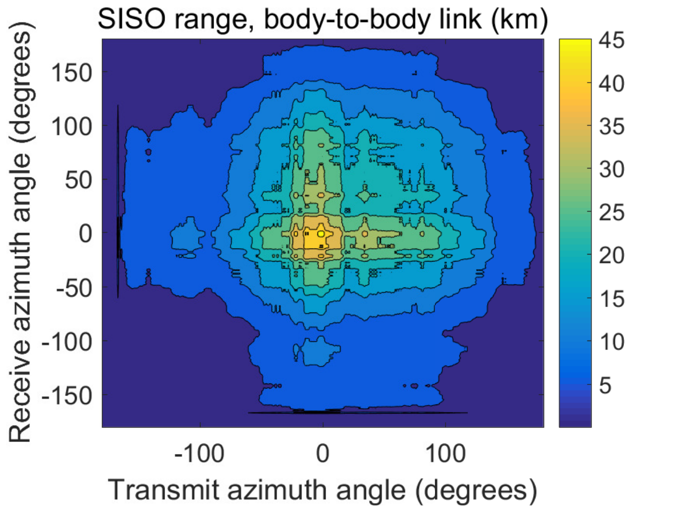

Fig. 5. Body-to-body SISO communication range as function of orientation of both persons in the azimuth plane.

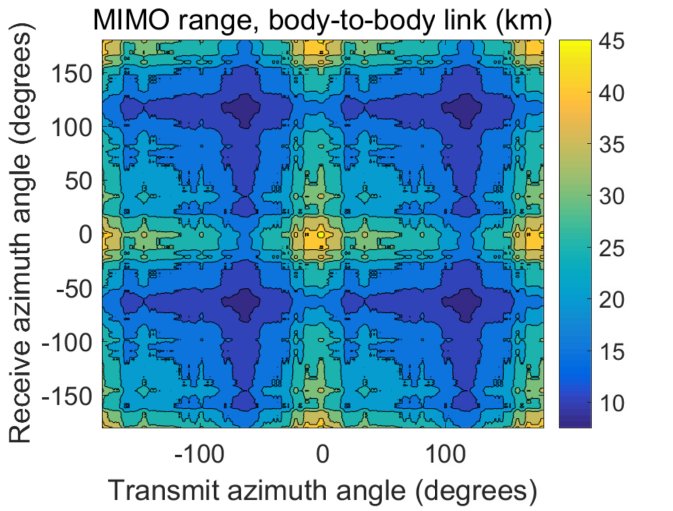

Fig. 6. Body-to-body MIMO communication range as function of orientation of both persons in the azimuth plane.

V. Conclusion

The radiation patterns of a wearable on-body LoRa node were measured in free-space conditions, showing a limited front-to-back ratio. The same node was also measured when worn on the front torso, communicating to a similar node on a second test person. The results clearly demonstrate the important influence of body shadowing, displaying a sharp notch in the radiation pattern for the backward direction, resulting in a 10% outage probability range of 1.6 km for wearable SISO systems with both antennas worn on the front torsos.

Employing the measurement results to determine the performance for a 2×2 MIMO system with selection combining, front-to-back diversity displays an increase in 10% outage probability range from 1.6 km to 13.2 km. These results were calculated by means of the Friis equation and measurements in anechoic conditions.

In real-life indoor or outdoor scenarios, not only the path loss exponent is different, but additionally, the presence of multipath can significantly alter the performance. However, based on the range increase by almost an order of magnitude in anechoic conditions, MIMO techniques are expected to allow a significant improvement in practical radio propagation environments too, because of the more omnidirectional azimuth coverage around both persons in a body-to-body wireless MIMO link and the diversity gain achieved by dual combining..

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