Body-Worn Channel Characterization Unit for the 868 MHz Band

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***Abstract*—With the development of the Internet of Things, wireless sensor networks are constantly being deployed over larger and larger areas. Compared to higher radio frequencies, sub-GHz frequency bands possess superior radio propagation properties for long-range wireless connections. However, as frequency decreases, efficient antennas become larger. The highest sub-GHz band at 868 MHz enables good radio propagation and provides the possibility to design efficient body-worn antennas by means of substrate-integrated waveguide technology. A number of standards, such as LoRa, Sigfox and Dash7 can be employed for communication in this band. Commercial transceivers for these standards often do not allow accurate measurement of the received signal strength. For off-body radio propagation research, a wearable measurement node for 868 MHz is proposed, exploiting an accurate logarithmic power detector. A prototype of the node was implemented and tested, yielding accurate channel measurements for this band. Recorded signal levels are documented in an indoor environment for Line of Sight as well as Non Line of Sight propagation paths. Different features caused by various radio propagation phenomena are clearly visible in the measurement results and illustrate the correct operation of the system.**

***Index Terms*—Body centric, textile SIW antenna, propagation, measurement.**

I. Introduction

With the advent of the Internet of Things (IoT), wireless communication systems need to be integrated into many objects. The IoT envisions wireless connectivity for a plethora of practical applications, often requiring long-range, low data-rate and low-power links. Sub-GHz frequency bands are optimal for long-range wireless links at a limited data rate, because of the better radio propagation characteristics in comparison to the higher frequency bands. The lower operating frequency goes hand in hand with a more limited available bandwidth, which is not a problem for low data-rate connections.

In the sub-GHz spectrum, license-free bands are available around 868, 434 and recently 169 MHz. Generally, the lower the frequency, the longer the expected communication range and the better the penetration of radio waves through walls and other building structures. For smart metering, for example, the 169 MHz band is of specific interest, allowing the readout of values by means of an antenna-equipped vehicle driving around in the area [1]. However, for off-body communication links, in the 169 MHz band the 1.77 m wavelength makes it difficult to construct efficient body-worn antennas. Even for the 434 MHz band, efficient body-worn antennas would be rather large. Therefore, for body-centric applications, the 868 MHz band offers the best compromise, enabling to exploit the band's interesting propagation properties without having to reduce the antenna performance [2]. In this band, the wavelength is 34.5 cm, allowing the construction of patch antennas which can be conveniently worn on the body, owing to Substrate Integrated Waveguide (SIW) technology, in which compact partial-mode topologies may be implemented [3].

For sub-GHz bands, a number of communication technologies are currently popular, such as LoRa [4], SigFox [5] and Dash7 [6]. LoRa is specifically suitable for long-range communication up to 20 km or more. It also offers an adjustable data rate. Sigfox is also a long-range standard, but has only a very limited data throughput. Dash7 technology, on the contrary, is more promoted as a medium range solution for links up to two kilometers. All the above modulations and associated protocols can be applied in the 868 MHz band with transceivers integrated into a single silicon chip, resulting in compact and low-power solutions. However, the downside of the system integration is the difficulty to measure channel properties. In case of LoRa, the current state-of-the-art RN2483 transceiver allows measuring the Signal to Noise Ratio (SNR) of a received signal only within a range of -20 to $+5$ dB. For SNRs above $+5$ dB the detector saturates and, therefore, measurements can only be performed for ranges near the end of the comfort zone of the wireless link [7], [8].

In this paper, a body-worn channel measurement device is proposed, designed and tested that measures the signal levels experienced by a fully integrated textile-antenna-based body-worn system within a practical range of -60 to $+10$ dB. This system is calibrated for measurement of a Continuous Wave (CW) carrier, as can be generated by the RN2483 LoRa transceiver. Hence, the channel measurement unit allows accurate propagation measurements using a signal from the LoRa system, which is not possible when employing only the RN2483 unit as a receiver. These propagation measurements are useful for predicting the performance of any of the standards that can be employed in the 868 MHz band. A measurement campaign is performed in an indoor office environment, where a person equipped with the wearable measurement node operates in Line of Sight (LoS) as well as Non Line of Sight (NLoS) conditions and also changes orientation. The recorded signal levels are documented as a function of the distance from the transmitter. With the body-worn antenna directed away from the transmitter, signals are received via reflection and scattering. The paper is further organized as follows. Section II describes the practical details of the measurement, including the environment, the equipment and protocol used. In Section III, the measurement results. They are further discussed in Section IV. Finally, the conclusions are outlined in Section V.

II. Materials and methods

A. Body-worn measurement node

The body-worn channel measurement node consists of an electronic circuit integrated onto a flexible textile Substrate Integrated Waveguide (SIW) antenna. The antenna design relies on partial-mode techniques to obtain a compact unit [3], measuring $96 \times 96 \times 12.5$ mm, which is very small for a sub-GHz patch antenna. A good match to a 50Ω impedance is obtained, resulting in a return loss of more than 10 dB. The radiation pattern approximately covers a half space in front of the body, with a forward gain of 4 dBi.

The circuit design exploits an ADL5513 wide-band logarithmic detector chip, manufactured by Analog Devices Inc. and specified from 1 MHz to 4 GHz [9]. The antenna signal provided to the logarithmic detector is filtered by a narrow bandpass Surface Acoustic Wave (SAW) filter, type B3725 by EPCOS/TDK, specifically selecting the 868 MHz band. The filter is specified for a typical insertion loss of 2.5 dB and a typical stop band attenuation of at least 30 dB outside the $853 - 879$ MHz range. An overview of the out of band attenuation as specified by the manufacturer is displayed in Table I [10].

TABLE I
SAW Bandpass filter out of band attenuation

Lower Freq. (MHz)	Upper Freq. (MHz)	Typ. Attenuation (dB)
10.0	300.0	50
300.0	845.0	45
845.0	853.0	41
879.0	883.0	30
883.0	915.0	55
915.0	945.0	45
945.0	1200.0	55
1200.0	2000.0	40

The logarithmic detector provides an analog voltage, proportional to the received signal power in dBm, which is sampled by a 16-bit Analog to Digital Converter (ADC). The ADC is read out via a serial bus by the central micro controller, running embedded software written in the C programming language. The circuit contains 32 Mbits of flash memory to store the results. At a rate of 100 measurements per second, the memory provides enough space to continuously log all data during a full week. The board is low power and is operated from a small Lithium Polymer (LiPo) battery, specified to provide 1200 mAh at 3.7 V. A picture of the wearable node is displayed in Fig. 1.

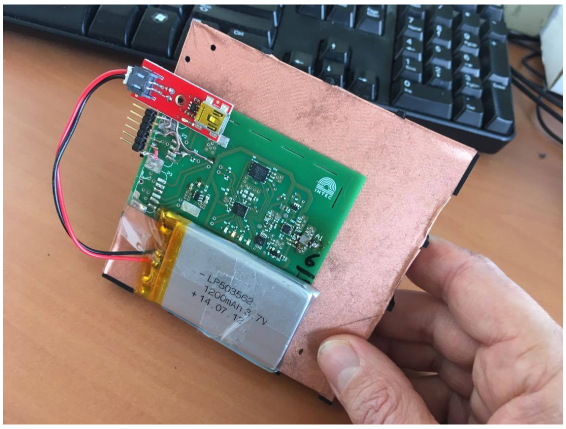

Fig. 1. Wearable channel measurement node, equipped with 868 MHz bandpass filter and textile SIW antenna.

B. Transmitter

The signal generator is a Rohde & Schwarz SMH generator, set to 869 MHz and providing a power of +14.9 dBm. The 868 MHz filter employed in the body-worn unit has an actual center frequency of 869 MHz and a bandwidth of 2 MHz. Interference by other 868 MHz band signals is possible but not expected, as no other 868 MHz devices are operating in the surroundings to our knowledge. However, in order to enable the detection of interference, the transmitted test signal is switched on and off at a rate of 25 Hz in order to constantly monitor the noise floor. Interference caused by other devices, if present, should be detected by a rising noise floor during the gaps in the transmission. The radio-frequency (RF) switch, which controls the transmitted signal, is a Mini-Circuits ZFSWA-2-46, exhibiting an insertion loss of 0.9 dB, resulting in a transmitted power of 14 dBm, as allowed according to the CEPT/ECC ERC Recommendation 70-03. In the off-state the switch provides an isolation of approximately 50 dB. The switch is controlled by two anti-phase 25 Hz square waveforms with a peak-to-peak amplitude of 8 V and a DC offset of -4 V, as required according to the specifications of the RF switch. These signals are generated by two synchronized Rigol DG1022 Arbitrary Waveform Generators. Note the DG1022 is a dual channel generator, but since the second channel is not able to produce a large enough voltage for the switch, the first channels of two synchronized generators are employed. The setup is illustrated by the four pictures in Fig. 2, from left top to right bottom:

- Rohde & Schwartz SMH Generator with RF switch
- Monopole transmit antenna
  with sloping ground radials
- Synchronized Rigol DG1022
  Arbitrary Waveform Generators
- Switching waveforms on an oscilloscope

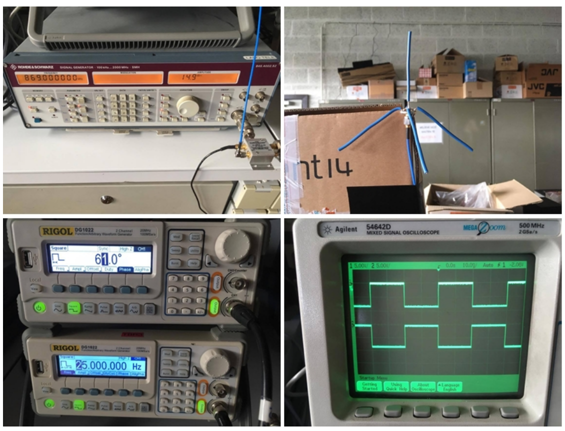

Fig. 2. Transmit setup, from left top to bottom right, Rohde & Schwarz SMH RF-generator, TX monopole antenna with sloping ground radials, synchronized switching waveform generators, switching waveforms on oscilloscope.

The SMH generator is connected via the RF switch to a ground plane antenna consisting of a quarter-wave vertical monopole and four quarter-wave radials, which were initially in a horizontal plane. The lengths of the monopole and radials were empirically optimized by shortening their lengths during network analyzer S11 measurement in order to obtain the desired center frequency. In a next step, the four radials were bent downward during measurement, to increase the antenna's impedance until a 50 Ω match was obtained. The Smith chart in Fig. 3 displays a network analyzer S11 measurement, illustrating a nearly optimal match at about 869 MHz.

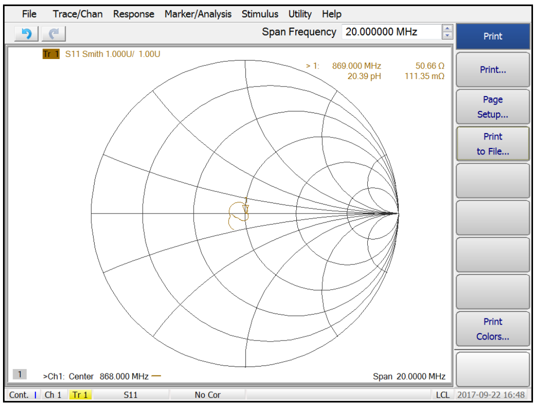

Fig. 3. Smith chart showing a network analyzer S11 measurement of the transmit antenna, showing an impedance of $50.66 + j0.11\Omega$ at 869 MHz

C. *Measurement procedure*

The detector in the wearable node is very fast, allowing an output video bandwidth of 10 MHz for spectrum sensing. The detected signal power is sampled at an 100 Hz rate, allowing to accurately measure the noise floor as well as the signal level. This is performed 25 times per second by determining the minimum and the maximum, respectively, over 4 subsequent samples. The measurement node is worn on the front of the torso, under a shirt. It is fully autonomous and battery operated. The test person walks around in an indoor lab/office environment while the node unobtrusively performs measurements, without the need of any extra portable equipment. The building consists of solid concrete walls and a reinforced concrete ceiling and floor. Many metal closets are installed along the walls, contributing to the reflection of the signals.

All data are stored into the local flash memory, which provides more than enough capacity for logging extensive measurements up to multiple days. The node records exactly 100 channel samples per second, hence this accurate timing can be used in post processing to extract the location of the user. A voice recorder was used in order to provide timed markers in the measurements. After the measurement, the wireless node is connected to a laptop via a USB cable to conveniently read out the data in MATLAB, as visible in Fig. 4. No extra hardware is necessary at the receiving side. Two different measurements were performed in order to assess the operation of the wireless channel measurement unit. In a first measurement, the signal level is measured at different ranges, whereas a second measurement is performed for a random walk in LoS as well as NLoS conditions.

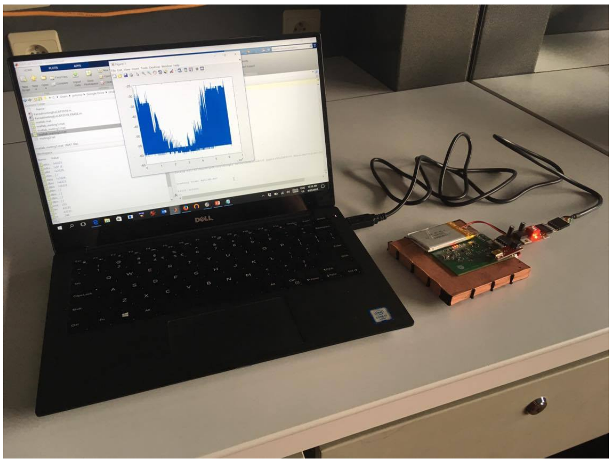

Fig. 4. Data readout via USB, using MATLAB.

III. Measurement Results

A. *Path loss measurement*

In the path loss measurement the wearable node is worn on the front of the torso of the test person. Data are recorded for a forward path walking away from the transmitter (TX) in a range from 0 to 32 m, as well as for the return path. The orientation of the receiving antenna is hence away from the transmitter for the outbound path and towards the transmitter for the return path.

The measurement was performed by stepping one meter forward per five seconds at a controlled speed, verified by a chronometer and a tape measure on the floor. The range over which the measurement is performed covers different lab spaces. The walk starts near the TX and is LoS up to the first door at a range of 9.3 m. As soon as the test person is in the second lab, the propagation is optically NLoS, as there is no direct view to the TX antenna via the door opening. At 21 m from the transmitter, there is another door to the third lab, where the NLoS range extends up to 32 m.

The data for the forward and return path are processed separately and are displayed as a function of the range to the transmitter in Fig. 5. The difference for signals impinging at the front or at the back of the body, with a front-worn antenna, is clearly visible. At the same time, the noise levels for both measurements are shown, indicating that the data are not compromised by any interference.

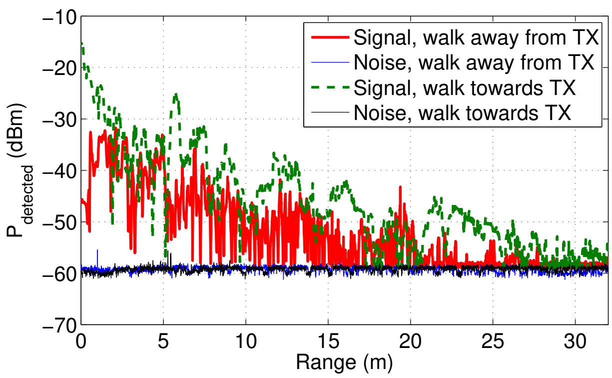

Fig. 5. Received signal power vs. range, with front-worn antenna directed to TX versus away from TX.

Fig. 6 displays a small part of the same measurement, illustrating the fading experienced in the environment. Clearly the signal is influenced much more by fading when the receive antenna points away from the TX, indicating the presence of dominant signals propagating through the door opening. Note the TX is in the adjacent room, with no optical LoS to the TX antenna.

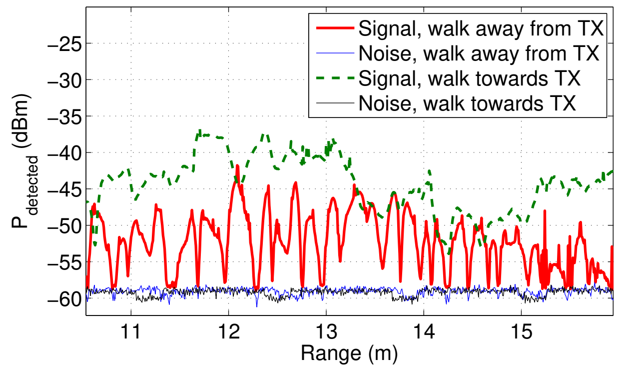

Fig. 6. Received signal power near the door opening, front-worn antenna directed to TX versus away from TX.

In order to reduce the influence of the small-scale fading visible in Figs. 5 and 6, the range measurement was repeated five times along the same trajectory and with accurate timing. The results were averaged and displayed in Fig. 7. Comparing to Fig. 7 and Fig. 5, the fading is drastically reduced, while the effects of path loss and shadowing are still present.

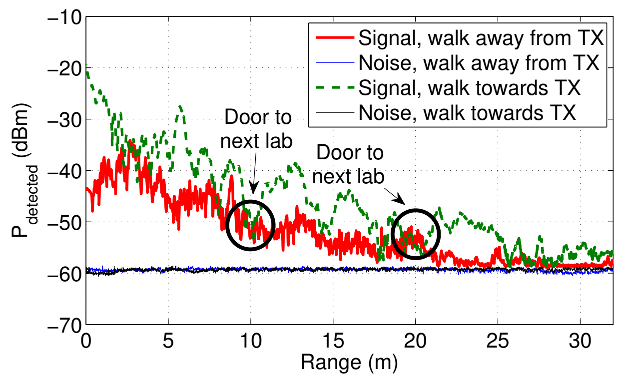

Fig. 7. Average of five measurements of received signal power vs. range, with front-worn antenna directed towards TX versus away from TX.

In Fig. 7, signals are clearly detected over the full range. Interestingly, when the receive antenna is facing the TX, the signal level drops when approaching a door opening. This phenomenon illustrates the important contribution of scattered components in the signal. When approaching the door, less scattered signals are received from the lab space behind the back of the test person.

As expected, the average signal is stronger when facing the TX, because of the directional radiation pattern of the antenna, combined with the shadowing by the human body. However, even in the LoS area, the average difference is only 8.7 dB, because of the reflections and scattering in the indoor environment. In the NLoS zone, corresponding to the lab adjacently to the TX, for ranges from 10 to 20 m, the average difference is further reduced to 5.8 dB. The lower average difference in signal strength for the NLoS area confirms the larger relative contribution of scattered and reflected components in this area. In the third lab, at a range of more than 21 m, the difference is further reduced but cannot be accurately determined due to the proximity to the noise floor of the signal captured with the antenna oriented away from the TX.

B. *LoS versus NLoS measurement*

A second measurement was performed with the test person performing a random walk in the indoor lab environment. The measurement covers three lab spaces. The data were recorded in one continuous measurement. Fig. 8 displays 4500 measurement points, corresponding to three minutes of measurement, being one minute in each room. The measurement rate is 25 Hz, resulting in a continuous trace of the fading and shadowing behavior.

The walk started at the third and farthest lab room, not adjacent to the lab where the transmitter is situated. Two solid concrete walls were blocking the signal, yielding NLoS conditions. The signals are shown in the first part of Fig. 8. They are clearly detectable, even if they are just above the noise floor when the antenna is oriented away from the TX. In this range, the noise measurement is also useful as a reference, helping to detect the presence of the transmitted signal at levels near the noise floor.

The middle part of the graph displays signals received in the second lab, adjacent to the TX lab. In this region the propagation still happens in NLoS conditions, but the signal was blocked by only one concrete wall. Additionally, the distance from the transmitter was shorter. In this area, signals were significantly larger than the noise floor of the detector.

The last part displayed in Fig. 8 corresponds to signals measured in the lab where the transmitter was located, resulting in LoS propagation. However, when the antenna was directed away from the transmitter during the random walk, the signals were received via reflections and scattering.

Specular reflections are highly probable, because of the many metal closets along the walls of the lab. Signals are strong in this area and fluctuate over a range of more than 30 dB, due to fading and shadowing by the body. Additionally, the random walk results in a differing path loss during the course of the measurement.

IV. Discussion

The current design allows continuous monitoring of signal levels in the whole 868 MHz European ISM bandwidth. According to the specifications of the ADL5513 detector, the signal levels detected by the body-worn channel measurement unit are accurate to 0.4 dB resolution, for a temperature range between 25°C and 85°C, whereas for the RN2483 LoRa transceiver, the accuracy is undocumented.

Although according to the specifications of the detector, the measurement range is 80 dB, strong signals in the range above -15 dBm are not present, given the limited power of the transmitter. According to the data sheet, the noise floor is located at -70 dBm, but this is, of course, the noise floor of the detector without any input signal. As soon as

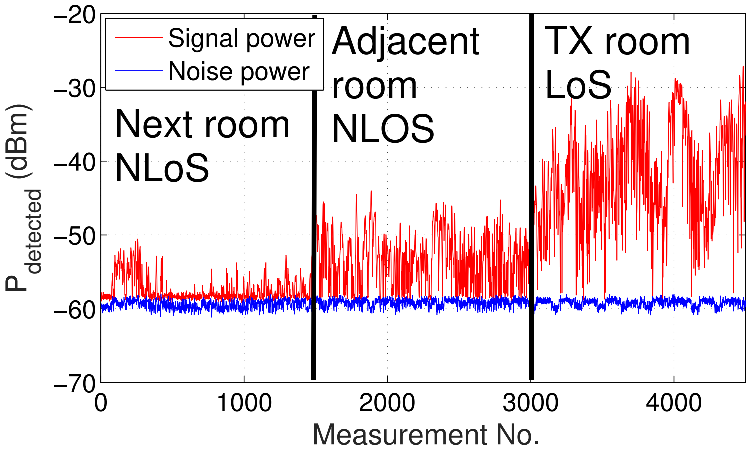

Fig. 8. Received signal power for NLoS two rooms from TX, NLoS rooms next to TX, LoS in TX room. Fading appears stronger than in previous graphs because of the random walk and the higher walking speed in this measurement.

an antenna is connected, the noise floor rises, even with a bandpass filter in between the antenna and the detector. The practical noise floor in the measurement is around -60 dBm. Therefore the actual dynamic range which can be measured by the node is 70 dB, being from -60 to $+10$ dBm. In our measurement, the range of the detected signals is from -60 to -15 dBm due to the limited transmit power.

Owing to the fast measurement rate and the unobtrusive nature of the node, measurements are performed quickly and in a convenient way. Therefore, measurements can be easily repeated to check reproducibility or to average the results, as was performed in this paper to reduce the impact of small-scale fading.

The noise-level measurement did not indicate interference problems due to other signals in the band. If such a problem occurred it should be noticed, given the 25 Hz detection rate, corresponding to a period of 40 ms, which is shorter than the duration of expected data transmissions in this band. However, the noise level of -60 dBm makes the device not very sensitive as transceiver chips can often receive packets at -90 dBm or even lower. Further lowering the noise floor is possible by employing a more narrow band filter, or switching to a super-heterodyne receiver topology, converting the detected signal to an intermediate frequency, where very narrow band filtering is more realistic.

V. Conclusion

A compact wearable channel measurement node was designed, implemented and tested. The node is very unobtrusive and can be worn invisibly on the body. Measurements in the 868 MHz band indicate the correct operation of the node and its convenient application for measuring and reading out the recorded data afterwards.

The measurement results demonstrate the suitability for channel measurements over the full bandwidth of the 868 MHz European ISM band. Although the dynamic range of the measurement node is large, the upper 25 dB of the range is not covered in measurements with a low-power transmitter providing only 14 dBm. The practical noise floor of the node, including antenna and filter, is -60 dBm, allowing a measurement range up to at least 32 m for the low power transmitter.

The off-body signal detector allows measurement of true body-centric communication, as the device is not connected to any external equipment during the measurement. Shadowing by the body and directionality of the antenna's radiation pattern certainly influence the received signal levels. However, thanks to reflections and scattering in the environment, signals are often still received well with the antenna directed away from the transmitter. Therefore, the average signal recorded on the front antenna facing the transmitter in LoS is only 8.7 dB stronger than for the antenna directed away from the transmitter along the same path.

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