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A Cost-Effective Directional Millimeter-Wave Channel Sounder for 60 GHz Industrial Wireless Communications

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***Abstract*—The millimeter-wave (mmWave) bands contain some properties that can be key enablers for future wireless communications in industrial scenarios, but, despite the potential this new medium presents, very few efforts have been carried out to characterize such environments. This paper presents a cost-effective and flexible channel sounder that aims to measure indoor industrial setups in order to develop models that will assist in the development of future protocols and standards. The complete design and selected hardware (HW) of the sounder are discussed, and three preliminary tests carried out in laboratory and machining workshop scenarios are also presented, where the performance of the sounder is validated.**

***Index Terms*—Industrial communication, millimeter wave devices, millimeter wave propagation**

I. Introduction

Wireless communications are playing an increasing role in the paradigm of the industry 4.0 revolution. Properties as the easy installation and deployment, network flexibility or the ability of being capable to operate in moving or rotating elements make this technology the preferred option for applications in the Process Automation (PA) and Factory Automation (FA) fields, among others. Regarding the latter, typical use cases are closed control cycles composed of a controller and several sensors/actuators. In this context, communication systems must guarantee a minimum performance in terms of throughput, latency and reliability to ensure the correct operation of these processes.

Existing commercial standards do not provide a performance that copes with the requirements of industrial scenarios, and for this reason several efforts have been carried out to develop new alternatives that can work in this environment. The nearly saturated 2.4 GHz or 5 GHz Industrial, Scientific and Medical (ISM) bands present difficulties for this use case, as interference is unavoidable and mechanisms to coexist with existing standards are always required. A key enabler to reach this goal could be the adoption of the Extremely High Frequency (EHF) bands (30 to 300 GHz), also known as mmWave bands. Additional resources that are present in these bands, like bandwidths of several GHz or the spatial reusability, can play a pivotal role in the development of standards that comply with the FA requirements. However, due to the novelty of these bands in the field of communication systems, this possibility is yet to be analysed.

The wireless medium of mmWave frequencies differs significantly compared to the lower frequency bands. Both propagation loss and material absorption are increased significantly, and due to this fundamental difference, existing channel measurements and models of lower frequencies are not capable of representing mmWave band propagation. For this reason, it is necessary to characterize these bands using appropriate sounding equipment.

Several channel sounders have been implemented for mmWave bands, most of which are oriented to 5G New Radio (NR) [1] use cases, where both outdoor (street canyon, rural, etc.) and indoor (home, office, etc.) scenarios are measured. Very few sounding solutions and channel models can be found to cover the 60 GHz band used by standards like IEEE 802.11ad/ay [2], [3], which are potential candidates for the development of future industrial standards. The required measurement equipment is prohibitively expensive in most cases, mostly due to the need of a mmWave Vector Network Analyser (VNA), atomic clocks for synchronization or custom made HW.

The main contribution of this paper is a novel channel sounder design oriented to industrial scenarios in the 60 GHz mmWave band that maintains a cost-effective and modular approach, yet achieving performance results close to the more expensive and rigid VNA-based architectures. The presented solution offers a remarkable resolution in angle and delay, which is perfectly aligned with typical industrial setups where the abundance of metallic surfaces generates a rich multipath channel response. The main novelty of the proposed channel sounding architecture is its cost, based on commercial off-the-shelf (COTS) equipment, its flexibility and the lack of complex synchronization schemes.

The rest of the document is organized as follows: Section II describes existing channel sounding solutions for the EHF bands. A description of the designed sounder and its main HW elements can be found in Section III. Section IV describes the sounding signals, algorithms and initial calibration of the equipment. The selected sounding parameters for preliminary tests can be found in Section V. Sounder validation experiments in laboratory/workshop environments are discussed in Section VI, and, finally, conclusions are exposed in Section VII.

II. EXISTING CHANNEL SOUNDING SOLUTIONS

Sounding can be carried out using different techniques that depend on the stimuli signal and processing methodology. The following paragraphs resume the different implementations from existing works in the EHF bands, and a table summarising all the relevant information can be found in Table I.

Multitone based sounders can be found in [4], [5]. These references present solutions for the 60 GHz band that apply Multiple-Input Multiple-Output (MIMO) technology to speed up the sounding process and obtain channel capacity related information. In [4], patch antenna arrays are used to make quick beam steering possible, obtaining directional channel responses in scenarios where mobility may be present. On the other hand, [5] presents a MIMO structure of two in two out horn antennas to measure parameters as path loss, delay spread or MIMO channel capacity.

In [6]–[9], Pseudo-random Number (PN) based sounders are presented. This kind of sounders operate with white noise as stimuli signals, providing an almost perfect auto-correlation. Receivers correlate the obtained signal with the original sequence, which is usually generated via a maximum-length Linear-Feedback Shift Register (LFSR). In [6], [8], a technique called sliding correlator is applied, where the reference signal is clocked at a slightly lower rate compared to the received one. This provokes an effect of dilatation in time that implies an increase in delay resolution at the cost of additional sampling time. Contrarily, [7] has an extremely short sounding time. To achieve this, 16 horn antennas are distributed along the azimuth, and a multiplexer selects one of them per two PN sequences. This electrical steering mechanism allows to take snapshots in 65.5 μs, enabling the characterization of directional channels in the presence of mobility.

[10], [11] describe a couple of VNA based solutions for the 60 GHz EHF band. This kind of sounder requires long periods of time to obtain the response of a channel, thus it is mostly oriented to static indoor environments. In [10], the sounding signal is provided by an external signal generator in order to avoid the use of amplifiers, which would introduce non-linearity to the system. The VNA receives signals from both Transmit (Tx) and Receive (Rx) ends, and computes the channel response by checking the difference between ports. Two different antenna configurations are also tested: horn antennas for a high dynamic range and uniform virtual arrays of omnidirectional antennas for high accuracy parameter estimation. [11] uses a VNA that generates tones in the 3 - 8 GHz range and converts them to the 60 - 70 GHz range via up/down conversion front ends. Horn and biconical antennas are installed in Tx/Rx to make the measurements.

Orthogonal Frequency-Division Multiplexing (OFDM) is applied in [12] as a sounding signal. A baseband signal of 800 MHz is converted to the 60 GHz EHF band, obtaining a delay resolution of 1.25 ns, and steerable directional horn antennas are used to perform the sounding process.

A COTS equipment based sounder can be found in [13]. In this solution, an IEEE 802.11ad compliant Access Point (AP) generates periodic beacon frames, which are later processed to obtain the channel response. Processing is carried out in 2 different manners: communicating two APs and extracting information from packets (where parameters as the beam pattern, Packet Error Rate (PER) and estimated Signal-to-Noise Ratio (SNR) are extracted) or by capturing signals via oscilloscope with a band converter and a horn antenna. In this last option, Channel State Information (CSI) is obtained and additional parameters as the real SNR or the modulation Error Vector Magnitude (EVM) are also recovered.

Regarding the sounding of industrial scenarios in the 60 GHz band, very few works can be found in literature. On one hand, the sounder presented in [13] provides some measurements in a mechanical room and service tunnel scenarios among others, which are aligned with the focus of this study. On the other hand, some ray tracing based industrial channel models can be found in [14]. To the best of our knowledge there are no further works related to this particular topic, which is the main motivation behind this work.

III. DESCRIPTION OF SELECTED EQUIPMENT

In order to make proper measurements in industrial setups, the properties of the typical scenario, standards of interest and the measured frequency band must be considered. A series of requirements were defined for the channel sounder after analysing all the aforementioned topics:

- Baseband sampling rate for generation/acquisition must be high enough to work with wideband signals (enough to cover the 2.16 GHz bandwidth of 802.11ad/ay).
- Antennas must be of high gain and directivity for spatial discretization. A far field response must also be achieved in proximity, as use cases as FA tend to define an effective range of few meters.
- Synchronization between Tx/Rx must be simple to avoid high costs.
- Multipath components are expected to travel from tens to hundreds of meters. Thus, a dynamic range of at least 40 dB is required to properly record them.

TABLE I: Existing channel sounding solutions for EHF bands

Ref.	Technique	Center Freq. (GHz)	Bandwidth (GHz)	Mobility	Antenna
[4]	Multitone	27.85	0.4	No	Patch array
[5]	Multitone	60	0.4	No	Horn, 2x2 MIMO
[6]	PN - Sliding Correlator	73.5	1	No	Horn
[7]	PN	83.5	2	Yes	Horn, 16 element for electrical steering
[8]	PN - Sliding Correlator	28	0.5	No	Horn
[9]	PN	60	0.5	No	Biconical Horn
[10]	VNA	60	2	No	Horn, Omnidirectional
[11]	VNA	69 to 74	5	No	Horn, Biconical
[12]	OFDM	60	0.8	No	Horn
[13]	IEEE 802.11ad	60	2.16	No	Horn

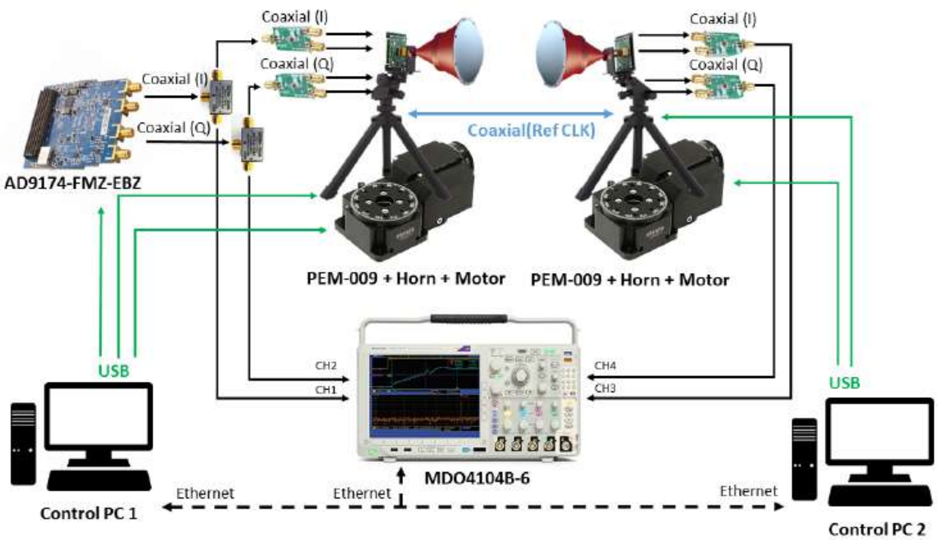


Fig. 1: Measurement equipment setup

All the equipment of the channel sounder was selected following these criteria, and the complete picture of the measurement system can be seen in Figure 1. Details of individual components are discussed in the following subsections.

A. Signal generation

The main idea behind the signal generator is to have a flexible system that can generate complex baseband signals over a wide frequency band. To achieve this goal, a high speed Digital to Analog Converter (DAC) has been selected. Concretely, the EVAL-AD9174 evaluation board form Analog Devices [15] is chosen, as it offers a dual channel output with data rates up to 12.6 Giga Samples Per Second (GSPS).

The control of the DAC board is carried out by the ADS7-V2EBZ pattern generator from Analog Devices [16]. This board is controlled via PC with a USB interface, and different signal patterns can be transferred to its internal memory. Communications with the DAC are managed with the JESD204B standard, and the HW is programmed to continuously transfer the stored pattern samples.

B. Band converters

Band converters are the devices that make the conversion between baseband signals and Radio Frequency (RF). The selected model for this task is the PEM009-KIT from Pasternack [17]. This equipment is controlled with a PC via a USB interface, and parameters like RF band, attenuation or filtering can be configured. Regarding the RF band, the center frequency can be configured to be in the 57.24 GHz - 64.8 GHz range, in 540 MHz steps. This is more than enough to cover the 4 channels of 2.16 GHz defined in the IEEE 802.11ad standard.

C. Antennas

Lens Horn Antennas (LHAs) have been selected for the sounder due to the high gain and directivity that can be achieved with this type of antenna. Additionally, the lens of the antennas aid to reach plane waves in a shorter distance, making it possible to achieve far field responses when both Tx and Rx components are in proximity. The selected model is LHA-30-WR15 from Anteral [18], these are its main specifications:

- **Frequency range:** 50 GHz - 75 GHz
- **Gain:** 30.3 dBi @ 62.5 GHz
- **3 dB Beamwidth, E-plane:** 4.9 deg
- **3 dB Beamwidth, H-plane:** 6.3 deg

D. Data acquisition

Both transmitted and received signals are sampled using a single 4 channel oscilloscope with high speed digitizing capabilities. The idea behind this device is to obtain the complex baseband signal in the transmitter/receiver simultaneously in order to avoid the need of mechanisms for synchronisation. The selected model for this task is the MDO4104B-6 from Tektronix [19]. This device allows to sample 4 channels simultaneously at a rate of 2.5 GSPS, and its internal memory is capable of storing up to 20 megasamples per channel. Data can be retrieved by both an external storage device or via Ethernet, and the device can be controlled remotely with Standard Commands for Programmable Instruments (SCPI), automating the acquisition process.

E. Positioning

In order to characterize the propagation parameters of a channel, it is necessary to perform the sounding considering all the possible orientations a system can have. To achieve this goal, rotating platforms have been installed under the Tx and Rx. These platforms rotate only through the azimuth, but future versions could also include the possibility of controlling elevation. The Standa 8MR174-11 [20] motorized positioners have been installed to control both Angle of Departure (AoD) and Angle of Arrival (AoA). An azimuth precision of 0.01 degrees can be obtained with this HW.

IV. Sounding technique and initial calibration

Thanks to the high flexibility of the signal generator, channel sounding can be carried out using any signal. Some preliminary results were obtained using chirp sequences, as they provide an ideal Peak-to-Average Power Ratio (PAPR) and an almost constant gain in all the frequency band of interest. The formula to generate such sequences can be found in (1), where n is the sample index, N represents the total amount of samples and f_{min} and f_{max} equal to the minimum and maximum frequencies normalized with the sampling rate.

$$x(n) = \exp\left(j2\pi\left(f_{min}n + \frac{f_{max} - f_{min}}{2N}n^2\right)\right) \quad (1)$$

This equation generates a complex baseband signal which is cyclically generated in the DAC. The oscilloscope captures sequences that are present in both transmission and reception, and the Channel Impulse Response (CIR) is computed by de-convolving them. This can be achieved by performing a convolution in time between the complex conjugate of the transmitted sequence and the received one (2). Alternatively, the systems transfer function can be calculated by dividing their frequency domain response (3), which is the selected approach for the preliminary results.

$$y(t) = x(t) \circledast h(t) \Leftrightarrow h(t) = x^*(t) \circledast y(t) \quad (2)$$

$$Y(f) = X(f)H(f) \Leftrightarrow H(f) = \frac{Y(f)}{X(f)} \quad (3)$$

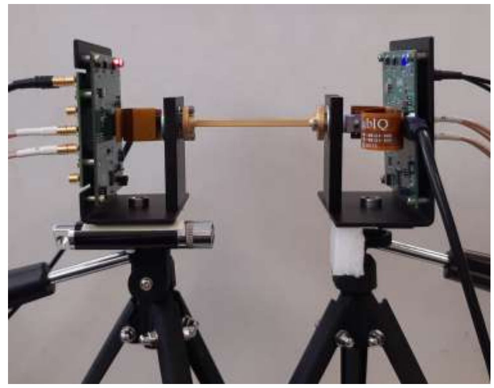


Fig. 2: Band converters connected with a waveguide

Once the channel response is calculated, HW induced effects must be removed from it. This step is necessary to cancel the delay and non-linearities introduced by the cables, splitters, baluns and band converters. To make this possible, some reference signals have been generated by connecting directly both band converters with a WR-15 waveguide, as it can be seen in Figure 2. With this setup, the obtained channel response contains all the effects introduced by the HW, and removing their effects of the measured CIR would result in the response of just the air interface.

Note that the antenna response is not compensated in this process, as it is not part of the circuit used for calibration. The frequency selective gain of this element has been computed in a simulated environment [18], from where a gain variation of approximately 0.5 dB per 1 GHz displacement has been estimated. Due to this low variation, it has concluded that, at least for a first version, antenna gain can be considered to be flat and that a compensation mechanism is not necessary for this element.

V. Parameter selection

The chirp signal was considered as a starting point for the selection of parameters. Standards as IEEE 802.11ad/ay perform communications over channels with a bandwidth of 2.16 GHz, which has been taken as reference for the sounding process. Some experimental results showed that the band converters have a non linear behaviour when frequency arises, and, consequently, that it is not wise to sound all the band with just one stimuli signal. Instead, an approach where all the band of interest is measured in two 1.08 GHz intervals is followed, where concatenating consecutive bands would produce a similar channel response while avoiding non-linearity problems.

Regarding the frequencies, the chirp signals amplitude must have a low ripple value in the [-540..540) MHz band. A bandwidth that covers the [-700..700) MHz range was chosen for the sounding signal generation to achieve this, Figure 3 shows the spectrum of the generated signal and the computed band.

Another parameter of interest is the total duration of the chirp. A signal length that provides both a delay resolution of

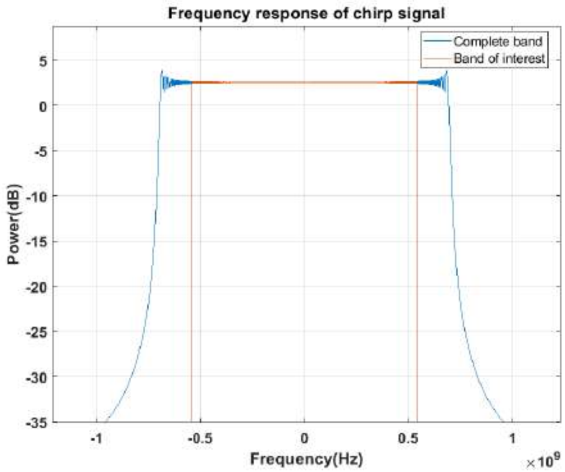


Fig. 3: Total vs valid frequencies of sounding signal, sampled at 2.5 GHz

at least few hundreds of meters and an effective dynamic range of ∼40 dB was chosen. In particular, a signal with a length of 10000 samples (1.2 km resolvable delay) was selected.

The oscilloscope was configured to retrieve a total amount of 100k samples in order to capture 10 complete chirp sequences per snapshot. This would allow to average several CIRs in the post-processing step, effectively improving the quality of the measurements.

The last configuration parameter is the antenna rotation step. 6º steps have been selected for the initial testing, as it is the rotation that would align the Half Power Beam Width (HPBW) point of contiguous positions for Tx and Rx antennas.

VI. Sounder validation

Three different tests have been performed with the channel sounder in order to test its behaviour. The tests, as well as the obtained results, can be found in the following sub-sections.

A. Comparison with a VNA

A COTS VNA that operates in the 60 - 90 GHz band has been used to generate some reference metrics, concretely the model N5252A from Keysight [21]. The goal of this test is to acquire CIRs with both devices for the same scenarios and compare their responses. Naturally, more accurate results are expected from the VNA, as it is oriented to operate directly over this frequency band and its calibration and synchronization mechanisms are more robust compared to the ones of the sounder. Nevertheless, the peaks of both CIRs should still be perfectly noticeable, and the delays should coincide in both pictures.

Two different scenarios have been selected for this testing: a Line-of-Sight (LoS) measurement with a separation of 0.4 meters between Tx/Rx and a reflection from a metallic plate located at 3 meters from Tx/Rx (both devices are in almost the same position in this case). Both tests were centered in the 62.1 GHz carrier with an effective bandwidth of 1.08 GHz. Results of these measurements can be found in Figure 4.

Both devices calculated a delay of 1.8 ns for the LoS scenario, which is in accordance with the expected value of 1.33 ns if quantization error is considered (each sample corresponds to a 0.92 ns step). For the Non-Line-of-Sight (NLoS) scenario, a total delay of 20 ns was expected, and the computed values were of 19.4 ns and 22.2 ns for the VNA and the sounder, respectively. This corresponds to a difference of 3 samples between both impulse responses, which is probably caused by the slight variation in position and orientation that is present between tests. Finally, the obtainable dynamic range of the sounder is considerably lower compared to the one of the VNA (∼40 dB vs ∼65 dB). As stated in the beginning of the section, this difference was to be expected due to the higher end of the VNA. Nevertheless, a dynamic range of 40 dB is still sufficient for indoor industrial channels, which means that the performance provided by the sounder is considered to be adequate for the designated task.

B. Delay and power at various distances

This test consists on selecting a scenario where reflections are negligible and making LoS measurements at various distances. The obtained CIRs should present a peak with a delay that is proportional to the distance and a power which could be modeled with the Friis transmission equation (4), where P_r, P_t stands for the signal power, G_r, G_t represents the antenna gain, λ is the wavelength of the signal and d the distance between the antennas.

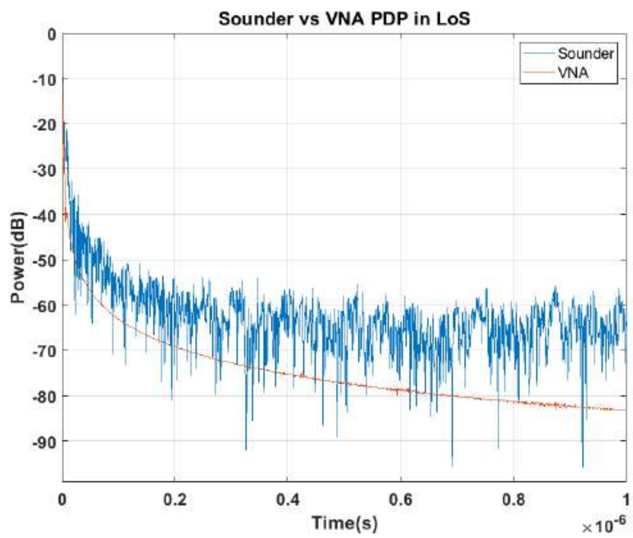
$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \tag{4}$$

The corridor shown in Figure 5 has been selected for this task, as the directivity of the antennas along with the absence of highly reflecting surfaces should provide a response similar to the one in free space. A separation of 1 meter is chosen as a starting point and distance is increased by 0.5 meters per capture until a range of 7.5 meters is reached. Table II shows the obtained results in each location after performing a sounding centered in the 59.95 GHz carrier with a bandwidth of 1.08 GHz. For the Friis equation coefficient estimation, a constant gain of 30 dBi for the antennas and a single wavelength of 60 GHz in vacuum have been considered.

Results show that the sounder is capable of making measurements with an accuracy that is valid for the scenarios of interest. Some variations are present in both fields, but considering that spatial resolution is of 27.7 cm and that antenna misalignment can introduce a high variation in power due to their high directivity, the obtained values are considered to be adequate.

C. Multipath estimation based on azimuth configuration

Sounder's ability to sense multiple paths in its surroundings is tested in this section. To do so, both Tx/Rx nodes are placed in a fixed position inside an environment with abundance of reflective surfaces. A machining workshop has been selected for such task, where measurements were carried out in a corridor between three vertical machining centers. The



(a) LoS scenario

(b) Reflection scenario

Fig. 4: CIR of sounder and VNA in LoS and reflection scenarios

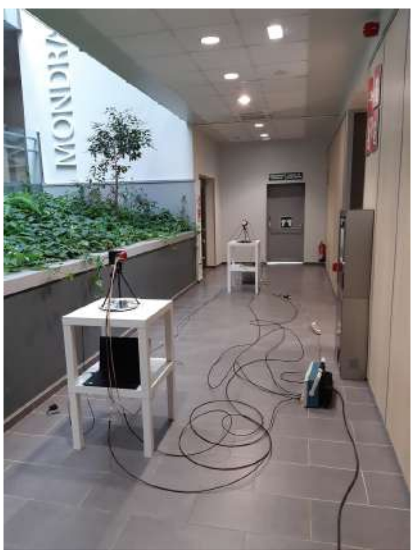


Fig. 5: Delay and power testing in corridor

TABLE II: Reference vs measured distance and power

Distance(m)		Power(dB)	
Real	**Measured**	**Friis ref.**	**Measured**
1	1.13	-8.01	-7.3
1.5	1.66	-11.53	-9.75
2	2.1	-14.03	-13.2
2.5	2.7	-15.96	-14.68
3	3.33	-17.55	-18.9
3.5	3.6	-18.89	-18.8
4	4.14	-20.05	-20.2
4.5	4.71	-21.07	-18.22
5	5.27	-21.98	-24.57
5.5	5.55	-22.81	-24.7
6	6.11	-23.57	-22.45
6.5	6.66	-24.26	-24.07
7	7.2	-24.91	-22.81
7.5	7.5	-25.51	-24.96

Fig. 6: Sounder in machining workshop

metallic cases of these stations, along other elements as the lockers that are closed to the wall or the various tool holders in the surroundings are expected to generate several multipath components that the sounder should be able to detect. Figure 6 displays the described environment.

Both antennas were separated by a distance of 5 meters, and a complete azimuth scan was carried out in 3º intervals for two 1.08 GHz bands, generating a total of 28800 CIRs. An aggregation of both bands was performed in the post-processing step, from where the strongest component in time domain was extracted to generate a heatmap with all the possible azimuth configurations. Figure 7 shows the obtained result.

As it can be seen, there is a variety of directions from where the signal arrives with a significant strength. Some of them have been marked in the heatmap, as they will be used

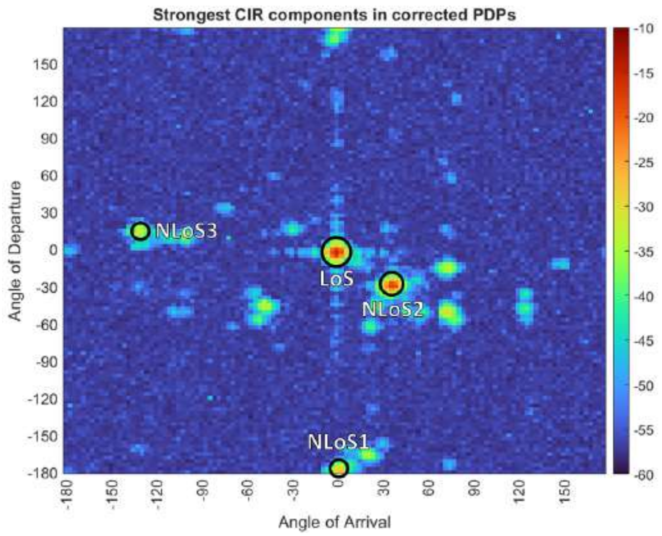


Fig. 7: Maximum power per AoD/AoA couple in workshop (3 degree resolution)

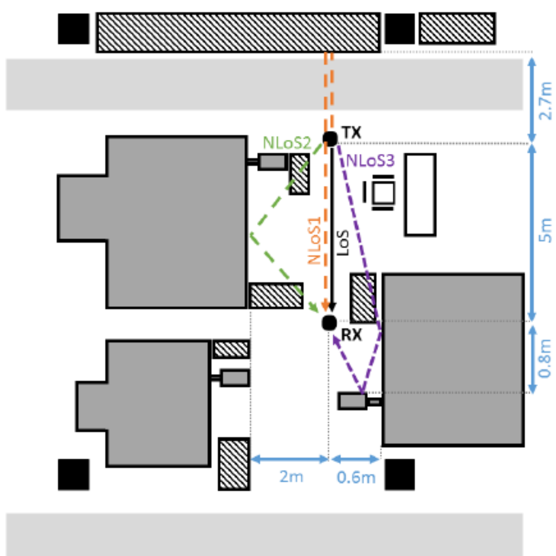


Fig. 8: Workshop layout with estimated strongest paths

for the validation process. The objective is to estimate the length and delay of each path only with the antenna angle combination and the layout of the testing environment, because the expected delay should coincide with the one that can be observed in the CIR. These estimations where carried with the layout described in Figure 8, and all the relevant results can be found in Table III.

As it can be seen, both measured and estimated delays are almost identical, which proves that the expected paths are close to the real ones and that the azimuth angles are correct. A further validation can be carried out by repeating the process with other directions that are present in the heatmap, but due to the high reflective nature of industrial environments, higher order reflections could be present, making their estimation more challenging.

TABLE III: Estimated and measured delays in azimuth test

Path	AoD(°)	AoA(°)	Estimation		Measurement
			Length(m)	Delay(ns)	Delay(ns)
LoS	0	0	5	16.67	16.66
NLoS1	-180	3	10.4	34.66	37
NLoS2	-30	36	6.4	21.33	19.44
NLoS3	15	-129	6.7	22.33	21.29

VII. Conclusions

This paper has presented a flexible and cost-effective directional channel sounder design oriented to the characterization of industrial scenarios in the 60 GHz mmWave frequency band. A description of the selected HW, sounding signals and algorithms has been provided along with a review of published channel sounding architectures in the 60 GHz band. Experimental results have shown that the sounder is capable of detecting power, delay and direction in azimuth correctly with a precision that is considered to be adequate for the use case of interest. Future works will focus on elaborating stochastic channel models of indoor industrial scenarios with real measurements obtained with this equipment, which can be used for the evaluation of wireless 60 GHz communication standards and proposals in industrial scenarios.

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