Characterization of an indoor propagation channel: the case of an industrial 4.0 environment

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***Abstract*— This article focuses on the characterization of the propagation channel in an industrial 4.0 environment, with the aim of improving the accuracy of indoor localization systems. The context of the study is based on the challenges associated with wireless communication in a complex and dynamic environment, where the presence of metallic obstacles and multipath phenomena can degrade geolocation performance. To overcome these limitations, we conducted an experimental measurement campaign in an assembly workshop equipped with industrial robots and conveyors. Different channel probing methods were studied, including temporal and frequency techniques. The preferred approach is based on the use of a Vector Network Analyzer (VNA) to measure channel parameters in the frequency domain. The results obtained show the significant impact of reflections and robot mobility on signal quality, enabling us to propose several solutions for improving localization, including exploiting frequency diversity, merging several metrics (TDOA and RSS), and using equalizing filters to compensate for distortions induced by the channel.**

***Index Terms*— industry 4.0, sounding the propagation channel, TDOA, impulse response.**

I. Introduction

With the accelerated growth of industrial technologies, Industry 4.0 is changing the game and transforming the production landscape. Real-time monitoring of products, machines, and personnel is essential to this new industrial revolution, which relies heavily on the integration of key technologies, including Wireless Sensor Networks (WSN). However, the complex and dynamic characteristics of industrial environments give rise to problems specific to WSN, such as delays and packet losses, which can degrade the performance of the communication system due to electromagnetic interference, the diversity of multi-source materials, spatial geometry, and so on. In such environments, the accuracy and reliability of the location system can be severely compromised, making traditional solutions unsuitable. So, in order to improve the accuracy of geolocation in such environments, it is important to obtain a finer characterization of the radio propagation channel for these complex environments. Measurement campaigns or simulators can achieve this.

In this article, we focus on measurement campaigns. Unlike the case using simulations, the experimental approach consists of exploring the propagation channel using instruments capable of measuring some of the relevant characteristics of the given system, such as the impulse response or the frequency response [1]. Generally speaking, channel probing techniques fall into two broad classes: time-domain approaches and frequency-domain approaches [2]. Time-domain methods are based on techniques such as impulse probing, matched filtering and sliding correlation methods. Other frequency-domain methods use frequency sweeps on a point-by-point or linear basis.

Finally, we present various solutions designed to improve the performance of our indoor localization system.

II. Description of environment

A. Industry 4.0

Submit Industry 4.0 represents the fourth industrial revolution, characterized by a digital transformation that integrates new technologies into production processes. It is based on the interconnection of machines, products, and systems within manufacturing chains via the Internet of Things (IoT) and Cyber-Physical Systems (CPS). This revolution is marked by advanced process automation, which includes robots capable of communicating with other machines and autonomously coordinating during different stages of production [3].

The robots are equipped with sensors and actuators, interacting within complex electromagnetic environments. These sensors collect data on the physical state of materials, such as resistance, temperature, etc., while the actuators allow real-time adjustments of processing or manufacturing conditions [4]. Through these interactions, machines can emit electromagnetic signals to transfer information to production management systems via wired or wireless networks.

The electromagnetic aspect is critical in the communication between different metallic components and control systems. For instance, technologies like RFID (Radio Frequency Identification) enable the identification and tracking of metal parts throughout the production process, relying on electromagnetic waves to transmit data between sensors and centralized or decentralized management systems. Cyber-Physical Systems leverage this data to automatically adjust production parameters, creating continuous feedback loops between the physical world of robots and the virtual world of computations and algorithms.

B. Problematics

Our study explores localization techniques through interferometry, leveraging the Time Difference of Arrival (TDOA) of signals between a transmitting source and receivers. In particular, the mobile device being localized uses a transmission source directed to a differential receiver system, as illustrated in Figure 1. This system comprises two -3dB couplers, with their output ports connected to a quadratic detector. The correlator output signals then provide the basis for further processing.

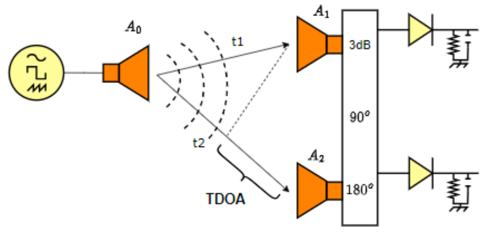

Fig.1: TDOA determination topology

These are referred to as I-Q signals, and their processing enables the extraction of the Time Difference of Arrival (TDOA), as depicted in Figure 1. In a free-space environment, the I-Q signals in the frequency domain are represented by the following expressions [5]:

$$Q(f) = E.sin(2.\pi.f.t) \quad (1)$$

$$I(f) = E.\cos(2.\pi.f.t) \quad (2)$$

In Industry 4.0 environments, omnipresent metallic structures such as machines, pipes, and frames can give rise to signal reflections, refractions, and diffractions. These effects lead to the creation of multiple signal paths (multipath), as shown in Figure 2.

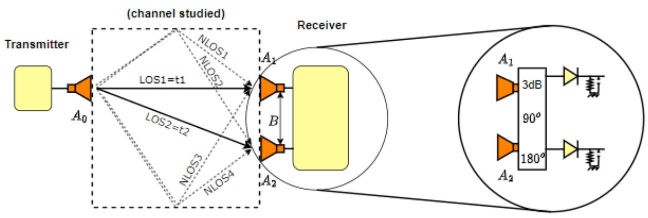

Fig.2: Channel topology in a confined environment

The I-Q signals in the frequency domain can therefore be represented by the following form [5]:

$$Q(f) = E_1.E_2 \cos(2.\pi.f(t_1 - t_2)) + \sum_{j=4}^{2k} E_1.E_j \cos(2.\pi.f(t_1 - t_j)) + \sum_{i=3}^{2k-1} E_2.E_i \cos(2.\pi.f(t_i - t_2)) + \sum_{i=3}^{2k-1}\sum_{j=4}^{2k} E_i.E_j \cos(2.\pi.f(t_i - t_j))$$

(3)

$$I(f) = E_1.E_2 \sin(2.\pi.f(t_1 - t_2)) + \sum_{j=4}^{2k} E_1.E_j \sin(2.\pi.f(t_1 - t_j)) + \sum_{i=3}^{2k-1} E_2.E_i \sin(2.\pi.f(t_i - t_2)) + \sum_{i=3}^{2k-1}\sum_{j=4}^{2k} E_i.E_j \sin(2.\pi.f(t_i - t_j))$$

(4)

The useful time information is contained in the term $t_1 - t_2$, which is our TDOA.

With:

- E_i and E_j representing the amplitudes of signals associated with paths *i* and *j;*
- $t_1 - t_j$ is the time difference caused by the path difference between LOS1 and all possible cases of NLOS paths j, assuming j is an even integer greater than 2.
- $t_i - t_2$ is the time difference associated with the length difference between LOS2 and all possible cases of NLOS paths *i*, where *i* is an odd integer greater than 1;
- $t_i - t_j$ is the time difference associated with the path difference between all possible combinations of NLOS paths, with *i* and *j* as integers (with *i* being an odd integer greater than 1 and j an even integer greater than 2).

In a localization system utilizing Time Difference of Arrival (TDOA), these multipath phenomena can impact the TDOA measurements, leading to errors in positioning accuracy.

Additionally, the continuous or random movement of objects such as robots, vehicles, and machines, along with frequent equipment rearrangements, creates highly dynamic environments. This results in rapid changes in the propagation channel, making multipath propagation conditions highly unpredictable.

The mobility of objects also raises the likelihood of Non-Line-of-Sight (NLOS) conditions between the transmitter and receiver, further complicating the accurate calculation of the TDOA.

In general, the channel undergoes significant changes due to object movement, as demonstrated by the studies reported in [6], [7], and [8].

To overcome these challenges, accurately characterizing the propagation environment known as channel sounding is essential. This process involves analyzing key parameters and the temporal variations in the channel caused by the movement of objects or machines. Channel sounding identifies propagation conditions, including multipath effects and Line-of-Sight (LOS) or Non-Line-of-Sight (NLOS) scenarios. Such characterization is critical for adapting real-time localization and communication algorithms to minimize errors induced by propagation phenomena [9].

III. METHODOLOGY

Propagation channel sounding consists of analyzing the impulse response (IR) of the channel, represented by h(τ,t), as a function of the delay τ, as well as, potentially, its evolution over time, symbolized by the variable t. In the next paragraph, we will present different methods of channel sounding.

A. Time-domain sounding methods

Channel probing in the time domain typically involves transmitting a broadband excitation signal, allowing the receiver to process multiple frequencies simultaneously and thereby reducing the measurement acquisition time. Several techniques have been developed based on this principle, including pulse measurement [10] and sliding correlation measurement [11], which are described below.

The pulse-based method is the most intuitive approach. It is essentially an application of the convolution operation, linking the received signal s(t) to the transmitted signal e(t). When e(t) takes the form of a Dirac-type impulse, the received signal s(t) becomes directly proportional to the channel's impulse response h(t,τ).

However, generating such an ideal impulse characterized by an infinite and uniform spectrum is practically impossible. To overcome this limitation, pulse generators are used to produce extremely short signals, typically lasting just a few hundred picoseconds. If we denote the transmitted pulse as $\Pi\ \Delta_t(t)$, the received signal can then be expressed as follows [12]:

$$s(t) = h(t,\tau) \otimes \Pi\ \Delta_t(t) \qquad (5)$$

This closely approximates the impulse response of the propagation channel.

For the receiver, capturing the signal at extremely high speed is crucial. To achieve this, a Digital Sampling Oscilloscope (DSO) is commonly used, offering acquisition speeds of up to 20 Gsamples/s.

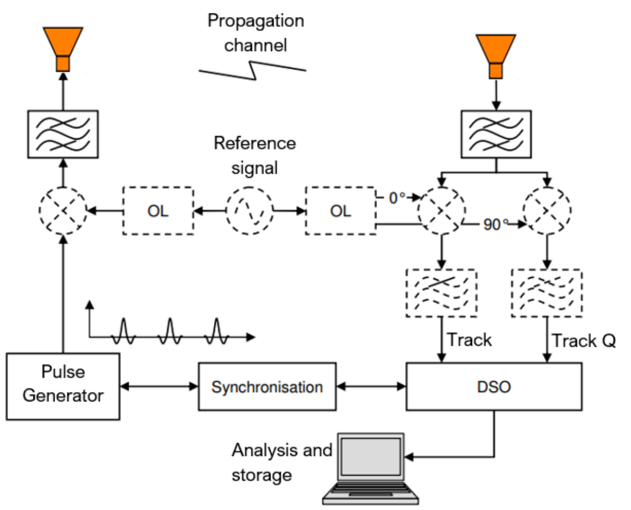

Fig.3: Propagation measurement using pulse sounding [12].

Sliding correlation measurement is widely used to reduce the effect of low SNR. This method uses the autocorrelation properties of maximal-length Pseudo-Random (PR) sequences. Two identical PR sequence generators of length L, which are integrated to create the digital mode of the PR sequence generator. The transmitted sequence c(t) is shifted to the desired frequency and transmitted. The sliding correlation occurs at the receiver, where a small difference in clock frequencies between the arriving sequence c(t) and the synchronized local sequence c'(t) creates a small-time shift. A correlation peak appears when the two sequences are in phase, which shows up as per the arrival of a path of the impulse response. This method extracts the complete impulse response of the channel by sweeping through all possible paths. This, in turn, allows the use of more selective filters at the receiver and will thus improve the system dynamic range, because the impulse is stretched by k in the time domain, while it is compressed by k in the frequency domain. The time domain sounders based on sliding correlation have a high dynamic range and allow real-time operation. However, they are limited by a complex implementation and, in the measured response, highly sensitive to the performance of the sounder's components. Additionally, accurate transmitter-to- receiver synchronization is essential for correct measurement. That led us to opt for a frequency domain approach.

B. Frequency-domain sounding methods

The basic idea of this method is that, by sending a narrowband signal of fixed frequency, we can sample the channel transfer function H(f,t), and the attenuation and phase shift of the received signal can represent the transfer function. Assuming that the frequency band can be represented by N (evenly spaced by Δf) samples, the impulse h(τ,t) is obtained by inverse Fourier transform of the transfer function H(f,t). Frequency domain implementations are usually top-level two types: stepwise scanned models [13], and linearly scanned models [14].

To do this, step-by-step scanning is performed in which the S parameters were measured using a Vector Network Analyzer (VNA). In order to characterize a channel, port 1 of the vector network analyzer (VNA) (which acts as the transmitter) is connected to the transmitting antenna and port 2 to the receiving antenna, and the S21 parameter is measured, which is the transmission coefficient between the two antennas, enabling the estimation of the channel transfer function. Usually, the frequency band is swept by a sinusoidal signal. This signal is down-converted to an intermediate frequency where it can then be filtered using a band-pass filter. This approach allows you to cover a very large part of the spectrum with very high precision, both in resolution and in dynamic range. However, the measuring range is limited, since the VNA is both transmitter and receiver, so this technique is limited to indoor environments.

Linear scanning is employed to overcome the limitations of the acquisition time of the VNA. This process compresses the frequencies and thus reduces the sampling frequency and background noise. In this case, the sweeping probing signal is no longer a simple sine wave, but is called a frequency sweep or chirp [15]. The desired metric (the channel impulse response) can be extracted by correlating the received mix-down signal the received mix-down signal with a replica of the transmitted signal, or by mixing and low-pass filtering the transmitted chirp with a chirp generated at the receiver. In the latter case, what is being measured is not the impulse response but the time-varying transfer function.

This approach offers similar advantages to the sliding correlation technique, while being performed in the frequency domain. In theory, the time resolution is the inverse of the analyzed bandwidth, after calibrating the frequency response. However, this resolution is affected by the windowing of the measured signal, necessary for performing the Fourier transform, which influences both the dynamic range and the time accuracy of the measurement system.

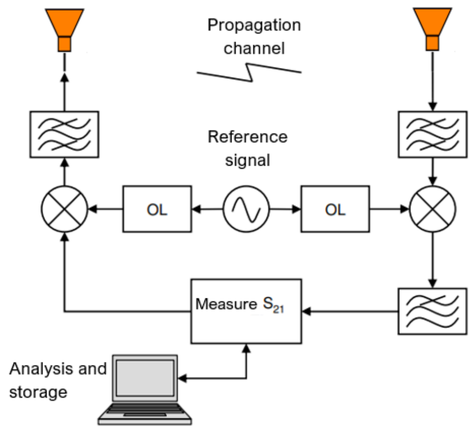

Fig.4: Frequency sounding propagation measurement [12].

C. Sounding parameters

From the impulse response, we extract parameters that are essential for describing the properties of the channel, such as Rice's K factor (equation 5), the delay spread (or RMS Delay Spread) (equation 8) and the coherence band (equation 9).

The impulse response provides information about the different propagation paths, each characterized by a distinct delay. The path with the largest amplitude is identified as the 'LOS' component. The other paths, representing reflected or scattered signals (NLOS), form what is known as the scattering power. The ratio between the power of the LOS $|h_{LOS}|^2$ and that of other routes $|h_{NLOS,i}|^2$ gives the K factor (equation 6) [16], which measures the preponderance of the direct signal compared with the surrounding echoes. If the K factor is high (K >> 1), we have a channel dominated by LOS, and if the K factor is low (K ≈ 0), we have a channel dominated by the multipath.

$$K = \frac{|h_{LOS}|^2}{\sum_{i=1}^{n} |h_{NLOS,i}|^2} \tag{6}$$

In addition, delay dispersion is a key indicator for assessing the risk of interference. It is determined by the second-order moment of the Power Delay Profile (PDP), which describes the distribution of power as a function of delay. To calculate this dispersion, it is necessary to evaluate the average delay (equation 8) and to have the PDP (as detailed in equation 7).

$$P(\tau) = |h(\tau,t)|^2 \tag{7}$$

$$\bar{\tau} = \frac{\int_0^{\tau_{max}} \tau P(\tau)d\tau}{\int_0^{\tau_{max}} P(\tau)d\tau} \tag{8}$$

$$\tau_{RMS} = \sqrt{\frac{\int_0^{\tau_{max}} (\tau-\bar{\tau})^2 P(\tau)d\tau}{\int_0^{\tau_{max}} P(\tau)d\tau}} \tag{9}$$

Delay dispersion also influences the correlation between spectral components in the frequency domain. This correlation can be quantified by the coherence band, which corresponds to the frequency interval over which the signal components are similarly affected by the channel. It is defined from the autocorrelation of the channel transfer function, but can also be estimated from the delay spread. A rough estimate of the coherence band can be made using equation 9.

$$B_{c,50\%} \approx \frac{1}{5\tau_{RMS}} \quad (\textit{Threshold at 50 \%}) \tag{10}$$

Knowing one of these two parameters is fundamental for effectively calibrating communication systems and preventing interference. If the communication band used is less than the coherence band, the channel is considered to be non-frequency selective; otherwise, the channel becomes frequency selective, which requires appropriate transmission strategies.

These parameters are essential for correctly calibrating communication systems, minimizing interference and ensuring optimum performance, particularly in environments where multipath plays a significant role.

IV. Sounding of Complex Environment

In this section, we provide a detailed overview of our channel sounding system.

A. Measurement environment

This study was conducted in an assembly room at the SMART site. This room is subdivided into several sections. Only the assembly section (flexible cells), equipped with robots as illustrated in Figure 5, and is of interest to us. It consists of:

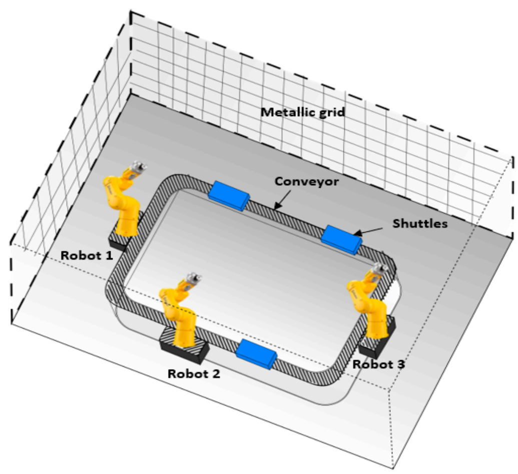

Fig.5: Macro-géométrie de l'environnement

Table 1 lists the main obstacles in our environment, according to their number and size in relation to the wavelength of our signal, whether at 2.45GHz or 5GHz.

Obstacles	Number	Size relative to wavelength	
		2.45 GHz	5 GHz
Montrac flexible conveyor	1	0,8 λ	1,6 λ
Flexlink conveyors	3	0,8 λ	1,6 λ
Industrial robots	3	10 λ	20 λ
Shuttles (mobile pallets)	10	1,25 λ	2,5 λ
RFID pallet identification system	3	0,4 λ	0,8 λ

Table 1 : obstacles in the environment

A metallic grid encloses the entire structure.

B. Channel sounding system

For channel sounding, our approach is based on a frequency-domain method using stepwise scanning, as outlined in Section III.

The measurement setup consists of the following equipment:

- A laptop used as a workstation;
- A Vector Network Analyzer (VNA);
- Two Vivaldi antennas covering a frequency range from 300 MHz to 18 GHz;
- Two omnidirectional biconical antennas (400 MHz to 8 GHz);
- Two SMA cables, one 10 meters long and the other 3 meters long, connecting the antennas to the VNA.

1) Preliminary measures

To validate our system, we first to carry out measurements in an open environment (the laboratory hall), where only a line-of-sight (LOS) path of 7.95 meters separated the transmitting and receiving antennas, a board of absorbent material is inserted to prevent reflection on the floor. We then introduced a reflector (a metal plate 1x1 m²), creating a non-line-of-sight (NLOS) condition with a length of 8.96 meters, and compared the impulse responses in the two configurations (with and without reflective surface), as shown in figures 6 and 7. The results clearly show that the difference in trajectory between the LOS and NLOS configurations corresponds to our measurements.

We can see that there is a shift in the position of the peak as the position of the plate changes.

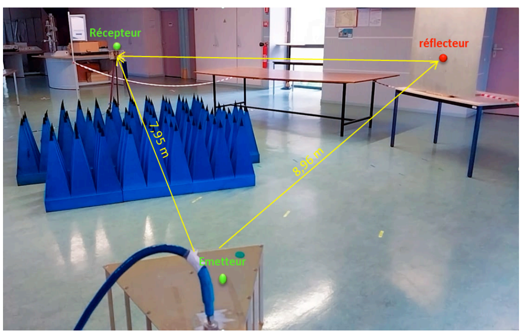

Fig.6. Environment of preliminary measures

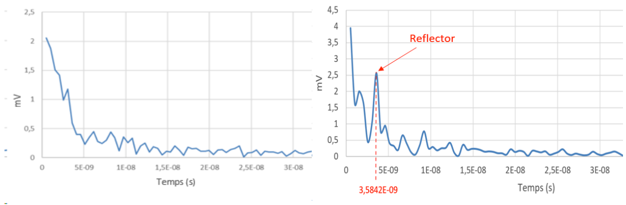

Fig.7: Preliminary measurements with and without reflector

In our approach, this impulse response is obtained by applying the inverse Fourier transform to the complex frequency response measured by our sounding system (described in section IV). It shows power peaks decreasing according to an exponential law, corresponding to the different paths or echoes as a function of their delay, and in order not to crush the graphs and to better highlight the reflections, we have removed the LOS component which is zero on the time axis, which will be the case for the other impulse responses presented.

It is important to note that we consider that there is a channel difference for two antennas separated by half a wavelength, the sounding carried out for one channel is valid for the second [5].

2) Application in a confined environment

After validating the system, we carried out measurements in a confined environment (Figure 5) at 2.45 GHz and 5 GHz, with resolutions of 400 MHz and 1 GHz for 5000 points. The distance between the transmitting and receiving antennas (horns or omnidirectional) was maintained (6 m) in the LOS configuration. The measurements were carried out in two phases: first with the fixed robots, then 10 consecutive measurements with the moving robots to obtain an average impulse response of the channel under these conditions.

To achieve this, we considered different topologies:

- Two line-of-sight antennas: horn antennas on the transmit side and omnidirectional antennas on the receive side.
- Two antennas with line-of-sight: omnidirectional antennas on transmit and receive.
- The two antennas without line of sight: horn antennas on transmit and omnidirectional antennas on receive.
- The two antennas without line-of-sight: omnidirectional antennas on transmit and receive.
- The configuration with horn antennas on transmits and receive was not chosen because, being directional antennas, we do not have all the possible reflected paths on receive.

V. ANALYSIS OF RESULTS

In this section we will begin by analyzing and interpreting the acquisitions made and characterizing our propagation channel. We will then propose a solution for our localization system.

A. Characteristics of the propagation channel

We used topologies comprising a horn antenna on transmit and an omnidirectional antenna on receive, as well as a configuration with omnidirectional antennas on transmit and receive. However, the configuration using omnidirectional antennas for both modes (transmit and receive) generate more reflections, which allows us to better visualize all the obstacles in our environment, unlike the configuration using a horn antenna, justifying our decision to favour a topology with omnidirectional antennas for transmit and receive.
The figures below show the impulse responses of our channel when the robots are stationary (blue curve) and when the robots are moving (red curve, average of 10 consecutive impulse responses), in the 400 MHz and 1 GHz frequency bands, with and without the LOS component.

1) With LOS at 2.45 GHz

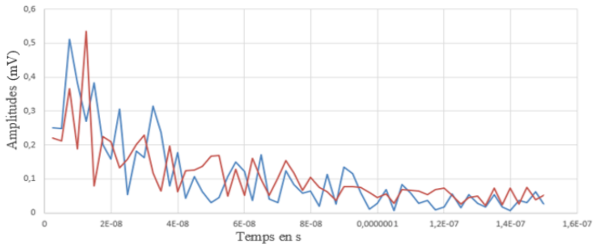

Fig.8: Impulse responses at 2.45 GHz with LOS (400 MHz band)

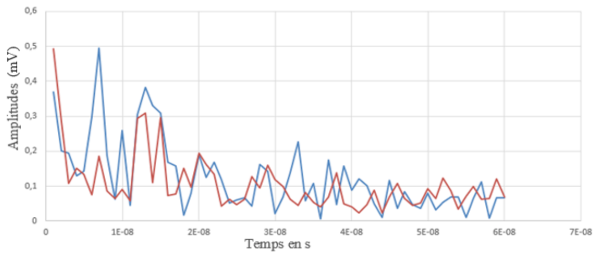

Fig.9: Impulse responses at 2.45 GHz with LOS (1 GHz band)

From these impulse responses we obtained the parameters of our channel presented in section III at 2.45GHz and represented in table 2.

Frequency bands	τ_{RMS} (ns)		$B_{c,50\%}$ (MHz)		K (dB)	
	Fix	Move	Fix	Move	Fix	Move
400 MHz	81.2	98.3	2.46	2.03	8.9	8.96
1GHz	81.2	116.7	2.46	1.7	8.25	9.31

Table 2: Characteristics at 2.45 GHz with LOS

2) With LOS et 5 GHz

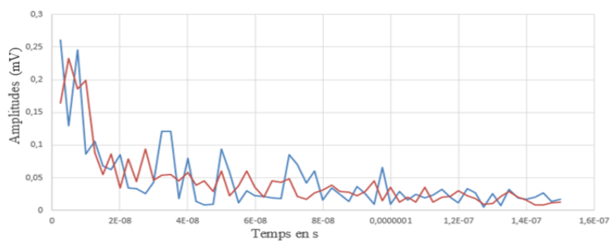

Fig.10: Impulse responses at 5 GHz with LOS (400 MHz band)

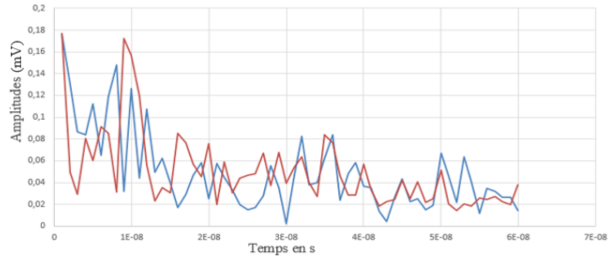

Fig.11: Impulse responses at 5 GHz with LOS (1 GHz band)

Table 3 shows the characteristics of our 5 GHz propagation channel:

Frequency bands	τ_{RMS} (ns)		$B_{c,50\%}$ (MHz)		K (dB)	
	Fix	Move	Fix	Move	Fix	Move
400 MHz	319.2	299.1	0.63	0.67	8.48	8.32
1GHz	123.6	116.4	1.62	1.72	8.63	8.39

Table 3: Characteristics at 5 GHz with LOS

In order to obtain an accurate analysis of the transmission phenomena, we introduced an absorber material (carbon-loaded foam) measuring 1.5x0.6 m² to eliminate the line-of-sight (LOS) component, as shown in Figure (12). This absorber allows us to focus exclusively on the non-direct contributions, in other words the non-line-of-sight (NLOS) components. This approach is particularly relevant to the study of environments where reflections, diffractions and scattering play a dominant role in signal transmission. By eliminating the LOS component, we can better characterize indirect paths, which is fundamental for our indoor localization system, where signals are mainly propagated by multipath.

Fig.12: Introduction of absorbent material

3) Without LOS at 2.45 GHz

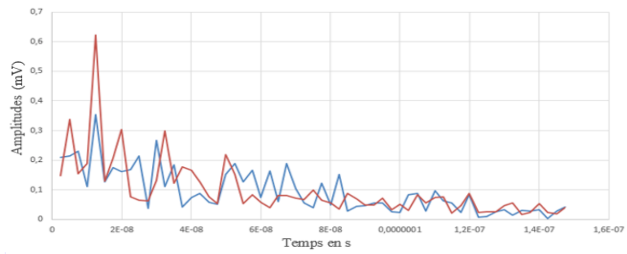

Fig.13: Impulse responses at 2.45 GHz without LOS (400 MHz band)

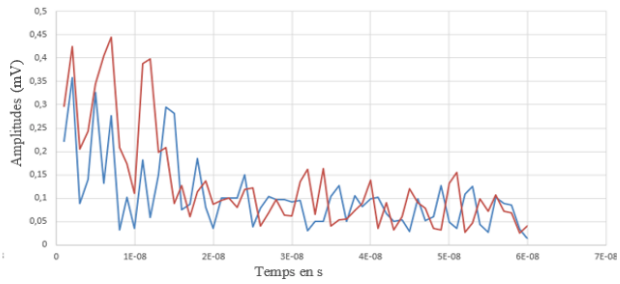

Fig.14: Impulse responses at 2.45 GHz without LOS (1 GHz band)

Based on these impulse responses, we can characterize our propagation channel at 2.45 GHz without line-of-sight (table 4):

Frequency bands	τ_{RMS} (ns)		$B_{c,50\%}$ (MHz)		K (dB)	
	Fix	Move	Fix	Move	Fix	Move
400 MHz	132.7	88.49	1.5	2.26	10.22	8.88
1GHz	157.6	127.1	1.27	1.57	9.08	7.34

Table 4: Characteristics at 2.45 GHz without LOS

4) Without LOS at 5 GHz

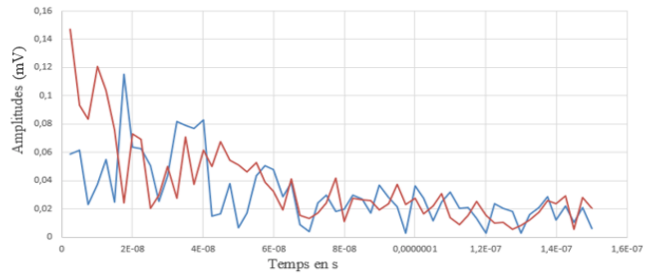

Fig.15: Impulse responses at 5 GHz without LOS (400 MHz band)

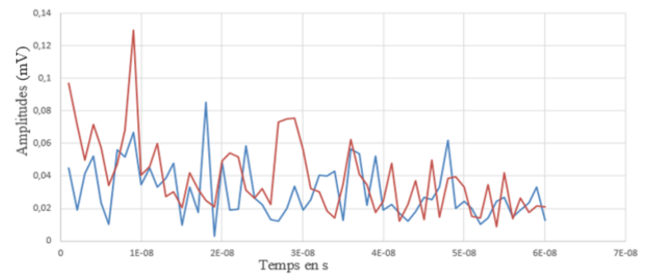

Fig.16: Impulse responses at 5 GHz without LOS (1 GHz band)

Table 5 shows the characteristics of our 5 GHz propagation channel without the LOS component:

Frequency bands	τ_{RMS} (ns)		$B_{c,50\%}$ (MHz)		K (dB)	
	Fix	Move	Fix	Move	Fix	Move
400 MHz	433.1	367.7	0.46	0.54	9.39	9.29
1GHz	203.3	146.1	0.98	1.37	8.85	8.84

Table 5: Characteristics at 5 GHz without LOS

The impulse responses analyzed above (Figures 8-11 and 13-16) show a progressive attenuation of the signal amplitude over time. This decrease can be explained by the superposition of multiple copies of the original signal, each with a different delay and attenuation due to reflections from surrounding obstacles.

The rapid fluctuations in amplitude observed on the two curves indicate the presence of multiple paths very close together in time.

Although the general shapes of the two curves are similar, there are some notable differences. The curve associated with moving robots (red curve) has generally lower amplitudes than the curve corresponding to stationary robots (blue curve). This result suggests that the movement of the robots induces additional attenuation of the signal, probably due to the rapid variations in the environment caused by this movement.

More specifically, the movement of the robots causes rapid temporal variations. These variations result in less dispersion of the received signal, i.e., a less wide temporal spread of the different copies of the signal, and in greater attenuation. These effects are particularly marked on the red curve, confirming the significant impact of robot movement on signal reception quality.

The parameters of the propagation channel that emerge are, coherence bands (fixed and moving robots) much lower than the band studied and the K factor greater than 1, which show us that the channel probed (without or with robot movement), is very selective in frequency but still dominated by the LOS component.

B. Solutions proposed to improve localization

In order to improve the accuracy and efficiency of our localization system, it is essential to develop robust solutions adapted to the specific constraints of the environment analyzed in the previous section.

1) Frequency diversity

In our context, frequency diversity means exploiting several frequencies, and each frequency used is used to calculate a position based on the specific signal propagation conditions at that frequency. These estimated positions vary due to the effects of multipath propagation, which are highly dependent on the frequency used.

By combining these estimated positions, usually by taking their average, it becomes possible to obtain a final position that is more accurate than that of the single-frequency mode [17]. This approach helps reduce frequency-specific errors in complex environments such as Factory 4.0. Indeed, given the frequency selectivity of our environment, some frequencies may be more sensitive to phenomena such as absorption or reflection on metal surfaces, while others may overcome these obstacles more effectively.

2) Merging several metrics

To enhance the accuracy of our localization system, we have combined the Time Difference of Arrival (TDOA) method with Received Signal Strength (RSS), which represents the amplitude of the signal received by the receivers from the transmitting beacon.

Before delving further into this approach, it is essential to explain the interferometric localization process based on

TDOA. A beacon emits signals that, once received and processed by the receivers, help define two hyperboloids with a constant TDOA in a 3D space. The intersection of these hyperboloids forms a hyperbola, indicating the possible location of the transmitting beacon [5].
The data obtained from RSS provides an estimate of the distance between the transmitting beacon and the receivers by analyzing the power level of the received signal. This estimation is then used to describe an iso-power sphere centered on each receiver.
The three-dimensional coordinates of the transmitting beacon are determined by intersecting the iso-power sphere with the hyperbola derived from the TDOA measurements.
This approach significantly enhances localization accuracy while enabling a precise three-dimensional estimation.

3) Channel equalizer filter

Equalization is a basic method for compensating the distortion and interferences introduced by the propagation channel in the digital and analog communication systems. This consists of digital filters with adaptive coefficients. Broadly, these filters are divided into two classes; finite impulse response (FIR) filters and infinite impulse response (IIR) filters. The selection of FIR or IIR Depends on Stability, Complexity and Latency Constraints of the system [18].
The structure of this filter can differ based on the desired specifications and learning techniques, and the adaptive learning algorithms are responsible for adapting the filter coefficients. These algorithms iteratively optimize the coefficients such that the overall impulse response of the filter/channel system is an inverse approximation of the impulse response of the transmission channel, as shown in the figure 17.

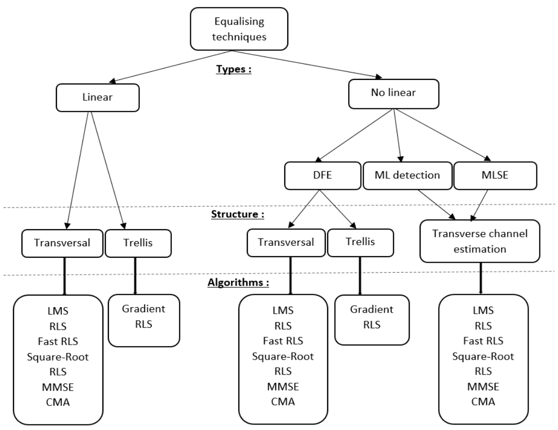

Fig.17: Equalization techniques

In summary, the proposed solutions aim to improve the accuracy and efficiency of the localisation system while taking into account the specific constraints of the environment. The use of frequency diversity helps to limit errors due to propagation effects, while the combination of several metrics, such as TDOA and RSS, provides a more reliable estimate of position in three dimensions. Finally, the integration of a channel equalisation filter helps to correct distortions and interference in the signal. These approaches will be tested to assess their relevance and effectiveness in the context studied.

CONCLUSION

Our in-depth study of the propagation channel in an industrial 4.0 environment highlighted several points. Measurements carried out in line-of-sight and non-line-of-sight configurations (LOS and NLOS) demonstrated the significant impact of multiple reflections and obstacle mobility on signal transmission quality. Time dispersion and poor band coherence in this type of environment illustrate the frequency selectivity of the channel, making it necessary to use suitable techniques to improve localization accuracy. To achieve this, we opted to exploit frequency diversity to reduce errors associated with multipath phenomena, integrate RSS (Received Signal Strength) measurements with the TDOA (Time Difference of Arrival) method to refine the estimated position, and implement equalizer filters to compensate for distortions due to the channel.
In addition, the characterization of several industrial 4.0 environments will enable us to develop a propagation model specific to this type of environment.
Taken together, these approaches represent a promising lever for optimizing the performance of localization systems in complex industrial environments.

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