Abstract—This paper presents an algorithm that interprets the specificities of the received waveforms associated with well-isolated multipath echoes, depending on the type of interaction and on the direction-dependent signal deformations due to antennas. The goal is to jointly estimate Direction of Arrival (DoA), Direction of Departure (DoD) and reflecting material for simple-bounce interaction in a peer-to-peer Impulse Radio - Ultra Wide Band (IR-UWB) communication context. The proposed technique is mainly based on prior antenna characterisation and on prediction of site-specific filtering effects due to simple electromagnetic interactions with environment (i.e. simple-bounce reflections). Simulation results are provided to illustrate the expected performance of such a system. The proposed technique discloses new perspective for context-aware services in wireless networks.

Index Terms—Antenna, Electromagnetic Interaction, Reflection, Indoor Environments, Direction of Arrival, Direction of Departure, Ultra Wide Band

I. INTRODUCTION

For security applications, robotics, control in confined or dangerous environment, house automation, or context-aware network optimization, the capability of radio devices to infer reliable environmental information (e.g. the presence, the distance, the orientation, or potentially, the nature of surrounding walls or obstructing obstacles) has recently appeared as a strategic stake.

Besides, the flexibility and the fine intrinsic properties of the Impulse Radio - Ultra Wide Band (IR-UWB) technology (e.g. low power consumption, scalability, advanced ad hoc networking, precise range measurements, etc.) have been exploited for wireless communications and radio-location (e.g. [1]).

Relying on the fine temporal resolution capability of UWB pulses, recent studies have also been initiated in the field of environment characterisation. Firstly, Radio Frequency (RF) indoor sensing and imaging are based on UWB radar (e.g. [2]). Then, geo-regioning exploits the prior knowledge of average power delay profiles as radio signatures (e.g. [3]). Finally, indoor mapping interprets a simplified Channel Impulse Response (CIR) thanks to basic geometrical laws (e.g. [4]). All the previous techniques focus only on a geometric reconstruction of the environment, while material recognition remains a problem never addressed in a communication context. Nevertheless, some contributions dealing with this technical problem are already present in the radar field (e.g. [5]). The previous work [6] presented a simple algorithm for joint Direction of Arrival (DoA) and Direction of Departure (DoD) estimation in the context of a standard peer-to-peer IR-UWB communication, giving a solution for the particular case of direct path.

The work presented in this paper constitutes an evolution of the latter. It concerns a UWB system and an algorithm that enable fusing classical Single Input Single Output (SISO) digital communications, transmitting and receiving directions finding and material recognition, relying on the interpretation of the specific deformations suffered by simple-bounce reflected paths on the receiver side.

First of all, the proposed technique requires the capability to predict site-specific filtering electromagnetic interactions with environment, as described for deterministic tools (e.g. [7], [8]) and the preliminary knowledge of antennas behaviour (e.g. through prior measurements or simulations). Some realistic material models have been fed by estimated parametric values. The material parameters have been obtained by an in situ method of characterisation. Secondly, predicted waveforms are compared through basic cross-correlations with ideally well-isolated paths so as to decide both which transmitting and receiving directions and material interaction may have resulted in observed paths. This step can be repeated iteratively, refining jointly directions estimation and potentially material characterisation.

The paper is organised as follows. In Section II, the effects of the most significant electromagnetic interactions are briefly presented. In Section III, a material model and the principles of an in situ method for its parameter estimation are discussed. Then, Section IV introduces the received signal model, while Section V proposes a simple algorithm for the joint estimation of both transmitting and receiving directions and material typecasting. Subsequently, Section VI presents the algorithm performance in a 2D scenario. Finally, Section VII concludes the paper.

II. CHANNEL EFFECTS ON UWB RECEIVED WAVEFORMS

A. Electromagnetic Interactions

In a typical indoor environment, transmission and reflection phenomena mainly affect radiated waveforms. Actually, as described in [9], the UWB pulse observed after a reflection on or a transmission through a slab (e.g. wall, window, door) appears to be deformed. In particular, in addition to the pulse fading, pulse shape is modified. This deformation mostly depends on the thickness $\delta$ of the slab, which causes multiple internal reflections, as well as on the complex dielectric permittivity $\epsilon$ and on the incidence direction $\theta_{in}$.

B. Antennas

Both measurements (e.g. [10]) and models (e.g. [8], [11]) have highlighted the filtering effects of UWB antennas. Any UWB received signal, even the one corresponding to the direct path, could be considerably distorted according to the transmitting and receiving antenna directions, respectively $s_{tx}$.
and \( s_{rx} \). These distortions make the waveforms in the temporal domain potentially very different.

## III. MATERIAL MODEL AND PARAMETERS ESTIMATION

In [12], various relations are presented for material dielectric permittivity \( \varepsilon = \varepsilon_0 \varepsilon_r \) modeling. One can mention the following:

- non frequency dependent: \( \varepsilon_r = \varepsilon_r' - j \varepsilon_r'' \)
- frequency dependent: \( \varepsilon_r = \varepsilon_r' + j \frac{\varepsilon_r''}{\omega \varepsilon_0} \)
- one pole Debye: \( \varepsilon_r = \varepsilon_r' + (\varepsilon_r'' - \frac{\varepsilon_r'}{\tau_0}) - j \frac{\varepsilon_r''}{\omega \tau_0} \)

In these relations, \( \varepsilon_r' \) and \( \varepsilon_r'' \) are respectively the real and imaginary parts of a slab complex relative permittivity for a given frequency band. \( \varepsilon_r'_{\omega=\infty} \) is the relative real permittivity at low frequency, \( \varepsilon_0 \) is the permittivity of the vacuum in \([\text{F} \cdot \text{m}^{-1}]\), \( \tau_0 \) is the relaxation time in \([\text{s}]\), \( \sigma \) is the static conductivity in \([\text{S} \cdot \text{m}^{-1}]\). In the following, the frequency dependent model of permittivity will be considered.

Several characterisation methods have been published in order to estimate the complex dielectric permittivity of classical slabs (e.g. [13] - [15]). These methods are mostly based on reflection and/or transmission coefficients measurements using ellipsometry method for various incidence angles, frequencies, polarisations and slab thicknesses. As they assume homogeneous complex permittivity, they consider Fresnel formula [16] and an estimation algorithm to deduce back the dielectric permittivity from the reflected or/and transmitted power obtained from measurement. As they use a power meter, the phase information are not obtained.

Indeed, the characterisation method used in [11] to obtain slab parameters (i.e. \( \varepsilon_r' \) and \( \sigma \)) provides for complex values of reflected and transmitted power. As a consequence, both amplitude and phase information are collected. The latter helps extracting multi-layered material properties. As illustrated in Figure 1, the characterisation method setup is portable and can easily be deployed anywhere. Then, such technique is very interesting for \textit{in situ} slab characterisation.

To perform reflection and transmission measurements, a Vector Analyser (VNA) covering the frequency band 2 GHz - 8 GHz has been employed. The slab permittivity parameters are estimated from measurement data using a processing optimization algorithm based on the Maximum Likelihood (ML) criterion. Afterwards, as discussed in [11], the \( \varepsilon_r' \) and \( \sigma \) parameters can be obtained for various slabs such as wall, door and window. The results of this estimation technique are shown in Table I. These values are the entries for the reflection coefficient model developed in [11]. The latter model is interesting as it presents the dependency of the reflection coefficient on \( \varepsilon_r' \), the incidence angle to the slab \( \theta_{in} \), and also the thickness \( \delta \) of the latter. In order to show the complexity of a material filtering effect, Figure 2 presents the module of the frequency response of a brick slab, fixing in (a) \( \theta_{in} = 0 \), \( 6 < \delta < 8 \) cm, and in (b) \( \delta = 7 \) cm, \( 0 < \theta_{in} < \frac{\pi}{2} \). Then, one can find that material filtering effects can change significantly as \( \theta_{in} \) and/or \( \delta \) vary. In the following, the discussed material model will be employed.

### IV. ASSUMED RECEIVED PATH MODEL

In the context of a noise UWB indoor transmission, the received signal \( \rho(t) \) is generally described as a sum of echoes, resulting from \( N_{int} \) electromagnetic interactions:

\[
\rho(t) = \sum_{i=1}^{N_{int}} r_i(t - \tau_i) + n(t) \tag{1}
\]

where \( r_i(t) \) is the \( i \)-th filtered received echo, \( n(t) \) is the filtered noise affecting the link and \( \tau_i \) is the \( i \)-th echo delay.

As the description of electromagnetic phenomena appears simpler in the frequency domain, it is worth transposing the generic received path \( r_i(t) \) into the latter domain. In particular, it has been shown in [7] that, after discarding deliberately the time shift due to the unknown distance travelled by the signal and omitting the dependency on variable \( i \) for the sake of simplicity, the tension \( R(f) \) corresponding to the generic received echo at the output of the receiving antenna can be written as follows:

\[
R(f) = H_{tx}(f, s_{tx}) C_{int}(f) H_{rx}(f, s_{rx}) S(f) \tag{2}
\]

where \( S(f) \) is the Fourier Transform of the unitary signal \( s(t) \) feeding the transmitting antenna, \( H_{tx}(f, s_{tx}) \) and \( H_{rx}(f, s_{rx}) \) are two complex two-dimension vectors accounting for the frequency domain behaviour of transmitting and receiving antennas respectively in radiating directions \( s_{tx} \) and \( s_{rx} \). Finally,

\[
C_{int}(f) = \begin{bmatrix}
C_{\varphi', \varphi'}(f) & C_{\varphi', \varepsilon}(f) \\
C_{\varepsilon', \varphi'}(f) & C_{\varepsilon', \varepsilon}(f)
\end{bmatrix}
\]

is the complex \( 2 \times 2 \) “wide-sense” echo channel matrix, accounting for all electromagnetic phenomena affecting the considered echo (i.e. path loss, reflections, refractions, etc.) over each pure and cross-polarised component. Note that, without loss of generality, this model implies that the same antenna is used on both transmitting and receiving sides.

Generally speaking, matrix \( C_{int}(f) \) is different for each of the \( N_{int} \) received echoes, as a function of the interactions it has suffered. Nevertheless, as the energy of cross-polarisation terms is usually much lower than diagonal terms energy, every “echo channel” could be approximated as follows:

\[
C_{int}(f) = \begin{bmatrix}
C_{\varphi', \varphi'}(f) & \varepsilon \\
\varepsilon & C_{\varepsilon', \varepsilon}(f)
\end{bmatrix}
\tag{3}
\]

where \( \varepsilon \) accounts for a negligible interaction effect. In addition, considering a linearly polarised antenna enables to further simplify equation (2). Using a vertical or horizontal antenna polarisation, one could consider that all the signal energy is concentrated in one field component. For instance, under a vertical antenna polarisation:

\[
H_{tx}(f, s_{tx}) = \sqrt{G} E_{\varepsilon}(f, s_{tx})
\]

and

\[
H_{rx}(f, s_{rx}) = -j \frac{\lambda}{4\pi} \sqrt{G} E_{\varphi}(f, s_{rx})
\]


<table>
<thead>
<tr>
<th>Materials</th>
<th>( \varepsilon_r' )</th>
<th>( \sigma ) [\text{S} \cdot \text{m}^{-1}]</th>
<th>( \delta ) [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>brick</td>
<td>3.8 \pm 3%</td>
<td>0.05 \pm 4%</td>
<td>7</td>
</tr>
<tr>
<td>wood</td>
<td>2.84 \pm 4%</td>
<td>0.0 \pm 5%</td>
<td>3</td>
</tr>
<tr>
<td>glass</td>
<td>3.1 \pm 2%</td>
<td>0.0 \pm 4.5%</td>
<td>0.5</td>
</tr>
</tbody>
</table>

| TABLE I: ESTIMATED MATERIALS PARAMETERS FOR THE FREQUENCY BAND 2GHz-8GHz |
where $\lambda$ is the wavelength corresponding to frequency $f$, $-j\frac{2}{\pi}$ accounts for the integration at the receiver side, $\sqrt{G}$ is the maximum antenna gain, $E_s$ terms account for the vector of the electric field that would be radiated, while $\varepsilon_f$ accounts for the usually negligible spurious field component. Then, recalling the results presented in [6], one could evaluate the received $i$-th path $r_i(t)$ as:

$$r_i(t) = F^{-1}[R(f)]$$

$$\approx F^{-1}[\frac{\lambda}{4\pi} G E_\theta(f, S_\theta^i, C_{\theta,f}^i(f)) E_\theta(f, S_\theta^i) S(f)]$$

(4)

where $F^{-1}[-\cdot]$ is the Inverse Fourier Transform operator. However, polarisation accuracy could impact the strength of the approximation in (4). Consequently, limiting spurious polarisation terms should be one important antenna design stake.

V. PROPOSED ESTIMATION ALGORITHM

The proposed algorithm relies on the capacity to predict waveforms corresponding to received echoes when a simple interaction occurs. It can follow an iterative process, as the prediction is expected to be refined at each step. This paper focuses on the first iteration process. The prediction of elementary waveforms enables the estimation of received echoes parameters ($S_\theta^i$ and $C_{\theta,f}^i(f)$) when they result from simple interactions (e.g. direct path, simple reflection on typical indoor materials). The algorithm also provides a simple reconstruction of the received echo. As direct path directions estimation is only a particular case of directions estimation (e.g. [6]), in the following a simple-bounce interaction will be considered. Moreover, a constant thickness $\delta$ of the material slab and a linear vertical antenna polarisation are assumed.

A. Probability Density Function of Incidence Angles

In a 2D context, if one considers uniform distributed transmitter and a receiver coordinates in an arbitrary four-walls room, the Probability Density Function (PDF) $f_{\theta,n}(\theta_m)$ of incidence angles to walls $\theta_m$ can be calculated. For every square room, $f_{\theta,n}(\theta_m)$ has been calculated as follows:

$$\begin{align*}
\gamma_{in} & = \frac{\lambda}{2} \tan \theta_m | + 2 |, \\
\gamma'(\frac{\tan \theta_m}{3} - \frac{1}{2} + \tan^2 \theta_m - \frac{1}{6} \tan \theta_m |)^2, & \quad 0 < \theta_m < \frac{\pi}{4} \\
\gamma''(\frac{1}{\tan \theta_m}), & \quad \frac{\pi}{4} < \theta_m < \frac{\pi}{2}
\end{align*}$$

(5)

where, for the sake of simplicity, $\gamma_{in} = 1 + \tan^2 \theta_m$. Figure 3 illustrates the PDF $f_{\theta,n}(\theta_m)$ for a square room. This latter PDF could be easily extended to describe the incidence angles PDF in a rectangular room which 2D dimensions respect a given ratio. In the latter typical indoor case, it is also expected to observe a non-uniform probability of incidence angles. This matter will be addressed in future works.

B. Expected Material Filtering Effect

As shown in (5), incidence angle in a 2D square indoor scenario are not equally probable and no more are the material filtering effects. Once the filtering effects $M_{*,*}(f, \theta_m)$ preliminary obtained, for instance by the in situ method discussed in Section III, they can be integrated over the incidence angle PDF $f_{\theta,n}(\theta_m)$, in order to obtain the expected filtering effect $M_{*,*}(f)$ for an arbitrary material as follows:

$$M_{*,*}(f) = \int_0^\pi M_{*,*}(f, \theta_m) f_{\theta,n}(\theta_m) d\theta_m$$

(6)

Therefore, integrating over the incidence angle provides a unique filtering model for each material, which is supposed to account for the more probable material behaviour. Note that marginalisation of the material filtering effects $M_{*,*}(f, \theta_m)$ could also be performed over other material parameters (e.g. slab thickness $\delta$).

C. Joint DoA, DoD and Material Estimation

In order to synthesise elementary energy normalised waveforms, the first step consists in choosing a set of $N_{dir}$ direction couples (e.g. $N_{dir} = 528$ for the presented simulations):

$$\left\{ \left( s_k(k), f_k(k) \right) \right\}_{k=1}^{N_{dir}}$$

(7)

Later on, $C^{(m)}(f)$ corresponds to the “wide-sense” echo channel matrix (3) for a simple-bounce interaction with the $m$-th characterised material:

$$C^{(m)}(f) = \left[ \begin{array}{c} M^{(m)}_{\theta,f} (f) \\ M^{(m)}_{\theta,f} (f) \end{array} \right]$$

where $C^{(m)}(f)$ has the same definition as in Section IV. Then, following the simplified model used in [6] for the local synthesised waveforms, the $k$-th elementary waveform for the simple-bounce interaction with the $m$-th characterised material in the frequency domain $R^{(m)}_k(f)$ is obtained as follows:

$$R^{(m)}_k(f) = \frac{j \lambda E_\theta(f, S_\theta^i, C_{\theta,f}^i(f)) E_\theta(f, S_\theta^i) S(f)}{\sqrt{C^{(m)}_k}}$$

(8)

Therefore, the set of elementary waveforms in the frequency domain is given by:

$$\left\{ \left\{ \hat{R}^{(m)}_k(f) \right\}_{k=1}^{N_{dir}} \right\}_{m=1}^{N_{mat}}$$

(9)

where $N_{mat}$ is the number of characterised materials. Note that the resulting waveforms are energy normalised.

The proposed algorithm performs the joint estimation of $S_\theta^i$ and $S_\theta^i$ through a simple cross-correlation method. It correlates an ideally well-isolated noised received path $r_i(t) + n(t)$ with each elementary waveform $\tilde{R}_k^{(m)}(f)$, obtaining $N_{dir} \times N_{mat}$ cross-correlation functions $C_k^{(m)}(\tau)$. Then, the maximum is extracted from each of the $N_{dir} \times N_{mat}$ cross-correlation functions with respect to time lag $\tau$, leading to the following maxima set:

$$\left\{ \max_{\tau} \left\{ \left| C_k^{(m)}(\tau) \right| \right\} \right\}_{k=1}^{N_{dir}} \left\{ \max_{m=1}^{N_{mat}} \right\}$$

(10)

Finally, the algorithm selects transmitting and receiving directions and the material corresponding to the maximum value among elements of cross-correlation maxima set (11). This enables to obtain $\hat{m}$, $\hat{S}_\theta^i$, $\hat{S}_\theta^i$ as an estimation of the material typecasting and of the transmitting and receiving directions ($S_\theta^i$, $S_\theta^i$) respectively.

Rigorously, the estimation of transmitting and receiving directions and material is performed according to the following rule:

$$\hat{m}, \hat{S}_\theta^i, \hat{S}_\theta^i = \arg \max_{k,m} \left\{ \max_{\tau} \left\{ \left| C_k^{(m)}(\tau) \right| \right\} \right\}$$

(11)

(12)
In the following, the indexes verifying (12) will be noted as \( \hat{m}, \hat{k}, \hat{\tau} \).

**D. Echo Reconstruction**

Once the echo parameters estimated, we can go ahead trying to reconstruct \( r_i(t) \) starting from the selected elementary waveform. Obviously, the perfect equalisation for the selected signal is provided by the following factor \( \alpha_{\theta_i^r, \varphi_i^r}(f) \):

\[
\alpha_{\theta_i^r, \varphi_i^r}(f) = \frac{R(f)(f)}{R_k^{(\hat{m})}(f)}
\]

A simple estimate \( \hat{\alpha}_{\theta_i^r, \varphi_i^r} \) for \( \alpha_{\theta_i^r, \varphi_i^r}(f) \) is available by the following identity:

\[
\hat{\alpha}_{\theta_i^r, \varphi_i^r} = \tilde{c}_{\hat{m}}^{(\hat{\tau})}(\hat{\tau})
\]

Note that this estimate is not frequency-dependent, but it only accounts for received signal energy (i.e. including losses of energy due to antennas and interaction). Then, \( \alpha_{\theta_i^r, \varphi_i^r} \) corresponds to an amplitude correction for \( R_k^{(\hat{m})}(f) \). Therefore, the \( i\)-th one-bounce received echo \( \hat{r}_i(t) \) can be estimated as:

\[
\hat{r}_i(t) = \mathcal{F}^{-1}[\hat{\alpha}_{\theta_i^r, \varphi_i^r} \cdot \tilde{R}_k^{(\hat{m})}(f)]
\]

Giving a frequency-dependent estimate of \( \alpha_{\theta_i^r, \varphi_i^r}(f) \) is obviously expected to provide a better echo estimation \( \hat{r}_i(t) \), as the mismatch between the material model described in V-B and the real filtering should be better compensated for. In a realistic multipath scenario, echo reconstruction could be exploited for path cleaning, which should improve estimation performances.

**VI. SIMULATION RESULTS**

**A. Introduction to Simulations**

The following simulations deal with a set of ideally well-isolated received waveforms. The latter is a sub-set of (10), made up of \( N_{test} \) synthesised waveforms for each characterised material. Consequently, \( N_{test} \) couples of transmitting and receiving directions (e.g. \( N_{test} = 66 \) is the arbitrary choice here) are simulated. Simulations take into account that the material filtering effect depends on the incidence angle \( \theta_{in} \) (e.g. [11]), but also that electromagnetic material parameters suffer from measurement uncertainty (see Table I). For each of the \( N_{test} \) received waveforms, performances are evaluated for a path with energy \( E_{pr} \), noised by an Additive White Gaussian Noise (AWGN) with power spectral density \( N_0/2 \), filtered in the signal band. Each estimation cycle leads to the estimated directions couple \( (\hat{\theta}_{ret}, \hat{\varphi}_{ret}) \) as well as to an estimated material indexed by \( \hat{m} \). The following performances are provided under the hypothesis of a 2D square indoor scenario, where only the azimuth angles for both transmitter and receiver are considered. In order to obtain an error metric for DoA and DoD estimation, the Euclidean error distance between the tested and the estimated directions is calculated. This computation respects the spherical nature of the metric space. A UWB Conical Monocile Antenna (CMA) (e.g. [6], [11]) and a synthesised antenna called Cardioid (e.g. [6]) have been tested. The latter has proved to give more directional diversity and then to improve the joint DoA-DoD estimation performance of the algorithm in the direct path case (e.g. [6]). Concerning the performance presentation, only the mean CDF and its confidence intervals are shown for each combination of antenna, transmission scenario and material. Each confidence interval is delimited by triangles, giving the lower (\(<\)) and upper (\(>\)) limits between which 90% of \( N_{test} \) couples CDFs are contained. This measures the spreading of the \( N_{test} \) couples CDFs with respect to the mean CDF. The performance analysis is completed by an evaluation of material identification success rates.

**B. Performance Analysis**

Figure 4, 5 and 6 present the DoA and DoD estimation performances using a CMA antenna for respectively a direct path (i.e. free space propagation), a reflection on a brick slab and a reflection on a wood slab. Figure 7, 8 and 9 show the respective performance curves, employing a Cardioid antenna. These figures report the performances when a correct (a) and a wrong (b) material typecasting have occurred. Taking as reference performances the case of direct path propagation (Figure 4 and 7), one can observe for each of the two antennas a performance degradation when a brick or a wood reflection take place. In (a) cases, this degradation is quasi-identical for the mean CDFs of the CMA and Cardioid antennas. In all these cases, the 40 dB transmission context seems to be the most affected by the loss of estimation accuracy, as it exhibits performances quite similar to the 20 dB transmission context. On the contrary, in references curves, the algorithm performs at 40 dB with a sharp gain with respect to 20 dB. It is interesting to note that the Cardioid antenna performs better that the CMA one in any tested case when the material recognition is successful.

Concerning the wrong material typecasting CDFs in (b), a generalised loss of estimation accuracy can be remarked, except for the case when the CMA antenna is tested with a direct path (Figure 4). In all other cases, a noticeable performance degradation occurs at 40 dB, while 20 and 0 dB CDFs are marginally concerned by this phenomenon. Particularly in the latter transmission context, one can substantially retains that performances do not change between a correct or a wrong material typecasting case.

Table II and Table III complete performance evaluation, presenting the material identification success rate for CMA and Cardioid antennas respectively. Their interpretation is not trivial, as the juxtaposition of the antenna and the material filtering apparently produces different error behaviours. For instance, when a direct path is received, the Cardioid antenna allows the algorithm to better identify that an air propagation has occurred, in comparison with CMA case (see the first columns of Table III and Table II). When an echo issued from a simple reflection on a brick slab is received, the Cardioid antenna performs a little worse than the CMA antenna, particularly at 20 and 40 dB, for which Cardioid performances are also affected by a larger dispersion. Finally, when a path has been reflected on a wood slab, Cardioid success rates become appreciably lower than CMA ones. In addition, they exhibit a very important dispersion. In this context, dispersion is due to different success rates with respect to each of the \( N_{test} \) DoA-DoD tested couples. Trying to extrapolate a tendency, one can say that a quasi-omnidirectional antenna like CMA apparently better isolates material filtering effect, allowing higher material identification success rates. On the contrary, using an antenna showing more directional diversity like the Cardioid, the signature of material filtering is less evident. Further antenna designs should try to find the best trade-off between giving high direction diversity and preserving sharp material filtering signature.
Therefore, these results tend to show that the algorithm can still be enhanced. Further studies would aim at limiting the dispersion of success rates and potentially improving both material recognition rates and DoA-DoD estimation error performance.

VII. CONCLUSION

This paper has presented a new simple algorithm for joint DoA-DoD estimation and material typecasting in an ordinary IR-UWB transmission context, for a direct path or simple-bounce reflections. The algorithm is mainly based on an accurate synthesis of expected received waveforms issued form such interactions. DoA-DoD estimation performances for a well-isolated received path have been provided, as well as success rates for three materials typecasting. A 2D square room constituted the simulated scenario.

Several enhancements, enabling to refine estimation and discard aberrations can be foreseen. Further studies may include several and more generic a priori statistical information, issued from geometric relationships and concerning the whole received signal. Indeed, since a sequence of paths generated by the same indoor environment carries more information than an isolated path, the extension of the discussed algorithm to multipath case may open the way to new techniques of indoor environment characterisation.

REFERENCES


\[
\begin{array}{c|c|c|c|c|c|c}
\hline
E_p/N_0 & \text{air} & \text{brick} & \text{wood} \\
\hline
0 \text{ dB} & 21\% \pm 4\% & 30\% \pm 1\% & 23\% \pm 1\% \\
20 \text{ dB} & 71\% \pm 14\% & 81\% \pm 4\% & 61\% \pm 10\% \\
40 \text{ dB} & 100\% & 86\% \pm 5\% & 95\% \pm 3\% \\
\hline
\end{array}
\]

\[
\begin{array}{c|c|c|c|c|c|c}
\hline
E_p/N_0 & \text{air} & \text{brick} & \text{wood} \\
\hline
0 \text{ dB} & 30\% \pm 5\% & 30\% \pm 1\% & 20\% \pm 1\% \\
20 \text{ dB} & 77\% \pm 13\% & 72\% \pm 8\% & 49\% \pm 11\% \\
40 \text{ dB} & 100\% & 80\% \pm 10\% & 74\% \pm 20\% \\
\hline
\end{array}
\]
Fig. 4. DoA-DoD error mean estimation CDF (solid line) and confidence interval (triangles), CMA antenna, (a) success and (b) failure case in material estimation (air)

Fig. 5. DoA-DoD error mean estimation CDF (solid line) and confidence interval (triangles), CMA antenna, (a) success and (b) failure case in material estimation (brick)

Fig. 6. DoA-DoD error mean estimation CDF (solid line) and confidence interval (triangles), CMA antenna, (a) success and (b) failure case in material estimation (wood)

Fig. 7. DoA-DoD error mean estimation CDF (solid line) and confidence interval (triangles), Cardioid antenna, (a) success and (b) failure case in material estimation (air)

Fig. 8. DoA-DoD error mean estimation CDF (solid line) and confidence interval (triangles), Cardioid antenna, (a) success and (b) failure case in material estimation (brick)

Fig. 9. DoA-DoD error mean estimation CDF (solid line) and confidence interval (triangles), Cardioid antenna, (a) success and (b) failure case in material estimation (wood)