Abstract—In order to provide reliable knowledge about the radio high resolution directional properties straight forward beam-forming has been used. Accurate measurement data based on an extreme size virtual antenna array (25x25x25=15625 elements) have been provided for an indoor scenario in both line of sight and non-line if sight. The results show that the distinct spikes observed in the power-delay profile are caused mainly by specular reflections. There is however also a significant contribution due to scattering caused by the many smaller objects of the environment.

I. INTRODUCTION

Radio channel measurements found in literature [1-3] which provide highly resolved directional characterization focus mainly on super resolution methods like SAGE and RIMAX [3]. These methods are based on the assumption that the radio channel may be decomposed by a set of discrete plane or spherical waves. It has been realized that this assumption may have limited validity [4-5]. Commonly the radio channel is modelled by one part which may be decomposed by a set of discrete waves and another diffuse part [3]. The diffuse part may not deterministically be decomposed by discrete waves. The problem with this approach is that the findings may be biased by the model assumptions. Moreover, the characteristics of the diffuse component are typically not modelled in detail. Motivated by these issues a measurement technique for providing unbiased highly resolved directional radio channel properties has been devised. In order to provide extreme antenna array size the virtual array method is used. This method is based on off-line analysis of multiple radio channel space samples the radio channel using a single antenna element.

II. MEASUREMENTS

The measurements were performed in an indoor office environment at 1.5 Tx-Rx distance in both LOS and NLOS conditions in the 57.68-59.68 GHz band (See Fig. 1). For the NLOS measurement a 2 x 1.2 m large whiteboard was placed in between the Tx and Rx antennas. The locations of Tx and Rx were the same in in both the LOS and the NLOS measurements.

A. Set-Up

The measurement setup was based on a vector network analyzer (VNA) and vertical dipole antennas in both the transmit (Tx) and the receive (Rx) ends. The RF signal of the VNA was in the range 2-4 GHz using 801 frequency samples. This signal was up-converted at the transmitter end and down-converted at the receiver end. Further the local oscillator was also distributed to both converters using optical fibers. In order to measure the channel directional properties with very high resolution the virtual antenna array method is used. By means of a 3D antenna positioning robot an extreme size virtual antenna array (25x25x25=15625 elements) was formed in the Tx end. The spatial sampling distance was 2 mm which corresponds to 0.4 wave lengths.

III. ANALYSIS

The analysis is based on straight forward beam-forming. However, as the data size is huge (801x25x25x25=12.5 mega-samples) this is a challenge. For this reason fast Fourier transformation (FFT) is used for transformation from space to wave vector domain and from frequency to delay domain. In both cases Hanning windowing is used for suppression of the side-lobes.
The FFT transformed data in the wave vector domain forms a three dimensional cube. However, the physical possible values lie on a sphere fulfilling
\[ |k| = \frac{2\pi}{\lambda} \]  
(1)
The directional power spectrum is obtained by interpolating desired azimuth and elevation angles on this sphere.

In Fig. 2 the full directional spectra for both the LOS and the NLOS measurement are shown. The LOS measurement is clearly dominated by the LOS paths. In contrast to the LOS measurement the NLOS measurement is much more spatially rich having around ten strong paths in different directions. The two measurements show however very similar directional characteristics except for the LOS path as shown in the right hand graphs of Fig. 2 for which the same power normalization is used. The channel seems to be composed of some distinct directions on top of a more smooth (diffuse) background.

A. Directional Spread

In this work the radio channel is subject for investigation of characteristics with respect to the full space angle. Common directional spread measures like ordinary r.m.s. azimuth and elevation spread are not adequate for the full space angle as they are both cyclic and non-Euclidian. In this study the following directional spread measure [6] is therefore used instead
\[
\sigma_{\text{dir}} = \frac{180}{\pi} \sqrt{\int \left| \hat{u} - \mu_n \right|^2 P(\hat{u}) d\Omega} , \quad \sigma_{\text{dir}} < 57.3^\circ
\]  
(2)
where \( \hat{u} \) is the direction unit vector. The spread may be determined for each of the three Euclidian components of \( \hat{u} \) (x,y,z) by
\[
[\sigma_{\text{dir}}]_n = \frac{180}{\pi} \sqrt{\int \left| \hat{u} - \mu_n \right|^2 P(\hat{u}) d\Omega} , \quad n = x,y,z .
\]  
(5)
For small values \( \sigma_{\text{dir}} \) corresponds to ordinary r.m.s. angle spread with \( [\sigma_{\text{dir}}]_x \) and \( [\sigma_{\text{dir}}]_y \), representing azimuth and \( [\sigma_{\text{dir}}]_z \) representing elevation. Further, there is an upper limit at 57.3°.

The directional spreads according to the definition above are shown in Fig. 3 versus propagation distance (delay times speed of light). It is clear that at delays where distinct spikes are observed in the power delay profile the angular spread is small. This is also observed in the corresponding power directional power distributions where essentially single spikes are observed suggesting specular type of scattering. For delays where the power delay profile show a more smooth exponentially decaying behaviour (between the spikes) the directional spread saturates at the upper limit. Here the directional power spectrum is considerable more spread (diffuse). Moreover, the directional spread with respect to the vertical z-axis and the y-axis decay faster than with respect to the x-axis. The x-dimension is the largest and the z-dimension the smallest of the room which may explain the different decay times.
B. Scattering Objects

In order to get some insight in which scattering objects of the environment and what scattering mechanisms are important, the measured directional power distributions have been put on top of a panoramic photograph taken from the Tx location. By investigating distributions for distinct delays different scattering objects are better discriminated.

In Fig. 4 are shown results for short delays for which first order scattering by objects in the vicinity of the antennas is expected. The LOS paths and diffracted paths by the upper and lower edges of the white-board are clearly observed. One interesting result is that diffraction is not only observed from the edges of the white-board, but also from the corners. In the LOS data the fluorescent lamps, objects on the table and the bookshelf on the right hand side seem to be significant scatterers.

In Fig. 5 the distributions two somewhat larger delays (pikes 8 and 9 in the power-propagation-distance plot in Fig. 4) corresponding to propagation distances 5 and 5.5 m are shown. Pike number 8 corresponds to a specular reflection off the window which is visible both in the LOS and the NLOS measurement. It is however obvious that the white-board blocks the paths (which are visible in the LOS data) which are scattered by objects on the table and the bookshelf. The same behavior can be observed for pike number 9 which is probably dominated by a ceiling-window reflection.

Fig. 3. Directional spread and angular spectra shown for delays indicated with numbers 1-5.
Fig. 4. Directional power distributions on top of panoramic photo from the Tx location. Distributions for short delays (1-7 marked in the lower right power-propagation-distance plot) of both the NLOS (left side) and the LOS (right side) measurement are shown. The blocking white-board is indicated in the NLOS graphs. The Rx antenna is marked with a red star.
Fig. 5. Same as Fig. 4 for the delays 8 and 9.
IV. CONCLUSIONS AND DISCUSSION

The main goal with this work is to improve the understanding of high resolution directional characteristics of radio wave propagation at millimetre wave frequencies. In order to avoid any bias and ambiguities (which may be the effect of super resolution methods like SAGE) straightforward high resolution beam-forming has been used. It is clear the distinct spikes in the power-delay profile are caused mainly by specular reflections. There is however a contribution due to scattering caused by the many smaller objects of the environment. This contribution is substantial, particularly in the NLOS measurement, pointing out the importance of modelling not only the large scale structure of a propagation environment in ray-tracing simulations.

Though the radio channel tends to be dominated by distinct specular components there is a significant underlying process which seems to provide a distribution which is spread out in direction. It is plausible that this process may be dominating in some environments in which large planar surfaces are rare or if the materials are rough at the particular radio frequency of interest. For this reason it is important that any proposed propagation model accounts also for the small scale characteristics of the environment.

The observed underlying process which provide propagation paths which are spread out in direction, and commonly referred to as diffuse in literature, seems to have continuous characteristics which are not specific for the link topology but for the environment. The characteristics are equal both for the LOS and the NLOS conditions. The azimuth spreads in y-axis direction and elevation decays with increasing delay. This is probably due to that the room dimensions are smaller in the y- and z-directions than in the x-direction. It is under investigation if it is possible to provide stochastic modelling of these distributions based on discrete sets paths. The results so far are promising.

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REFERENCES