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COMPARISON OF RAY TRACING SIMULATIONS AND MILLIMETER WAVE CHANNEL SOUNDING MEASUREMENTS

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ABSTRACT

Temporal-Angular channel sounding measurements of an indoor millimeter wave channel (60 GHz) is analyzed to determine the location of two dimensional clusters of arrivals at the receiver. The measurement scenarios are also emulated by a ray tracing tool. The results are similarly analyzed to verify possible agreements and determine the effectiveness of such tools in predicting cluster locations as well as ray arrival statistics within clusters in millimeter wave indoor channel.

I. INTRODUCTION

Millimeter wave technology is becoming increasingly important in many military and commercial applications. Remote sensing, radio astronomy, passive imaging, radar and high data rate communication are among these applications. To establish a high data rate communication link between two nodes, acceptable Signal to Noise Ratio (SNR) at the receiver is required. However, due to the high propagation path loss and signal attenuation that is associated with the millimeter wave signal, it is extremely valuable to have knowledge of how millimeter wave signals propagate in the environment. Such information along with appropriate smart antenna technology could enable a system to maximize the quality of the received signal and therefore, achieve higher throughput.

Indoor environments create challenging multipath propagation scenarios with significant time and angular spread. Joint temporal-angular clustering phenomenon have been observed at frequencies commonly used in wireless networks and 2-D statistical channel models have been proposed based on such phenomenon [1,2]. However, at millimeter wave frequencies, and to the best of our knowledge, very few reports have been made for such clustering behavior. The clustering of arrival rays can have a significant impact on channel capacity. Un-clustered models tend to overestimate the capacity if the multipath components are indeed clustered [10].

Considering angular (i.e. spatial) aspects of indoor channel is extremely important for systems employing multiple antennas. Millimeter wave wireless communication systems can greatly benefit from this knowledge as the physical size of such array antennas makes them amenable for practical implementation [3]. Knowledge of cluster locations is especially useful for such systems as it could be exploited by various spatial diversity combining or beamforming algorithms to enhance the system's performance.

The objective of this paper is to study the 2-D clustering phenomenon of millimeter wave propagation (60 GHz) at indoor environments and particularly verify the usefulness of ray-tracing to predict the cluster locations and some of their corresponding statistics.

The rest of this paper is organized as follows. Measurement setup and the corresponding environments will be described in section 2. In section 3, we will outline the simulation methodology. Results are provided in section 4 and finally, conclusions and future work will be discussed in section 5.

II. MEASUREMENT SETUP & ENVIRONMENTS

Field measurements have been conducted in [4] for both residential and office environments. The residential environment is a Line of Sight (LOS) scenario as shown in Fig. 1. The room where the measurements took place has no furniture and a LOS path exists between the transmitter and receiver. The floor, ceiling and the door are made of wood. The surface of the walls and ceiling is covered with wallpaper. There are also 3 large windows (plane glass) on the two intersecting walls. The height of the ceiling and the window is 2.47m and 2.11m respectively. The transmitter and receiver are located 1.1m above the floor.

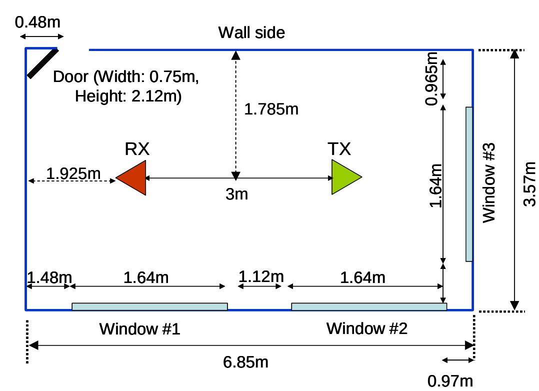


Figure 1: Layout of the residential room

The office environment is a Non-Line of Sight (NLOS) scenario as shown in Fig. 2. The room is made of steel wall, steel ceiling and steel floor. The floor and the ceiling are covered with carpet and plaster board, respectively. Glass windows exist on one side of the office.

To obtain the angular component of the received millimeter wave signal, a directional antenna with a narrow angular resolution of 15 degrees was used at the receiver. The antenna was positioned to face the transmitter initially and then mechanically rotated in steps of 5° until full 360° was obtained. A Vector Network Analyzer (VNA) was used as the signal generator and receiver. All measurements were conducted in the frequency domain using the VNA. The receiver antenna used in [4] is a pyramid horn antenna with

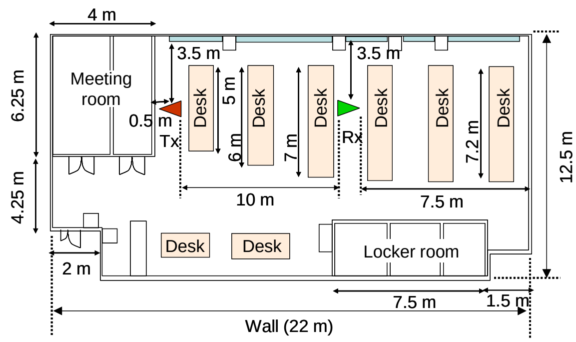
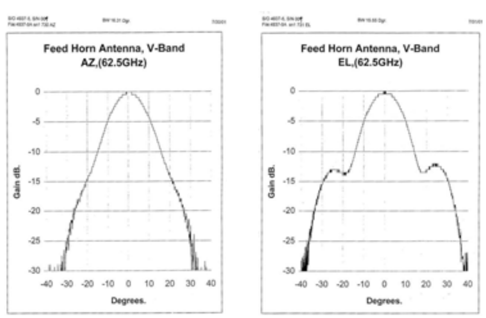


Figure 2: Layout of the office

22 dBi gain (see Fig. 3). The 3dB beamwidth of the antenna in horizontal direction is 15°. At the transmitter, in addition to an omni-directional antenna, various pyramid horn antennas with 10, 16 and 22 dBi gains were used for the measurements. These are equivalent to 60°, 30°, and 15° 3-dB beamwidths. Calibration was performed in an anechoic chamber with one meter reference distance to remove the antenna effects.

During the measurements, the VNA was set to transmit 401 (801 for the office) continuous waves tones uniformly distributed over the frequency range 61-64 GHz which results in frequency steps of 7.5 MHz (3.75 MHz for the office). This frequency resolution gives maximum excess delay of about 133.3 ns (266.7 ns for the office). The 3 GHz bandwidth results in a temporal resolution of 0.25 ns.

An example of the raw data produced by this setup is shown in Fig. 4. This is a 3-D plot of the received power with respect to time and azimuth angle. The frequency band for the experiment was 61-64 GHz. In order to reduce the effect of non-stationarity in the channel and improve the signal-to-noise ratio, 128 measurements were taken for each angle and the results were averaged.



(a) (b)

Figure 3: Sample pyramidal horn antenna pattern at the receiver (a) H-plane (b) E-plane

III. SIMULATION METHODOLOGY

In this paper, we have used WiSE to emulate the millimeter wave channel sounding experiment described in the previous section. Wireless System Engineering (WiSE) is a sophisticated ray-tracing tool that has been developed and verified by Bell Laboratories [5]. The main difficulty in simulating an indoor RF channel is the strong dependence of the received signal on the layout of the building and all other obstacles inside (i.e. multipath channel). In particular, all walls, windows and other objects that affect the propagation of RF waves will directly impact the signal strength and more importantly the directions from which RF signal is received. Using ray-tracing will give us the opportunity to mimic the conditions of an indoor channel to the extend possible and at the same time provide a geometric interpretation of the results

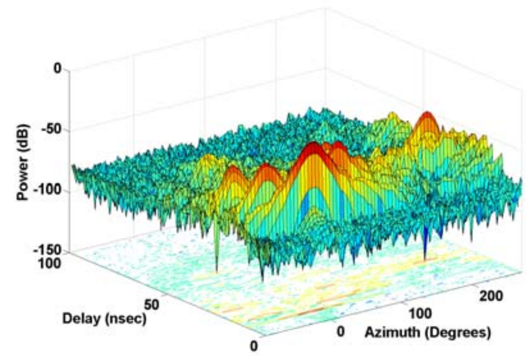


Figure 4: Example of raw data produced by the measurement

The parameters of the simulation were set to closely match both the measurement environments and the process. The precise geometry of both residential and office environment were entered into the WiSE building modeler and in this way, the 3-D layouts of the measurement environments were constructed as seen in Figures 5 and 6. Here, we have only focused on the room where the measurement was conducted and ignored the rest of the building layout. The assumption is that the signals that leave the room and bounce back inside are too weak to be considered. This is a valid assumption due to the usually high attenuation of the walls for millimeter wave signals.

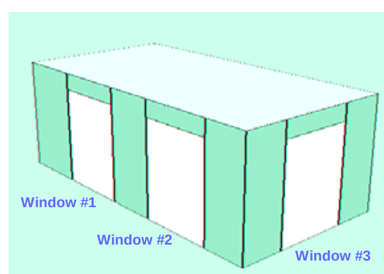


Figure 5: Simulated residential layout

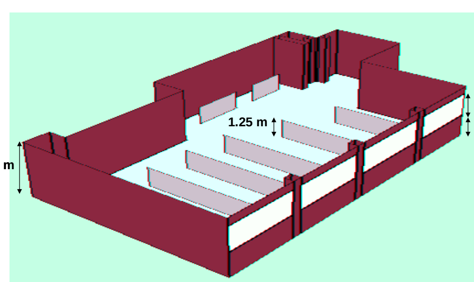


Figure 6: Simulated office layout

To reduce the complexity of the model representing the office environment, each row of tables with desktop computers has been replaced by a wall-type obstacle of appropriate height and attenuation. This was done to re-create the NLOS condition between the receiver and transmitter. The radio characteristics of the walls (i.e. dielectric properties) were also chosen to approximately match the construction materials of all objects in the measurement environments. 3-D Antenna pattern files were also created to match the gain pattern of all the antennas used in the experiment.

Finally, the measurement process was also re-created in WiSE by rotating the directional antenna at the receiver with 5° steps until full 360° coverage was obtained. For each direction of the receiver antenna, the frequency range of 61-64 GHz was swept by a continuous tone in steps of 7.5.MHz (3.75 MHz for the office) in order to generate the transfer function of the indoor channel. The complex two-dimensional impulse response of the channel was produced by using the same windowing function as in the VNA and then taking the inverse Fourier Transform of the data.

IV. CLUSTER IDENTIFICATION METHODOLOGY

Kernel Density Estimation (KDE) is a nonparametric Probability Density Function (PDF) estimation approach that can be applied to a given set of measured data [6,7]. KDE is a robust, simple and convenient method to estimate the PDF of a random variable given its sample realization. We have used the two dimensional version of this technique in order to estimate the temporal-angular distribution function of the ray arrivals at the receiver. Having this distribution function and using an appropriate threshold, all 2-D clusters (i.e. temporal-angular) can be easily identified.

Let (t,θ) denote the random variable that represents the time and angle of arrival of a ray at the receiver. If $f(t,\theta)$ is the 2-D PDF of these arrivals, then the multivariate kernel density estimate of this function (i.e. $\hat{f}(t,\theta)$) can be expressed by:

$$\hat{f}(t,\theta)=\frac{1}{Nh_t h_\theta}\sum_{i=1}^{N}K\left(\frac{(t,\theta)-(t_i,\theta_i)}{h_t h_\theta}\right)$$

Where h_t and h_θ are the temporal and angular bandwidths respectively; $K(x,y)$ is the kernel function, (t_i,θ_i) $i=1,2,....,N$ are sample realizations of the random variable (t,θ) (i.e. arrivals) with the unknown density function $f(t,\theta)$ and N is the number of samples. Here, we have two sets of samples which have been obtained through measurement and simulation.

The kernel function is often selected to be a PDF that is symmetric both in time and angle. In our study, we have used the 2-D *Normal* distribution to be the kernel function as written below:

$$K(x,y)=\frac{1}{2\pi}\exp\left(-\frac{1}{2}\left\|(x,y)\right\|^2\right)$$

Therefore, the kernel density estimate of $f(t,a)$ will be:

$$\hat{f}(t,\theta)=\frac{1}{Nh_t h_\theta}\sum_{i=1}^{N}\frac{1}{2\pi}\exp\left(\frac{-\left\|(t,\theta)-(t_i,\theta_i)\right\|^2}{2h_t h_\theta}\right)$$

Using this approach, we have processed the time-angle impulse response of the channel obtained through both measurement and simulation. In the next section, we provide the results of this analysis and discuss their geometric relevance.

V. RESULTS

One dimensional temporal clustering phenomenon has been observed in indoor channels and wideband statistical channel models have been proposed accordingly [8]. Here, we also observe that arrivals come in few groups (i.e. clusters) scattered in different coordinates throughout the time-angle space. These 2-D clusters are identified by using the KDE and an appropriate threshold representing the noise floor of the receiver. Figures 7 and 8 display the clusters obtained by processing the measurement and simulation data when an omni-directional antenna is used in the residential environment. In general, strong resemblance in cluster shape and location is observed between the results derived from measurement and simulation.

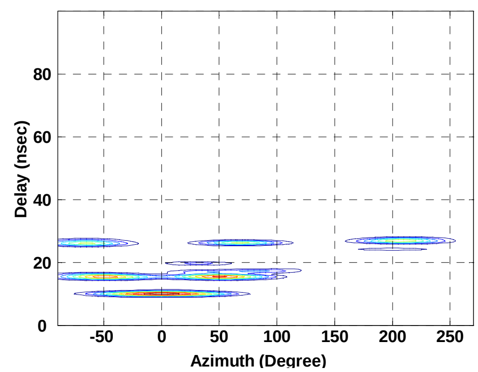


Figure 7: 2-D clusters identified from the measurement data (Residential LOS environment)

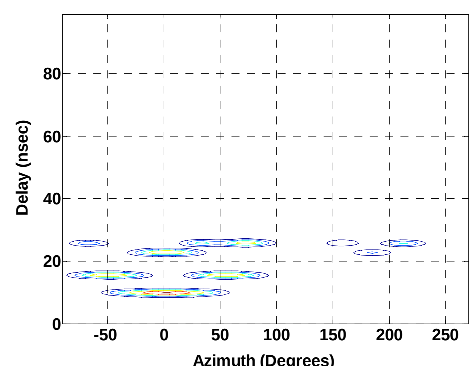


Figure 8: 2-D clusters identified from the simulation data (Residential LOS environment)

A comprehensive geometric interpretation of these results can be provided by considering the main paths that the RF signal travels between the transmitter and receiver. The ray-tracing simulation displays 9 clusters of arrivals at the receiver. The coordinate of these clusters are listed in Table 1. Each cluster formation is the result of a unique path between the transmitter and receiver. These paths which include direct LOS and various single-reflected and double reflected signals have been graphically identified in Figure 9.

A total of 9 clusters are observed in the simulated data. Clusters 1 through 8 are also present in the measurement data with the exception that the clusters 6 and 7 have been merged and form a bigger cluster. Cluster number 8 which is the result of the reflection from the wall behind the receiver does also exist in the measured data. However, cluster number 9 which represents the reflection from the transmitter's back wall is not present in the measurement data. This is due to the fact that the equipment at the transmitter (covered by electromagnetic absorbers) blocks the path of the reflected signal from the back-wall. Such equipment does not physically exist in the simulation; and therefore, this cluster forms as a result of the reflection from the wall behind the transmitter.

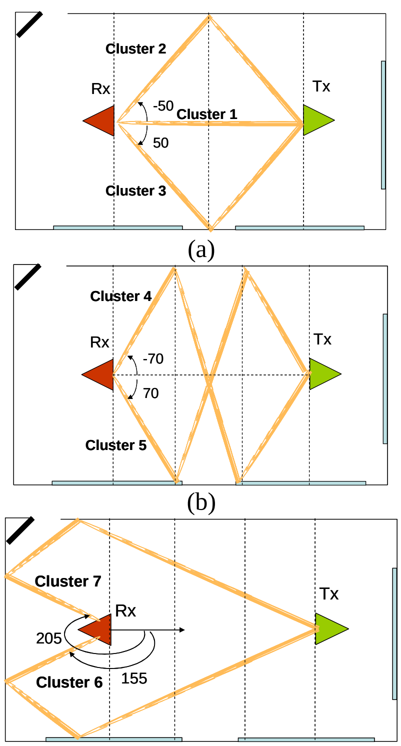


Figure 9: Paths resulting to clusters (a) 1,2,3 (b) 4,5 & (c) 6,7

The plots indicating the clusters for the case when directional antennas with different beamwidths were used at the transmitter also showed strong resemblance between the simulated and measured data. These plots have been omitted for brevity.

We have also investigated the distribution of rays within a cluster in both measured and simulated data. Two types of distribution can be obtained: relative ray angle and time of arrival. The term relative indicates the angular or temporal displacement with respect to the cluster coordinate. Figure 10 displays the distribution of the relative angle of arrivals for both measured and simulated data. Similarly, Figure 11 shows the distribution of the relative time of arrivals for both measured and simulated data. A close match for ray distribution is observed in both figures.

Table 1: Matched Cluster center's coordinates

Cluster #	Cluster Arrival Angel (Deg)	Cluster Arrival Time (nsec)	Exist in Experiment	Exist in Simulation
1	0	10	Yes	Yes
2	-50	15.5	Yes	Yes
3	50	15.5	Yes	Yes
4	-70	25.75	Yes	Yes
5	70	25.75	Yes	Yes
6,7	155, 205	25.75	Yes (merged)	Yes
8	180	22.75	Yes	Yes
9	0	22.75	No	Yes

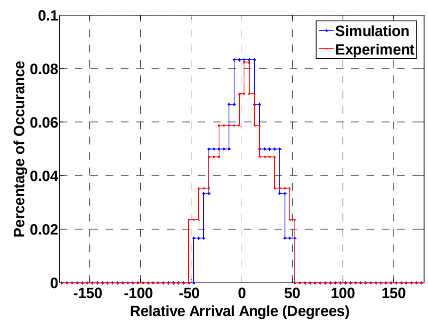


Figure 10: Distribution of the relative angle of arrivals

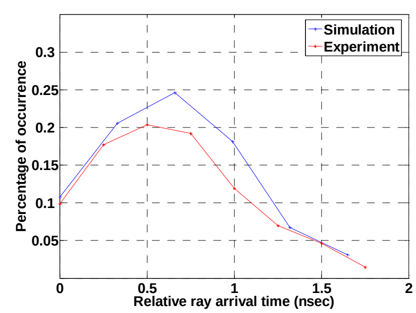


Figure 11: Distribution of the relative time of arrivals

The data from the NLOS office environment was also processed for cluster identification. Figures 12 and 13 demonstrate the achieved clusters for the measured and simulated data. The scattering effect of the furniture and other office equipment in this environment, which cannot be accurately modeled by the ray-tracing tool, causes some differences in the shape and in some cases location of the clusters. Again, in general, 4 clusters are observed that are the results of the LOS and single-reflected paths. The clusters due to the reflection from the wall with glass windows and the direct path between the transmitter and receiver have merged and form a bigger cluster in the measured data. As mentioned before, this is caused by the scattering effect that all the furniture in the office generates. The other two clusters occur because of the single reflection from the wall with no windows and the wall behind the receiver. Looking at the time coordinate of the latter cluster, a mismatch is observed between the result of the simulation and measurement. A physical explanation for this discrepancy can be given by noticing the velocity change of RF waves as it goes through different materials that exist on its path between the transmitter and receiver [9]. In general, the exact coordinate, shape and size of the clusters depends on the details of the propagation environments; however, as seen in this study, the locations of the main clusters (i.e. high density) can be reasonably approximated by the ray-tracing tool.

The clusters in figures 12 and 13 are due to the use of an omni-directional antenna at the transmitter. If a directional antenna is used instead, the resemblance of cluster's shape and location obtained through measurement and simulation is increased. The RF energy transmission in that case is more focused toward certain direction and therefore, the impact of the scattering phenomenon on the ray arrivals is reduced. Further results demonstrating this point have been omitted for brevity.

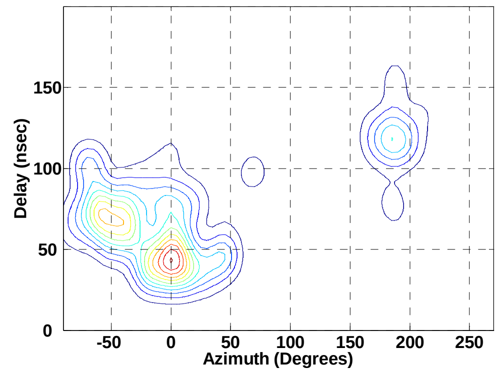


Figure 12: 2-D clusters identified from the experiment (Office NLOS environment, Omni TX)

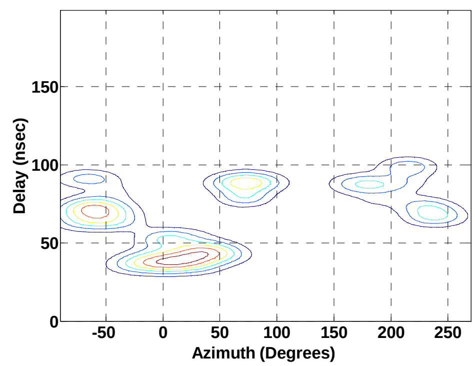


Figure 13: 2-D clusters identified from the simulation (Office NLOS environment, Omni TX)

VI. CONCLUSION

In this paper we have captured the influence of geometry on the clustering phenomenon of a millimeter wave channel through the use of a ray tracing tool. We have shown that for indoor environments ray-tracing could be an effective tool to predict the location of the clusters around a receiver.

For scatter-free environments and LOS scenarios ray-tracing seems to provide a good match for cluster location and intra-cluster arrival statistics. For environments with heavy scattering, NLOS scenarios and directional antennas at the receiver and transmitter, ray-tracing prediction of the clusters still seems to be reasonably close to the result of empirical measurement. More studies are required to further validate the above assertions and investigate further details.

Knowledge of the spatial distribution of RF energy around the receiver in conjunction with array antennas and appropriate signal processing algorithms can lead to systems that provide superior performance by taking advantage of clusters location and their corresponding characteristics. Also, statistical models that contain both the angular and temporal components of the millimeter wave indoor channel are needed to ensure more efficient design of millimeter wave systems.

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