LOS and NLOS Millimeter-wave MIMO Measurements at 24 GHz in a Hallway Environment

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***Abstract*—Indoor $4{\times}4$ MIMO measurements in a hallway environment at 24 GHz for both LOS and non-LOS (NLOS) conditions are presented. Initial characterizations of the measured channels include receive power, delay spread, and wideband channel capacity.**

I. Introduction

There is growing interest in the use of mm-wave communications, due to the large potential bandwidth coupled with the decreasing cost of mm-wave devices. The goal of this work is to characterize multiple-input multiple-output (MIMO) channels in the 24 GHz band, which exhibit lower loss than 60 GHz and therefore less reliance on line-of-sight (LOS) conditions. Low-cost multi-channel devices are also becoming readily available due to the 24 GHz automotive radar market.

II. Measurement Setup

The prototype 24 GHz measurement system is basically equivalent to that shown in [1], which operates like an FMCW radar. A 500 MHz chirp at 24 GHz is generated at the receive (Rx) node and remoted to the transmit (Tx) node using an RF over fiber link. The signal from receive antennas is mixed down locally with the chirp and sampled with a slow (1 MS/s) A/D converter with high resolution (16-bits).

Enhancements were made to the system described in [1]: A new Tx board was developed with better isolation between the channels, allowing full $4{\times}4$ MIMO measurements, whereas only $3{\times}4$ measurements were possible in [1]. Better signal integrity was obtained by removing baseband gain and setting Rx RF gain to 50 dB. Finally, channel matrices were calibrated to remove the effect of unequal channel gain, thus providing a more system-independent measure of channel capacity.

The Tx and Rx antennas that were used in this study are uni-directional ground-backed tapered slots, providing 3 dB gain and -10 dB reflection coefficient over the band of interest. Four-element uniform linear arrays (ULAs) were used with an inter-element spacing of 0.45λ at 24 GHz.

III. Measured Results

Measurements were performed on the fourth floor of the Clyde Engineering building on the BYU campus as shown in Fig. 1. In the main set of measurements, the transmitter is placed at Location **TxA** and the receiver is moved along a path at 0.6 m increments in the hallway indicated with a line labeled **RxA**. Key Rx positions for this measurement are labeled 1-6. A fixed measurement from **TxB** to **RxB** was performed to test penetration from the hallway to a room. Arrows on the map show the direction of peak antenna gain for the Tx/Rx arrays.

At each measurement location 300 channel snapshots were acquired, corresponding to an acquisition time of 12 seconds. Since Tx and Rx did not move during the snapshots, and measurements were taken during low activity, channels are reasonably static over that time.

Fig. 2 plots the power-delay profile averaged across antennas for Locations 1 and 2 of the TxA/RxA case, where raw de-chirped receive data is Blackman windowed and fast-Fourier transformed to obtain delay-domain data. Fig. 2(a) and (b) show the result of coherent averaging over 300 snapshots, which provides a significant improvement in dynamic range compared to that of a single snapshot, as suggested by the corresponding power-averaged data in Fig. 2(c) and (d).

Coherent averaging over 300 snapshots was used to improve the dynamic range needed for receive power and delay spread results. However, single channel snapshots were used for capacity computations to avoid changing the sensitive channel structure. Any averaging of capacity was thus performed *after* computing capacity of individual channel snapshots.

Fig. 3(a) plots the root mean square (rms) delay spread (τ) as a function of distance for the TxA/RxA case, where the key points along the RxA path are noted in the plot. To avoid including noise in the computation, a threshold 10 dB above the observed noise floor is computed and only delay bins above that threshold are considered. Also note that these results are averaged over all Tx/Rx combinations and smoothed over RxA location with a 1.5 m window. As expected, τ increases with increasing Tx-Rx separation when moving from Location 1 to 2. Peak delay spread is seen near the corner at Location 2, which indicates high reflections and multipath at that position. It is somewhat surprising that the delay spread drops sharply at Location 3, indicating that less multipath is able to propagate around the corner.

Relative receive signal power is shown in Fig. 3(b),

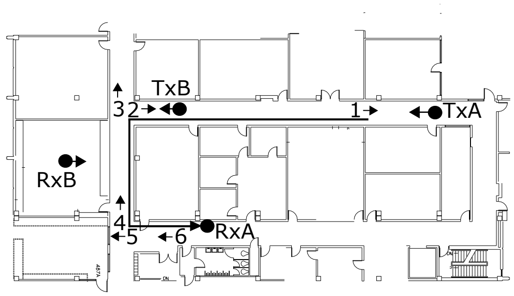

Fig. 1. Measurements were taken with Tx at **TxA** and Rx along the **RxA** path, or at the single points **TxB/RxB**. Arrows indicate orientation of the Tx/Rx ULAs.

which is obtained by integrating receive power lying above the 10 dB threshold described previously for rms delay spread. Note that transmit power can be varied, which is removed from these results. The plot shows expected decreasing power as Tx-Rx separation increases. Also note that there are significant drops in receive power moving around corners at Locations 3 and 5. It is interesting that signal power and multipath richness (delay spread) are not necessarily complementary at 24 GHz as is often seen at lower microwave (< 6 GHz) communications bands.

Fig. 4(a) plots the uninformed Tx capacity for the 4×4 MIMO system as Rx moves from Location 1 to 4 for an assumed SNR of 10 dB. Capacity is computed separately for each channel snapshot and then averaged over the 300 snapshots. The true SNR of the measurements was estimated by integrating the power delay profile lying above a 3 dB threshold over the noise and dividing by the noise level integrated over the same interval. This estimated SNR is shown in Fig. 4(b), indicating that the true SNR was never less than the assumed SNR of 10 dB. The results indicate that the multipath present in the channel usually provides a significant increase in capacity over the case of pure LOS. Although not plotted, capacity for the Location pair TxB/RxB is 10.8 bits/s/Hz, which is close to the i.i.d. channel capacity for 10 dB SNR.

IV. Conclusion

This paper has presented 4×4 MIMO measurements at 24 GHz in a hallway environment. The measurements indicate that although significant drops are seen in the signal power when moving around corners, NLOS communications are still likely to be possible. Further, the results indicate that sufficient multipath is available to provide capacity near that of an i.i.d. channel for the 4×4 system with 10 dB SNR.

References

[1] R. Mehmood, J. W. Wallace, and M. A. Jensen, "24 GHz indoor MIMO channel measurements," in *IEEE Antennas and Propag. Soc. Intl. Symp.*, Vancouver, Canada, July 19-24, 2015, pp. 1786–1787.

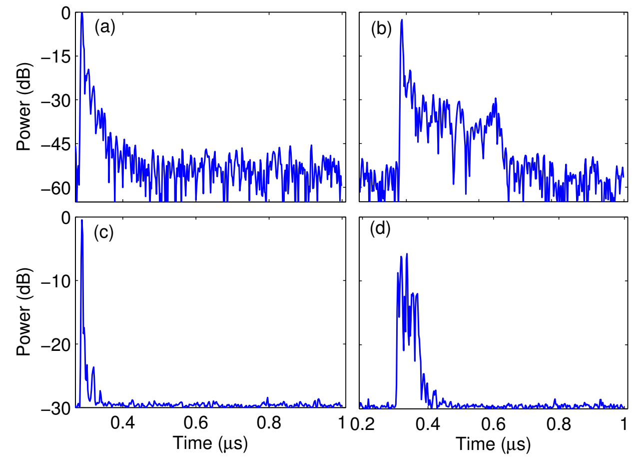

Fig. 2. Power-delay profiles for coherent averaging at (a) TxA/RxA Loc. 1, (b) TxA/RxA Loc. 2, and power averaging at (c) TxA/RxA Loc. 1, (b) TxB/RxB.

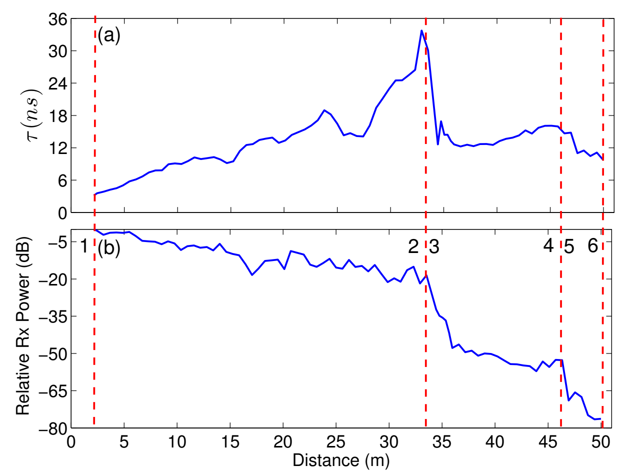

Fig. 3. Delay spread (a) and receive power (b) versus Tx-Rx separation.

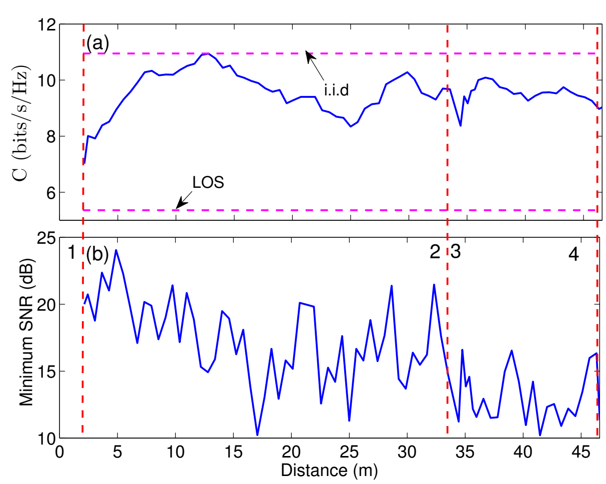

Fig. 4. (a) MIMO Capacity as receiver moves from Location 1 to 4. (b) Estimated SNR of measured channels.