Analog Radio-Over-Fiber Supported Increased RAU Spacing for 60 GHz Distributed MIMO Employing Spatial Diversity and Multiplexing

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***Abstract*—The improvements in coverage through spatial diversity and increased data rates through spatial multiplexing using a distributed multiple-input multiple-output (MIMO) system are important targets for future wireless communications. Here, the appropriate separation of remote antenna units (RAUs) at several user locations in a millimeter-wave system is demonstrated. An analog radio-over-fiber (RoF) fronthaul is used to achieve flexible spacing of distributed RAUs and transports two Gb/s data streams over 2.2 km of fiber and up to 8 m of 60 GHz wireless transmission distance. A performance comparison is performed between single-input single-output and MIMO operation using different antenna spacing and transmission distance. Results show that the wider RAU spacing enabled by the RoF distribution provides improved results at longer distances, for both spatial diversity and for spatial multiplexing. Verification of a method for measuring each channel coefficient individually and using subsequent MIMO processing on these coefficients enables an extension to the results showing the feasibility of 30 m indoor transmission.**

***Index Terms*—Millimeter wave (mmW), multiple-input multiple-output (MIMO), radio-over-fiber (RoF).**

I. Introduction

THE advancements in mobile communications and demands for higher data rates has led to increased interest in the use of millimeter-wave (mmW) frequencies due to the large available bandwidth, especially in the unlicensed band around 57–66 GHz, and in the likely future 5G band extending up to 71 GHz [1], [2]. However, there are associated technical challenges, such as: (1) high path loss which, even in Line-of-Sight (LOS) scenarios, limits coverage distances; (2) the need for an ultra-high capacity fronthaul or fiber distribution network in cases where Centralized-Radio Access Network (C-RAN) or distributed antenna system (DAS) deployments are favored [3]; and (3) the more costly, and generally less capable, integrated hardware compared to lower frequencies [4].

Multiple-input multiple-output (MIMO) techniques provide enhanced coverage through spatial diversity, and high aggregate data rates through spatial multiplexing, as compared to single-input single-output (SISO) transmission [5], [6]. Spatial diversity can be achieved using Alamouti Space-Time Block Coding (STBC) which is a prominent transmit diversity technique using a set of orthogonal codes for the transmission, with the received signals then combined coherently to provide an improvement in the performance [7]. Multiplexing gain through MIMO is achieved when individual data streams are combined in moderate SNR conditions, where transmission of a single higher data-rate data signal over large bandwidth is not possible [8]. In a system with distributed radio units, the MIMO processing of the distributed wireless signals is referred to as Co-ordinated Multipoint (CoMP) transmission, which has been demonstrated in systems using Radio-over-Fiber (RoF) links at lower frequencies [9]. At mmW frequencies, it has been shown that MIMO gain can be achieved in LOS operation [10]. Recently, a few groups have demonstrated 60 GHz LOS MIMO with single RAU operation [11]–[13] and CoMP using a two RAU configuration [14]. But the analysis on Distributed MIMO (or CoMP) transmission to exploit *spatial diversity* and *spatial multiplexing* at *multiple user locations* remains to be performed, to understand the performance enhancement in terms of coverage and data rate improvements that may be gained from such systems. The deployment of such mmW distributed MIMO systems will require RAUs to be placed at appropriate distances in order to provide coverage at various user locations, and high bit-rate services. RoF transport provides a robust, low loss, and flexible means for deploying the fronthaul connecting the RAUs to a centralized unit [15], [16], enabling the more widely spaced RAUs.

For example, Fig. 1 shows a mmW transmission system where N RAUs are connected to a Central Unit (CU) through a RoF fronthaul, as might be expected in shopping malls, outdoor downtown areas, etc. A user is served with a Gb/s mmW link from a single RAU (RAU1) with a limited coverage region through a directed beam. When the user moves, the SNR, and hence performance, degrades considerably at the boundaries of

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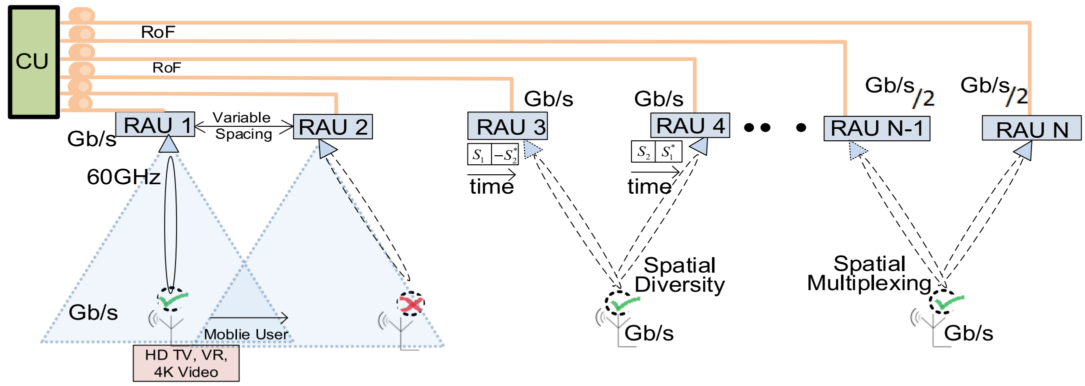

Fig. 1. Coordinated access scenario through multiple RAUs at mmW for Mobile User.

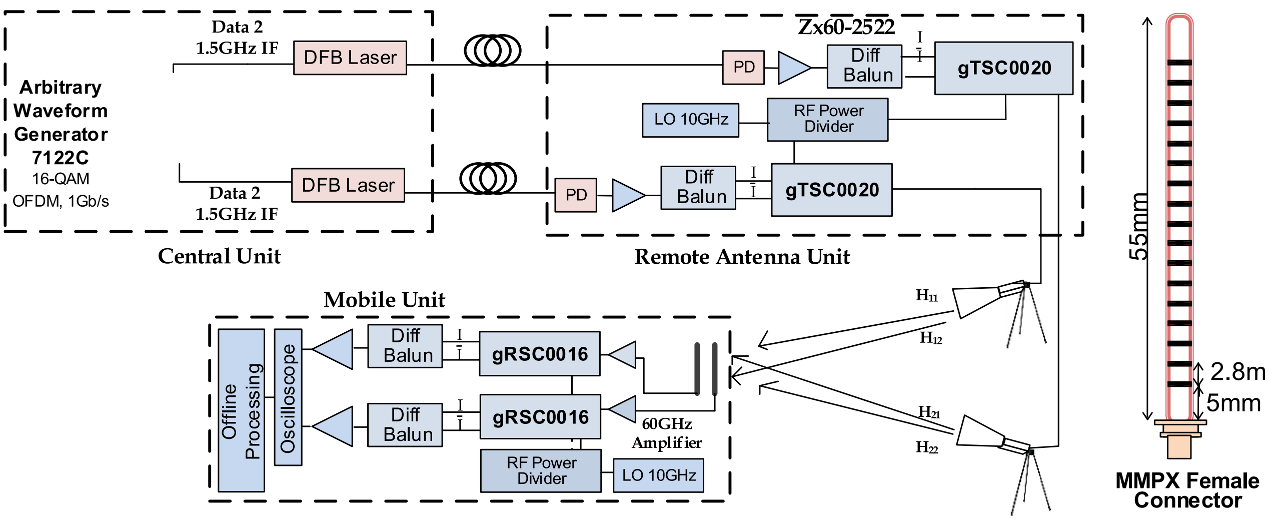

Fig. 2. System architecture for the RoF transported 60 GHz Distributed MIMO transmission (left) 15 dBi Gain Quasi-discoidal slot-array antenna (right).

the coverage region. The degradation of performance can even result in loss of link connection at the edges of the RAU's coverage span (as with RAU2). Coordinated transmission from two RAUs (RAU3 and RAU4) can provide a solution in this case, resulting in enhancement of performance and link quality through STBC encoded data streams (transmitting symbols S_1, S_2 over the first symbol period and complex conjugate symbols $-S_2{}^*$, $S_1{}^*$ over the second symbol duration). For spatial multiplexing, in cases where moderate SNR is available from more than one RAU, multiple Gb/s data streams can be combined to obtain very high aggregate data rate. The integration of RoF transport and mmW MIMO is a promising solution to transport large bandwidth signals from the CU.

In this paper, a complete system combining RoF transport, integrated mmW components and 60 GHz MIMO is presented, with experimental demonstration of improvement using Alamouti STBC and Zero-Forcing (ZF) algorithms. Also, for the Orthogonal Frequency Division Multiplexing OFDM-RoF transported system, the effect of transmit antenna separation (enabled by the separated RAUs) and the extent of the improvement achieved through mmW MIMO compared to SISO is investigated. This work extends our previous realization of 2×2 MIMO where performance projections were made using measurements from a single transmit antenna [17] and were validated for 1.5 m wireless distance through real MIMO [18]. Here we present the first demonstration of mmW MIMO exploiting spatial diversity *and* spatial multiplexing at wireless distances of the order of what might be expected in real, future mm-wave systems (up to 8 m), with projections to much longer distances (up to 30 m) using further validation of single antenna measurements. The experimental arrangement is explained in Section II while results for the two MIMO algorithms applied to different RAU spacings and user positions are discussed in Section III. In Section IV, the processing using individual channel coefficient measurements and comparison with 2×2 MIMO is described. Conclusions follow in Section V.

II. Experimental Methodology

A. *Experimental Setup for RoF-OFDM Based 60 GHz Distributed MIMO Transmission*

Fig. 2 shows the experimental setup where two 16-Quadrature Amplitude Modulation (QAM) OFDM signals at an IF of 1.5 GHz are generated from separate channels of a Tektronix

7122C Arbitrary Waveform Generator (AWG). The OFDM (IFFT size of 512, Cyclic Prefix 1/8, 16-QAM modulation) baseband symbols were generated in MATLAB/Simulink and uploaded to the AWG which creates the IF waveform signals. These directly modulate a pair of similar Emcore 1935 F Distributed Feedback (DFB) laser diodes having 3 dBm output optical power. The input drive power level to the DFB of each data modulated IF signal was set to 0 dBm to avoid significant laser nonlinear effects.

The optical signals were each transmitted over 2.2 km length single mode fibers (SMF) from the CU to the RAUs. Each RAU includes a 2.5 GHz bandwidth photodiode to retrieve the data modulated IF signal. A 21 dB gain RF amplifier is used to compensate for the loss of the RoF link. The IF signal is up-converted to mmW frequency using an integrated transmitter (Gotmic gTSC0020) after being passed through a differential balun and DC blocker (8.5 dB loss). The integrated transmitter gTSC0020 includes an upconverter, which converts the IF signal to a 61.5 GHz signal, and an amplifier. It also includes a $\times 6$ multiplier which means it is driven at around 10 GHz, with an LO power of 10 dBm. The 61.5 GHz data modulated signal is transmitted using a 20 dBi gain V-band horn antenna. At the receiver end, a wideband, distributed-slot antenna with 15 dBi gain is used [19]. The developed pluggable antenna, shown in Fig. 2 (right), is a low-cost, small size design and has a quasi-discoidal radiation pattern which permits reception from a wide range of angles compared to the horn antennas. The received signal is amplified by a V-band amplifier with 30 dB gain and is down-converted to IF using a (Gotmic gRSC0016) integrated receiver, which also requires an LO power of 10 dBm at 10 GHz. The IF signal at 1.5 GHz is amplified by the integrated receiver and is then passed through DC blockers, RF Balun and amplified by a 15 dB gain broadband amplifier. The output of this IF amplifier is captured using a Tektronix Digital Oscilloscope DPO72304DX for offline processing. The offline processing includes manual time alignment using a MATLAB script, carrier synchronization and channel estimation. OFDM preambles (which are known to both transmitter and receiver) transmitted with the data symbols are used to perform Least Square (LS) estimation. The singular values of the channel matrix H for the two MIMO channels are obtained from the Singular Value Decomposition (SVD) and are used for MIMO processing using the STBC or ZF algorithms.

QAM Demodulation for EVM Analysis.

B. Geometrical Arrangement of RAUs for Measurements Using Spatial Diversity and Spatial Multiplexing

To perform the analysis of the coverage of the 60 GHz transmission system, seven user locations for the receiver were selected over a span of 2.5 m as shown in Fig. 3. At the location M, which is the mid-point on the span, the receiver is at 0° with respect to the normal from the SISO transmitter. To evaluate the improvement in performance through MIMO, SISO transmission measurements were performed as a baseline.

The SISO measurements were taken by capturing the data at each user location by pointing the horn antenna (placed on a small tripod) towards the receiver unit. MIMO experiments

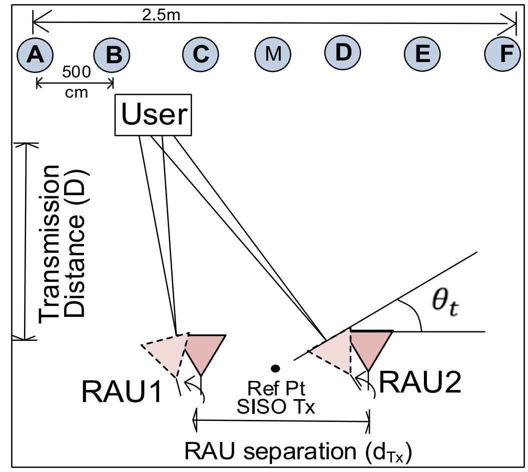

Fig. 3. Geometrical Orientation of the Antennas and User Locations.

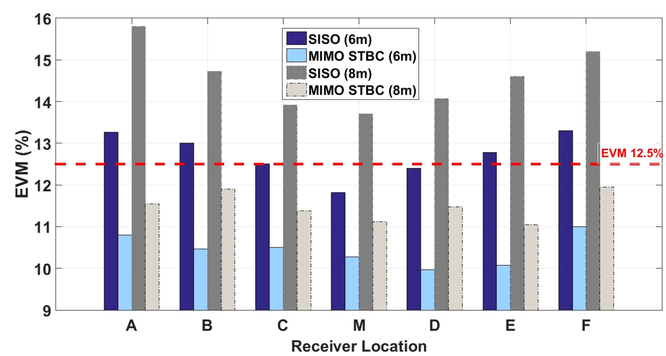

Fig. 4. EVM comparison of SISO (1 Gb/s) versus STBC MIMO processing (1 Gb/s) for 6 m (RAU spacing: 60 cm) and 8 m (RAU spacing: 120 cm).

were performed by tilting the two transmit antennas towards the user locations to ensure the reception of a LOS component. The total transmit power was kept the same for SISO and MIMO. The EVM limit of 12.5% for Long-Term Evolution (LTE) standard for 16-QAM is used to benchmark performance. Although this requirement is for the transmitter, it has been considered here for the end-to-end system, for example, to allow for the addition of a Power Amplifier (PA) which is often a significant contributor to distortion. For MIMO, different separations of 30 cm, 60 cm, 90 cm and 120 cm experiments were performed for transmission distances of 5 m, 6 m, 7 m and 8 m.

III. Distributed MIMO Performance and Effect of Transmit Antenna Spacing

The results for MIMO transmission show the performance improvement through spatial diversity and spatial multiplexing using the STBC and Zero Forcing receiver, respectively. Fig. 4 shows the achieved improvement in EVM through spatial diversity using Alamouti STBC compared to SISO, for the transmission distances of 6 m (an intermediate distance during the experiment) and 8 m (the longest distance considered for this experiment). For 6 m transmission with transmit antenna spacing of 60 cm, an improvement in coverage can be observed through

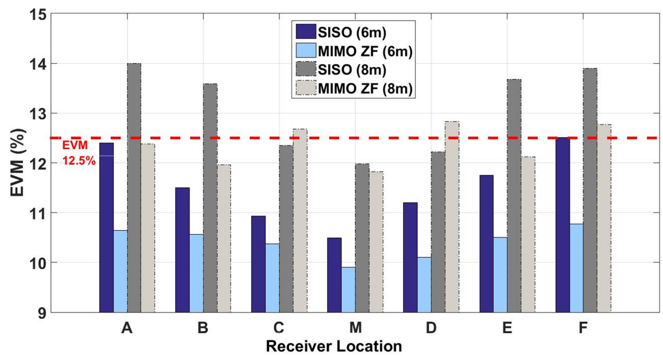

Fig. 5. EVM comparison of SISO (0.5 Gb/s) versus Zero Forcing MIMO processing (1 Gb/s) for 6 m (RAU spacing: 60 cm) and 8 m (RAU spacing: 120 cm).

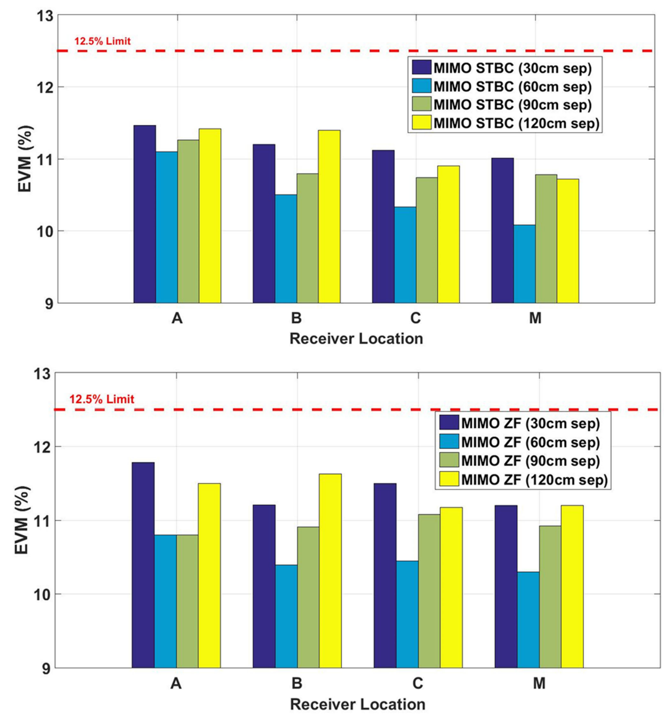

Fig. 6. EVM comparison of 2 × 2 MIMO for various Transmit antenna separation at 6 m transmission distance using STBC (upper) and ZF (lower) processing.

using Alamouti STBC coding, as EVM below the 12.5% limit is achieved for the user locations at the boundaries of the coverage area (locations A,B,D and F) where SISO performance was above this EVM limit. The improvement in coverage is more obvious from MIMO results at 8 m transmission with 120 cm of transmit antenna separation. Experiments were performed with different RAU separation which will be discussed in the following paragraphs. The best RAU separation which gave the minimum set of EVM has been selected, to show the MIMO results, in Fig. 4 to compare with SISO.

The analysis for spatial multiplexing is presented in Fig. 5. This shows that SISO transmission at 0.5 Gb/s and the MIMO transmission with a multiplexed data rate of 1 Gb/s (for optimal RAU separation) both have EVM values below the 12.5% limit after 6 m and 8 m wireless transmission. The transmitter separation distance was maintained at 60 cm for 6 m transmission and 120 cm for 8 m transmission distance in the results of Fig. 5, to achieve the best MIMO performance.

To experimentally analyze the effect of transmit antenna separation on the MIMO performance, the experiments were performed for the experimental configuration of 30 cm, 60 cm, 90 cm and 120 cm transmit antenna separation for each transmission distance of 5 m, 6 m, 7 m and 8 m. The effect of changing the transmit antenna separation for four user locations is shown in Fig. 6 (for simplicity, results for only6 m and 8 m are examples), for the transmission distance of 6 m. The lowest set shown, as well as only locations on one side of the normal, as of EVM was obtained for the separation distance of 60 cm after STBC and ZF processing. As a comparison, the results after 8 m transmission are shown in Fig. 7 for STBC and ZF, which shows that overall the best set of EVM was obtained at a larger spacing of 120 cm.

Theoretical models for mmW 2 × 2 MIMO predict that the optimal performance through LOS operation [20] for a wireless transmission distance of *D* can be achieved by having a transmit antenna separation given by

$$d_{Tx} = D\lambda\ /2d_{Rx}\cos\left(\theta_t\right)\cos\left(\theta_r\right) \tag{1}$$

where λ is the mmW transmission wavelength and d_{Tx}, d_{Rx} are the separation distances between the transmitting and receiving antennas, respectively. θ_t represents the angle of tilt of the transmit antennas in the plane of transmission and θ_r is the tilt of receiving antennas. For 61.5 GHz, if θ_t, θ_r are considered to be ideally 0° at the transmitter and receiver side (which is difficult to achieve accurately, experimentally), and keeping d_{Rx} to be constant at 2.1 cm (minimum separation that was possible and used in the experiments), the optimal transmit antenna separation for wireless transmission distances according to (1) is shown in Fig. 8. The experimental results have also been shown for the RAU separation giving the lowest set of EVM values (out of the four values of 30, 60, 90 and 120 cm) at a particular transmission distance, noting that the actual best separation may have been between those set of values which were used. Error bars for the experimental results shows the range of spacing in which the minimum set of EVM values can be obtained. For example, the best experimental MIMO results after 7 m wireless transmission were found for the spacing of 90 cm, when only four set of spacing were used. The minimum set of EVM can lie between 90 cm ± 30 cm as shown by the error bar. For 8 m, what can be determined, again as shown by the error bars, is that the best spacing is greater than 90 cm. Overall, the general trend from the measurement is in agreement with the theoretical prediction using (1).

To summarize, the analysis in this section shows that RAU separation has a significant effect on MIMO processing. Using RoF fronthaul with distributed RAUs provides the possibility for increasing the inter-antenna distance (which will generally be required considering the theoretical and experimental values in Fig. 8), in addition to system benefits such as deployment flexibility, centralized access, low loss and low power consumption [11].

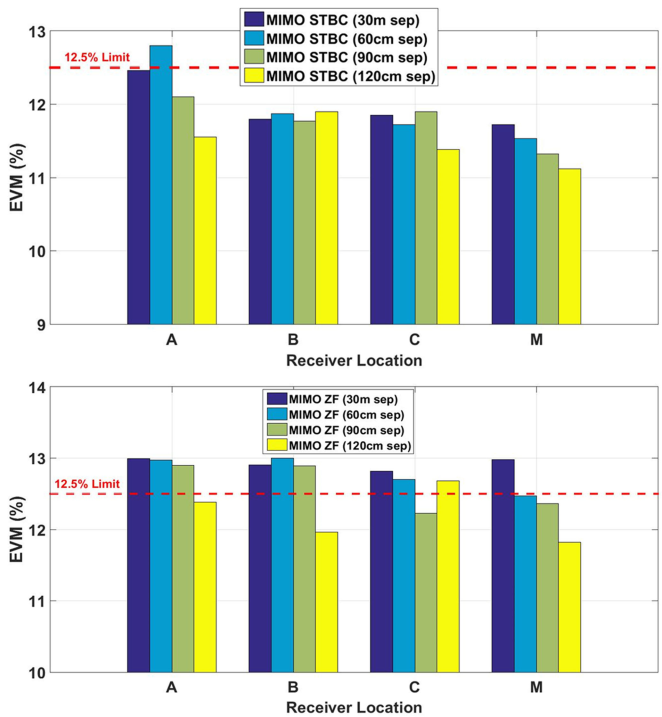

Fig. 7. EVM comparison of 2 × 2 MIMO for various Transmit antenna separation at 8 m transmission distance using (upper) STBC (lower) ZF processing.

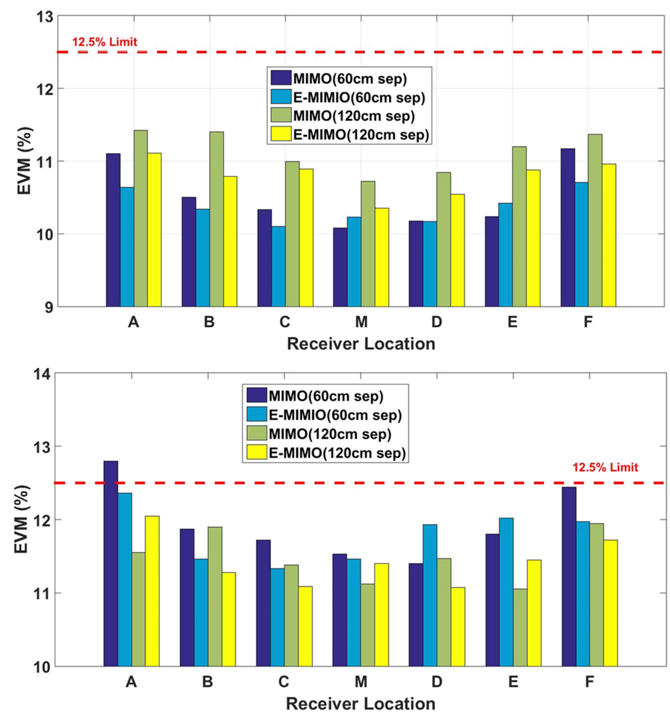

Fig. 9. EVM comparison of 2 × 2 MIMO using STBC processing at 6 m (top) and 8 m transmission distance (bottom) and equivalent emulated measurements.

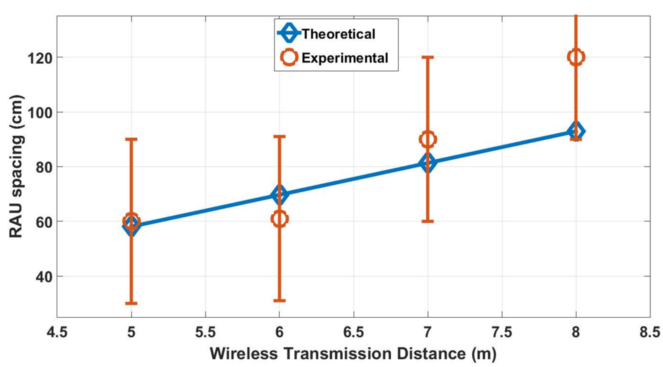

Fig. 8. Theoretical Optimum Antenna Spacing for 2 × 2 MIMO versus Experimental values with error bars to represent the ranges between discrete points at which measurements were taken.

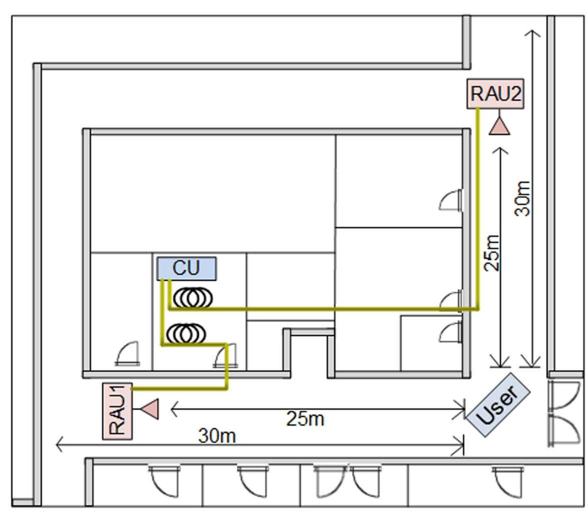

Fig. 10. Layout of the Measurement Location.

IV. MIMO Processing Using Separate Channel Coefficient Measurements

The study of the previous section has been limited to 8 m wireless distance due to a lack of components in our laboratory; a second 60 GHz amplifier, allowing one for each transmitting antenna, would allow measurements to be extended to longer distances. In order to demonstrate the feasibility of the MIMO system in this situation, the approach described in [18] can be followed. The transmitter is placed sequentially at two RAU locations. For each RAU transmitter location, the received signal is captured at two receiving antenna positions (2.1 cm apart), constituting one user location. Through post-processing, the 2 × 2 channel matrix is obtained [21] although only one RAU (and mm-wave amplifier) is used at any one time. Then, processing using the STBC and ZF algorithms is performed on the captured waveforms. The captured data is processed using the STBC and ZF algorithms.

Fig. 9 shows a good agreement of the results for STBC processing from the emulated approach and real MIMO, for 6 m and 8 m wireless distances, demonstrating the validity of the approach at different transmission distances. The optimum RAU spacing for MIMO operation also agrees with the previous results. This "emulated MIMO" processing technique can be used to extend the analysis to much longer distances.

Fig. 10 shows such a scenario in the corridors of our building, where a receiver has LoS access to two RAU positions

TABLE I
SISO VERSUS EMULATED MIMO PROCESSING RESULTS

Distance	SISO (1Gb/s)	STBC (1Gb/s)	SISO (0.5Gb/s)	ZF (1Gb/s)
25m	14.5%	12.1%	12.3%	12.9%
30m	15.1%	12.4%	12.8%	13.3%

supported by separate RoF links from the CU. Emulated MIMO is performed by placing the transmit antenna at the positions of RAU1 and RAU2, and capturing the data at the receiver. The results of SISO transmission are compared with STBC and ZF processing in Table I, showing the feasibility of using MIMO for performance improvement at 25 m and 30 m. Although close to the requirement, some values after ZF processing are slightly above 12.5%, but these still satisfy the requirement for 16-QAM with Forward Error Correction (FEC) [22].

V. CONCLUSION

Analog RoF fronthaul has been presented for 60 GHz distributed MIMO to achieve flexibility and performance improvement with increased RAU spacing. The RAU spacings at several wireless transmission distances demonstrate improved mmW coverage through spatial diversity and improved data rate through spatial multiplexing. Results at different user locations show that wider transmit antenna separations, more easily obtained through the RoF transport, are required for longer wireless distances. A technique to process measured individual channel coefficients with CoMP/MIMO algorithms has been used to verify that the channels are relatively static and to show the MIMO performance benefits at distances of up to 30 m for the 60 GHz wireless transmission. Future work will include projections of MIMO performance to NxN massive MIMO system in dense user environments, to optimize the number of RAUs and improve mmW coverage.

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