D-Band Line-of-Sight MIMO Link Demonstration

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***Abstract*—In this work, preliminary results from the prototyping phase of a 2x2 D-Band Line-of-Sight MIMO link are presented. Aiming to demonstrate ultra-high throughput for point-to-point fixed wireless links, line-of-sight MIMO is implemented and evaluated with the large modulation bandwidth that is available in the D-Band (110 - 170 GHz) of the millimeter-wave frequency range. The link demonstration is performed in a hardware-in-the-loop setup, at a 2 m range in an indoor conference hall environment. It is based on IHP's D-Band 130-nm SiGe BiCMOS analog front-ends operating at a carrier frequency of 135 GHz, in combination with dielectric lenses. In order to obtain a near-orthogonal MIMO channel in line-of-sight conditions, the setup is relying on optimal arrangement between the transmit and receive antennas, according to the Rayleigh criterion. By performing spatial multiplexing of 2 QPSK-modulated data streams with 4 GHz modulation bandwidth, an aggregated throughput of 16 Gb/s is achieved during a live link demonstration. As the system is in its early development phase, it is subject to ongoing work to further enhance the link range and throughput.**

***Index Terms*—D-Band, Dielectric Lens, Line-of-Sight MIMO, Spatial Multiplexing, Hardware-in-the-Loop, Demonstration**

I. Introduction

In the advent of the 6th generation of mobile networks, there is a growing need to address the increase in user data traffic, by providing higher throughput wireless link solutions. This particularly holds for point-to-point backhaul and fixed wireless access links, where link capacity in the order of tens of Gb/s is required. Line-of-Sight (LoS) multiple-input multiple-output (MIMO) is one of the candidate schemes that is suitable for fixed point-to-point links [1]. In combination with a large modulation bandwidth, this scheme has the potential to meet the growing capacity demand, e.g. by operating in the millimeter-wave (mmWave) frequency range. Recent advances in semiconductor technologies have made mmWave transceivers readily available and led to multiple commercial-off-the-shelf devices, primarily in the V-Band (40-75 GHz). However, due to the large bandwidth requirements, the higher frequency mmWave bands such as the D-Band (110-170 GHz) are of greater interest. Employing D-Band front-ends [2] in practically feasible multi-antenna link solutions, presents a number of challenges that need to be identified and addressed, in order to aid the proliferation of this technology. It is therefore, of great significance to evaluate the performance of the D-Band front-ends and gain insight by performing experimental work on system prototypes.

In this paper, preliminary results from the prototyping phase of a 2x2 D-Band LoS MIMO link, including system setup and performance metrics, are presented. In Section II, the underlying principle of LoS MIMO is discussed. In Section III the used D-Band front-ends and dielectric lenses are described, whereas Section IV provides an overview of the hardware setup. Section V presents the goals of the link demonstration, with the preliminary results shown in Section VI. Finally, Section VII summarizes the main conclusions of this work.

II. Line-of-Sight MIMO Principle

Assuming planar wave propagation, it is a common notion that MIMO channels exhibit low rank channel matrices in LoS conditions, which in turn limits their multiplexing gain. However, considering the more accurate spherical wave propagation model, it can be shown that with a specific and optimal antenna arrangement, a near-orthogonal and high rank channel can be obtained, as discussed in [1]. Hence, spatial multiplexing can be performed to maximize the link capacity, by transmitting independent data streams from each antenna [3]. The optimal antenna spacing d_{OPT} can be determined through the Rayleigh criterion [3] and depends on the carrier wavelength λ, number of antennas N and link range D:

$$d_{\text{OPT}} = \sqrt{\lambda D/N} \quad (1)$$

As the performance of a LoS MIMO link relies inherently on the orthogonality of the wireless channel, the condition number of the channel matrix can be used as a metric to evaluate its spatial multiplexing gain. The condition number κ represents the ratio of the largest σ^2_{max} to the smallest singular value σ^2_{min} of the channel matrix:

$$\kappa = \sigma^2_{max}/\sigma^2_{min} \quad (2)$$

III. D-Band RF Front-End and Dielectric Lens

The LoS MIMO system prototype described in this work relies on IHP's 130-nm SiGe BiCMOS D-Band transceiver front-end [2], featuring a 4-channel phased array with on-chip patch antennas. One set of front-ends is configured in Tx mode, and another set in Rx mode. To enhance the link budget, a dielectric lens is employed on top of each front-end IC, as shown in Fig. 1a. The dielectric lens has a nominal gain of 12 dB and features a proprietary design with an anti-reflective surface that increases its transmissivity. It has an outer diameter of 23.5 mm and thickness of 5.75 mm, and is mounted at a height of 4.7 mm above the IC using an acrylic bracket.

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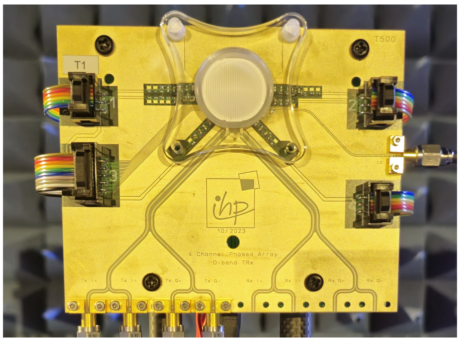
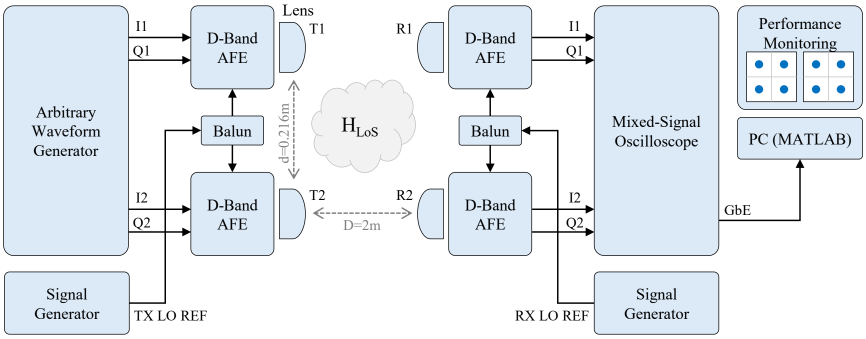


(a) D-Band transceiver front-end and lens.



(b) Hardware-in-the-loop processing.

Fig. 1: Overview of the D-Band LoS MIMO experimental setup.

IV. Hardware-in-the-Loop Setup

The evaluation of the D-Band LoS MIMO link is performed using the hardware-in-the-loop method, with the setup described in Fig. 1b. An Arbitrary Waveform Generator (AWG) is used to generate two independent data streams to the I/Q inputs of the D-Band front-ends in Tx mode, whereas the output of the D-Band front-ends in Rx mode is sampled by a Mixed-Signal Oscilloscope (MSO). The recorded data frames are post-processed in MATLAB and the performance metrics are plotted in quasi-real time using a custom developed graphical interface, shown in Fig. 7. The Tx and Rx arrays are locally fed with a shared Local Oscillator (LO) reference of 33.75 GHz, that is used to generate the 135 GHz carrier frequency after passing through the on-chip frequency quadrupler. In order to evaluate the link in realistic operating conditions, the timing and frequency synchronization are performed digitally in the receiver post-processing, i.e. there is no wired synchronization between the transmit and receive side. The applied signal processing scheme, as well as the frame format, can be inferred from the previous work in [4]. An overview of the Tx and Rx setup used for the link demonstration is shown in Fig. 2 and Fig. 4, respectively. The front-end modules were mounted on custom built mechanical fixtures, that allow for manual linear adjustment across the array axis with fine resolution. Depending on the desired link range, the front-end modules can be positioned at the correct spacing to achieve channel orthogonality, as per (1). In addition, this setup allows to demonstrate the impact of antenna spacing on the link performance by e.g. displacing a single front-end.

V. Link Demonstration and Goals

The link is operating at a carrier frequency of 135 GHz and set up at 2 m range in an indoor conference hall environment, as depicted in Fig. 5. Due to the application of lenses, it is assumed that the transmission is conducted dominantly over the line-of-sight path. According to LoS MIMO theory, there are multiple optimal antenna spacings that can be set to achieve an orthogonal LoS MIMO channel for the given arrangement. The inverse of the condition number is plotted for convenience in Fig. 3, with the marked local maxima corresponding to

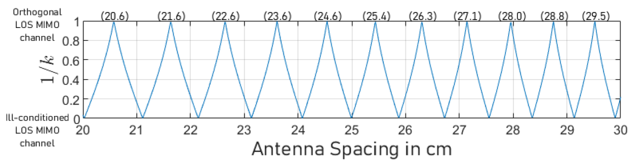


Fig. 3: Inverse of the channel matrix condition number as a function of the antenna spacing.

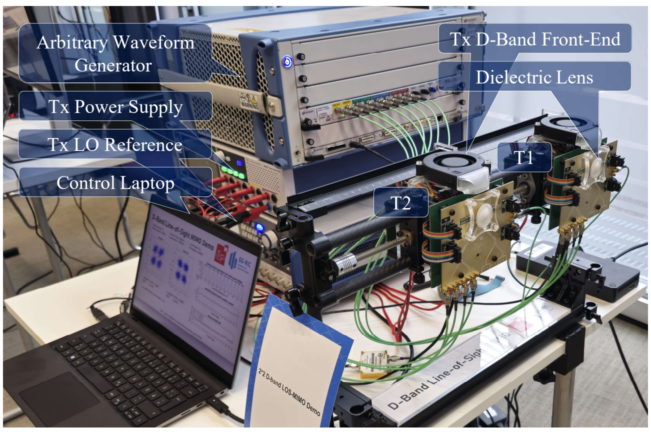


Fig. 2: Transmitter array setup.

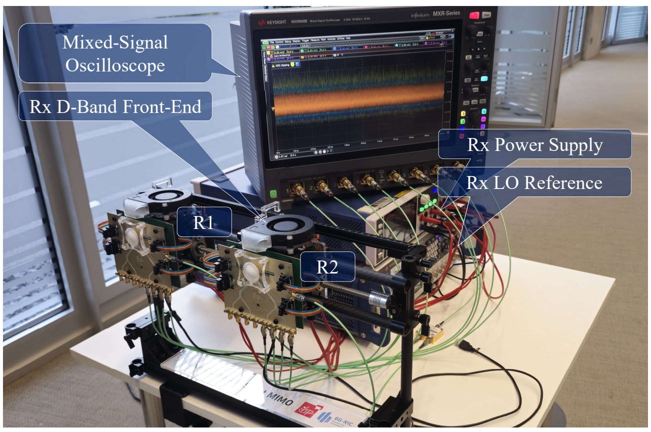


Fig. 4: Receiver array setup.

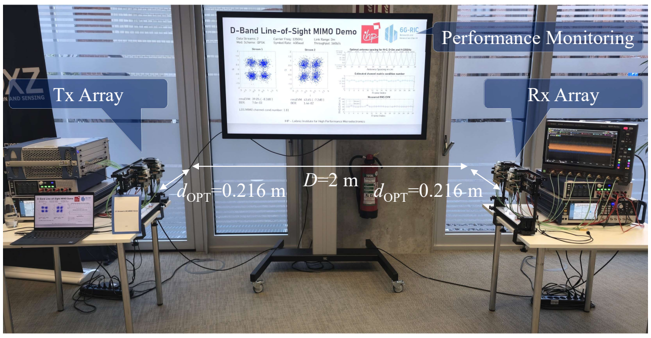


Fig. 5: D-Band LoS MIMO link demonstration.

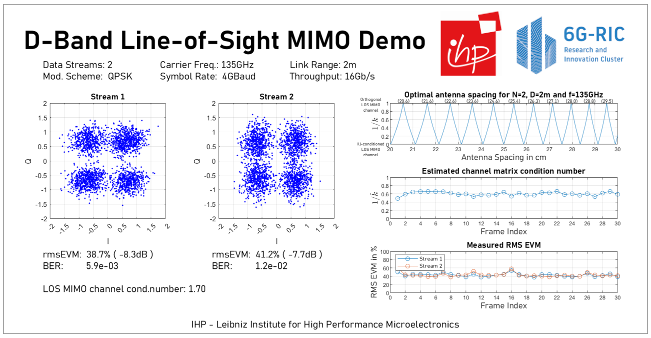


Fig. 7: User interface for real-time performance monitoring.

the optimal and the local minima to the ill-condition spacing, respectively. An optimal antenna spacing d_{OPT} of 21.6 cm was initially selected for the purpose of the demonstration. The goal is to demonstrate: a) that the LoS MIMO link performance is strongly determined by the channel conditioning. This can be shown by moving one of the front-ends along the sliding rail (Fig. 2) while the channel condition number is monitored, and b) that high throughput in the order of tens of Gb/s can be achieved by applying spatial multiplexing under LoS MIMO conditions, based on optimal antenna arrangement.

VI. Performance Evaluation

In order to evaluate the performance of the D-Band LoS MIMO link presented in this work, a set of 30 consecutive data frames recorded during the on-site demonstration is processed. The real-time tracking of the link metrics in terms of channel matrix condition number and measured rmsEVM for this set is presented in Fig. 6. The demonstration was performed at an update rate of approx. one frame per second, mainly limited by the receiver processing overhead in the hardware-in-the-loop setup. This corresponds to an observation window of approx. 30 seconds. The estimated average LoS MIMO channel matrix condition number (2) yielded 1.7 and remained relatively stable throughout the set, suggesting the channel is deterministic and highly orthogonal. The measured rmsEVM of the equalized data streams, e.g. in the last recorded frame are 38.7% (-8.3 dB) and 41.2% (-7.7 dB), whereas the BER yielded 5.9E-3 and 1.2E-2 for the first and second stream, respectively. In general, it can be observed that both streams exhibited a similar rmsEVM throughout the set. By applying spatial multiplexing of two QPSK modulated data streams at a modulation bandwidth of 4 GHz, the D-Band LoS MIMO link achieved an aggregated uncoded throughput of 16 Gb/s. Although only QPSK modulation with BER in the order of 1E-2 is presented, the system is subject to ongoing work to further improve link quality and throughput by supporting higher order modulation schemes.

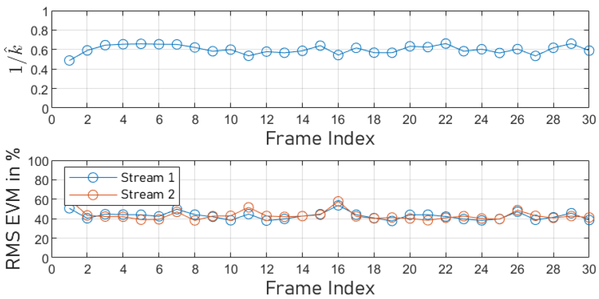


Fig. 6: Inverse of the channel matrix condition number and measured rmsEVM of the equalized data streams.

VII. Conclusion

This work presents the preliminary results of a D-Band Line-of-Sight MIMO link prototype, that was demonstrated in October 2024 at the 6G-RIC Industry Advisory Board (IAB) Meeting in Berlin, Germany. To the best knowledge of the authors, it is the first occurrence of a live demonstration of a 2x2 D-Band LoS MIMO link in a hardware-in-the-loop setup. The D-Band link is based on IHP's 130-nm SiGe BiCMOS front-end technology enhanced by dielectric lenses. By spatial multiplexing of two QPSK modulated data streams with 4 GHz modulation bandwidth at a carrier frequency of 135 GHz, the system is able to achieve an aggregated uncoded throughput of 16 Gb/s. Considering the system is presented in its early prototyping phase in this work, it is subject to ongoing development to further enhance its performance.

VIII. Acknowledgment

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References

[1] X. Song, C. Jans, L. Landau, D. Cvetkovski, and G. Fettweis, “A 60GHz LOS MIMO Backhaul Design Combining Spatial Multiplexing and Beamforming for a 100Gbps Throughput,” in *2015 IEEE Global Communications Conference (GLOBECOM)*, 2015, pp. 1–6.

[2] A. Karakuzulu, W. A. Ahmad, D. Kissinger, and A. Malignaggi, “A Four-Channel Bidirectional D-Band Phased-Array Transceiver for 200 Gb/s 6G Wireless Communications in a 130-nm BiCMOS Technology,” *IEEE Journal of Solid-State Circuits*, vol. 58, no. 5, pp. 1310–1322, 2023.

[3] F. Bohagen, P. Orten, and G. E. Oien, “Design of Optimal High-Rank Line-of-Sight MIMO Channels,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 4, pp. 1420–1425, 2007.

[4] D. Cvetkovski, T. Hälsig, B. Lankl, and E. Grass, “Four-Stream Line-of-Sight Spatial Multiplexing for 60 GHz Backhaul Applications,” *IEEE Wireless Communications Letters*, vol. 10, no. 8, pp. 1648–1651, 2021.