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Abstract: The evolution to ultra-dense next generation networks requires a massive increase in throughput and deployment flexibility. Therefore, novel wireless backhaul solutions that can support these demands are needed. In this work we present an approach for a millimeter wave line-of-sight MIMO backhaul design, targeting transmission rates in the order of 100 Gbit/s. We provide theoretical foundations for the concept showcasing its potential, which are confirmed through channel measurements. Furthermore, we provide insights into the system design with respect to antenna array setup, baseband processing, synchronization, and channel equalization. Implementation in a 60 GHz demonstrator setup proves the feasibility of the system concept for high throughput backhauling in next generation networks.

Keywords: MIMO, millimeter wave, line-of-sight, backhaul, multi-subarray system, spatial multiplexing

1 Introduction

In 2020–2030, peak user data rates in cellular networks are expected to be in the order of 10 Gbit/s [1]. Base stations will serve multiple sectors and the network will be organized in smaller cells [2]. Further network

densification can also provide the low latency required by future time-critical applications [3]. The cost of deploying wired front-/backhaul links can become prohibitive in the network expansion while wireless links can offer greater scalability and flexibility. By using carrier aggregation and simultaneous transmission of differently polarized signals, microwave wireless systems currently available on the market can provide only up to 4 Gbit/s for Line-of-Sight (LoS) backhaul links [4]. To support the expected cellular peak data rates of 10 Gbit/s, the throughput of small-cell backhaul must be at least one order of magnitude higher, e.g., 100 Gbit/s.

Millimeter wave (mmWave) frequencies have become popular for meeting the growing demands on the throughput of next generation networks due to their large available bandwidths. Applying beamforming on very densely packed antennas, referred to as sub-arrays in this work, allows extending the coverage range [5]. Therefore, single stream Gigabit-per-second backhaul communication has become feasible by using mmWave frequencies [6], [7]. In order to meet the throughput requirements on backhaul links of next generation ultra-dense networks, in addition to using wide bandwidth and high signal-to-noise ratio (SNR), spatial multiplexing must be performed for further throughput enhancement. In contrast to logarithmic increase w.r.t. SNR, works in [8], [9] have shown that multiple antenna systems are capable of increasing the capacity linearly w.r.t. the minimum number of transmit and receive antennas. Thus spatial multiplexing of multiple streams can be performed using the same time-frequency resources. Considering planar wave modelling and a finite number of paths with certain angle-of-arrival (AOA) and angle-of-departure (AOD) vectors, mmWave wireless channels are found to exhibit low rank. Although the channel is of limited scattering, work in [10] has shown that employing additional reflected paths is feasible for mmWave backhaul applications.

In this work, we summarize our contributions on a proposed LoS multi-subarray system. Since the planar wave model is just an approximation of point source electromagnetic wave propagation, *high rank* channels can be obtained under specific antenna arrangements with the more accurate *spherical wave model*. Instead of exploiting

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the spatial multiplexing between different LoS/reflected paths, LoS MIMO approaches have shown the existence of spatial multiplexing gain within a single path direction [11] and [12]. With smart arrangements on parallel planes [13], [14] and [15], orthogonal channel matrices can be obtained. This allows transmitting parallel streams with well balanced SNRs. The work in [15] additionally showed the high robustness of the spatial multiplexing gain of LoS MIMO with respect to array translations and rotations.

One other important aspect of our work is to investigate the issues that arise in practical millimeter wave system designs and how to effectively handle them using signal processing techniques. Hardware impairments can limit the performance of the system significantly [16], if left uncompensated. Due to the wide bandwidth, most of the effects in the system should, for example, be considered as frequency-dependent, such as imbalances due to differences in the inphase and quadrature branch of the transceivers, and the wireless channel itself. Additionally, accurate timing algorithms and system designs simplifying synchronization are required. This is due to the small wavelengths, wide bandwidths and increased impact of timing jitter and phase noise [17]. This becomes even more critical for MIMO systems where these effects occur in multiple different transceivers which demands more effort spent on estimation and compensation [18]. Finding simple yet efficient ways of addressing these challenges is an important task in order to find the optimal partitioning between analog and digital processing complexity.

The rest of this paper is organized as follows: In Section 2, we first present a LoS multi-subarray MIMO system. The system design exploits the spatial multiplexing gain offered by LoS MIMO, in order to achieve high throughput at long range for applications like wireless backhaul. Its specific channel model is discussed in Section 2.1. This is followed by Section 2.2 where the validation of the channel model is performed. Channel measurements of different arrangements at a range of interest for wireless backhaul applications are presented. The system architecture for the intended wireless backhaul application is proposed in Section 3. For reducing the hardware complexity and increasing the efficiency, the data processing is parallelized on two different levels as described in Section 3.1. A synchronization setup for mmWave MIMO systems is presented in Section 3.2. The outcomes of a hardware-in-the-loop demonstration of the proposed LoS MIMO concept are described in Section 3.3. Finally, we summarize the main contributions and outline further steps for improving the system in Section 4.

2 Long range LoS MIMO

The potential throughput of MIMO systems, commonly expressed in terms of the capacity C depends on three parameters [9], namely bandwidth W , SNR γ and MIMO gain, referred to as spatial multiplexing gain in this work. Considering a time and frequency flat channel with channel state information at receiver side, the channel capacity of a system with symmetric transceiver arrays is given by

$$C = W \cdot \log_2[\det(\mathbf{I}_N + \frac{\gamma}{N} \cdot \mathbf{H}\mathbf{H}^H)] \text{ bit/s}, \quad (1)$$

where $\mathbf{H} \in \mathbb{C}^{N \times N}$ is the channel coupling matrix between transmitted vector and received vector of length N , whereby N denotes the number of supported spatial streams.

In order to maximize the capacity specified by eq. (1), a LoS multi-subarray MIMO system intended for backhaul applications is proposed by our earlier work [19], as also shown in Figure 1, where different antenna configurations are illustrated in terms of N_x and N_y supporting 9, 6 and 3 spatial streams, respectively. The proposed system is a two-level hierarchical MIMO system operating in the mmWave frequency range, where wide bandwidths are available, e.g., a bandwidth of 1.88 GHz at a carrier frequency of 60 GHz [20]. On the bottom level of the system, beamforming is applied at the subarrays for providing

Figure 1: A LoS multi-subarray MIMO system. The top level is a MIMO system that consists of $N = N_x \cdot N_y$ subarrays at each transceiver node for spatial multiplexing gain. Subarrays, modeled as compact square arrays, provide beamforming gain on the bottom level [19]. The directions of x -, y -, and z -axes are illustrated, while the origin of the coordinate system is chosen at the phase center of the transmit array.

sufficient array gain and to compensate for the small effective aperture of a single antenna. The subarrays are modeled as compact uniform square arrays of M^2 antenna elements. The antenna elements within the subarrays are equally spaced with half a wavelength $\lambda/2$. To achieve spatial multiplexing, the antenna topology required by LoS MIMO is applied on the top level, where the $N = N_x \cdot N_y$ subarrays at both sides are separated by much larger spacings $d_x, d_y \gg \lambda$. The transmission model is therefore given as

$$\mathbf{y} = \alpha \cdot g_r \cdot g_t \cdot \mathbf{H}_{\text{LoS}} \mathbf{s} + \mathbf{n}, \quad (2)$$

where $\mathbf{s}, \mathbf{y}$ are transmitted and received symbol vectors of size $N \times 1$, respectively. The variables α, g_r and g_t indicate the channel gain, and the subarray gains at the receiver and transmitter, respectively. The noise $\mathbf{n}$ is zero mean complex white Gaussian distributed as $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \sigma_n^2 \cdot \mathbf{I}_N)$ and the matrix $\mathbf{H}_{\text{LoS}} \in \mathbb{C}^{N \times N}$ is the channel coupling matrix with unitary entries. The transmit power is defined as $P_T \triangleq \mathbb{E}(\mathbf{s}^H \mathbf{s})$. Therefore, the SNR γ of a LoS MIMO system is influenced by several parameters with $\gamma = (\alpha g_r g_t)^2 P_T / \sigma_n^2$.

In the rest of this section, it is shown how to make $\mathbf{H}_{\text{LoS}}$ full rank by exploiting the spherical wave model, in order to achieve orthogonal phase vectors. These vectors are the columns of matrix $\mathbf{H}_{\text{LoS}}$, and become orthogonal by appropriately choosing d_x and d_y .

2.1 LoS MIMO channel and its 3D channel factorization

In contrast to the prevailing interpretation of the channel rank of LoS communication, spatial multiplexing can be achieved within the *line-of-sight* path under particular antenna arrangements. The state-of-the-art works on LoS MIMO consider antenna arrays with large element spacing d_x, d_y , where transmit array (Tx) and receive array (Rx) are roughly facing each other. In the rest of this section, we focus on the spatial multiplexing gain of the coupling matrix $\mathbf{H}_{\text{LoS}}$ on the top level of the LoS multi-subarray system. For simplification of the discussion, $M = 1$ is assumed on the lower level.

We assume that the Tx is separated from the Rx by a distance of D , which is referred to as transmit distance. With *planar wave modeling*, channel matrices with a rank higher than one are not obtainable. However, the planar wave model is just an approximation of spherical wave propagation under a *small* antenna spacing assumption [22]. Assuming the transmit distance D to be much larger than the size of the arrays, the receive signals of LoS

MIMO systems are of approximately equal power but are of different phases. Large antenna separations are required by LoS MIMO for observing the curvature of spherical waves. Therefore, the desired phase differences can be constructed by particular antenna arrangements. Considering the *spherical wave model*, the elements of the phase coupling matrix $\{\mathbf{H}_{\text{LoS}}\}_{lk}$ satisfy

$$\{\mathbf{H}_{\text{LoS}}\}_{lk} = e^{-j \frac{2\pi}{\lambda} \cdot D^{(lk)}}, \quad (3)$$

where $D^{(lk)}$ denotes the link distance between the l -th receive antenna (Rx- l) and the k -th transmit antenna (Tx- k) via the LoS path.

The works in [13–15] have given the solution to the optimized spatial arrangements on parallel planes that provide orthogonal MIMO channel matrices. Considering two parallel *Uniform Linear Arrays* (ULAs) or *Uniform Planar Arrays*, the arrangements following the design in [15] can fully exploit the spatial multiplexing gain of LoS MIMO systems. The optimal arrangements and their optimal inter antenna/subarray spacings d_{x0}, d_{y0} mainly depend on the transmit distance D , wavelength λ and antenna/subarray number N_x, N_y . In symmetric cases, the optimal inter antenna/subarray spacings d_{x0}, d_{y0} satisfy

$$d_{x0} \triangleq \sqrt{\lambda D / N_x} \quad \text{and} \quad d_{y0} \triangleq \sqrt{\lambda D / N_y}, \quad (4)$$

respectively. By using optimal antenna arrangements, the link distance $D^{(lk)}$ between Rx- l and Tx- k can be derived as

$$D^{(lk)} = \sqrt{D^2 + (n_x^{(l)} - n_x^{(k)})^2 d_{x0}^2 + (n_y^{(l)} - n_y^{(k)})^2 d_{y0}^2}, \quad (5)$$

where $n_x^{(l)}, n_y^{(l)}, n_x^{(k)}, n_y^{(k)}$ are the x- and y-indices of Rx- l (Tx- k) among all N_x coordinates on x-axes and N_y coordinates on y-axes, respectively, $1 \leq n_x^{(l)}, n_x^{(k)} \leq N_x, 1 \leq n_y^{(l)}, n_y^{(k)} \leq N_y$. Then it is found that $\mathbf{H}_{\text{LoS}}$ becomes a spatially orthogonal matrix $\mathbf{H}_0$ with $\mathbf{H}_0 \cdot \mathbf{H}_0^H = N \cdot \mathbf{I}_N$. With the hierarchical MIMO architecture, the LoS multi-subarray systems proposed in [19] show a great potential in achieving throughputs higher than 100 Gbit/s over a distance of 100 m with practical super-array sizes. The outcome of the link budget estimation with respect to the multi-subarray system design can be found in Table 1.

The existing work on the optimal arrangements of LoS MIMO only considers antenna topologies on tilted non-parallel lines/planes [23]. Specifically, the optimal solutions for planar arrangements are only known for limited planar rotating directions. Based on an analysis of antenna positions in 3D space, the work [24] shows that

Table 1: Exemplary link budget of 60 GHz LoS MIMO backhaul systems under FCC Equivalent-Isotropically-Radiated-Power limit [21], $W = 1.88$ GHz. We assume an antenna element gain of 6 dBi, a noise figure value of 5 dB, a temperature value of 293 K, and a path loss value of 115.3 dB at a distance of $D = 100$ m.

Ind.	$N = N_y \times N_x$	M^2	P_T [dBm]	Super-array size	C [Gbit/s]
1	$6 = 3 \times 2$	10^2	16	$0.82\text{m} \times 0.50\text{m}$	101.4
2	$9 = 3 \times 3$	8^2	18	$0.82\text{m} \times 0.82\text{m}$	141.3
3	$10 = 5 \times 2$	8^2	18	$1.26\text{m} \times 0.50\text{m}$	157.1
4	$16 = 4 \times 4$	8^2	18	$1.06\text{m} \times 1.06\text{m}$	251.1

the channel matrices of any LoS MIMO topology in free space can be factorized into a product of three matrices as

$$\mathbf{H}_{\text{LoS}} = \mathbf{D}_{\parallel,r} \cdot \mathbf{H}_{\perp} \cdot \mathbf{D}_{\parallel,t}, \quad (6)$$

where $\mathbf{D}_{\parallel,t}$, $\mathbf{D}_{\parallel,r}$ are diagonal matrices that represent the phase shifts caused by the offsets along the transmit direction at transmitter and receiver, respectively. Furthermore, $\mathbf{H}_{\perp}$ is influenced by the projection of the antenna arrays onto the broadside relative to the transmit direction. It is also shown by [24] that the achieved capacity of LoS MIMO systems under any antenna arrangement is only determined by $\mathbf{H}_{\perp}$. In other words, the projection on the plane that is perpendicular to the transmit direction influences the capacity of LoS MIMO systems. Besides providing 1D/2D antenna topology solutions for any oblique angle/angular tilt, this important outcome allows an extension of the system concept to 3D antenna topologies, as long as the phase relations are preserved [24].

Figure 2: Receiver setup for 2×2 ($N = N_x = 2$, $N_y = 1$) LoS MIMO channel measurements, comprised of two 60 GHz transceiver front-ends mounted on an adjustable mechanical fixture and their shared reference clock. The transceiver front-ends have in-package patch antennas with a gain of 7.5 dBi and output power level of 16 dBm.

2.2 Channel measurement results

In order to verify the spherical wave model eq. (3) and the fundamental properties of the LoS channel model for backhaul scenarios, various channel measurements at a mmWave carrier frequency were carried out. The transmit waveforms used in the measurements were generated by an arbitrary waveform generator and transmitted using 60 GHz analog transceivers, shown in Figure 2. At the receiver side the baseband output waveforms were recorded by a real-time oscilloscope and used for offline post-processing. A detailed description of the setup and measurement procedure can be found in [25] and [26]. We denote, henceforth, estimated values coming from the measurements by a hat, e.g., $\hat{\mathbf{H}}_{\text{LoS}}$ as the measured LoS channel matrix.

LoS MIMO Channel Property: First, we investigate if orthogonal channel matrices can be obtained when the spacing criterion is fulfilled and if spherical wave propagation can be utilized in general for LoS MIMO systems operating at mmWave carrier frequencies. In order to assess the orthogonality of the channel matrix, we rely on the *condition number*, defined by

$$\kappa = \frac{\Lambda_{\max}(\mathbf{H}_{\text{LoS}})}{\Lambda_{\min}(\mathbf{H}_{\text{LoS}})} \quad (7)$$

with $\Lambda_{\min}(\cdot)$ and $\Lambda_{\max}(\cdot)$ giving the smallest and largest singular value of a matrix, respectively, and the channel matrix is orthogonal if $\kappa = 1$.

In Figure 3 we show measurement results for a 2×2 LoS MIMO link for a transmission distance of 50m with different antenna spacings d_x . Since there is some gain imbalance in the different transceivers, results for the normalized channel matrix $\hat{\mathbf{H}}_{\text{LoS, norm}}$, where only the phase differences in the matrix are considered, are also evaluated. Condition number eq. (7) and capacity eq. (1) results based on the observed channel matrices and an estimated SNR of $\hat{\gamma} = 25$ dB are shown and match very well with theory. When the spacing criterion is fulfilled, orthogonal channel matrices can be generated achieving high spectral efficiencies. A more complete investigation and discussion of the LoS properties also including further results for different distances, spacings, and up to 3 spatial streams, can be found in [25].

Frequency-Selectivity: The investigation of the complete channel impulse response over multiple channel realizations [26] yield two important conclusions. First, the LoS channel appears fairly stable, repeatedly estimated over the complete measurement duration of approx. 4ms,

Figure 3: Measurement results for a 2×2 ($N = N_x = 2, N_y = 1$) LoS MIMO system with transmit distance $D = 50\text{m}$ and wavelength $\lambda = 5\text{mm}$: (a) Estimated condition number for different antenna spacings; (b) Estimated capacity for different antenna spacings at SNR $\hat{\gamma} = 25\text{dB}$.

which is several orders of magnitude greater than the symbol duration, e.g., 0.8ns . Consequently, the channel can be considered *quasi-static* [26] and, therefore, less resources need to be allocated for training sequences. Furthermore, only a limited number of reflected paths is observed with a maximum excess delay from the LoS component of around 10 symbol durations. The components of the channel impulse response beyond the maximum excess delay are 20 dB below the LoS peak power level and could be neglected when only the line-of-sight path is used [27]. Hence due to the observed sparsity of the mmWave LoS channel, attributed to the antenna directivity and power loss of the 60 GHz band, time-domain MIMO equalization with FIR filters of a limited number of taps could be performed, as discussed in Section 3.1. An example set of the complex channel coefficients obtained by measurements is presented in Figure 4.

Figure 4: Estimated channel coefficients for 2×2 LoS MIMO channels at a transmit distance of $D = 1.876\text{m}$ with the LoS channel tap marked in the plots. The y-axis is normalized to the LoS peak power across all coefficients, whereas the x-axis is normalized to the symbol duration of 0.8ns .

3 LoS MIMO system design approach

3.1 Parallel processing architectures

Processing spatially multiplexed data streams at Gbit/s datarates poses serious challenges for the MIMO receiver architecture. Highly parallel architectures are suitable both for reducing the computational complexity of the stream separation and for the further baseband processing of independent streams. In this section two different approaches to achieving the required parallelism in the physical layer (PHY), i.e., digital/analog-based processing are discussed, as well as its extension to the higher MAC level.

Lane-based Digital Baseband Processing: Having in mind that our proposed LoS MIMO concept achieves phase orthogonality to aid the separation of the spatially multiplexed data streams, no MIMO pre-coding is performed by the transmitter. Since the major processing complexity lies on the receiver side, only the structure of the proposed LoS MIMO receiver is further described in this subsection (Figure 5).

The channel estimation is the first processing stage where signal inputs from different antennas are cross-correlated with pre-defined orthogonal training sequences. The magnitude and phase of the extracted channel coefficients are then used for the estimation and correction of the sampling and carrier frequency offsets, as well as frame synchronization. Upon the aforementioned corrections, a two-stage MIMO equalization is

Figure 5: MIMO receiver architecture with digital lane-based parallel stream processing and optional analog equalization network. Downconversion after the analog equalization network is omitted for simplicity.

performed in order to separate the spatially multiplexed data streams. The LoS stream separation in the initial stage can be performed with e.g. multiplying the received signal vector with the pseudo-inverse of the estimated LoS channel matrix [28], also known as zero-forcing. A decision-feedback loop represents the latter stage, where the detected symbols are used to cancel the inter-symbol interference (ISI) on the incoming symbols in the initial stage. Our analysis of the mmWave LoS channel impulse response suggested that the equalization can be performed in the time domain, with a relatively short decision-feedback filter length of several taps, as shown in Section 2.2. After the stream separation is performed, each stream is individually processed for demodulation and decoding.

With a wide bandwidth, e.g., 1.88 GHz in the 60 GHz Industrial Scientific Medical (ISM) band, the spectral efficiency required to achieve 100 Gbit/s amounts to approximately 53 bit/s/Hz, which is beyond the processing power of present day DSPs with clock frequencies of around 1 GHz. Novel digital baseband architectures need to be, therefore, developed that provide a high inherent level of parallelism to support the high bandwidth mmWave stream transmission. Parallelization can be performed in two different domains, namely before the stream separation in the joint MIMO processing sections and afterwards on the decoupled data streams. In the joint MIMO sections, particularly in the channel estimation and equalization, computationally intensive matrix operations are performed, e.g. matrix inversions and multiplications. One

viable solution for the real-time implementation of these operations is to use a grid-like, pipelined processing structure referred to as systolic array [29]. This approach is particularly well suited for high bandwidth applications and scales well with the number of MIMO streams. The concept of independent *lane-based baseband processing* of the streams after they have been separated [30] assures scalability in the second processing domain as well. From this point there is virtually no dependence between the lanes.

The natural parallelism of the PHY baseband is extended to the medium access (MAC) layer [31], where each PHY baseband lane has its correspondent in the higher layer. The MAC layer is responsible for the adaptive stream coding and modulation w.r.t the obtained error rates. It is controlled through a register file allocated in the PHY. Apart from the PHY/MAC interface, special care needs to be taken when designing the interfaces from the baseband processor to the other hardware modules (e.g. data converters, higher OSI layers) to avoid signal processing bottlenecks at these high data rates.

LoS MIMO Analog Channel Equalization: In order to achieve high energy efficiency and low transceiver complexity, low resolution Analog-to-Digital Converters are preferable [32]. However, the required dynamic range in multi-stream communication increases along with number of streams due to larger peak-to-average power ratios. Therefore, separating the streams before quantization can reduce the dynamic range requirements significantly, and also lower the latency/complexity introduced by digital baseband channel equalization.

Since applications like wireless backhaul operate in quasi-static channels, as discussed in Section 2.2, the channel parameters exhibit high temporal stability allowing the usage of analog components for the channel equalization. LoS MIMO is also known for high capacity robustness w.r.t. antenna displacement, i.e., translation and rotation [15]. With highly static channels and an optimal antenna arrangement, fixed analog equalization can be used for short range LoS MIMO communication links [33]. However, it is also noticed that the elements of $\mathbf{H}_{\text{LoS}}$ are very sensitive w.r.t. displacement errors. Therefore, fully controlled analog equalization networks are needed for equalizing the channel with displacements [34]. In this case, due to a large number of variable analog components, the complexity of fully controlled networks is much larger than that of fixed analog equalization designs.

A sensitivity study of the elements of channel matrices is carried out in [35] and can be explained via the 3D

channel factorization as proposed in [24]. The two diagonal matrices $\mathbf{D}_{\parallel,r}$, $\mathbf{D}_{\parallel,t}$ in eq. (6) are very sensitive w.r.t. displacement errors, while the matrix $\mathbf{H}_\perp$ is very robust. Therefore, a novel multi-stage analog equalization network was presented [35], [36]. We propose using variable analog components for equalizing the two diagonal matrices $\mathbf{D}_{\parallel,r}$, $\mathbf{D}_{\parallel,t}$ and a fixed analog network for equalizing $\mathbf{H}_\perp$. It is shown in [35] that the new design requires dynamic elements in the order of $O(N)$ only, while the fully controlled analog equalization design requires a larger number of dynamic elements, in the order of $O(N^2)$. Furthermore, the proposed multi-stage analog equalization network only introduces minor mutual information losses compared to fully controlled analog equalization designs [36].

3.2 Approaches to synchronization challenges

A critical factor for system design is the achievable accuracy of frequency and timing synchronization among multiple transceivers. One straightforward option to achieve frequency synchronization is to have a shared oscillator setup where one single carrier frequency is distributed to the different front-ends. This can reduce pilot overhead and, due to the geometrical structure of the LoS channel eq. (3), also simplify the channel estimation procedure [37]. Distribution of the mmWave carrier is, however, a very challenging analog design task, especially for large transceiver separations, as may be required for LoS MIMO backhaul. Thus, a better alternative may be the distribution of a *low frequency derivative of the carrier* [18], which was also done for the measurements in Section 2.2. The benefit of that approach is that the distribution is fairly simple, there is still only one frequency offset that needs to be estimated and compensated, and the frequency derivative could also be used for sample timing synchronization. The drawback is that for each transceiver additional phase locked loops (PLLs) generating the actual carrier frequency and sampling frequency are required, which increases complexity and power consumption of the system.

Phase noise is an oscillator-related impairment that can have a significant impact on the performance of MIMO backhaul systems [38], especially if high-order modulation alphabets are used. The effect is further amplified by the large bandwidth of millimeter wave systems, because phase noise contributions far from the carrier, which appear almost white, play an increasingly important role [17]. Nevertheless, having a shared oscillator or refer-

ence frequency setup also helps to lower the performance degradation experienced due to phase noise. The benefit of the structure is that phase noise is partially correlated and can be averaged across the different receiving streams by using pilots or a decision-directed approach [18], [39], when the PLL bandwidths are designed accordingly. The same approach also helps in dealing with sampling jitter.

3.3 Hardware-in-the-loop LoS MIMO demonstrator

The verification of the LoS MIMO system proof of concept was performed with a hardware-in-the-loop setup described further in this section. The system was initially modeled and verified at the algorithmic level. Transmission experiments were then performed with the setup shown in Figure 2 and described in Section 2.2. The sampling frequency offset, estimated to around 6ppm, and the carrier frequency offset, in the range of 6 to 10 KHz, were corrected for in the post-processing. Due to the sufficiently high SNR in the setup standard zero-forcing (ZF) MIMO equalization was used to separate the two streams. Two different measurement scenarios were set up at a short link range of 1.876m in order to investigate both the performance of the optimally arranged 2×2 LoS MIMO system and its sensitivity to single module displacements along the x- and z-axis [26]. The system has shown significantly greater sensitivity of the condition number κ to x-axis compared to z-axis displacements, matching the theoretical results [15], [24]. Provided the dimensions of the LoS MIMO system are properly scaled, the aforementioned conclusions would also hold for greater transmit distances D of ca. 100 m that are of interest to backhaul applications.

In our experiments an uncoded BER of 10^{-3} was observed, mainly attributed to the significant phase noise of the used analog front-ends (-87 dBc/Hz at a frequency offset of 1 MHz) and non-optimal equalization. Furthermore, the uncoded BER was found to be monotonically increasing with the estimated channel condition number, averaged over multiple channel realizations. Figure 6 shows that maximum system performance could be achieved with near-optimal MIMO setups. Using a modulation bandwidth of 625 MHz, an aggregate transmission throughput of close to 2.5 Gbit/s was demonstrated with the MIMO setup of a relatively low complexity. It is worthwhile noting that the system throughput can be considerably increased, i.e., tripled if the complete ISM channel bandwidth is used. Increasing the number of transmitted streams and the order of the modulation alphabet would

Figure 6: Hardware-in-the-loop system performance as a function of channel condition number κ . The results are obtained by zero-forcing MIMO equalization with a decision feedback loop for BPSK modulated streams under equal and high SNR [26]. The BER is calculated for data blocks of length 1000 bits, averaged across the two received data streams.

further increase the throughput. Hence data rates of tens of Gbit/s can be demonstrated, approaching the requirements of next generation wireless backhaul applications.

4 Conclusion

In this work, we have outlined the basic assumptions and design approaches for a millimeter wave LoS MIMO backhaul system, potentially supporting data rates well above 100 Gbit/s. A two-level LoS multi-subarray system is proposed, deploying spatial multiplexing on top of analog beamforming for the mmWave frequency range. The system concept relies on the carrier phase orthogonality between transmit and receive antenna arrays provided by a specific antenna arrangement. Measurement results have confirmed the basic assumptions about the orthogonality of LoS channels and substantiate that high spectral efficiencies can be achieved. Methods for parallelization of the MIMO system architectures that are capable of efficiently handling multiple streams at high data rates are discussed on two levels. Furthermore, lane-based processing of individual streams is introduced as a viable approach that scales well with the number of MIMO streams. We have considered synchronization approaches for these multi-transceiver systems, concluding that a shared low-frequency reference clock yields the most feasible system design, also lowering estimation complexity and increasing robustness to phase noise.

Finally, a demonstrator implementation showed that with fairly simple processing algorithms, spatial multiplexing within a single path can be achieved for near-optimal LoS MIMO setups.

4.1 Future Work

Further efforts are required on equalization processing in terms of improving its performance and efficiency, possibly by using hybrid signal processing approaches. Additionally, the observed multipath components could be exploited by MIMO processing in order to increase the throughput of the backhaul system and make it more flexible for different deployment scenarios. Naturally, considering a migration of the system concept to higher frequency bands [40] would provide even higher throughput, since more bandwidth is available, the channel becomes even more sparse, and the optimal antenna spacing is further reduced due to the even smaller wavelength. All of the obtained results and the outlined future steps should fuel the commercialization of LoS MIMO backhaul system developments, providing practically feasible solutions for next generation wireless networks.

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References

- [1] G. P. Fettweis, “Foreword LTE: The move to global cellular broadband,” *Intel. Technol. J.*, vol. 18, no. 1, pp. 7–10, 2014.
- [2] N. Bhushan, J. Li, D. Malladi, R. Gilmore, D. Brenner, A. Damnjanovic, R. T. Sukhavasi, C. Patel, and S. Geirhofer, “Network densification: The dominant theme for wireless evolution into 5G,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 82–89, 2014.
- [3] G. P. Fettweis, “The tactile internet: Applications and challenges,” *IEEE Veh. Technol. Mag.*, vol. 9, no. 1, pp. 64–70, 2014.
- [4] DragonWave Inc., “Multi-gigabit microwave backhaul with enhanced^{MC},” pp. 1–9, 2016, White Paper.
- [5] J. Brady, N. Behdad, and A. M. Sayeed, “Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3814–3827, 2013.

- [6] Z. Pi, J. Choi, and R. Heath, "Millimeter-wave gigabit broadband evolution toward 5G: Fixed access and backhaul," *IEEE Commun. Mag.*, vol. 54, no. 4, pp. 138–144, 2016.
- [7] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," *IEEE Trans. Commun.*, vol. 61, no. 10, pp. 4391–4403, 2013.
- [8] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Labs Tech. J.*, vol. 1, no. 2, pp. 41–59, 1996.
- [9] I. E. Telatar, "Capacity of multi-antenna gaussian channels," *Eur. Trans. Telecommun.*, vol. 10, pp. 585–595, 1999.
- [10] Z. Gao, L. Dai, D. Mi, Z. Wang, M. A. Imran, and M. Z. Shkir, "MmWave massive-MIMO-based wireless backhaul for the 5G ultra-dense network," *IEEE Wirel. Commun.*, vol. 22, no. 5, pp. 13–21, 2015.
- [11] P. F. Driessen and G. J. Foschini, "On the capacity formula for multiple input-multiple output wireless channels: A geometric interpretation," *IEEE Trans. Commun.*, vol. 47, no. 2, pp. 173–176, 1999.
- [12] S. Calabrò, B. Lankl, and G. Sebald, "Multiple co-polar co-channel point-to-point radio transmission," *Int. J. Electron. Commun.*, vol. 57, no. 5, pp. 1–7, 2003.
- [13] D. Gesbert, H. Bölcskei, D. A. Gore, and A. J. Paulraj, "Outdoor MIMO wireless channels: Models and performance prediction," *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 1926–1934, 2002.
- [14] T. Haustein and U. Krüger, "Smart geometrical antenna design exploiting the LOS component to enhance a MIMO system based on rayleigh-fading in indoor scenarios," in *Proc. IEEE Int. Symp. Pers. Indoor Mob. Radio Commun.*, 2003, pp. 1144–1148.
- [15] P. Larsson, "Lattice array receiver and sender for spatially OrthoNormal MIMO communication," in *Proc. IEEE 61st Veh. Technol. Conf.*, 2005, pp. 192–196.
- [16] X. Zhang, M. Matthaiou, E. Björnson, M. Coldrey, and M. Debbah, "On the MIMO capacity with residual transceiver hardware impairments," in *Proc. IEEE Int. Conf. Commun.*, 2014, pp. 5299–5305.
- [17] H. Mehrpouyan, M. R. Khanzadi, M. Matthaiou, A. M. Sayeed, R. Schober, and Y. Hua, "Improving bandwidth efficiency in E-band communication systems," *IEEE Commun. Mag.*, vol. 52, no. 3, pp. 121–128, 2014.
- [18] A. Puglielli, A. Townley, G. LaCaille, V. Milovanovic, P. Lu, K. Trotskovsky, A. Whitcombe, N. Narevsky, G. Wright, T. Courtade, E. Alon, B. Nikolic, and A. M. Niknejad, "Design of energy- and cost-efficient massive MIMO arrays," *Proc. IEEE*, vol. 104, no. 3, pp. 586–606, 2016.
- [19] 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 *Proc. IEEE Glob. Commun. Conf.*, 2015, pp. 1–6.
- [20] IEEE Std 802.11ad-2012, "Specific requirements-Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 3: Enhancements for very high throughput in the 60 GHz Band," pp. 1–598, 2012.
- [21] Federal Communications Commission, "Part 15 rules for unlicensed operation in the 57–64 GHz band," 2013, Report and Order.
- [22] F. Bøhagen, P. Orten, and G. E. Øien, "On Spherical vs. Plane wave modeling of line-of-sight MIMO channels," *IEEE Trans. Commun.*, vol. 57, no. 3, pp. 841–849, 2009.
- [23] F. Bøhagen, P. Orten, and G. E. Øien, "Optimal design of uniform planar antenna arrays for strong line-of-sight MIMO channels," in *Proc. IEEE 7th Work. Signal Process. Adv. Wirel. Commun.*, 2006, pp. 1–5.
- [24] X. Song and G. Fettweis, "On spatial multiplexing of strong line-of-sight MIMO with 3D antenna arrangements," *IEEE Wirel. Commun. Lett.*, vol. 4, no. 4, pp. 393–396, 2015.
- [25] T. Hälsig, D. Cvetkovski, E. Grass, and B. Lankl, "Measurement results for millimeter wave pure LOS MIMO channels," in *Proc. IEEE Wirel. Commun. Netw. Conf.*, 2017, pp. 1–6.
- [26] D. Cvetkovski, E. Grass, T. Hälsig, and B. Lankl, "Hardware-in-the-loop demonstration of a 60GHz line-of-sight 2x2 MIMO link," in *Proc. IEEE EUROCON*, 2017, pp. 631–636.
- [27] S. Salous, S. M. Feeney, X. Raimundo, and A. A. Cheema, "Wideband MIMO channel sounder for radio measurements in the 60 GHz band," *IEEE Trans. Wirel. Commun.*, vol. 15, no. 4, pp. 2825–2832, 2016.
- [28] M. Chouayakh, A. Knopp, C. Ahokpossi, and B. Lankl, "Low effort MIMO detector for frequency selective indoor channels," in *Proc. 14th Eur. Wirel. Conf.*, 2008, pp. 1–5.
- [29] K. Seki, T. Kobori, J. Okello, and M. Ikekawa, "A Cordic-Based Reconfigurable Systolic Array Processor for MIMO-OFDM Wireless Communications," in *Proc. IEEE Work. Signal Process. Syst.*, 2007, pp. 639–644.
- [30] D. Cvetkovski, T. Hälsig, B. Lankl, and E. Grass, "Next Generation mm-Wave Wireless Backhaul Based on LOS MIMO Links," in *Proc. Ger. Microw. Conf.*, 2016, pp. 69–72.
- [31] L. Lopacinski, M. Brzozowski, and R. Kraemer, "A 100Gbps Data Link Layer with a Frame Segmentation and Hybrid Automatic Repeat Request," in *Proc. Sci. Inf. Conf.*, 2015, pp. 1062–1069.
- [32] P. B. Kenington and L. Astier, "Power Consumption of A/D Converters for Software Radio Applications," *IEEE Trans. Veh. Technol.*, vol. 49, no. 2, pp. 643–650, 2000.
- [33] K. Hiraga, K. Sakamoto, T. Seki, T. Nakagawa, and K. Uehara, "Effects of weight errors on capacity in simple decoding of short-range MIMO transmission," *IEICE Commun. Express*, vol. 2, no. 5, pp. 193–199, 2013.
- [34] C. Sheldon, M. Seo, E. Torkildson, M. Rodwell, and U. Madhow, "Four-Channel Spatial Multiplexing Over a Millimeter-Wave Line-of-Sight Link," in *Proc. Int. Microw. Symp.*, 2009, pp. 389–392.
- [35] X. Song, W. Rave, and G. Fettweis, "Analog and Successive Channel Equalization in Strong Line-of-Sight MIMO Communication," in *Proc. IEEE Int. Conf. Commun.*, 2016, pp. 1–7.
- [36] X. Song, T. Hälsig, W. Rave, B. Lankl, and G. Fettweis, "Analog Equalization and Low Resolution Quantization in Strong Line-of-Sight MIMO Communication," in *Proc. IEEE Int. Conf. Commun.*, 2016, pp. 1–7.
- [37] T. Hälsig and B. Lankl, "Channel Parameter Estimation for LOS MIMO Systems," in *Proc. 20th Int. ITG Work. Smart Antennas*, 2016, pp. 98–102.
- [38] G. Durisi, A. Tarable, C. Camarda, R. Devassy, and G. Montorsi, "Capacity Bounds for MIMO Microwave Backhaul Links

- Affected by Phase Noise,” *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 920–929, 2014.
- [39] T. Haelsig and B. Lankl, “Performance Evaluation of LOS MIMO Systems under the Influence of Phase Noise,” in *Proc. 19th Int. ITG Work. Smart Antennas*, 2015, pp. 1–5.
- [40] J. Antes, F. Boes, T. Messinger, U. J. Lewark, T. Mahler, A. Tessmann, R. Henneberger, T. Zwick, and I. Kallfass, “Multi-Gigabit Millimeter-Wave Wireless Communication in Realistic Transmission Environments,” *IEEE Trans. Terahertz Sci. Technol.*, vol. 5, no. 6, pp. 1078–1087, 2015.