Beam Pattern Optimization Method for Subarray-based Hybrid Beamforming Systems

Joerg Eisenbeis 1, Jonas Pfaff 2, Christian Karg 2, Jerzy Kowalewski 2, Yueheng Li 2, Mario Pauli 2, and Thomas Zwick 2

1Karlsruhe Institute of Technology
2Affiliation not available

October 30, 2023

Abstract

Subarray-based hybrid beamforming (SBHB) systems represent an efficient architectural solution to realize massive multiple-input multiple-output (MIMO) systems. Thereby, the beamforming is no longer realized exclusively in the digital domain, but in coordination with an analog beamforming network by connecting each digital channel to a dedicated number of antenna elements via phase shifters. Most channel estimation and beamforming algorithms for SBHB systems are based on beam steering approaches, demanding a precise calibration of the analog beamforming network. In this letter, the SBHB system is calibrated by over-the-air (OTA) scattering parameter measurements and two criteria to optimize the beam pattern are formulated exploiting the ambiguities of the phase shifters. Both optimization criteria are evaluated using a designed SBHB receiver system operating at 27.8 GHz.
Beam Pattern Optimization Method for Subarray-based Hybrid Beamforming Systems

Joerg Eisenbeis*, Student Member, IEEE, Jonas Pfaff, Christian Karg, Jerzy Kowalewski, Member, IEEE, Yueheng Li, Student Member, IEEE, Mario Pauli, Member, IEEE, and Thomas Zwick, Fellow, IEEE

Abstract—Subarray-based hybrid beamforming (SBHB) systems represent an efficient architectural solution to realize massive multiple-input multiple-output (MIMO) systems. Thereby, the beamforming is no longer realized exclusively in the digital domain, but in coordination with an analog beamforming network by connecting each digital channel to a dedicated number of antenna elements via phase shifters. Most channel estimation and beamforming algorithms for SBHB systems are based on measurements and two criteria to optimize the beam pattern are formulated exploiting the ambiguities of the phase shifters. Both optimization criteria are evaluated using a designed SBHB receiver system operating at 27.8 GHz.

Index Terms—MIMO communication, Mobile communication, Calibration, Measurement uncertainty

I. INTRODUCTION

Massive multiple-input multiple-output (MIMO) systems operating in the centimeter-wave (cmWave) and millimeter-wave (mmWave) region are considered for the further expansion of mobile communication networks [1]–[4]. Those massive MIMO systems can achieve huge spectral efficiencies by exploiting the multipath wireless channel [5]. However, fully digital MIMO architectures consist of a separate transceiver for each antenna element, which makes them expensive and energy-hungry [6], [7]. An efficient architectural solution is the concept of hybrid beamforming systems, separating the beamforming process into a digital part of reduced size in combination with an analog beamforming network [8]–[10]. These hybrid beamforming systems reduce the number of digital channels, i.e. the number of digital-to-analog and analog-to-digital converters (DACs/ADCs), while conserving precise beamforming employing an analog beamforming network. A low-complex architectural realization of the analog beamforming network is the subarray-based (also denominated as sub-connected or partially-connected) hybrid beamforming (SBHB) architecture [11]–[13]. The SBHB architecture connects each digital channel to a subarray of antenna elements via a dedicated phase shifter.

To steer the antenna beam into the desired direction and to generate the desired beam pattern, a calibration in amplitude and phase of the different radio frequency (RF) branches is required [14]. This functionality is crucial for currently investigated channel estimation and beamforming algorithms [15]–[22]. To tackle the calibration problem over-the-air (OTA) calibration methods seem to be promising, as no additional RF calibration branches have to be integrated into the analog beamforming network. Note that a RF calibration branch per antenna element is technically and economically challenging, as massive MIMO arrays consist of hundreds of densely packed antenna elements [23], [24]. The presented OTA method in [25] for retrodirective antenna arrays calibrates the phases of the elements regarding a reference transmitter. This allows precise beam steering towards the reference, but does not calibrate the amplitude and phase imbalances between the RF branches. Another OTA approach is shown in [26], where the OTA calibration is performed using the equivalent currents technique with a spherical near-field multiprobe system. Nevertheless, the utilized measurement system is limited to 18 GHz and the size of the measured object is constrained. In [27] the amplitude and phase of a phased array system are calibrated by performing OTA scattering parameter measurements.

This letter follows the OTA calibration concept in [27], applying it to a SBHB receiver operating at 27.8 GHz. In contrast to related works, the beam patterns are further optimized after calibration by exploiting the ambiguities of the phase shifters by selecting the optimal initial setting of phase shifter of the first antenna element of the array. For selecting the initial setting, two optimization criteria are formulated and evaluated within measurements. The presented results indicate a clear performance improvement of the resulting beam pattern.

This letter is structured as follows. First, the developed SBHB receiver is presented in section II. Subsequently, the OTA calibration method is discussed in section III, including the required measurement setup and calibration result. Finally, in section IV two optimization criteria are proposed and evaluated in measurements exploiting the phase shifter ambiguities to further improve the antenna beam pattern.

II. SUBARRAY-BASED HYBRID BEAMFORMING RECEIVER

The overall receiver system consists of an independent antenna board, a SBHB receiver backend module, and two software-defined radios (SDRs). This modular setup enables characterizing the SBHB receiver independently and allows...
consists of an uniform linear array with $N\lambda$ arranged in the horizontal plane. The element spacing is $\lambda/2$ creating $N_{\text{ant}} = 16$ antennas arranged in the horizontal plane. To improve the antenna element gain two serially fed microstrip patch antennas. To improve the antenna element gain two serially fed microstrip patch elements are vertically stacked, narrowing down the half power beam width (HPBW) in elevation direction to $40^\circ$. The HPBW in azimuth is $86^\circ$ and measured realized element gain, including the connector and feed line losses, is 4 dBi. The SBHB receiver combines four antenna elements to one digital channel as shown in Fig. 1. A system on a chip (SoC) by Anokiwave of type AWMF-0108 [29] with four input channels and one output channel represents the core of the SBHB receiver. Each of the four input channels of the AWMF-0108 consists of a phase shifter and digital attenuator with 5 bit resolution each. The branches are then connected via power combiner on the AWMF-0108 SoC. The digital attenuators and phase shifters of the AWMF-0108 are controlled via a serial peripheral interface (SPI) using an Arduino Due microcontroller. A software interface is implemented onto the microcontroller translating the desired phase and attenuation settings defined by a host computer into the required code sequence to control the AWMF-0108 SoC. This software interface also enables to define an offset vector between the phase and amplitude states of the RF branches, which is utilized to take into account the calibration carried out later. Furthermore, a switch-off function for each RF branch is implemented by controlling the power supply of the first low noise amplifier (LNA) after the antenna element and setting the digital attenuator within the AWMF-0108 SoC to its maximum value. After combining the four input channels the receive signal is further amplified and down-converted from the RF at 27.8 GHz to an intermediate frequency (IF) at 2.46 GHz. The required local oscillator (LO) signal for down-conversion is provided externally at half the LO frequency, i.e. 12.67 GHz. The antenna board, as well as the SBHB receiver, are designed using a four layer printed circuit board (PCB) with a RO4003C substrate of 200 $\mu$m thickness and a dielectric constant of $\varepsilon_r = 3.38$ from Rogers Corporation. For electromagnetic shielding, protection, and better heat dissipation, the SBHB receiver is integrated into a metallic housing. Each amplifier stage is enclosed in a metallic chamber, which is lined with absorber material of type ECCOSORB GDS from Laird Performance Materials. Finally, the four IF outputs of the SBHB receiver are connected to two SDRs. The SDRs perform IF signal processing, down-conversion as well as the analog-to-digital conversion. As SDRs, we employ the commercially available platforms provided by Ettus Research LLC, i.e. universal software radio peripherals (USRP)s of type X310. A photo of the SBHB receiver without the housing cover is shown on the right side in Fig. 1.

### III. OTA Calibration Method

In general, the parallel RF branches in the analog beamforming network of the SBHB systems are prone to amplitude and phase differences, caused by non-ideal circuit board manufacturing, deviations between the used integrated circuits, connectors, and soldering tolerances. Especially the phase imbalances between the RF branches are more pronounced at higher frequencies due to the low wavelength, which leads to strong phase differences caused by small line length differences. As a result, a precise calibration between the parallel RF branches is required. This calibration becomes challenging as in massive MIMO systems several hundreds of antennas are closely packed. Classical out-coupling of a part of the receive or transmit power close to the antenna is technically challenging and inefficient, as it requires a huge number of feedback branches [23]. As a consequence, this letter focuses on OTA calibration methods. To correct phase and amplitude imbalances between the RF branches digital phase shifters and digital attenuators are utilized provided by the AWMF-0108 SoC. This means that the achievable accuracy of the calibration is limited by the phase shifter and digital attenuator resolution.

For the OTA calibration the measurement setup presented in Fig. 2 is utilized. The setup aims to measure the complex transmission coefficients, namely $S_{21}$, between a reference transmitter and each receiver of the SBHB system. Therefore the transmitter and SBHB receiver are separated by 6 m and
ideally aligned in an anechoic chamber. At the transmitter side a mixer of the same type as used for the SBHB receiver is employed in combination with a quad ridged horn antenna from RFSpin Ltd. of type QRH40 offering 14 dBi antenna gain and a half-power beamwidth (HPBW) of 27.8° at the selected center frequency $f_{\text{RF}} = 27.8$ GHz. To enable a measurement of the complex transmission factor the local oscillator signal for IF to RF up- and down-conversion is provided by the same signal generator. Moreover, the utilized network analyzer (NWA) from Keysight Technologies of type N9952A is operated at the IF frequency band from 1.26 GHz to 3.66 GHz resulting to a RF frequency band between 26.6 GHz to 29 GHz. The NWA is synchronized with the signal generator via a 10 MHz reference signal. The transmit power is set to $P_{\text{Tx}} = -17$ dBm resulting in a received power of $P_{\text{Rx}} = -76$ dBm with a FSPL $= 77$ dB at 27.8 GHz.

With the presented measurement setup the complex transmission matrix $S \in \mathbb{C}^{N_q \times N_{\text{ant}}}$ can be measured for all $N_{\text{ant}}$ receive antennas and for all $N_q = 2^q$ phase shifter states, where $q$ represents the resolution of the utilized digital phase shifter. The digital attenuators are set to their minimum for all branches to increase the receive signal-to-noise ratio (SNR). The measurements between the reference transmitter and each receiver branch are performed subsequently. As the phase and amplitude differences between the subarrays can be corrected in the digital domain, only the imbalances between the $N_{\text{sub}}$ antenna elements of a subarray must be compensated. Therefore, we reformulate the complex transmission matrix $S$ as $[S_1, \ldots, S_{N_{\text{dig}}}]$, where the transmission matrix of the $d$-th subarray has the shape $S_d \in \mathbb{C}^{N_q \times N_{\text{ant}}}$ for all $d \in \{1, \ldots, N_{\text{dig}}\}$.

The measured phase of the transmission matrix $\angle S$ is presented in Fig. 3. It can be observed that large phase imbalances exist between the different RF branches. The measurement results also show a deviation from the desired phase difference between the phase shifter states of the individual branches. Based on the measured transmission matrix the calibration vector for each subarray $c_d = [c_{d,1}, \ldots, c_{d,N_{\text{ant}}}]$ with $c_{d,i_s} \in \{1, \ldots, N_q\}$ for all $i_s \in \{1, \ldots, N_{\text{sub}}\}$ subarray antenna elements can be determined. This is done by finding the optimal calibration vector

$$
c_{d}^{\text{opt}} = \arg \min_{c_d} \left\{ \sum_{i_s=1}^{N_q} \sum_{i_s=1}^{N_{\text{ant}}} \angle S_d(i_q, i_s) - \frac{1}{N_{\text{sub}}} \sum_{p=1}^{N_{\text{ant}}} \angle S_d(i_q, p) \right\}
$$

minimizing the phase differences between the RF branches of the $d$-th subarray with

$$
i_q = \begin{cases} i_q + c_{d,i_s}, & i_q + c_{d,i_s} \leq N_q \\ i_q + c_{d,i_s} - N_q, & i_q + c_{d,i_s} > N_q \end{cases}
$$

The measurement result of the phase of the transmission matrix after applying the determined optimal calibration vector is shown in Fig. 4. The average phase error could be reduced from 28.8° before calibration to 6.6° at 27.8 GHz. The average phase error stays below 12° within 690 MHz from 27.59 GHz to 28.28 GHz. The reduction of the phase error over a larger bandwidth can be further improved by utilizing true-time delay phase shifter [30].

IV. Optimized Beam Pattern by Phase State Selection

For the SBHB system, precise alignment of the beam in the desired spatial direction is crucial. The alignment of the individual subarrays is achieved, as in classical phased arrays, by setting a phase difference $\Delta \phi$ between the RF branches. The adjustable phase difference depends on the resolution of the digital phase shifter. This results in the possible phase differences $\Delta \phi = \beta \varphi_\delta$ with the minimal phase difference $\varphi_\delta = 2\pi/2^q$ and the differences of the phase shifter states $\beta$. The adjusted phase difference between the antenna elements results for a uniform linear array in a steering towards [31]

$$
\phi = \arcsin \left\{ \frac{\Delta \phi}{kd_a} \right\}
$$

with the wave number $k = 2\pi/\lambda$ and the antenna element spacing $d_a$. The equation shows that only the relative phase between neighboring antenna elements is of importance to steer the beam into the desired direction. The possible phase shifter states $\beta \in \{-\beta_{\text{max}}, \ldots, -1, 0, 1, \ldots, \beta_{\text{max}}\}$ depend on the maximum desired steering angle $\phi_{\text{max}}$ resulting to

$$
\beta_{\text{max}} = \lfloor kd_a \sin \{\phi_{\text{max}}\} \rfloor.
$$

As the beam steering into the desired angular direction can be achieved by $N_q$ different phase shifter settings, this ambiguity
can be exploited to further optimize the beam pattern. As degree of freedom serves the phase index of the first antenna element $\xi_\beta \in \{1, 2, \ldots, N_q\}$, which can be freely selected. The phases of all other antenna elements are then adjusted relative to the phase setting of the first antenna element.

One possibility is to select $\xi_\beta$ leading to the minimum deviation between the desired phase difference $\beta \varphi_\beta$ and the actual phase difference between two adjacent branches. The optimization problem results to

$$\xi_{\beta}^{\text{ph,opt}} = \arg \min_{\xi_\beta} \left\{ \sum_{i_s=1}^{N_{\text{ant}}-1} \left| \angle S_d(i_{\xi_\beta}^{i_s+1}, i_s + 1) - \angle S_d(i_{\xi_\beta}^{i_s}, i_s) - \beta \varphi_\beta \right| \right\}$$

where the indices are defined as

$$i_{\xi_\beta}^{i_s+1} = \begin{cases} \xi_\beta^{i_s+1} & \xi_\beta^{i_s+1} \leq N_q \\ \xi_\beta^{i_s+1} - N_q & \xi_\beta^{i_s+1} > N_q \end{cases}$$

$$i_{\xi_\beta}^{i_s} = \begin{cases} \xi_\beta^{i_s} & \xi_\beta^{i_s} \leq N_q \\ \xi_\beta^{i_s} - N_q & \xi_\beta^{i_s} > N_q \end{cases}$$

Another possibility is to select $\xi_\beta$ maximizing the mean conversion gain (CG) over all branches. The optimization problem therefore results to

$$\xi_{\beta}^{\text{am,opt}} = \arg \max_{\xi_\beta} \left\{ \sum_{i_s=1}^{N_{\text{ant}}} \left| S_d(i_{\xi_\beta}^{i_s}, i_s) \right| \right\}$$

The changes of the phase error and the mean CG averaged over all possible angular directions is given by Table I. As reference serves the root-mean-square (RMS) value over all phase indices $\xi_\beta$ for both criteria. The results show that for $\xi_{\beta}^{\text{ph,opt}}$ the phase error could be reduced to 2.1°, while the mean CG is identical to the RMS value. For $\xi_{\beta}^{\text{am,opt}}$ the mean CG could be increased by 2.4 dB compared to the RMS value, while at the same time the phase error is slightly improved compared to the reference. As the phase error is sufficiently low to achieve a directional beam in the desired direction, the CG plays a more important role in increasing the SNR of the system. This becomes clear by looking at the beam pattern of the complete antenna array shown in Fig. 5. The blue shaded area within the figure represents the range of all possible $\xi_\beta$. As a reference serves the ideal beam pattern obtained from simulation. The necessity of a calibration becomes obvious by measuring the beam pattern of the uncalibrated system shown in Fig. 5a. Due to the imbalances in amplitude and phase between the RF branches the beam pattern is strongly distorted. The results for both optimization criteria indicate that the beam points towards the desired spatial direction. Moreover, the optimization of the mean CG achieves an increased antenna array gain compared to the optimization of the phase error by 1.2 dB for $\phi = 0^\circ$ and 2.2 dB for $\phi = -34^\circ$ compared to the optimization of the phase error. The measured RMS sidelobe level over all steering angles result for both optimization criteria to 10.5 dB, which is only slightly below the simulated RMS sidelobe level of 11.4 dB.

### Table I

| Phases of all other antenna elements are then adjusted relative to the phase setting of the first antenna element. The optimization problem results to |
|---|---|---|
| RMS | $\xi_{\beta}^{\text{ph,opt}}$ | $\xi_{\beta}^{\text{am,opt}}$ |
| Phase error | $7.0^\circ$ | $2.1^\circ$ | $6.3^\circ$ |
| SBHB mean CG | $45.2$ dB | $45.2$ dB | $47.6$ dB |

**V. Conclusion**

This letter presents a beam pattern optimization method exploiting the ambiguities of the phase shifters based on OTA scattering parameter measurements. Two optimization criteria are formulated and examined using a novel SBHB receiver system operating at 27.8 GHz. The results show that by optimizing the amplitude, the CG can be increased by 2.4 dB compared to the RMS value while ensuring a sufficiently low phase error of 6.3°. Thus the measured beam pattern achieves approximately the performance of the results obtained by numerical simulations.

**Acknowledgment**

Many thanks to A. Lipp and A. Gallego for their support in assembling the SBHB receiver. Furthermore we thank T. Bross from Richardson Electronics GmbH and A. Crofts from Anokiwave for their help with the utilized AWMF-0108 SoC.