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Cost-Effective and Power-Efficient Beamforming Remote Antenna Units for Millimeterwave Distributed Antenna Systems

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Abstract

To support the most demanding new applications, beyond-5G systems will more than ever rely on multi-antenna deployments and mm-wave spectrum. Unfortunately, due to its propagation properties, ultra-reliable high-data-rate mm-wave coverage seems elusive. Distributed antenna systems based on mm-wave-over-fiber constitute a strong candidate technology to unlock reliable mm-wave coverage, although the concept critically depends for a large part on the availability of cost-effective and power-efficient remote antenna units (RAUs). This contribution identifies two promising implementations for cost-effective and power-efficient beamforming at RAU-level, being a wideband Butler-matrix-based solution and a leaky-wave antenna (LWA), and validates them by means of system-level measurements. While the LWA-based RAU results in the lowest complexity with continuous beamsteering control, accurate control of the signal's carrier frequency is required, which is unacceptable for many applications. Notwithstanding its slightly higher complexity, the Butler-matrix-based RAU is widely applicable and allows reuse of the same frequency spectrum for multiple sectors.

1 Introduction

As the deployment of the first 5G networks takes place, the focus of industry and academia is shifting towards beyond-5G and 6G networks. To support exciting new applications, such as multisensory augmented/virtual reality (AR/VR) and connected robotics and autonomous systems (CRAS), beyond-5G networks will have to support unprecedented trade-offs in terms of data rate, reliability, latency and capacity [1]. This performance leap will not rely exclusively on novel disruptive technologies, such as large intelligent surfaces and artificial intelligence, but will also be based on the continuation of past trends, most notably massive multi-antenna deployments and the exploitation of fresh frequency spectrum (especially mm-wave/sub-THz frequencies) to boost data rate and capacity. Despite being a cornerstone technology, unlocking the full potential of frequency spectrum real-estate beyond 6 GHz proves challenging. On-board/on-chip mm-wave interconnections are often prone to high loss and susceptible to bandwidth-limiting parasitics and crosstalk, urging for a dense integration and co-design of the RF front-ends with the antenna elements (AEs) [2]. In addition, mm-waves suffer from more challenging propagation properties, in particular an increased path loss and severe shadowing. The former can be compensated by maintaining a sufficiently large antenna aperture, such as through array deployment. Unfortunately, the latter largely limits mm-wave systems to line-of-sight (LoS) scenarios [2], precluding applications such as AR/VR, where body shadowing frequently occurs, and Industry 4.0, characterized by harsh propagation environments with frequent non-line-of-sight conditions [3]. Current mm-wave systems respond to LoS blockage by either exploiting an alternative propagation path, such as a strong reflection, or even by resorting to sub-6 GHz communication, compromising on data rate. While the propagation environment can be made more hospitable to mm-waves, such as by installing relays and/or innovative intelligent reflective surfaces (IRSs) [4], such solutions are generally expensive and power-hungry, or still lack maturity [3].

This contribution discusses how reliable indoor mm-wave coverage may be unlocked by a distributed antenna system (DAS), which deploys several remote antenna units (RAUs) in the user equipment's (UE) propagation environment [3]. Subsequently, we focus on two promising cost-effective strategies to implement local analog beamforming at the RAU, more specifically a wideband Butler matrix compactly integrated with a highly efficient antenna array [5], and an efficient leaky-wave antenna (LWA) [6], both operating in the 26/28 GHz 5G bands (24.25 GHz–29.5 GHz). Both solutions are compared in-depth and validated through system-level measurements.

2 Distributed Antenna Systems based on mm-wave-over-fiber

Recently, DASs have been identified as a prime candidate architecture to unlock ultra-reliable indoor mm-wave coverage [3]. As shown in Fig. 1, by installing a number of RAUs at strategic locations, the UE maintains LoS to at least one RAU at almost all positions (robot A), even in a harsh propagation environment with several obstacles blocking LoS communication, typical in Industry 4.0 applications. In addition, at some locations, distributed multiple-input multiple-output (MIMO) techniques can be exploited to boost data rate (robot B). To implement the efficient exchange of wideband mm-wave signals between the RAUs and the central office (CO), which centralizes control over the radiated signals, [3] advocates a mm-wave-over-fiber backbone, following Fig. 1. Since the mm-wave signals are directly modulated onto the optical carrier, mm-wave-over-fiber-based DASs result in power-efficient and low-complexity RAUs, incorporating only electrical amplifiers, optoelectronic transducers and an antenna (array). Furthermore, this modulation scheme inherently ensures tight synchronization between the different RAUs, which further reduces complexity and facilitates the implementation of coherent beamforming by multiple RAUs. Finally, the DAS's performance may be enhanced by extending the RAUs with analog beamformers [7] for hybrid beamforming. The latter is considered particularly suited for mm-wave massive MIMO, since it enables an effective trade-off between power consumption, cost, and performance by realizing the precoder partly in the analog and digital domains [8].

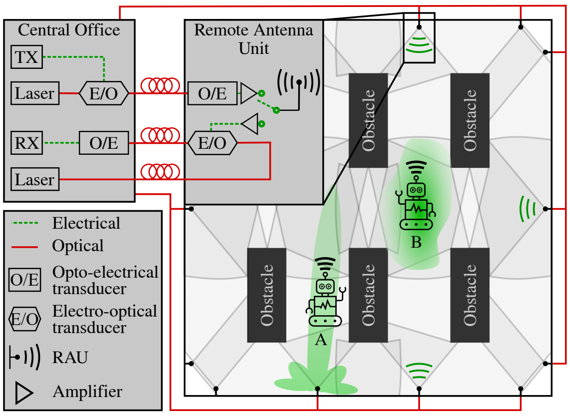


Figure 1. Distributed antenna systems with mm-wave-over-fiber backbone [3] unlock reliable mm-wave coverage. High-data-rate line-of-sight communication can be retained even in harsh propagation environments (Robot A). Distributed MIMO may even boost data rate (Robot B).

3 Cost-Effective Beamforming RAUs

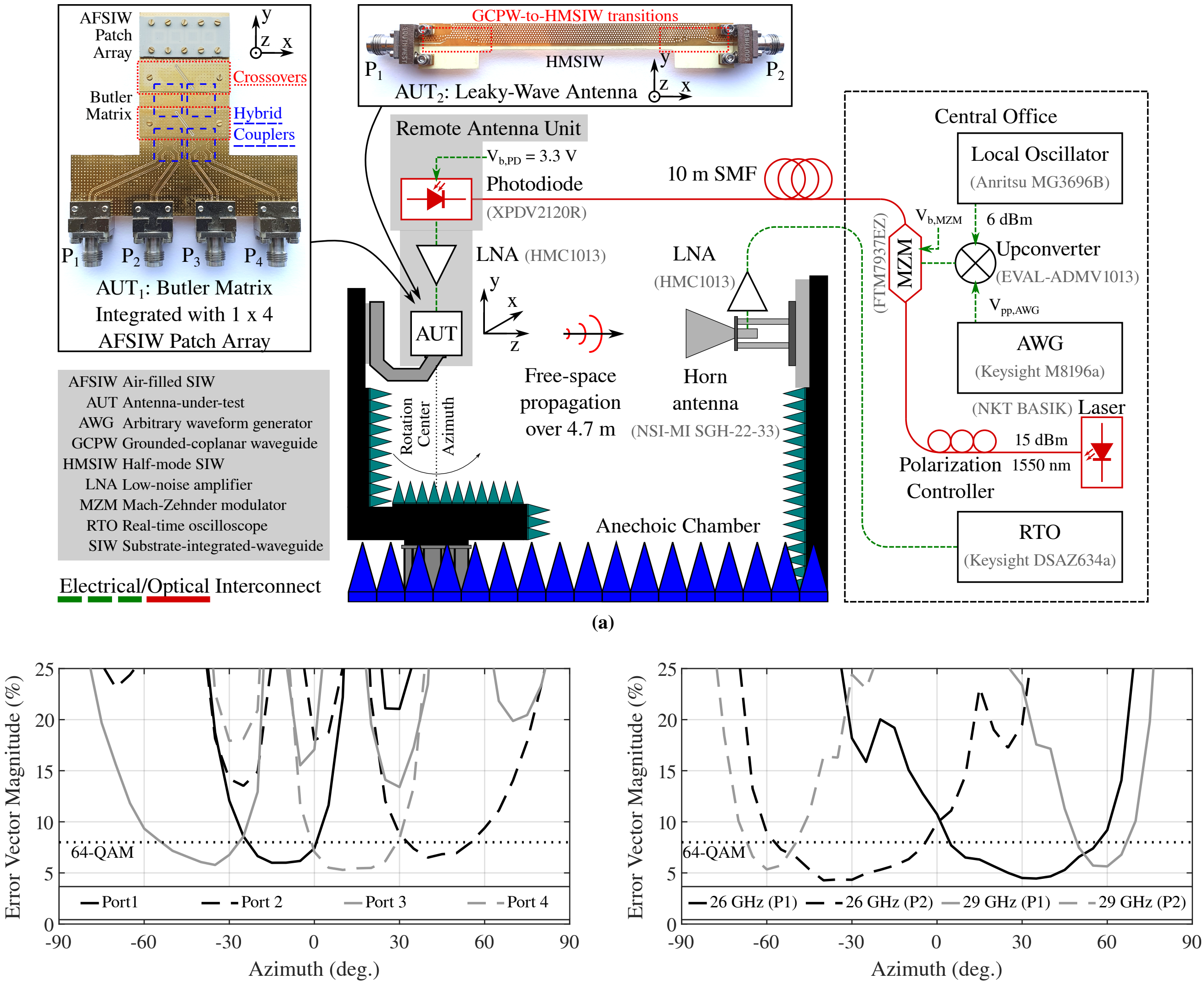
This section focuses on two analog beamforming implementations that are ideally suited for integration in power-efficient and cost-effective RAUs, being a Butler-matrix-based antenna array [5], and a compact LWA [6]. Both solutions are compared in-depth and validated by means of system-level measurements.

3.1 AFSIW-based Array with Butler Matrix

The first analog beamforming implementation [5] consists of a wideband 1×4 uniform linear array (ULA) [9], complemented by a compact and efficient Butler matrix (Fig. 2a, AUT_1). The four AEs adopt an aperture-coupled cavity-backed patch topology and are implemented in air-filled substrate-integrated-waveguide (AFSIW) technology [9]. The latter leverages air-filled regions inside cost-effective stacked printed circuit boards (PCBs) to create low-loss and wideband mm-wave components with performance rivaling bulky rectangular waveguide components. Practically, the ULA is realized by a stack of three single-layer PCBs: a 10-mil-thick RO4350B PCB containing the grounded co-planar waveguide (GCPW) feed lines and the hour-glass-shaped coupling slots, a central 1-mm-thick FR-4 PCB integrating the air-filled cavities (created through milling and subsequent edge-plating) that contain the antenna's fields, and a final 10-mil-thick PCB integrating the radiating patches. The low-loss AFSIW cavities not only maximize total efficiency (AE: $> 85\,\%$) and peak gain (AE: 7.4 dBi), but, in combination with the resonant coupling slots, also realize broadband performance (-10 dB impedance bandwidth > 7 GHz). In addition, the miniaturizing capacitive loading of the AFSIW cavities allows for a very compact ULA inter-element pitch of only 5.4 mm ($0.53\,\lambda_0$ at 29.5 GHz), enabling grating-lobe-free beamsteering from $-50°$ to $50°$. As shown in Fig. 2a (AUT_1), the 4×4 Butler matrix [5] is implemented entirely in GCPW technology and is densely integrated with the AE feeds on the same single-layer 10-mil-thick RO4350B PCB, minimizing interconnection losses. Depending on the selected input port (P_1-P_4), the Butler matrix is designed to excite the four AEs with equal amplitude but a different linear progressive phase, such that the phased array's main beam is steered towards one of four distinct directions ($-14°$, $40°$, $-40°$, and $14°$). To this end, it is composed of four quadrature hybrid couplers, two multilayer crossovers (using an additional, locally bonded 10-mil-thick RO4350B PCB), and phase-matching GCPW sections (Fig. 2a, AUT_1). Similar to its constituent components, the assembled Butler matrix exhibits excellent performance, with a measured excess insertion loss below 3.5 dB and a maximum amplitude imbalance of only ± 0.9 dB in the 26/28 GHz 5G bands. The integrated ULA/Butler matrix [5] yields state-of-the-art performance with a measured peak realized gain of 12.3 dBi, side lobe levels below -7 dB, and a fractional impedance bandwidth over 25 %, while occupying a compact footprint of only 21.4 mm × 46.0 mm. The measured beamsteering directions stay within $\pm 3°$ of the nominal values, ensuring a -3 dB beamwidth coverage of 110°. Despite its high performance, the integrated unit is assembled entirely of standard single-layer PCBs, and is therefore ideal to implement cost-effective RAU-level beamforming.

3.2 Leaky-Wave Antenna

Next, a half-mode SIW (HMSIW) LWA, shown in Fig. 2a (AUT_2), is used to implement phase-shifter-less beamforming at the RAU. The LWA is inspired on [6], but is reoptimized for wide-angle beamsteering in the targeted 24.25–29.5 GHz frequency band by using CST Microwave Studio. First, a full-mode dielectric-filled rectangular SIW is created, with its height and width selected such that only the fundamental mode (quasi-TE10) is propagating. Next, the SIW is cut in half along its center symmetry plane (acting as a virtual magnetic wall) to achieve a half-mode leaky-wave structure that preserves the advantages of SIW while



(a)

(b)

(c)

Figure 2. (a) Fiber-wireless measurement setup to validate the beamforming performance of the remote antenna units (RAUs) based on the Butler-matrix (b) [5] and the leaky-wave antenna (c) [6].

halving its footprint. The width of this HMSIW section is selected to fix the quasi-cut-off frequency of the fundamental mode at 23 GHz. Such unbounded HMSIW structure exhibits strong radiation, especially when operating near its quasi-cut-off frequency. This strong radiation leads to a highly-directive fan beam in the XZ-plane, with the main beam direction dictated by the carrier frequency. Subsequently, the HMSIW's bottom conductive layer is extended from the open aperture side to improve the LWA's front-to-back-ratio, essential to guarantee robust performance with minimal integration platform effects. Next, a three-section GCPW-to-HMSIW transition [10] is designed to achieve broadband matching between the HMSIW LWA and both edge-launch connectors (Fig. 2a, AUT$_2$). A prototype is implemented on a standard single-layer 20-mil-thick RO4350B PCB. Measurements reveal a total antenna efficiency of at least 70 % and a fractional bandwidth over 24 % (23.5 GHz to 30 GHz) in a compact footprint of only 103 mm × 15 mm. Furthermore, the LWA's main beam steers continuously from 12° to 62° (−12° to −62°), when the frequency of the signal exciting port 1 (port 2) changes from 24.25 GHz to 29.5 GHz while the other port is terminated.

3.3 Validation and Discussion

Prototypes of both beamforming implementations are validated with the fiber-wireless measurement setup shown in Fig. 2a. The antenna-under-test (AUT), being the Butler-matrix-based array (AUT$_1$) or the LWA (AUT$_2$), is mounted on a rotational stage (azimuth axis). Combined with the photodiode (bias voltage $V_{b,PD} = 3.3\,\text{V}$) and low-noise amplifier (LNA), the AUT implements the downlink of a RAU, which is connected to the CO by a mm-wave-over-fiber link. At the CO, the arbitrary waveform generator (AWG) generates a 1 GBd quadrature phase-shift keyed (QPSK) signal at an IF of 2 GHz, which is upconverted (ADMV1013) by a local oscillator to the carrier frequency. This mm-wave signal is modulated onto an optical carrier by a quadrature-biased ($V_{b,MZM} = 3.9\,\text{V}$) Mach-Zehnder modulator (MZM), resulting in an optical double-sideband signal, which is transmitted over a 10-m-long fiber towards the RAU. The RAU reconstructs and amplifies the mm-wave signal and radiates it towards the UE over a distance of 4.7 m in an anechoic chamber. The UE is implemented by a horn antenna, another LNA and the real-time oscilloscope (RTO).

To validate the beamforming performance of both RAUs (AUT_1 and AUT_2), the received signal quality, characterized by the received constellation's rms error-vector-magnitude (EVM), is recorded as a function of azimuth angle. By selecting the appropriate port, the Butler-matrix-based RAU (Fig. 2b) can serve a UE in one of four distinct sectors of ±25° with sub-8 % EVM values, allowing 64-QAM modulation and a data rate of 6 Gbps. Considering all four input ports, a total azimuth sector of about 110° is covered. Although fully passive, practical application of Butler-matrix-based beamforming at RAU-level requires integration of additional active devices to implement routing of the RF signals and remote control by the CO. The LWA-based RAU (Fig. 2c) covers a slightly larger total sub-8 % azimuthal sector of over 130°. In contrast to the Butler-matrix-based RAU, beamsteering is realized by changing the carrier frequency, with the signals at 26 GHz and 29 GHz setting up sectors around an azimuth angle of 35° and 60°, respectively. In addition, the inner sectors are significantly wider (55°) than the outer ones (20°), although this can be solved by further optimization of the LWA. While LWAs are very simple, cost-effective and power-efficient, mobility requires the users to change their carrier frequency, which is unacceptable for some applications. Nevertheless, it results in extremely low-complexity RAUs with full and continuous beamforming control at the CO. Finally, in principle, both RAU implementations allow multi-UE serving, although the LWA-based solution cannot serve two distinct frequency bands in an identical sector.

4 Conclusion

In this contribution, we have identified two promising implementations for cost-effective and power-efficient beamforming at the level of the remote antenna units (RAUs) in a distributed antenna system, being an efficient Butler-matrix-based solution [5], and a leaky-wave antenna (LWA) [6]. They were validated by system-level measurements. It is concluded that, while the LWA-based RAU results in the lowest complexity with full and continuous beamsteering control at the central office, changing of the signal's carrier frequency is required, which is unacceptable for many applications. In contrast, the Butler-matrix-based RAU is more widely applicable and allows reuse of the same frequency spectrum for multiple sectors.

Acknowledgements

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