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mmWave-over-Fiber Distributed Antenna Systems for Reliable multi-Gbps Wireless Communication

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Abstract

Recent technological advancements in the field of antenna design and microwave photonics have paved the way for broadband and efficient mmWave-over-fiber distributed antenna systems. In this work, we discuss the practical realization and measurement setup of a mmWave-over-fiber link and tackle the unfavorable propagation conditions that arise at mmWave frequencies. First, we demonstrate a 24 Gbps fiber-wireless link through the use of highly efficient and robust air-filled substrate-integrated-waveguide antennas and a custom co-designed photoreceiver with low-noise amplifier. Next, we deploy multiple antennas at the user equipment and analyze various combining methods to mitigate the self-blocking problem arising at these frequencies. To demonstrate its potential in harsh real-life environments, a mmWave-over-fiber distributed antenna system is set up in an environment resembling an Industry 4.0 workplace. We showcase how this system solves self-blocking and other problems that arise when the line-of-sight path is blocked. Moreover, by leveraging two tightly-synchronized remote antenna units distributed MIMO techniques double the channel capacity to 48 Gbps.

1 Introduction

The mmWave (30 GHz–300 GHz) frequency band is a key enabler for the Internet of Everything (IoE) in the (beyond-)5G era. Next-generation IoE applications, such as cyber-physical systems in Industry 4.0 and immersive multisensory interactive augmented and virtual reality, require enhanced mobile broadband (eMBB) access at ultra-low latency and high reliability. mmWave frequencies, however, suffers from increased path loss, higher penetration loss, and significant shadowing. Yet, their short wavelengths enable compact integration of multiple antenna elements to form highly-directive co-located antenna arrays that are capable of overcoming the higher path loss. However, such an approach is still prone to non-line-of-sight (NLoS) problems, such as shadowing or self-blocking. Different solutions have been proposed in case these unfavorable propagation conditions arise. Falling back to sub-6 GHz or exploiting a strong reflected path, either created by placing intentional reflectors or by exploiting existing reflections in the environment, compromises on link capacity and quality, respectively. Recently, some innovative solutions to provide reliable, high-data-rate wireless communication were proposed, such as the deployment of intelligent reflective surfaces (IRSs) at strategic positions in the user equipments' (UE) environment [1], or the exploitation of a large intelligent surface (LIS) [2]. The latter can be seen as a large contiguous surface filled with electromagnetic radiators surrounding the UE. This places the UE in the LIS's near field, enabling unprecedented energy focusing in three dimensions. Furthermore, [3] advocates the use of mmWave-over-Fiber distributed antenna systems (DAS) to provide high throughput and reliable coverage. Here, multiple antennas are distributed in the UEs' environment while a central office (CO) directly distributes the mmWave signal over fiber towards the different antennas. The major advantages of using mmWave-over-fiber are (1) the low-loss distribution of broadband mmWave signals, (2) the inherent potential to synchronize different remote antenna units (RAUs), and (3) cost-effective and relative simple RAUs, which only need to perform opto-electrical conversion, amplification, and potentially RF beamforming. Additionally, this approach enables the practical realization of the aforementioned LIS concept [3]. [4] compares mmWave-over-fiber to other fiber-wireless distribution options in a DAS.

In Section 2, a technical overview is given of the measurement setup for a single mmWave-over-fiber wireless link. Section 3 leverages multiple antennas at the UE to solve self-blocking problems in an anechoic environment. Finally, in Section 4, a DAS is built in a realistic environment encountered in future applications. The DAS deploys two fiber-wireless links to increase the total throughput of the system by leveraging distributed MIMO (DMIMO) techniques.

2 Measurement Setup Overview

Fig. 1 depicts a technical overview of the measurement setup of a single mmWave-over-fiber downlink, consisting of the equipment at the CO, a RAU, and the UE. At the CO, a 65 Gsps Keysight M8195 arbitrary waveform generator (AWG) generates the electrical baseband signals, which are upconverted to a 26.5 GHz carrier with an Analog ADMV1013 quadrature mixer. The optical side consists of a 10 dBm laser at 1550 nm and a polarization controller (PC). A variable gain amplifier (HMC943APM5E) drives a Fujitsu H74M-5208 lithium niobate Mach-Zehnder modulator (MZM). Since mmWave-over-fiber is used, the RAU only needs to perform opto-electronic conversion, amplification, and radiation. For this, a custom developed photoreceiver, consisting of a co-optimized silicon-photonic photodetector and GaAs low-noise amplifier (LNA) [5], is used together with an additional HMC1040 LNA and an HMC943APM5E power amplifier (PA) to ensure a constant transmit power of 20 dBm in all measurements. Air-filled substrate-integrated-waveguide (AFSIW) technology is leveraged as highly efficient, cost-effective and scalable antenna platform at the RAU and UE [6]. At the RAU, a 1x4 corporate-fed antenna array [7] is deployed with a peak gain of 10.1 dBi. At the UE, four single antenna elements with 7.4 dBi peak gain are spatially distributed. These antennas the antennas are attached to a 30 cm-high metal shaft of 20 cm diameter, resembling the harsh integration platforms encountered in real-life Industry 4.0 applications, such as metallic robots. The signals received by the UE's antennas are then amplified by a HMC100 LNA and sampled with a 80 Gsps real-time oscilloscope (Lecroy LabMaster 10Zi-A). Both the UE and the RAU can be seen in Fig. 2 in the anechoic environment. The metal shaft is able to rotate and is placed at a distance of 2 m from the RAU. The technical overview and the results in the remainder of this paper are only discussed in downlink communication, as we have shown that the fiber-wireless uplink features similar performance [3].

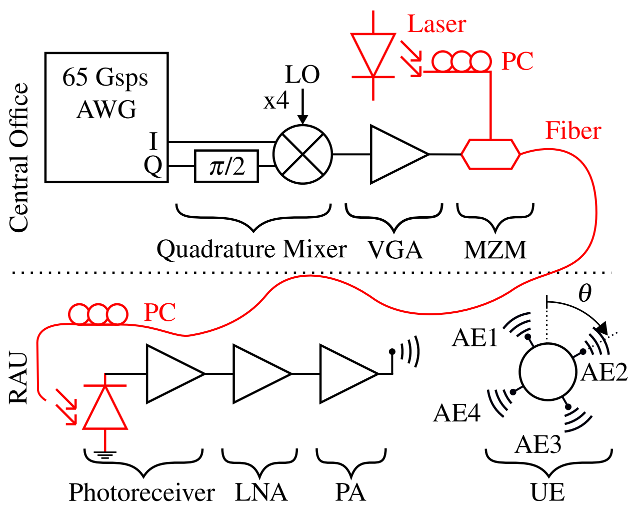

Figure 1. Measurement setup containing central office, remote antenna unit (RAU), arbitrary waveform generator (AWG), Mach-Zehnder modulator (MZM), polarization controller (PC), and the rotating user equipment (UE), equipped with four receiving antenna elements (AEs).

To analyze link performance, the root-mean-square error vector magnitude (rms EVM) of a QPSK-modulated signal is analyzed after the sampled signals are post-processed by a zero-forcing (ZF) equalizer. 3GPP states that reliable transmission of QPSK, 16-QAM, or 64-QAM symbols is possible if the rms EVM afer ZF is lower than 17.5 %, 12.5 %, 8 % respectively [8]. A pseudo random bit sequence (PRBS) is transmitted, where part of the symbols are treated as a pilot stream to construct the equalizer. Furthermore, a root-raised cosine filter is applied with a roll-off factor of 0.35.

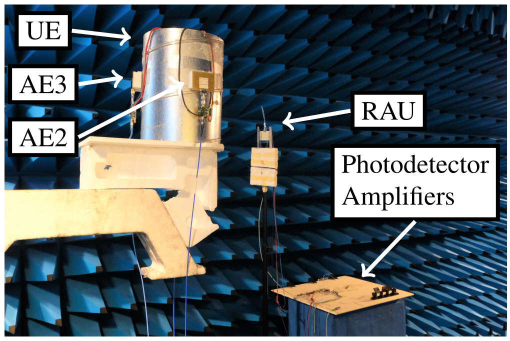

Figure 2. Picture of the measurement, showing the user equipment (UE) with two out of four antenna elements (AEs), the remote antenna unit (RAU), and the electronics.

As a baseline performance measurement, the single link as depicted in Fig. 1, is tested in an anechoic environment for modulated signals with baud rates from 2 GBd up to 7 GBd. Fig. 3 shows the rms EVM received at a single UE antenna as a function of the rotation angle of the UE. Independent from the baudrate, the link quality drastically reduces for $|\theta| > 45°$, caused by the 70° half-power beamwidth of the deployed AFSIW antennas, and the metal integration platform causing self-blocking. In the region of good coverage, the 2 GBd–4 GBd and 5 GBd–6 GBd signals result in data rates of 12 Gbps–24 Gbps and 20 Gbps–24 Gbps, respectively. The limited bandwidth of the total system, both caused by the co-optimized photoreceiver [5] and the antenna characteristics [7], yields an unusable link for signals with a symbol rate larger than 7 GBd (corresponding to a total bandwidth of 9.45 GHz due to the root-raised cosine filtering).

3 Spatial Diversity at the User Equipment

By deploying four antennas at the UE (Fig. 1) and spacing them equally, good link quality over 360° is guaranteed without self-blocking because of the 90° coverage of one antenna and the spatial diversity that is introduced. Fig. 4 shows the rms EVM of the received signals for the four different antennas as a function of the UE's rotation angle, for a 3 GBd and 6 GBd symbol rate. The solid line indicates the rms EVM value when the best possible link is selected, by applying selection combining (SC). This results in complete coverage with a symbol rate of 3 GBd. However, for a symbol rate of 6 GBd, the EVM exceeds the threshold for reliable transmission of 16-QAM symbols at the handover regions. With SC, the receiver only demodulates the signal

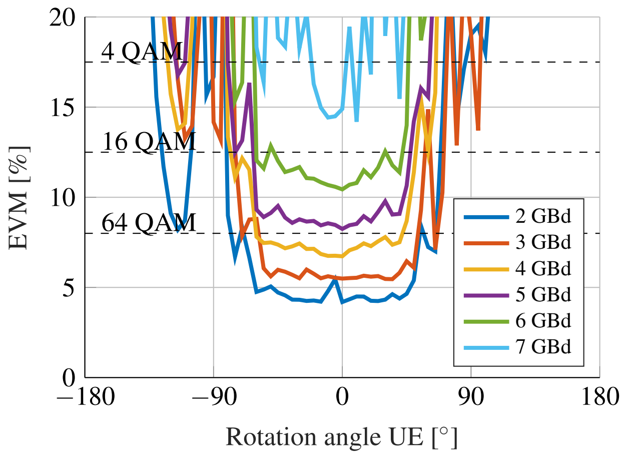

Figure 3. Root mean square error vector magnitude (rms EVM) for the downlink mmWave-over-fiber link when only one antenna is deployed on the UE (AE1).

received by the antenna that provides the best link quality and the energy received at the other antennas remains unused. At the handover regions, this issue can be resolved by adopting maximum ratio combining (MRC). In that case, the received signals are weighted with respect to their link quality and then summed. This guarantees an rms EVM below 12.5 % over 360° for the 6 GBd symbol rate (dashed line), leading to a stable 24 Gbps wireless link without self-blocking effects.

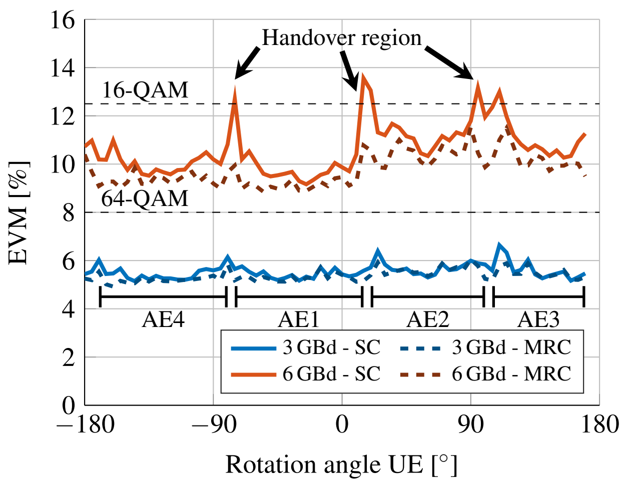

Figure 4. EVM as a function of the UE's rotation angle for a symbol rate of 3 GBd and 6 GBd, when deploying four antenna elements (AEs) at the UE. Selection combining (SC) guarantees a stable 18 Gbps wireless link (64-QAM at 3 GBd), while maximum ratio combining (MRC) guarantees a stable 24 Gbps wireless link (16-QAM at 6 GBd).

4 DMIMO in Realistic Environment

Previous measurements have already resolved the self-blocking problem in an anechoic environment by spatial diversity at the UE together with adequate combining techniques. In real-life scenarios, other NLoS problems may still occur (such as line-of-sight blocked by another user or a metal rack). An appropriate amount of RAUs distributed in the environment can tackle this problem. When LoS between a RAU and UE is blocked, the CO can direct the mmWave signal to a RAU with LoS to the target UE. In addition, this approach also paves the way towards distributed MIMO (DMIMO) and holographic beamforming.

To demonstrate the potential of this mmWave-over-fiber DAS, two RAUs are now deployed in our lab, mimicking the harsh propagation conditions of an Industry 4.0 environment. Fig. 5 shows the CO and the mmWave-over-fiber links to both two RAUs. The environment has a 4 m-high ceiling, metal walls, concrete floor, and it contains a lot of metal. The RAUs are placed at both ends of a corner with a metal rack in between. The mobile UE is placed at different locations, at 0.5 m-intervals along this path according to the orientation indicated in the figure.

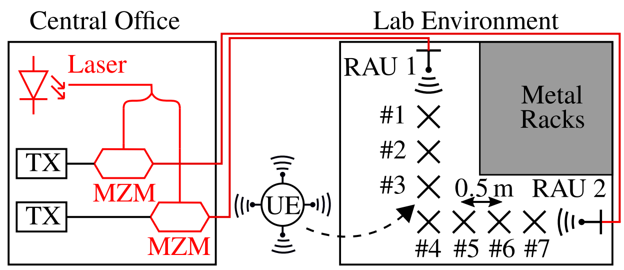

Figure 5. Measurement setup in our lab, representing a realistic propagation environment.

In the first measurement, the UE is moved from position #1 to #7 with only RAU 1 active. Fig. 6 shows the performance along the track for a symbol rate of 3 GBd and 6 GBd, for both SC and MRC. Although MRC extends the link quality up to location #5, if the UE is beyond the metal rack at positions #6 and #7, the LoS path is blocked and no usable signal is received.

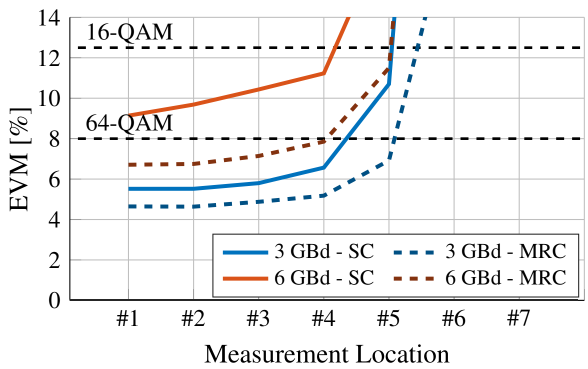

Figure 6. Selection combining (SC) and maximum ratio combining (MRC) in a realistic environment (Figure 5).

In Fig. 7, the complementary link quality is also shown (dashed line) for the UE moving from location #7 to #1 when only RAU 2 is active and SC is applied. Notice that this indeed allows switching between RAUs in case of blocking and, hence, increasing reliability and providing a stable link of 18 Gbps and 24 Gbps for symbol rates of 3 GBd and 6 GBd, respectively.

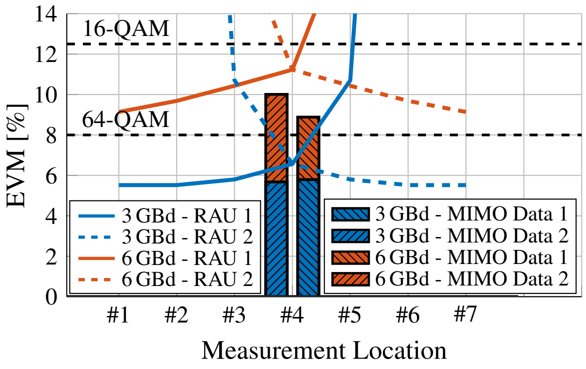

Figure 7. At location #4, where both remote antenna units (RAUs) have line-of-sight, double throughput is achieved leveraging distributed MIMO techniques.

Additionally, when the UE is located in a region where both RAUs provide a good link, such as in location #4, DMIMO techniques can be exploited to increase the total system throughput. In the measurement, both RAUs simultaneously transmit a signal with a different PRBS data stream. Part of both streams consists of known pilot symbols, which allows the UE to separate the signals coming from RAU 1 and RAU 2. Both streams are well below the 3GPP threshold for both 3 GBd and 6 GBd. Due to the distribution of RAUs and the spatial diversity created at the UE, the mmWave-over-fiber DAS realizes a double throughput of 36 Gbps and 48 Gbps for symbol rates of 3 GBd and 6 GBd, respectively.

5 Conclusion

This contribution described a measurement setup for a mmWave-over-fiber distributed antenna system. First, the baseline performance of a single fiber-wireless link is characterized, yielding a fiber-wireless data rate of 24 Gbps. This is achieved by leveraging the highly efficient air-filled substrate-integrated-waveguide antenna platform and the custom co-designed photoreceiver and low noise amplifier. To solve the inherent self-blocking problem in Industry 4.0 applications, combining methods, such as selection combining and maximum ratio combining, are exploited. Finally, two remote antenna units (RAUs) are deployed to form a mmWave-over-fiber distributed antenna system in combination with multiple antennas at the user equipment (UE). This experiment in a harsh real-life environment showed that combining methods and switching between RAUs can resolve self-blocking and other non-line-of-sight problems. In case both links have a stable connection to the UE, the channel capacity can be increased by leveraging distributed MIMO. Future research will focus on increasing the number of RAUs and UEs. In the process, we will explore optimal placement of the RAUs, and optimal number of antenna elements per RAU. This will eventually pave the way towards the practical realization of a large intelligent surface.

6 Acknowledgements

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