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Citation for published version (APA):

Budé, R., Versluis, M. M. A., Nazarikov, G., Rommel, S., van Ark, B., Johannsen, U., Tafur Monroy, I., & Smolders, A. B. (2021). Millimeter-Wave Outphasing using Analog-Radio over Fiber for 5G Physical Layer Infrastructure. In *2020 50th European Microwave Conference, EuMC 2020* (pp. 288-291). [9337942] Institute of Electrical and Electronics Engineers. <https://doi.org/10.23919/EuMC48046.2021.9337942>

DOI:

[10.23919/EuMC48046.2021.9337942](https://doi.org/10.23919/EuMC48046.2021.9337942)

Document status and date:

Published: 02/02/2021

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Millimeter-Wave Outphasing using Analog-Radio over Fiber for 5G Physical Layer Infrastructure

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Abstract— In this paper we propose to combine the concepts of outphasing and analog-radio over fiber. The analog outphasing signals are generated centrally and transported to the remote antenna system over fiber. There, high-performance and highly non-linear power amplifiers can be used. This approach creates an energy efficient communications infrastructure based on a centralized radio network. A first demonstrator is built at Ka-band using discrete components, experimentally showing the feasibility of this concept at millimeter-wave. Preliminary results show a measured error-vector magnitude of 4.18% over a wireless channel.

Keywords— 5G mobile communication, millimeter-wave communication, analog-radio over fiber, outphasing

I. INTRODUCTION

Next generation mobile and fixed wireless access networks such as the 5G network require the use of higher frequencies in order to accommodate transmission rate requirements. Increasing the carrier frequency gives access to a large amount of spectrum, which motivates the move to millimeter-wave (mm-wave) communications. Frequency bands that are of interest are Ka-band (26-40GHz) and E-band (71-86GHz), where Ka-band is considered mostly for mobile communications and E-band for point-to-point, point-to-multipoint and backhaul systems. One particular challenge at these frequencies is the efficient generation of RF power. It is well known that the efficiency of Power Amplifiers (PAs) at high frequencies is very low and for antenna arrays, for example, this leads to high thermal stress. Outphasing can be used to significantly improve amplifier efficiency. It is a concept that originates from 1935 [1], which allows two PAs to operate in saturation, and each PA amplifies a purely phase-modulated signal. When the outputs of the PAs are combined, any phase-and-amplitude modulated signal, such as a quadrature amplitude modulation (QAM) or orthogonal frequency division multiplexing (OFDM) signal can be reconstructed. This way high performance and highly non-linear amplifiers can be used to achieve linear transmission.

In this paper, the combination of outphasing and analog-radio over fiber (ARoF) [2][3] is proposed and demonstrated, where the two outphasing signals are generated at the central office (CO) and transported over fibers to the remote antenna systems. This situation is depicted in Fig. 1. The advantage of this system is that the data processing including the signal-component-separation takes place at the

Fig. 1. A conceptual overview of an Analog-Radio over Fiber 5G infrastructure, where the analog signals are generated at the central office, and transported to the remote antenna systems [2].

CO, allowing the antenna and transmission systems to operate in a strictly analog way.

In the future we intend to use this concept for point-to-multipoint E-band antenna systems. Here we present and demonstrate a first proof of concept of using outphasing in combination with ARoF, using a 16-QAM modulated signal at Ka-band.

II. OUTPHASING AND AROF

In an outphasing system the waveforms are generated using a signal-component-separator in the following way. A phase-and-amplitude modulated signal $S(t)$ can be written as

$$S(t) = A(t) \cos(2\pi ft + \theta(t)) \quad (1)$$

where $A(t)$ is the amplitude, f the carrier frequency and $\theta(t)$ is the phase of the signal. This can be decomposed in the two constant-envelope components $S_1(t)$ and $S_2(t)$ such that we have

$$S_1(t) = A_{\text{peak}} \cos(2\pi ft + \theta(t) + \phi(t)), \quad (2)$$

$$S_2(t) = A_{\text{peak}} \cos(2\pi ft + \theta(t) - \phi(t)) \quad (3)$$

with

$$A_{\text{peak}} = \max|A(t)| \quad (4)$$

and $\phi(t)$ the outphasing angle given by

$$\phi(t) = \arccos\left(\frac{A(t)}{A_{\text{peak}}}\right). \quad (5)$$

By summing $S_1(t)$ and $S_2(t)$ we end up with the original signal $S(t)$. Because $S_1(t)$ and $S_2(t)$ are purely phase modulated highly non-linear and efficient PAs can be used.

There are several methods that can be used to perform the summation. The author of [1], who originally introduced

the concept of outphasing, intended to use non-isolated power combiners. With non-isolated power combiners, the PAs are connected to each other through the load, which in this case would be a two-port antenna such as in [4][5] or a balun. Because the PAs are non-isolated load-modulation occurs. Being the most efficient of the methods, it is also the most complex, because the PAs need to be designed to handle highly reactive loads [6].

In our demonstration we will use two different simplified approaches as a first step. The first approach is using a Wilkinson combiner, which combines all in-phase power to the output while dissipating all out-of-phase power in a resistor. Because the inputs are isolated from each other, no load modulation occurs, but the efficiency is limited because of dissipation the resistor. Outphasing using isolated combiners is also referred to as Linear Amplification using Nonlinear Components (LINC) [7]. The second approach is free-space outphasing or *outsourcing*, where the $S_1(t)$ and $S_2(t)$ signals are radiated by different antennas. If there is no mutual coupling, this essentially becomes an isolated combiner as well, but instead of dissipating the out-of-phase power, it is radiated in a different direction than broadside. Some studies have suggested to combine this method with a phased array in order to achieve high gain and high efficiency [8][9]. To further simplify the system we use class-AB amplifiers in this first demonstrator.

To combine this concept with ARoF, the signals $S_1(t)$ and $S_2(t)$ are modulated onto an optical carrier. It is then transported over fiber to the remote antenna system with negligible losses. Here beamforming can take place and the outphasing signals are recombined at the antenna level or in free-space. The combination of ARoF and outphasing enables a truly efficient communications infrastructure, and this is the novelty of this work. A challenge that comes to mind with this system is that the amplitudes of the outphasing signals

should be equal and the phases should be tightly controlled in order to achieve good linearity and low error-vector magnitude (EVM). The purpose of this first demonstrator is to show that outphasing in combination with ARoF is feasible. Moreover, the robustness against a difference in power between the two branches is investigated.

III. EXPERIMENTAL SETUP

A. Outphasing transmitter

A schematic of the experimental setup is shown in Fig. 2. A laser with a wavelength of 1550nm serves as the source of the optical signal, which is fed into the first Mach-Zehnder modulator (MZM) biased at V_π , in order to suppress the main carrier. It is driven by a sinusoidal signal with a frequency of 13GHz. In this regime the MZM generates two side bands at a distance of 26GHz. The resulting optical spectrum is shown in Fig. 2a. The signal is amplified by an erbium doped fiber amplifier (EDFA) and divided into two channels using a 50/50 coupler. Variable optical attenuators (VOAs) are added to control the power in each branch. After polarization control the optical signals go into two parallel MZMs which are driven by the $S_1(t)$ and $S_2(t)$ signals. The resulting optical spectrum is shown in Fig. 2b.

The outphasing signals $S_1(t)$ and $S_2(t)$ are generated using the same setup as in [9][10]. First, 4000 random 16-QAM symbols are generated in Matlab. The complex symbols are convoluted with root-raised cosine pulses and decomposed according to (4) and (5). This leads to two complex constant amplitude signals according to

$$S_{BB}[n] = A_{\text{peak}} \exp^{j(\theta[n] \pm \phi[n])} \quad (6)$$

with $S_{BB}[n]$ the discrete baseband signal and n the sample number. In order to transmit $S_{BB}[n]$ it is decomposed in I and Q components such that there are now two pairs of

Fig. 2. Schematic overview of the experimental setup with a) the optical spectrum of the signal after the first MZM and b) the optical spectrum of the signal after the second pair of MZMs when modulated with data.

real-valued baseband signals, where one pair corresponds to the first outphasing component ($S_{I1}[n]$ and $S_{Q1}[n]$) and the other pair to the other component ($S_{I2}[n]$ and $S_{Q2}[n]$). Matlab is interfaced with two FlexRIO digital-to-analog-converters (DACs) via National Instruments' PXIe-1082. The two pairs of discrete baseband signals from the FlexRIOs are transmitted with a symbol rate of 5Mbaud and are converted to the analog domain. Then they are mixed to an intermediate frequency (IF) of 2.4GHz by two Maxim max2022 I/Q modulators, such that they are now in the forms of (2) and (3). The two resulting signals are amplified to increase the power to 14.5dBm.

Because control of not only the power but also the phase is required, optical time delays (TDs) are added as well. After 20m of fiber, self-heterodyning occurs on the photodiode (PD) converting the signal to RF. This finally generates the wanted frequency of 28.4GHz modulated with data in addition to another peak containing data at 23.6GHz, as well as other mixing products.

B. Receiver and setup configurations

After the conversion by the photodiodes from the optical to the RF domain, two different setups are considered for the recombination of the outphasing signals. In the first setup (the 'outspacing' setup) the two signals are amplified and transmitted over 8m using two separate antennas. This is the setup shown in Fig. 2. In the second setup (the 'outphasing' setup) the signals are combined using a Wilkinson combiner and no wireless transmission takes place.

For the outspacing setup a low-noise amplifier (LNA) and an additional PA amplify the received signal. For both setups, a mixer with an LO of 26GHz mixes the received signals at 28.4GHz and 23.6GHz back to an IF of 2.4GHz. A 100MHz reference signal is used to synchronize the 13GHz and 26GHz sources. After demodulation using a third Maxim max2022 I/Q modulator, the signals are discretized, filtered with root-raised cosine pulses and the data is recovered. The EVM is now processed in Matlab, where the RMS of the EVM is used, defined as

$$EVM_{RMS} = \frac{\sqrt{\frac{1}{M} \sum_{m=1}^M |S_i(m) - S_r(m)|^2}}{\sqrt{\frac{1}{M} \sum_{m=1}^M |S_i(m)|^2}} \quad (7)$$

with $S_i(m)$ and $S_r(m)$ the ideal and the received constellation points respectively.

IV. EXPERIMENTAL RESULTS

A. Outspacing measurements

First the outspacing setup is built. A picture of the transmitter of this setup is shown in Fig. 3. In Fig. 4 several spectra are shown. In a) the spectrum of the RF signal is measured after the PD, when no data is modulated onto the carrier. A clear peak at 26GHz is present. In b) the spectrum after the PD is shown when the data signal is modulated onto the carrier, showing the data is not only present at 28.4GHz but also at 23.6GHz. In c) the spectrum that is received and amplified by the LNA at the receiver side of the setup

Fig. 3. The wireless transmitter of the experimental setup. 1) Photodiode; 2) Power amplifier; 3) standard gain horn antenna.

Fig. 4. The power spectral density of the output of the photodiode a) without modulated data b) with modulated data and c) after wireless transmission and amplification by LNA with modulated data.

is shown. From this it becomes clear that the antennas do not attenuate the component at 23.6GHz significantly, but frequency components below 20GHz are cut off.

The constellation diagram of the received signal over the wireless channel is shown in Fig. 5. The best obtained EVM when using the outspacing transmitter is 4.18% which is better than the maximum required EVM for base station radio transmission using 16-QAM modulation [11]. The EVM is however highly dependent on the placement and alignment of the antennas, and the tuning of the TD. This might be because of the harsh multi-path environment in the Faraday measurement chamber and likely also the fact that the data is transmitted at several frequencies. A solution to this could be using OFDM to cope with reflections in combination with filtering the signal before amplification by the PAs, to remove signal components that are at unwanted frequencies.

B. Outphasing measurements

Now the outphasing setup is built and used to investigate the robustness of the system against differences in the optical power between the branches, without external RF interference and reflections in the chamber. For this test the EVM is

Fig. 5. The constellation diagram of the received signal for the outphasing setup. The blue dots are the received symbols, the red stars are the ideal locations of the symbols.

Fig. 6. Measured EVM for an increasing mismatch in optical power between the branches, when no compensation takes place and when compensation in baseband takes place.

measured when a difference in optical power is introduced and increased in steps of 1dB from 0dB to 4dB by using one of the VOAs. Keep in mind that the RF power generated by the PD scales with the square of the optical input power.

The result of this is shown in Fig. 6. The EVM that is measured for a 4dB difference is 22.73%. By digitally changing the amplitude and phase of the baseband signals, this can be partly compensated for. When this compensation is applied at each step, the EVM at 4dB becomes 12.95% and the lowest measured EVM is at 1dB with 3.18%. It is clear that mismatch increases the EVM, but this can be compensated to a certain degree. A measurement of the EVM degradation when changing the phase between the two branches should also be done in the future.

V. CONCLUSION AND FUTURE WORK

In this paper, we demonstrated a proof of concept of using outphasing in combination with ARoF at mm-wave. The measured EVM was 4.18% when the wireless outphasing setup is used. It is demonstrated that the effect of a power imbalance between the two optical paths can be reduced when compensation is applied digitally in baseband.

Future work will focus on improving and maturing this concept. In a new system the baseband signals can directly be upconverted to mm-wave using optical phase modulators which allows for generating only one peak in the radiated spectrum. Alternatively a higher IF can be used in combination with filtering. Either of these techniques will remove the unwanted frequency components of the signal. The new system will use a different waveform to cope with reflections in the measurement chamber. Carrier frequency offset estimation will make the 100MHz reference redundant. Research in later stages should also focus on replacing the class-AB PAs with PAs in non-linear region that are connected with a non-isolated combiner to prove that this concept increases the efficiency.

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