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Citation for the original published paper (version of record):
Olofsson, F., Aabel, L., Karlsson, M. et al (2022). Comparison of Transmitter Nonlinearity Impairments in externally modulated Sigma-Delta-over
Fiber vs Analog Radio-over-Fiber links. 2022 Optical Fiber Communications Conference and Exhibition (OFC)

Comparison of Transmitter Nonlinearity Impairments in externally modulated Sigma-Delta-over Fiber vs Analog Radio-over-Fiber links

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Abstract: Sigma-Delta-over-Fiber and Analog-Radio-over-Fiber are compared in terms of non-linearity impairments in a transmitter with external optical modulation. The results show that Sigma-Delta-over-Fiber is more robust towards nonlinear characteristics in the modulator.

1. Introduction

It has been shown that the coverage and capacity of future communication systems can be improved by distributing the base station radio units [1]. In Radio-over-Fiber (RoF) systems, optical fiber cables are used as medium to enable the distribution. There are three common techniques to modulate an information signal onto an optical carrier. In Analog-Radio-over-Fiber (ARoF), a radio-frequency (RF) signal is directly modulated on an optical carrier, with the advantage of high spectral efficiency. Although it promotes simple designs of remote radio units as only a photodetector is needed to recover the analog waveform, it is sensitive to non-linearities in the components [2]. In Digital-Radio-over-Fiber (DRoF) the information signal is transmitted as a binary bit stream in the fiber, with the advantage that it is robust towards non-linearities [3]. However, DRoF is often considered unattractive since it requires Digital-to-Analog converters in the remote radio unit, which are high power consuming at high sampling rates [4], DRoF is therefore not considered in this study. Sigma-Delta-over-Fiber (SDoF) can be considered a compromise between ARoF and DRoF, since it displays robustness towards non-linearities similar to DRoF, while resembling the implementation simplicity of ARoF, at the cost of high oversampling [5].

In [6], the performance of SDoF and ARoF was compared in a system where information signals were used to directly modulate a laser. Linearity performance was evaluated by doing two tone measurements for both SDoF and ARoF, as well as comparing Error Vector Magnitude (EVM). It was found that SDoF is more robust towards non-linearities in the laser and can achieve a lower EVM. Directly modulating the laser is however not the only implementation alternative, it is also possible to use a continuous wave laser with an external modulator. Using external modulators opens up for building more advanced transmitters, since different wavelengths can be modulated separately before being transmitted in the same fiber. This has previously been considered impractical as it requires a larger number of optical components in the chain, making the system bulky. However, due to the recent advancements within the field of photonic integrated circuits (PIC-s) it is now possible to place many optical components on the same chip, making solutions with several external modulators feasible. For example in [7], a SDoF transmitter with two Electro-Absorption-Modulators integrated on a PIC together with a splitter, a combiner and two fiber-to-grating couplers was presented.

SDoF and ARoF has been compared for direct - but not for external optical modulation [6]. In this work we therefore compare the non-linearity impairments of SDoF and ARoF when using an externally driven optical modulator, by evaluating symbol EVM and shape of frequency spectrum. The results show that SDoF is more robust towards non-linearities in the modulator and can therefore achieve higher dynamic range with a corresponding lower symbol EVM.

2. Method

Measurements were performed using the hardware setup in Figure 1. Baseband signals at a symbol rate of 40 MBd were created in MATLAB using a root-raised-cosine filter of roll-of factor 0.2, followed by digital up-conversion to passband with center frequency 2.35 GHz. For ARoF, the passband signal was inserted directly to the modulator with a RF vector signal generator. For SDoF, the passband signal was bandpass sigma-delta modulated

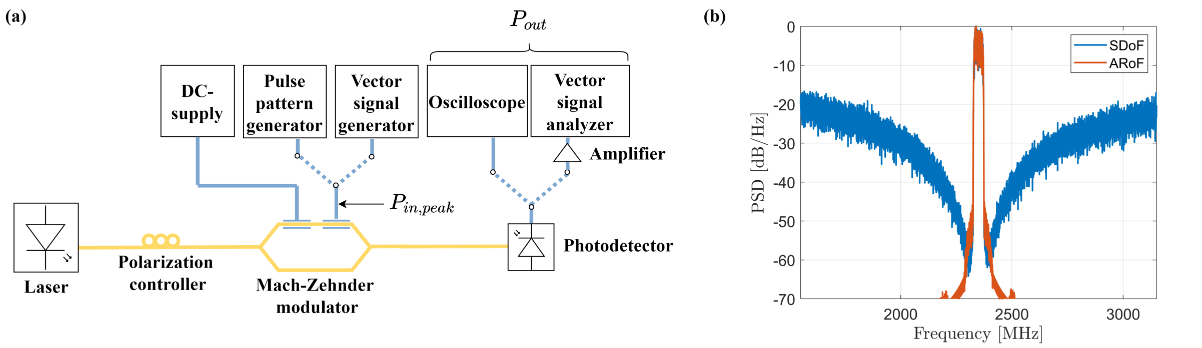

Fig. 1: (a) Schematic of the hardware setup. Blue lines are electrical signals and yellow lines are optical signals. The information signal is inserted to the modulator using either a Pulse Pattern Generator (Anritsu, MP1900A) for SDoF or Vector Signal Generator (Rhode&Schwarz, SMU200A) for ARoF. The modulator is biased at quadrature point with a DC-supply. A laser is used to generate an optical continous wave signal and before inserting it to the modulator with 25GHz bandwidth the polarisation is aligned with a polarisation controller. The modulated signal is then inserted to a photodetector with 50 GHz bandwidth before it is inserted to either an amplifier and vector signal analyser (Keysight, N9030A) or a real-time oscilloscope (Keysight, UXR1102A). b) Simulated frequency spectra of SDoF and ARoF passband signals showing the characteristic quantisation noise of Sigma-Delta modulation.

using MATLAB toolbox [8], an then applied to the modulator as a binary signal using a pulse pattern generator. The sigma-delta modulator had a sample frequency of 10 GS/s, corresponding to an over-sampling-ratio of 125 and the order was set to 4. The simulated spectra of SDoF and ARoF passband signals can be seen in Figure 1(b), showing the characteristic out-of-band quantisation noise of sigma-delta modulation.

The optical link consisted of a laser with wavelength $\lambda = 1554$ nm and average output power of 13.3 dBm, followed by a polarisation controller, an intensity modulator of Mach-Zehnder type with 25 GHz bandwidth, and a photodetector with 50 GHz bandwidth. The output RF-signal from the photodetector was either amplified using an amplifier with bandwidth 4.2 GHz and 30 dB gain and detected with a RF vector signal analyzer with 140 MHz bandwidth or detected with a high speed real-time oscilloscope with bandwidth of 60 GHz and 256 GS/s sampling frequency. In order to isolate the non-linear effects of the two links, the noise in the system was reduced by averaging the received symbols from 500 transmissions of the same signal. The comparison between SDoF and ARoF was done by biasing the modulator at the quadrature point and sweeping the corresponding input signal power. The input signal power was chosen such that all other components were used in their linear regimes.

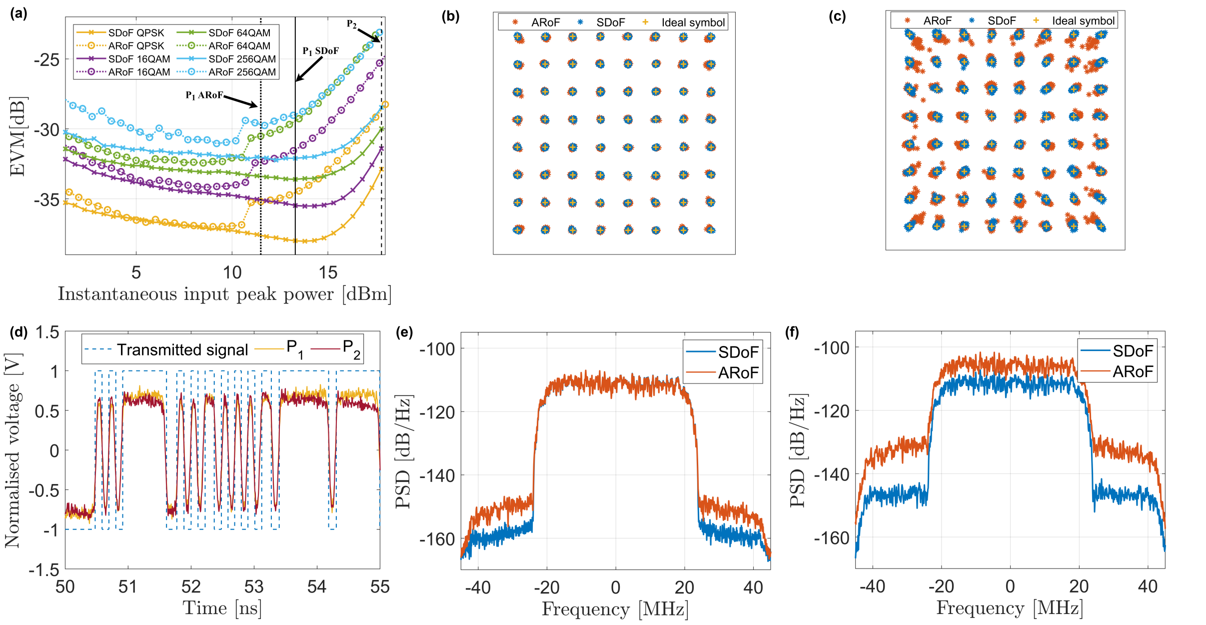

Fig. 2: (a) EVM versus instantaneous input peak power for SDoF and ARoF, using four different modulation formats. (b) Constellation diagram for SDoF and ARoF at P_1, using the same average output power of P_{out} = -22.2 dBm. (c) Constellation diagram for SDoF and ARoF at operating point P_2, using the same instantaneous input peak power of $P_{in,peak}$ = 17.8 dBm. (d) Time-domain normalised output voltage for SDoF at P_1 and P_2 together with transmitted signal. (e) Frequency spectrum for SDoF and ARoF at P_1. (f) Frequency spectrum for SDoF and ARoF at P_2.

3. Results and Discussion

Figure 2 compares SDoF and ARoF in terms of EVM vs instantaneous input peak power for four modulation formats. Instantaneous input peak power is defined as the largest instantaneous peak of the modulator input power, $P_{in,peak}$ in Figure 1(a). Hence, for ARoF it is the largest instantaneous power in the passband signal and for SDoF it is the peak power of the binary pulses. For $P_{in,peak}$ up to approximately 10 dBm ARoF and SDoF perform similarly, with a slightly better EVM for SDoF when using higher modulating formats. For $P_{in,peak}$ above 10 dBm, the ARoF waveform starts to get affected by the non-linearities of the modulator and the EVM thus increases. As $P_{in,peak}$ is increased above 15 dBm, also the SDoF performance is affected by the non-linearities, resulting in an increasing EVM.

Two operating points were investigate further. Operating point P_1 where the average in-band output power, P_{out} in Figure 1(a) was the same for SDoF and ARoF, and operating point P_2, where the instantaneous peak power of the modulator input power, $P_{in,peak}$ in Figure 1(a) was the same for SDoF and ARoF. P_1 was defined as when $P_{out} =$ -22.2 dBm and P_2 when $P_{in,peak} = 17.8$ dBm. The operation points are marked in Figure 2(a) where EVM is plotted vs instantaneous input peak power, $P_{in,peak}$. Figure 2(b) shows the constellation diagrams using 64-QAM modulation for both SDoF and ARoF at P_1. For SDoF an EVM = -33.6 dB, and for ARoF an EVM = -30.5 dB is obtained. Looking at the constellation of ARoF in Figure 2(b) in detail, it can be noted that the symbols with the highest symbol energy are affected by non-linearities. This is not seen as prominent in 2(b) for SDoF. Figure 2(c) shows the constellation diagram at P_2, where SDoF has an EVM = -30.0 dB and ARoF has an EVM = -22.3 dB. It can be noted from the distorted constellations that both SDoF and ARoF are affected by non-linearities at operating point P_2, however ARoF is more affected resulting in an 8 dB worse EVM.

The spectra of the output signals using 64-QAM modulation can be seen in Figure 2(e) for P_1 and in Figure 2(f) for P_2. At P_1, ARoF has higher adjacent channel power than SDoF, which is characteristic for a signal affected by non-linearities. Also at P_2, a higher adjacent channel power can be seen for ARoF. Furthermore, it can be noted that P_{out} for SDoF appears to be approximately the same in (e) and (f), even though $P_{in,peak}$ increases. To investigate this further, the time-domain signal of SDoF was observed using a real-time oscilloscope, see Figure 2(d). It can be seen that the normalised output voltage level for each pulse is slightly lower for P_2 than for P_1, which is consistent with the observation in the spectrum plot. It can also be noted that the binary waveform of the sigma-delta modulated signal is maintained through the system.

4. Conclusion

In summary, SDoF and ARoF have been compared in terms of non-linearity impairments in a transmitter with external optical modulation. The results shows that better dynamic range and lower symbol EVM can be achieved using SDoF, due to that ARoF is more limited by non-linearities in the modulator. The robustness towards non-linearities and the low implementation complexity of SDoF, together with the potential of integrating several optical modulators on one chip shows great prospects for building scalable distributed radio systems.

Acknowledgement

This work was funded by the Swedish Research Council (grant VR-2019-05174).

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