MIMO Capable RoF System with Improved SFDR using Quadruple Sidebands

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***Abstract*—An RoF system using a quadrature-multiplexing technique is shown experimentally to improve the 3rd order SFDR by 2.7dB over an intrinsic optical link. As a result of orthogonality between quadrature sidebands, the system can support MIMO.**

***Keywords*—Radio over Fiber, multiplexing, optical communication, nonlinearity**

I. INTRODUCTION

Owing to the wide bandwidth and low loss of optical fiber, analogue radio over fiber (RoF) technology has been widely used in distributed antenna systems (DAS) to transmit signals between a basestation (BS) and remote antenna units (RAUs) to provide reliable wireless signal coverage. However, new techniques have to be developed to accommodate multiple-input-multiple-output (MIMO) RF services, which are increasingly being introduced to improve spectral efficiency and throughput. Several methods have been reported to date to transmit MIMO signals over RoF [1-3]. In the main these techniques require additional optical fibers or optical wavelength channels, and hence there has been interest in single sideband (SSB) and double sideband (DSB) frequency translation systems which use a single optical wavelength channel operating over a single optical fiber, and are therefore relatively low-cost solutions [4-6].

In a quadrature-multiplexed frequency translation system, such as a DSB system, two MIMO channels are multiplexed onto sidebands with a 90° phase shift. At the RAU side, the signals are demultiplexed back to the original frequency. The noise from the upper and lower sidebands adds incoherently but the wanted signals add coherently at the output [5, 6]. As a result, the DSB system can theoretically have a 2dB higher spurious free dynamic range (SFDR) than the SSB system. The SFDR is a particularly important metric and one of the performance limiting factors for RF services on RoF links.

In this paper, we extend this concept and show that if the original RF signal is translated onto more than two sidebands, for instance quadruple sidebands (QSB), the system is not only MIMO-capable, but can also exceed the 3^{rd} order SFDR limit of the intrinsic optical link. This shows that, in a general radio over fiber system, the optical bandwidth can be traded for electrical SFDR by increasing the number of sidebands onto which the original RF signal is modulated.

II. THEORY OF THIRD ORDER SFDR IMPROVEMENT IN A QUADRATURE-MULTIPLEXED FREQUENCY TRANSLATION SYSTEM

Fig.1(a) shows a DSB system where the quadrature-multiplexed frequency translation is used to convert the original MIMO signals into the sidebands of the LO and multiplexes the two MIMO channels in quadrature. The multiplexed signals are pre-amplified and directly modulated onto the optical link. At the remote antenna unit (RAU) side, a similar arrangement to the basestation (BS) side is used to de-multiplex the MIMO signals. Fig. 1(b) shows the system layout when the MIMO signals are each translated onto four sidebands (QSB) to improve SFDR. If the original signals are translated into 2^n sidebands, n pairs of mixers are needed.

At the RAU side, frequency mixers combine all the sidebands back to the original MIMO signal frequency. The wanted signals add coherently, but the noise adds incoherently, giving the potential for a higher system SFDR as a result. Practically, the SFDR improvement is limited by the mixer nonlinearity, conversion gain, and the noise figure(NF) of the electrical amplifier required to compensate for the additional RF loss. Mathematically, this can be expressed by the following equations. The system 3rd order SFDR has the maximum value when the gain of pre-amplifier is given by:

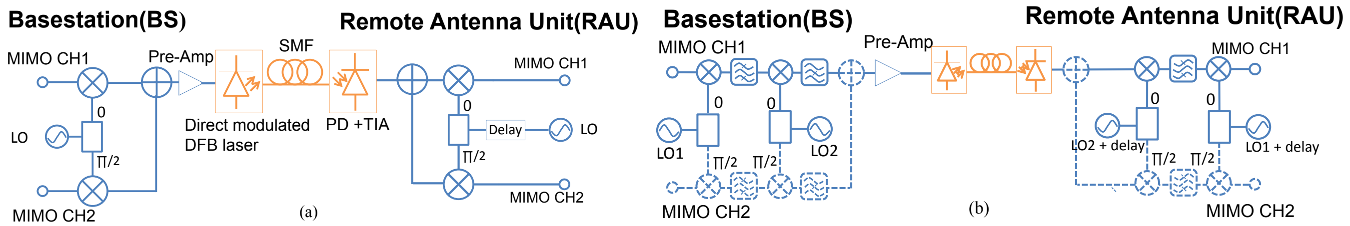


Fig. 1: Layout for quadrature-multiplexed frequency translation system.
(a)DSB system (b)QSB system (dash line part is not used in SFDR test)

$$g_{amp} = \sqrt{\frac{\left(\frac{1}{iip3_{mix1}g_{mix1}}+\frac{1}{iip3_{amp}}\right)(nf_{opt}-1)}{\left(\frac{1}{iip3_{opt}}+\frac{g_{opt}}{iip3_{mix2}}\right)(nf_{amp}-1)}} \qquad (1)$$

where g_{amp}, g_{mix1}, g_{opt} and $iip3_{amp}$, $iip3_{mix1}$, $iip3_{opt}$ are respectively the gain and iip3 of the pre-amplifier, the BS side mixers and the intrinsic optical link; $\mathrm{nf}_{\mathrm{opt}}$ and $\mathrm{nf}_{\mathrm{amp}}$ are optical link and pre-amplifier noise figures.

The system's maximum 3rd order SFDR follows the equation below:

$$sfdr3(max) \approx \left[\frac{n_{th}nf_{opt}}{m}\left(\frac{1}{iip3_{opt}}+\frac{g_{opt}}{iip3_{mix2}}\right)\right]^{-\frac{2}{3}} \qquad (2)$$

where n_{th} is the thermal noise; m is the number of sidebands that the system uses (for example, $m = 4$ if it is a quadruple sideband system).

In (2), if $m \geq 2$ and $\frac{1}{iip3_{opt}} > \frac{g_{opt}}{iip3_{mix2}}$ (3)

then,

$$\left[\frac{\mathrm{n_{th}nf_{opt}}}{\mathrm{m}}\left(\frac{1}{\mathrm{iip3_{opt}}}+\frac{\mathrm{g_{opt}}}{\mathrm{iip3_{mix2}}}\right)\right]^{-\frac{2}{3}} > \left(\mathrm{n_{th}} * \frac{\mathrm{nf_{opt}}}{\mathrm{iip3_{opt}}}\right)^{-\frac{2}{3}} \qquad (4)$$

Thus,

$$sfdr3(max) > sfdr3\ of\ intrinsic\ optical\ link \qquad (5)$$

It can be seen from (4) and (5) that if the conditions in (3) have been satisfied by selecting suitable frequency mixers and pre-amplifier, the 3rd order SFDR of a quadrature-multiplexed frequency translation system can be higher than that of the intrinsic optical link. However, because multiple frequency mixers are used, the mixers' overall conversion gain ($\mathrm{g_{mix1}}$ and $\mathrm{g_{mix2}}$) and IIP3 ($\mathrm{iip3_{mix1}}$ and $\mathrm{iip3_{mix2}}$) will be lowered, requiring a higher pre-amplifier gain ($\mathrm{g_{amp}}$) to compensate.

III. SIMULATION AND EXPERIMENT RESULTS

A. *Simulation on the SFDR improvement using multiple sideband frequency translation technique*

Simulation results for system 3rd order SFDR are shown in Fig.2. It is assumed that the intrinsic optical link has -33dB gain, 57.3 dB NF and 37.5dBm IIP3; each frequency mixer has 22dBm IIP3 and -8dB conversion gain. These values are to the same as in the experiment in Section III.B.

Fig.2 shows that the system has increasing SFDR with an increasing number of sidebands. On the other hand, in order to achieve the maximum SFDR, the required gain of the pre-amplifier also becomes higher. It can also be seen that if the pre-amplifier NF is >3dB, the maximum system SFDR does not increase much for more than 8 sidebands. For higher noise figures the additional impairments introduced exceed the benefits and the SFDR eventually decreases.

B. *Experiment of 3rd order SFDR measurement using DSB and QSB frequency translation*

A proof-of-principle experiment has been carried out using DSB and QSB frequency translation. A two-tone test has been performed at 800MHz, with a 1MHz frequency separation on one of the input channels with the other terminated, as shown in Fig.3. If both MIMO channels are occupied, the optimum

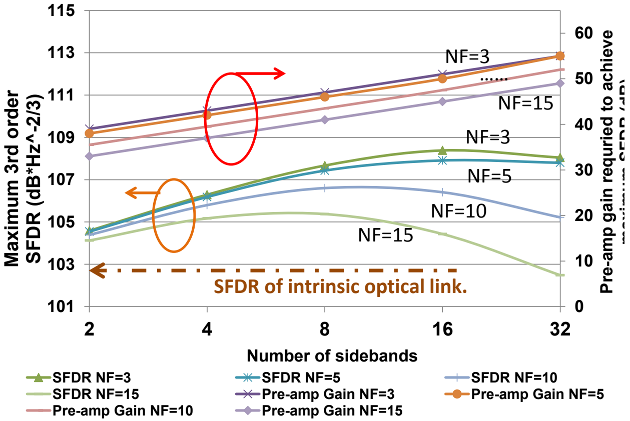


Fig. 2: Simulation result: the system maximum possible 3rd order SFDR and pre-amplifier gain required to achieve maximum SFDR

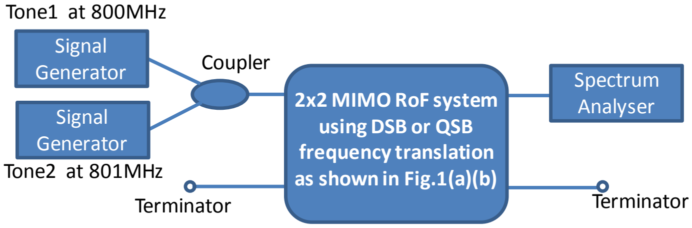


Fig. 3: Experiment layout: two tone test for 3rd order SFDR measurement of a 2x2 MIMO RoF system

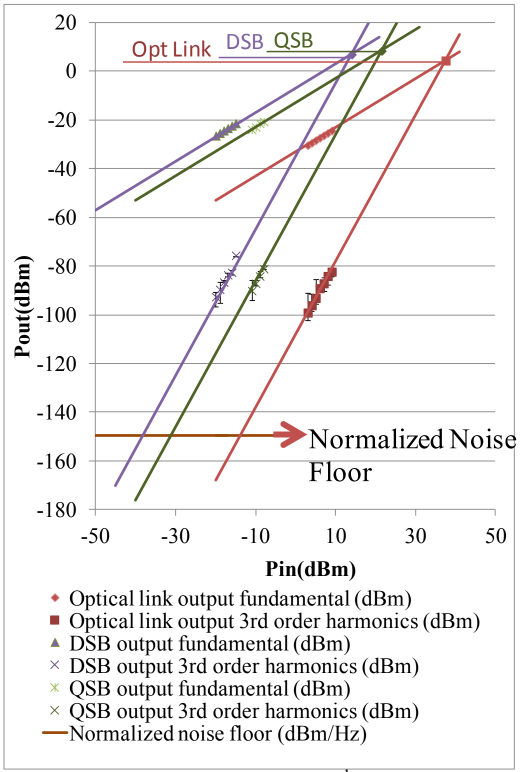
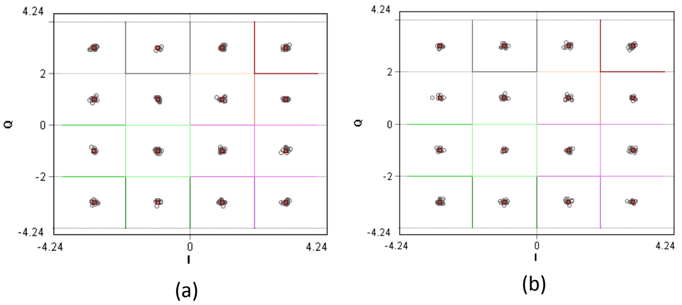


Fig. 4: Experimentally measured 3rd order SFDR of DSB and QSB system at 800MHz center frequency, comparing with intrinsic optical link



(a)

(b)

Fig. 5: Simulation result: received 64QAM constellation diagram using QSB, (a)channel 1 EVM = 2.45% (b)channel 2 EVM = 2.50%

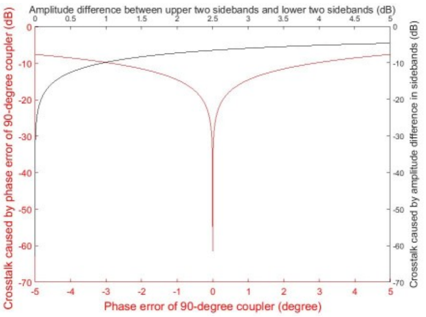


Fig. 6: System crosstalk vs. phase error in 90-degree hybrid couplers for a QSB system.

pre-amplifier gain is lower so that the same composite power is presented to the optical link. However the maximum SFDR is only slightly reduced since the optical ink is the most significant noise source, so the output noise is largely unaffected by the change in amplifier gain [6]. The layouts for the DSB and QSB systems are as shown in Fig.1(a)(b).The optical link in the experiment uses a directly modulated DFB laser, a 500m SMF link and a PIN photodiode with transimpedance amplifier (TIA). The RF pre-amplifier has 40dB maximum gain and 10dB NF.

The experimental results for the SFDR measurement are shown in Fig. 4. It can be seen that the 3rd order SFDR of the DSB and the QSB systems are 104.5 dB·Hz$^{-2/3}$ and 105.5 dB·Hz$^{-2/3}$ respectively, while the 3rd order SFDR of the intrinsic optical link is 102.8 dB·Hz$^{-2/3}$. Therefore, by using DSB and QSB frequency translation, the system 3rd order SFDR has been improved by 1.7dB and 2.7dB beyond that of the intrinsic optical link respectively. The results are achieved using a pre-amplifier gain of 30dB for the DSB system and 35dB for the QSB system. These results are in line with the theory presented above.

C. *Simulation on the capability to transmit MIMO-type signals using QSB frequency translation*

In order to show the system's full MIMO capability, a simulation has been performed in VPItransmissionMaker^{TM} with the same QSB system layout as in Fig.1(b). The optical link used in the simulation is identical to the experiment parameters in the SFDR measurement, as described in section III.A and III.B.

Two MIMO channels, with 20MHz bandwidth at 800MHz carrier frequency and 0dBm power have been simulated at the system input. The preamplifier gain has been chosen to be 30dB in the simulation. The mixer nonlinearity has been considered in the simulation by using nonlinear components with the same IIP3 (22dBm) as in the experiment. By selecting LO1 = 50MHz, LO2 = 1.0GHz, two MIMO channels are orthogonally multiplexed into four frequency bands, respectively centered at 150MHz, 250MHz, 1.75GHz and 1.85GHz. The 90° hybrid couplers used in the simulation have 3° phase error, which is a typical value in a commercial product [7]. Fig.4 shows the constellation diagram of the received 64QAM signals. The optimum EVM for both channels are ~1%, which is well below standard requirement in the LTE standard [8].

The crosstalk between two MIMO channels depends on the phase error in the 90-degree hybrid couplers and the amplitude variance among four sidebands as shown in Fig.5. If crosstalk<-10dB, the phase error of the 90-degree hybrid coupler should be <3° and the amplitude difference among four sidebands after frequency translation need to be within 1dB.

IV. CONCLUSION

A quadrature-multiplexed frequency translation RoF technique has been presented which can improve system the 3rd order SFDR beyond that of the intrinsic optical link, by trading optical bandwidth. A QSB system has been demonstrated experimentally with a 3rd order SFDR 2.7dB higher than the intrinsic optical link. It is also capable of supporting 2x2 MIMO.

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Additional data related to this publication is available at the University of Cambridge data repository: https://doi.org/10.17863/CAM.6779

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