Radio-over-Air with a Face-to-Face EML Transceiver Pair

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Abstract. A coherent-optical free-space link for local cloud radio access networks is proposed and experimentally evaluated. Conceptual simplicity is obtained by reducing opto-electronic sub-system complexity at both link ends to a single externally modulated laser. Full-duplex 64-QAM OFDM transmission over a transparent coherent optical pipe is shown over an optical budget of 21.3 dB, or an estimated reach of ~100 m in case of bad atmospheric conditions. The penalty in error vector magnitude is less than 1% when compared to a PIN/TIA-based receiver. Cost-effectiveness is achieved by off-loading the directional split in the signal chain to the RF domain and the dismissal of digital signal recovery functions typically associated to coherent reception.

1 Introduction

The required network densification for 5G deployments and the resulting high number of remote radio heads (RRH) suggests the adoption of local cloud-based radio access networks (C-RAN) [1]. In such an antenna remoting scheme, which is sketched in Fig. 1, a baseband unit (BBU) hosting computational resources connects to multiple RRH in its vicinity through an analogue or digital mobile fronthaul. Despite the progress in mm-wave RF communications [2], a radio-based fronthaul might not suit the capacity requirements since its capability to haul multi-GHz wideband signals is limited by the system bandwidth and propagation effects. In light of this, optics, and in particular optical free-space communications, can act as an enabler for the flexible deployment of such fronthaul links [3-5] – provided that the associated optical sub-systems are very cost-efficient.
In this work we experimentally demonstrate, for the first time to our best knowledge, bidirectional analogue radio-over-air transmission using an externally modulated laser (EML) as both, transmitter and receiver, at both, head- and tail-end site of the optical fronthaul link. We show full-duplex 64-QAM OFDM transmission over an optical budget of 21.3 dB at a small <1% penalty in error vector magnitude (EVM) compared to a half-duplex PIN/TIA receiver. These results are accompanied by long-term measurements to investigate the stability of such a transparent, coherent optical radio pipe.

2. Methodology: EML-to-EML fronthaul

Mobile optical fronthauling greatly relies on deployed fibre [6]. In fibre-scarce areas a local C-RAN may build on alternative solutions such as free-space optics. Unlike point-to-multipoint fibre networks where a complex transceiver can be cost-shared at the head-end BBU, such free-space point-to-point links require conceptually simple transceivers at both, RRH and BBU sites.
Traditional optical transmission systems employ dedicated transmitter and receiver sub-systems. Moreover, the directional split between down- and uplink is implemented through WDM or any other multiplexing dimension, in order to share the same channel in a bidirectional fashion. In this work, we exploit a pair of transistor-outline (TO) packaged EMLs (see inset in Fig. 1) to facilitate full-duplex radio-over-air transmission. We have recently demonstrated the coherent homodyne transceiver functionality of an EML [7]. In brevity, the distributed feedback (DFB) laser section of the EML is exploited as injection-locked local oscillator, which together with the electro-absorption modulator (EAM) as co-integrated photodiode yields an analogue coherent homodyne receiver. Although the spectral selectivity provided by coherent detection is not exploited in this work, it can support the robustness of the free-space link to residual near infra-red components of the sunlight or other luminaries installed in the vicinity of the communication link. Moreover, the reception sensitivity is improved so that no transimpedance amplifier (TIA) is required. Since the free-space channel is non-birefringent, polarisation management can be neglected.

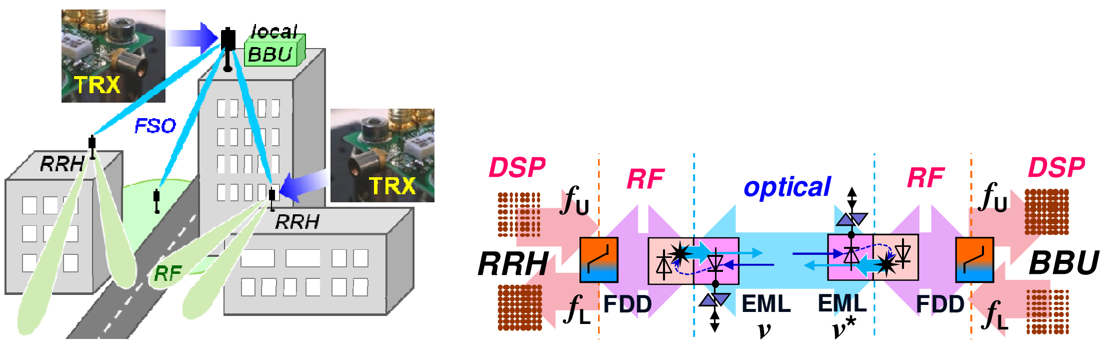

Fig. 1 Local C-RAN with free-space optical fronthaul based on a face-to-face EML arrangement and its signal chain.

Our proposed solution therefore builds on bidirectional RRH and BBU optics featuring one optical fibre port and one electrical RF port, yielding simple component assembly and packaging. Its bidirectional nature allows to off-load the directional split between down- and uplink radio path to the RF domain. The corresponding signal flow is included in Fig. 1. Frequency division duplex (FDD) of the radio signals at the two carrier frequencies f_U and f_L is employed for this purpose. Such an FDD scheme is foreseen in 5G radio systems with a paired spectrum [8], but can be in principle substituted by a common carrier frequency through a frequency-agnostic RF circulator with high isolation between its ports.

Compared to our previous work [9], the same transceiver methodology is employed at both ends of the optical link. A symmetrical optical pipe with low-cost transceivers at both sites is yielded, which allows for deployment in point-to-point systems with no access to cost sharing.

3 Experimental free-space optical radio link

The setup for the experimental evaluation of the proposed radio fronthaul in a lab environment is presented in Fig. 2. An EML at ~1547.7 nm is used as optical transceiver at BBU and RRH. The EMLs are coupled to a telescope through a PM fibre. A 2-inch collimation lens ensures good coupling between the two telescopes, which were spaced by 5 meters. A neutral density (ND) filter has been inserted between the telescopes to further emulate increased free-space path loss due to an extended reach.

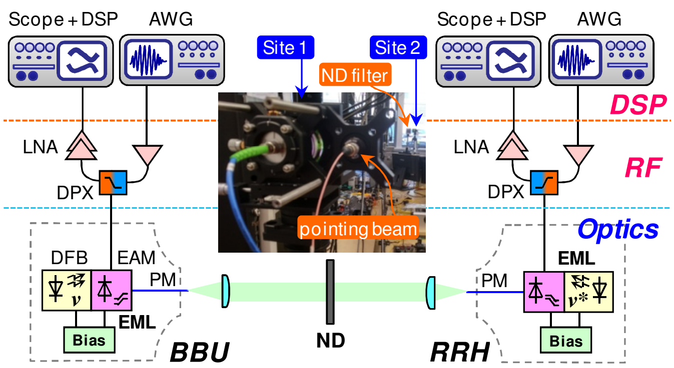

Fig. 2 Experimental setup of the free-space optical lab link.

The RF plane connects to the dual-function EAM photodetector/modulator element of the EML. A duplexer (DPX) with an edge frequency of 3.1 GHz splits the lower (f_L) and upper (f_U) frequency band for bidirectional radio signal transmission. Generation of the radio signals is conducted through an arbitrary waveform generator (AWG), while the reception performance is evaluated through off-line signal demodulation and EVM estimation.

In order to perform correct homodyne reception, the emission frequencies ν,ν^* of both EMLs are tuned so that one is falling within the injection locking range of the other. Figures 3(a) and 3(b) show the received signal spectra under this condition at the RRH and the BBU, respectively.

64-QAM loaded OFDM radio signals with 128 sub-carriers over a bandwidth of 125 MHz have been used for the down- and the uplink. The downlink OFDM signal δ transmitted from the BBU at f_L = 1.5 GHz is received with excellent signal integrity, meaning that there is no frequency offset in virtue of the coherent homodyne detection. When activating the uplink transmitter at the RRH, the finite RF isolation at the DPX leads to a crosstalk ξ that can be noticed at the uplink band at f_U = 5 GHz. However, there is no increase in background noise below the edge frequency ψ of the DPX.

In case of the uplink receiver at the BBU, for which the spectrum is shown in Fig. 3(b), an active downlink transmitter at f_L causes a crosstalk signal ς in the lower frequency band, which also leads to higher-order products at 3 and 4.5 GHz. At both full-duplex operated transceivers, analogue coherent reception is providing a correct signal translation during the medium conversion between the RF and the optical domain, even without assistance through DSP.

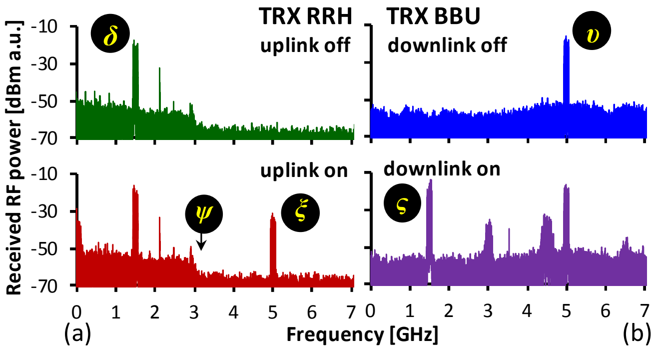

Fig. 3 Received RF spectra at RRH and BBU for half- and full-duplex down-/uplink transmission.

4 Results: Full-duplex signal transmission

The transmission performance of the free-space optical fronthaul has been assessed in terms of EVM measurements for full-duplex radio transmission. In order to perform this compelling task with a single EML, the EAM bias point has to be optimised. Figure 4(a) shows the average EVM at the BBU for the received 64-QAM OFDM signal at f_U in half-duplex mode, meaning that the radio signal transmission at f_L is switched off. First, the bias of the transmitting EML at the RRH is kept constant at -0.8V and the bias of the receiving EML at the BBU is varied (curve ρ). The average EVM drops with lower bias since crosstalk from direct-detection terms is reduced. The fast saturation of the detected signal magnitude with increasing EAM bias [9] renders the operation at a low bias of -0.35V as feasible. In a second step and in view of full-duplex operation at a common bias value, the bias of the receiving EML was fixed to this optimal value and the bias of the transmitting EML was pulled down to the same level (curve τ). Due to a reduced intensity modulation index the EVM increases as the bias falls to -0.35V, however, it remains below the EVM limit of 8%.

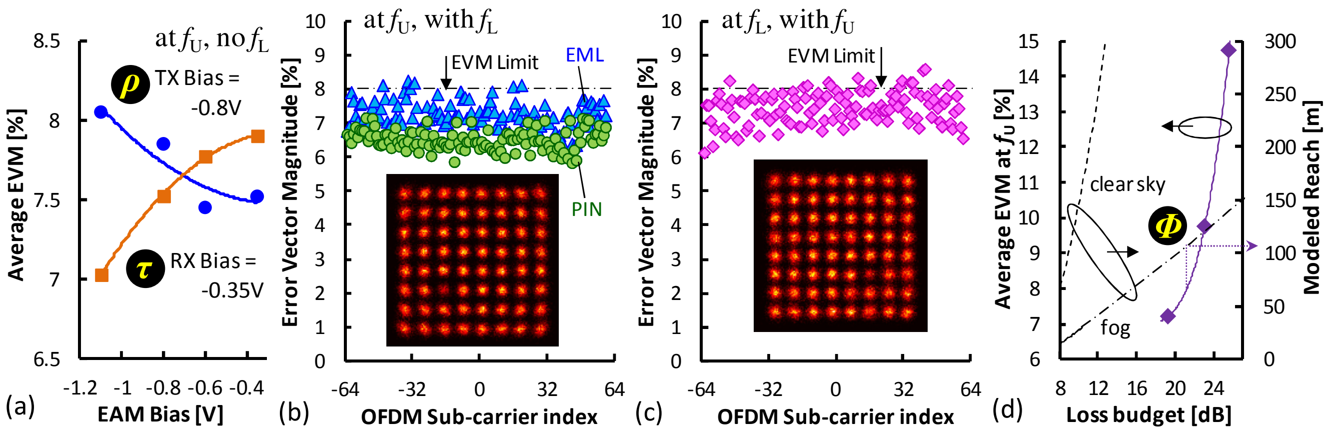

Fig. 4 (a) Reception performance during EAM bias optimisation. EVM under full-duplex operation for (b) the uplink and (c) the downlink channel. (d) Reception performance as function of the loss budget and estimated link reach.

The EVM measurements for full-duplex up- (f_U) and downlink (f_L) transmission are presented in Fig. 4(b) and 4(c), respectively. The uplink (▲) shows an average EVM of 7.21% for an optical loss budget of 19.3 dB between the PM-fibre ends, including the entire free-space optical path. The clear constellation diagram evidences that coherent homodyne reception and full-duplex operation is supported without extra DSP functions. Only 6 of the 124 data sub-carriers show a performance above the EVM limit. A PIN/TIA receiver has been used for comparison with a traditional detector in a half-duplex architecture (●). It shows an average EVM that is slightly improved by 0.73%. However, it cannot be used as transmitter at the same time, thus preventing a cost-optimized full-duplex transceiver solution. The EVM at the downlink af f_L (◆), shown in Fig. 4(c), is 7.46% in average and performs slightly worse than the uplink.

The dependence of the average EVM on the optical loss budget between the fibre-coupled EMLs is presented in Fig. 4(d) for the insertion of the ND filter. The compatible loss budget is 21.3 dB at the EVM limit of 8%. In order to estimate the corresponding reach for the free-space optical link, geometric losses and fibre coupling inefficiency have been taken into consideration. The resulting “clear-sky” loss vs. reach function corresponds to an ideal scenario, while dense fog causes a

typical link attenuation of 110 dB/km [10]. Comparing against such a scenario with unfavourable atmospheric conditions (Φ), we estimate a compatible reach of ~100 meters. This fits well to the targeted application scenario of a local C-RAN.
Finally, long-term EVM measurements have been conducted at f_U in order to investigate the stability of the face-to-face EML link architecture. Figure 5 presents the EVM per sub-carrier over more than one hour. Only a few EVM excursions have been noticed. These are attributed to the cavity nature of the link, which is believed to result in sporadic mode hops. However, for the majority of the measurement duration, stable radio transmission is observed.

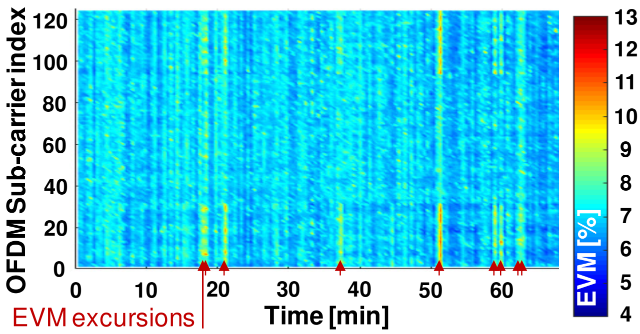

Fig. 5 Long-term reception performance for the uplink channel under full-duplex operation.

5 Conclusion

A conceptually simple, bidirectional free-space optical link has been experimentally demonstrated for analogue transmission of 64-QAM OFDM radio signals. Low-cost EMLs at the RRH and the BBU are used as full-duplex transmitter and coherent receiver in a face-to-face link architecture. There was no need for DSP-assisted signal recovery, which results in a truly transparent optical radio link. A small EVM penalty of 0.73% has been noticed with respect to a PIN/TIA receiver. A compatible reach of ~100 m has been estimated in agreement with local C-RAN applications. Long-term measurements have confirmed the stability of the the coherent optical free-space link.

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7 References

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