Real-Time Demonstration of an Optically Powered Radio Head for Low-Power Small Cells with 94 dB End-to-End Budget

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Abstract *End-to-end analogue down- and uplink radio transmission with real-time signal processing is experimentally demonstrated using a technologically lean and energy-conscious remote radio head. Powering through the fronthaul at an optical feed of 290 mW enables a centralised power supply.*

Introduction

In the upcoming years we anticipate a continuous increase in wireless data rates. Hence, small cell techniques increasing network density have an important role to play[1]. This entails that baseband processing is off-loaded to the CO while simple remote radio head (RRH) technology remains at the cell site. However, as load conditions in wireless networks are shifting rapidly with the mobility of its users, RRHs that are distributed across the network infrastructure need to be dynamically taken into operation to optimize the interplay of macro- and small cells. Such a scenario is unfavourable for practical deployment: even in case of strongly localized cells, each site needs to be supplied with data and energy, thus being subject to high cost.

In this work we experimentally demonstrate a remotely powered RRH with low-cost VCSEL transmitter and energy-conscious RF amplification. End-to-end real-time transmission of OFDM radio signals with PRBS and HDTV payload is shown over a radio and fronthaul loss budget of 84 and 10 dB, respectively.

Low-Power Remote Radio Head

In the proposed radio access scheme conventional high-power RRHs of macro-cells are assisted by additional low-power distributed RRHs during on-peak, especially in overloaded spots where the user density is peaking regularly. With the introduction of numerous small cells associated to fewer macro-cells the complexity of these additional RRHs becomes a critical parameter since cost attributed to RRH subsystems is shared among a smaller number of network users. Simplicity is therefore of paramount importance and can be facilitated by: (1) Analogue radio-over-fibre transmission as an attractive solution to handle high CPRI-equivalent data rates at the fronthaul[2] while also assuring lean small-cell RRHs based solely on low-noise amplification (LNA) and an linear optical transceiver. (2) Energy reclamation at the RRH fronthaul interface allows to centralize power supply units of RRHs at the CO.

Down- and uplink performance of a small-cell RRH has been evaluated in the setup shown in Fig. 1. At the CO the downlink I/Q data signal is up-converted to a RF carrier at 2.05 GHz. A post-amplified Mach-Zehnder modulator (MZM) transmits the signal at 1547.72 nm with a power of 10 dBm over the 4 km SMF-based fronthaul. At the RRH the signal is boosted by energy-conscious LNA towards the radio equipment (RE) where real-time block error ratio (BLER) estimation is performed on a payload size of 9024 bits/packet. OFDM with an IEEE 802.11a compliant format having a modulation bandwidth of 20 MHz and 64 subcarriers was employed. The real-time DSP at transmitter and receiver performs OFDM (de-)modulation with insertion of pilots, synchronization sequences and cyclic prefix. Moreover convolutional coding with code generator polynom (171_8, 133_8) and code rate $^1/_2$ is employed. The DSP stack was implemented using the NI USRP-2953R software-defined radio and was fed by either PRBS for real-time BLER measurement or by

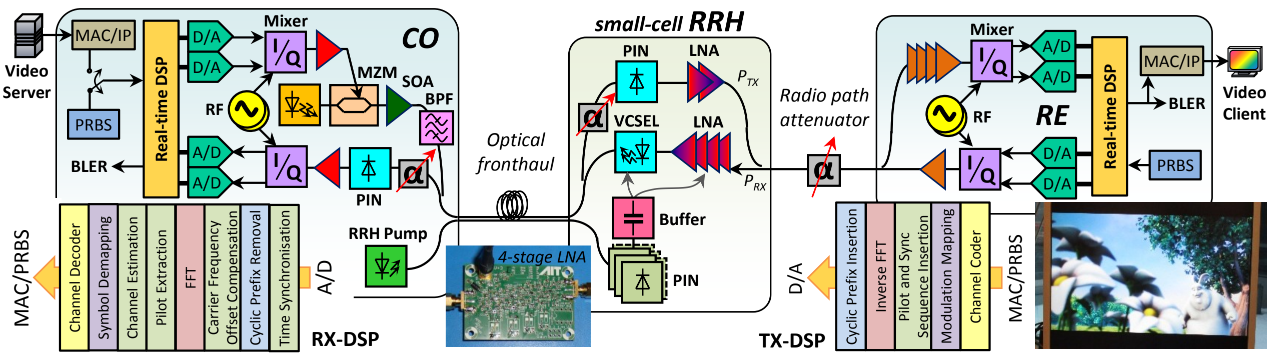

Fig. 1: Experimental setup and DSP stack for evaluating a low-power RRH that is supplied with energy through its fronthaul.

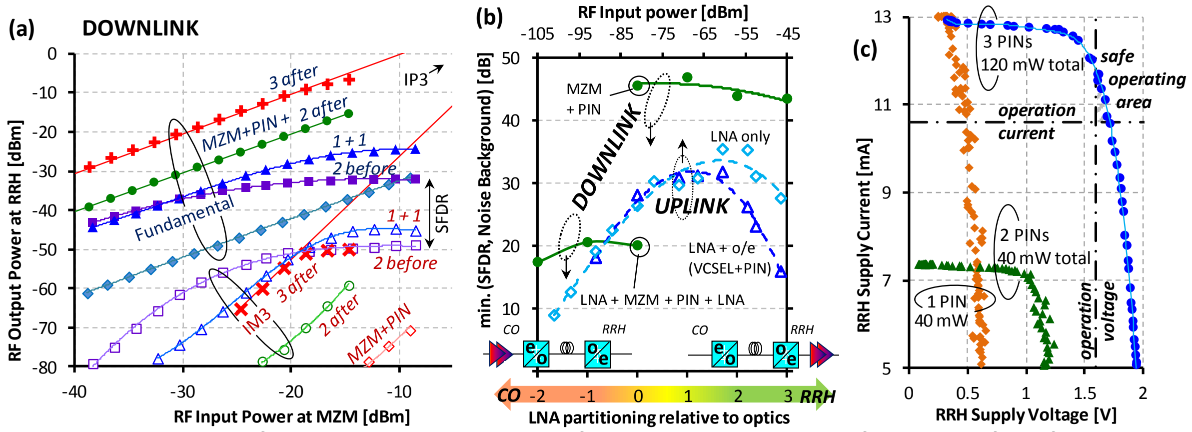

Fig. 2: (a,b) Linearity of the RRH. (c) V/I supply budget after energy reclamation at the fronthaul interface of the RRH.

high-definition video traffic.

In case of uplink transmission, the RE radio signal at 1.93 GHz is received at the RRH with a multi-stage LNA. The small-signal gain of a 4-stage LNA element is 45 dB at a low supply bias of 8.3 mA at 1.6V.[3] A low-cost multi-mode vertical cavity surface emitting laser (VCSEL) is used as energy-efficient uplink transmitter at the RRH. The VCSEL has a low threshold current of 1.6 mA and a light-current slope of 60 µW/mA.

The linearity of the RRH was evaluated in terms of IM3 distortion through LNA block and opto-electronics. In case of downlink the power consumption of the RRH can be minimized by off-loading LNA stages to the CO. However, the non-linear MZM transfer function will reduce the spurious-free dynamic range (SFDR). Figure 2a compares different combinations for this partitioning, such as both LNA stages before the optical transmitter at the CO (■,□), both stages after the optical receiver at the RRH (●,○), one stage at CO and RRH (▲,Δ), and 3 stages after the optical receiver (+,×). The baseline MZM+PIN link without extra amplifier (♦,◊) is also shown as a reference. The IM3 products significantly enhance by 10 dB and more once a single LNA stage is placed before the MZM (Δ,□) while clipping effects reduce the achievable RF launch of the RRH to less than -20 dBm. In the optimal case that all 3 LNAs are placed after the PIN diode a launch of -6 dBm at a SFDR > 40 dB can be achieved at a power consumption of 11 mW (● in Fig. 2b). The input IP3 point is 6.7 dBm (×,+ in Fig. 2a). For uplink direction high RF input power levels beyond -58 dBm at the RRH input lead to a SFDR reduction for nonlinear VCSEL-based optics (Δ in Fig. 2b), which amounts to 6 dB and more with respect to the case of having only the uplink LNA (◊). Degradation due to LNA noise at very low RF input levels can also be observed.

In order to supply the RRH with energy, the RRH is optically powered by the CO through a dedicated MMF-based fronthaul link using a 980 nm pump. A stack of 3×3 PIN diodes in photovoltaic mode provides opto-electronic feeding of the RRH. The consumption for all subsystems including opto-electronic conversion amounts to 6.9 (downlink), 8.3 and 10.6 mA (uplink) at a supply of 1.6V. With the given V/I characteristics of 1×N PIN stacks (Fig. 2c), a feed of 290 mW is required to scavenge the required energy for full LNA gain. It shall be noted that remote powering been demonstrated for up to 40W using double-clad fibre.[4]

End-to-end Radio Transmission Performance

Figure 3 shows the end-to-end downlink BLER performance for real-time PRBS transmission. The reception penalty for 16QAM-OFDM subcarrier modulation with respect to BPSK is 4.5 dB at a BLER of 10^{-1} (Fig. 3a). Logarithmic iso-BLER for (b) QPSK and (c) 16QAM subcarrier modulation is shown as function of the received power at RE and RRH. Ideally the iso-BLER curves correspond to a constant compound power level comprising the arithmetic sum of received RF power at RE and received optical power at RRH. However, saturation effects occur at the RRH and are specifically pronounced in case of higher-order 16QAM modulation (see region *I*, Fig. 3c). The optimal point of operation at the optical fronthaul can be determined by excess noise: In case of QPSK modulation the difference in reception penalty between low delivered optical signal levels of -4 and -2 dBm is 4.8 dB at a BLER of 10^{-2} (see points *II*, *III*). However, this improvement at a higher signal feed has to be offset by the 2 dB of required optical excess power. The observation of the compound power is therefore adequate to evaluate compatible transmission path losses in each domain. When increasing the optical feed further to 0 dBm the RF reception performance improves by another 2 dB (point *IV*), however, the 2 dB higher feed erodes any improvement in terms of loss budget. Off-loading of bandwidth-hungry services that would otherwise congest the macro-cell is evidenced by real-time video

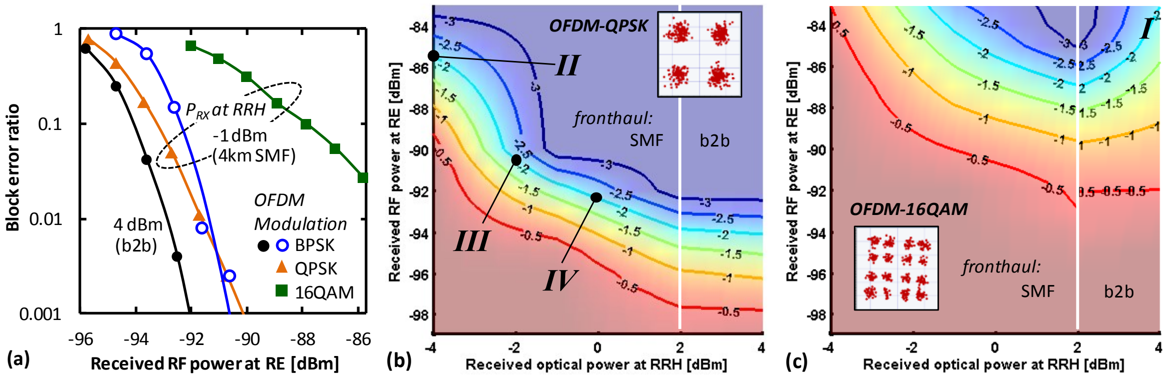

Fig. 3: (a) Downlink BLER and iso-BLER (logarithmic) as function of received RF power at RE and received optical power at the RRH for (b) QPSK and (c) 16QAM subcarrier modulation.

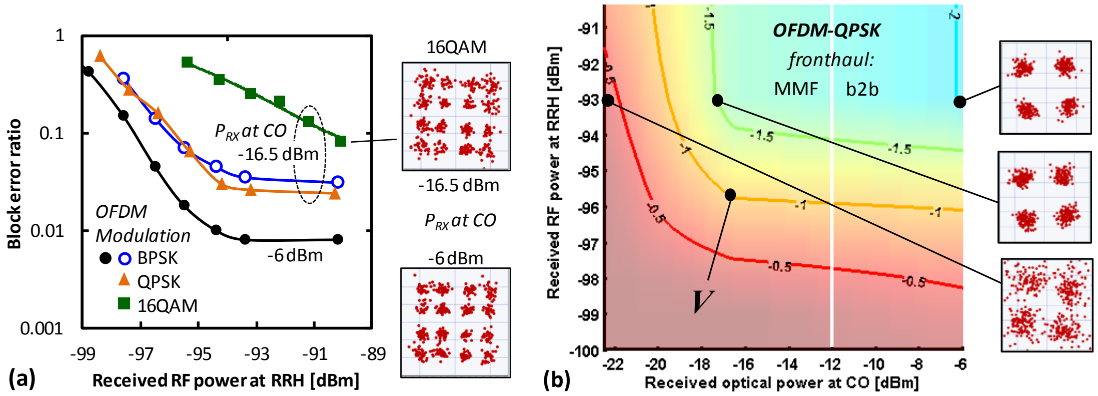

Fig. 4: (a) Uplink BLER as function of received RF power at RRH. (b) Iso-BLER (logarithmic) for QPSK subcarrier modulation.

streaming at a 720_p resolution (Fig. 1). Neither lost frames nor artefacts have been observed for end-to-end transmission between video server at the CO and video client at the RE.

The compatible downlink loss budgets can be found according to the RRH power transfer characteristics that relate optical feed to launched radio signal (Fig. 2a). An optimization of the compatible RF loss budget would favour a high delivered optical power for the RRH, which is explained by the square-law relation between the generation rate of photoelectrons and the optical field incident on the photodetector. For an optical signal feed of 2 dBm a radio path loss budget of 83.8 dB is found for QPSK subcarrier modulation and a BLER of 10^{-2}. This corresponds to a line-of-sight reach of ~500m.[5]

The error floors found in the uplink BLER (Fig. 4a) are determined by the optical reception sensitivity of the fronthaul receiver at the CO. 16QAM subcarrier modulation is negatively affected by non-linear effects and partition noise arising at the low-cost VCSEL. The penalty with respect to BPSK amounts to 5.6 dB at a BLER of 10^{-1}. The logarithmic iso-BLER for QPSK (Fig. 4b) shows a similar compatible fronthaul loss budget of ~10 dB. The optimal point of upstream operation can be found at the cross-section where neither optical nor RF noise is imposing a limitation for the compound sensitivity. For a targeted BLER of 10^{-1} a received RF power of -95.8 dBm and an optical budget of >10 dB can be obtained (point *V*). The typically high RE launch of 10 dBm and more renders the uplink loss budget as less critical.

Conclusions

An optically powered RRH was proposed. Real-time analogue OFDM transmission including error-free video streaming was demonstrated despite the use of a low-cost VCSEL for opto-electronic conversion at the RRH. The compatible radio loss budget of 84 dB suits short-reach applications, for which the RRH can be electrically supplied by scavenging an optical power of 290 mW at the fronthaul.

Acknowledgements

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