Hybrid CAP / mm-wave OFDM Vector Modulation for Photonic Frequency Conversion in a Single-Sideband Feeder

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Abstract: We demonstrate the simultaneous radio-over-fiber feed of 16-QAM 10-Gb/s CAP and 1-GHz OFDM radio at 28-GHz for HetNets. Independent sideband modulation yields photonic up-conversion to the mm-wave band and a dispersion-tolerant feed over 70km.

1. Introduction

Given the ever-growing demand for high mobile data rates, mm-wave analogue radio-over-fiber (aRoF) is seen as one of the key-enabling technologies for future networks as it offers an extremely broad bandwidth. However, mm-wave networks are handicapped by high path loss from outdoor base stations into buildings. Recently, these problems have been improved by adopting beamforming and directional antennas increasing the SNR at the reception site [1]. The most economic approach is the deployment of robust sub-6GHz macro-cells backhauled by digitized radio-over-fiber (dRoF) and augmented by mm-wave small-cells in heterogeneous network (HetNet) configurations, which achieve sufficient coverage and high data rate at the same time [2].

Few works have been carried out on hybrid optical sub-6GHz dRoF and mm-wave aRoF networks, despite that there are different proposals on how to fuse them. Concerning the single-wavelength feed for hybrid dRoF/aRoF, one can, for example, take benefit of the spectral characteristics of dRoF broadband signals using the spectral null filling technique [3]. Further options are polarization division multiplexing with simplified polarization tracking [4], orthogonal modulation [5], or non-orthogonal multiplexing with feed-forward cancellation [6].

In this work, we experimentally demonstrate the hybrid transmission of 10 Gb/s broadband signaling and analogue 1-GHz OFDM radio, which are simultaneously fed over a single wavelength using 16-QAM carrierless amplitude-phase (CAP) modulation and 16-QAM OFDM, respectively. We exploit complex inphase/quadrature (I/Q) modulation to simultaneously accomplish opto-electronic up-conversion of the radio signal to a 28-GHz mm-wave carrier frequency and its optical single-sideband (SSB) transmission. Dispersion-tolerant signal transmission over up to 70 km will be shown for both, the 10 Gb/s CAP and the mm-wave OFDM signals.

2. Simultaneous Macro/Small-Cell Feed with Photonic Up-Conversion

The present work accomplishes simultaneous transmission of a digitized and an analogue radio-over-fiber feed for the macro- and small-cell through independent sideband modulation of an optical carrier λ. Figure 1 presents the concept. The broadband CAP signal for the macro-cell and the OFDM signal for the small-cell are first generated, the former at a center frequency f_C and the latter at a low intermediate frequency f_{IF}. As will be validated shortly through experiment, the choice of CAP modulation is motivated by its robustness against optical beat interference of the simultaneously transmitted OFDM signal. Independent sideband modulation, as introduced in [7] and adopted for mm-wave single-sideband modulation in [8], then mixes these two signals with a complex carrier wave at frequency $\pm f_\lambda$, which at the same time allows to transpose the signals to the upper and lower sideband of the optical carrier λ. In the present work, we additionally suppress the optical carrier through the bias setting of the I/Q modulator. This leads to a photonic up-conversion of the OFDM signal to a frequency $f_{RF} = 2f_\lambda – f_{IF}$, characterized by the new optical carrier that is now located at $+f_\lambda$ with respect to the original (and now suppressed) optical carrier λ. By choosing f_λ = 14.75 GHz and f_{IF} = 1.5 GHz, we up-convert the OFDM signal to a mm-wave carrier frequency of f_{RF} = 28 GHz. The CAP signal, intended for baseband transmission, remains at its original center frequency f_C with respect to $+f_\lambda$.

The advantages of the proposed concept are manifold. First, only one optical receiver is necessary since the feeds for dRoF and aRoF can be easily separated using a frequency duplexer without resorting to DSP methods or a dual-receiver

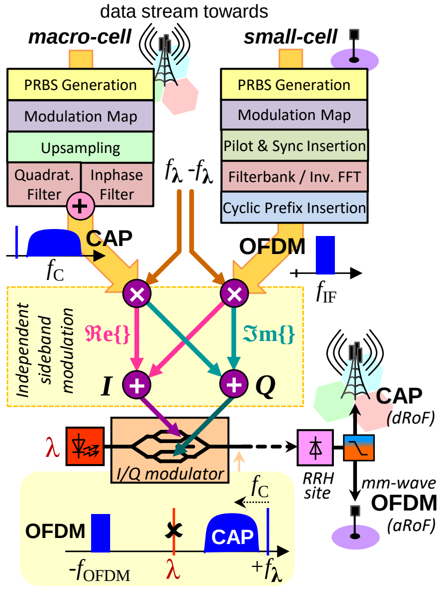

Fig. 1. Hybrid CAP/OFDM feed in a HetNet.

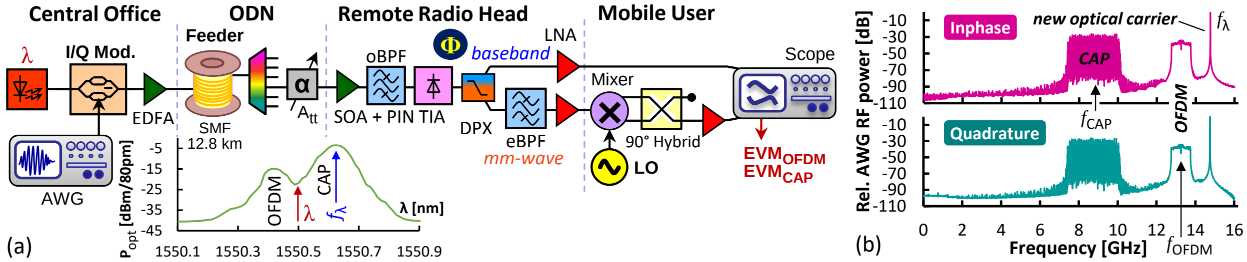

Fig. 2. (a) Experimental setup for hybrid broadband signaling and mm-wave radio downlink transmission. (b) AWG drive signal spectrum.

scheme. Second, photonic up-conversion is performed, which greatly relaxes the requirements in the RF domain since the necessary (broadband) image-reject mixer can be omitted. On top of this, the chosen modulation scheme mitigates the chromatic dispersion penalty typically associated to the double-sideband signal transmission of radio signals at high carrier frequencies, such as found for optically fronthauled mm-wave radio.

3. Experimental Setup of the HetNet Downlink

Figure 2a shows the experimental setup for the proposed hybrid broadband / analogue RoF downlink. At the central office, the broadband CAP (fC = 6 GHz) and the OFDM radio signal (fIF = 1.5 GHz) are sourced by an arbitrary waveform generator (AWG). The signals are independently modulated on the sidebands of a suppressed optical carrier at λ = 1550.5 nm. A 16-QAM was chosen for both, CAP and OFDM signals. The CAP symbol rate was 2.5 Gbaud and the OFDM signal had 128 sub-carriers over a bandwidth of 1 GHz. Figure 2b presents the RF spectra for the AWG I/Q drive signals, according to the aforementioned modulation scheme. The hybrid CAP+OFDM signal is boosted by an EDFA and launched with 3 dBm at an OSNR of 35.4 dB/0.1nm into the optical distribution network (ODN). The inset in Fig. 2a reports the transmitted optical signal spectrum with its suppressed optical carrier λ.

The ODN comprised of a 12.8 km long, ITU-T G.652B compatible single-mode fiber (SMF) used as feeder span, a 200-GHz optical bandpass filter (oBPF) emulating a demultiplexer of a WDM-based mobile optical fronthaul, and a variable optical attenuator (Att) that sets the optical budget of the ODN.

A SOA-preamplified 40G PIN/TIA receiver with a CWDM bandpass filter centered at 1551 nm is employed at the antenna site to detect both, CAP and OFDM signal. An RF diplexer with a cross-point frequency of 19 GHz then separates the broadband CAP signal from the up-converted OFDM radio at the mm-wave band. While the CAP signal at fC is directly digitized for the purpose of off-line EVM estimation, the 28-GHz OFDM signal is filtered by a Ka-band bandpass (eBPF) and down-converted to a baseband frequency using an LO at 29.5 GHz feeding a balanced image-reject mixer. The OFDM signal is then digitized at its original fIF of 1.5 GHz for off-line EVM estimation.

4. Hybrid CAP + OFDM Feed after Photonic Up-Conversion through Optical Carrier Suppression

Figure 3 presents the received (blue) RF spectrum that has been acquired directly after photodetection with the PIN/TIA receiver (Φ in Fig. 2a). The 2.5-Gbaud 16-QAM CAP signal at 6 GHz and the up-converted 1-GHz 16-QAM OFDM signal at 28 GHz can be clearly distinguished. The optical carrier, which is suppressed by the complex I/Q modulation at the transmitter, is transposed to 14.75 GHz (λ) after beating with the resident carrier of the CAP signal (fλ in Fig. 2b). Major beat interference terms are visible at the baseband (OFDM × OFDM and CAP × CAP) and around 23 GHz (OFDM × CAP). The beat tone at 2fλ = 29.5 GHz arises due to non-linearity. The impact of a sub-optimal bias point alignment at the transmitter-side I/Q modulator is included in Fig. 3 as grey spectrum. First, the optical carrier recovers. Moreover, CAP and OFDM images appears at 8.75 and 13.25 GHz. These frequencies resemble the respective RF carriers at the AWG drive (fCAP, fOFDM in Fig. 2b). The additional beat terms narrow down the available spectrum for hybrid broadband / analogue RoF transmission and lead to increased beat noise during signal reception in case of this sub-optimal biasing.

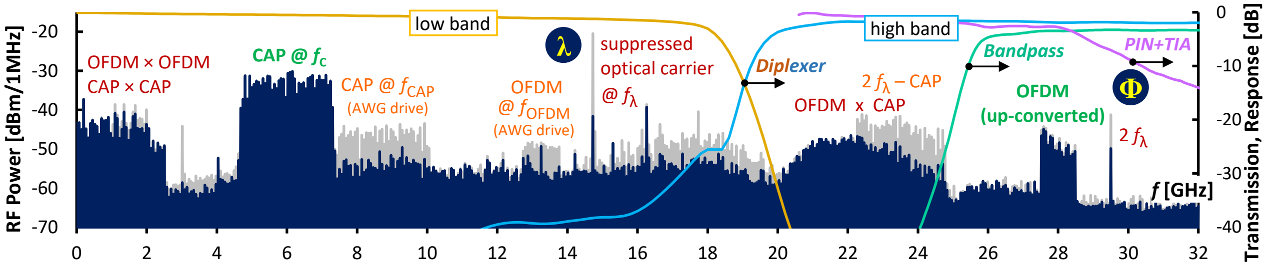

Fig. 3. Received RF spectrum after photodetection at the RRH (blue) and additional beat terms due to sub-optimal I/Q modulator biasing (grey).

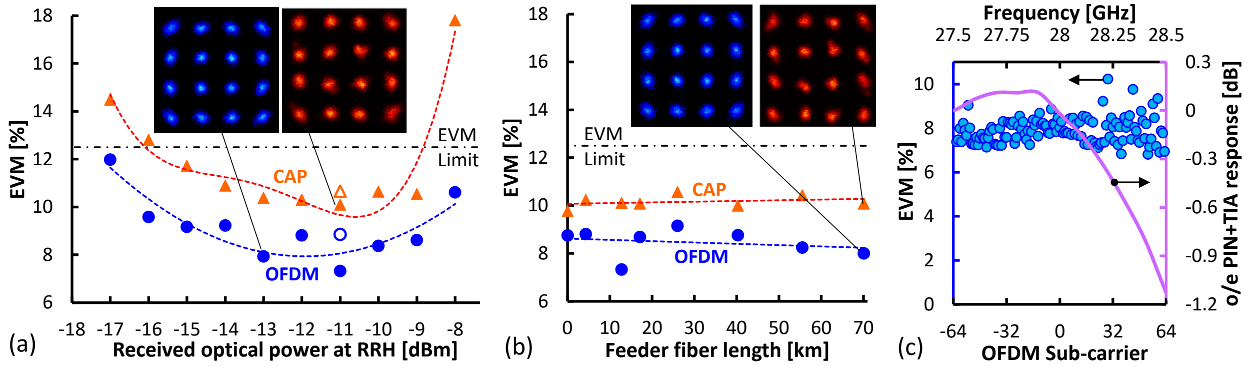

Fig. 4. CAP and OFDM EVM performance over (a) input power (for 12.8 km), and (b) feeder length (for -11 dBm). (c) EVM per sub-carrier.

5. Transmission Performance for Baseband CAP and mm-wave OFDM

The performance for simultaneous 10 Gb/s CAP signaling and analogue 1-GHz 16-QAM OFDM transmission at its 28-GHz mm-wave carrier has been evaluated in terms of EVM measurement as function of received optical power to the remote radio head (RRH) and feeder reach, respectively. The corresponding results are reported in Fig. 4.

The average EVM for OFDM (●) and CAP (▲) transmission over a 12.8 km ODN are 7.9% and 10.1% for a received optical power around -12.5 dBm (Fig. 4a), meaning an optical budget of 15.5 dB. This EVM, which is clearly below the 16-QAM antenna limit, is confirmed by the clear constellation diagrams. Two regions of EVM degradation can be noticed in Fig. 4a. These are due to the reception sensitivity of the receiver (-15.7 dBm for CAP, -17.6 dBm for OFDM) and due to saturation of the SOA + PIN/TIA receiver (-9.4 dBm for CAP, -6.3 dBm for OFDM). We did not observe a penalty due to joint CAP + OFDM transmission (▲,●) when comparing to the cases of solely transmitting either CAP (△) or OFDM (○), as evidenced for a received optical power of -11 dBm.

We further investigated the sensitivity of the signal transmission to accumulated dispersion inherent to an extended feeder length. Figure 4b shows that there is no increase in average EVM, even for an ODN reach of 70.1 km, for which EVM margins of more than 2% and 3% are achieved for 10 Gb/s CAP and 1-GHz 16-QAM OFDM transmission, respectively. This confirms the dispersion-tolerant hybrid broadband dRoF / mm-wave aRoF feed by virtue of the single-sideband RoF format, accomplished through the independent sideband modulation scheme. Figure 3(c) shows the EVM per OFDM sub-carrier for transmission over 70.1 km. The spread in EVM towards high sub-carrier indices is attributed to the roll-off in the opto-electronic response of the PIN+TIA receiver (Φ in Fig. 3).

6. Conclusion

We have experimentally demonstrated the simultaneous feed of 10 Gb/s CAP and 1-GHz 16-QAM OFDM mm-wave radio at 28 GHz in a HetNet downlink, employing a single wavelength, a single transmitter, and a single receiver. Photonic up-conversion due to independent sideband modulation eliminated the need for RF mixing and a mm-wave local oscillator, thus further simplifying the optical/RF layer. At the same time, the chosen modulation method enables dispersion-tolerant signal transmission, as evidenced for a feeder reach of up to 70 km.

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