Duobinary-Coded Coherent ΣΔ Radio-over-Fiber Transmission at 9 GHz Downlink Channel Spacing

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Abstract: We show digitized radio-over-fiber transmission using coherent envelope detection. A low EVM of 1.3%, a high optical budget of 34.6dB and 25% improvement in spectral occupancy are found when introducing duobinary signaling and coherent detection.

1. Introduction

The imperative for seamless wireless connectivity continues to drive the development of novel radio access architectures. As such, distributed MIMO is touted as an attractive candidate [1]. As an emerging cooperative wireless scheme where antennas are distributed over a large area rather than being co-located at a single site, it enables coherent transmission and reception from many cells with improved interference mitigation and quality for the macro-cell connectivity. In contrast to small cells, the radio bandwidth of macro cells is typically moderate and permits bandwidth- and energy-efficient digitized radio-over-fiber (RoF) transmission [2], which in contrast to analogue radio transmission is not impeded by non-linear opto-electronic converters of dynamic range limitations but instead necessitates high transmission line rates associated to the typically high oversampling ratio for digitized radio signals. Even though these rates can be supported by commercial transceivers, the poor spectral efficiency for the optical replica of digitized radio waveforms can have implications on the overall access network: Operators seek for a tighter integration of fixed and mobile access networks at the optical layer [3], which is typically flavored by splitter-based optical distribution network (ODN) configurations where optical carriers are shared among network users. However, antenna remoting would instead seek for virtual point-to-point links between the field-distributed remote radio heads and a centralized baseband processor. In case that coherent access technology is being employed to provide such connectivity while retaining a filterless ODN, a high density of wired and wireless network terminals can be potentially supported, provided that a spectrally efficient transmission methodology is employed.

In this work, we investigate the spectrally efficient digitized RoF transmission of a 250-MHz OFDM waveform supported by duobinary coding and coherent reception. We show that a low error vector magnitude (EVM) of 1.3% is retained when introducing duobinary signaling and coherent detection, which enables an optical budget of 34.6 dB at the EVM antenna limit. We further prove compatibility with an ultra-dense WDM channel spacing of 8.9 GHz.

2. Sigma-Delta Modulation for Narrowly-Spaced Transmission in Coherent ODN and Experimental Setup

In order to provide a better trade-off between a robust digital signal transmission and the outstanding spectral efficiency of analogue RoF transmission, we have chosen duobinary signaling for a sigma-delta (ΣΔ) modulated radio waveform. ΣΔ modulation [4-6] digitizes the analogue radio waveform while exploiting a simplified one-bit quantizer, yielding a high-rate non-return-to-zero baseband signal. Moreover, the noise shaping technique employed for ΣΔ modulation ensures that the quantization noise falls out-of-band for the bandpass OFDM radio signal.

Duobinary signaling greatly benefits from its implementation simplicity as it does neither require complex optical modulators nor high-bandwidth multi-level RF signal conditioners. Instead, bandwidth-limited transceivers can be employed [7]. The spectrally-shaped digitized RoF signal will then be received by a polarization-insensitive coherent receiver with phase-diversity architecture, allowing for a transparent optical pipe in a filterless ODN, without the need for complex digital signal recovery [8].

To prove this point, an OFDM signal with 128 sub-carriers carrying 64-QAM data over a bandwidth of B_R = 250 MHz centered at a RF carrier frequency of f_c = 2 GHz has been ΣΔ-modulated (ς in Fig. 1a) at a line rate of 10 Gb/s, yielding the spectrum shown as τ in Fig. 1a. This electrical signal is then applied to intensity-modulate an optical carrier at λ = 1550.5 nm, using a Mach-Zehnder modulator (MZM). Duobinary signaling is applied while regular on-off keyed (OOK) transmission without spectral shaping was evaluated additionally for comparison. In principle, duobinary symbol shaping could be conducted in the analogue RF domain [7]. The signal at λ is then launched with P_{TX} = 6 dBm. Two independently modulated adjacent channels are spectrally appended to the target channel $\lambda = c_0/\nu$ at a spacing of ±δΛ, in order to emulate an ultra-dense WDM transmission scheme. The spacing was tracked

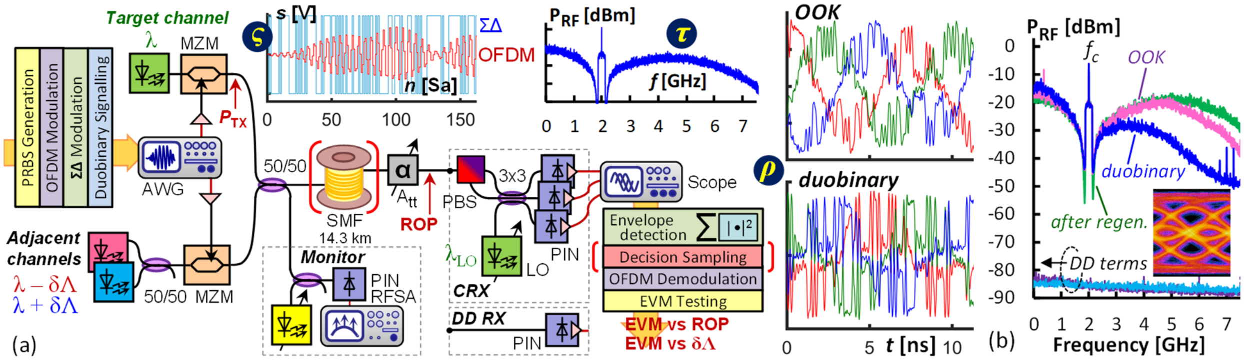

Fig. 1. (a) Experimental setup and received signals in time domain before signal recovery and (b) in the spectral domain after signal recovery.

through heterodyning the compound optical signal for its down-conversion to an intermediate frequency (IF) and monitoring with a broadband RF spectrum analyzer (RFSA).

At the receiving site, a coherent receiver (CRX) with a polarisation-diversity 120-degree configuration is being employed, similar as studied in [9]. The local oscillator (LO) of the CRX at $\lambda_{LO} = c_0/\nu_{LO}$ had a power of 6 dBm and was tuned so that $|\nu_{LO} - \nu| > B_R$, to ensure suppression of beat noise. The three detected photocurrents $i_{1...3}$ (ρ in Fig. 1a) show the characteristic 120 degree phase shift for their IF, on which the transmitted OOK and duobinary data is modulated. The subsequent signal processing was accomplished in the digital domain and includes envelope detection of the intensity-modulated RoF signal through squared addition of the photocurrents, $\sum i_j^2$, which can be in principle accomplished through analogue RF electronics [9], and OFDM demodulation.

The coherently received signal spectra after envelope detection and before regeneration are presented in Fig. 1b for OOK and the duobinary signal. For both signals, the OFDM signal at f_c is clearly delimited with respect to its spectral boundaries, indicating correct operation of the signal recovery at the CRX. The faster roll-off of the duobinary signal will be beneficial for implementing ultra-dense WDM at the optical link, provided that no large reception penalty is incurred due to the spectral shaping. The spectra, which have been acquired for a received optical power (ROP) of -18 dBm, further prove that direct-detection (DD) terms fall far below the coherent terms. Figure 1b further includes the spectrum of the regenerated duobinary signal, which shows a clear SNR enhancement.

3. Transmission Performance and Permissible Spacing for Ultra-Dense Channel Allocation

We have evaluated the transmission performance of the OOK ΣΔ-modulated OFDM signal and its spectrally shaped duobinary replica in terms of EVM for RF and optical back-to-back transmission, and for transmission over a single-mode fiber (SMF) span of 14.3 km, as function of the ROP and the channel spacing δΛ. Comparison is made with a DD receiver (DD RX) based on the same PIN/TIA photodetectors as used in the CRX. The average EVM for RF back-to-back transmission is as low as 1.35% for both, the OOK and duobinary ΣΔ signal.

Figure 2a reports the EVM for optical back-to-back transmission with the **DD RX**. An equally low EVM value of 1.3% can be accomplished for OOK (▲) and duobinary (○) transmission for a ROP > -16 dBm. There was no penalty when transmitting the duobinary signal over the SMF span (+). The EVM antenna limit of 8% for 64-QAM OFDM transmission is reached at a ROP of -23.1 dBm for OOK (▲) and at -19.3 dBm for duobinary (○), respectively, meaning a ~4 dB implementation penalty for duobinary signaling.

The low EVM values that have been accomplished for both formats evidence the expressiveness of ΣΔ modulation and its ability to regenerate the digital RoF signal after optical transmission. Towards this direction, Fig. 2a also shows the clean constellation diagram of a ΣΔ-modulated and duobinary-coded 1024-QAM OFDM signal received at -10 dBm, bearing a wireless data rate of more than 2 Gb/s. For comparison, Fig. 2a also includes the EVM performance of the duobinary ΣΔ signal without digital regeneration at the receiver (■). The minimum EVM is then 3.5%, which would prevent the transmission of OFDM signals based on such high-order QAM.

The EVM for **coherent** optical signal reception is discussed in Fig. 2b, together with the obtained 64-QAM constellation diagrams. A similar EVM performance is obtained, however, the sensitivity at the EVM limit of 8% is shifted towards a lower ROP by virtue of coherent detection, which in case of duobinary signaling is -28.3 dBm (○). Again, we did not experience a penalty for fiber transmission (+). The compatibility of OFDM transmission with a CRX enables a filterless ODN with ultra-dense channel spacing, as will be proven shortly. Without regeneration, the duobinary transmission shows a minimum EVM of 5.33% (■).

The EVM per subcarrier is presented in Fig. 2c for a ROP of -24 dBm, meaning an optical budget of 30 dB

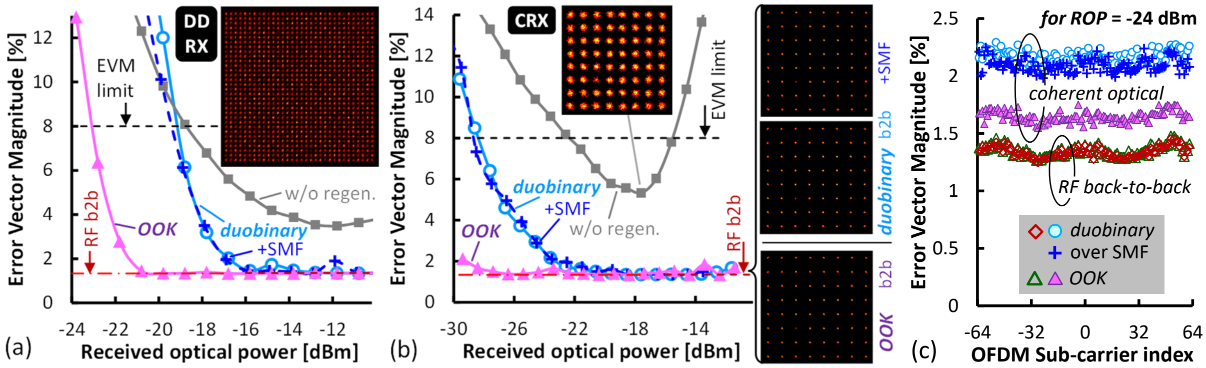

Fig. 2. EVM for (a) the direct-detection and (b) the coherent receiver. (c) EVM vs subcarrier for coherent and RF back-to-back transmission.

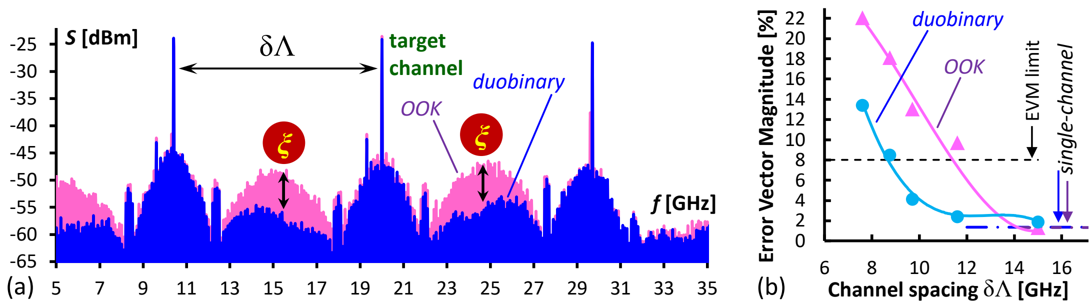

Fig. 3. (a) Heterodyned spectrum for ultra-dense channel allocation adjacent to the target channel λ. (b) EVM as function of the channel spacing.

between transmitter and CRX, and for RF back-to-back transmission. The latter yields an average EVM of 1.35% for OOK (△) and duobinary signaling (◇). When advancing transmission to the coherent optical domain, the EVM of the OOK (▲) increases by 0.3%. We find an acceptable EVM penalty of 0.77% for the duobinary format (●,○).

Finally, we have evaluated the transmission performance at the target channel λ when the adjacent channels at ±δΛ are appended. Figure 3a presents the double-sideband ΣΔ-modulated signals for OOK and duobinary signaling, acquired by the RFSA at an IF of 20 GHz and δΛ = 9.7 GHz. While the duobinary signals feature a strong roll-off for their signal power, the OOK signals span over a much wider spectral range and features an 8.7 dB higher RF power at the boundary between two channels (ξ), thus leading to a stronger inter-channel crosstalk. The corresponding EVM penalty is reported in Fig. 3b, together with the reference EVM for signal-channel transmission at λ. With decreasing channel spacing δΛ, the EVM of the spectrally broader OOK signal (▲) grows rapidly and reaches the EVM antenna limit of 8% at δΛ = 11.4 GHz. The spectrally more efficient duobinary signaling surpasses this limit at 8.9 GHz, meaning a 25% higher spectral occupancy at the ODN feeder.

4. Conclusion

We have experimentally demonstrated the robustness and spectral efficiency of duobinary-coded ΣΔ OFDM radio transmission in combination with simplified coherent receiver. There was no penalty in the minimum EVM of 1.3% when introducing duobinary signaling or coherent detection, as evidenced by 1024-QAM OFDM transmission. Although there is a sensitivity penalty of 4 dB for duobinary signaling, the boost in sensitivity through coherent detection allows for a filterless ODN with an optical budget of 34.6 dB at the 64-QAM EVM limit, compatible with the XGS-PON Class E1. Bidirectional RoF transmission integrating an uplink channel is left for future investigation.

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5. References

[1] H. Ammar et al., "User-Centric Cell-Free Massive MIMO Networks: A Survey of Opportunities, Challenges and Solutions," IEEE Comm. Surveys & Tutorials **24**, 611 (2022)
[2] Y. Zhou et al., "1λ 10.5Tb/s CPRI-Equivalent Rate 1024-QAM Transmission via Self-Homodyne Digital-Analog Radio-over-Fiber Architecture," Proc. ECOC, Basel, Switzerland, Th3A.5 (2022)
[3] J.-I. Kani et al., "Solutions for Future Mobile Fronthaul and Access-Network Convergence," JLT **35**, 527 (2017)
[4] L. Zhong et al., "An SNR-improved Transmitter of Delta-sigma Modulation Supported Ultra-High-Order QAM Signal for Fronthaul/WiFi Applications," JLT **40**, 2780 (2022)
[5] H. Li et al., "Real-Time 100-GS/s Sigma-Delta Modulator for All-Digital Radio-Over-Fiber Transmission," JLT **38**, 386 (2020)
[6] S. Luo et al., "Digital mobile fronthaul based on delta-sigma modulation employing a simple self-coherent receiver," OpEx **30**, 30684 (2022)
[7] M. Omella et al., "10 Gb/s RSOA Transmission by Direct Duobinary Modulation", Proc. ECOC, Brussels, Belgium, vol. 2, p. 121 (2008)
[8] C. Xie et al., "Colorless coherent receiver using 3x3 coupler hybrids and single-ended detection," Opt. Expr. **20**, 1164 (2012)
[9] E. Ciaramella, "Assessment of a Polarization-Independent DSP-Free Coherent Receiver for Intensity-Modulated Signals," JLT **38**, 676 (2020)