Digital SNR Adaptation of Analog Radio-over-Fiber Links Carrying up to 1048576-QAM Signals

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Abstract *Analog radio-over-fiber links have been vulnerable to SNR degradations. We exploit a digital SNR adaptation method by flexibly adjusting the phase modulation index which achieves an SNR range from 29 to 62 dB supporting up to 1048576-QAM signals in a 400G-ZR equivalent coherent system.*

Introduction

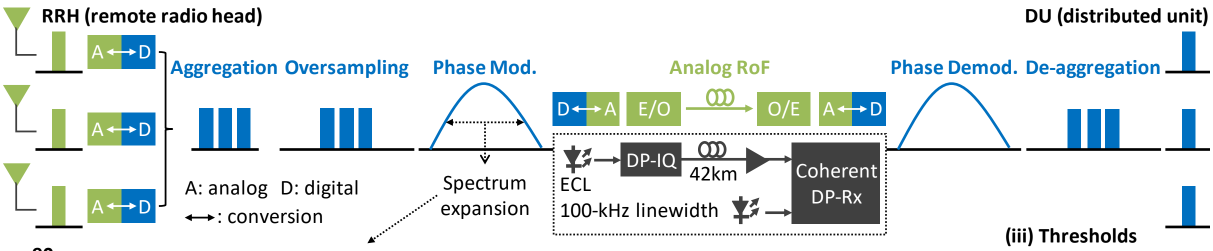
Fiber-based mobile convergence underpins the infrastructure of modern wireless communication networks. There long exists a debate whether the analog or digital link is better suitable for these radio-over-fiber (RoF) applications. Digital RoF (D-RoF) offers guaranteed fidelity as its signal-to-noise ratio (SNR) is solely determined by quantization noise. Though the digital interface has been widely adopted by industry like the common public radio interface (CPRI), it is limited by an intrinsic bottleneck, namely, a huge optical bandwidth consumption due to the need of high digitization resolution, which stimulates a variety of D-RoF research like CPRI compression and flexible quantization algorithms to improve the spectral efficiency [1-4]. On the other hand, analog RoF (A-RoF) inherently achieves high spectral efficiency by using an optical bandwidth close to that of the wireless signal. However, it inevitably confronts an SNR ceiling set by analog channel impairments like transceiver nonlinear distortions and fiber chromatic dispersion. Despite some A-RoF demonstrations of >1-Tb/s CPRI-equivalent data rate [5-6], their SNR is usually limited to below 25 dB, which only supports up to 64-QAM signals while the latest 3GPP standard has introduced 1024-QAM [7]. Moreover, the link SNR is fixed physically by the analog system which lacks the flexibility and agility to adjust the RoF fidelity.

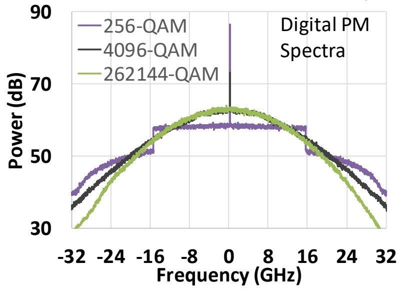
In canonical analog communications, it is well known that the spectrum expansion via angle modulations like phase or frequency modulation (PM or FM) can enhance the SNR. While the PM-based RoF have been studied for years [8], it usually works in the narrow-band PM region with no spectrum expansion, namely, the PM signal has a similar bandwidth with the baseband signal. It was revealed that a large modulation index (MI) of PM could significantly enhance the SNR for A-RoF [9]. In Ref [10], MI was enhanced by cascading 2 optical phase modulators to support 1024-QAM A-RoF for the first time. However, the approach of cascaded modulators is not scalable for higher SNR region due to its high hardware complexity, and it inherits the drawback of fixed analog SNR without flexibility. While it is usually uncommon and difficult for an optical system to realize the PM with an ultrahigh MI, the recent advance on high-speed digital subsystem sheds light on a promising solution. In this paper, we utilize digital signal processing (DSP)[9] for the SNR adaptation of A-RoF links. DSP was first introduced to A-RoF for channel aggregation [11] to get rid of the analog radio frequency (RF) processing. By its software-defined nature, it offers A-RoF the versatility to aggregate various type of signals with a universal interface. For the digital adaptation of SNR (DA-SNR), DSP not only enables the flexible PM-MI adjustment, but also an ultrahigh achievable MI to greatly enhance the SNR. We demonstrate the tradeoff between the SNR and the achievable aggregation bandwidth (AABW) (i.e. the spectral efficiency) by a coherent transceiver resembling a 400G-ZR system [12], the low-cost pluggable coherent solution for short-reach interconnects. The system carries A-RoF signals ranging from 256-QAM (2^8) to 1048576-QAM (2^{20}) with flexible fidelity for both back-to-back (B2B) and 42-km standard single mode fiber (SSMF) links. The maximum B2B AABW is 30.8 GHz for 256-QAM and 1.6 GHz for 1048576-QAM.

Digital adaptation of SNR (DA-SNR)

While DA-SNR can be applied to any A-RoF applications, we take the fronthaul as an example to introduce its principle as shown in Fig. 1. In the fronthaul uplink, remote radio heads (RRHs) receive multiple wireless signals from antennas, which are down-converted and digitized for the processing in digital domain. These signals are first aggregated by time- or frequency- division multiplexing (TDM[6] or FDM[11]). Considering PM utilizes spectrum expansion to enhance the SNR, a critical step before digital PM is to over-sample the aggregated signal to avoid sampling aliasing. As DA-SNR exploits high-MI PM with a phase variation up to tens of radians, the over-sampling ratio should be big enough to limit the phase jump below $\pm\pi$ between the adjacent digital sampling points, which guarantees the receiver unwraps the phase without ambiguity. The aggregated signal $s(t)$ is then modulated to the phase as

$$E(t) = exp\ [i(\omega t + k_p s(t))] \qquad (1)$$





(iii) Thresholds

(i) Tx DSP	(ii) Rx DSP	QAM	SNR	EVM
Baseband QAM generation	Chromatic dispersion compensation	256	29.1	3.5
DMT subcarrier mapping	Carrier recovery based on pilot tone	1024	32.0	2.5
Oversampling	2×2 polarization demultiplexing	4096	37.8	1.29
Flexible-MI phase modulation	Phase demodulation	16384	43.6	0.66
Pilot tone insertion	Down-sampling	65536	49.4	0.34
Pre-equalization	DMT demodulation	262144	55.2	0.17
Quantization to 8 bits	QAM SNR/EVM evaluation	1048576	61.0	0.09

Fig. 1: A mobile fronthaul link with channel aggregation and digital adaptation of SNR. The blue color highlights the operations in digital domain. Inset (i-ii) transmitter/receiver DSP; (iii) thresholds of SNR (dB) and EVM (%) used in the paper. (De-)Mod.: (de-) modulation; ECL: external cavity laser; DP: dual polarization; IQ: IQ modulator; DMT: discrete multitone; MI: modulation index.

where E is the signal field, ω is the carrier frequency and k_p is the MI. A larger MI broadens the PM spectrum and enhances the SNR. The relation between SNR and MI is

$$\Delta SNR = 2\Delta k_p \text{ (both in } dB) \qquad (2)$$

namely, SNR increases by 6 dB for each doubling of the PM signal bandwidth [9]. Such digital adjustment of MI (and together, the oversampling ratio) enables DA-SNR. The signal is converted to analog domain by digital-to-analog converters (DAC). The optical PM signal can be generated with an intensity-modulation direct-detection (IM-DD) system by up-converting the signal to an intermediate frequency [9], or a system capable of field modulation and recovery, like coherent [8] or advanced direct detection [6,10] systems. After the A-RoF link, the distributed unit (DU) digitizes the analog signal by an analog-to-digital converter (ADC), and then performs PM demodulation and channel de-aggregation in digital domain. The downlink reverses the above procedures.

Experiment

We experimentally demonstrate the A-RoF with DA-SNR in a 1550-nm standard dual-polarization coherent system. The transmitter contains 4 DAC sampling at 88 GSa/s with 8-bit resolution and around 30-GHz analog bandwidth. The receiver uses a 4-channel real-time oscilloscope as 4 80-GSa/s ADC with 8-bit resolution and 33-GHz bandwidth. The system resembles a 400G-ZR transceiver, making it practical to be implemented by the future 400G-ZR platform. The operation in RF and digital domains is emulated by offline DSP as shown in Fig. 1(i-ii). We generate square-QAM signals with the order ranging from 256 up to 1048576 to emulate RF signals after frequency down-conversion. We use subcarrier mapping of the discrete multitone (DMT) signal as a generic emulation for the aggregation of various type of RF signals, and the total aggregation bandwidth is altered by the number of subcarriers. Despite the varying DFT size and oversampling ratio for different QAM orders, the subcarrier spacing for DMT is kept as 10 MHz. By digitally adjusting the MI, the PM signal bandwidth is expanded up to 31.5 GHz. RF pilot tones are inserted at 32 GHz for the carrier recovery [13]. The signal is either B2B detected or transmitted over 42-km SSMF. The coherent receiver performs routine coherent DSP and the baseband processing for A-RoF signals as in Fig. 1(ii). We use both SNR and error vector magnitude (EVM) to evaluate the A-RoF fidelity, calculated from signal constellations. Under the fixed bandwidth limitation of 31.5-GHz, a higher SNR requirement reduces the AABW, as DA-SNR tradeoffs the spectral efficiency with the SNR. In the experiment, we aim to maximize the AABW (i.e. the DMT bandwidth before PM) for each QAM order while guarantee its required SNR. In 3GPP technical specification [7], the EVM requirement is 3.5% for 256-QAM and 2.5% for 1024-QAM, and no EVM is defined beyond 1024-QAM. To make a fair comparison among higher-order QAMs, we translate the EVM threshold of 1024-QAM to the bit-error ratio (BER) of 5.9e-3 under the assumption of additive white Gaussian noise (AWGN) channels. The requirements of EVM and SNR for the QAM orders beyond 1024 are defined as the threshold that leads to the BER of 5.9e-3, as listed in Fig. 1(iii). It is noted that a different threshold definition would not affect the main conclusion of this paper, as we focus on the system capability of SNR adaptation rather than the absolute SNR requirements.

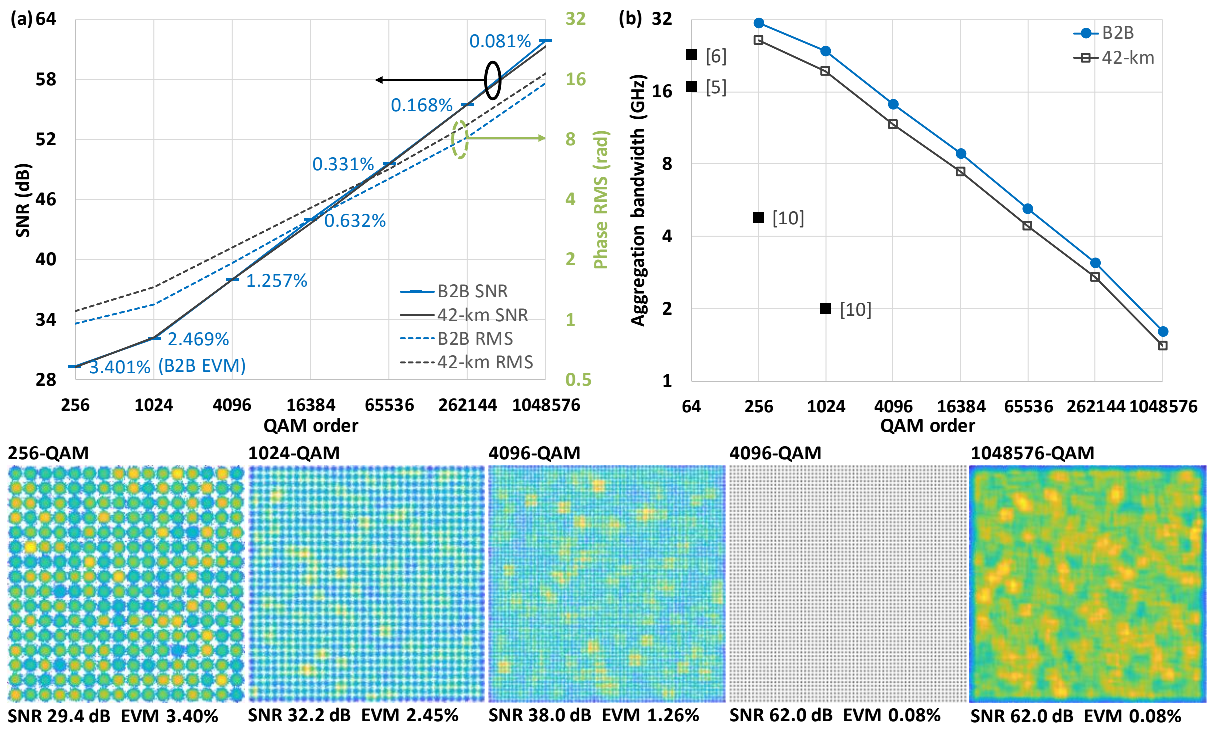


Fig. 2: (a) SNR achieved in the experiment, and the corresponding PM-MI characterized by root-mean-square (RMS) phase [9]; (b) achievable aggregation bandwidth (AABW) for various orders of QAM when their SNR/EVM meet the thresholds defined in Fig. 1(iii). Fig. 2(b) also shows the previous A-RoF AABW records, including those with >1-Tb/s CPRI-equivalent data rate [5-6].

Results

Fig. 2(a) illustrates the relation between SNR and MI in the experiment, where MI is characterized by the root-mean-square (RMS) phase after PM [9]. In logarithmic scales, the SNR almost linearly increases with the MI as predicted by Eq. 2, but the coefficient inferred from Fig. 2(a) is slightly less than 2, namely, it requires less than 2-time bandwidth expansion for 6-dB SNR increment in the experiment. Such excess SNR enhancement aside from the PM spectrum expansion can be explained as follows. As shown by the digital PM spectra in Fig. 1, when a higher-order QAM signal shrink the AABW to achieve a higher MI under the fixed system bandwidth limitation, its power spectral density is lower at the high frequency region, where the performance is usually worse than that of the low frequency region in a high-speed system due to less effective number of bits (ENOB) of the DAC/ADC, weaker frequency response of opto-electronic components and so on. Another notable phenomenon in Fig. 2(a) is the signal after 42-km SSMF requires higher MI than the B2B signal to achieve the same SNR, leading to smaller AABW than the B2B case, as revealed in Fig. 2(b). Such transmission penalty is induced not only by the OSNR degradation but also the chromatic dispersion (CD). Though CD is digitally compensated in the coherent receiver, it significantly enhances the peak-to-average power ratio (PAPR) of a PM signal, making it more vulnerable to the nonlinearity of the receiver components and the finite ADC ENOB. Such CD impact can be avoided by O-band transmission or optical CD compensation [10] .With all the QAM signals met the SNR/EVM threshold as shown in Fig. 2(a), Fig. 2(b) shows the AABW of each QAM order. For B2B, the system aggregated 30.8-GHz 256-QAM signals and 1.6-GHz 1048576-QAM signals; while after 42 km, the AABW reduced to 26.2 GHz for 256-QAM and 1.4 GHz for 1048576-QAM. Fig. 2(b) also shows the previous A-RoF records including those with >1-Tb/s CPRI-equivalent data rate [5-6], which all locate at the very left side due to their limited SNR. The inset at the bottom of Fig. 2 shows the received QAM constellations at various SNR. Note that it is not possible to show a 1048576-QAM constellation clearly with millions of points crowded in such a small chart. Therefore, at the highest SNR of 62 dB, we also collect a 4096-QAM constellation to show the superb A-RoF fidelity.

Conclusions

We demonstrate an SNR adaptation scheme for A-RoF with an ultra-wide dynamic range, setting the records of both the aggregation bandwidth (which can be translated to CPRI equivalent rate) beyond 30 GHz with 256-QAM and the link fidelity supporting up to 1048576-QAM. The tradeoff between the spectral efficiency and link fidelity offers A-RoF a flexible yet reliable way to sustain future mobile convergence applications.

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