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Experimental characterization of Sigma Delta Radio over fiber system for 5G C-RAN downlink

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Abstract

Radio over Fiber is a promising technology for the 5G Cloud Radio Access Network. We demonstrate experimentally Sigma Delta Radio over Fiber by means of Sigma Delta Modulator (SDM) subsequently replacing expensive digital to analog converters. A second order SDM is proposed for LTE 20 MHz signal having 256 QAM modulation on a carrier frequency of 3.5 GHz for 10 Km of fiber length. The performance is reported in terms of error vector magnitude, adjacent channel leakage ratio and eye-opening penalty. The results show that the proposed architecture performance is cost and power efficient solution for next-generation wireless networks.

Keywords: Radio over fiber; Sigma delta modulation; 5G C-RAN; EVM; ACPR

1. Introduction

The fifth generation (5G) technology is envisaged to provide convulsive increase in internet access with low cost and latency [1]. The enhancement of capacity and wireless coverage has posed significant challenges to the existing optical and wireless access networks. Cloud radio access network (C-RAN) architecture is one of the key enablers to achieve these goals. The 5G C-RAN should be able to control the centralized base band units (BBU) coming from many base stations and remote radio heads (RRHs). The interconnectivity of BBUs with RRHs is economically coherent with the distribution network known as the 'fronthaul' as shown in Fig. 1. The fronthaul network should meet the high-capacity and low-latency requirements. Similarly, the most important aspects are cost, complexity and power consumption of the RRH. While considering these factors, the radio-over-fiber (RoF) technologies are the feasible candidates for the fronthaul networks [2].

Many schemes of RoF exist; each has its own implementation methodology and RRH implementation as shown in Fig. 2. A-RoF scheme is the simplest and undemanding solution having many adaptations such as [3,4] which is susceptible to nonlinearities [5,6]. To avoid these issues, linearization of A-RoF links has been proposed [7–11]. However, it is a very complex operation which leads to additional complexities.

Recently, D-RoF has been demonstrated experimentally for 70 km of fiber length using optimized value of analog to digital converter (ADC) resolution bits [12]. Even though D-RoF are immune to nonlinearities that are faced in case of A-RoF, D-RoF is not the best option due to poor efficiency, low bandwidth and exorbitant digital to analog converter (DAC) cost at higher carrier frequencies.

More recently, an alternative approach known as Sigma Delta Modulated Radio over Fiber (S-DRoF) has been proposed which combines the benefits of A-RoF and D-RoF [13,14]. In S-DRoF, Sigma delta modulation ($\sum\Delta$M) is employed that oversamples the baseband signal and quantizes it to a 1-bit signal. At the receiver end, a band-pass filter (BPF) filters out the out of band noise. In this paper, we illustrate with experimental bench an application of SDRoF which is based on 1-bit bandpass Sigma-Delta (SD) modulator

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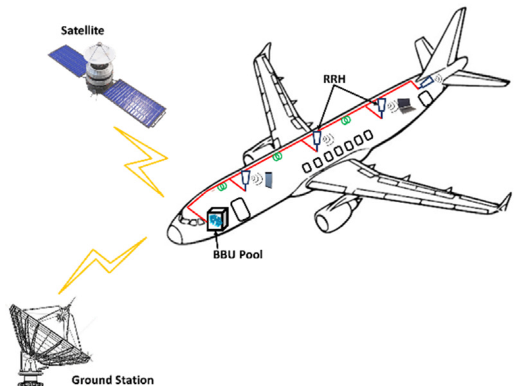


Fig. 1. Basic C-RAN architecture showing optical fronthaul.

at the transmitter side applicable to 5G sub-6 GHz band. The paper is organized as follows. Section 2 discusses the proposed SDM. Section 3 describes the experimental setup. In Section 4, performance analysis of S-DRoF is presented in terms of Error Vector Magnitude (EVM), Adjacent to Channel Leakage Ratio (ACLR) and Eye-Opening Penalty (EOP). Section 5 concludes the paper.

2. System description

The proposed system characterization has been outlined in Fig. 2. The combination of integrators Y_1 and Y_2 gives a second order SDM. In our previous work [13], we have proposed the simulation-based study of this model on VPI Transmission maker. The derivation and detailed explanation of this model can be seen in [14]. The second order SD modulator is expressed in z-domain as follows:

$$b(z) = STF(z) + a(z) + NTF(z)\,Q_e(z) = z^{-1}a(z) + \left(1 - z^{-1}\right)^2 Q_e(z) \quad (1)$$

where $y(z)$ is the output, $x(z)$ is the input and $Q_e(z)$ is the quantization error. The integrators Y_1 and Y_2 are given as:

$$Y_1 = \frac{1}{(1 - z^{-1})} \quad (2)$$

$$Y_2 = \frac{z^{-1}}{(1 - z^{-1})} \quad (3)$$

Similarly, the in-band noise power of the output for 2nd order SDM can be calculated as:

$$\sigma_{in}{}^2 = \int |NTF|^2 .S_p(f)\,df = \frac{\pi^4}{15 * (OSR)^5} \quad (4)$$

where $S_p(f)$ is the power spectral density and OSR is Over Sampling Ratio. The noise transfer function (NTF) is the transfer function from the quantization noise input to the output.

The main objective of $\sum\Delta$M is to perform the quantization of the baseband signal with a very low resolution and a sampling rate higher than the Nyquist criteria. With low number of resolution bits, the considerable amount of quantization noise is added. Therefore, the high quantization out of band noise can be filtered out in order to reduce it in the useful band. Thus, the BPF of the refiltered spectrum subdues the quantization noise that results in retrieving of the original signal. By employing BPF, it does not only annihilate the need of costly DACs, but also outmaneuvers the data-rate bottleneck linked with Common Public Radio Interface (CPRI) [15] and Open Base Station Architecture Initiative (OBSAI).

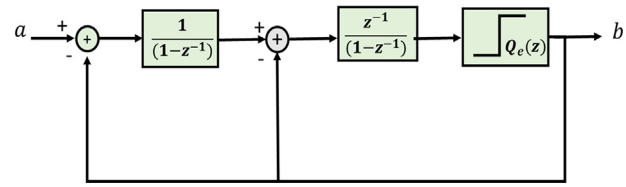


Fig. 2. Structure of the SD modulator utilized in this paper. The integrators Y_1 and Y_2 combination yields second order SD modulator. Resolution of quantizer is one bit.

3. Experimental bench

The experimental setup is shown in Fig. 3. The RF signal is generated by a Vector Signal Generator (VSG) which is then sigma delta modulated by 2nd order SDM implemented in MATLAB®. This operation converts the RF signal to 1-bit. The RF signal digitized by 1 bit 2nd order SDM is LTE signal of 20 MHz having 256 QAM modulation format. The carrier frequency f_c is 3.5 GHz. Then, this stream of 1-bit data is sent to Pulse Pattern Generator (PPG Keysight 81134A edition). This directly modulates the Distributed Feedback Laser (DFB) having 1550 nm wavelength. Standard Single Mode Fiber (SSMF) of length up to 10 km is utilized in this evaluation. The optically transmitted signal is then converted to electrical domain by photodiode with 9.3 GHz of bandwidth. The received signal is then passed through low noise amplifier (LNA) which amplifies the signal followed by analog band pass filter that filters the out of band noise. The band pass signal is fed to Real time oscilloscope that runs vector analysis software for parameters evaluation. For the parameters evaluation, fiber length utilized is 100 m, 1 km, 2 km, 5 km and 10 km. For all lengths, since fiber utilized has attenuation of 0.5 dB/Km, while two connectors are utilized for transition with each having attenuation of 0.6 dB, the total loss becomes (0.5 dB*Fiber Length in km) +1.2 dB. DFB utilized has a threshold level of 10 mA and the saturation region reaches at 100 mA, the biasing point is carried out with a 50 mA bias intensity. Table 1 contains details of the parameters.

4. Experimental results and discussion

At first, the performance of S-DRoF is evaluated by the EVM. It is a quantity that determines the difference between the 'expected' complex value of a demodulated symbol w.r.t 'actual' value of the received symbol. EVM can be mathematically expressed as:

$$EVM(\%) = \sqrt{\frac{\frac{1}{M}\sum_{m=1}^{M}\left|S_m - S_{0,m}\right|^2}{\frac{1}{M}\sum_{m=1}^{M}\left|S_{0,m}\right|^2}} \quad (5)$$

Table 1
Parameters utilized in experimental setup.

Parameter		Value
RF signal		Carrier frequency = 3.5 GHz Constellation format = 256 QAM
Optical link	Laser	Wave Length = 1550 nm Average Power = 10 mW
	Fiber	Fiber Dispersion = 16 $\frac{\text{ps}}{\text{nmkm}}$ Fiber Distance = 0.1, 1, 2, 5, 10 km
	Photo-detector (PD)	Responsivity 0.6 A/W Bandwidth: 9.3 GHz
Bandpass filtering		Band Pass Bandwidth = 210 MHz Conversion gain (Complete Receiver (PD+BPF) = 220 V/W

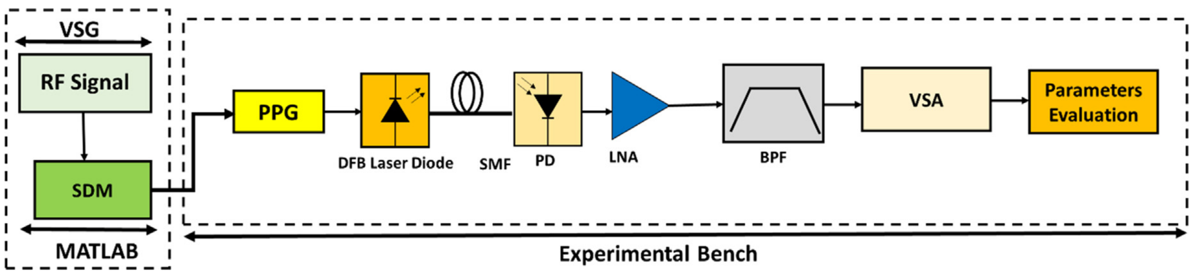


Fig. 3. Experimental Bench for setup for Sigma Delta Radio over Fiber system. SDM: Sigma Delta Modulation. SMF: Single Mode Fiber. PPG: Pulse Pattern Generation. BPF: Band Pass Filtering. VSG: Vector Signal Analyzer. LNA: Low Noise Amplifier.

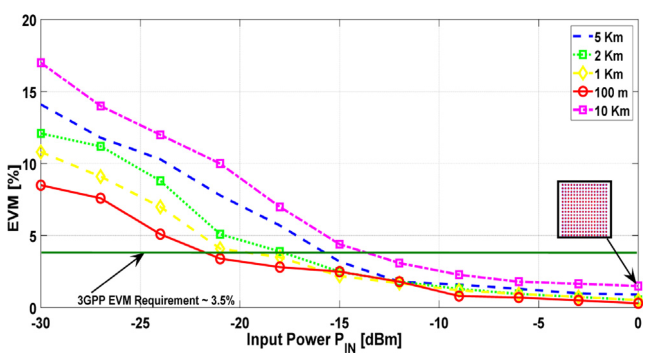


Fig. 4. EVM for varying fiber lengths vs. input powers.

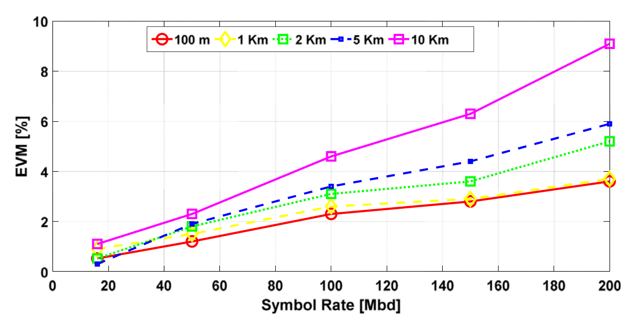
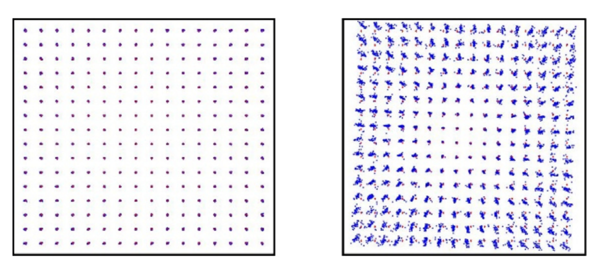


Fig. 5. EVM for varying symbol rate for varying fiber lengths.



(a) EVM= 1 % (b) EVM= 4 %

Fig. 6. EVM performance for 10 km at (a) 20 Mbd and (b) 100 Mbd.

where S_m is the normalized mth symbol in the stream of measured symbols, $S_{0,m}$ is the ideal normalized constellation point of the mth symbol and M is the number of unique symbols in the constellation. The 3GPP has set an EVM limit for LTE signals modulated by 256 QAM modulation format to be 3.5% [16]. To evaluate the dynamic behavior of the system proposed, the EVM is calculated for varying input RF powers for different fiber lengths as shown in Fig. 4. The quantization noise has a band stop shape which results in the increasing behavior of the EVM degradation with the increasing length.

Fig. 5 shows the EVM vs. symbol rates up to 200 Mbd. The fiber lengths reported are 100 m, 1 km, 2 km, 5 km and 10 km. The degradation in EVM performance is observed for all the fiber lengths. It is observable that 10 km SSMF link is downgraded faster than others. The reason for this behavior is the low power of received signal due to the path loss. Similarly, a higher baud rate will result in a higher total noise power in the signal band and thus leads to an increased EVM.

Similarly, in Fig. 6, constellation diagram is reported for 10 km case for 20 and 100 Mbd respectively. This signifies that EVM increases with higher baud rate as it leads to higher total noise power in the signal band.

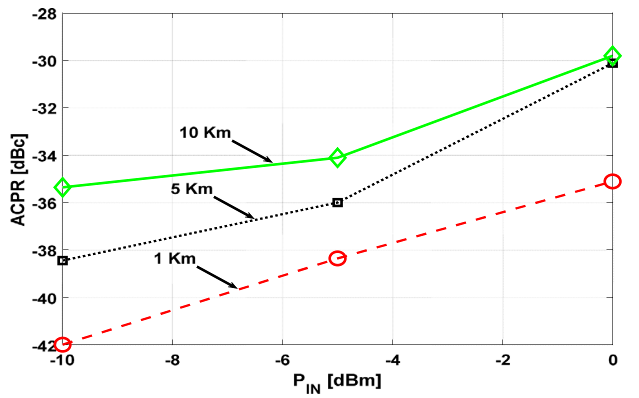


Fig. 7. ACLR performance for varying RF input power and fiber lengths.

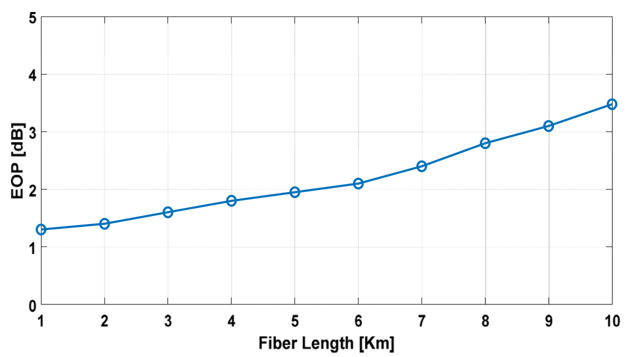


Fig. 8. EOP performance for varying fiber lengths for 0 dBm.

Additionally, the performance is evaluated by finding the adjacent channel leakage ratio (ACLR). It is defined as [8]:

$$ACLR\,(\text{dB}) = 10\,log_{10}\left[\frac{\int_{adjacent\_band\_l}^{adjacent\_band\_u} S\,(f)\,df}{\int_{useful\_band\_l}^{useful\_band\_u} S\,(f)\,df}\right] \quad (6)$$

where $adjacent\_band\_l$ and $adjacent\_band\_u$ are the frequency limits of the adjacent channel, $useful\_band\_u$ and $useful\_band\_l$ are the lower and upper frequency limits of the useful channel respectively. The ACLR is represented in Fig. 7 with changing input RF power and fiber length respectively. The trend signifies that ACLR increases with increasing fiber length and higher input power as it leads to higher order of distortions in the adjacent channels.

The transmission performance of the proposed S-DRoF is evaluated by the Eye-Opening Penalty (EOP) which measures the deterioration in the eye diagrams. EOP is the ratio of the non-distorted reference eye called Eye Opening Amplitude (EOA) to the eye opening of the distorted eye, i.e. the Eye Opening Height (EOH) [10]. EOP is defined in (7) as:

$$EOP\,(\text{dB}) = 10\,log\left(\frac{EOA}{EOH}\right) \quad (7)$$

The EOP for varying link lengths is shown in Fig. 8.

The parameters evaluated in this demonstration are summarized in Table 2.

Table 2
Performance evaluation of 0 dBm.

Length (km)	EVM (%)	ACLR (dBc)	EOP (dB)
1	0.55	−38.12	1.3
10	1.1	−31.81	2.4

The cost of the S-DRoF realization is an important consideration to be evaluated. $\sum\Delta$M has high quantization noise with only few quantization bits, therefore the need of very fast digital circuitry is not required. In D-RoFs, the remote antenna units require a DAC which needs to be high speed to handle the operations while S-DRoF replaces these DACs by band pass filter which further decreases the cost. However, Sigma delta modulation requires high oversampling ratio to achieve the performance. To overcome the speed limit of existing FPGAs, several parallel processing techniques have been reported that can be used [14–17].

5. Conclusion

We have demonstrated a 2nd order SDM experimentally for the use of S-DRoF for the 5G fronthaul downlink applicable to the 5G sub-6 GHz band. It can eliminate the high cost of ADCs and DACs. The experimental bench is demonstrated for LTE signal of 20 MHz having 256 QAM modulation for a 3.5 GHz carrier frequency. The measurement results show that an EVM of less than 1% and ACLR of −30 dBc is achieved for a high value of input power of 0 dBm for 10 km of link length.

The real time implementation of single bit SDM proposed is envisaged.

Declaration of competing interest

The authors declare that there is no conflict of interest in this paper.

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