Fully-Photonic Analogue-to-Digital Conversion Technique for Super-Broadband Digitized-Radio over Fibre Link

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***Abstract*—Digitized-Radio over Fibre (DRoF) techniques provide higher dynamic range and are more robust against optical link impairments. In this paper, a fully-photonic DRoF system is proposed and its performance is investigated in an integrated system with an analogue Radio over Fibre (ARoF) system. In this simulation based evaluation, DRoF and ARoF systems performance in the presence of other channels interference, and mode-locked laser diode's jitter are investigated through an integrated transportation system over 30 km of single mode fibre length.**

Keywords— Integrated Optical and Wireless Communication, Radio over Fibre and Analogue-to-Digital Conversion (ADC).

I. Introduction

Radio over Fibre (RoF) or Analogue Radio over Fibre (ARoF) technique has been considered as a cost-effective and reliable solution for the distribution of the future wireless access networks by using optical fibre with vast transmission bandwidth capacity. An ARoF link includes optical source, modulator, optical amplifier & filters, optical channel and photodiode as a receiver, electronic amplifiers and filters, for example a simple architecture is shown in Fig. 1. In some cases, the RF signal is directly modulated by optical source, but as the laser is usually a significant source of noise and distortion in a radio over fibre link, so laser diode normally exhibits nonlinear behaviour. Analogue optical link suffer from nonlinearity of both microwave and optical components that constitute the optical link [1][2]. In the downlink of RoF system, RF signals are distributed from a central station (CS) to many BS known as a Radio Access Point (RAP) through the fibres, while, the uplink signals received at RAPs are sent back to the CS for any signal processing. RoF has the following main features: (1) it is transparent to bandwidth or modulation techniques. (2) Needs simple and small BSs. (3) Centralized operation is possible. (4) Support multiple wired and wireless standards, simultaneously. (5) Lower power loss [3].

This paper is focus on proposing and investigating an all-photonic DRoF architecture to overcome future super-broadband radio frequency and mm-wave carrier signal sampling problem in the conventional EADC, for using the free spectrum of the public fibre optic network infrastructure as much as possible. Using the all-photonic DRoF technique, centralizes the signal processing more than a conventional RoF link. This architecture increases the percent of resource sharing of expensive equipment because of the possibility for signal transportation over longer length of fibre with minimum disruption. Therefore, each CS can cover more numbers of remote access points for future super-broadband DRoF access network.

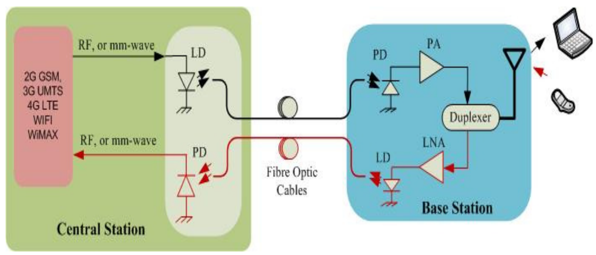


Figure 1: A Generic Full-duplex ARoF Concept

The remaining of this paper is organized as follows: Section II discuses digital RoF (DRoF) system's architecture. Section III deals with a novel all-photonic DRoF and its features and at the end of this section the integrated transportation system is introduced. Section IV provides the simulations and discussions. Finally, conclusions are presented in Section V.

II. Digital Radio over Fibre

Digital systems are flexible and more conveniently interface with other systems, and are more reliable and robust against additive noises of devices and channel and achieve better dynamic range than analogue systems. In an analogue system the bandwidth is limited by devices performance and parasitic components introduced. In a DRoF system, an electrical RF signal is digitized by using an Electronic ADC (EADC) by the Nyquist or -

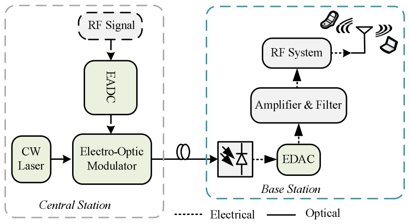


Figure 2: DRoF Architecture using EADC [4].

bandpass sampling theorem. Subsequently, the generated digital data modulated with a continuous coherent optical carrier wave either using direct modulation technique or by using an external electro-optical modulator as shown in Fig. 2. The modulated optical carrier is transmitted through the fibre. At the base station, after detecting the optical signal by a photo diode, a digital detected data converted back into analogue domain by using an EDAC. Finally, the analogue electrical signal fed to an antenna [4].

III. All-Photonic Digital Radio over Fibre

The recent EDAC systems experience problems such as jitter in sampling clock, settling time of the sample and hold circuit, speed of comparator, mismatches in the transistor thresholds and passive component values [5]. These limitations imposed by all of these factors become more severe in higher frequencies. Wideband analogue to digital conversion is a critical problem encountered in broadband communication and radar systems. Due to the future beyond Gigabit/s mobile and wireless end-users traffic demand's growth rate [6] and, furthermore, the electronic technology limitation for providing ultra high-speed, high performance and resolution data converters, deployment of the conventional DRoF link's is not simply achievable and cost effective[3]. Moreover, in spite of the implementation complexity of using the WDM techniques, digital serial high traffic rate, creates new challenge for this architecture to use more number of electro-optical modulators and photo diodes for implementing the WDM to overcome the chromatic dispersion caused by fibre modulation bandwidth limitation. Therefore, An all-photonic DRoF architecture is proposed in Fig. 3, which is only used an electro-optical modulator that is shared as an optical sampling moreover of a modulating device at the CS.

In this architecture, a photonic ADC by using a mode-locked laser diode (MLLD) and electro-optical modulator is able to scale the timing jitter of the laser sources to the femtosecond level, which will allow designers to push the resolution bandwidth by many orders of magnitude beyond what electronic sampling systems can achieve currently,[6][7]. Therefore, the proposed system has included an all-photonic signal processing block for optically quantization and wavelength conversion of the sampled and symmetrically split signals power, as shown in Fig. 4. By using wavelength division multiplexing (WDM) techniques, exceeding the modulation bandwidth of the fibre on each wavelength is prevented.

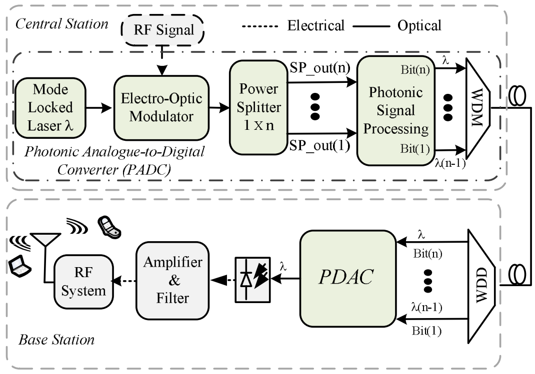


Figure 3: Proposed All-Photonic DRoF Architecture.

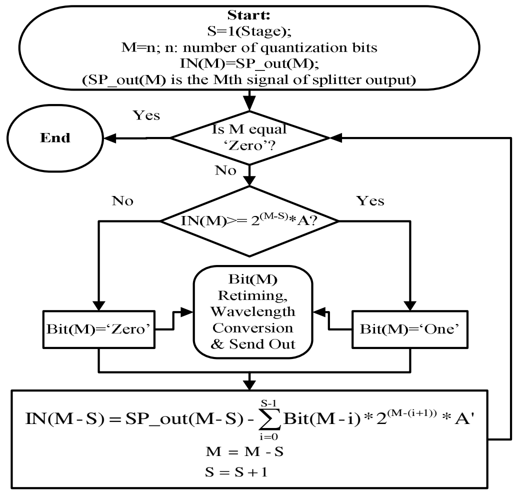


Figure 4: All-Photonic Signal Processing Technique.

In Fig. 3, at the CS, the RF signal is sampled and modulated by optical train pulses that are generated by using a passive mode-locked laser. The optical power of sampled pulses is split to n levels by using a symmetrical optical splitter, as n denotes the number of quantization bits. Finally, the split signals are fed to a photonic signal processing block for quantization and wavelength conversion operations. The quantization process is performed by the flowchart that is presented in Fig. 4; that A, A', A'' are constant parameters. After wavelength conversion, the digital photonic signals are multiplexed in wavelength domain by using a WDM and transmitted over a standard single mode fibre. At the BS, first the received signal is demultiplexed by wavelength division demultiplexer (WDD) and fed to the PDAC. In the PDAC block, the received digital optical signals on different wavelengths are converted back to their original wavelength at λ. By using an avalanche photo diode (APD), the RF signal is detected and after following a RF analogue signal filtering and amplification process it was fed to antenna.

IV. Analysis and Simulation Results

In this Section, mathematical analysis and simulation results of the proposed architecture are presented. In this architecture, an eight-bit photonic ADC has been designed with 5 effective number of bits at 15 Gigasample/s. The most important block in the broadband RoF technology is the electro-optical modulator. In this system, the Mach-Zehnder Modulator (MZM) has been used as an electro-optical modulator and RF signal sampler. The transfer function of MZM is given by

$$E_{out}(t) = E_{in}\, cos\left({}^{V(t)\pi}/_{2V_\pi}\right) \qquad (1)$$

where $E_{out}(t)$ is the electrical modulated field at the output of MZM. E_{in} is the input optical carrier electrical filed of laser diode that is lunched to the MZM, $V(t)$ is applied RF signal voltage and V_π is the bias voltage that generate π radians phase difference between optical signals of two arms of MZM [8]. We assume the optical field at the input of the MZM that is lunched from laser diode can be represented by

$$E_{in}(t) = E_o cos(\omega_0 t) \qquad (2)$$

where E_o and ω_0 denote the amplitude and angular frequency of the optical carrier, respectively [6]. Mathematically, an Amplitude Shift Keying (ASK) signal's carrier can be described as a complex wave by

$$S(t) = A_c m_0(t) e^{j[\omega_c t + \varphi_c]} \qquad (3)$$

The actual signal is the real part of $S(t)$. Both A_c and φ_c, the amplitude and the phase values of the RF carrier are constant and $m_0(t)$ denotes a sample bit of a binary information sequence that can vary on a bit by bit basis with a bit time duration T. The ASK signal consists of N bits, thus the complex signals $S_s(t)$, is represented by

$$S_s(t) = \sum_{n=0}^{N-1} A_c m_n(t) e^{j[\omega_c t + \varphi_c]} \qquad 0 \le t \le N.T \quad (4)$$

The ASK modulated RF signal is the real part of the signal given by (4) and is given by

$$V(t) = \sum_{n=0}^{N-1}[A_c m_n(t) . cos(\omega_c t + \varphi_c)] \qquad (5)$$

Substituting (5) in (1), the optical field at the output of modulator is represented by

$$E_{out}(t) = E_o\{Cos(\omega_0 t).Cos(U \sum_{n=0}^{N-1}[m_n(t) . Cos(\omega_c t + \varphi_c)])\} \qquad (6)$$

where U is the modulation index equals to ${}^{(A_c.\pi)}/_{(2V_\pi)}$.

Expanding the inside element of the braces by using the Bessel function [9], the output optical field can be rewritten as,

$$E_{out}(t) = E_o cos(\omega_0 t) \times [J_0(U) + 2(\sum_{k=1}^{\infty}(-1)^k J_{2k}(U) \sum_{n=0}^{N-1}[m_n(t) . Cos(\omega_c t + \varphi_c)])] \qquad (7)$$

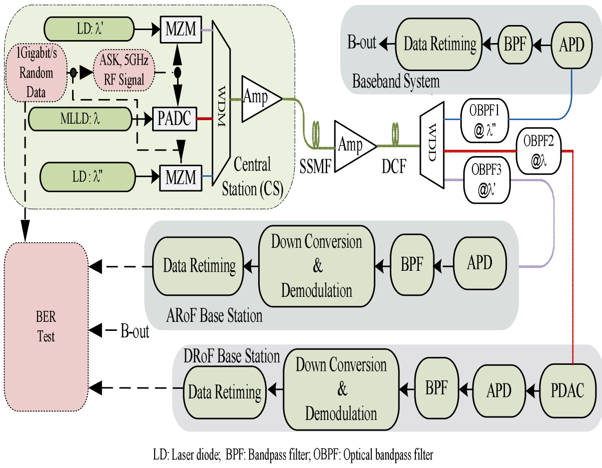


Figure 5: Simulated Model of Integrated Digital and Analogue Links.

where, $J_k(U)$ denotes the Bessel functions and for any integer k,

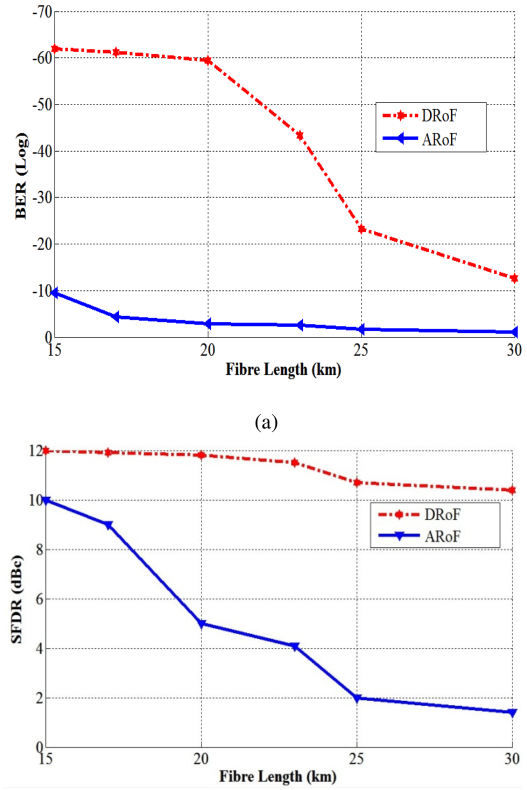
$$J_k(U) = \frac{1}{\pi}\int_0^{\pi} cos(U . sin\,\theta - k\theta)\, d\theta \qquad (8)$$

The sampled signal at $t = l.\Delta T$ of (7), represents the output of MZM in the proposed all-photonic DRoF that can be given by

$$E_{out}(l.\Delta T) = E_o J_0(U) cos(\omega_0 l.\Delta T) + E_o \sum_{k=1}^{\infty}\left\{(-1)^k J_{2k}(U).\sum_{b=0}^{N-1} m_n(l.\Delta T) \times \begin{bmatrix} cos\big((\omega_0+\omega_c)l.\Delta T + \varphi_c\big) + \\ cos\big((\omega_0-\omega_c)l.\Delta T - \varphi_c\big) \end{bmatrix}\right\} \qquad (9)$$

where l is an integer and ΔT is the period of MLLD pulses. The first term of (9) is the optical carrier and the second term discuses the sidebands of RF or mm-wave signal. As represented in this equation, the nonlinearity of MZM modulator produces infinite terms of signal spurious band that affects the link's performance.

The simulated model of the proposed integrated transportation system is shown in Fig. 5. For investigation of the system's performance, a sample ASK modulated, 1 Gbps NRZ pseudo-random data with 5 GHz RF carrier, is simultaneously transported through the integrated link. Fig. 6 shows the transmission systems performance with bit error rate and spurious free dynamic range (SFDR) of the received signals. In this figure, the performance comparison of received signal by using digital, baseband and analogue systems has been investigated over 30 kilometres of fibre length. In this system, chromatic dispersion of single mode fibre is assumed about 17 ps/(nm.km) that is compensated by using a dispersion compensation fibre. The BERs of this system for a 15 km length of fibre were less than 10^{-61} and about $10^{-9.5}$ for DRoF, and ARoF, respectively, which illustrates the DRoF link's performance is considerably better than ARoF link. By increasing the length of fibre link up to 30 km and analysing the -



(a)

(b)

Figure 6: BER and SFDR Comparison of DRoF with ARoF for 1 Gbps ASK Modulated Signal with 5 GHz Carrier over 30 km SSMF (a) BER (b) Spurious-Free Dynamic Range (SFDR).

generated waveforms, the BER of DRoF and ARoF were $10^{-12.6}$ and about 0.1, respectively. The SFDR of the DRoF link is considerably independent on the fibre link's length in comparison with ARoF. Therefore, the ARoF link strongly suffers with fibre link's impairment and its performance depends on the laser source power, fibre length and the interference of other channels. However, DRoF is more independent of fibre lengths [4] and the proposed all-photonic DRoF system, by gaining an optical low phase noise MLLD's sampling pulse that – can support high bandwidth RF signals sampling, it is achievable to transport super-broadband digitized-RF traffic over integrated metro and access networks. Consequently, in addition of using present digital optical communication infrastructures the number of CSs will decrease and as a result, the service provider and operators cost overhead per bit will be reduced. The link performance investigation based on received power strength at BS is shown in Fig. 7 that evaluate the DRoF and ARoF links comparison with modelled 192.7 femtoseconds rms jitter on MLLD's pulses for DRoF. However, it is clear in Fig. 7 that the interferences of other channels, remarkably affect the performance of ARoF link while DRoF link is more robust.

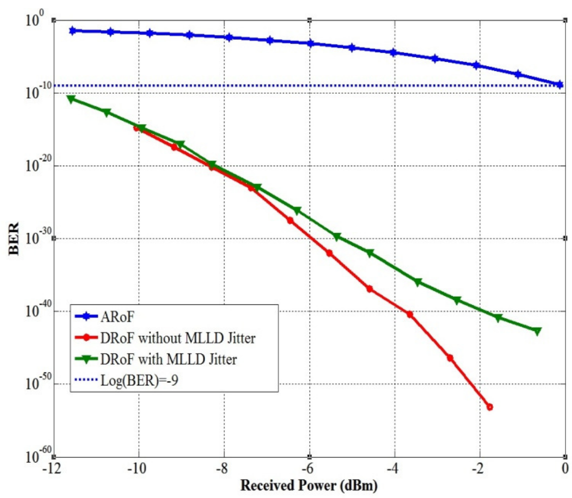


Figure 7: BER of the ARoF and DRoF VS. Received Power at the BS over 15 km Dispersion Compensated SSMF.

V. CONCLUSIONS

In this paper, the proposed problem for digitizing the future super-broadband analogue radio frequency (RF) wireless signal by using a novel all-photonic signal conversion technique is overcome. For system performance investigation, an integrated DRoF and a conventional ARoF system are simulated by Optiwave-Optisystem and Matlab simulation tools for super-broadband wireless signal transportation and distribution over 30 km of single mode fibre. By using the proposed all-photonic DRoF, the 5 GHz, ASK modulated RF signal with 1 Gbps bandwidth is sampled with 15 Gigasample/s of MLLD's pulse with about 192.7 femtosecond modelled rms timing jitter. In this integrated transportation system, the BER of DRoF was reported less than $10^{-12.6}$, that is significantly better than ARoF link performance with reported BER about 10^{-1}.

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