A Digital Fronthaul Link Based on Optimised Digital Radio over Fibre System

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Abstract: The high optical bandwidth requirement in the mobile fronthaul link of the next generation cloud radio access network represents one of the major design constraints. In this paper, a digital fronthaul link based on DRoF system that integrates the duobinary coding scheme with the optical single sideband (OSSB) transmission is proposed. This system reduces the spectral occupancy of the transmitted signals as well as the chromatic dispersion effects induced by fibre in both the electrical and optical domains. The OSSB signal is created by driving two cascaded optical modulators with a combination of a baseband digital signal and the Hilbert Transform of that signal. The transmission performance of a digitised 16-Quadrature Amplitude Modulation 16-QAM radio frequency signal with a bit rate of 1.25 Gb/s over a Standard Single Mode Fibre (SSMF) is investigated. The results show that the fronthaul transmission length can be extended by 75% and 16.6% relative to the case of transmitting the digitised signal using Double Sideband (DSB) and Single Sideband (SSB) transmission formats, respectively. The power budget is improved by 10 dB compared to the SSB case with respect to the measured OSNR at 70 km fibre distance, while maintaining the EVM below the standardised values of the 3GPP.

1. Introduction

Radio over Fibre (RoF) technology has been considered as the most promising solution to cope with the exponential growth in mobile data traffic. Such RoF technology can provide the essential platform required to build a Centralised Radio Access Network (C-RAN). In C-RAN, a new concept of Base Station (BS) design is proposed based on co-locating the Baseband Processing Units (BBU) in a centralised BBU pool while keeping the relative Remote Radio Heads (RRHs) at the cell site. C-RAN provides many advantages over conventional RAN, such as BS design simplification, reduced power consumption even with the densely deployment of the RRHs, centralisation of the Radio Frequency (RF) signal processing, the ability to perform a dynamic resource allocation, cooperative radio techniques, and network functionalities virtualisation to perform dynamic load balancing [1].

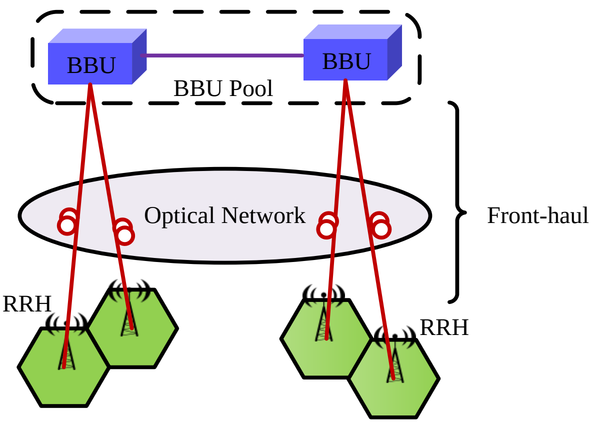


Fig. 1 *Basic C-RAN Structure*

Under C-RAN, a new paradigm of a transport network connecting the RRHs to the BBU pool based on an optical distribution network called the “fronthaul” is proposed as shown in Fig. 1 [2]. Optical techniques applied for this transportation segment might make use of either analogue or digitise waveform of the RF signal to be transmitted over the fronthaul. However, transmitting RF signals over fibre in the analogue domain needs to have an infrastructure that is capable of supporting high carrier frequencies by adopting analogue optical devices with high linearity [3]. Analog RoF (ARoF) systems are highly vulnerable to nonlinear distortion, such as Intermodulation Distortion (IMD) and the link dynamic range degrades linearly with increasing transmission distance [3]. Furthermore, the Chromatic Dispersion (CD) effect in such a communication system represents one of the major challenges that limit both the transmission bandwidth and distance, consecutively. Digital RoF (DRoF), where analogue RF signals are digitised and converted into a serial bit stream at the transmitter side before being transmitted over fibre, has recently been suggested as a feasible alternative to ARoF systems due to its advantages: it can remove linearity concerns in the optical devices, extend the transmission reach as it addresses the dynamic range degradation issue presented in ARoF, transparency with various modulation formats and radio protocols, and its compatibility with the existing and future broadband access systems since the transmission is in the digital domain over fibre [4], [5]. Nevertheless, the increasing demand for higher data rates in the fronthaul using either ARoF or DRoF transmission scenarios places stringent requirements on this optical transport network. Currently, telecommunication operators have considered the fronthaul link as a purely digital entity that can be based on either the Common Public Radio Interface (CPRI) [6] or the

Open Base Station Architecture Initiative (OBSAI) [7] transmission protocols.

In digital fronthaul transmission based on CPRI protocol, digitised in-phase and quadrature (I/Q) samples are transmitted over the fronthaul link by one of its standardised options which are multiples of (1, 2, 4, 5, 8, 10, and 16) by 614.4 Mbit/s [8]. The CPRI data rate is mainly dominated by the sampling frequency of the analogue RF signal and the Analogue-to-Digital Converter (ADC) resolution bits. In addition, it also depends on many other factors, such as the carrier bandwidth, number of multiples sectors and number of antennas per each sector, and CPRI coding factor (either 10/8 for 8*B*/10*B* code or 66/64 for 64*B*/66*B* code) [9]. Therefore, a CPRI based fronthaul produces a very high bit rate that needs to be accommodated by this digital optical link. For instance, the data rate required to transmit an LTE signal with 20 MHz bandwidth using 2x2 multi-inputs, multi-outputs (MIMO) and 3 sectors per each RRH would be 2.5 Gb/s [10]. As a result, CPRI based fronthaul suffers from a low spectral efficiency, and consequently limits the fibre distance between the BBU pool and corresponding RRHs to a few tens of metres [11].

Many approaches have been proposed to investigate how to increase the spectral efficiency and how to circumvent the high data-rate bottleneck associated with CPRI. It has been indicated in [12] that a trade-off between the ADC sampling rate and bit resolution might alleviate the consequent optical line rate. However, it is not possible to maintain the same link performance, while lowering the hardware requirement, by simply reducing the ADC sampling rate and/or bit resolution. Another approach comprises of employing compression on the data transmitted over the fronthaul. Although many techniques have enabled compression percentage up to 50%, they detriment some of the transmitted data and produce an additional processing delay [13]. Authors in [14] have proposed data regeneration architecture for DRoF transmission based on time stretching, optical sampling and hard limiting, but this technique might be susceptible to non-linear impairments in the optoelectronic devices since it depends on an All Photonic ADC (AP-ADC). More recently, a mobile fronthaul link based on Delta-Sigma modulation has been demonstrated in [15] as a new digitisation interface for a digital fronthaul link to replace the traditional CPRI. However, this system requires expensive high sampling rate DSP circuitry.

With the high data rates produced by CPRI that require high optical bandwidth, the impact of the chromatic dispersion (CD) is one of the principle challenges with regards to higher transmission rates and distances. Therefore, the main aim of this paper is to investigate how to reduce the optical bandwidth requirements for CPRI based digital fronthaul link, so that to decrease the influence of the CD and to increase the transmission distance. This bandwidth reduction was achieved by employing a combination of two bandwidth-efficient modulation formats, namely Duobinary coding scheme, which has been used to encode the digital data of the ADC output instead of the conventional Non-Return-to-Zero (NRZ), and digital Optical Single Sideband (OSSB) modulation.

The use of multilevel modulation and partial response signalling has attracted substantial research interest, as they can reduce the spectral width of the baseband signal [16], [17]. In the same context, transmitting the digital signal in an OSSB form allows for the effects of CD to be reduced relative to transmission in double sideband (DSB) form [18]. Also, the use of duobinary signalling has two advantages over the conventional coding schemes, such as NRZ. First, it is more tolerant to CD compared to NRZ and hence, offers a reach extension. Second, it introduces the Inter-Symbol Interference (ISI) induced by the chromatic dispersion in a controlled manner that reverses its effect positively at the receiver side [19].

In this paper, a physical layer design of a digital fronthaul link employing an optimised DRoF system that integrates a duobinary coding scheme with a digital (OSSB) modulation format has been presented. As a result, in this link, the overall transmission bandwidth is reduced over two stages; First, in the electrical domain using duobinary encoding and the second, in the optical domain using OSSB transmission. By doing so, the performance of the fronthaul based optimised DRoF link is greatly improved as the nonlinear impairments are directly related to the transmission bandwidth.

For the sake of integration compatibility, many design modifications have been done not only to gain more bandwidth reduction but also to achieve even more sideband suppression. Moreover, a physical design to a Finite Impulse Response (FIR) digital filter is proposed to provide the required Hilbert Transformation to baseband digital signal in the proposed OSSB configuration. By using the proposed scheme, the digitised transmission of a 16-QAM RF signal over a SSMF with CPRI equivalent data rate is enabled for transmission distances reached up to 70 km. The performance of the proposed system is analysed and compared with two different digital transmission scenarios in order to highlight its proficiency. This comparative study is demonstrated between the proposed system and each of a DRoF fronthaul link based on the OSSB and Optical Double Sideband (ODSB) transmission scenarios, which both use the NRZ encoding scheme. A comprehensive analysis and performance evaluation of the proposed system is undertaken using VPITransmission Maker as a simulation tool [20], which focuses only on the optical design aspect.

The rest of this paper is organised as follows: in section 2, the proposed duobinary coding scheme is explained. Section 3 presents a theoretical analysis of the proposed OSSB transmission scheme. Section 4 introduces the designed Hilbert Transform using a truncated order low pass FIR digital filter. Section 5 explains how the integration between the duobinary signalling and OSSB modulation scheme has been enabled, whilst the simulation of the proposed fronthaul transmission scenario is illustrated in section 6. Simulation results are discussed in section 7. Finally, the conclusion is presented in section 8.

2. Proposed Duobinary Encoder

Duobinary is a bandwidth efficient coding scheme, in which the binary digital signal is encoded into a three-level baseband signal using a particular precoding technique [21]. The performance of high data rate optical communication systems is primarily dispersion limited. Duobinary signaling can be considered as an effective way to reduce the influence of chromatic dispersion in optical fibre. It reduces the bandwidth requirement for transmitting a data rate of *R* bit/s to less than *R/2* Hz of the transmission bandwidth. The immediate disadvantage of this signaling scheme is related to the fact that it will introduce an ISI into the transmitted pulses, according to the Nyquist criteria in the sampling theorem [22]. It has been proven in [23], [24] that ISI can be mitigated by using one of the partial response signaling techniques, such as the duobinary signaling, by introducing a deterministic amount of ISI into the transmitted signal so that it can be counteracted upon detection at the receiver. This, in fact, constitutes another advantage of using this encoding scheme in addition to the reduced bandwidth. In order to understand why this makes sense, one must understand how duobinary data is generated. The coding rule for duobinary signal is given by [25]:

$$c_k = b_k + b_{k-1} \tag{1}$$

where, b_k is the k^{th} element of the binary sequence. Meaning that the duobinary encoder output c_k correlates present binary input bits and the previous input bits (i.e. there are three output levels {-1 0 1} depending on b_k and b_{k-1}). An important property of the three-level sequence is that the combinations {1 0 1} as well as {-1 0 -1} can never occur at the output of the encoder; only {-1 0 1} and {1 0 -1} can occur as shown in Fig. 2. This sequence is another reason why duobinary encoding is resilient to dispersion.

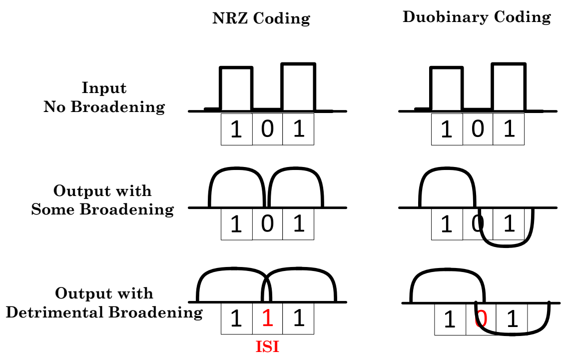


Fig. 2 *Dispersion Effect on NRZ and the Duobinary Coding Schemes*

The receiver can recover the transmitted data sequence b_k by the following rule:

$$b_k = c_k - b_{k-1} \tag{2}$$

This means that a single ISI error will propagate at the receiver due to correlation between symbols. To overcome this, a precoding scheme is used before the duobinary encoder at the transmitter. The data bits are pre-coded or differentially encoded as follows:

$$c_k = b_k \oplus c_{k-1} \tag{3}$$

where, $\oplus$ denotes the modulo-2 addition. Hence, the receiver samples the value:

$$c_k \oplus c_{k-1} = c_{k-1} \oplus b_k \oplus c_{k-1} = b_k \tag{4}$$

To implement the differential encoder, an exclusive OR (XOR) gate can be used, as shown in Fig. 3.

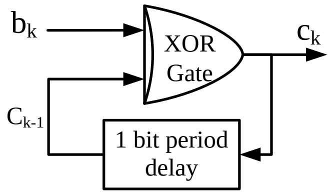


Fig. 3. *Conventional Duobinary Pre-Coder*

However, it is hard to implement the 1 bit delay feedback at data rate beyond 10 Gb/s. To address this, the precoder circuit reported in [26] is implemented, in which the precoder is implemented using an inverter and (AND) gate followed by a Toggle flip-flop (T-ff). The latter is used as a divider by two counter to perform the same precoder function in (4). Here, the T-ff clock is AND gated with the inverse version of the input data. Hence, the counter changes state only when the input data are high, and remains the same when these are low, which is equivalent to a module 2 function. Fig. 4 illustrates the functional bit sequence of the designed precoder.

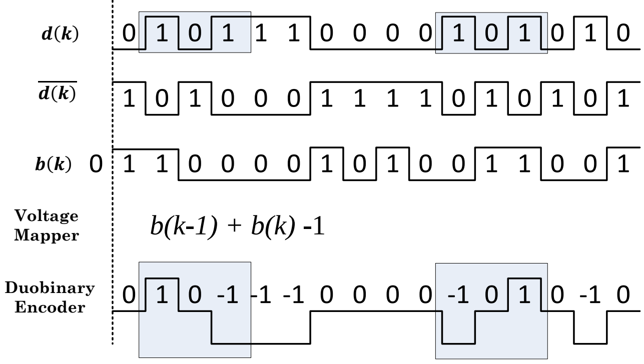


Fig. 4. *Bit Sequences illustrate the operation of the Duobinary Pre-Coding System*

In the proposed duobinary coding scheme, which is shown in Fig. 5, the duobinary encoder is realised using a 5th order Low Pass Filter (LPF) with Bessel transfer function and 2.5 GHz cut-off frequency. A single driver amplifier is utilised after the encoder to provide the required bias voltage to the optical transmitter.

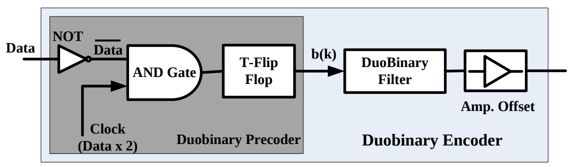


Fig. 5. *Duobinary Coding Scheme*

3. Optical Single Sideband Transmitter

Figure 6 below shows a schematic diagram of the OSSB modulator used in the proposed system.

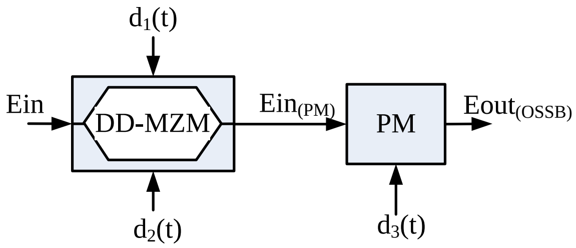


Fig. 6. *Optical Single-Sideband Configuration*

It consists of a Dual Drive Mach Zehnder Modulator (DD-MZM) followed by a Phase Modulator (PM) [26]. An OSSB baseband digital signal is achieved using this configuration without the requirement for an optical filter. The electrical field output of the chirp free DD-MZM and PM is represented in (5) and (6), respectively:

$$E_{out(MZM)} = E_{in(PM)} = \frac{E_{in}}{2} exp\left(j\pi \frac{d_1}{V_\pi}\right) + \frac{E_{in}}{2} exp\left(j\pi \frac{d_2}{V_\pi}\right) \quad (5)$$

$$E_{out(PM)} = E_{out(OSSB)} = E_{in(PM)} exp\left(j\pi \frac{d_3}{V_\pi}\right) \quad (6)$$

where, $V_{\boldsymbol{\pi}}$ is the modulator biasing voltage, whilst d_1, d_2 and d_3 are the electrical drive signals, which can be expressed as:

$$d_1(t) = xV_\pi m(t) - \frac{V_\pi}{2} \quad (7)$$

$$d_2(t) = -xV_\pi m(t) + \frac{V_\pi}{2} \quad (8)$$

$$d_3(t) = xV_\pi \widehat{m}(t) \quad (9)$$

where, x is the modulation index, $m(t)$ is the original version of the encoded baseband digital signal and $\widehat{m}(t)$ is the Hilbert Transform of $m(t)$. Mathematically, the SSB signal can be obtained by using the Tylor series expansion to solve the resultant equation from substituting (7), (8) and (9) into (5) and (6), and by taking only the first order terms (i.e. the linear terms).

$$E_{out(OSSB)} = exp(j\omega_\circ t) exp\big(jz\widehat{m}(t)\big) \cos\left(zm(t) - \frac{\pi}{4}\right) \quad (10)$$

where, $z = \boldsymbol{\pi}x$. It can be seen from (10) that the output SSB signal represents the cascade of amplitude modulation (cosine term) and phase modulation (exponential term).

4 Hilbert Transformer Design

The discrete time impulse response of the Hilbert Transformer or 90° phase shifter is given as [27]:

$$h(n) = \begin{cases} \frac{2}{\pi} \frac{\sin^2(n\pi/2)}{n} & for\ n \neq 0 \\ 0 & for\ n = 0 \end{cases} \quad (11)$$

Fig. 7 shows the impulse response of an ideal Hilbert transformer.

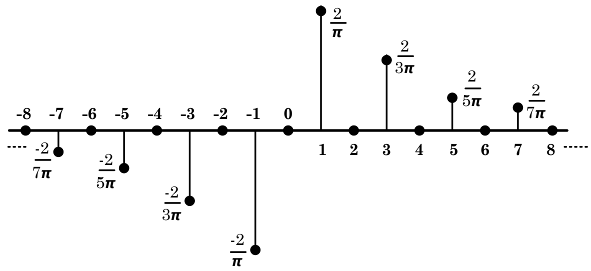


Fig. 7. *Impulse Response of an Ideal Hilbert Transformer*

Thus, a discrete time Hilbert transform can be formulated using a casual low-pass Finite Impulse Response (FIR) digital filter with constant group delay since they have the same impulse responses. The ideal FIR transfer function is expressed as [28]:

$$H(z) = \sum_{n=0}^{N-1} h[n] z^{-n} \quad (12)$$

where, n is the filter order, N is the filter length and z^{-n} represents the unit delay (τ) between filter's taps, which can be calculated as:

$$Unit\ Delay = \tau = \frac{N-1}{2 * f_s} \quad (13)$$

where, f_s is the sampling frequency.

In our proposal, the Hilbert transformer needed for the drive signal of PM is designed by considering an anti-symmetric FIR digital filter with an odd length of 7 (order 6), as shown in Fig. 8 below, as it is more stable. The FIR filter order is truncated to this order as the improvement in the performance using more than 6 taps is minimal.

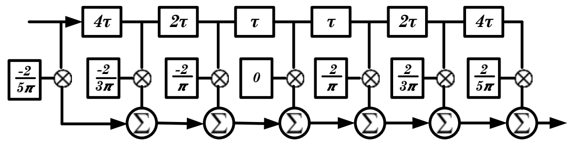


Fig. 8. *FIR Filter Designed as Hilbert Transformer*

5 Integration of OSSB Transmission with Duobinary Signalling

It was mentioned earlier that one technique of limiting the chromatic dispersion impact is to reduce the optical bandwidth that is required to transmit a given bit rate. It was also mentioned that transmitting the digital signal in duobinary format reduces the chromatic dispersion as the effective transmission bandwidth for duobinary transmission is one-half relative to the conventional binary transmission. Moreover, it has been found that encoding the digital data at the transmitter using duobinary signalling scheme introduces the ISI in a controlled manner at the receiver which counteracts its effect.

Implementing the duobinary signalling in the OSSB transmission would then result in an even more bandwidth reduction. With this implementation, the transmission bandwidth is furtherly reduced from both the duobinary coding format and the OSSB status to the optical electric-field signal. However, it must be mentioned that integrating the duobinary signalling with the OSSB transmitter would only be possible if the biasing points of the MZM are chosen so that to maintain the three levels manner of the Duobinary signal through the transmission. The Duobinary signal can be applied to an optical modulator biased at ($V_\pi/2$) to generate a three-level intensity modulated optical Duobinary signal (E, 0, -E) as shown in Fig. 9 [29]. Biasing the optical modulator at this point is essential to maintain the three optical intensity levels through the transmission. In this case, *m(t)* in equation (10) would represent the three-level signal. Therefore, the amplification parameter (x) of *m(t)* must be relatively small, so that to maintain the three-level signal and hence to deter signal distortion upon detection, and also to gain a good sideband cancellation in the resultant optical signal.

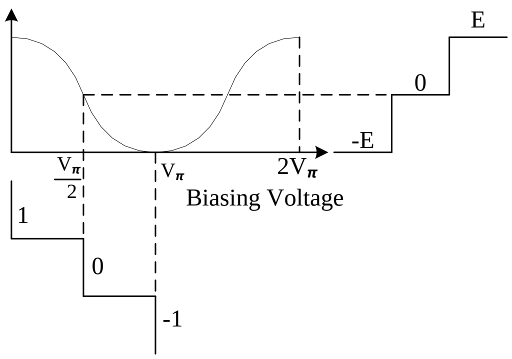


Fig.9 *Biasing Condition for Generating a Regular Duobinary Intensity Modulated Signal*

6 Proposed System Simulation

The proposed system is simulated for a digital fronthaul link in the scenario with 10 Gb/s based on an optimized DRoF system, and the system structure is shown in Fig. 11. In this system, a carrier frequency of 5 GHz is modulated with a bit rate of 1.25 Gb/s using a 16-QAM modulation scheme. The modulated RF signal is then down-converted into an Intermediate Frequency (IF) of 400 MHz to alleviate the sampling frequency requirements of the existing ADC, according to the Nyquist criteria in the sampling theorem. Frequency down-conversion is established using a combination of a Local Oscillator (LO) of 4.6 GHz and mixer, followed by a Band Pass Filter (BPF) with BW of 400 MHz. This bandwidth value was chosen since it covers the minimum bandwidth requirements for the 16-QAM RF signal with a data rate of 1.25Gb/s [30]:

$$B = \left(\frac{f_b}{\log_2 M}\right) \tag{14}$$

where, B is the minimum Nyquist bandwidth, f_b is the channel capacity (bps) and M is the number of discrete signal or voltage levels. The dynamic range limits of the utilised ADC lay between 0 and 1 and thus, a normaliser is used to match the amplitude of the input signal in accordance with the ADC limits. The digitisation process is performed by the ADC component provided by the simulator.

In our design, the intention was to use a different coding scheme and consequently, the existing ADC processes are redesigned so as to be compatible with our requirements. Initially, the signal is quantised into a number of levels given by 2^n, where n is the ADC bit resolution and thus, the signal is transferred into a discrete time signal with multi-level integer values. The digital bit stream is obtained by an integer-to-bit converter. The obtained bit stream is converted into a serial sequence and then coded using the duobinary coding scheme presented in Fig. 5. The output of the duobinary precoder is pulse-shaped using a Butterworth LPF with 3-dB cut-off frequency at 2.5 GHz, which is 25% of the resultant bit rate, so as to achieve a 3-level baseband signal. The eye diagram of the corresponding electrical duobinary signal is shown in the inset (a) of Fig. 11, which has two eyes since duobinary has two decision thresholds. Whilst the duobinary signal is a 3-level signal in terms of the electrical domain, it exhibits two levels in terms of the optical power while preserving a 3-level nature in the optical phase. This is in turn reduces the ISI effect as an opposite phase between any adjacent one-bits will be introduced. At the optical stage, the digitised RF signal is externally modulated using the following categories: Optical Double Sideband (ODSB) that applies the NRZ coding scheme, Optical Single Sideband (OSSB) transmission using the NRZ coding scheme as well and finally, OSSB that employs duobinary coding format. Regarding the ODSB transmission, the DD-MZM is set up as a balanced Mach-Zehnder Modulator by disabling the upper DC and the lower RF drive inputs as shown in Fig. 10.

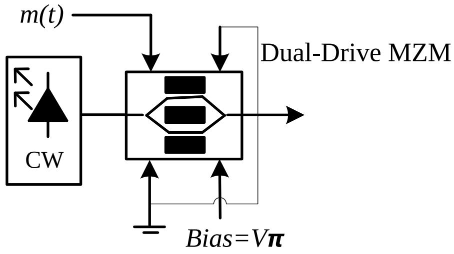
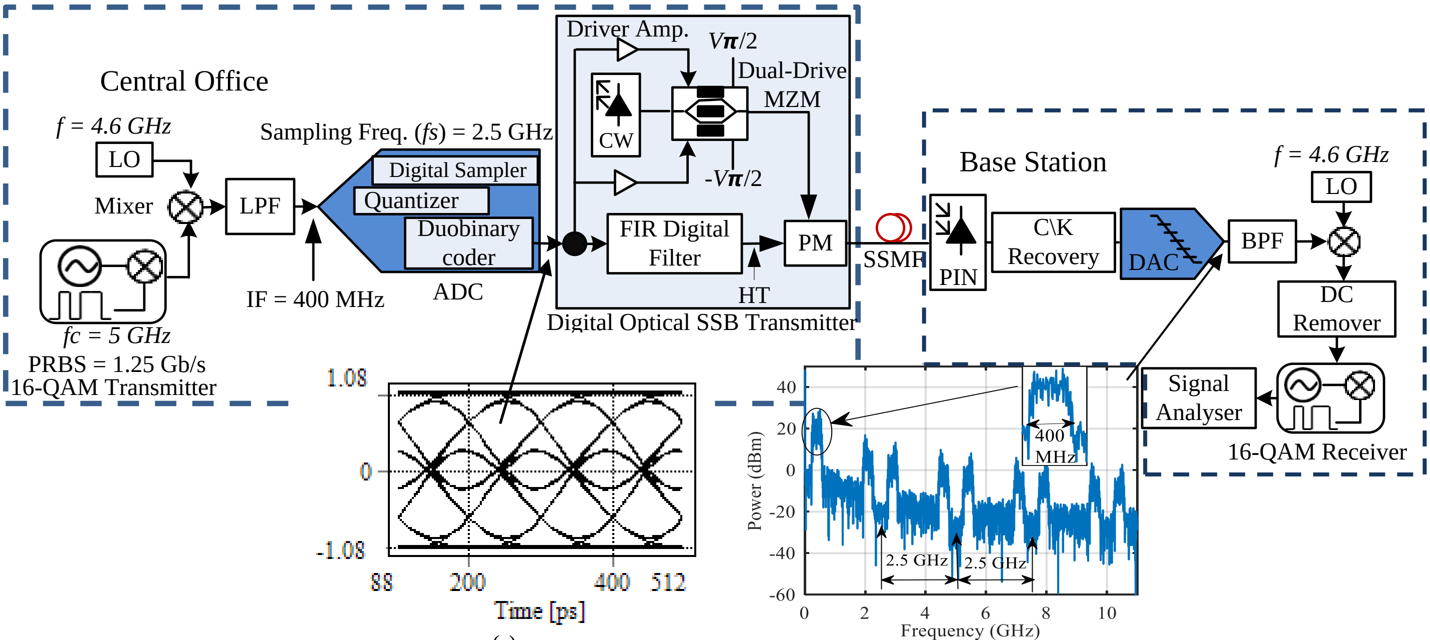


Fig. 10. *Digital Optical DSB Transmitter*

It is important to note that the three transmission scenarios use the same pulse-shape LPF characteristics, which is placed after the coding stage. In the proposed system, the OSSB transmission is performed using the configuration shown in Fig. 6, in which the duobinary coded modulating signal is fed to two paths. The first path is fed to the Low Pass FIR digital filter presented in Fig. 8 to achieve the Hilbert Transformation (HT) required for the drive signal of the PM. The second path is applied equally to each arm of the dual-drive MZM (DD_MZM), which has the same DC bias voltage of ($V\pi/2$) for each arm in order to drive the modulator between the maximum and minimum extinction ratio. The amplitude of the RF drive signals applied to each arm is equal to $V\pi$ multiplied by the modulation depth (x). The output of the DD-MZM and the FIR digital filter are both modulated using the PM to obtain the required OSSB signal, which is then transmitted over a Standard Single Mode Fibre (SSMF) using a continuous wave (CW) laser source with a wavelength of 1552nm. A PIN photo-detector is used at the receiver side to detect the transmitted base band signal, which is regrouped from serial to parallel in order to be processed by the DAC component so as to recover the analog IF signal.



(a) *Fig. 11 The Proposed System* (b)

The DAC output signal has spectral replicas repeated at frequency points equal to the sampling frequency (f_s) [31], as shown in the inset (b) of Fig. 11. Therefore, a Gaussian function BPF centred at the IF value is used after the DAC to extract the IF signal from its replicas. Finally, an LO and mixer are used to regenerate the RF signal, which is analysed in terms of the received BER, EVM, Q-factor, Eye Opening Penalty and OSNR, using the 16-QAM receiver component provided by the simulation software.

7 Simulation Results and Discussion

The overall bit rate in the fronthaul link based on the proposed DRoF transmission system is equal to the product of the ADC sampling rate by the ADC bit resolution. It is evident that DRoF system with ADC bit resolution of 4 bits and ADC sampling rate of 2.5 GHz can achieve acceptable performance [32]. Consequently, all measurements were taken at these values. In other words, the transmission of a 5 GHz 16-QAM RF signal with a bit rate of 1.25 Gb/s is mapped into a digital signal with an overall bit rate of 10 Gb/s for the optical link. This bit rate, in fact, is equivalent to transmit 4 aggregated LTE signals each one with 20 MHz bandwidth with 2x2 MIMO for a 3 sector RRH. Therefore, the designed digital link supports and enables carrier aggregation requirements for LTE-Advanced (LTE-A) Release 10 and beyond.

To show the distinction of the proposed system, the performance of the designed transmission technique has been compared to those of two other transmission formats, namely ODSB and OSSB, using the same simulation parameters that are listed in table 1. The MZ modulator in the case of ODSB is driven to full extinction, while the DD_MZM and PM in the OSSB case are driven to levels so that they optimise the received EVM. This was achieved by using a modulation depth x of 0.2 and biasing voltage Vπ of 5 V in the OSSB case. The comparison of the produced DRoF optical spectrum for the three transmission scenarios is shown in Fig. 12. It clearly demonstrates that the OSSB spectrum has not completely canceled the unwanted sideband, which is the upper sideband and the suppression ratio is about 4.38 dB.

This imperfect suppression is a result of the signal driving the PM as it is not the perfect Hilbert Transform of the modulating signal. It also can be seen that the OSSB transmission that employs duobinary coding scheme requires much less bandwidth, while reserving the same data rate. In addition, more than 2 dB suppression ratio was achieved in the unwanted sideband. This contributes to the high bandwidth reduction due to the use of the duobinary coding scheme that shows more effect on the optical spectrum than that of the OSSB.

Table 1 Simulation Parameters

Parameter	Value
Modulation	16-QAM
Fibre Attenuation	0.2 dB/km
Dispersion	16 ps/nm.km = 16×10^{-6} s/m^2
Laser Frequency	193.1×10^{12} Hz
Laser Linewidth	1.0×10^{6} Hz
PIN Responsivity	0.9 A/W
ADC Resolution	4 bits

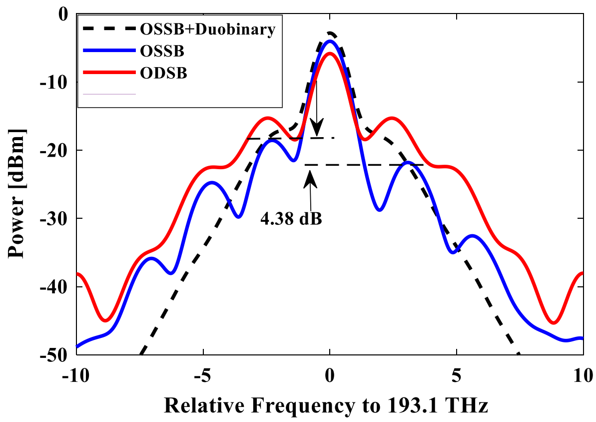


Fig. 12 Optical Spectrum for the three transmission scenarios

It should be noted that the value of the sampling frequency default parameter in the simulation session was chosen to be 80 GHz. According to (13), the delay time τ between the FIR filter taps is calculated to be 31.25 ps for the incoming 10 Gb/s bit rate. Figure 13 plots the receiver sensitivity of the three compared systems versus fibre distance. To achieve a fair comparison, the receiver sensitivity was calculated based on a received BER of 10^{-4}, which is acceptable for a 16-QAM transmission system without the requirement of error correction [33].

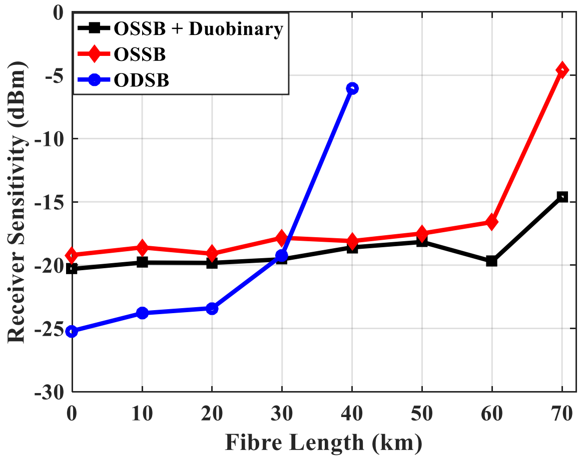


***Fig.13.** Receiver Sensitivity versus Fibre Distance*

It can be seen from Fig. 13, that the transmission of the DRoF signal in OSSB format can achieve better receiver sensitivity than ODSB at distances over than 30 km. It is also evident that there is a power penalty of about 5 to 6 dB at 0 km in the case of both OSSB and the proposed formats with respect to ODSB. This is because of the MZ modulator is not being driven to the full extinction in the case of OSSB, unlike in the case of ODSB. The receiver sensitivity improves further when the DRoF system employs the proposed transmitting scenario due to the use of the duobinary coding scheme, which reduces the chromatic dispersion effect, resulting in a -66.44% sensitivity enhancement at 70 km fibre distance relative to the OSSB case. However, link performance is degraded after this fibre length, because of the additional effects, such as the fibre non-linear effects and the accumulated fibre attenuation.

The Quality factor (Q factor) is related to the received BER by:

$$BER = \frac{1}{2} erfc \frac{Q}{\sqrt{2}} \tag{15}$$

This relationship implies that the minimum value of Q that will satisfy a BER of 10^{-9} is 6 as it can be shown in Fig. 14 below. Hence, this Q factor value is considered as the threshold level to compare between the three transmission schemes. Figure 15 shows the measured Q factor versus the Optical Signal-to-Noise Ratio (OSNR). The simulation results of Fig. 15 were taken at a fibre length of 20 km. It indicates that the threshold level cannot be reached in the case of the ODSB transmission scenario. This confirms the feasibility of the suggested bandwidth-efficient transmission schemes for DRoF systems. It should be noted that the OSSB scheme can achieve the threshold value of Q at OSNR values higher than 29 dB.

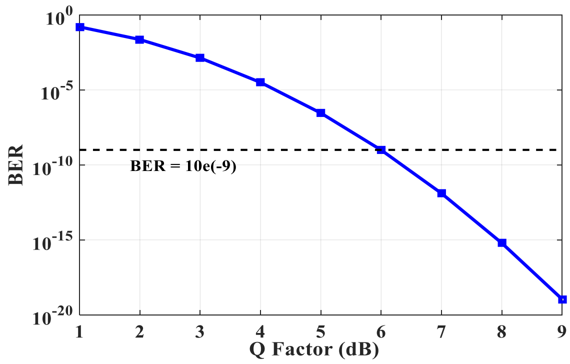


***Fig. 14.** Q Factor versus BER*

It should also be stressed that the OSNR of the proposed scheme is enhanced by 5.8 dB relative to the OSSB system in meeting the same requirement. This enhancement is contributed to the major reduction in the chromatic dispersion effect by utilising the duobinary coding in the proposed scheme.

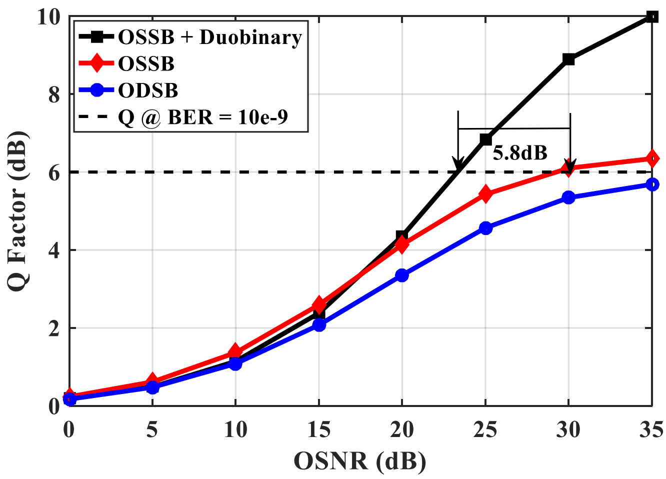


***Fig. 15.** Q Factor versus OSNR*

Eye diagrams of the transmitted signals were used to evaluate the transmission performance of the compared systems. The Eye Opening Penalty (EOP) is used to measure the degradation in the eye diagrams, which is defined as the ratio of the non-distorted reference eye, namely the Eye Opening Amplitude (EOA), which can be obtained from the back-to-back measurement and the eye opening of the distorted eye, i.e. the Eye Opening Height (EOH). In fact, EOP is the ratio of the inside and outside opening of the eye diagram as shown in the inset of Fig. 14. EOP is usually given in dB as [34]:

$$EOP(dB) = 10 \log\left(\frac{EOA}{EOH}\right) \tag{16}$$

Figure 16 shows the measured EOP against the fibre distance. It can be seen that the EOP increases exponentially with increasing distance. In the figure, EOH in the ODSB case closes after 30 km distance owing to the EOP approaching infinity, according to (16), since the eye diagram is completely closed at 40 km distance. In the

OSSB case, the EOH does not close until 50 km distance, where 8.1 dB of the EOP is obtained, since the optical bandwidth is half that of the ODSB case.

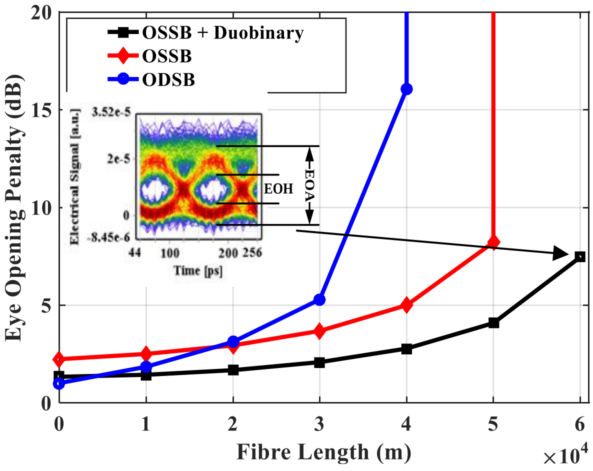


Fig. 16. *Eye Opening Penalty versus Fibre Length*

In the OSSB case, the EOH does not close until 50 km. In the proposed system, the digital signal is pre-compensated for the CD effect via duobinary coding. This has resulted in a further extension to the fibre distance in terms of the measured EOP. In addition, a significant improvement can be observed in the EOP along the whole transmission distance relative to the OSSB case, because of the optical bandwidth is more reduced. As a result, the EOH can be partially reopened for a distance beyond the OSSB case, but it can never be reopened after 60 km due to the second order effect of the CD.

Another important finding is depicted in Fig. 17 regarding the measured Error Vector Magnitude (EVM) of the 16-QAM digitised RF signal at different fibre distances. Initially, it should be mentioned that the minimum requirement for the EVM value, according to the 3rd Generation Partnership Project (3GPP) specifications for a 16-QAM signal in LTE, is 12.5% [35]. Regarding the ODSB transmission scenario, the measured EVM values remain constant from 0 to 40 km of fibre distance, despite the signal is subjected to an 8 dB penalty resulted from the fibre attenuation. This confirms the fact that DRoF systems are capable of maintaining the signal dynamic range independent from the fibre length until it goes below the receiver sensitivity. Similarly, measured EVM values remain stable and below the 3GPP requirement in the case of OSSB transmission, but this time for a longer distance that reaches up to 50 km. This increment is directly related to the optical bandwidth reduction. However, the attenuation and dispersion effects become more severe after this distance, thus causing a distortion in the received constellation diagram, as shown in the inset (a) of Fig. 17. In the proposed scenario, it should be noted that there is an observable EVM enhancement of 7% along the whole transmission distance when compared with the other ones. It is evident that the received I/Q symbols forming the constellation diagram are mainly penalised by the ISI effect produced by the CD. Employing the duobinary coding reduces the ISI effect and consequently, the received symbols are more concentrated, which improves the EVM values, as shown in the inset (b) of Fig. 17. Moreover, the transmission distance is increased up to 70 km, while still satisfying the EVM requirement. This resulted from the further reduction in the optical bandwidth presented in this transmission scheme.

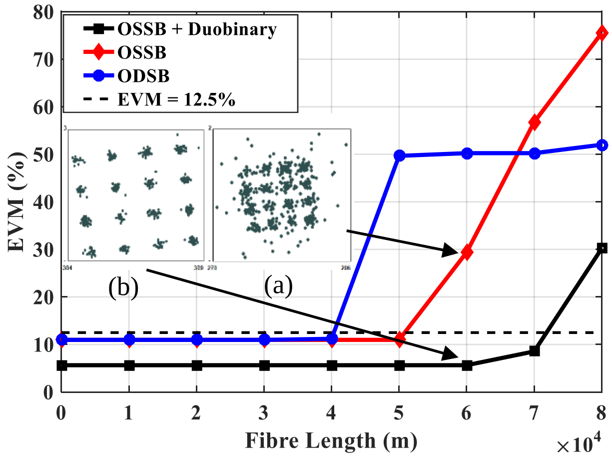


Fig. 17. *Error Vector Magnitude versus Fibre Length*

8 Conclusion

In this paper, a theoretical analysis and a physical layer design of a digital fronthaul link based on an optimized digital radio over fibre DRoF system has been presented. The main challenges associated with the CPRI based fronthaul implementation, such as high optical line rate and high optical bandwidth requirement have been discussed. To address these limitations, a digital fronthaul link with a transmission scenario based on the integration of digital optical single sideband modulation and duobinary coding scheme in a DRoF platform has been proposed. The proposed scheme reduced the dispersion effects introduced in the fibre by first, diminishing the spectral occupancy of the transmitted optical signal and second, by countering the ISI effects induced by the chromatic dispersion. For comparison, two other transmission scenarios for the fronthaul link, based on ODSB and OSSB, respectively, have been considered. Simulation results have proven that by employing the proposed DRoF scenario in the CPRI based fronthaul; transmission distance can be extended up to 70 km without dispersion compensation requirement. Moreover, it has been shown that the proposed link can achieve EVM values below the limits required by the 3GPP LTE specifications over a typical fronthaul distances reaches up to 70 km, while significantly requiring less optical bandwidth than the legacy fronthaul.

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