Experimental Demonstration of Soft-ROADMs with Drop Signal Phase Independent Performance for PTMP 5G Fronthauls

Omaro Fawzi Abdelhamid Gonem  
School of Computer Science and Electronic Engineering  
Bangor University  
Bangor, UK  
o.gonem@bangor.ac.uk

Roger Philip Giddings  
School of Computer Science and Electronic Engineering  
Bangor University  
Bangor, UK  
r.p.giddings@bangor.ac.uk

Jianming Tang  
School of Computer Science and Electronic Engineering  
Bangor University  
Bangor, UK  
j.tang@bangor.ac.uk

Abstract—A dual-arm IQ soft-ROADM drop element is demonstrated to dynamically and adaptively drop any IQ channel pair, from a single optical wavelength containing multiple sub-wavelengths, whilst maintaining an acceptable BER independent of drop RF signal phase offset. Such soft-ROADMs simplify the practical implementation of Point-to-Multipoint 5G fronthauls.

Keywords—5G, digital filtering, digital signal processing, fronthaul, optical switching, point-to-multipoint, ROADMs.

I. INTRODUCTION

To manage the extreme growth in mobile network applications with significantly different requirements on connectivity, latency, QoS, and bandwidth, such as video streaming, IoT and cloud-based applications, it is envisioned that the current point-to-point (PTP) 5G fronthaul architectures will migrate towards point-to-multipoint (PTMP) architectures, to realise improved flexibility with adaptive capacity allocation, high peak throughputs, low latency and high reliability, whilst still maintaining acceptable cost-effectiveness [1].

Reconfigurable optical add/drop multiplexers (ROADMs) offer a key reconfigurable optical switching device to enable the future flexible PTMP 5G fronthauls as they allow the seamless transformation of the current PTP links between radio units (RU) and distributed units (DU) into dynamically reconfigurable DU-to-multi RU 5G fronthauls [2]. Numerous wavelength selective switch (WSS)-based color-less, direction-less, and contention-less ROADMs (CDCROADMs) have been proposed [3], and in addition, low-loss, small-scale, integrated photon ROADMs have also been introduced into high-capacity 5G fronthauls [4]. However, these newly reported ROADM designs and currently commercially available ROADMs are only capable of providing the switching functionality at wavelength level, this constrains their flexibility for future 5G fronthauls, where fine bandwidth granularity channel switching is highly desirable.

Digital signal processing (DSP)-based, software-reconfigurable, digital filter enabled, O-E-O conversion- and optical filter-free, software-defined networking (SDN)-controllable ROADMs, termed soft-ROADMs, have been recently proposed and experimentally demonstrated [5,6], which offer flexible optical switching at wavelength, sub-wavelength (SW) and spectrally-overlapped orthogonal (I and Q) sub-band (SB) levels. The low cost and flexibility of the soft-ROADMs make them promising for application in future PTMP 5G fronthauls.

To drop a targeted sub-band (TSB) signal, the soft-ROADM employs a simple intensity modulation operation on the input optical signal in an optical intensity modulator (IM) driven by a local oscillator (LO)-generated sinusoidal drop RF signal. When both the frequency and phase of the drop RF signal match the TSB, the TSB is shifted to an unoccupied baseband region with a reversed spectrum. However, as experimentally observed [5], the performance of a dropped TSB in the single-arm I/Q soft-ROADM drop element [5,6] is highly sensitive to drop RF signal phase offset $\theta_{RF}$, (deviation of the LO phase from the optimum phase), as the phase offset results in inter-SB leakage between spectrally overlapped orthogonal I and Q SBs, thus limiting the practical realization of the soft-ROADMs.

To eliminate the soft-ROADM drop RF signal phase offset effects, in this paper, we propose and experimentally demonstrate a new dual-arm IQ soft-ROADM drop element incorporating a novel multi-input multi-output (MIMO)-based I/Q crosstalk mitigation technique, based on which, LO phase-insensitive performance is achieved. This significantly simplifies the practical realization of future soft-ROADM-based PTMP 5G fronthauls.

II. MIMO-BASED I/Q Crosstalk Mitigation

For any transmission system consisting of an arbitrarily modulated single carrier ($k=I$) or multiple subcarriers ($k=I$) located in a given SB, the received I or Q data for the $k^{th}$ subcarrier is:

$$y_{k,I} = h_{k,I} x_{k,I} + w_{k,I}$$

$$y_{k,Q} = h_{k,Q} x_{k,Q} + w_{k,Q}$$

where $y_{k,I}$ and $y_{k,Q}$ are the received (transmitted) encoded data conveyed on the $k^{th}$ subcarrier of I and Q SBs in the Ith SW-band respectively. $h_{k,I}$ and $h_{k,Q}$ are the intra-SB channel coefficients, and $w_{k,I}$ and $w_{k,Q}$ represent noise. The single-arm I/Q drop element employs the conventional pilot-based subcarrier channel estimation/equalization for data recovery [7] which cannot compensate the drop RF signal phase offset-induced inter-SB leakage where:

- Some power from the desired SB is lost during the drop operation which decreases the optical-SNR (OSNR) of the TSB.
- Some power from the undesired orthogonal SB is also down-converted to the baseband spectral region with the desired SB.

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- Some power from the undesired orthogonal SB is also down-converted to the baseband spectral region with the desired SB.
To solve this issue, the proposed MIMO-based I/Q crosstalk mitigation technique assumes, for any subcarrier \( k \), each received data symbol is a combination of an I and Q SBs:

\[
y_{k,i}^I = h_{k,i}^I x_{k,i}^I + h_{k,i}^Q x_{k,i}^Q + w_{k,i}^I \tag{3}
\]

\[
y_{k,i}^Q = h_{k,i}^I x_{k,i}^I + h_{k,i}^Q x_{k,i}^Q + w_{k,i}^Q \tag{4}
\]

where \( h_{k,i}^I \) and \( h_{k,i}^Q \) are the inter-SB channel coefficients. Eqs. (3) and (4) can be regarded as a 2x2 MIMO system, the matrix representation is:

\[
\begin{bmatrix}
y_{k,i}^I \\
y_{k,i}^Q
\end{bmatrix} =
\begin{bmatrix}
h_{k,i}^I & h_{k,i}^Q \\
h_{k,i}^I & h_{k,i}^Q
\end{bmatrix}
\begin{bmatrix}
x_{k,i}^I \\
x_{k,i}^Q
\end{bmatrix}
+ 
\begin{bmatrix}
w_{k,i}^I \\
w_{k,i}^Q
\end{bmatrix} \tag{5}
\]

The 2x1 received encoded data vector is:

\[
y_{k,i} = H_{k,i} x_{k,i} + w_{k,i} \tag{6}
\]

where \( x_{k,i} \) is the 2x1 transmitted signal vector, \( H_{k,i} \) the is 2x2 MIMO SB channel coefficients matrix, and \( w_{k,i} \) is the 2x1 noise vector. To estimate \( H_{k,i} \), we consider \( f \) training symbols \( p_{1k}, \ldots, p_{f k} \). The received signal matrix is:

\[
Y_{k,i} = H_{k,i} P_{k,i} + W_{k,i} \tag{7}
\]

where \( P_{k,i} = [p_{1k}, \ldots, p_{f k}] \) is the 2x\( f \) training symbol matrix, \( Y_{k,i} = [y_{k,i}^I, \ldots, y_{k,i}^Q] \) is the 2x\( f \) matrix of received signals, and \( W_{k,i} = [w_{k,i}^I, \ldots, w_{k,i}^Q] \) is the 2x\( f \) noise matrix. \( p_{mk,i}, y_{mk,i}, y_{mk,i}^Q \), and \( w_{mk,i} \) are all 2x1 vectors where \( m = 1, 2, ..., f \). The least squares (LS) approach [8] can now be used to find an estimate of \( H_{k,i} \):

\[
\hat{H}_{k,i} = Y_{k,i} P_{k,i}^\dagger \tag{8}
\]

where \( p_{k,i}^\dagger = P_{k,i} H_{k,i}^{-1} \) is the pseudo-inverse of \( P_{k,i} \). \((\cdot)^{\dagger}\) denotes Hermitian transpose, and \((\cdot)^{-1}\) represents a pseudo-inverse operation. As \( \hat{H}_{k,i} \) is now known, the zero-forcing (ZF) estimate [9] of the transmitted data is:

\[
\hat{x}_{k,i} = \hat{H}_{k,i}^\dagger y_{k,i} \tag{9}
\]

### III. EXPERIMENTAL SETUP AND RESULTS

The new dual-arm IQ drop element shown in Fig. 1(a) is employed to realize the proposed MIMO-based I/Q crosstalk mitigation, where data-aided MIMO LS channel estimation and ZF detection are used for IQ demultiplexing. The dual-arm IQ drop element simultaneously recovers both I and Q SBs in the same SW-band. Fig. 1(b) shows the architecture of the single-arm I/Q drop element [5,6] where, to recover both SBs, two independent single-arm I and Q drop elements are used for performance comparisons.

Fig. 2(a) shows the experimental setup of the soft-ROADM drop operation. The key system parameters are listed in Table I. OFDM modulation is employed here to demonstrate compatibility with advanced modulation formats. In the transmitter, 6 I and Q SBs occupying 3 SW-bands are generated, digitally combined, and converted into an analogue electrical signal using the 1\( ^{st} \) channel (CH) of an AWG (Keysight-M8195A). In the AWG-embedded MatLab program, for each SB signal, a real-valued OFDM signal is generated, digitally up-sampled and digitally filtered by an appropriate I/Q Hilbert-pair-based shaping filter [10]. All SBs signals are then digitally combined. Prior to D/A conversion, the total signal is oversampled by a factor of 2 to limit the signal bandwidth to 8 GHz. The baseband region is kept free for the TSB as shown in Fig. 2(b). An IM (Thorlabs MX35D) is employed to generate the optical signal in the transmitter.

AWG CH-2 is used to generate the drop RF signal. An electrical power splitter (PS) is then employed to split the RF signal into two paths (I and Q), where each signal is then individually amplified. To intentionally demonstrate the tolerance to received I/Q signal power imbalance, different drop RF signal powers are employed on the I and Q arms. An RF delay line (DL) is employed in the 2\( ^{nd} \) path \( \phi \) to achieve a 90° phase shift.

In the dual-arm IQ drop element, an EDFA followed by an optical band-pass filter (OBPF) is used to boost the received optical signal. A 3 dB optical splitter is then utilized to direct the optical signal into the two arms. Two quadrature-point biased MZMs (Thorlabs LN81S-FC) are then employed to perform I and Q drop operations. In each arm, a PIN detector (Thorlabs RXM40AF) is then employed for O-E signal.
conversion, an RF amplifier, and a low-pass filter (LPF) are then employed to remove the ruined SBs and out-of-band noise shown in Figs. 2(c) and 2(d). It is important to note that the use of the LPF significantly relaxes the A/D conversion speed requirement. The received electrical signals from both arms are then digitized by a digital sampler using the LPF, significantly relaxing the A/D conversion.

Table 1: List of Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAC sample rate</td>
<td>32 G/s</td>
<td>ADC sample rate</td>
<td>4 G/s</td>
</tr>
<tr>
<td>Cyclic prefix</td>
<td>12.5%</td>
<td>DAC/ADC resolution</td>
<td>8 bits/10 bits</td>
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<tr>
<td>Digital filter length</td>
<td>32</td>
<td>Digital filter roll-off factor</td>
<td>0</td>
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<tr>
<td>SW-band 2 I-arm drop RF signal power</td>
<td>15.9 dBm</td>
<td>SW-band 2 Q-arm drop RF signal power</td>
<td>18.4 dBm</td>
</tr>
<tr>
<td>MZM bandwidth</td>
<td>10 GHz</td>
<td>MZM RF V_e @ 1 GHz</td>
<td>5.6 V</td>
</tr>
<tr>
<td>Clipping level</td>
<td>14 dB</td>
<td>Optical launch power</td>
<td>6 dB</td>
</tr>
<tr>
<td>Bit rate per SB</td>
<td>2.67 Gb/s</td>
<td>PIN detector sensitivity</td>
<td>0.7 A/W</td>
</tr>
</tbody>
</table>

Fig. 3. Effect of drop RF signal phase offset when (a) 3-I SBs occupied, (b) 3-Q SBs occupied, (c) 3-I and 3-Q SBs occupied.

IV. CONCLUSION

A new dual- arm IQ soft-ROADM drop element which eliminates the need to dynamically control the drop RF signal phase is experimentally validated, thus simplifying the practical realization of soft-ROADMs for 5G fronthauls.

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