Experimental Demonstration of the Compensation of Nonlinear Propagation in a LTE RoF system with a Directly Modulated Laser

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Abstract—This paper reveals that nonlinear propagation is a critical problem for the long term evolution (LTE) technology based on the radio-over-fibre (RoF) system. Therefore, a direct modulation based frequency dithering (DMFD) method is proposed for nonlinear propagation compensation, namely the self phase modulation (SPM) and stimulated brillouin scattering (SBS). We found that DMFD method operates substantially different in RoF systems. The major difference is that DMFD signal frequency f_0 has to be much smaller than the RoF carrier frequency f_{RoF}; thus the condition of {f_0 << f_{RoF}} has to be stringently obeyed. Analysis of the optical launch power (OLP) with DMFD method reveals that the SBS threshold is above ~6 dBm for LTE-RoF system. In addition, we also unfold that DMFD method does not induce an additional distortion for the linear and optimum OLP regions, which are frequency chirp dependent. Hence the proposed method improves the LTE-RoF system without any shortcoming. Finally, at OLP values of 8 dBm and 10 dBm, LTE-RoF system exhibits an average error vector magnitude (EVM) improvement of ~4.32% and ~6.18%, respectively, for the 50 km transmission span.

Index Terms—Long Term Evolution (LTE); Radio-over-fibre (RoF); Nonlinear Compensation; Optical OFDM (OOFDM)

I. INTRODUCTION

The mobile communication sector is facing an exponentially growing demand for mobile broadband usage due to the increasing number of end users and advancement in applications. Hence, the 3rd generation partnership program (3GPP) has introduced a sophisticated technology known as the 4th generation technology LTE to meet the demand of mobile broadband users [1].

The former mobile broadband technology’s base station is known as NodeB. LTE base station is termed as evolved NodeB (eNB) due to the technological evolution of the existing infrastructure. However, this evolution is at the cost of computational power due to the 2 node architecture leading to an operating characteristic of without a central controller, which leads to costly infrastructure. In addition, the operating carrier frequency of LTE in the urban area is 2.6 GHz, which burdens the wireless propagation with excessive losses, thus limiting the cell radius to 1 km as a result of degradation in the signal-to-noise ratio (SNR) performance at the cell edge [2]. The throughput for the user equipment (UE) at the cell edge is < 20 Mb/s from the maximum of 100 Mb/s owing to the deteriorating SNR, thus resulting in consecutive deployment of eNB at every 1 km radius in an urban area [2]. Such drastic deployment of eNB is necessary to maintain the high data throughput, which is the priority of LTE technology.

We recently established a cell extension technology for eNB utilizing the amplifying and forwarding relay node (RN) with RoF as the interface between eNB and RN [3–5]. In other word, instead of eNB, RN delivers LTE signal to UE at the cell edge. An in-depth LTE-RoF integrations were carried out theoretically [3] and experimentally [4] for single antenna systems. In terms of multiple-input and multiple-output application, both theoretical and experimental LTE-RoF system design was demonstrated in [5]. The aforementioned literatures exhibits a minimum system penalty in the optimum OLP region ranged from ~3 to ~2 dBm. LTE-RoF system experiences degradation in the quality of service (QoS) for OLP of ~3 dBm, and more detrimental for OLP greater than 2 dBm. At OLP less than ~3 dBm, also known as the linear region, the QoS could be easily improved by including an optical amplifier. However, this is not the same case for OLP of more than 2 dBm, where the system will initiate a nonlinear propagation state, known as the nonlinear region. Considering the LTE signal power required following photodetection in RN for UE delivery, it is important for LTE-RoF system to operate in the nonlinear region to ensure the link power budget. Therefore this paper focuses on the nonlinear compensation of LTE-RoF system to provide a higher power budget in RN for UE transmission.

The well known optical fibre nonlinearities are the Kerr effect and the scattering phenomena. SPM, cross phase modulation (XPM), and four wave mixing (FWM) are known as the Kerr effect. In terms of the scattering phenomena, the widely known effects are the SBS and the stimulated Raman scattering (SRS). Since LTE-RoF system in this paper operates on a single wavelength in the C-band transmitted through a single mode fibre (SMF); XPM, FWM and SRS are clearly negligible [6, 7]. Therefore, the nonlinear region is only SPM and SBS dependent. In this paper, we are aiming to provide a higher power budget, which requires higher OLP, hence SBS phenomenon becomes a dominant factor with a narrow linewidth and incidently forms a grating that produces a high back-reflecting power [8].

There are few methods introduced on compensating the
SBS effect. Downie et al [8] introduced a co-propagating signal in the wavelength division multiplexing (WDM) system to induce XPM as the compensating agent for SBS. Though this method suffices for SBS mitigation, it is only applicable for WDM system. Sisto et al [9] introduced an optimization method for the modulator biasing to control OLP, which in turn reduces the SBS effect. However, the biasing optimization adds on to the system complexity and to the inherent system noise floor due to optical amplification. As much as SBS depends on OLP, it also depends on the effective area of an optical fibre. Sauer et al [10] utilized an enhanced SBS threshold optical fibre, which is designed with a bigger effective area to compensate for SBS. Enhanced SBS threshold optical fibre is not applicable for our system, because the whole idea of proposed LTE-RoF integration is based on the existing legacy SMF backhaul to maintain a lower deployment cost [4].

A. Proposed Solution

Considering the proposed single wavelength system, with minimum complexity and using the existing SMF infrastructure, for the first time, we are proposing the usage of DMFD method for SBS mitigation in a RoF system and further identifying SPM and SBS threshold levels for LTE-RoF system. The DMFD method successfully compensates SBS by broadening the linewidth of a laser, which will be greater than the SBS linewidth and effectively blocking the grating formation, thus reducing the back-reflected power. Frequency dithering was initially proposed for baseband applications [11, 12], where the condition of dithering frequency \( f_d \) has to be bigger than twice the highest signal frequency \( f_m \). The condition of \( f_d \) in RoF systems is substantially different compared to the baseband system, where \( f_d \) for DMFD method in RoF systems have to be much smaller than the carrier frequency \( f_{RF} \). Further discussion on this will be carried out in the section III.B.

The DMFD method is primarily introduced to compensate the severe distortion in the nonlinear region. In addition to the nonlinear region, we have also introduced two different propagating regions for LTE-RoF in [3-5], namely linear, and optimum OLP. The linear region is positive frequency chirp (PFC) and chromatic dispersion (CD) dependent. The optimum OLP region is intermixing of linear and nonlinear regions. Since DMFD method intentionally introduces additional frequency chirp, part of the finding of this paper will be whether DMFD further deteriorates the linear and optimum OLP regions.

The rest of the paper is organized as follows. Section II explains the experimental system and the theoretical background. Section III presents and discusses the obtained results. Finally, Section IV concludes the findings of the paper.

II. FUNDAMENTALS OF THE EXPERIMENTAL SYSTEM

The experimental setup of LTE-RoF system with DMFD method for SBS mitigation is presented in Fig. 1 along with the system parameters provided in Table I. The fundamental of the experimental system are as follows:

A. LTE Baseband and Passband

The vector signal generator, Agilent ESG E4438C is utilized for LTE signal is generation. The single carrier modulations (SCMs) in the baseband domain are composed of quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM) and 64-QAM schemes. The baseband signal can be expressed as \( X(m) \) where \( X(m) : m = 0, 1, \ldots, N-1 \), \( m \) is the subcarrier index and \( N \) is the number of subcarriers. \( X(m) \) are then modulated onto orthogonal frequency division multiplexing (OFDM) \( S(n) \) [13]:

\[
S(n) = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} X(m) e^{j 2 \pi m n / N},
\]

where \( n = 0, 1, \ldots, N-1 \) is the time domain index. The up conversion of \( S(n) \) after a digital-to-analog converter can be described as:

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**TABLE I: SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCM modulations</td>
<td>QPSK, 16-QAM, 64-QAM</td>
</tr>
<tr>
<td>Bit rate (Mb/s)</td>
<td>33, 66, 100</td>
</tr>
<tr>
<td>Baseband multiplexing</td>
<td>OFDM</td>
</tr>
<tr>
<td>Signal bandwidth (MHz)</td>
<td>20</td>
</tr>
<tr>
<td>Carrier frequency (GHz)</td>
<td>2.6</td>
</tr>
<tr>
<td>DFB bias current (mA)</td>
<td>60</td>
</tr>
<tr>
<td>Optical launch power (dBm)</td>
<td>-8 to 10</td>
</tr>
<tr>
<td>Linewidth (MHz)</td>
<td>11</td>
</tr>
<tr>
<td>RIN (dB/Hz)</td>
<td>-149.6</td>
</tr>
<tr>
<td>SMF length (km)</td>
<td>10 - 50</td>
</tr>
<tr>
<td>EDFA: gain, NF (dB)</td>
<td>4, 3.5</td>
</tr>
<tr>
<td>PD responsivity</td>
<td>0.42</td>
</tr>
<tr>
<td>LNA: gain, NF (dB)</td>
<td>18, 2.5</td>
</tr>
</tbody>
</table>
$$S_{RF}(t) = \text{Re}\{S(t) \ast \cos(\omega_{RF}(t))\} + \text{Im}\{S(t) \ast \sin(\omega_{RF}(t))\},$$  
(2)

$$\omega_{RF} = 2\pi f_{RF},$$  
(3)

where $S_{RF}(t)$ is the passband radio frequency (RF) OFDM signal modulated at $f_{RF}$ of 2.6 GHz.

### B. DMFD Signal

The distributed feedback laser (DFB) used in this work is intentionally dithered or frequency chirped with a DMFD signal $S_d(t)$ to broaden the linewidth of the laser. $f_d$ only effectively dithers the DFB laser at the condition of $|f_d| < f_{RF}$ as specified earlier. If $|f_d| > f_{RF}$, then $f_d$ will not generate the dithering phenomenon due to the existing 2nd order harmonics in that frequency region. In other word, DFB laser have already experienced frequency chirping from the modulation of $S_{RF}(t)$ and its 2nd order harmonics altogether. Therefore, if $f_d$ is above $f_{RF}$, it does not induce any additional chirping. However, $f_d$ does not display similar characteristic for the baseband system, because the baseband signal itself will be centered or close to the direct current (DC). Therefore $f_d$ has to be much higher than $f_{min}$, which has been defined as twice higher in [11, 12]. Thus, in our work, $S_d(t)$ is generated at $f_d$ of 100 MHz as a sinusoidal signal from a continuous wave generator (CWG), Agilent E8247C, which maintains the $|f_d| < f_{RF}$ condition. However, it is also important to specify that $f_d$ cannot be smaller than 13 MHz as the intermodulation (IMD) products between $S_{RF}(t)$ and $S_d(t)$ will fall within the 20 MHz bandwidth of $S_{RF}(t)$. $S_{RF}(t)$ is then combined with $S_d(t)$ before direct modulation (DM).

### C. DM and DFB

In this section, the description of DM of $S_{RF}(t) + S_d(t)$ onto the DFB is carried out. Owing to the bipolar nature of the electrical signal, a sufficient amount of the bias current $I_{bias}$ is coupled with $S_{RF}(t) + S_d(t)$ into the 1754C DFB laser:

$$i_{RFd}(t) = I_{bias}[1 + \mu(S_{RF}(t) + S_d(t))]$$  
(4)

where $i_{RFd}(t)$ is the DFB driving current, and $\mu$ is the modulation index.

$$\frac{dN_{RFd}(t)}{dt} = \frac{i_{RFd}(t)}{edwl} - \frac{N_{RFd}(t)}{\tau_c} - BN_{RFd}(t)^2$$

$$-CN_{RFd}(t)^3 - G \frac{N_{RFd}(t) - N_i}{1 + \zeta S_{ORFd}(t)} S_{ORFd}(t),$$  
(5)

$$\frac{dS_{ORFd}(t)}{dt} = \Gamma G \frac{N_{RFd}(t) - N_i}{1 + \zeta S_{ORFd}(t)} S_{ORFd}(t) +$$

$$\zeta BN_{RFd}(t)^2 - \frac{S_{ORFd}(t)}{\tau_p},$$  
(6)

$$P_{ORFd}(t) = \frac{\xi w_v w_b w_t \rho S_{ORFd}(t) c}{2n_f},$$  
(7)

The DM of $i_{RFd}(t)$ is carried out by the DFB laser at the operating wavelength of 1551.11 nm. (5), (6), and (7) are the laser rate equation which theoretically describes the intensity modulation (IM) performed via the DM. $dN_{RFd}(t)/dt$, $dS_{ORFd}(t)/dt$ and $P_{ORFd}(t)$ are the rate of change of the carrier density, rate of change of the photon density and OLP at the DFB facet, respectively [14]. $\xi$ is the electronic charge; $d$ is the thickness, $w$ is the width, and $l$ is the length of the lasing cavity; $N_{RFd}(t)$ and $S_{ORFd}(t)$ are the carrier density and photon density, respectively. $\tau_c$ is the linear carrier recombination lifetime, $B$ is the bimolecular carrier recombination coefficient and $C$ is the Auger carrier recombination coefficient. $G$ represents the linear optical gain coefficient, $N_i$ is the transparency carrier density, $\zeta$ is the nonlinear gain coefficient and $\Gamma$ is the mode confinement factor. $\zeta$ represents the fraction of spontaneous emission. $\tau_p$ is the photon lifetime, $\chi$ is the coupling efficiency from the laser chip to the SMF, $w_v$ and $w_b$ are the vertical and horizontal widths of the guided mode power distributions, respectively. $h$ is the Planck’s constant, $v$ is the optical frequency, $c$ presents the speed of light in the vacuum.

The linewidth broadening of the DFB laser can be described from the Van der Pol model of laser noise [15]:

$$\Delta f(t)^2 = \frac{2n t_p}{2n \tau_c}$$  
(8)

where $\alpha$ is the linewidth enhancement factor, $n$ is the number of photons in the laser resonator and $\tau_c$ is the coherence time of the laser which is related to the full width at half maximum (FWHM) of the DFB laser linewidth by:

$$\Delta v_{FWHM} = \frac{2}{\tau_{coh}}$$  
(9)

The effect $S_d(t)$ is approximately equivalent of producing multiple random spontaneous emission events, which leads to a Wiener process to the phase of the DFB laser [16].

$$\Delta S_d(t)^2 = \frac{2(t)}{\tau_{coh}}$$  
(10)

where $\tau_{coh}$ is the coherence time of $S_d(t)$. The original coherence time of the DFB laser is $\tau_{coh}$ but by applying the random phase modulation with $S_d(t)$, the new reduced effective coherence time of the laser at the FWHM is:

$$\frac{1}{\tau_{coh}} = \frac{1}{\tau_{coh}} + \frac{1}{\tau_{coh}}$$  
(11)

where the reduced coherence time is equivalent to a broadened linewidth. From (11), it is clear that $P_{ORFd}(t)$ propagates along SMF with a broader linewidth and capable of blocking the formation of SBS grating. Hence, resulting in the reduced back-reflected power.

In order to investigate the impact of DMFD method in the linear region, the optimum OLP and nonlinear regions [4], $P_{ORFd}(t)$ is varied between -8 to 10 dBm. The lower values of $P_{ORFd}(t)$ is achieved via the Link A of Fig. 1, which consists of a variable optical attenuator. The erbium doped fiber amplifier (EDFA) and the optical bandpass filter (OBPF) in the Link A are only utilized for the link span of 50 km and above to compensate for the SMF loss as the photodetector responsivity is low. The Link B is utilized for higher value $P_{ORFd}(t)$ analysis and performed via EDFA with OBPF.
D. SMF

We have utilized SMF as the transmission medium in this paper, ranging from 10, 25, 35 and 50 km. The analytical model that governs SMF characteristics can be adopted from [4]. After propagating through the varying SMFs, the signal is detected via the Newport D8-ir photodetector with the direct detection (DD) scheme. Following photodetection, the received RF LTE signal $R_{RF}$ is passed through a low noise amplifier for amplification the output of which is demodulated via the signal analyzer (SA), Agilent 9020A MXA.

III. RESULTS AND DISCUSSION

Figs. 2(a), (b), and (c) depict the electrical power penalty against OLP for QPSK, 16-QAM and 64-QAM systems, respectively, for uncompensated transmission spans of 10, 25, 35 and 50 km, as well as SBS compensated links. Back-to-back SNR is exploited to measure the power penalty. There are three major distinctive regions shown in Fig. 2, namely I) linear region- PFC and CD induced distortion, II) intermixing region- reduced distortion achieved by the interaction between CD and PFC with SPM and SBS, and finally III) nonlinear region- nonlinearity based distortion from SPM and SBS effects.

It is clear from Fig. 2 that the DMFD method only effectively compensates for SBS in the region III.B, where SBS is dominant above $P_{O_{RF}}(t)$ of $-6$ dBm (the SBS threshold). The region III.A does not experience any effect from DMFD method, this is because it is solely dominated by SPM. In other word, $P_{O_{RF}}(t)$ of above $-2$ dBm to $-6$ dBm induces nonlinearity in the form of harmonics and intermodulation products (IMDs), but with no scattering or back-reflecting power. Additionally, Fig. 2 depicts that the introduction of DMFD method does not alter the LTE-RoF response for regions I and II. Despite the fact that DMFD method broadens the linewidth of DFB laser, it does not initiate an optical mode re-growth. Therefore the optical spectral characteristic of the DFB laser with DMFD is not similar to a Fabry-Perot laser, hence regions I and II remains more or less unchanged.

The discussion on Fig. 2 is focused on $P_{O_{RF}}(t)$ of 8 dBm and 10 dBm within region III.B due to the effectiveness of DMFD in this range. Furthermore, only 10 and 50 km transmission spans as the best and worst case scenarios are contemplated, respectively. At $P_{O_{RF}}(t)$ of 8 dBm in Figs. 2 (a), (b), and (c) for QPSK, 16-QAM and 64-QAM, the system improvements observed for the 10 km span are $-2.33$ dB, $-2.25$ dB and $-2.23$ dB, respectively, while the 50 km span experiences improvements of $-5.04$ dB, $-4.79$ dB and $-4.59$ dB, respectively. The aforementioned EVM improvements are measured from the differences of uncompensated and compensated SBS link, as shown in region III.B. The improvement of 50 km span is higher than the 10 km span evidently showing the system deterioration due to SBS particularly for higher transmission spans. In terms of 10 dBm of $P_{O_{RF}}(t)$, the improvement for QPSK, 16-QAM and 64-QAM at a 10 km span are $-3.3$ dB, $-3.22$ dB, and $-3.2$ dB, respectively, while at 50 km the improvement are $-6.04$ dB, $-5.97$ dB, $-5.89$ dB, respectively. The improvement at $P_{O_{RF}}(t)$ of 10 dBm is superior to 8 dBm, outlining the linear increase of back-reflecting power with $P_{O_{RF}}(t)$. The system transmission span is limited to 50 km and anything beyond this limit fails to meet the required EVM and will be discussed in detail with reference to Fig. 4.

Fig. 3 presents the nature of power penalty improvement discussed earlier. Fig. 3 (a) shows a broad frequency range where the decrease in the noise floor with DMFD method can be clearly observed at $S_{R}(t)$ and $S_{RF}(t)$. $S_{R}(t)$ harmonics and IMDs associated with DMFD method can be easily filtered at RN prior to UE transmission. In order to further enhance on $S_{RF}(t)$, we present a narrow frequency range in Fig. 3(b) where it clearly shows the effectiveness of DMFD method on reducing the out-of-band emission.

As the power penalty only unveils the system impact in terms of the out-of-band distortion, it is very vital to analyze the in-band distortion by utilizing EVM to understand the explicit system QoS. Figs. 4 (a), (b) and (c) illustrate the EVM.
of QPSK, 16-QAM and 64-QAM systems, respectively. We aim to achieve an EVM of 8% in the system design according to the 3GPP LTE requirement [17]. The categorization of regions and impact of DMFD on regions I and II in Fig. 4 is similar to Fig. 2. Focusing on the region III.B, at 8 dBm of $P_{\text{ORF}(t)}$, the EVM improvement associated with QPSK, 16-QAM and 64-QAM for a 10 km span are $-2.78\%$, $-2.73\%$ and $-2.67\%$, respectively, while the improvements for a 50 km span are $-4.35\%$, $-4.31\%$ and $-4.3\%$, respectively. The improvement observed for 50 km are much higher compared to 10 km, which correlates to the pattern observed in the power penalty analysis. At a 10 km span, the EVM improvement of QPSK, 16-QAM and 64-QAM for 10 dBm of $P_{\text{ORF}(t)}$ are $-5.16\%$, $-5.11\%$ and $-5.09\%$, respectively, while the 50 km span exhibits an EVM improvement of $-6.21\%$, $-6.18\%$ and $-6.15\%$, respectively. The physical improvement of QPSK, 16-QAM and 64-QAM EVM can be observed from Figs. 5 (a), (b) and (c).

For the 50 km transmission system, the average EVM across all modulation schemes at $P_{\text{ORF}(t)}$ of 8 dBm and 10 dBm are $-7.95\%$ and $-8.51\%$, respectively. The average EVM shows that $P_{\text{ORF}(t)}$ of 8 dBm is only achieved below 8%, hence revealing that the 50 km transmission span is the limit of DMFD method in LTE-RoF system.

IV. CONCLUSION

In this paper, we have proposed and demonstrated the nonlinear compensation of LTE-RoF system based on DMFD method. By utilizing this method, we found that the SBS threshold of LTE-RoF system was $-6$ dBm. Furthermore, it was also shown that despite the fact that DMFD induces frequency chirp, but it does not deteriorate the signal propagating in the linear and optimum OLP regions. LTE-RoF system average power gain observed at OLP of 8 dBm and 10 dBm for the 50 km transmission span are $-4.81$ dB and $-5.97$ dB, respectively. Finally, we revealed that the DMFD method is effective for up to 50 km of transmission span with SMF.

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