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Experimental Verification of LTE Radio Transmissions over Dual-polarization Combined Fibre and FSO Optical Infrastructures

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This paper describes the experimental verification of the utilization of long-term evolution (LTE) radio over fibre (RoF) and radio over free space optics (RoFSO) systems using dual-polarization signals for cloud radio access network (C-RAN) applications determining the specific utilization limits. A number of FSO configurations is proposed and investigated under different atmospheric turbulence regimes in order to recommend the best setup configuration. We show that the performance of the proposed link based on the combination of RoF and RoFSO for 64-QAM at 2.6 GHz is more affected by the turbulence based on the measured difference error vector magnitude value of 5.5 %. It is further demonstrated that the proposed systems can offer higher noise immunity under particular scenarios with the signal-to-noise ratio reliability limit of 5 dB in the radio frequency domain for RoF and 19.3 dB in the optical domain for combination of RoF and RoFSO links.

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1. INTRODUCTION

The deployment of small cells and the use of higher radio frequency (RF) bands (e.g., millimetre-wave) are two possible options to fulfill the demand for higher data rates in the next generation wireless access networks. The 3rd generation partnership project (3GPP) of long-term evolution (LTE) with low latency, also known as the 4th generation technology supporting high data rates of up to 300 Mbps and 75 Mbps for the down and uplinks respectively, has been proposed and developed [1, 2]. LTE intended for urban areas and operating at a carrier frequency of 2.6 GHz, imposes higher loss in wireless transmission which limits the cell radius because of the degradation of the signal-to-noise ratio (SNR) [3]. In small-cell based systems optical fibres are considered as an ideal backhaul medium to provide sufficient bandwidth, as well as a future-proof capacity upgrade. More recently, the cloud-based radio access networks (C-RAN) technology is being proposed as a cost-effective and power efficient option for deploying small cells to meet the capacity demand of future wireless access networks. C-RAN decouple the digital baseband processing unit (BBU) from the largely analogue remote antenna unit (RAU) and move it to the BBU pool or BBU hotel, thus, allowing the centralized operation of BBU and a scalable deployment of RAUs as small cells [4]. In such schemes the optical fibre (OF) communications technology plays a significant role when developing network infrastructures, particularly for connections between adjacent cells, RAU and a central unit pool. OF technology covers approximately 35% of the connections between base stations (BS) while the remaining 55% are based on RF wireless technology [5]. This will rise to over 60 % of fibre connected based stations making 4th and upper generations of mobile communications resulting in optical infrastructures becoming the most suitable medium for transportation of radio signals from/to RAUs. The functions of RAUs can be further simplified by transmitting analogue RF signals over OF backhaul networks. Unlike the conventional digital baseband transmission schemes supporting only one service at a time, the radio-over-fibre (RoF) transmission network [6] enables the coexistence of multi-service and multi-operators in a shared resources, thereby offering increased link capacity, advanced networking (i.e., dynamic resources and allocations) and features such as wavelength division multiplexing (WDM) [7] without the need for frequency up-down conversion. Transmission of the LTE signals over OFs was presented in [8] and highlighted improvements of the OF backhaul in terms of power and cost effectiveness. A field trial
of RoF and RoFSO. The performance of RoFSO system is highly influenced by environmental factors, thus, we focus on the FSO channel under the turbulence regime. Based on the investigation of the channel dynamic range and noise immunity tests, we have extended the measurement results to include EVM characteristics and have derived specific limits of utilizations of RoF and RoFSO systems. We show that the performance of the proposed link based on the combination of RoF and RoFSO for 64-QAM at 26 GHz is more affected by the turbulence based on the measured difference EVM value of 5.5 %. We further show that the proposed systems can offer higher noise immunity under particular scenarios with the SNR limit of 5 dB in the RF domain for RoF and 19.3 dB in the optical domain for combination of RoF and RoFSO links.

The rest of the paper is structured as follows: section 2 introduces the properties of the proposed system with different configurations and atmospheric turbulence. Results from the measurements and simulations are discussed in section 3, and the conclusions are presented in section 4.

2. EXPERIMENTAL SETUP

A. Main setup description

The experimental setup consists of transmitter (Tx), channel, and receiver (Rx) parts as shown in Fig. 2. On the Tx side both branches are modulated by two independent RF signals prior to the application of a polarization-multiplexing technique for transmitting over the optical channel (OF and FSO).

A distributed feedback (DFB) laser diode (1D-Photonics TL CoBrite Dx4) at a wavelength of 1550 nm was used as the optical source (OS). The output of OS, passing through a power splitter (PS) (Opneti PBS 15-1-L-1-FA), is externally modulated with two digital RF signals (vector signal generators – R&S SMBV 100 A and SMW 200 A) of the same carrier frequency and equal bandwidth using Mach-Zehnder modulators (MZM) (Thorlabs LN81S). For a detailed description of the influence of MZM on RoF, please refer to [23]. The two orthogonal polarization states of the modulated light beams were controlled using two polarization controllers (PC) and combined via the polarization beam combiner (PBC) prior to being launched into standard SMFs (SSMF). As shown, erbium-doped fibre amplifiers (EDFA) (Kepsys – KPS-BT2-C-10-LN-SA) were used to compensate for the channel loss. Four types of the RoF/RoFSO-based channel configurations were investigated:

i) Setup-A: 5 km of SMF and EDFA

ii) Setup-B: EDFA and the FSO channel

iii) Setup-C: 5 km of SMF, EDFA and the FSO channel

iv) Setup-D: EDFA, 5 km of SMF (representing the typical transmission span for RoF links) and the FSO channel.
Since the focus in this work was only on the RoF and RoFSO parts of the RAN system, we did not consider retransmission or signal recovery between OF and FSO parts, which is typically done by the remote RoF units. At the Rx PC was used to adjust the polarization states of the incoming optical signal before being fed into a polarization beam splitter (PBS) according to (10) and (11). PDM optical signals can be potentially demultiplexed by coherent detection and digital signal processing. Polarization dependence of coherent detection can be then managed by means of optical dynamic polarization control or a polarization diversity Rx [24][25]. In a conventional polarization diversity Rx, two sets of Rxs are used to independently detect signal components in the two orthogonal polarization states and the original signal is recovered after combining two components, which is rather inefficient in terms of hardware. However, when two PDM channels are simultaneously transmitted at orthogonal polarization states, a polarization diversity Rx in principle can receive both channels, for example, by using optical dynamic polarization control at the Rx. All-optic scheme for PDM systems using dynamic PC has been proposed in [26]. It has been suggested that PDM optical signals can potentially be demultiplexed by combining coherent detection and polarization/diversity [27].

The Rx is composed of a pair of encapsulated balanced PIN photodiodes (PD) and a transimpedance amplifier (TIA) (Newport 1544-B50). The output of the TIA was captured for further processing using a signal analyzer (R&S FSV). We used LTE evolved universal terrestrial radio access (E-UTRA) test models with 16-QAM and 64-QAM in the polarization state 1 (noted as Pol 1). An independent digital mobile radio service with 16-QAM, having the same parameters (frequency, bandwidth and power) as the signal in Pol 1, was launched to the polarization state 2 (Pol 2).

The polarization orthogonality was continuously verified by monitoring the parameters at the Rx for one polarization state (i.e., Pol 1) while the signal in the second polarization state (i.e., Pol 2) was switched off and on with no influence observed on either the original power magnitude, the SNR, the optical signal to noise ratio (OSNR), or the corresponding EVMs. In the experimental setup we used two commonly adopted LTE frequency bands of 800 MHz and 2.6 GHz with the bandwidth set to 10 MHz. We also set the peak envelope power below the limit of 15 dBm to avoid harmonic distortions at the recovered RF spectrum. All key adopted system parameters are listed in Table 1. For the FSO links graded-index lenses (Thorlabs 50-1550A-APC) with an aperture of 1.8 mm and convex lenses with a diameter of 25.4 mm (SMPF_115-APC) were used to launch and couple light from/into the SMF. FSO links were subjected to the atmospheric turbulence in order to assess the performance of the proposed system.

**B. Noise conditions**

In this section we outline the noise sources associated with the link, in particular the shot noise, thermal noise and relative intensity noise (RIN).

The power of the shot and thermal noise sources can be expressed as the fundamental noise [28]:

\[
N_{\text{fund}} = \left( g_{rf} + 1 \right) k_B T \Delta f + \frac{1}{2} q I_{\text{DC}} \Delta f R_{\text{out}},
\]

where \( g_{rf} \) is the RF gain, \( k_B \) is Boltzmann’s constant, \( T \) is the temperature, \( q \) is the electronic-charge constant, \( I_{\text{DC}} \) is the average PD DC current, and \( R_{\text{out}} \) is the matching load resistance.

Additionally, there is the excess photon noise due to fluctuations of the intensity of the light source as a result of the beating of various spectral components having random phases. For a purely spontaneous source it is given as [29]:

\[
\langle \Delta I_{sp}^2 \rangle = \left( \frac{1}{\Delta \omega_{eff}} \right),
\]

where \( \alpha \) is the degree of polarization, and \( \Delta \omega_{eff} \) is the effective bandwidth. Though all three noise sources can be used to estimate the RIN, it should be noted that \( \langle \Delta I_{sp}^2 \rangle \) should only be used for optical sources with a purely spontaneous emission profile.

The RIN, associated with the optical devices, represents the total amount of photon noise per unit bandwidth and is defined as:

\[
RIN_{\text{total}} = \frac{\Delta I_{sp}^2}{P^2} = \frac{\langle \Delta I_{sp}^2 \rangle}{\langle \Delta I_{sp}^2 \rangle} = \frac{4 N_{\text{total}}}{I_{\text{DC}} R_{\text{out}}},
\]

where \( P^2 \) is the auto-correlated value of the optical power fluctuation at frequency \( f \), which can be measured using an electrical spectrum analyser to represent the total output noise power spectral density \( N_{\text{total}} \) delivered to \( R_{\text{out}} \). \( P \) is continuous wave optical power, which contributes to \( I_{\text{DC}} \).

Note that the shot noise is divided into two branches (matching circuit and load). With the links employing optical amplifications there are additional noise contributions. The primary noise source in optical amplifiers (e.g., EDFA) adopted in the optical communications is the amplified spontaneous emission (ASE) with a spectrum almost the same as the gain spectrum of the amplifier. When detected, these spontaneously generated photons result in signal spontaneous (sig-sp) and spontaneous-spontaneous (sp-sp) beat noise currents. The sp-sp beat noise power density is inversely proportional to the OSNR whereas the sig-sp beat noise power density is inversely proportional to the OSNR. The sp-sp beat noise also depend on the baseband frequency, with the noise density decreasing with increasing the
In principle, the sp-sg beat noise intensity spectrum could be as wide as the optical amplifier bandwidth in the absence of optical filtering. From practical point of view the excess noise regime is highly important, where the noise level is higher than the level of shot noise, due to the influence of sig-sg beat noise, etc. Therefore, here we only consider the sig-sg beat noise, which is given as [28]:

$$RIN_{\text{sig-sg}} = \frac{4n_{sp}\nu}{g_{opt}f_{\text{sig}}},$$

where $n_{sp}$ is the spontaneous emission factor, $\nu$ is Planck’s constant, $v$ is optical frequency, $g_{opt}$ represents the optical power gain of the EDFA, $F_{\text{opt}}$ is the noise factor of the EDFA, and $P_{\text{sig}}$ stands for average optical signal power input to the EDFA. Assuming that $g_{opt} >> 1$ the equation (4) can be expressed as:

$$RIN_{\text{sig-sg}} = \frac{2F_{\text{opt}}\nu}{P_{\text{sig}}},$$

$F_{\text{opt}}$ is related to the shot noise and the detection scheme. For an ideal detector $F_{\text{opt}} = 2n_{sp}$. The degradation of SNR in RoF and RoFSO links is represented by the RF noise factor $F_{\text{rf}}$ with respect to thermally limited input and is defined in terms of the the RoF link output noise power $N_{\text{out}}$ as [28]:

$$F_{\text{rf}} = \frac{N_{\text{out}}}{g_{\text{rf}}kT},$$

Typically $F_{\text{rf}}$ is enumerated under $T = 290$ K. We can rewrite the definition of the noise factor by using eq. (3) and the RF gain as:

$$F_{\text{rf}} = \frac{\sqrt{2R_{\text{in}}}}{n_{\text{sp}}
u\lambda kT},$$

where $R_{\text{in}}$ is the input resistance of the MZM and $V_{\text{g}}$ is a convenient parameter to specify the efficiency of an electro-optic intensity modulator, which is defined as the voltage required to change the optical power transfer function from the minimum to the maximum.

In the experimental test setup, the SNR was set in the RF domain directly via the signal generator by including an adding additional noise source while the OSNR was controlled by adding a variable optical attenuator placed directly behind the EDFA in setups A and C to avoid amplifier’s gain induced OSNR fluctuations as depicted in fig. 2. In the setup C, we positioned the optical attenuator in front of the optical link to maintain the desired OSNR level over the FSO channel. OSNR was measured using an optical spectrum analyzer (OSA). Here we have adopted the intensity modulation with direct detection (IM/DD) scheme and used single-drive MZMs, which were biased at their maximal transmission point. At the input of the MZM, the field waveform (in time t) can be expressed as [28]:

$$E_{\text{IN}}(t) = \kappa \sqrt{2P_{\text{laser}}e^{j\omega t}},$$

where $P_{\text{laser}}$ is average laser power at angular frequency $\omega$ and $\kappa$ is a constant relating field and average power. The input voltage to the MZM is defined by:

$$V_{\text{IN}}(t) = V_{\text{dc}} + V_{\text{RF}}sin(\omega t),$$

where symbol $V_{\text{dc}}$ stands for bias voltage and the expression $V_{\text{RF}}sin(\omega t)$ defines the modulating RF signal $V_{\text{RF}}$. Among other factors, IM/DD introduces additive noise to the hybrid radio and photonic system.

### C. FSO turbulence effects

There are a number of methods for generating turbulence within an indoor controlled environment including near index matching, liquid filled chambers, spatial light modulators, ion-exchange phase screens, surface etching, and hot air chambers [30]. For assessing the performance of the proposed scheme we have adopted the latter and used an artificial turbulence generator with known, realistic, and repeatable characteristics. Two fans were used to blow hot air into the channel perpendicular to the propagating optical beam. To measure the temperature profile and determine the temperature gradient along the channel, we placed 20 thermal sensors at an interval of 10 cm along the FSO channel. We used Rytov variance and the refractive index structure parameter to characterize strength of the turbulence according to [22]. The variance of the log-intensity signal fluctuation defined by Rytov variance $\sigma_{R}^{2}$ is given by [31]:

$$\sigma_{R}^{2} = 1.23k\lambda L_{\text{p}}^{2},$$

where $k = 2\pi/\lambda$ is the wavenumber and $\lambda$ is the transmission wavelength.

$C_{n}^{2}$ is the refractive index structure parameter (the main measure of the turbulence scale), which is given as [18]:

$$C_{n}^{2} = (79 \times 10^{-6} \frac{P_{\text{at}}}{T_{\text{at}}})^{2}C_{\text{T}}^{2},$$

where $P_{\text{at}}$ is the atmospheric pressure in millibars. $C_{\text{T}}^{2}$ is the temperature structure constant, which is defined as [18]:

$$C_{\text{T}}^{2} = (T_{\text{i}} - T_{\text{s}})^{2}/L_{\text{p}}^{3}.$$

$T_{\text{i}}$ and $T_{\text{s}}$ are temperatures at two points separated by distance $L_{\text{p}}$. Knowing the thermal distribution along the FSO propagation path, it is possible to determine $C_{\text{T}}^{2}$ and then $C_{n}^{2}$.

### 3. EXPERIMENTAL AND SIMULATION RESULTS

The experimental section is divided into three parts. In part A the transmission properties of four selected scenarios (setsups A, B, C and D; see Fig. 2) were tested under the steady-state condition with no turbulence. Part B describes the detailed investigation of the dynamic range and noise conditions of the RoF system compared to the hybrid RoF and RoFSO (setsups A and C) systems. Finally, part C outlines the comparison of the links including the FSO channel under turbulence regimes (setsups B, C and D).

### A. System properties

We have tested the suitability of proposed scenarios A, B, C, and D using the polarization multiplexed technique for RF signals. Two standardized E-UTRA test models were selected for the investigation of the channel quality: E-UTRA Test model 2 and E-UTRA Test model 3.2 [32]. Both test models are specified for testing E-UTRA systems with an emphasis on either the dynamic range or the quality of the transmitted signal using 64- and 16-QAM, respectively.

Scenarios A and B evinced EVM around 1 % meanwhile scenarios C and D evinced EVM between 2 % and 3%. It can be observed scenarios A and B offer roughly two or three times better EVM performance when compared to the hybrid RoF and RoFSO systems (C and D). Nevertheless, all scenarios show EVM values dramatically below the maximal 3GPP LTE EVM threshold of 8 % recommended for high data rate systems [33]. Note that for the setup A, with 5 km of SMF, the output power of EDFA had to be decreased in order to ensure that the PIN PD was not saturated or damaged. The gain of the EDFA was preserved throughout the experimental work in order to maintain similar conditions. Last but not least, we simulated the

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<th>Table 1. Setup Parameters</th>
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In Section 2B, which can significantly reduce both OSNR and SNR values. These tests were focused on the hazard noise effects described in Section 2B, which can significantly reduce both OSNR and SNR, thus degrading the performance of RoF and RoFSO systems. At first, we carried out simulations for the EVMs for the proposed system featuring SMF and FSO sections (setups A and C). Subsequent measurements using a frequency of 2.6 GHz and 64-QAM were also carried out to validate the simulated results. The constellation diagrams of the 64-QAM and the evolution of the EVM parameter were evaluated both experimentally and by mean of simulation, which was then correlated. Figures 3 and 4 depict the predicted and measured EVM as a function of the OSNR for setups A and C, respectively. For the setup A, there is a mismatch between the measured and predicted EVMs, with the maximum difference of ~7.0E-21 dB. This is, in all probability, caused by the slightly different properties of simulated and real behavior of EDFAs, which are due to ASE as being the main noise source in the optical domain. For the setup C, there is a good match between the measured and predicted plots. The measured (red) and simulated (black) constellation diagrams are also shown in Figs. 3 and 4. These plots show that the RoF with a 5 km of fibre can operate over a wide range of OSNR (i.e., from 36 to 21 dB), whereas for the hybrid RoF and RoFSO links the OSNR range is only 10 dB (from 29 to 19.3 dB). In the case of the FSO channel, this can be attributed to the power budget being significantly lower and the noise floor belonging to a particular scenario. The experimental and simulated EVM curves for the setup C show the same trend for OSNR values of 29 dB and 21 dB as in the setup A with the only difference being the initial EVM values. In addition, as described above, the EDFA power had to be reduced while using the setup A, which resulted in a minimal OSNR value of ~21 dB. It can be observed that the proposed systems even operate over the recommended 8 % EVM limit when using 64-QAM, but at the cost of higher error probability.

Next we investigated the EVM as a function of the SNR, which was measured on the Rx side, for the setup C for 64-QAM at a frequency of 2.6 GHz with no turbulence as shown in Fig. 5. The insets illustrate the corresponding constellation diagrams. The plots demonstrate a good agreement between the measured and simulated results. The SNR dynamic range show a decrease of ~5 dB compared to the setup A (while employing only a 5 km of SMF). Both scenarios meet dynamic range requirements for home, local and wide area BSs specified by [32].

C. Turbulence

Finally, we compared the performance of both RoFSO (setup B) and the hybrid RoF and RoFSO (setups C and D) systems under the influence of atmospheric turbulence. The average values of ΔEVM for these particular scenarios were captured for a range of the refractive index structure parameter $C_n^2$. Since the initial magnitude of EVM was different for particular scenarios, all EVM values were aligned by showing the ΔEVM. We have adopted the frequency of 2.6 GHz for further detailed investigations since the performance of the systems for 800 MHz and 2.6 GHz are almost the same. We compare all optical-based systems including the FSO part (Setups B, C and D from Fig. 2) at 2.6 GHz for 64-QAM for different turbulence regimes in terms of changes in EVM, as illustrated in Fig. 6.

The higher is $C_n^2$ the larger is the fluctuation of the power magnitude and its corresponding EVM values, which can exceed the reliability limits of the RAN system. The proposed LTE test model for 64-QAM fulfills the reliability and the high data rate limit of EVM (i.e., < 8 %). Results indicate a RoFSO scenario evinces the best properties comparable to the hybrid RoF and RoFSO setups C and D where tolerable limits were exceeded approximately beyond the threshold $C_n^2$ of ~7.0E-11 m^2/3, in particular because of high fluctuations observed in EVM. In other words, the use of the RoF technology,
together with RoFSO under the turbulence condition, resulted in slightly reduced performance compared with the RoFSO link in terms of increased mean value of ΔEVM by 2.5 % and 5.5 % in the setups C and D, respectively at C\textsubscript{20} of 18-10 m\textsuperscript{-2/3}. This cannot be attributed only to added SMF (with an average EVM of 1 %), and therefore the overall system EVM has to be determined. The hybrid setups (C and D) offers a reliable high data rate transmission for the C\textsubscript{20} value up to 37.76-14 m\textsuperscript{-2/3}, which corresponds to C\textsubscript{20} of 5.37E-14 m\textsuperscript{-2/3} in the case of a 100 m long FSO link, extrapolated through Rytov variance expression (11). The predicted values largely fall into the moderate turbulence regime, thus representing a typical maximal turbulence strength according to [18] and [34] where a 1 km long FSO link under a real turbulence condition was investigated. By placing the EDFAs between the RoF and RoFSO systems, to compensate for the loss in the RoF link and boost the incoming signal prior to RoFSO link, the EVM is improved by ~3 %, as shown within the high fluctuation region in Fig. 6. Note that the optical output power (OS and EDFAs) levels were kept at a relatively low level to avoid the more significant role of nonlinear effects in OF.

### 4. CONCLUSION

Having proposed an optical dual-polarization LTE RoF & RoFSO system for C-RAN networks and having evaluated its performance in terms of the measured and simulated EVM statistics, we showed the configuration of radio systems for 64-QAM at 2.6 GHz, incorporating FSO under the turbulence regimes, which lead to EVM values below 8 % for C\textsubscript{20} of up to 5.37E-14 m\textsuperscript{-2/3} when considering a 100 m long FSO link. We also showed that the performance of the proposed link based on the combination of RoF and RoFSO was more affected by the turbulence with the measured ΔEVM value increased to 5.5 % However; the EVM was reduced by ~3 % when placing EDFA between RoF and RoFSO links. The proposed systems can offer higher noise immunity under particular scenarios with the SNR reliability limits of 5 dB in the RF domain for RoF and 19.3 dB in the optical domain for RoFSO links. There were no significant changes in the polarization of the radio PDM system while propagating through the fibre and FSO channels, thus illustrating proposed system attributes to a higher transmission capacity. The employment of the dual-polarization solutions, as part of the C-RAN infrastructures, creates a dense network between the RF base-end parts and central cloud pools, thus making the infrastructure simpler and more robust. Moreover, the proposed technique can be adopted for other radio services such as WiFi or WiMax, thus leading to improved network convergence.

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