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Adaptation of transmitting signals over joint aged optical fiber and free space optical network under harsh environments

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ABSTRACT

Over the last two decades, a large amount of optical fiber (OF) cables has been deployed as part of the global communication networks. Both the aging of OFs as well as the need to increase transmission data rates, particularly in the backbone, have become hot topics. We present the study of the aged OF deployment in various optical networks including free space optics (FSO) link as a part of modern optical communication networks. Here, we show extended results obtained using a dedicated OF testbed focusing on the long-term monitoring of polarization mode dispersion (PMD) because of its time-varying nature. The adaptation of polarization multiplexed radio over fiber (RoF) and radio over FSO (RoFSO) systems as well as 10 Gbps on-off-keying (OOK) non-return-to-zero (NRZ) intensity modulation with the direct detection system, which is common cost-effective transmission system in passive networks, are demonstrated. Moreover, simulation of 100 and 200 Gbps return-to-zero (RZ) differential quadrature phase shift keying (DQPSK) with direct detection is outlined to verify the impact of aged OF network connected with FSO under turbulence conditions. Results reveal more than 6 dB of power penalty with the aged OF route for 100 Gbps systems. In addition, there is a 0.8 dB power penalty due to the strong seasonal induced PMD fluctuations. The influence of scintillations in terms of Rytov variance for the FSO link is also investigated for weak to moderate turbulence. Finally, we derive an expression for the long-term mean PMD value determined over one-month measured frequency response.

1. Introduction

The optical technologies are finding still new areas of applications and challenges due to the increasing demands on the capacity, cost reduction or safety [1]. In [2] the utilization of both optical fiber (OF) and optical wireless infrastructures as part of the next generation networks was discussed. The optical infrastructures are frequently utilized for mobile networks

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fronthauls, where the radio over fiber (RoF) technology [3] can be adopted to benefit from the combined features of OF fronthaul and the simplification of base stations. The long-term evolution (LTE), known as the 4th generation of mobile network, has been widely deployed worldwide and furthermore, the technology provides challenges for RoF applications leading to cost reduction [4,5]. One of the key benefits of the RoF technology is its utilization as a solution for the cloud radio access network (C-RAN) architecture where baseband units (BBUs) are centralized in a central office or BBU hotel [6]. The converged optical/wireless systems can support the distribution of broadband signals in future wireless systems such as 5 G and 60 GHz networks. The capacity of RoF-based links can be significantly increased by using the polarization division multiplexing (PDM) technique as proposed in [7]. A dual polarization (DP) scheme was utilized for transmission of LTE-A 2×2 multiple-input multiple-output (MIMO) over up to a 100 km of single mode fiber link.

Large sections of the OF based telecommunication networks, which are still in-service, are many years old. For example, more than 222 million kilometers (corresponding to the distance between the Mars and the Sun) of OFs were installed between 1998 and 2000 [8] and many of them have been still in use with some even under harsh environments. Such infrastructures were initially designed to support on-off keying (OOK) non-return-to-zero (NRZ) signal formats with a speed of 2.5 Gbps or 10 Gbps. However, the subsequent higher bit rate systems (>40 Gbps) are mostly operating with higher optical transmit power and minimum system requirements of 50 GHz spacing, optical signal-to-noise-ratio (OSNR) tolerance not greater than 16 dB and a maximum mean polarization mode dispersion (PMD) tolerance of 30 ps with an outage probability of 10^{-5} [9]. Therefore with the coexistence of old and new OF based telecommunication infrastructures, it is essential to ensure that OF properties are fully characterized to ensure the quality of services. One of the cost-effective and energy-efficient solutions for 100 Gbps systems is the deployment of differential quadrature phase shift keying (DQPSK) modulation format enabling dense wavelength division multiplexing (DWDM) with a spacing of 100 GHz [10,11].

However, replacing of the existing OFs and installing new ones is highly time-consuming and costly especially in dense urban areas. Alternatively, the free space optics (FSO) technology, which offers OF features (i.e., high data rates and longer transmission span), could be one option that can be deployed rapidly over a transmission spans up to a few km [12,13]. In [14,15], a combination of radio over FSO (RoFSO) and the RoF technology with PDM was reported to transmit two independent radio signals at the same radio frequency within the optical channel. The authors investigated the performance and reliability of the system under the atmospheric turbulence. Note that OFs, used as part of the system, were kept inside the laboratory environment. However, there is the need for assessing the system performance under a real environmental condition, where OFs are also exposed to the harsh outdoor conditions.

In this paper, we present original results on the utilization of the real aged OF infrastructure affected by thermal changes and interconnected with the FSO subsystem under a harsh environment. The paper provides analyses of the various types of optical transmission systems and discusses a methodology to achieve improved statistics and reliability of the network. The unique extended results are and based on, to our best knowledge, the longest studies and monitoring of PMD, capturing long-term drift. The paper is organized as follows. Section 2 describes OF testbed and its characterization obtained from long-term PMD monitoring. Section 3 provides the comparison of experimental campaigns for (i) DP RoF and RoFSO, and (ii) 10 Gbps NRZ system, which is still very commonly used in practice, over the tested infrastructure. We compare statistics for three cases – an optical power load aged OF, aged OF without load, and new OF infrastructure – all interconnected with FSO subpart. Moreover, to extend the influence of atmospheric conditions on the proposed link, additional simulation results at higher data rates are provided under specific conditions. Finally, the summary concludes the paper.

2. Accelerated aging process in old optical infrastructure

One of the key parameters in OF communications, which limits the higher bit rate transmissions, is PMD (the mean value of differential group delays (DGD)) [16]. Due to its strong structural dependence, random behavior and high sensitivity to strain or temperature, PMD has become a useful indicator of the OF's aging process [17]. Moreover, to fully characterize an OF link in terms of PMD, a longer period of measuring is required. A long-term PMD measurement based on Jones matrix method using installed G.653 optical cables with exposed sections was carried out over a 5 months period [18]. The optical path with the exposed sections displayed a significantly higher variance of the mean of DGD. In [19] longer-term PMD measurement (~10,000 h) using an installed OF link span from 30 to 273 km was carried out by means of observing the state of polarization on the Poincaré sphere. Although these research findings have demonstrated a strong daily temperature based PMD fluctuations, they do not show longer-term seasonal PMD drift, especially for systems with exposed installed OFs.

In [20] one of the most extensive investigations on monitoring PDM of old and exposed OF over a long period (>2.5 years) was reported. In this paper, we extend the results from [20] to fully characterize experimental testbed over a long-term monitoring campaign in order to further analyse data transmission over a combined OF and FSO link span. The measurement campaign is mostly focused on monitoring of the key OF parameters and its characteristics under a harsh test environment as well as investigating the long-term system reliability.

Fig. 1(a) shows an aerial view of the building at Czech Technical University in Prague where the proposed testbed is located on the edge of the roof. The fiber routes are consisting of a 1 km long optical cable containing 72 fibers (type G.652) [21] from 1997, which are spliced together with a total length of 72 km and are laid on the roof next to the banister (green dashed line). The link is divided into two 36 km long sections – the reference and testing paths. An optical signal with a power of 27 dBm at 1550 nm is launched into the testing route for emulating accelerated aging process and high power load

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