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Abstract of Doctoral Dissertation

Studies on RF Signals Transmission over a Turbulent Free Space Optical Channel

擾乱のある自由空間光チャネル上での RF 信号伝送に関する研究

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The ever-increasing demand for capacity and quality in wireless communication links has continued to inspire researchers to innovate new design methodologies and concepts over wireless systems and networks with the ultimate aim of achieving a next-generation network. Among the emerging technologies is the new innovative radio on free-space optics system, referred to as RoFSO, which is the main interest of this research work. RoFSO systems have been recognized as a promising wireless interconnecting technology for addressing the emerging broadband network requirements, ensuring data rates similar to those offered by optical fiber systems but at the fraction of its deployment cost. Such system combines the radio over fiber (RoF) technology comprising heterogeneous wireless services and an FSO link. In RoF implementation, to distribute the radio frequency (RF) signals from central station to remote stations, multiple independent bit streams are first modulated onto subcarriers at different frequencies, then multiplexed in the RF domain and transmitted finally over high capacity optical fiber link using intensity modulation direct detection (IM/DD) method. However, the implementation of RoF solutions is dependent on the availability of installed optical fiber cables and the installation costs. In the absence of installed fiber cables, FSO links can conveniently be used to transmit RF signals through free space between end-points without the use of the fiber medium. Therefore, RoFSO technology combines the advantages of high transmission capacity enabled by optical device technologies and ease of deployment of wireless links.

The advantages of RoFSO were trumpeted throughout the telecommunications sector. These advantages include: rapid deployablility; support for high bandwidth transmissions; high security; the ability to extend the reach of the optical fiber backbone; and use in disaster recovery situations. Considered as the next generation cost-effective solution, the RoFSO technology can be applied as a universal platform for enabling seamless convergence of fiber and free-space optical communication networks, thus extending broadband connectivity to underserved areas, ensuring last mile access and serving as fiber back up. Hence, such technology has an important role to play in areas such as supporting rural communities, tackling isolation, delivering improved services to remote areas, and increasing opportunities to enterprises.

However, even with the significant capital investment in FSO during the past decade, researchers have not solved yet the technology's reliability problems due to high optical power loss in the outdoor environment impaired by adverse weather conditions, atmospheric turbulence, link misalignment due to sway and vibration in the building, and eye safety, multipath effect and background light, coming from the sun and/or artificial lighting, in the indoor environment. The performance of FSO systems is highly influenced by the deployment environment characteristics, mainly its susceptibility to weather conditions that fade the received signal and deteriorate the link performance. In fact, the transmitted optical beam may experience important distortions due to the refractive-index random variations, commonly referred to as scintillation, which can lead to temporarily deep fades or even annihilate the FSO link. Moreover, any misalignment between the transmitter and receiver caused by the building sway leads to pointing errors that may impair significantly the performance of FSO links. Undoubtedly, one of the main challenges for FSO communication systems is to mitigate the channel fading caused by the atmospheric turbulence. Turbulence causes intensity scintillation and beam wander from propagation through turbulent eddies of varying sizes and refractive index. The research presented here demonstrates techniques to mitigate the distortions induced on the optical beam by atmospheric turbulence.

In this research work, the primary contribution consists in a novel analytical framework to investigate the performance transmission of wireless services signals over FSO link and determine a design trade-off between configuration parameters in both the transmitter and the

receiver sides in order to achieve a substantial scintillation fade reduction and thus enhancing the overall system performance when the aperture averaging (AA) technique is considered. Our previous results obtained from experimental demonstration of the newly developed advanced dense wavelength division multiplexing (DWDM) RoFSO system capable of simultaneously transmitting multiple wireless services including Wideband code division multiple access (W-CDMA) and the Japanese standard Integrated services digital broadcasting-terrestrial (ISDB-T) signals over a 1 km link have been exploited in order to validate my new analytical model. The proposed RoFSO system is implemented by combining a new-generation FSO which uses narrow beam transmission and direct coupling to the SMF fiber core, with RoF technology. In next-generation FSO system, the challenge is not only to design an effective beam tracking and optical alignment technique between the FSO transceivers, but also an efficient method to focus the light directly into an SMF core. Although the system utilizes an innovative technique to control and steer the received beam to the SMF core and compensate for atmospheric turbulence induced signal fading, it is still difficult to maintain stable link performance especially when transmitting RF signals under strong turbulence regime.

In order to investigate analytically the RoFSO system able to transmit wireless services under different weather conditions, I derived new analytical models including closed-forms of bit error rate (BER) and outage probability expressions for optimization of two important multiplexing formats, i.e., the code division multiple access (CDMA) adopted by 3G cellular W-CDMA signals over FSO links and the multiple subcarrier modulation (MSM) signals employing different M-ary PSK modulation schemes. Recently, many researchers have studied the transmission of RF signals over fiber optics links and FSO links. However, these studies do not provide MSM and CDMA signals transmission over FSO links under strong atmospheric turbulence. Unlike these earlier works, my model takes into consideration the effect of using the AA technique modeled by the gamma-gamma distribution, the optical noises, the intermodulation distortion term due to the laser diode non-linearity. An important merit of this research work was the proposal of a system design trade-off based on an appropriate choice of the receiver antenna aperture size and the selection of an optimal optical modulation index in the transmitter to achieve high quality MSM/CDMA signals reception over the RoFSO system.

In this contribution, I demonstrate that the choice of an optical modulation index for the design of CDMA-FSO systems is less stringent than that in the case of OFDM-FSO systems since a wide range of optimal optical modulation index is available. My theoretical study provides guidelines to optimally configure the RoFSO system by applying an optimum optical modulation index in the transmitter side and an appropriate aperture lens in the receiver antenna.

Another contribution of this research work is to perform a comparison between the theoretical and measured system metric, i.e., carrier-to-noise-plus-interference ratio (CNIR). The obtained results confirm that the newly proposed analytical model can be applied for the performance evaluation and prediction of CDMA-based wireless service transmission using FSO links. Therefore, my presented work constitutes a complete study, including theoretical as well as experimental analysis that can serve as preliminary guidelines to both the transmitter and receiver design for the FSO communication systems transmitting RF signals, where several technical issues, such as size and weight should be considered. The obtained results can be useful for designing, predicting and evaluating the RoFSO system's ability to transmit wireless services over turbulent FSO links under actual conditions.

DISSERTATION STRUCTURE

This thesis is organized in six chapters detailing the theory, experimental work including design, evaluation and analysis as well as RoFSO system modeling. The rest of the thesis is organized as follows:

Chapter 2 reviews the FSO system, its operating principle and its applications. The challenges and limitations of FSO technology will be discussed. The main challenge is caused by the atmospheric effects especially optical scintillation which severely reduces the laser power and the range of the optical link. The most limiting factors that affect the performance of systems with their analytical models and the relevant techniques used to mitigate the effect of these factors are outlined.

Chapter 3 investigates the transmission performance of the M-ary PSK MSM signals over a turbulent FSO channel, in terms of the average carrier to noise-plus-distortion ratio (CNDR), BER and outage probability. At first, the Gaussian wave beam theory is briefly described and the choice of the corresponding propagation model is illustrated. Also, the AA technique which is employed to mitigate the atmospheric turbulence-induced fading is presented. A brief introduction about the MSM signals is given and the main issues to transport MSM signal over optical fiber are explained. The analytical model for optimization of the MSM RoFSO link is then presented with a derivation of new closed-form expressions for BER and outage probability, taking into account the LD nonlinearity effect and using the lognormal distribution to describe the turbulence-induced fading across weak to strong regimes.

In **Chapter 4**, the transmission performance of the CDMA signals over FSO links under weak to strong atmospheric turbulence regimes is evaluated analytically in terms of the average CNIR, BER and outage probability. Therefore, the nonlinearity of the LD, the multi-carrier interference and the scintillation in a Gamma-Gamma turbulent channel are considered. Closed-form expressions for CDMA signals BER and outage probability are derived, taking into account both atmospheric turbulence and the non-linearity distortion of the LD and the multiple access interference. The main purpose of this chapter is to provide a new analytical model able to assess the transmission performance limits of an analog optical link for CDMA-based wireless services systems.

In **Chapter 5**, the newly developed mathematical model is validated by performing a comparison with the experimental results obtained from the W-CDMA signal transmission over RoFSO experiments. The RoFSO system setup is optimally engineered to achieve a high quality W-CDMA signals reception based on the design trade-off between an optimum optical modulation index in the transmitter side and the receiver aperture size proposed in the last chapter. Experimental investigations using commercial RoFSO antennas operating at 785 nm wavelength and being 1-km far-away from each other to characterize such transmission are presented. Important performance metric parameters like CNIR and adjacent channel leakage ratio (ACLR) have been measured and analyzed to evaluate and quantify the influence of atmospheric effects relevant in the design of the RoFSO system. Also performed is a comparison between the numerical and measured CNIR and good agreement is found between them. Hence, the obtained results confirm that the proposed analytical model in the last chapter can be applied for the performance evaluation and prediction of CDMA-based wireless service transmission using FSO links.

And finally **Chapter 6** provides the concluding remarks of this thesis work. Critical analysis of the results is presented and areas of future research are outlined.