Graduate School of Global Information and Telecommunication Studies, Waseda University

Abstract of Doctoral Dissertation

Study on Transmission Characteristics of Optical Wireless Communication Systems

光無線通信システムの伝送特性に関する研究

Candidate's name

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Significant progress has been made in recent years in the research, development and deployment of affordable, ubiquitous and always-on broadband wireless access technologies that meet the demands and requirements of business, academic and residential end user markets. One of the emerging technologies for broadband wireless connectivity which has also been receiving growing attention is optical wireless communication (OWC) known also as free-space optics (FSO). FSO communication systems represent one of the most promising approaches for addressing the emerging broadband network requirements. The increase demand of wireless links which are easier, faster and less expensive to deploy has revived the interest in the use of free-space optics in digital signal transmission in the atmosphere, which can offer data rate comparable to optical fiber. FSO is the technology in which modulated optical signal is propagated over free space without using optical fiber medium. The advantages of FSO communications include ease of deployment, license free operation, high transmission security, high bit rates, full duplex transmission and protocol transparency. Depending on deployment scenario and applications, FSO communication systems are suitable for terrestrial and space based communications. In terrestrial communication, FSO systems are usually deployed for last mile access, enterprise connectivity and fiber back up.

In order to facilitate broadband wireless access and design an optimum network infrastructure able to transmit wireless services signals between base stations and remote antennas, the transmission of these signals by means of optical fiber links has been utilized for many years. This configuration commonly referred to as Radio over Fiber (RoF). The RoF technology has been developed to provide high transmission capacity, significant mobility and flexibility, as well as economic advantage due to its broad bandwidth and low attenuation characteristics. In addition, RoF systems allow multi-operator multi-service operation, and dynamic resource allocation. These potentials have made it suitable for a wide range of applications including last mile solutions, extension of existing radio coverage and capacity, and backhaul. In RoF implementation, to distribute the RF signals from central station to remote stations, RF signals are placed on optical carriers and transmitted over high capacity optical fiber cables. However, the use of RoF is dependent on the availability of installed optical fiber cables between various network facilities. In the absence of installed fiber cables, FSO links can conveniently be used to transmit RF signals, similar to RoF but excluding the fiber medium. Transmission of RF signals using FSO links, referred to as Radio-on-Free Space Optics (RoFSO), combines the advantages of high transmission capacity enabled by optical device technologies and ease of deployment of wireless links.

The primary research contribution presented in this work is an analytical and experimental investigation on transmission of wireless services signals over FSO link. I introduce methods of measuring, characterization and quantifying the influence of atmospheric effects relevant in the design of RoFSO communication system. In general, the major source of errors in RoFSO communications systems, are atmospheric turbulence, rain, fog and low visibility which affect the propagation of optical waves in the atmosphere. In fact, atmospheric turbulence effect, manifested as beam wander and scintillation, are the major source of errors in FSO communication links often causing link quality deterioration and sometimes unavailability. Furthermore, the performance of RoFSO systems can also be affected by the nonlinearity of the RoF link, such as the RF power amplifier, the laser diode (LD) and the optical fiber. Moreover, the RoF links are subject to optical noise sources, which include the LD's relative intensity noise (RIN), the photodiode's shot noise and thermal noise.

In this thesis an experimental demonstration of the newly developed advanced dense wavelength division multiplexed DWDM RoFSO system capable of simultaneously transmitting digital signals and multiple wireless services including W-CDMA, wireless LAN IEEE802.11g/a and terrestrial digital broadcasting TV (ISDB-T) signals over a 1-km link is presented. Therefore, the important performance metric parameters for evaluating the quality of each signal digital and

wireless services i.e. W-CDMA, ISDB-T and Wireless LAN IEEE 802.11g/a signals transmission using RoFSO link have been measured and characterized under various atmospheric influences and weather conditions. The proposed RoFSO system is implemented by combining the RoF technology with the new-generation FSO system which uses narrow beam transmission and direct coupling to the single mode fiber (SMF) fiber core. The system utilizes an innovative technique to control and steer the received beam through the SMF core and compensate for atmospheric turbulence induced signal fading. This work provides insight into the system design and performance characteristics relevant in implementing economical links for RoFSO system especially in areas lacking fiber infrastructure.

Another contribution of this research work is to investigate analytically the RoFSO system able to transmit broadband wireless services under different weather condition. An analytical model for optimization of the transmission of orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA) signals over FSO links are presented. The OFDM is the most popular technique adopted by ISDB-T and WLAN, whereas in W-CDMA standards the CDMA technique is used. In this work, a closed-form bit error probability and outage probability expressions taking into account the optical noises, the laser diode nonlinear distortion and the atmospheric turbulence effect on the FSO channel modeled by the gamma-gamma distribution is derived. This research reports the most significant parameters that degrade the transmission performance of the OFDM and CDMA signals over FSO links and indicates the cases that provide the optimal operating conditions for the link. Indeed. The performed analysis indicates the limiting factors for transmitting the OFDM and CDMA signals over gamma-gamma modeled turbulent RoFSO channel, such as scintillation, FSO channel attenuation, optical noises, i.e. thermal noise, shot noise and RIN, intermodulation distortion, multiple access interference (MAI), and number of users for CDMA signal. However, to achieve high quality OFDM and CDMA signals reception over the RoFSO system, the link has to be engineered to perform optimally in terms of received optical power, number of carriers and selecting an appropriate optimal optical modulation index. 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 system modeling. The rest of the thesis is organized as follows:

The first chapter "Introduction" describes the objective of this research by introducing briefly the FSO, RoF systems and the concept of the developed DWDM RoFSO system. It also discusses the main research contribution. Finally, the organization of the thesis is presented.

Chapter 2 "Free Space Optics Systems Overview", reviews of FSO systems, its operating principle and its application. The most significant 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 "OFDM-based Wireless Services Transmission over FSO Link", investigates the transmission performance of the OFDM signals over a turbulent FSO channel, in terms of the average carrier to noise-plus-distortion ratio (CNDR), bit error probability (BEP) and outage probability. A brief introduction about the OFDM signal is given and the main issues to transport OFDM signal over optical fiber are explained. The analytical model for optimization of the OFDM RoFSO link is then presented with a derivation of closed-form expressions for BEP and outage probability, taking into account the LD nonlinearity effect and using the

gamma-gamma distribution to describe the turbulence-induced fading across weak to strong regimes. The main purpose of this chapter is to assess the performance limits of an analog optical link for OFDM- based wireless services systems such as wireless LAN IEEE802.11g/a and terrestrial digital broadcasting TV.

In Chapter 4 "CDMA-based Wireless Services Transmission over FSO Link", the transmission performance of the CDMA signals over FSO links under strong atmospheric turbulence is evaluated analytically in terms of the average Carrier-to-Noise-plus-Interference Ratio (CNIR) and Bit Error Rate (BEP). This analysis is based on the subcarrier intensity multiplexing (SCM) technique, which is used to transmit modulated RF signals over fiber optical link and the FSO technology. Therefore, the nonlinearity of the LD, the MAI and the scintillation in a Gamma-Gamma turbulent channel are considered. A closed-form expression for CDMA signals BEP is derived, taking into account the atmospheric turbulence, optical noises, the non-linearity distortion of the LD and the MAI. The main purpose of this chapter is to assess the performance limits of an analog optical link for CDMA- based wireless services systems like W-CDMA.

In Chapter 5 "Experimental Evaluation of advanced DWDM RoFSO System", the design concept and performance evaluation of the newly developed advanced DWDM RoFSO system capable of simultaneously transmitting multiple Radio Frequency (RF) signals carrying various wireless services including W-CDMA, WLAN IEEE802.11g/a and ISDB-T signals over 1-km FSO link are presented. First, details of the RoFSO antenna design and tracking mechanism used in this experimental system are described. Then, the setup and specifications of the FSO systems used in this experiment are outlined. The atmospheric effects like FSO channel loss, beam wander and scintillation on the transmission of each wireless service signal is measured and characterized. The transmission performance is analyzed and presented, by comparing data collected on different weather conditions. This work represents a pioneering attempt, based on a realistic operational scenario, aiming at demonstrating the RoFSO system can be conveniently used as a reliable alternative broadband wireless technology for complementing optical fiber networks in areas where the deployment of optical fiber is not feasible.

Finally **Chapter 6 "Conclusion"**, provides the concluding remarks of this thesis work and makes suggestions for further research directions.

List of academic achievements

Category (Subheadings)	
Articles in refereed journals	○ Abdelmoula Bekkali, C. Ben Naila, K. Kazaura, K. Wakamori, M. Mastumoto, ” Transmission Analysis of OFDM-based Wireless Services over Turbulent Radio-on-FSO Links modeled by Gamma-Gamma Distribution ” *IEEE Photonics Journal, Vol.2, No.3, pp.510-520 , June 2010.* ○ Abdelmoula Bekkali, C. Ben Naila, P.T. Dat, K. Kazaura, K. Wakamori, M. Mastumoto, “Transmission Performance Analysis of Digital TV Broadcasting Signals over Turbulent FSO Channel” *Journal of The Institute of Image Electronics Engineers of Japan , Vol.39, No.3, pp.236-247, May 2010.* ○ Abdelmoula Bekkali, P.T. Dat, K. Kazaura, K. Wakamori, M. Mastumoto, T. Higashino, K. Tsukamoto, S. Komaki “Performance Evaluation of an Advanced DWDM RoFSO System for Transmitting Multiple RF Signals” *IEICE Transaction on Fundamentals of Electronics, Communications and Computer Sciences, Vol.E92-A,No.11, pp.2697-2705, Nov. 2009. Best Paper Award*
Presentations at International conferences	○ Abdelmoula Bekkali, P.T. Dat, K. Kazaura, K. Wakamori and M. Matsumoto: Performance Analysis of SCM-FSO Links for Transmission of CDMA Signals under Gamma-Gamma Turbulent Channel, *IEEE Military Communications Conference (MILCOM) 2009,* World Trade Centre, Boston, 18-21 October, 2009. *IEEE Travel Grant Award* Abdelmoula Bekkali, P. Tien Dat, K. Kazaura, K. Wakamori, T. Suzuki, M. Matsumotoi, T. Higashino, K. Tsukamoto, and S. Komaki: Experimental study of transmitting RF signals over free space optics system, *International Conference on Space Optical Systems and Applications (ICSOS 2009)*, Tokyo, Japan, 4-6 Feb. 2009.
Presentations at domestic conferences	Abdelmoula Bekkali, T.D. Pham, M.S. Alam, K. Kazaura, K. Wakamori, T. Suzuki, M. Matsumoto, T. Nakamura, T. Higashino, and K. Tsukamoto: Development of Radio on Free Space Optics System for Ubiquitous Wireless Services - (3) RF Signal Transmission using RoFSO Links - IEICE 2009 General Conference C-14-3, Ehime University, Matsuyama, 17-20 March 2009.

	Abdelmoula Bekkali, A.M. Shah, P.T. Dat, K. Kazaura, K. Wakamori, T. Suzuki, K. Takahashi, K. Omae, T. Satou, M. Matsumoto, Y. Aburakawa, T. Nakamura, T. Higashino, K. Tsukamoto, and S. Komaki: Development of Radio on Free Space Optics System for Ubiquitous Wireless Services - (4) RoFSO system performance Measurement - 2008 IEICE Society Conference, C-14-13, Meiji University, Kawasaki, Sept. 2008 Abdelmoula Bekkali, P.T. Dat K. Kazaura, K. Wakamori and M. Matsumoto;" Performance Evaluation of an Advanced DWDM RoFSO System for Transmitting Multiple Wireless Services", GITS/GITI Research Festival 2009, October 7th, 2009, Waseda Campus, Waseda University. Abdelmoula Bekkali, P.T. Dat K. Kazaura, K. Wakamori and M. Matsumoto;" Researches on RoFSO System for Transmitting Multiple Wireless Services", GITS/GITI Research Festival 2008, October 8th, 2008, Waseda Campus, Waseda University.
'Other achievements'	
Papers or articles in journals	Abdelmoula Bekkali and M. Matsumoto, .RFID Indoor Tracking System based on Inter-tags Distance Measurement., *in book "Wireless technology: Applications, Management and Security",* edited by S. Powell and B.J. Shim, Springer Science + Business Media.Inc, ISBN: 978-0-387-71786-9, Norwell, MA, USA. 2009.
Presentation at International conferences	Abdelmoula Bekkali and M.Matsumoto "Bayesian Sensor Model for Indoor Localization in Ubiquitous Sensor Network" *International Standardization Union, ITU-T Kaleidoscope Conference,* 12-13 May. Geneva, Switzerland. *Young Student Research Award* Abdelmoula Bekkali, H.Sanson and M.Matsumoto "RFID Indoor Positioning based on Probabilistic RFID Map and Kalman Filtering" In proc. *IEEE International Conference on Wireless ad Mobile Computing, Networking and Communication* (IEEE WiMob2007) White Plains, NY, USA. October 2007. (*Google Cited 20 times/ May 2009*).