Graduate School of Global Information and
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Abstract of Doctoral Dissertation

Studies on Performance of Ultra High Speed Free-Space Optical Communication Systems

超高速光空間通信システムにおける伝播特性の研究

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Free-space optical (FSO) communication systems are increasingly being adapted to provide high-speed, improved capacity, cost effective, secure and easy to deploy wireless networks. These systems have proven to be an attractive technology for broadband wireless communication when optical fiber links are unavailable or their deployment is simply not feasible (cost prohibitive). This thesis presents experimental work and results on the design, evaluation, prediction and comparison of a new ultra high speed FSO system performance in operational environments.

Currently, the typical channel capacity for optical fiber transmission is from 2.5 Gbps to 40 Gbps, and so far there is no deployed wireless communication network which can deliver this kind capacity. Innovative broadband wireless technologies (for both fixed and mobile applications) operating in the RF, microwave and millimeter wave regions of the electromagnetic spectrum are currently being deployed or are under active research investigations. These technologies include IEEE 802.11 based WLAN systems, IEEE 802.16 based WMAN (WiMAX) systems and ultra wideband (UWB) PAN systems. Unfortunately, these advanced wireless technologies still do not meet the capacity of current optical fiber transmission. Therefore, there is a need for a flexible full optical wireless network (free-space optical communication system) which can provide capacity equivalent to optical fiber.

Conventional FSO systems operate near the 800 nm spectral range and before transmission through the space, the optical signal is converted to electrical signal by the optical transceiver. The electrical signal is amplified by a laser driver and the modulated light from the laser diode is directed through space. At the receiver the optical beam is focused to a photo detector then converted to electrical signal. The electrical signal is again converted back to optical for transmission through optical fiber. Unfortunately, optical devices using the 800 nm spectral range can not operate above 2.5 Gbps because of the power limitations imposed for eye safety. In order to overcome these bandwidth and power limitations, 1550 nm wavelength is selected for new ultra-high speed FSO systems and its advantages apart from being eye safe include, reduced solar background radiation and compatibility with existing optical fiber technology infrastructure. By using the 1550 nm wavelength, multi-gigabit per second wireless transmission can be achieved by leveraging the technology developed for long haul optical fiber communication e.g. erbium-doped fiber amplifier (EDFA) and wavelength division multiplexing (WDM) as well as advanced optical sources and detectors.

In this thesis, experimental studies on a newly designed FSO communication system operating at 1550 nm wavelength where the optical beam is emitted directly from the fiber termination to free-space and then coupled directly to fiber (usually single mode fiber SMF) at the receiver point is presented. The need for converting the optical signal to electrical and vice versa is omitted. The merits of this wireless communication system include being data rate and protocol independent thus the necessity of reconfiguring the transceivers is eliminated when the nature of the transmit signal changes due to varying bit rates, signal

format (analogue or digital) or wavelength channel. The key technology in this kind of FSO communication system is a high-speed beam tracking and control mechanism which is able to suppress the effects of atmospheric turbulence so as to couple as much of the received optical beam to the SMF core having a diameter of about 10 μm. Therefore it is important to investigate the free-space atmospheric propagation properties necessary in the design, evaluation, prediction and comparison of FSO system performance in operational environments. The design of the high-speed beam tracking and control mechanism is a key element.

The primary goal of this thesis is to experimentally study the design and performance of a new ultra high-speed FSO communication system. It is well known that atmospheric turbulence, aerosols and molecular absorption affect the propagation of optical waves in the atmosphere. Atmospheric turbulence effect, manifested as beam wander and scintillation, is the major source of errors in FSO communication links often causing link quality deterioration and sometimes unavailability. Most of the techniques used to improve FSO communication system performance work by suppressing atmospheric turbulence which is a major source of deep signal fades. The experimental study is conducted using a 1 km link FSO communication system setup in the Waseda campus area.

A relative simple technique for atmospheric turbulence mitigation is introduced. The technique utilizes a fast beam tracking miniature fine pointing mirror (FPM). The FPM function is to control and steer the beam to the fiber connection port. The advantages of using the miniature FPM for atmospheric turbulence mitigation compared to the other techniques is that the FPM can improve the FSO system performance with less complexity and minimum electronic overhead and at the same time maintaining a compact size antenna of about 10 cm cubed.

A method to determine the FPM optimum tracking speed has been proposed. This method determines the tracking speed by measuring the received signal intensity fluctuations as a result of atmospheric induced scintillations effects and comparing it with the signal variations caused by angle-of-arrival (AOA) fluctuations. The frequency response characteristics for the two measured data set (after performing FFT to the time series data) show similarity in the magnitudes of intensity fluctuation. From this result, an approximation for the antennas' fast beam steering FPM tracking speed has been determined. In this case, the FPM tracking speed is chosen to respond faster than the AOA fluctuations and is set to 1 kHz. The beam intensity fluctuations because of AOA fluctuations were suppressed remarkably.

The ultra high-speed FSO communication system performance evaluation in terms of bit-error-rate (BER) after setting the antenna tracking speed to 1 kHz was conducted. The improvement in atmospheric turbulence suppression is evident from the reduced errors and continuous stable full-duplex (bi-directional) transmission at 2.5 Gbps and 10 Gbps has been demonstrated under clear and quiet weather conditions.

A comparison on the performance of free-space optical systems operating in the 800 nm and 1550 nm wavelengths is presented. Up to now, there is no comprehensive long term statistical analysis data collected comparing

the atmospheric turbulence effects on the performance and propagation characteristics of conventional 785 nm and new 1550 nm wavelength FSO communication systems deployed in the same environment. In this thesis an opportunity to conduct such experiment by measuring and analyzing collected data over a long period of time was presented.

The thesis also focuses on long-term experimental measurement, characterization and quantifying the effects of atmospheric turbulence experienced on ultra high speed FSO communication system. Among the results after careful observation of the measurement data is that the magnitude of atmospheric induced scintillation fluctuation is not only determined by high temperature, but rather the difference between the ground and the air temperature. When this temperature difference is high, the degree of scintillation fluctuation is also high. Also by comparing the atmospheric turbulence measurement during arbitrary chosen summer and winter months, it was shown that the midday maximum of refractive index structure constant parameter, C_n^2, could change by a factor of 2.3. Therefore, the increased occurrence of bursts errors in the ultra high speed FSO system during the summer months, because the FPM could not suppress the strong atmospheric turbulence ($C_n^2 > 10^{-13} m^{-2/3}$).

And finally, this thesis explores a method to suppress burst errors which occur in periods of strong atmospheric turbulence ($C_n^2 > 10^{-13} m^{-2/3}$). Under such events, the FPM signal fading suppression capability is diminished. Therefore in order to avoid signal fading in such situation, the use of a soft-computing (SC) based multi-layer neural network predictor (MNNP) is proposed. The SC based tools are used for the prediction of key parameters of the FSO communication system. Measured data collected from the experimental FSO communication system is used as training and testing data for a proposed MNNP used to predict future parameters. From simulation studies, the parameters values predicted using the proposed tool show acceptable conformity with the original measurements. This demonstrates that soft-computing based tools can be used to enhance the performance and reliability of FSO communication systems especially in periods of strong atmospheric turbulence when the antenna tracking and control unit temporary looses it tracking capability.

List of academic achievements

Category (Subheadings)	
Articles in refereed journals	○K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, E. Mutafungwa, T. Murakami, K. Takahashi, H. Matsumoto, K. Wakamori, and Y. Arimoto, "Performance Evaluation of Next Generation Free-Space Optical Communication System," (forthcoming *IEICE Transactions on Electronics Special Section on Evolution of Microwave and Millimeter-Wave Photonics Technology*, vol. E90-C, no. 2, February 2007) ○K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, E. Mutafungwa, T.O. Korhonen, T. Murakami, K. Takahashi, H. Matsumoto and K. Wakamori, "Enhancing Performance of Next Generation FSO Communication Systems using Soft Computing-Based Predictions," *Optics Express – International Journal of Optics*, vol. 14, no. 12, pp. 4958-4968, June, 2006. ○K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, E. Mutafungwa, T. Murakami, K. Takahashi, H. Matsumoto, K. Wakamori, and Y. Arimoto, "Free Space Optical Antenna with High Speed Tracking for Improved Atmospheric Turbulence Mitigation," *Journal of the Japan Society of Infrared Science and Technology*, vol. 15, No. 1+2, pp. 1-6, Dec, 2005.
Presentations at International conferences	○K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, E. Mutafungwa, T. Murakami, K. Takahashi, H. Matsumoto, K. Wakamori, and Y. Arimoto, "Experimental Demonstration of Next Generation FSO Communication system," *SPIE Optics East 2006 Conference*, (Hynes Convention Centre, Boston, Massachusetts), 1~4 October 2006. ○K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, E. Mutafungwa, T. Murakami, K. Takahashi, H. Matsumoto, K. Wakamori, and Y. Arimoto, "Experimental Performance Evaluation of Next Generation FSO Communication System," *Asia Pacific Microwave Photonics Conference (AP-MWP 2006)*, (Kobe, Japan), pp. 289-292, 24~26 April 2006. ○K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, T. Murakami, K. Takahashi, H. Matsumoto, K. Wakamori, and Y. Arimoto, "Mitigation of Atmospheric Effects on Terrestrial FSO Communication Systems by Using High-speed Beam Tracking Antenna," *SPIE Photonic West LASE 2006 Conference*, (San Jose California), pp. 167-176, 24~26 January 2006.
Presentations at domestic academic meetings held by study groups	K. Kazaura, K. Omae, M. Matsumoto, A. Samejima, T. Suzuki, K. Takahashi, H. Matsumoto and K. Wakamori, "Study on the Development of Free Space Optical Antenna with Transparency of fiber, Telecom Summit," *6th Academy and Industry Symposium (CINAG)*, (Yokosuka, Japan), pp. 112-113, 15~16 June 2005.
Presentations at domestic conferences	K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, E. Mutafungwa, T. Murakami, K. Takahashi, H. Matsumoto, K. Wakamori, and Y. Arimoto, "Quantifying Effects of Atmospheric Turbulence in FSO Communications System," *IEICE General Meeting*, pp. B-1-25, Kokushikan Univ. Setagaya, 24~27 March 2006. K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, T. Sato, M. Hatori, T. Murakami, K. Takahashi, H. Matsumoto, K. Wakamori, and Y. Arimoto, "Study of Free-space Optical Communication System with transparency of fiber (3) – Scintillation Measurement for FSO Communication System," *IEICE Society Meeting*, Hokkaido Univ.、 Hokkaido, 20~23 September 2005.

	K. Kazaura, K. Omae, M. Matsumoto, T. Sato, K. Asatani, M. Hatori, A. Samejima, T. Suzuki, K. Takahashi, H. Matsumoto and K. Wakamori, "Study of Free-space Optical Communication Systems with transparency of fiber," *IEICE General Meeting*, Osaka, 21~24 March 2005.
Others	K. Kazaura, "Experimental Study on Next Generation Free-Space Optical Communication System," Technical Lecture given at the meeting of the Institution of Engineering and Technology, Japan Centre, Tokyo, 6 September 2006.
'Other achievements'	K. Kazaura, L. Jun and M. Matsumoto, "A Simulation Based Evaluation on the Performance of Integrated 3G – Wireless LAN Networks," *IEEE International Technical Conference (TENCON 2004*), Chiang Mai, Thailand, 21~24 November 2004.
Presentations at International conferences	K. Kazaura, E. Mutafungwa and M. Matsumoto, "An Investigation into the Optimum Integration Scenario. For Traffic Handling in a Combined 3G – WLAN Network System," *The Sixth International Symposium on Wireless Personal Multimedia Communications (WPMC03)*, Yokosuka, Japan, 19~22 October 2003. K. Kazaura, E. Mutafungwa P. Ulanga, T. Wakahara and M. Matsumoto, "Delivering Wireless Data Application in East Africa: Opportunities provided by MM-Wave Communication Systems," *The East African Telecommunications, Broadcasting Conference*, Nairobi, Kenya, 7~9 March 2002. K. Kazaura, T. Mwakabaga, E. Mutafungwa and M. Matsumoto, "Investigation on the Efficient Multimedia Traffic Handling for an Integrated 3G – WLAN Network," *The 2003 International Conference on Electrical Engineering and Technology (ICEET03)*, Dar Es Salaam, Tanzania, 18~19 August 2003.
Presentations at domestic academic meetings held by study groups	K. Kazaura, L. Jun and M. Matsumoto, "Deployment Strategies for Optimal Performance in Integrated Wireless LAN and 3G Cellular Networks," *Telecom Summit, 5th Academy and Industry Symposium (CINAG)*, (Yokosuka, Japan), 7~8 July 2004
Presentations at domestic conferences	K. Kazaura, T. Wakahara and M. Matsumoto, "Delivery of Multimedia Using High-Speed Millimeter Wave Communication Links," 2002 画像電子学会第 30 回年次大会画像電子学会&GITS/GITI 合同セッション 2 pp. 147-148, 2002.6. K. Kazaura, T. Wakahara and M. Matsumoto, "Modeling of High Speed Campus Network Using Millimeter Wave Communication Links," 年電子情報通信学会総 合大会 SB-12-6, 2002.3. カザウラカムギシャ、対馬正宏、若原俊彦、松本充 司, "60GHz Millimeter Wave Communication Links for High Speed Point-to-Point Communications – Waseda University Campus Network Case Study," 2001 年電子情報通信学会ソサイチィ大会 B-5-45, 2001. 9. カザウラカムギシャ、対馬正宏、若原俊彦、松本充 司, 60GHz 無線におけるポイントトポイント通信のシミュレーション検討, 2001 年電子情報通信学会総 合大会 B-5-233, 2001. カザウラカムギシャ、三宅、若原俊彦、松本充 司, "Experimental Study of Wireless Lecture Support System," 画像電子学会第 28 回年次大会, pp. 1-2 (2000)

Others	E. Mutafungwa, K. Kazaura, K. Omae, T. Suzuki, M. Matsumoto, T.O. Korhonen, T. Murakami, K. Takahashi, H. Matsumoto, K. Wakamori, and y. Arimoto: Soft Computing-based Prediction to Enhance Performance of Next Generation FSO Communication Systems, Asia Pacific Microwave Photonics Conference (AP-MWP 2006), (Kobe, Japan), pp. 59-62, 24~26 April 2006. 鈴木敏司, カザウラカムギシャ, 松本充司, 村上匡亮, 大前和憲, 高橋浩一, 松本秀樹, 若森和彦, “光無線と光ファイバのフル光接続技術の研究開発”, 電子情報通信学会MWP研究会 於, 神戸, 2001.11 大前和憲, 鈴木敏司, カザウラカムギシャ, 松本充司, 佐藤拓朗, 淺谷耕一, 羽鳥光俊, 村上匡亮, 高橋浩一, 松本秀樹, 若森和彦, “光波とミリ波の相互補完性に関する一検討”, 電子情報通信学会総合大会, 世田谷, 2006.3 松本秀樹, 大前和憲, カザウラカムギシャ, 松本充司, 鈴木敏司, 羽鳥光俊, 村上匡亮, 高橋浩一, 若森和彦, 有本好徳, ” フル光接続光無線システムの有効性評価”, 電子情報通信学会総合大会, 世田谷, 2006.3 若森和彦, 高橋浩一, 松本秀樹, 村上匡亮, 羽鳥光俊, カザウラカムギシャ, 大前和憲, 松本充司, 鈴木敏司, 有本好徳, “次世代光無線システムの研究開発”, 電子情報通信学会総合大会, 世田谷, 2006.3 鈴木敏司, カザウラカムギシャ, 松本充司, 佐藤拓朗, 淺谷耕一, 羽鳥光俊, 鮫島彰孝, 大前和憲, 高橋浩一, 松本秀樹, 若森和彦, “フル光接続光無線システムの研究開発(1) － 光無線と60GHz帯ミリ波無線との併用に関する評価の一検討(1) －”, 電子情報通信学会 ソサエティ大会 於, 2005.9 大前和憲, 鈴木敏司, カザウラカムギシャ, 松本充司, 佐藤拓朗, 淺谷耕一, 羽鳥光俊, 村上匡亮, 高橋浩一, 松本秀樹, 若森和彦, “フル光接続光無線システムの研究開発(2) － 光無線と60GHz帯ミリ波無線との併用に関する評価の一検討(2)－”, 電子情報通信学会 ソサエティ大会 於, 2005.9 松本秀樹, 大前和憲, カザウラカムギシャ, 松本充司, 佐藤拓朗, 鈴木敏司, 羽鳥光俊, 村上匡亮, 高橋浩一, 若森和彦, 有本好徳, “フル光接続光無線システムの研究開発(4) －光軸追尾とBER計測システム－”, 電子情報通信学会 ソサエティ大会 於, 2005.9 高橋浩一, 松本秀樹, 若森和彦, 羽鳥光俊, 村上匡亮, 有本好徳, 大前和憲, カザウラカムギシャ, 松本充司, 佐藤拓朗, 鈴木敏司, “フル光接続光無線システムの研究開発(5) －光学システム系概要－”, 電子情報通信学会 ソサエティ大会 於, 2005.9 村上匡亮, 村上匡亮, 大前和憲, カザウラカムギシャ, 松本充司, 佐藤拓朗, 鈴木敏司, 羽鳥光俊, 高橋浩一, 松本秀樹, 若森和彦, 有本好徳, “フル光接続光無線システムの研究開発(6) －光波伝搬特性評価のための, 気象計測システムの評価－”, 電子情報通信学会 ソサエティ大会 於, 2005.9 大前和憲, カザウラカムギシャ, 松本充司, 佐藤拓朗, 淺谷耕一, 羽鳥光俊, 村上匡亮, 鈴木敏司, 高橋浩一, 松本秀樹, 若森和彦, “フル光接続光無線システムの回線設計における一検討”, 画像電子学会 年次大会 於, 長野, 2005.6

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