Title	Studies on characterizing the transmission of RF signals over a turbulent FSO link
Author(s)	Dat, Pham Tien; Bekkali, Abdemoula; Kazaura, Kamugisha et al.
Citation	Optics Express. 2009, 17(10), p. 7731-7743
Version Type	VoR
URL	https://hdl.handle.net/11094/3429
rights	
Note	

Studies on characterizing the transmission of RF signals over a turbulent FSO link

Pham Tien Dat[1,*], Abdemoula Bekkali[1], Kamugisha Kazaura[1], Kazuhiko Wakamori[1], Toshiji Suzuki[1], Mitsuji Matsumoto[1], Takeshi Higashino[2], Katsutoshi Tsukamoto[2], Shozo Komaki[2]

[1] *GITS/GITI, Waseda University, Tokyo, Japan*
[2] *Graduate School of Engineering, Osaka University, Osaka, Japan*
[*] *Corresponding author: ptdat@fuji.waseda.jp*

Abstract: In this paper, we present an experimental study on transmission of RF signals over turbulent free-space optics (FSO) channel by using off-the-shelf Radio Frequency – FSO (RF-FSO) antennas. The results demonstrate potential of utilizing FSO links for transmission of RF signals and are used as a guideline in the design, prediction and evaluation of an advanced Dense Wavelength Division Multiplexing (DWDM) RoFSO system we are developing capable of transmitting multiple RF signals. An analytical modeling of the system is also conducted to identify key parameters in evaluating the performance of RF signal transmission using FSO links. The results confirm that the effect of scintillation on RF-FSO system performance can be estimated by using a simple estimation equation and satisfactory result are obtained from comparing the experimental and theoretical derived data under weak to strong turbulence condition.

OCIS codes: (060.2605) Free-space optical communication; (010.1330) Atmospheric turbulence.

References and links

1. H. Al-Raweshidy and S. Komaki, eds., *Radio over Fiber Technologies for Mobile Communications Networks* (Artech House Publishers, first ed., 2002).
2. W. Chang, ed., *RF Photonic Technology in Optical Fiber Links* (Cambridge University Press, first ed., Oct. 2002).
3. Seeds, "Microwave Photonics," IEEE Trans. on Micro. Theory Techniq. **50**, 877-887 (2002).
4. J. Wu, J. Wu, and H. Tsao, "A Radio-over Fiber Network for Microcellular System Application," IEEE Trans. Veh. Technol. **47**, 84-94 (1998).
5. Davis, I. Smolyaninov, and S. Milner, "Flexible Optical Wireless Links and Networks," IEEE Commun. Mag. **41**, 51-57 (2003).
6. Mahdy and J. Deogun, "Wireless Optical Communications: A Survey," Proc. IEEE WCNC 2399-2404 (2004).
7. K. Takahashi, T. Higashino, T. Nakamura, Y. Aburakawa, K. Tsukamoto, S. Komaki, K. Wakamori, T. Suzuki, K. Kazaura, and M. Matsumoto, "Design and evaluation of optical antenna module suitable for Radio on Free-Space Optics link system for ubiquitous wireless," Proc. SPIE **6877**, 112-123 (2008).
8. H. Refai, J. Sluss, and M. Atiquzzaman, "Comparative study of the performance of analog fiber optic links versus free-space optical links," Opt. Engin. **45**, 025003.1-10 (2006).
9. 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," IEICE Trans. Electron. **E90-C**, 381-388 (2007).
10. K. Tsukamoto, S. Komaki, and M. Matsumoto, "Development Project of Radio on Free Space Optics," Proc. SPIE **6788**, 677606.1-8 (2007).
11. L. Andrews and R. Phillips, *Laser Beam propagation through Random Media*, second ed, (SPIE Press, 2005).
12. L. Wasiczko and C. Davis, "Aperture averaging of optical scintillations in the atmosphere: experimental results," Proc. SPIE **5793**, 197-207 (2005).
13. L. Andrews, R. Phillips, C. Hopen, and M. Al-Habash, "Theory of optical scintillation," J. Opt. Soc. Am. A **16,** 1417-1429 (1999).

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

14. G. Katz, S. Armon, P. Goldgeier, Y. Hauptman, and N. Atias, "Cellular over optical wireless networks," IEE Proc.-Optoelectron. **153**, 195-198 (2006).
15. 3GPP TS 25.141, 3rd Generation Partnership Project. http://www.3gpp.org/, 2002.
16. K.Wakamori, T. Hayashi, H. Yamashita, Y. Kimura, and M. Hosoda, "155-Mbps ATM Backbone for Interbuilding Intranet using an Optical Wireless System," Proc. PIMRC (1999).
17. G. Keiser, "Optical Communications Essentials," by The McGraw-Hill Companies, Inc., 2003.
18. O. BoucheII, T. Marquis, M. Chabane, M. Alnaboulsi, and H. Sizun, "FSO and Quality of Service Software Prediction," Proc. SPIE **5892**, 589204.1-12 (2005).
19. Giggenbach, and H. Henninger, "Fading-loss assessment in atmospheric free-space optical communication links with on-off keying," Opt. Engin. **47,** 046001.1-6 (2006).

1. Introduction

Recently, user's demand for multimedia services has increased rapidly with high requirements for any-time, anywhere and any-situation communication. To realize a ubiquitous communication network, a universal platform in which broadband heterogeneous wireless services can be deployed easily is the most important issue. Transmission of RF signals by means of optical fiber links has been utilized for many years, referred to as Radio over Fiber (RoF). This is because of extremely high capability of fiber links in transporting signals, including microwave and millimeter wave, at low cost, over long distance and low attenuation [1], [2]. RoF technology has been used widely in cellular phone networks to provide connectivity between central and remote universal stations, resulting in the emergence of microcellular system and helps to increase the capacity [3], [4]. Optical fibers, however, are not always easy and feasible to install, especially in rural or dead-zone areas in the city. Wireless communication links based on free-space optical (FSO) communication systems can be utilized as an alternative technology in that case providing similar capacity to optical fiber.

FSO communication technology has been successfully utilized to offer high-speed digital transmission for a variety of applications. It can provide a cost effective alternative to fiber optical systems in last mile applications, enterprise connectivity, metro network extension, fiber backup [5], [6]. Beside the above-mentioned applications, FSO links can be attractive means for RF signal transmission. It can play a similar role to an optical fiber in the layer 1 of the RoF network to transport radio signals in some applications. However, the transmission of RF signals over FSO links is essentially an analog transmission channel, so the communication quality is easier to deteriorate compared with digital systems [7]. Therefore, higher reliability and stability are required and higher accurate system is necessary.

A well designed FSO link can be used to reliably transport multiple RF signals comprising of various kinds of communication and broadcasting signals. These signals can comprise of terrestrial digital TV, cellular signals like Wideband Code Division Multiple Access (W-CDMA), Wireless Local Area Network (WLAN) and/or new advanced wireless services signals. The transmission of these wireless signals using FSO links is referred to as Radio on Free-Space Optics (RoFSO). This technology has attracted a lot of attention from research community recently. In [8], for example, the authors set up an indoor 3m link experiment to characterize the end-to-end communication channel for transmission of modulated RF signal over a FSO link while omitting the atmospheric influences. Unfortunately, unlike RoF system, the performance of RoFSO system is highly affected by atmosphere environment due to absorption, scattering and especially scintillation. To design such a RoFSO system capable of transporting multiple RF signals, it is necessary to consider the dynamic operation environment influences on RF signals performance. However, to our knowledge, there is no research work so far considering the effects of atmosphere especially atmospheric turbulence on the performance of RF signals transmission over FSO systems. In this work, we aim at experimenting in actual deployment environment scenario the performance of RF signal transmission using a FSO link.

In this paper, we present an attempt to characterize the performance of RF signal transmission using a 1 km FSO channel. The experiment is conducted by transmitting a W-CDMA signal using a radio frequency FSO (RF-FSO) system setup. We measure and analyze the W-CDMA performance metric parameters including Adjacent Channel Leakage Ratio

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

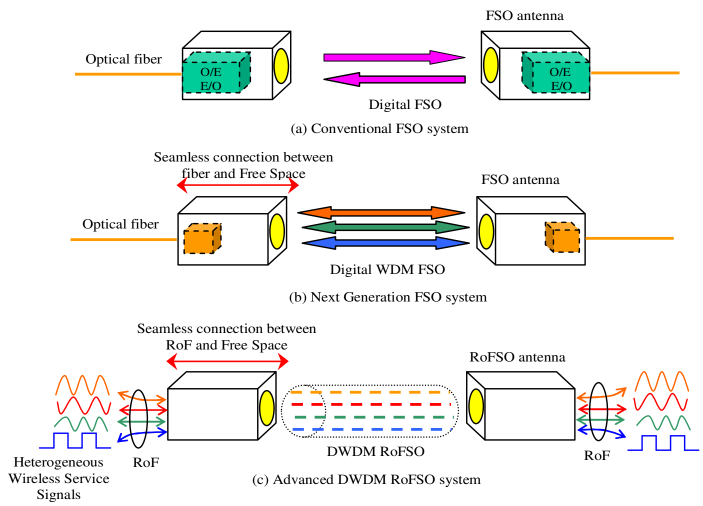


Fig.1. FSO communication system concepts.

(ACLR) and Carrier to Noise Ratio (CNR) under various atmospheric conditions. A statistical analysis on atmospheric attenuation and fading loss of the RF-FSO system is also presented from the viewpoint of the link margin design. These performance results can be significant in the design and evaluation of an advanced DWDM RoFSO system we are developing. We also use an analytical modeling approach in an attempt to derive a theoretical evaluation of the system. The obtained results show some similarity when compared to the experimentally derived performance data. This similarity clarifies that the effect of scintillation on RF signal transmission can be estimated by using a simple estimation equation.

2. FSO communication system concepts

FSO systems can be categorized in 3 broad groups i.e. conventional FSO based systems, new generation FSO based systems and advanced RoFSO systems. These different categories of FSO systems are shown in Fig. 1. Conventional FSO systems shown in Fig. 1(a) operates at 800 nm wavelength band, and needs to use O/E and E/O conversions before emitting/coupling optical signals from/into an optical fiber. They have been used extensively for digital data transmission with different data rate, but due to power and bandwidth limitation of optical devices operating in this wavelength band, it is not possible to operate above 2.5 Gbps data rates.

Recently, new generation FSO technology has been developed in order to overcome the limitation of the conventional FSO systems (Fig. 1(b)). In our work reported in [9], we developed and successfully demonstrated a full-optical FSO communication system operating at 1550 nm wavelength band with the single channel transmission rate up to 10 Gbps. Unlike conventional FSO systems, in the new generation FSO systems the necessity of converting the signal from electrical to optical and vice versa before transmitting or receiving through free-space is eliminated. In this configuration the signal is emitted directly to free-space from the fiber termination point and at the receiving end focused directly into the fiber core. Therefore, a protocol and data rate transparent FSO link is achieved.

We propose to develop a new advanced DWDM RoFSO system [10] based on the successful system we developed [9], which is capable of simultaneous transmitting multiple RF signals as shown in Fig. 1(c). The proposed system aims at using new generation FSO links for transmission of multiple wireless services simultaneously including 3GPP cellular phone, wireless LAN, terrestrial digital TV and other new wireless services using RoF and DWDM technology with more than 4 wavelengths. The system is expected to be used as an alternative means for RoF link where the fiber cable is not available, and can become a

#105231 - $15.00 USD   Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

feasible technique for heterogeneous wireless services to achieve ubiquitous communication in the near future.

However, unlike RoF implementations the performance of a RoFSO link is strongly affected by the limitations of the FSO segment. An impaired received FSO signal after transmission over a turbulent atmosphere link may result in poor performance for the wireless services. To achieve a good performance, the system has to be engineered to operate in a dynamic environment affected by atmosphere turbulence, low visibility, high attenuation, vibrations and so forth. Thus, it is important when designing the system to take the atmospheric environment characteristics and its influences on the RF signal transmission into consideration. The work presented in this paper uses a conventional FSO based system operating at 785 nm to transmit RF signals and is aimed at providing general guidelines and performance characteristics in the design, prediction, evaluation and comparison of the proposed advanced DWDM RoFSO system.

3. Experiment evaluation of RF signal transmission over a FSO link

The performance of RF signal transmission over a FSO channel is highly influenced by the conditions of atmospheric environment. These conditions include high attenuation which can be as a result of rain, fog, snow and scintillation due to optical turbulence in the air. Attenuation can be to some extent solved by increasing transmitting power or using amplifiers. However, it is difficult to eliminate fluctuations in received power due to scintillation effect resulting in saturation or loss of signal. Optical turbulence, therefore, is considered as the limiting factor for RF-FSO systems. Usually, intensity fluctuations strength is indicated by *Scintillation Index* and defined as the normalized variance of the intensity fluctuations,

$$\sigma_I^2 = \frac{\langle [I - \langle I \rangle]^2 \rangle}{\langle I \rangle^2} \tag{1}$$

where I is light intensity and <.> is ensemble average.

Refractive index structure constant, C_n^2, is the parameter commonly used to describe the strength of atmospheric turbulence. C_n^2 can be calculated from Rytov variance parameter [11],

$$\sigma_R^2 = 1.23 k^{7/6} L^{11/6} C_n^2 \tag{2}$$

where $k=2\pi/\lambda$ is optical wave-number, L is propagation distance.

Andrews and Philips developed a model to describe plane wave characteristics over the entire range of fluctuation conditions, from weak to strong turbulence [11], [12]. The *Scintillation Index* for a plane wave is,

$$\sigma_I^2(D_{RX}, L) = \exp\left[\frac{0.49\sigma_R^2}{(1+0.65d^2+1.11\sigma_R^{12/5})^{7/6}} + \frac{0.51\sigma_R^2(1+0.69\sigma_R^{12/5})^{-5/6}}{1+0.90d^2+0.62d^2\sigma_R^{12/5}}\right] - 1 \tag{3}$$

where $d = \sqrt{kD_{RX}^{\ 2}/4L}$ is the ratio of the aperture radius to the Fresnel zone size.

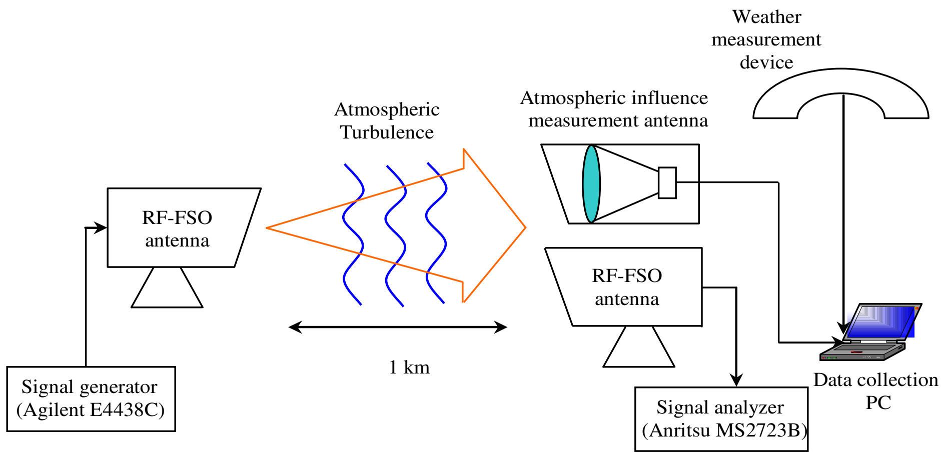
It is known that the scintillation index increases with the increasing values of C_n^2 until it reaches a maximum value in the regime characterized by random focusing, so called because the focusing caused by large scale inhomogeneities achieves its strongest effect. With increasing inhomogeneity strength, the focusing effect is weakened by multiple scattering, and the fluctuations slowly begin to decrease [13]. Atmospheric turbulence manifested as scintillation effect has a significant impact in performance of the FSO channel therefore it is an important characteristic to consider when evaluating RF signal transmission using FSO links.

Unlike FSO systems, the performance of RF-FSO systems can be evaluated in the same generally accepted criteria typically applied to conventional RF links like CNR and frequency response [14]. In this paper, by evaluating RF signals quality metrics parameters, the possibility of using FSO systems for transmission of RF signals will be investigated.

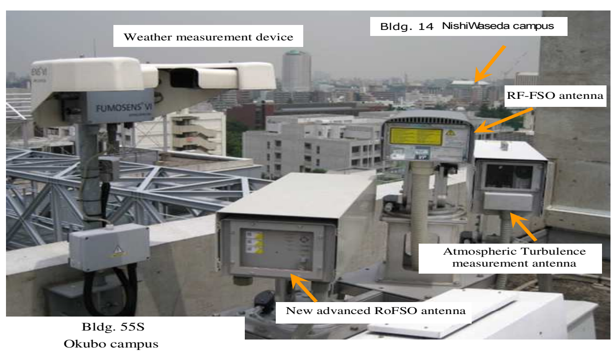
#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

3.1. Experimental setup

The experimental setup for conducting transmission of RF signals over a FSO channel is illustrated in Fig. 2(a). Two RF-FSO antennas (Canobeam DT-170 antennas) operating at 785 nm wavelength are installed on the rooftop of two buildings at Waseda University campus in Tokyo. The FSO link distance is about 1 km. Also co-located at one site is another antenna used for atmospheric turbulence and optical power attenuation measurement. A weather measurement device for recording temperature, rain rate and visibility data is also available. The weather data is used to correlate the system performance with the weather conditions. A photo showing the device installation on the rooftop of one of the Waseda university campus buildings is shown in Fig. 2(b). The specification of the RF-FSO antenna is given in table 1.



(a)



(b)

Fig. 2. Experimental setup for RF signal transmission measurement (a) and Devices setup on the rooftop (b).

Table 1. Specifications of RF-FSO system

Parameter	Value
Operating wavelength	785 nm
Transceiver aperture	100 mm
Max. output power	14 mW
Beam divergence	± 0.75 mrad
Tracking method	Auto tracking

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

Unlike the proposed advanced DWDM RoFSO system, the current RF-FSO antennas used in our experiment are based on the conventional FSO systems i.e. use optical-to-electrical conversion and vice versa before transmission to or reception from the atmosphere. The RF-FSO antennas have several limitations though including it is not possible to transmit simultaneously multiple RF signals using WDM technology like the proposed RoFSO system. The RF-FSO antennas are being utilized to obtain general idea and characteristics of RF signal transmission in real operational environment.

In our setup at the transmitter site, an RF signal (W-CDMA signal in our experiment) is generated by using an RF signal generator (Agilent E4438C) and is propagated through the atmosphere using the RF-FSO antenna. A digital mobile radio transmitter tester (Anritsu MS2723B) is used to measure the quality metrics of the received RF signal after extracting from optical signal by the corresponding RF-FSO antenna at the receiver. The RF frequency range of operation for the RF-FSO transceiver is from 450 kHz to 420 MHz. Because of this limitation, in this experiment the center frequency is shifted to 120 MHz instead of typical W-CDMA carrier frequency of 2 GHz.

The signal used in our experiment is W-CDMA test model 1 with input power of -5 dBm. We focus on measuring the ACLR because it is the stringent quality metric parameter for W-CDMA signal transmission performance evaluation. As described in 3GPP standard [15], the standard specifies the value for ACLR to be larger than 45 dB at 5 MHz offset and 50 dB at 10 MHz offset.

3.2. Experimental results

The first exercise is determining the minimum required value of CNR to satisfy the quality of W-CDMA signal carried by the RF-FSO system. From the collected measurement data using the RF-FSO set up, the relation of CNR and ACLR under dynamic operational condition is shown in Fig. 3. From the figure, it is determined that the minimum required CNR value to satisfy an ACLR of more than 45 dB at 5MHz offset is 112 dB. A similar result was obtained by using neutral density (ND) filters of different attenuation (static case measurement). This CNR value is used as a threshold requirement to evaluate performance of the system under different atmosphere conditions.

After determining the required minimum value of CNR for W-CDMA signal transmission, using the RF-FSO link we measure the received RF signal transmission performance using CNR and ACLR quality metrics after propagation over 1 km. The measurement is made under different weather conditions to obtain a baseline of the system performance and characteristics.

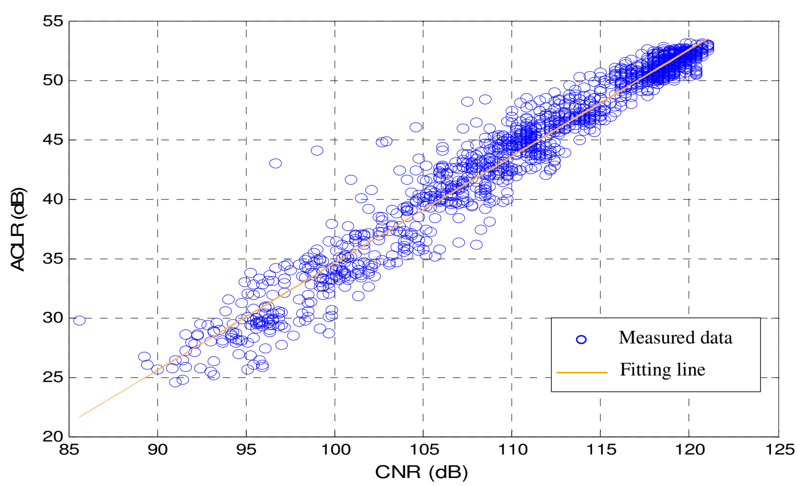


Fig. 3. Relation of ACLR and CNR under dynamic operation measurement.

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

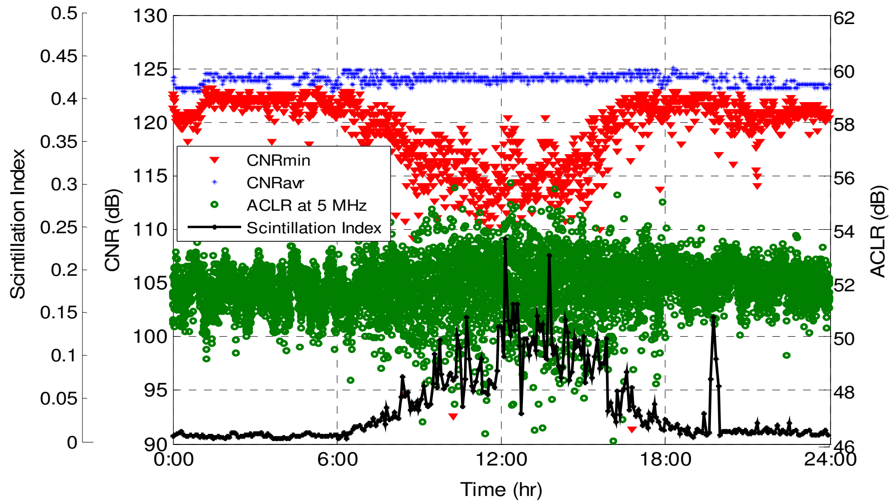


Fig. 4. System performance in a clear sunny day.

As an example, the RF-FSO system performance under influence of atmosphere turbulence measured for a continuous 24-hour period is illustrated in Fig. 4. The weather condition on this day was clear and sunny. The measured parameters include CNR, ACLR and scintillation index. The CNR data is sampled at 100 Hz and CNR average (CNRavr) is calculated in 1-minute intervals. CNRmin represents the minimum value of CNR recorded in 1-minute intervals. The ACLR is the defined as the ratio of the amount of leakage power in an adjacent channel to the total transmitted power in the main channel, and recorded in 2-second intervals. Scintillation index data derived from the intensity fluctuations measurement using a separate FSO antenna with the same aperture diameter co-located with the RF-FSO system is also presented.

From the Fig. 4, increased fluctuations in both CNR and ACLR are observed especially at noon time due to effects of atmospheric turbulence. Because the air needs time to heat up, atmospheric turbulence is typically greatest at the middle of the day and weakest an hour after sunrise or sunset. Therefore, significant reduction in ACLR and CNR is recorded sometimes during period from 10:00 am to 16:00 pm. From 16:00 pm the temperature starts to decline and the difference between the air's and the ground's temperature reduces, the system achieved better performance. In this example for a continuous 24-hour period a satisfactory performance of the RF-FSO system is observed with the measured ACLR being higher than the required value specified by the 3GPP standard requirement even under strong atmosphere turbulence period.

A statistical analysis of the system performance in terms of ACLR parameter for 15 days data characterized with clear weather condition collected during summer season in 2008 is shown in Fig. 5. The data is analyzed by calculating the empirical cumulative distribution function (CDF) of the ACLR parameter at 5 MHz and 10 MHz offset. It is observed that at 5 MHz offset most values of ACLR parameter are higher than required value of 45 dB, while the percentage of ACLR at 10 MHz offset drops under the required value is just 6%. It is necessary to mention that the ACLR values at 5 MHz and 10 MHz are close together as shown in Fig. 5 is because of property of the RF-FSO antenna used in the experiment. The system operates at 785 nm wavelength, with limitation of the input optical power due to eyes safety and also the linearity characteristics of the laser diode, leading to limitation in modulation depth for the RF signals. Irrespective of this, the statistical data shows satisfactory

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

performance of the RF-FSO system when considering atmosphere turbulence as the main affecting factor.

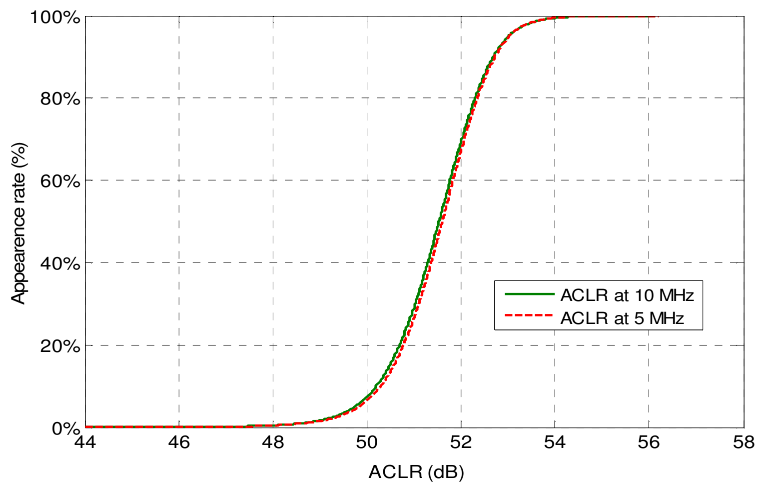


Fig. 5. Statistics of system performance in clear sunny days in 2008 summer.

Our next attempt is to determine the correlation between scintillation index and CNR deviation. The deviation between average and minimum CNR may indicate carrier loss caused by scintillation at the receiver. Using experimental data collected on clear days in 2008, as illustrated in Fig. 6, it can be observed that there is some correlation between CNR deviations variations and the increasing scintillation index as indicated by the fitting curve. However, many scattered points are also observed due to the difference in the measurement methods for the two parameters. The scintillation index derived from intensity fluctuations is recorded once in every 5-minute interval while the CNR deviation data is calculated for every 1-minute interval. As a result, during 5-minute interval with only one value of scintillation index recorded, CNR deviations might vary significantly due to fluctuations in received power. Also from the figure a maximum fading of about 12 dB in recorded CNR data can be presumed due to scintillation influence in our system. For a different RF-FSO system, this fluctuation fading may change depending on the aperture-averaging factor and deployment environment characteristics.

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

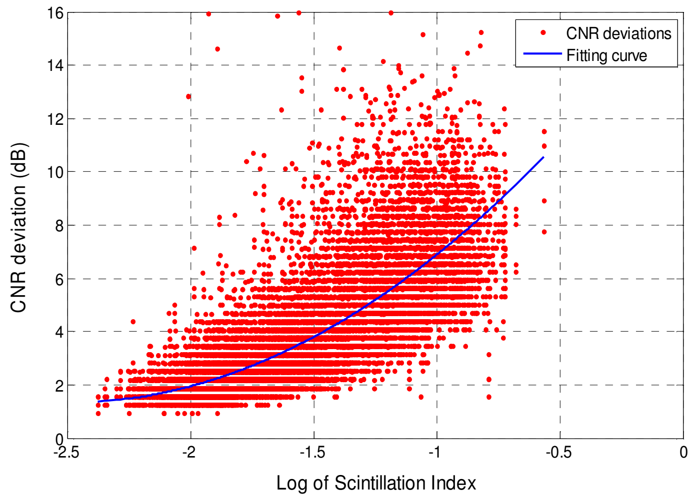


Fig. 6. Correlation between CNR deviation and Scintillation index

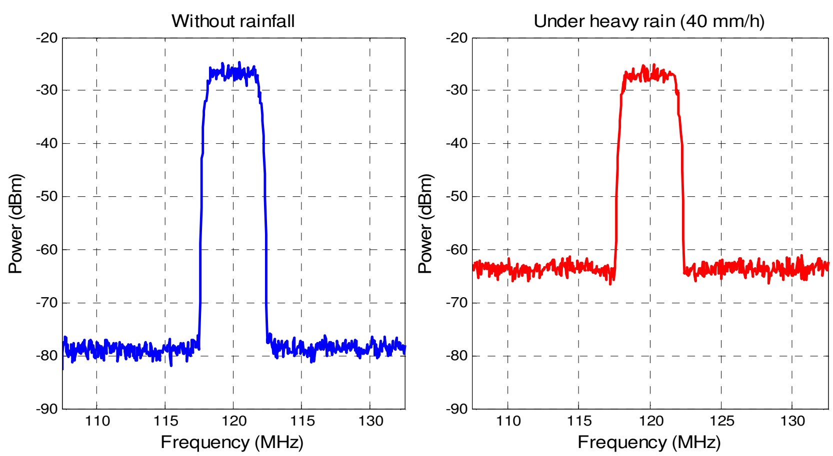


Fig. 7. Received spectrum of W-CDMA signal after being transmitted over FSO Link

Besides atmospheric turbulence, rain also affects performance of the RF-FSO system because of attenuation caused by geometric scattering. Generally, the effect of rain can be derived as a function of the precipitation intensity R [16],

$$Att_{rain} = \alpha * R^{\beta} \tag{4}$$

Rain intensity is a fundamental parameter used to locally describe the rain. The parameters α and β will be given according to the location [16]. For the case of Japan, (4) becomes,

$$Att_{rain} = 4.9R^{.63} \tag{5}$$

where R is rainfall rate over 10 minutes (mm/10 mins).

Figure 7 depicts a trace of the received W-CDMA signal spectrum recorded in clear weather and in presence of heavy rainfall (about 40 mm/hr). It is observed that in the presence of heavy rainfall, the signal can experience an attenuation of more than 15 dB. In this situation, the W-CDMA signal quality metric drops below the specified ACLR required threshold. Note that because the RF-FSO antenna is equipped with an automatic gain control

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

(AGC), the peak signal power is maintained at the same level even when the noise floor is raised.

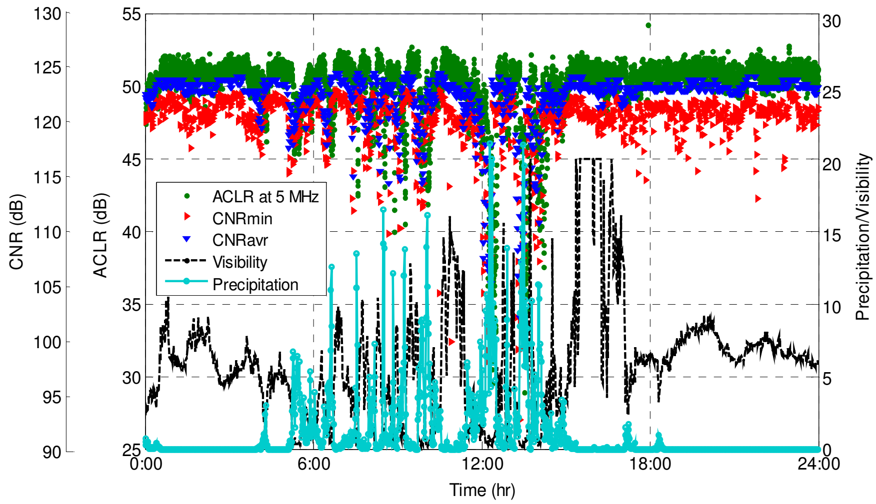


Fig. 8. Variation of ACLR and CNR in rain event (October 24, 2008).

The variation of CNR and ACLR characteristics in a rain event is shown in Fig. 8. A correlation between the measured CNR and ACLR with the rain and visibility condition can be observed. The CNR and ACLR values deteriorate corresponding to the increased rainfall and deterioration of the visibility condition. At some point with a rain rate of about 22 mm/hr, around 12:00, the measured value of ACLR drops to about 30 dB which is below the required value for W-CDMA signal transmission. It should be noted that the link attenuation during rainfall has two components – link path attenuation due to rain and attenuation due to heavy rain falling on the FSO transceiver window [16].

3.3 Statistical link margin

Performance of RF-FSO system is affected by different weather conditions, therefore, when designing a link margin for a RF-FSO system to operate under dynamic environment, it is necessary to take all the effects into consideration. Table 2 shows a statistics of optical signal loss of the RF-FSO system recorded for a period of one year from July 2007 to June 2008. The data involves scintillation loss in clear weather and attenuation loss for the cases of rain, low visibility and fog conditions. In clear weather conditions, the loss data statistics is derived from CDF of CNR deviation data shown in Fig. 6. In other weather conditions, as an example shown in Fig. 8, not only CNRmin but also CNRavr drop because of attenuation. In these conditions, therefore, the loss data statistics is calculated from CDF of CNR differences when comparing average CNR with the data recorded in clear weather days. From this statistics, the link availability is presumed to obtain 99% or more if the link margin is set to be 20 dB or more. This information is very helpful for design of the new advanced DWDM RoFSO system to provide a reliable link for heterogeneous wireless services. The link margin of 20 dB is for the case of high attenuation when the system operates under severe weather conditions. This margin is large enough to compensate for the fluctuations in the received optical power due to atmosphere turbulence.

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

Table 2. Atmospheric loss statistics of the RF-FSO system

Loss (dB)	Appearance percentage (%)
20 ~	0.435
13 ~ 20	0.248
10 ~ 13	0.821
3 ~ 10	6.79
0~3	91.706

4. RF-FSO system analytical evaluation

In this section, we present an analytical modeling approach to evaluate the performance of the RF-FSO system in terms of CNR parameter. This analysis using experimental data is an attempt to derive a theoretical methodology which can be applied to evaluate other quality metrics parameters that are difficult to measure directly, for example Spurious Free Dynamic Range (SFDR) which is an important parameter in RF optical systems, to confirm the suitability of FSO channel in transmitting RF signals.

CNR parameter of a RF-FSO system using APD photo-detector is given as [17],

$$CNR = \frac{\frac{1}{2}(OMI.r.M.P_{pd})^2}{RIN(rP_{pd})^2 + 2eM^{2+F}(rP_{pd} + I_{dr}) + (4KT/R_f)} \tag{6}$$

where *OMI* is optical modulation index, *M* is the photodiode gain, *K* Boltzmann's constant (1.38×10^{-23} *J/K*), *T* the temperature in Kelvin, *e* the electrical charge, I_{dr} is the photodiode dark current, *F* the excess noise factor and R_f is the photodiode output resistance, *r* is the photodiode responsivity and RIN is relative intensity noise.

The received power at the detector, P_{pd}, is formulated as,

$$P_{pd} = P_t - L_{optr} - L_{geo} - L_{atm} - (L_{\text{point}}) \quad (dBm) \tag{7}$$

where P_t is output power from transmitter, L_{optr} is optical coupling loss at receiver, L_{geo} is geometrical loss, L_{atm} is atmospheric loss and L_{point} is loss due to pointing error.

The geometrical loss in a FSO system is due to broadening of the laser beam and depends on the optical antenna structure, and can be calculated as [18],

$$L_{geo} = 10\log\left(\frac{D_{RX}}{D_{TX} + L.\theta}\right)^2 \quad (dB) \tag{8}$$

where D_{TX} and D_{RX} are diameters of the transmitter and receiver optics, respectively, *L* the length of the link and θ is the divergence angle of the transmitted laser beam.

Pointing loss is due to pointing error between transmitter and receiver antennas, and with the systems utilizing auto-tracking function, this loss can be ignored. Coupling loss is internal losses inside the optical antennas due to connectors and depends on construction of the antennas.

Atmospheric loss is the most important source of losses in FSO systems. The above mentioned losses are fixed and can be quantified for a FSO system operating in any kind of transmission environment, atmospheric loss changes randomly depending on characteristics of atmosphere conditions. This is due to the fact that atmosphere environment induces different effects on FSO system performance. In a clear weather condition, atmospheric loss can be considered to equal with fading loss due to scintillation influence. Recently, D. Giggenbach et. al, developed a fading loss model describing the effect of the atmosphere turbulence on FSO systems using concept of power scintillation index [19] which is represented as,

#105231 - $15.00 USD   Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

$$a_{scin} = 4.343\left\{erf^{-1}(2p_{thr} - 1).[2\ln(\sigma_P^2 + 1)]^{1/2} - \frac{1}{2}\ln(\sigma_P^2 + 1)\right\} \tag{9}$$

with p_{thr} is the fraction of outage time and equals the possibility that the actual power fall below the threshold minimum received optical power, erf^{1} is inverse error function and σ_P^2 is power scintillation index.

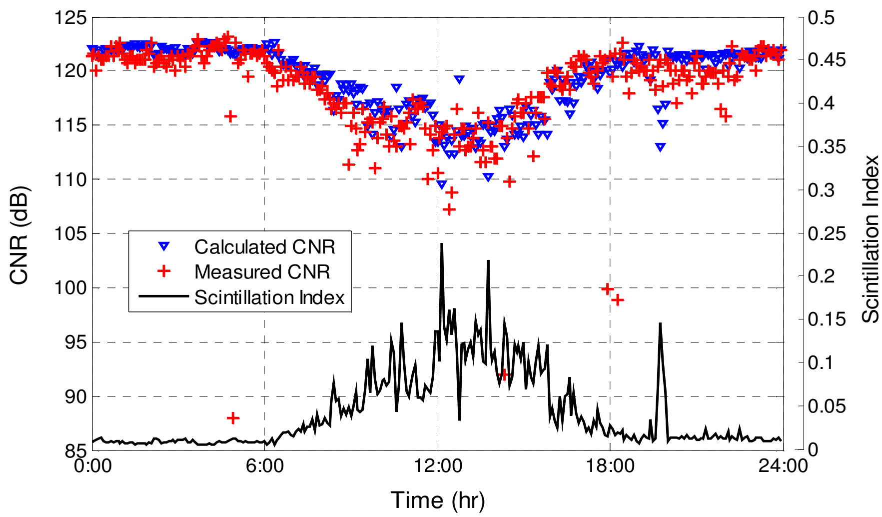


Fig. 9. Calculated and measured CNR for the RF-FSO system in a clear sunny day.

Applying the fading loss model to our RF-FSO system, the calculated CNR values together with experimentally measured CNR values for a clear sunny day (2008 August 7th) is shown in Fig. 9. The calculation takes the experiment system's parameters shown in table 1 and the scintillation index data derived from the intensity fluctuations measurement into consideration. The other parameters used in the calculation including OMI of 17.5%, photodiode gain of 15, RIN of -160 dB/Hz and fraction of outage time of 10^{-9}. From the figure it can be observed that there is a close similarity between calculated CNR values using the fading loss model and the actual experiment measured CNR from weak to strong turbulence. Even at the time of strong turbulence when the scintillation index of about 0.24 was recorded, the calculated data shows the same variation with the experiment result. This similarity shows the possibility of using the analytical approach to approximate the system performance under effects of atmospheric turbulence. From Fig. 9 we also can see that Eq. (9) can be considered to estimate adequately the effect of scintillation on the RF-FSO system. It therefore can be used when designing a link margin for RF-FSO systems to operate in atmospheric turbulence conditions with σ_P^2 parameter can be calculated using Eq. (3).

5. Conclusion

In this paper we attempt to establish from actual experimental measurements the performance related parameters for transmission of RF signals using FSO link. The experimental results confirm the possibility of RF signal transmission over FSO channel with acceptable performance provided that the link margin is large enough to compensate against atmospheric losses. A link margin of more than 20 dB is necessary when transmitting a W-CDMA signal with required availability rate of 99%. This margin can compensate for attenuation in the atmospheric environment as well as fluctuations due to turbulence in clear sunny weather days.

The analytical modeling result gives a reasonable approximation when compared with experimental data. From the similarity of calculated and experiment results, it is possible to

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009

use the analytical approach to evaluate the other quality metrics parameters which are difficult to measure directly, like SFDR, to confirm the possibility of FSO link in transmission of RF signals. The evaluation results also clarified that the estimation equation of fading loss provided an adequate estimation of scintillation effect on RF-FSO system performance.

Considering that the RF-FSO system used in this experiment is based on the conventional FSO antenna design and has limitation on the RF frequency range of operation i.e. up to 420 MHz, we expect that the new advanced DWDM RoFSO antenna will be able to offer better performance because it operates in the 1550 nm wavelength and can operate up to 5 GHz RF frequency range. A better understanding of transmission of RF signals using FSO links will be derived from experiments using the new DWDM RoFSO system we have developed. The current data is being used to offer a general guideline and idea in evaluating the system performance.

Acknowledgment

This work is supported by a grant from the National Institute of Information and Communications Technology (NICT) of Japan.

#105231 - $15.00 USD Received 17 Dec 2008; revised 24 Mar 2009; accepted 22 Apr 2009; published 27 Apr 2009