Experimental Demonstration of a Radio on Free Space Optics System for Ubiquitous Wireless

Kamugisha Kazaura\textsuperscript{1}, Toshiji Suzuki\textsuperscript{2}, Kazuhiko Wakamori\textsuperscript{2}, Mitsuji Matsumoto\textsuperscript{3}, Takeshi Higashino\textsuperscript{4}, Katsutoshi Tsukamoto\textsuperscript{1}, and Shoza Komaki\textsuperscript{4}

\textsuperscript{1}Research Institute for Science and Engineering (RISE), Waseda University, Japan
\textsuperscript{2}Global Information and Telecommunication Institute (GITI) Waseda University, Japan
\textsuperscript{3}Graduate School of Global Information and Telecommunication Studies (GITS) Waseda University, Japan
\textsuperscript{4}Department of Electrical, Electronic and Information Engineering Graduate School of Engineering, Osaka University, Japan

Abstract — One of the ultimate goals in next generation network design is to achieve an ubiquitous environment enabling connectivity between any wireless access system with optical fiber core network. Radio on Fiber (RoF) technology has been applied to realize a universal platform for transparently carrying various types of wireless services. By applying free-space optics (FSO) communication techniques combined with RoF, this concept can be extended to free space channels. This paper presents a new DWDM Radio on Free-Space Optics (RoFSO) system, which can be used to realize a universal platform to quickly and effectively provide ubiquitous wireless services to underserved areas avoided due to prohibitive costs associated with deploying optical fiber. To realize this RoFSO system, a next generation FSO system which provides seamless connection between free-space and optical fiber links by directly coupling the free-space propagated beam to a single mode fiber (SMF) is used. We have evaluated this new DWDM RoFSO system by conducting field experiments in simultaneous transmission of various kinds of wireless services; for example, 3GPP cellular, WLAN, terrestrial digital broadcasting TV (ISDB-T) signals; over extended durations. The preliminary results demonstrate the potential to utilize the RoFSO system for stable and reliable transmission of optical and radio frequency (RF) signals.

1. INTRODUCTION

Radio over fiber (RoF) technology has successfully been implemented to transmit RF signals over optical fibers to provide links between various network facilities. Transmission of RF signals using RoF implementation has many advantages including transmission and distribution of RF signals at low costs, longer distances with low attenuation [1]. However, RoF implementation is dependent on availability of installed optical fiber cables. In some cases, it is not always feasible to deploy optical fiber networks due to the prohibitive cost and delays associated in laying cables etc. In such situations, wireless systems are an attractive means for providing rapid connectivity to network facilities.

In recent years, free-space optics (FSO) communication technology has greatly matured and is increasingly being used as an alternative solution for proving high-speed, reliable connectivity between end-points in the absence of a fiber medium [2]. Interest in applying FSO links for carrying RF signals which can be compared to RoF technology but in this case without the fiber medium is increasing. This technology, referred to as Radio on Free-Space Optics (RoFSO), takes advantage of the rapid deployment, high-speed and flexibility of FSO wireless systems for transmission of RF signals.

In this paper, we report on preliminary results obtained from the first experimental demonstration of an advanced DWDM RoFSO system capable of simultaneously transmitting multiple RF signals carrying various wireless services. We present the performance evaluation of the DWDM RoFSO system when transmitting the multiple RF signals which include cellular 3GPP based W-CDMA signals, Wireless LAN IEEE802.11g/a signals and terrestrial digital broadcasting TV (ISDB-T) signals over a 1 km link. In the absence of severe weather conditions, we confirm that this RoFSO system we have developed is capable of providing stable and reliable simultaneous transmission of multiple RF signals.
2. ROFSO SYSTEM DESCRIPTION AND EXPERIMENTAL SETUP

The design concept and operation of the RoFSO antenna is based on the next generation FSO system reported in [3] which operate in the 1550 nm wavelength range. For transmission or reception through the atmosphere in the next generation FSO system, an optical beam is emitted directly from the fiber termination point using the FSO transceiver and at the receiving end the optical beam is focused directly to the single mode fiber (SMF) core using the receiver optics in the receiving antenna. In this configuration a protocol and data rate transparent communication link is realized.

Detailed design features and operation of the new DWDM RoFSO system have been reported in [4, 5]. In the RoFSO configuration for transmission through the atmosphere direct optical amplification and emission of RoF signal into free-space is employed and at the receiving end the optical signal is directly focused into a SMF.

Similar efforts investigating the transmission of RF signals using FSO links have been reported in [6] and [7]. In [6], investigation of simultaneous transmission of multiple analog RF signals over a FSO link spanning 3 m using WDM technology is presented. In this setup the antenna used does not utilize any tracking function because of the short distance and real operational environment characteristics is not reflected. Whereas in [7], transmission of single cellular signal using conventional FSO systems operating at 810 nm and 1550 nm over a 500 m link is investigated. In contrast with the previous reported work outlined, in this paper we presents investigation on the performance of a DWDM RoFSO system while simultaneously transmitting multiple RF signals over a 1 km path. This work represents a more realistic operational scenario with the aim of demonstrating long term system performance under different deployment environment conditions.

A schematic diagram representing the experimental setup of the RoFSO system is shown in Figure 1 (a) and a photograph showing the various measurement devices setup in the laboratory is depicted in Figure 1 (b). Placed at one site are signal generators for generating the different kind of wireless service signals which are then multiplexed together and transmitted via the DWDM RoFSO link by the RoFSO antenna placed on the buildings rooftop. At the second site, signal analyzers (as depicted in Figure 1 (b)) and other devices for measuring and recording the quality of the received RF and optical signals, weather data which includes temperature, visibility, precipitation etc as well as atmospheric conditions like scintillation effects are placed. The specifications of the RoFSO system are given in Table 1.

![Figure 1: RoFSO system setup (a) schematic and (b) devices setup in the laboratory.](image)

In the RoFSO system configuration two interface units are included: an optical interface unit (optical IF unit) and a RoF interface unit (RF IF unit). The optical interface unit consists of a wavelength multiplex and de-multiplex device, boost and post amplifier and an optical circulator to isolate the transmit and received signals. On the other hand, the RoF interface unit has a RoF module responsible for the electrical to optical signal conversion and vice versa corresponding to each wireless service signal under investigation.

In the current experimental setup the test signals include 3GPP cellular signals (W-CDMA signal) at 2 GHz, Wireless LAN signal (IEEE802.11g/a at 2.4 GHz and 5 GHz respectively) as well as terrestrial digital broadcasting (ISDB-T) signal at the UHF band.
Table 1: Specifications of the advanced DWDM RoFSO antenna.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating wavelength range</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Transmit power</td>
<td>100 mW (20 dBm)</td>
</tr>
<tr>
<td>Antenna aperture</td>
<td>80 mm</td>
</tr>
<tr>
<td>Coupling losses</td>
<td>±47.3 µrad</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>±47.3 µrad</td>
</tr>
<tr>
<td>Fiber coupling technique</td>
<td>Direct coupling using FPM*</td>
</tr>
<tr>
<td>WDM</td>
<td>Automatic using QPD</td>
</tr>
<tr>
<td>Tracking method</td>
<td>Rough: 850 nm beacon</td>
</tr>
<tr>
<td></td>
<td>Fine: 1550 nm</td>
</tr>
</tbody>
</table>

*FPM: Fine Pointing Mirror used for control and steering the optical beam to single mode fiber (SMF) core

3. RESULTS AND ANALYSIS

The DWDM RoFSO system performance is evaluated by measuring and analyzing the quality of the RF signals transmitted over it based on the quality metric parameters specified for transmission of the different kind of wireless service signals.

The received optical signal WDM spectrum is shown in Figure 2. The wavelengths are separated using the ITU-T Recommendation G.692 100 GHz grid spacing. The level of the wavelength carrying the terrestrial digital broadcasting signal is slightly less intentionally so as to match the best input level for the RoF receiver (−10 dBm). This level is set and controlled at the transmitter side. The received WDM spectrum shows a stable performance. The wireless services signals downlink and uplink wavelength assignments are shown in the side table above. Channel 33 is used for evaluating the RoFSO system performance in terms of BER measurements by transmitting a 2.5 Gbps optical signal.

3.1. 3GPP W-CDMA Signal Transmission

In W-CDMA system, the downlink signal transmitted by the base station is designed to fulfill the specifications set in 3GPP standard [8]. The spectral properties of the signal are measured by the adjacent channel leakage ratio (ACLR), considered to be a more stringent quality metric parameter, and is defined as the ratio of the amount of leakage power in an adjacent channel to the total transmitted power in the main channel. The 3GPP specifies one main channel and two adjacent channels. The standard requires the ACLR to be better than 45 dB at 5 MHz offset and
50 dB at 10 MHz offset. A signal generator (Agilent E4438C) is used to generate a test signal (W-CDMA Test Model 1) with a signal power of -20 dBm which is transmitted over the RoFSO link and at the receiver side a digital mobile radio transmission tester (Anritsu MS8609A) is used to measure and record the quality of the W-CDMA signal. Figure 3(a) shows a received W-CDMA signal ACLR spectrum after transmission over the 1 km RoFSO link. The spectral properties of the signal satisfy the 3GPP specified values of ACLR at the 5 MHz and 10 MHz offsets.

The variation of the measured received optical power and the W-CDMA signal ACLR characteristics is shown in Figure 3(b). Two cases are considered, i.e., first case is back-to-back measurement (B-to-B) using the RoF modules, signal generator and analyzer and an optical attenuator (HP8156A) for incrementing the attenuation to represent channel losses and in the second case actual transmission over the RoFSO link is conducted. The ACLR is measured for both 5 and 10 MHz offsets. The back-to-back actual transmission over the RoFSO system measurements shows almost similar characteristics and the minimum optical received power to satisfy the prescribed 3GPP value at 5 MHz and 10 MHz offsets is about -15 dBm. Using a post EDFA the required received optical power can be even as low as -25 dBm and -20 dBm and still satisfy the 3GPP specification for W-CDMA signal transmission at 5 MHz and 10 MHz offsets respectively.

Figure 3: (a) Received W-CDMA signal ACLR spectrum and (b) variations of ACLR and optical received power.

3.2. Terrestrial Digital Broadcasting Signal Transmission

A vector signal generator (Anritsu MG3700A) is used to output simple BER data and video waveforms for terrestrial digital broadcasting (ISDB-T) transmission evaluation. In this example the generated waveform pattern is ISDBT_16QAM_1_2 (A-Layer: 1seg, 16QAM and B-Layer: 12seg, 64QAM) with a power of -20 dBm. At the receiving site a digital broadcasting signal analyzer (Anritsu MS8901A) is used measure the quality of the received ISDB-T signal. A modulation error ratio (MER) quality metric parameter used to evaluate the modulation signal quality of the digital broadcasting signal directly and quantitatively is measured and analyzed. An example of modulation analysis constellation for the digital terrestrial broadcasting signal made of A-Layer 16QAM and B-Layer 64QAM is shown in Figures 4(a) and (b) respectively captured when the recorded average received optical power was -12.67 dBm. The constellation is very useful for analyzing the condition of the received signal by monitoring the modulation symbol movement. In Figures 4(a) and (b) the received signals exhibits little signal distortion (in terms of amplitude or frequency fluctuations) and the signal deterioration is minimal thus confirming the suitability of the RoFSO system for ISDB-T signal transmission conforming to the specified standard [9]. In this example the measurement was made in the evening under weak to moderate atmospheric turbulence conditions.

3.3. Wireless LAN Signal Transmission

Using another vector signal generator (MG3700A) an IEEE802.11g/a compliant signal waveform pattern at -20 dBm is generated and after transmission through the RoFSO link a spectrum an-
alyzer (Anritsu MS2687B) is utilized to measure and analyze the quality of the received WLAN signals. A pass/fail judgment of the spectrum mask as defined in the IEEE specification 802.11a/b/g is used. Figure 5(a) depicts a WLAN signal with spectrum mask in this case IEEE802.11g waveform at 2.4 GHz with 54 Mbps, 64QAM. The WLAN signal modulation analysis shown as a constellation graph with error vector magnitude (EVM) value is depicted in Figure 5(b). Both these figures where captured when the measured received optical power was \(-12.18\) dBm. In weak to moderate atmospheric turbulence conditions the measured EVM RMS figure is consistently within the required value demonstrating a good overall transmitter quality. The minimum optical received power is required not fall below approximately \(-12\) dBm for the quality the WLAN signal transmission to meet the specified standard.

![Figure 4: ISDB-T modulation analysis constellation (a)A Layer 1 Seg (16QAM) and (b) B Layer (64QAM).](image)

![Figure 5: WLAN (a) spectrum mask and (b) modulation analysis constellation.](image)

4. CONCLUSION

Simultaneous transmission of different kinds of wireless services using a newly developed advanced DWDM RoFSO system has been presented. The system performance in terms of the specified quality metric parameters for cellular W-CDMA, terrestrial digital broadcasting (ISDB-T) and
WLAN signals has been evaluated. In weak to moderate turbulence conditions as well as absence of severe weather conditions, we have demonstrated that the DWDM RoFSO system is suitable for deployment as universal platform for providing ubiquitous wireless services.

Further experiments are ongoing to collect measurement data required for a comprehensive and statistical analysis of the system performance in different weather conditions.

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REFERENCES