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New Investigation of Image Transmission using Radio over Fiber System

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ABSTRACT

In this study, the feasibility of image transmission over Radio Over Fiber (ROF) system using Coded Orthogonal Frequency Division Multiplexing (COFDM) is presented. The performance analyses based on Bit-error Ratio (BER) are extensively investigated. In addition, the effect of fiber length on the image quality is introduced. Moreover, the effect of the exponent refractive index profile of the Multimode Fiber (MMF) on the BER of COFDM is studied. Consequently, both Peak Signal to Noise Ratio (PSNR) and Mean Square Error (MSE) of the received image are evaluated. Moreover, the measured multimode fiber link is included in the analysis to investigate the image quality and its BER.

Key words: Bit error rate, coded-orthogonal frequency division multiplexing, optical fiber, radio over multimode fiber, image transmission, signal to noise ratio

INTRODUCTION

The increasing demand for multiuse-multimedia services and broadband convergence to combine voice, data, images, videos and automated applications in a single device has led the Radio over Fiber technology (ROF) to become a feasible technology. The ROF technology has some virtues such as reliability, relatively low attenuation loss, a good potential for cost and large affordable information capacity. These features have made ROF an attractive solution for future broadband wireless data networks (Kim *et al.*, 2003). In particular, Radio over Multimode Fiber system (ROMMF) has gained much attention recently for its suitability to deliver high purity signals in analogue and digital format for short-reach coverage such as Wireless Local Area Networks (WLANs) and Ultra-wideband (UWB) radio signals (Guennec *et al.*, 2009).

Since Orthogonal Frequency Division Multiplexing (OFDM) is widely used today in many applications, such as Digital Audio Broadcasting (DAB), High Definition TV (HDTV) and ROF technology and many other examples, a considerable attention has been given to OFDM as one of the favourable modulation schemes for next generation systems. In ROF, OFDM impact has been demonstrated with multimode fiber (MMF) as a capable modulation scheme for mitigating the modal dispersion penalty (Dixon *et al.*, 2001). OFDM is efficient in utilizing the system bandwidth (up to 1.98 Bd/Hz) because it has a high spectral efficiency (Hanzo and Keller, 2003). OFDM is inherently able to transfer a frequency selective fading channel into a number of flat fading sub-channels. However, inserting cyclic prefix between subcarriers relaxes the Intersymbol Interference (ISI) which can destroy the orthogonality among subcarriers (Zou and Wu, 1995).

By implementing coding and interleaving across the sub-carriers, the effect of multipath-fading can be tailored since interleaving rearranges the number of bits in such away to avoid the effects of fading. Convolutional coding is being used commonly in OFDM systems and it can give coding gain at different coding rates (Hanzo and Keller, 2003; Prasad, 2004). Therefore, coded-OFDM (COFDM) makes the transmitted signal robust to multipath fading and distortion.

MMF is being used for short distance applications; it is typically a popular choice for in-building networks. MMF has better coupling efficiency with an optical source due to large diameter and enabling low cost electro-optic devices that can be incorporated in the ROF system such as VCSEL (Das *et al.*, 2006; Gomes *et al.*, 2008). In addition, it is cheaper than Single Mode Fiber (SMF) since it has lower installation and maintenance costs. Thus, a wide selection of services with different signal characteristics such as fast and gigabit Ethernet, video, audio and control signals are likely to be supported by MMF within a range of a few kilometers (Sauer *et al.*, 2007). As a low cost route, MMF is an attractive and cost-effective solution for transporting multiple services. However, the signal propagation through MMF suffers from attenuation and time spread of the transmitted signal. The latter is caused basically by material dispersion and modal dispersion. Dispersion causes pulse spreading as the pulse propagates along the fiber which limits the information carrying capacity of an optical fiber and is determined by bandwidth-distance product which typically is measured in bandwidth-distance product (MHz km). In contrast to SMF, modal dispersion exists in MMF due to the large number of fiber modes being propagated inside the core of MMF. The modal dispersion is a result of the different group velocities (leading to different group delays) of the large number of modes that the fiber allows to propagate. The effect of modal dispersion is considerably reduced (but not totally removed) by the use of graded index MMF (GI-MMF) fiber, which can, to a great extent, equalize these group velocities by varying the refractive index of the fiber as a function of the radial distance from the core centre (Yabre, 2000).

The research effort towards modelling of ROF using OFDM and electro-optic modulator has been recently reported (Song and Islam, 2008) using SMF. Very recently, an interesting and useful study of the transmitting OFDM over MMF has been carried out and the corresponding BER results has also been reported (Matarneh and Obayya, 2011). In this study, a comprehensive modelling study of OFDM transmission over MMF is used to investigate the multimedia transmission. In particular, this model is used to test the quality of image transmission/reception. In the context of this work, the dispersion and losses of MMF have been accurately taken into account by adopting the transfer function model of MMF proposed (Matarneh and Obayya, 2011; Gasulla and Capmany, 2006). It is analytical models which can be easily incorporated into the system model and accurately consider the nonlinearity effects of MMF. Moreover, the effect of fiber length and the exponent refractive index profile (α) on the image quality have been investigated. The theoretical findings of the modelling study have also been supported by measurements taken from our experimental setup of this system.

This study takes into account the nonlinearity effects and signal degradation of MMF for the investigations of image transmission over fiber and employing COFDM. The performance analyses in terms of BER analyses are discussed in detail. Furthermore, the measured MMF response is included in the analysis for BER simulation. Both Peak Signal to Noise Ratio (PSNR) and Mean Square Error (MSE) of the received image are evaluated and presented against fiber length and exponent refractive index profile (α), respectively. The conclusions are then drawn.

ROF-COFDM MODEL

The system implementation process of COFDM is described as follows:

- The data bits are encoded by a conventional encoder with a code rate 2. The encoded bits are bit-interleaved and then mapped into in-phase and quadrature components of the complex symbol using gray-coded mappings. Then, the complex symbols are modulated by OFDM
- The MMF channel is assumed to be stationary channel for, at least, transmission of one COFDM symbol. Also, the noise is assumed to be a complex Additive White Gaussian Noise (AWGN). At the receiver, each modulation symbol could be recovered by using one-tap frequency domain equalizer (Tosato and Bisaglia, 2002). The decoding process employs the soft-decision Viterbi decoding algorithm. Table 1 summarizes COFDM parameters (Matarneh and Obayya, 2011)

In the following analysis, Quadrature Amplitude Modulation (QAM) is used to modulate the COFDM subcarriers for the BER simulation. The advantage of using convolution coding with Soft/Hard-Viterbi decoding with OFDM has been reported in the literature. It has shown that more than 3 dB of the signal to noise ratio is saved to achieve the BER of 10^{-6} when employing coding (Matarneh and Obayya, 2011).

SYSTEM SIMULATION

The block diagram of the ROMMF system used for analysis and simulation is shown in Fig. 1. In this system the COFDM signal generated out of the OFDM transmitter at the carrier frequency was directly injected into the Laser Diode (LD) at desired signal level with dc-biasing that is well above the laser threshold. The optical intensity signal out of the laser diode is fed into a MMF followed by a photodetector (PD). The received COFDM signal will be equalized, demodulated and decoded to get back the data. This system can be used for analyzing the performance of the image transmitted over fiber. The image data bits are transmitted through the COFDM-ROF described above and the received data bits are then compared with the transmitted data bits, the performance evaluation is carried out by the bit error rate, PSNR and MSE.

Table 1: COFDM parameters

Parameter	Value
Code rate	1/2
Generator polynomials	133_8[1]
	171_8
Constraint length	7
No. of OFDM data subcarriers (N_c)	200
Subcarrier spacing (MHz)	0.84

[1]The generator polynomial values are octal No. 8

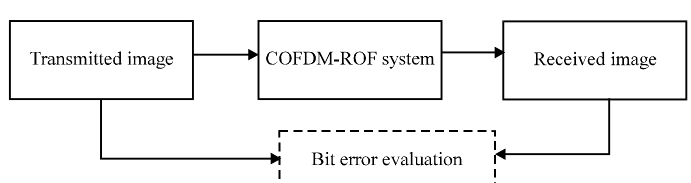

Fig. 1: Demonstration of image transmission over ROF system

Next, the analytical form of the system model by considering the transfer function of the MMF system which has been presented (Gasulla and Capmany, 2006; Capmany and Gasulla, 2007) based on the electric field propagation through MMF using Eq. 1:

$$H(\omega) = \sqrt{1 + a_c^{\ 2}}\ e^{\frac{-1}{2}\left(\frac{\beta_0^2(\omega Z)}{\sigma_c}\right)^2} \text{Cos}\left(\frac{\beta_0^2 \omega^2 Z}{2} + \arctan(\alpha_c)\right) \sum_{v=1}^{M} 2v(C_{vv} + G_{vv})\ e^{-2 a_v z}\ e^{-j\omega\tau_v} \quad (1)$$

In the above equation, Z is the fiber length and $\beta^2{}_0$ is the second-order chromatic dispersion parameter which is equivalent to the second derivative of the propagation constant β_v and is assumed to be equal for all the fiber modes. α_v is the fiber attenuation and α_v is the chirp parameter, ω is RF angular modulation frequency, $\sigma_c = 1/(\sqrt{2}\,W)$ is the optical source RMS coherence time and W is the source RMS line width, it is assumed that an optical source has a finite line width spectrum with a Gaussian time domain autocorrelation function, v is the mode group number, C_{vv} and G_{vv} are coupling and uncoupling fiber mode coefficients, respectively, their equations can be found (Gasulla and Capmany, 2006) and τ_v is the group delay corresponds to v-group. Table 2 summing up the MMF fiber used in the simulation (Matarneh and Obayya, 2011).

In this study, COFDM transmission over MMF is used to test the quality of image transmission/reception. As a benchmark image, Lena image will be used for this investigation which is shown in Fig. 2. The transmitted image quality is evaluated by both MSE and PSNR which are computed using Eq. 2 and 3, respectively (Al-Sbou, 2012):

$$MSE = \frac{1}{m\,n}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j) - K(i,j)]^2 \quad (2)$$

$$PSNR = 10.\log_{10}\left(\frac{MAX^2}{MSE}\right) \quad (3)$$

where, I and K are the original and the distorted images, respectively. m and n are the number of pixels in both images (dimensions of the images) and MAX equal to the maximum possible pixel value (in our case it is 2^8-1 = 255 for 8-bit images).

Table 2: MMF parameters

Parameter	Value
Laser source RMS line width (MHz)	10
Fiber dispersion parameter [psec/(nsec km)]	-94
Fiber attenuation (α_0) (dB km^{-1})	1.25
Wavelength (λ) (nm)	850
Core refractive index (n_1)	1.46143
Clad refractive index (n_2)	1.45274
Material group index (N_1)	1.47517
refractive index contrast (Δ)	0.00595
Core diameter (a) (μm)	62.5
Laser chirp (a_c)	0

PSNR is the ratio between the reference signal and the distorted signal in an image, measured in decibels. Generally, the higher the PSNR, the closer the noisy image is to the original. MSE is the mean squared discrepancy between a reference image and a distorted image. It is computed pixel-by-pixel by summing up the squared differences of all the pixels and dividing by image size. Both MSE and PSNR are very widely used in image quality assessment (Wang *et al.*, 2004).

RESULTS

Performance results are presented in terms of BER for the 16-QAM-COFDM system. The information data of the image bits is encoded with a rate-1/2 convolutional coder. The block interleaver with interleaver depth equal to one OFDM symbol has been selected to exploit the available frequency diversity.

The measured frequency response of MMF is shown in Fig. 3 (Matarneh *et al.*, 2008), using lightwave component analyzer (8703A) for 3 m and 800 m fiber length, respectively. The type of MMF is a Graded Index (GI) with 62.5/125 Fm core/clad diameter. The laser source is a Vertical Cavity Surface Emitting Laser (VCSEL) and directly coupled to the MMF. It can be observed from Fig. 3 that the flat response is shown to appear clearly in the passband region

Fig. 2: Lena image used as a test image

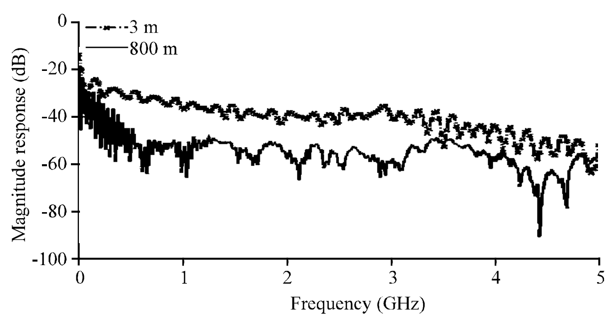

Fig. 3: Frequency response of the GI-MMF at fiber length 3 and 800 m

(i.e., beyond 3 dB bandwidth) for 3 m and 800 m fiber, it is therefore possible to transmit multi-channel data at carrier frequencies much greater than the of 3-dB bandwidth of MMF.

The measured MMF response is included in the simulation of BER of 16QAM-COFDM system. The number of equally-spaced subcarriers (N_c) is chosen as 200 around the channel center frequency 3 GHz with subcarrier frequency equal to 0.84 MHz and equivalent data rate 168 Mbps. It can be shown from Fig. 4 that for the measured response with 800 m length, E_b/N_0 degrades by more than 1.5 dB than the measured response with 3 m length at BER of 10^{-6}. The received image for different E_b/N_0 is presented in Fig. 5.

According to Matarneh and Obayya (2011), the optimum value of α (α_{opt}) for the frequency response at 850 nm wavelength is found to be 2.089, whilst for 1300 nm is 1.9377. It is worth mentioning that at the optimum profile of the refractive index, the delay spread is at minimum leading to the dispersion being at minimum. Figure 6 depicts the BER evaluations for different values of α. It shows that the BER increases as α moves away from its optimum value. Compared with α close to the optimum value (i.e., $\alpha = 2.15$ and $\alpha = 2.089$), around 2 dB is required to achieve the same BER at $\alpha = 1$. As a result, increasing α leads to more degradation of the system performance. By further increase of α (α>25) the refractive index profile becomes approximately constant and therefore, the fiber tends to be as step-index (SI) mode profile. Consequently, the expense of achieving the required BER becomes higher due to an increase in modal dispersion. It is clear that the best performance is achieved using MMF with α optimum. However, practical MMF is designed and fabricated with nearly parabolic shape (i.e., α~2).

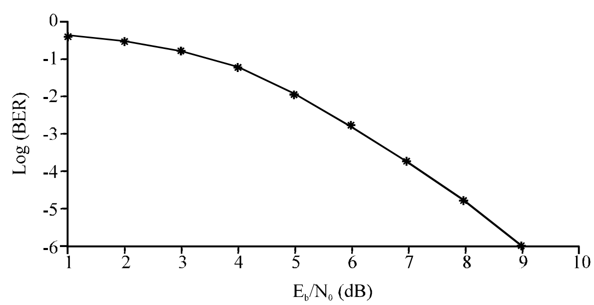

Fig. 4: BER against E_b/N_0 for 16QAM-COFDM transmission over measured 800 m-MMF

Fig. 5(a-b): Received image with fiber length = 800 m and E_b/N_0 of (a) 7 and (b) 9 dB

The impact of the fiber length on the system performance is displayed in Fig. 7 with N_c equal to 200-COFDM subcarrier spaced equally by 0.84 MHz with and equivalent data rate 168 Mbps and modulated by 16-QAM. The received signal was equalized by a conventional one-tap frequency optimum value of exponent refractive index domain equalizer. It can be seen that there is no significant degradation of BER until the fiber length becomes greater than 10 km due to the considerable COFDM tolerance of modal dispersion. The degradation is much more pronounced for fiber length longer than 12 km. It thus appears that for fiber length = 12 km the system performance is inferior to that at 1 km fiber length by about 4.2 dB. After that, the signal distortion cannot be tackled due to the significant increase in modal dispersion and the signal amplification becomes necessary to compensate for losses and to be able to recover the image with acceptable quality.

Figure 8 depicts the PSNR versus fiber length for fixed α = 2.3. It is shown that the PSNR deteriorates with increasing the fiber length; the significant decrease of the PSNR can be clearly seen after 10 km of the fiber length. Hence, image quality will be very low. To overcome this low quality issue, the E_b/N_0 needs to be increased which results in few dB penalty.

Figure 9 describes the MSE versus fiber length for fixed α = 2.3. It can be seen that MSR increases with fiber length. It emphasized that increasing the fiber length is reflected negatively on the image quality. Therefore, it is well recommended that, under prescribed system parameters, the fiber length should not be greater than 10 km in order to receive the image with acceptable quality as shown in Fig. 10.

In order to investigate the PSNR response with respect to α, the fiber length is kept fixed at 3 km. an Example of this can be readily seen regarding PSNR in Fig. 11. Around 3 dB of the PSNR

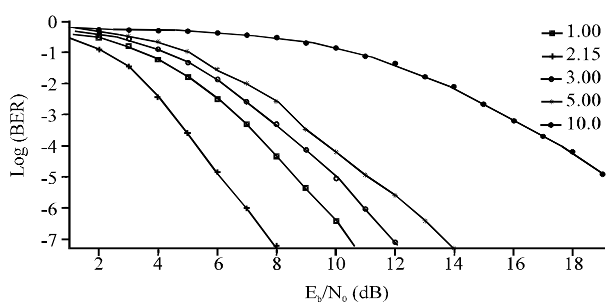

Fig. 6: BER against E_b/N_0 for 16QAM-COFDM with different values of α, z = 3 km

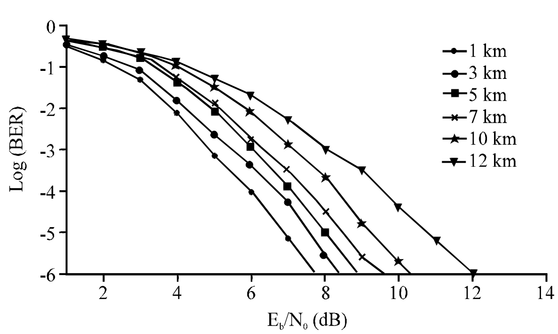

Fig. 7: BER against E_b/N_0 for 16QAM-COFDM with different values of α, z = 3 km

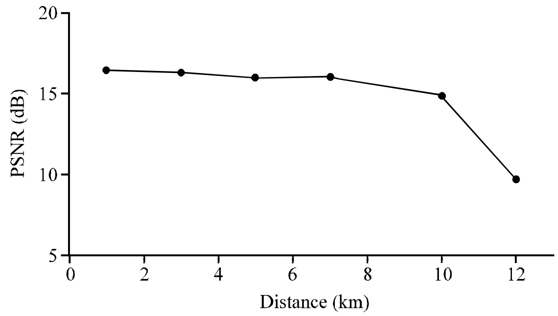

Fig. 8: PSNR vs. fiber length for fixed α = 2.3

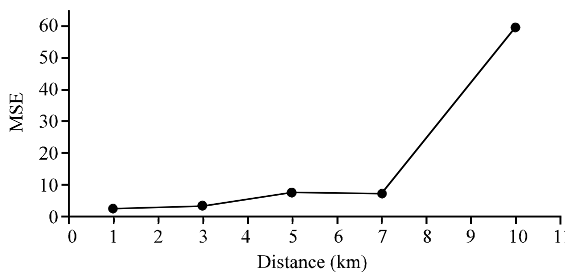

Fig. 9: MSE vs. fiber length for fixed α = 2.3

Fig. 10(a-b): Received image with E_b/N_0 = 10 dB α = 2.3 and fiber length of (a) 10 and (b) 12 km

improvements are achieved by changing the value α from 1 to be close to the optimum value of α (α = 2.089 at 850 nm). Having maintained the core profile of MMF close to the optimum, the image quality is enhanced considerably. Moreover, the MSE is presented in Fig. 12; the minimum MSE is observed when the fiber is fabricated close to the optimum α, any deviation away from the optimum α would result in a significant increase of the MSE. MSE becomes larger when α gets larger and farther than from optimum α, as illustrated in Fig. 13.

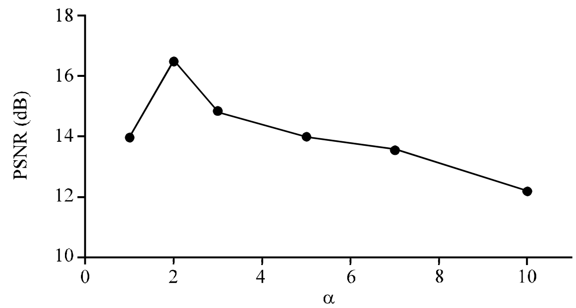

Fig. 11: PSNR vs. α with fixed fiber length 3 km

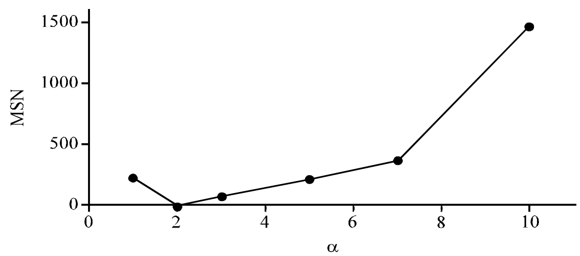

Fig. 12: MSE vs. α with fixed fiber length 3 km

Fig. 13(a-b): Received image with E_b/N_0 = 9 dB, fiber length = 3 km and α, (a) 2 and (b) 10

CONCLUSIONS

Image transmission over ROF system has been presented and the BER evaluation of ROMMF system using COFDM has been introduced. The system model incorporated all the nonlinearities and signal degradation imposed by ROF system. Both the effect of MMF length and the exponent refractive index profile have been taken into account as well as the measured MMF response. The simulation results characterized by the BER, PSNR and MSE show that increasing the length of MMF degrades the system performance and consequently the image quality even though with efficient use of COFDM due to dispersion and losses. However, for short-distance applications, COFDM can be used efficiently for high data rate signal delivery and to tolerate the effect of modal dispersion. Also, the exponent refractive index profile effect has been studied and shown that the best performance can be achieved near the profile. Further work is now under processing to consider an accurate nonlinear laser model into the ROMMF system model and to investigate the overall system performance under different types of multimedia transmission.

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