MZ변조기를 이용한 ROF링크에서 OFDM신호의 비선형왜곡 효과

정회원 A.H.M. Razibul Islam*, 송 주 빈*

Nonlinear Distortion Effects of OFDM Signals in a Radio over Fiber Link Involving in a Mach-Zehnder Modulator

A.H.M. Razibul Islam*, Ju Bin Song* *Regular Members*

요 약

Radio over Fiber(ROF) 채널에서의 비선형효과는 시스템의 성능을 감소하는 주요 원인 중에 하나이다. 특히, 휴대인터넷 및 고속무선통신에서 Orthogonal Frequency Division Multiplex(OFDM) 방식이 주로 사용되는데 이 신호가 ROF 링크를 통하여 전송될 때 전체 시스템의 성능을 충족하여야 한다. 본 논문에서는 Mach-Zehnder (MZ) 변조기를 사용한 5.8GHz의 OFDM 신호기반 RoF 링크의 비선형효과를 해석하였다. OFDM-RoF 시스템의 평균자승오차 성능을 구하였다. 변조 왜곡된 후 RoF 링크에서 단일 캐리어에 대한 평균자승오차 성능과 SNR이 20dB로 고정된 경우 왜곡이 없는 OFDM신호를 사용한 경우의 평균자승오차 성능을 비교 검증하였다. OFDM-RoF 링크를 선형화하기 위하여 offset 바이어스 등 pre-distortion기술을 사용하였다. Pre-distortion기술에 따른 distortion-free dynamic range 및 SNR의 성능결과를 비교하였다.

Key Words : Nonlinear Distortion Effects, Rof Link, Ofdm Signals, Bcn

ABSTRACT

The performance of ROF systems can be severely degraded due to nonlinear effects in the channel. Also, Orthogonal Frequency Division Multiplex(OFDM), as a standard for broadband wireless and mobile internet networks, is being proposed for deployment with ROF systems to facilitate the total performance of a system. In this paper, at first, the performance of the OFDM-based RoF system with a Mach-Zehnder(MZ) modulator distortion effects has been analyzed at 5.8 GHz. Evaluation of mean-squared error of the proposed OFDM-RoF system was carried out to compare with the conventional single carrier system based RoF link after the modulator distortion case and also for fixed signal to noise ratio(SNR) of 20 dB using undistorted OFDM signal. Nominal and offset baising pre-distortion techniques are applied in proposed system to linearize the OFDM-RoF link. Finally, a comparison between the aforementioned pre-distortion techniques applied showed important observation in terms of distortion-free dynamic range and SNR to choose offset pre-distortion technique for our proposed system.

I. Introduction

Due to high Peak to Average Power Ratios (PAPR), nonlinear distortion effects have become an important parameter to consider for OFDM[1]. However, OFDM proved its robustness against

* 경희대학교 전자정보대학 통신연구실 (jsong@khu.ac.kr)
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time-dispersive impairments such as multi-path fading and impulsive interference combined with a spectral efficiency that rivals single carrier systems. So, these factors have eventually led OFDM to be a universally-adopted modulation schemes for broadband wireless deployments.

For broadband fixed-point wireless access systems, RoF is a proposed solution for alternative network architecture[1]. RF technology is appropriate to interconnect control stations(CS) and base stations (BS) in these recently proposed wireless networks, thereby allowing the concentration of complex equipments in the CS and the simplification of CS[2]. Optical modulators are the primary sources of nonlinear distortion in RoF links. Mach-Zehnder modulator used in many analog optical links causes a highly deterministic non-linearity. Since OFDM is subjected to high PAPR, it is of particular interest to observe the effects and suitability of OFDM in an OFDM-RoF linked system.

Previous research demonstrated the congeniality of RoF for the transmission of single-carrier and spread spectrum signals[3, 4]. Therefore, similar experimentation is required for OFDM whether it performs similarly in a RoF link using Mach-Zehnder modulator under nonlinear distortion effects than that of single carrier systems, particularly in IEEE 802.11a wireless LAN standard.

Also, the distortion effects can be mitigated using suitable pre-distortion techniques in an OFDM based RoF link and thus the system performance can be improved in terms of increased distortion-free dynamic range and SNR. Previous research only concentrated on the OFDM system to evaluate performance by applying PAPR reduction techniques or pre-distortion techniques as in[5, 6] and did not consider an OFDM based RoF link to assess similar performance.

In this paper, the performance is simulated for an OFDM-RoF system at 5.8 GHz to observe the non-linear distortion tolerance of OFDM signal on a link using Mach-Zehnder modulators in terms of mean-squared error(ME). After that, the results are compared with the single carrier based RoF link systems. Then, nominal and offset biasing pre-distortion techniques are applied on OFDM-RoF links and compared with the original system without applying pre-distortion techniques to finally decide an efficient optical interconnected wireless system.

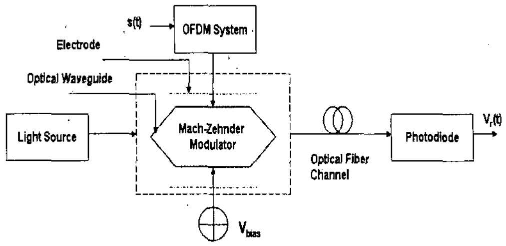

Figure. 1. System Model

Ⅱ. System Modeling

Consider a single OFDM symbol

$$s(t) = \sum_{n=-N/2}^{N/2-1} d_n \cos((\omega_c - n\Delta\omega)t + \theta_n) \tag{1}$$

where N is the number of subcarriers separated from each other by $\Delta\omega$ and centered at ω_c. d_n and θ_n are respectively the magnitude and phase of n subcarriers.

The OFDM signal $s(t)$ is transmitted over an optical link as shown in Figure1. The electrical signal i.e. OFDM signal is used to modulate the intensity of light to be used in the fiber channel. This electro-optic (E/O) conversion can be accomplished in two ways: by directly modulating the intensity of the light source or by using a constant-intensity source followed by an external modulator.

Because OFDM has large peaks due to its high PAPR and is normally used at RF center frequencies above 5 GHz, external modulation e.g. Mach-Zehnder modulator is preferred for the transmission of the standard OFDM signals of interest. A block diagram of the proposed system is shown in Figure 1.

The detected power after the signal has travelled through a length L_f of fiber is[7]

where D is a dispersion parameter usually expressed in units of ps/(nm-km), λ_0 is the wavelength of the optical source, and c is the speed of light in free space.

$$P_0(L_f)_{dB} \,\alpha\, 10\log\left\{\cos^2\left(\frac{\pi D L_f \lambda_0^2 f_c^2}{c}\right)\right\} \tag{2}$$

For the 1550nm wavelength optical fiber, the fiber attenuation ranges from 0.3 dB/km to 0.5 dB/km for fiber lengths up to 80 km. For the OFDM based RoF link in our model, the loss due to fiber attenuation would be no more than 3 dB assuming the base stations in the central offices will not be located more than 5 to 6 km from the remote stations. Therefore, it is insignificant in comparison to the large losses expected in the wireless components of the channel and is not considered in our model therefore.

In this paper, only power gain G_{fiber} was assumed for the fiber without considering other distortions of the fiber and therefore at the input of the PD the optical power becomes

$$P_{0,r}(t) = G_{fiber} P_{0,t}(t) \tag{3}$$

Here, $P_{0,t}(t)$ is the optical output of the Mach-Zehnder modulator.

Disregarding all noise in the link, the received signal generated by a photodetector (PD) driving a load of R_L ohms is[2]

$$v'_r(t) = R_L(R_{PD} G_{fiber} P_{0,t}(t) + N_r(t)) \tag{4}$$

where R_{PD} is the responsivity of the PD expressed in units of amps/watt (A/W), $N_r(t)$ is the noise in the received optical signal arising from relative intensity noise and other sources as well as noise generated at the PD itself and R_L is the load at PD. PD noise sources include thermal noise, shot(or quantum) noise, dark current and surface leakage current.

The relationship between the electric field E_{in} of the lased light input to the Mach-Zehnder modulator and the output electric field E_{out} is[8]

$$E_{out} = E_{in}\cos\left(\pi\frac{\hat{v}}{V_\pi}\right)\exp\left(j\pi\frac{\bar{v}}{V_\pi}\right) \tag{5}$$

where $\hat{v} = \dfrac{v_1(t) - v_2(t)}{2}$ and $\bar{v} = \dfrac{v_1(t) + v_2(t)}{2}$.

Here, $v_1(t)$ and $v_2(t)$ are the time-varying electrical signal applied to each electrode, V_π is the extinction voltage of the modulator and a constant bias voltage is applied to one electrode which is for RoF applications expressed as

$$V_{bias} = \frac{K V_\pi}{2} \tag{6}$$

Here, K is an integer.

Since the power of an electromagnetic(EM) wave is proportional to the square of the magnitude of its electric field, the optical power at the output of the Mach-Zehnder modulator is

$$\begin{aligned} P_{0,t}(t) &\,\alpha\, \left|E_{out}^2\right| \\ &\,\alpha\, E_{in}^2 \cos^2\left(\pi\frac{\hat{v}}{V_\pi}\right) \end{aligned} \tag{7}$$

When a Mach-Zehnder modulator is optimally biased and driven by complementary small-signal inputs, substituting Equations (5) and (6) into Equation (4) gives the electrical output of the link as a function of the electrical input as

$$\begin{aligned} v'_r(t) &= \left(K_1\left(\cos\left(\pi\left(\frac{2s_i(t)}{V_\pi} - \frac{1}{2}\right)\right) + 1\right) + N_r(t)R_L \\ &= \left(K_1\left(\sin\left(2\pi\left(\frac{s_i(t)}{V_\pi}\right)\right) + 1\right) + N_r(t)\right)R_L \end{aligned} \tag{8}$$

Here K_1 is the proportionality constant. By ac coupling, dc offset can be removed and the final expression can be written as

$$v_r(t) = K_1\left(\sin\left(2\pi\left(\frac{s_i(t)}{V_\pi}\right)\right)\right) + N_r(t)R_L \tag{9}$$

Thus, $s(t)$ is transmitted to the analog RoF link which uses a Mach-Zehnder modulator and finally expanding the sin term of Equation(9) into Taylor series, the electrical output of the optical link becomes

$$\begin{aligned} v_r(t) &= K_1(\pi(\frac{2s_i(t)}{v_\pi}) - (\pi(\frac{2s_i(t)}{v_\pi}))^3/3! + (\pi(\frac{2s_i(t)}{v_\pi}))^5/5! - .... \\ &+ (-1)^n(\pi(\frac{2s_i(t)}{v_\pi}))^{(2n+1)}/(2n+1)! + ...) + R_L N_r(t) \\ &= K_2 s_i(t) + P_{NL}(t) + R_L N_r(t) \end{aligned} \quad (10)$$

$K_2 = (2K_1\pi)/v_\pi$ and $P_{NL}(t)$ is the nonlinear distortion contributed by all of the terms in the Taylor expansion of order greater than unity.

The system output as found in Equation(10) will now be used to determine the distortion effects in terms of mean-squared error(ME) and also pre-distortion functions will be applied to mitigate the distortions. In each case, the simulation results are followed with discussion to analyze the performance.

Ⅲ. Compared ME Performance

3.1 ME calculation

As mentioned previously, a square-law PD together with a Mach-Zehnder modulator is considered in the RoF system to observe the effects of optical link nonlinearities in terms of ME on an OFDM signal. Later on, a single carrier time domain signal is used on similar RoF system to compare and finally determine the performance of OFDM's high PAPR in the presence of optical link nonlinearities.

The distorted output signal of Equation(10) is used for the computer simulation. Input SNR is kept fixed and the average carrier amplitude $C_{carrier}$ of OFDM input signal $s(t)$ is sent through a range of levels.

The ME of one OFDM symbol's normalized constellation can be expressed as

$$ME = \frac{1}{N}\sum_{k=0}^{N-1}|EVM(k)|^2 \quad (11)$$

where $|EVM(k)|$ is the error vector magnitude and

$$|EVM(k)| = |d_r(k) - d_t(k)| \quad (12)$$

Here, k is the subcarrier index and $d_r(k)$ and $d_t(k)$ are the received and transmitted data symbols respectively.

The modulation index of Mach-Zehnder modulator which can be expressed as

$$\Gamma_{MZM} = \frac{C_{carrier}}{(v_\pi/2)}. \quad (13)$$

3.2 Simulation and results

Using the equations for ME and modulator index as in (11) and (13), the performance of the proposed system is compared with the single carrier based RoF link to finally evaluate the distortion experienced in our proposed system. The simulation parameters used in this simulation are listed in Table 1 shown. Initially, signal degradation due to Mach-Zehnder in terms of ME is plotted in Figure 2 against modulator index for OFDM signal based RoF link in our system.

The dashed line in the plot represents constellation ME of undistorted signal with an SNR of 20 dB. From the Figure 2, it is clear that the modulation indices increase due to increase in Γ_{MZM}. Eventually after unity value of Γ_{MZM}, it exhibits change at a rate that is function of both modulation index and the instantaneous amplitude at that particular instant. So, the average amplitude increases with higher PAPR as the modulation index and the instantaneous amplitude are based on average amplitude.

A time domain single carrier 16-QAM signal is used replacing OFDM signal under similar environment with using raised cosine filtering to allow the signal occupy the same bandwidth as OFDM signal. The plot is shown in Figure 3 in this case. The undistorted ME in this case is 9.2×10^{-4} shown by the dashed lines in the plots which was previously 1.6×10^{-3} in the OFDM signal case as in Figure 2. Also, the slope of the time-domain curve at unity value of Γ_{MZM}, increases in this case unlike in the OFDM case.

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Table 1. Simulation Parameters

Parameter	Value
OFDM Data Rate	12 MSymbol/s
Number of Subcarriers	64
Carrier Frequency	5.8 GHz
Subcarrier Frequency Separation	312.5 KHz
Voltage Extinction Ratio of Mach-Zehnder Modulator	4.5 V
Fiber Path Loss	0.5 dB/km
Fiber Length	5 km- 6 km
Responsivity of the Photo Detector	1 A/W
Photo Detector Load	50 Ω

the signal occupy the same bandwidth as OFDM signal. The plot is shown in Figure 3 in this case. The undistorted ME in this case is 9.2×10^{-4} shown by the dashed lines in the plots which was previously 1.6×10^{-3} in the OFDM signal case as in Figure 2. Also, the slope of the time-domain curve at unity value of Γ_{MZM}, increases in this case unlike in the OFDM case.

In the presence of Mach-Zehnder modulator distortion, frequency domain equalization techniques seem to the reason for OFDM to show superior performance than the single carrier case. Pre-distortion techniques now will be employed to better performance of OFDM systems.

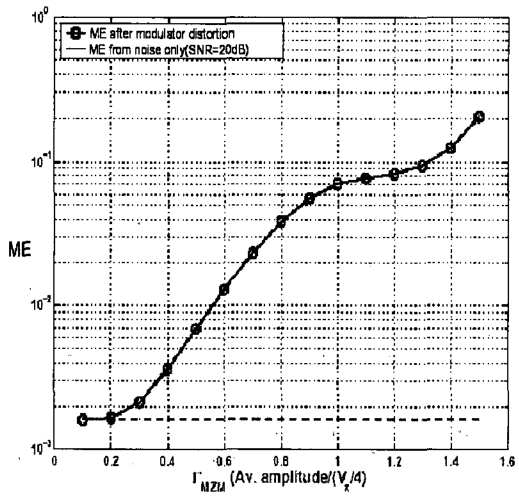

Figure 2. Mach-Zehnder modulator distortion on OFDM signal

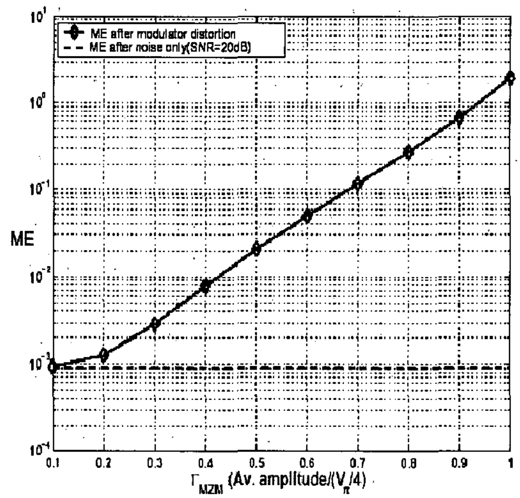

Figure 3. Mach-Zehnder modulator distortion on single carrier signal

Ⅳ. Compared Pre-distortion Techniques

4.1 Pre-distortion function

Generally, to mitigate the non-linear distortion, pre-distortion techniques are used. Hence, in our proposed system, a pre-distortion function $f_{pre}(V)$ is applied to the optical link input voltage to linearize the link and thus to produce a pre-distorted Mach-Zehnder modulator input voltage

$$V_{MZ,\,pre} = f_{pre}(V) \tag{14}$$

The output of the pre-distortion function is hard-limited so that $|V_{MZ,\,pre}| = V_{in,\,peak}$. Otherwise, transfer function of the Mach-Zehnder modulator would cause the output to decrease in response to the increase in V_{in}. So, after applying hard-limiting and letting $V_{in,\,peak} = |V_{in}|_{\max}$, the pre-distortion function can be written as,

$$\begin{aligned} f_{pre}(V) &= \frac{v_\pi}{\pi}\sin^{-1}\left(\frac{2SI_{lin}V_{in}}{P_{o,L}}\right) && |V_{in}| \le V_{in,\,peak} \\ &= -V_{in,\,peak} && V_{in} < -V_{in,\,peak} \\ &= V_{in,\,peak} && V_{in} > V_{in,\,peak} \end{aligned} \tag{15}$$

The pre-distortion function of Equation(15) is used to the OFDM input signal for the computer simulations before the input signal is distorted by Mach-Zehnder modulator. The performance of the pre-distorted signal is then compared with the signal which was not subjected to pre-distortion i.e. original signal which is modulated without any pre-distortion.

In order to exploit better pre-distortion techniques, the experiments were done under nominal biasing and offset biasing pre-distortion techniques. In the nominal biasing technique, the Mach-Zehnder modulator is biased at $V_{bias,nom} = \frac{V_\pi}{2}$. In this particular point, the transfer function of the modulator exhibits linear behaviour and thus provides the best power efficiency. In the later offset biasing technique, $V_{bias,off}$ is set to zero to hard-clip the signal at its original level. In this approach, the main intention is to clip the passband signal at dc level so that the signal is recovered without any distortion by applying a band-pass filter to remove all out-of- band distortions [8].

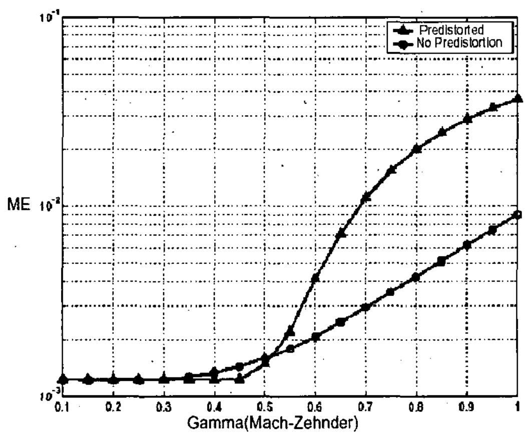

Figure 4. Mean Square error curves using nominal Mach-Zehnder modulator biasing technique

In each technique, no noise was taken into account in the simulations to observe the effects of the pre-distortion techniques on the system.

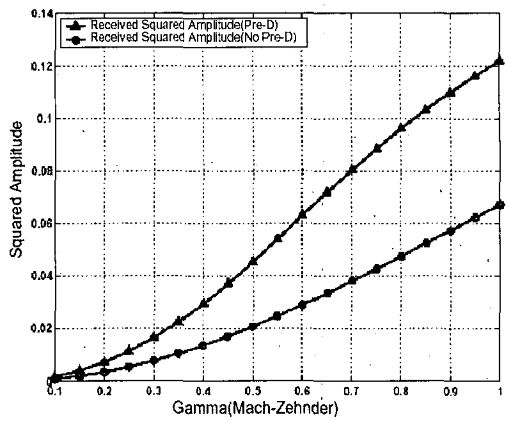

Figure 5. Received squared amplitude power at nominally biased point

4.2 Simulation and results

Figure 4 shows the results for the nominally biased pre-distorted signal with the original signal without any pre-distortion. Similar results are shown in Figure 5 for offset biasing technique.

For lower values of Γ_{MZM}, as can be seen from Figure 4, both curves remain constant at a value near to 10^{-3}. For the original signal, constellation degradation starts due to Mach-Zehnder modulator distortion effects at a value near to $\Gamma_{MZM} = 0.4$.

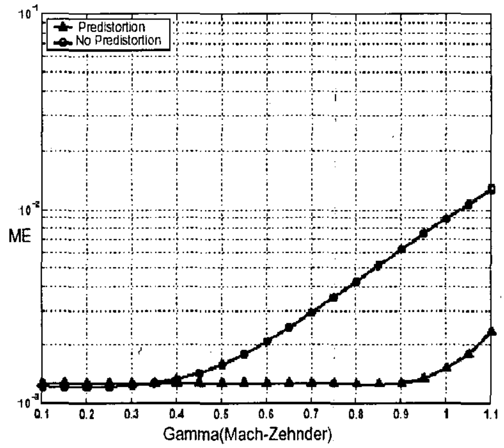

Figure 6. Mean Square error curves using offset Mach-Zehnder modulator biasing technique

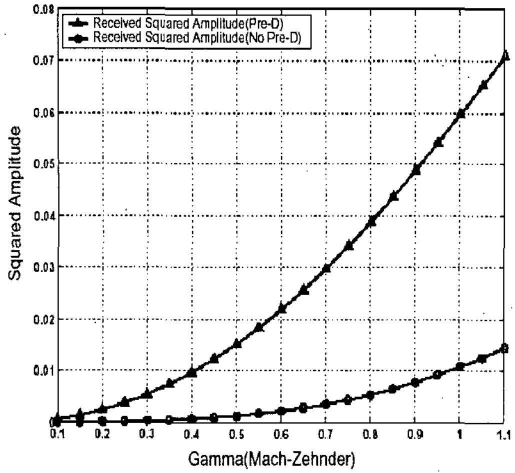

Figure 7. Received squared amplitude power at offset biased point

For the pre-distorted one, degradation starts from Γ_{MZM} = 0.45. For values greater than Γ_{MZM} = 0.5, ME for pre-distorted curve rapidly exceeds than that of original signal curve. The small improvement is therefore observed using the pre-distorted curve in the range of Γ_{MZM} = 0.35 to 0.5, which is not of that much use to mitigate the mean-square error experienced due to Mach-Zehnder modulator nonlinear distortion. If the dc component is removed from the receiver, using this technique can offer a power gain of more than 3 dB when Γ_{MZM} = 0.5 as can seen in Figure 6. So, the only usefulness that can be extracted from this technique is to boost received SNR.

On the other hand, until Γ_{MZM} > 0.9, the pre-distorted signal does not begin to degrade when offset biasing technique is used as shown in Figure 5. The constellation error is less in the pre-distorted signal curve than that of original signal curve by almost an order of magnitude. Also, the error in this case is far below than that of original curve in the Figure 4 where nominal biasing was used. Therefore, a distortion-free dynamic range of more than 6dB can be enjoyed using offset biasing technique.

With the increase of Γ_{MZM}, power of the pre-distorted signal input decreases. The reverse happens to power of the original signal. Previously, in the nominal biasing case, power of the pre-distorted input power increased at a higher rate than original signal. The ac power output from the PD which is proportional to the received square amplitude is shown in the Figure 7. At Γ_{MZM} = 0.5, squared amplitude of the undistorted original signal is 10^{-3}, which is much smaller than that of nominally biased value. But for the offset pre-distorted signal, at Γ_{MZM} = 0.9, the squared amplitude is 0.05, which is 4 dB more than that of the nominally biased case. So the distortion-free dynamic region is more here.

Finally, the offset biasing pre-distortion technique has the potential to increase both the distortion-free dynamic range and the SNR of the Mach-Zehnder based optical link.

V. Conclusion

It has been found that, the optical non-linear distortion due to Mach-Zehnder modulator has less impact on OFDM than that of single-carrier systems and hence OFDM system is more suitable to be used in RoF applications. With increasing Mach-Zehnder modulator input levels, the rate of increase in nonlinear distortion for OFDM is much lower than that of single-carrier systems. And also, if pre-distortion techniques are applied, offset biasing technique offers better advantages in terms of distortion-free dynamic range and SNR. This work will eventually help to design an OFDM based RoF link at 5.8 GHz frequency employing Mach-Zehnder modulator for the microcell and picocell applications in future networks. Hence, it will be possible to implement ultra-high speed networks economically if suitable offset biasing pre-distortion is applied for OFDM-RoF links to eventually receive more output power. A similar research is being carried out to employ IEEE 802.16a standard for long-haul outdoor wireless links as 802.16a is more tolerant than 802.11a in terms of the delay spreads and propagation times.

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A.H.M. Razibul Islam 정회원

He is currently a master student and a member of Telecom. lab in the School of Electronics and Information at Kyung Hee University. He received his Bachelor degree in Electrical and Electronic Engineering from Islamic University of Technology(IUT), Bangladesh. He is also a Lecturer(on leave) of Department of Electrical and Electronic Engineering, Islamic University of Technology(IUT), Bangladesh. His research interest includes nonlinearity of OFDM systems and WiBro multihop relay systems.

송 주 빈 (Ju Bin Song) 정회원

He is currently a professor in the Dept. of EE/RE, Kyung Hee university from 2003. He received BS and MS degree in 1987 and 1989, respectively and received PhD degree in the Department of Electronic and Electrical Eng., University College London, UK in 2001. He was a senior researcher in ETRI from 1992 to 1997 and a research fellow in UCL, 2001. He was a professor in Hanbat National University from 2002 to 2003. His research interest include telecommunications, mobile multihop networks, and next generation communications. He is a member of IEEE, KICS and KIEE.