Performance Enhancement using Unitary Frequency Modulation with PLC and VLC Cooperation

Ye Tian and Chang-Jun Ahn

Abstract— Visible light communication (VLC) is expected as a means for ubiquitous communication using increasingly popular LED lights. However, for indoor optical channel, the received signals are with line of sight (LOS) component but also delayed components due to reflected secondary paths. Therefore, the energy is spread over the time, resulting in a reduction of the converted current at the photodiode. From this reason, the diversity gain of VLC is rarely expected as compared to radio frequency systems. To improve the VLC performance, we consider the combination of power line communication (PLC) and VLC systems for achieving the frequency diversity with unitary space-time modulation. In this paper, we propose the diagonal components of unitary signal constellation with splitting over the coherence bandwidth, and evaluate the system performance for PLC-VLC/OFDM.

Keywords—VLC, PLC, USTM, frequency diversity, coherence bandwidth, optical wireless.

I. Introduction

Using increasingly popular LED lights, the visible light communications (VLC) is expected as a means for ubiquitous communication [1][2]. VLC has some of the noteworthy advantages over radio frequency and infrared systems. In general, visible light does not damage to human body and eyes and VLC has high security of data because the optical signal does not pass the wall, resulting that the communication space is limited to a certain range. Moreover, since LED lighting has recently become part of a building infrastructure, making visible light communication infrastructure is fairly easy by adding communication function to LED lighting. As these features, VLC is widely considered as a new way of wireless communi-cation technology.

However, for indoor optical channel, the received signals are with line of sight (LOS) component but also delayed components due to reflected secondary paths. Therefore, the energy is spread over the time, resulting in a reduction of the converted current at the photodiode. Furthermore, the reflected signal power is significantly reduced due to surface reflectivity. From these reasons, the diversity gain of VLC is rarely expected as compared to radio frequency (RF) systems [3]. To improve the VLC performance, we consider the combination of power line communication (PLC) and VLC systems for achieving the frequency diversity. PLC systems have many advantages and are assumed to be one of prospective solutions for short distance or in-home communication networks [4] [5] [6]. PLC takes the advantage of use in everyplace at home without additional network line. VLC is easily implemented by using PLC system. However, power line channel is the time-and-frequency variant and exhibits remarkable difference between locations, according to its network topology, the types of wire lines. Moreover, many electrical appliances frequently cause man-made electromagnetic noise on power line channels. Due to the above-mentioned PLC properties, the performance of PLC system would be degraded. However, using time-and-frequency variance of PLC channel, the diversity gain is also expected.

To overcome the above-mentioned problems and improve the system performance of PLC-VLC/OFDM, in this paper, we consider the unitary signal constellation scheme. Unitary signal constellation scheme has been proposed to perform space-time diversity in wireless communications system. Marzetta and Hochwald proposed and investigated unitary space-time modulation (USTM) as a mean of achieving capacity [7] [8]. These unitary signal constellations may be viewed as a multiple antenna extension. A unitary signal constellation is a matrix, whose columns are transmitted from multiple antenna elements and mutually orthogonal to each other. Such constellations have been designed and shown to perform well for uncoded transmission [9]. In this paper, we consider the unitary signal constellation [10] and we propose the diagonal components of unitary signal constellation with splitting over the coherence bandwidth, and evaluate the system performance for PLC-VLC/OFDM. The system model is described in Section II. In Section III, we show the proposed PLC-VLC/UFM-OFDM system. In Section IV, we show the simulation results. Finally, the conclusion is given in Section V.

II. System Model

A. Indoor Optical Wireless Cannel

An electrical current $y(t)$ at the receiver due to the transmitted optical intensity waveform $x_v(t)$ can be expressed as

The authors are with the Department of Electrical and Electronic Engineering, Chiba University, 1-33, Yayoi, Inage, Chiba, 263-0022, Japan (e-mail: hittomato@chiba-u.jp)

$$y(t) = r\zeta h_v(t)x_v(t) + w(t) \quad (1)$$

where r is the responsivity of the photodiode at the receiver, ζ is the effective receiver area, $h_v(t)$ is the optical channel impulse response, and $w(t)$ is the noise component. For the free-space indoor optical channel, the received signals are with LOS component but also delayed components due to reflected secondary paths. Therefore, the energy is spread over the time, resulting in a reduction of the converted current at the photo-diode. Furthermore, the reflected signal power is significantly reduced due to surface reflectivity. From these reasons, the diversity gain is rarely expected as compared to RF systems. Therefore, the combination of PLC & VLC is considerable approach for achieving the diversity gain

B. PLC Channel Model

Power line channel is the time-and-frequency variant and exhibits remarkable difference between locations, according to its network topology, the types of wire lines. Moreover, many electrical appliances frequently cause man-made electromagnetic noise on power line channels. Such man-made noise has the impulsive characteristics. Here, we introduce Middleton's class A noise model [11] into a statistical model of impulsive noise environment. This model is widely applicable by adjusting parameters, and provides fine closeness to experimental values. Middleton's noise model is composed of sum of Gaussian noise and impulsive noise. The class A model is defined that the bandwidth of the noise is narrower than the bandwidth of the receiving system. According to the class A noise model, the PDF (Probability Density Function) of the noise amplitude ς is as follows,

$$P_a(\varsigma) = \sum_{m=0}^{\infty} \frac{e^{-A}A^m}{m!} \frac{1}{\sqrt{2\pi\sigma_m^2}} \exp\left(-\frac{\varsigma^2}{2\sigma_m^2}\right), \quad (2)$$

where $\sigma_m^2 = \sigma^2 \frac{\left(\frac{m}{A}\right)+\Gamma}{1+\Gamma}$, A is the impulsive index, $\Gamma = \sigma_G^2/\sigma_I^2$ is the GIR (Gaussian-to-impulsive noise power ratio) with Gaussian noise power σ_G^2 and impulsive noise power σ_I^2, and $\sigma^2 = \sigma_G^2 + \sigma_I^2$ is the total noise power. The noise amplitude ς followed by Eq. (2) always includes the background Gaussian noise with power σ_G^2. On the other hand, sources of impulsive noise are distributed with Poisson distribution $(e^{-A}A^m)/m!$. One impulsive noise source generates noise which is characterized by the Gaussian PDF with variance σ_I^2. The parameter A is defined as the average number of impulses on the receiver in unit duration times the mean duration of them. The larger A, the impulsive noise will be more continuous, and then the class A noise is led to be more likely to the Gaussian noise. Conversely, the smaller A, the class A noise will be more impulsive. In particular, if A is nearly equal to 10, the statistical feature of the class A noise is almost similar to that of the Gaussian noise. As the Gaussian noise power σ_G^2 is comparatively larger in the total noise power σ^2, that is, $\Gamma$is larger, the class A noise will approach to the Gaussian noise. Conversely, the smaller Γ, the class A noise will be more impulsive.

C. Unitary Space-Time Signal Constellations

Unitary space-time signal is a matrix, whose rows are transmitted from the transmitted elements and mutually orthogonal to each other in wireless communication systems. Let $C \geq 2$ denotes the size of a unitary signal constellation. We define $\theta_C = 2\pi/C$. For any given integers $\eta_1, \eta_2, \eta_3 \in Z$, we define the following unitary signal constellation of size C

$$\nu = \nu(\eta_1, \eta_2, \eta_3) = \{\xi(c\eta_1, c\eta_2, c\eta_3) | c \in Z_c, \quad (3)$$

where $Z_c = (0,1,\cdots,C-1)$, and, $\xi(c\eta_1, c\eta_2, c\eta_3)$ is given by

$$\xi(c\eta_1, c\eta_2, c\eta_3) = \begin{pmatrix} e^{j\eta_1\theta_C} & 0 \\ 0 & e^{j\eta_1\theta_C} \end{pmatrix}^c \quad (4)$$
$$\cdot \begin{pmatrix} \cos(\eta_2\theta_C) & \sin(\eta_2\theta_C)\,0 \\ -\sin(\eta_2\theta_C) & \cos(\eta_2\theta_C) \end{pmatrix}^c$$
$$\cdot \begin{pmatrix} e^{j\eta_3\theta_C} & 0 \\ 0 & e^{j\eta_3\theta_C} \end{pmatrix}^c .$$

For any given constellation size $C \geq 2$, we will find a unitary signal constellation from the following class

$$\Omega_C \equiv \{\nu(\eta_1, \eta_2, \eta_3) | \eta_1, \eta_2, \eta_3 \in Z_C\}, \quad (5)$$

such that the unitary signal constellation has the largest diversity product in the constellation class as Eq. (5). The above unitary signal constellation is built from the parametric form of 2×2 unitary matrices. The signal constellation as Eq. (4) is called *parametric code*. It is seen that when $\eta_2 = \eta_3 = 0$ is imposed in the constellation class as Eq. (5), the parametric code as Eq. (4) is exactly the *diagonal code* in the case $M = 2$ where M is the number of diagonal element. There have been several classes of 2×2 unitary space-time constellation which were proposed in the previously [8][9]. A diagonal code cyclic group code for a general M was introduced. A main difference between the diagonal code and the parametric code is that the diagonal code is in general a non-group signal constellation.

III. Proposed Method

Here, we employ the diagonal code for achieving a diversity gain in the PLC channel. The data stream is divided into bit sequences that consist of $R \cdot M$ bits, where R and M denote information bits per parallel symbol to be transmitted, and the number of diagonal element. Each $R \cdot M$ bit sequence is mapped into the constellation $\nu(c)(c \in Z_C)$ selected from $C = 2^{RM}$. The constellation of unitary matrix can be written as

$$\mathrm{diag}\{\nu(c)\} = \left[e^{jc\,\theta_C}, \cdots, e^{jc\,\theta_C}\right], (c \in Z_C) \quad (6)$$

where $\nu(c)$is $M \times M$ unitary matrix, $\mathrm{diag}\{\cdot\}$ is the diagonal operator, respectively. For example, in the case of $M = 2$ and $R = 1$, which is equal to BPSK modulation. In this case, one of 2×2 unitary matrix $\nu(c)$ assigned.

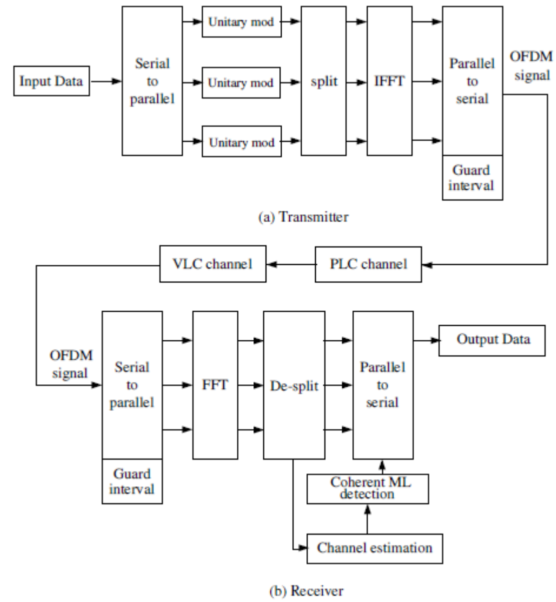

Fig. 1: Proposed PLC-VLC/UFM-OFDM system.

In a PLC channel, we assume that a propagation channel consists of L discrete paths with different time delays due to the power line. The impulse response $h_p(\tau,t)$ is represented as

$$h_p(\tau,t)=\sum_{l=0}^{L-1} h_l(t)\delta(\tau-\tau_l), \tag{7}$$

where h_l and τ_l are the PLC complex channel gain and the time delay of the l th propagation path, respectively. Through the VLC channel, the channel transfer function $H(f,t)$ is the Fourier transform of $r\zeta h_v(t)h_p(\tau,t)$ and is given by

$$\begin{aligned} H(f,t) &= \int_0^\infty r\zeta h_v(t)h_p(\tau,t)\exp(-j2\pi f\tau)\,d\tau \\ &= r\zeta \sum_{l=0}^{L-1} h_v(t)h_p(\tau,t)\exp(-j2\pi f\tau_l). \end{aligned} \tag{8}$$

Observing Eq. (8), the channel response at a particular subcarrier frequency is not supposed to be totally different from its neighboring frequencies, and hence, they must have correlation which depends on the coherence bandwidth of the channel B_c. When we assign the diagonal components of the unitary signal constellation on neighboring frequencies. In this case, the diagonal components do not achieve the frequency diversity. However, we split the diagonal components over the coherence bandwidth, the detected signal can achieve the frequency diversity. In this paper, we employ the diagonal code and split diagonal components of the selected code over the coherence bandwidth. Hereafter, we call this processing as a unitary frequency modulation for PLC-VLC/OFDM (PLC-VLC/UFM-OFDM). In the PLC-VLC/UFM-OFDM systems, the diagonal components of the selected unitary signal constellation are splitting over the coherence bandwidth and are transmitted to the receiver via PLC and VLC channels. In this case, the received signal $Y(k)$ of the k -th subcarrier at receiver side is given by

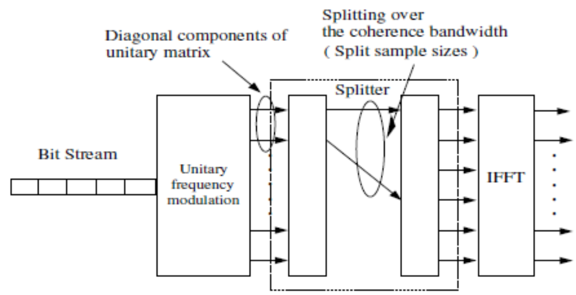

Fig. 2: Frequency splitter.

$$Y(k)=H(k)X(k)+N(k) \qquad k=1,\cdots,K, \tag{9}$$

where $X(k)$ is the split diagonal component of unitary signal constellation over the coherence bandwidth, and $N(k)$ is the impulsive noise and additive white Gaussian noise. After de-splitting of the received signals and channel estimation, the frequency domain signals $N(k)$ are divided into M bits. Here, we consider the same structure of unitary signal constellation for $M\times M$ as Eq. (6). Each M bit of frequency domain signals is demodulated by ML estimator. The ML decision rule of the signal model as Eq. (8) is given by

$$\begin{aligned} \hat{v} = \arg\min \sum_{k=1}^{K} |Y(k) - H(k) \\ \cdot \sum_{c=1}^{C} \operatorname{diag}(v)_{mod\,(k,M)+1}(c)|^2, \end{aligned} \tag{10}$$

where $\sum_{c=1}^{C} \operatorname{diag}(v)_{mod\,(k,M)+1}(c)$ is the diagonal component of unitary signal constellation. The neighboring signals of $\sum_{c=1}^{C} \operatorname{diag}(v)_{mod\,(k,M)+1}(c)$ without splitting must have correlated channel responses, however, the split signals over the coherence bandwidth achieve totally different channel responses. It means that PLC-VLC/UFM-OFDM systems can achieve a frequency diversity gain.

IV. Simulation Results

In this section, the system performance of the proposed PLC-VLC/UFM-OFDM system is compared with the conventional VLC/OFDM. Fig. 1 shows the simulation model of UFM-PLC/OFDM for $N_c=128$ subcarriers over the impulsive noise and multipath PLC & VLC channels. In the transmitter, data stream is serial-to-parallel(S/P) transformed, and the diagonal components of unitary signal constellation are split over the coherence bandwidth as shown in Fig. 2. The OFDM time signal is generated by an IFFT and is transmitted over the frequency selective and time variant PLC and VLC channel after the cyclic extension has been inserted. The transmitted signals are subject to 2-path quasi-static PLC channel and 3-path VLC channel. In the PLC channel model, 2-path as an independent identically distributed (i.i.d.) complex random variable according to Middleton's class A noise model. This case causes a severe frequency selective channel. Maximum delay spread of PLC and VLC are 0.5μs and 0.3μs, respectively. In our simulations, we consider two different impulsive noise scenarios [6]. The first one corresponds to a power line channel that is heavily disturbed by impulsive noise because the inter-arrival times between strong

Table 1: Simulation parameter.

Parameter	Specification
Data Modulation	ML Detection
Demodulation	4Msymbol/s
OFDM Symbol Duration	65 μs
Number of Carriers	128
Channel	2path quasi-static
Maximum Path Delay	0.5 μs (PLC)
	0.3 μs(VLC)
Noise Model	Middleton's class A
	A=(0.001, 0.01)
	Γ=(0.001, 0.01)

impulses are very short (A=0.001, Γ=0.001). The second one corresponds to a power line channel that is weakly disturbed by impulsive noise because the inter-arrival times between impulses are very long (A=0.01, Γ=0.01). We simulate this situation by considering the complete summation in Eq. (2). In the receiver, the received signals are S/P converted and N_c parallel sequences are passed to a FFT operator, which converts the signal back to the frequency domain. This frequency domain signals are desplit and coherently demodulated by using ML detection. The simulation parameters are listed in Table 1.

Fig. 3 shows the BER performance of PLC/OFDM and PLC/UFM-OFDM with splitting size of 16 and 64 for power line channels heavily distributed by impulsive noise (A=0.001, Γ=0.001). From Fig. 3, it is clear that the PLC/UFM-OFDM outperforms PLC/OFDM over E_b/N_0. For BER of $2 \cdot 10^{-3}$, the PLC/UFM-OFDM with splitting size of 16 and 64 performs better than PLC/OFDM by 4dB and 7dB. This is because PLC/UFM-OFDM can achieve diversity with splitting the diagonal components over the coherence bandwidth for frequency diversity.

Fig. 4 shows the BER performance of PLC/OFDM and PLC/UFM-OFDM with splitting size of 16 and 64 for power line channels weakly distributed by impulsive noise (A=0.01, Γ=0.01). PLC/UFM-OFDM and PLC/OFDM with weak noise achieve better BER performance than those of with strong noise. For BER of 10^{-3}, PLC/UFM-OFDM with splitting size of 16 and 64 performs better than PLC/OFDM by 7dB and 10dB.

Fig. 5 shows the BER performance of VLC/OFDM, PLC-VLC/OFDM and PLC/UFM-OFDM with heavy and weak noises. From the simulation result, VLC/OFDM and PLC-VLC/OFDM show the approximately same BER performance under the heavy and weak noises. On the other hand, VLC-PLC/UFM-OFDM with splitting size of 64 shows the superior BER performance for heavily and weakly distributed impulse noise channel. This is because PLC/UFM-OFDM can achieve diversity with splitting the diagonal components over the coherence bandwidth for a frequency diversity in the PLC channel. From the simulation results, it is effective to improve the BER performance of VLC system.

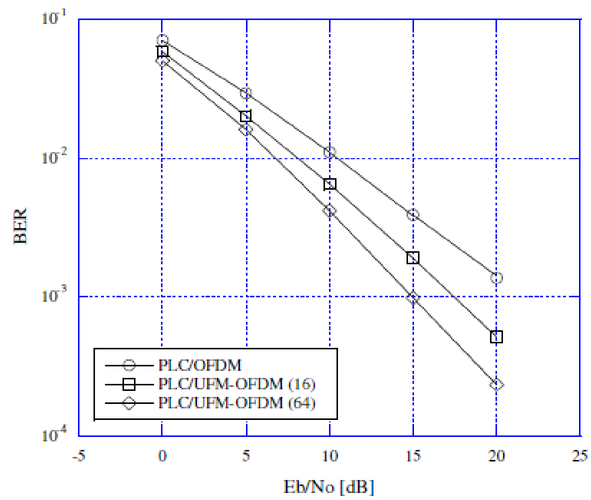

Fig. 3: BER performance of PLC/OFDM and PLC/UFM-OFDM with splitting size of 16 and 64 for power line channels heavily distributed by impulsive noise (A=0.001, Γ=0.001).

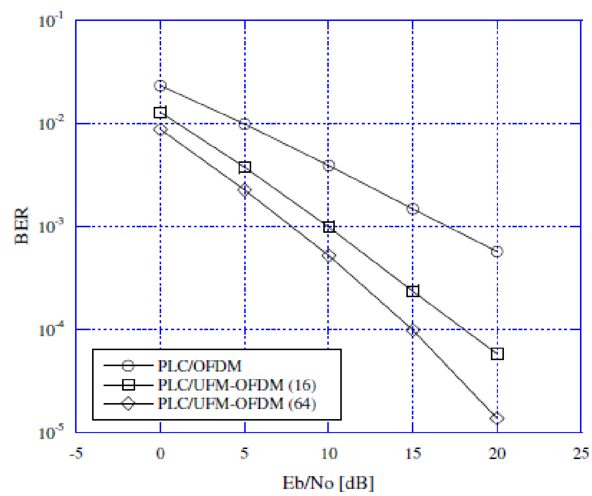

Fig. 4: BER performance of PLC/OFDM and PLC/UFM-OFDM with splitting size of 16 and 64 for power line channels weakly distributed by impulsive noise (A=0.01, Γ=0.01).

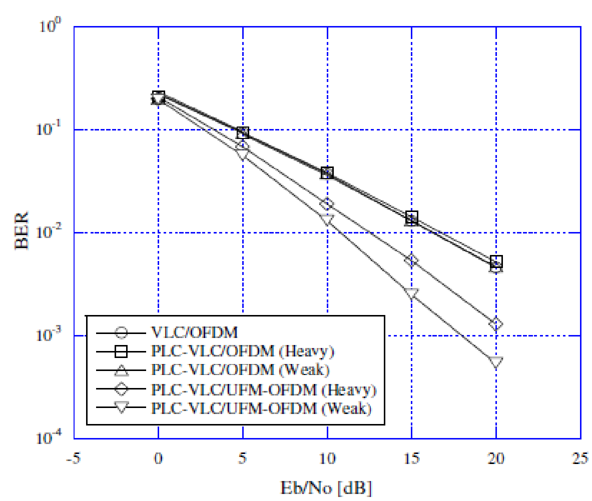

Fig. 5: BER performance of VLC/OFDM, PLC-VLC/OFDM and PLC/UFM-OFDM with heavy and weak noises.

V. CONCLUSION

We have investigated the performance improvement of PLC-VLC/UFM-OFDM over the multipath and impulsive noised PLC and VLC channels, and evaluated the BER performance. The proposed PLC-VLC/UFM-OFDM system can achieve 5 and 4dB gains compared with VLC/OFDM for BER of 10^{-2}, under the heavy and weak noises, respectively.

REFERENCES

[1] T. Komine and M. Nakagawa, Fundamental analysis for visible-light communication system using LED lights. *IEEE Transactions on Consumer Electronics*, vol. 50(1), pp. 100-107, Jun. 2004.

[2] M. Kavehrad, "Sustainable Energy-Efficient Wireless Applications using Light," *IEEE Communications Magazine*, December 2010.

[3] M. Biagi and A. Vegni, "Enabling high data rate VLC via MIMO-LEDs PPM," *in Proc. IEEE Globecom Workshops*, pp. 1058–1063, Dec. 2013.

[4] M. Crussiere, J. Y. Baudais, and J. F. Helard, "Robust and high-bit rate communications over PLC channels: a bit-loading multi-carrier spreadspectrum solution," in *Proc. International Symp. Power Line Commun. Applications*, 2005, pp. 37-41, Apr. 2005.

[5] Y.-H. Kim, S.-C. Kim, and H. M. Oh, "OFDM receiver performance analysis with measured power line channel model for coded OFDM system," in *Proc. 2005 IEEE International Symposium on Power Line Communications and Its Applications*, pp. 201- 205.

[6] C. L. Giovaneli, B. Honary, and P. G. Farrell, "Space-frequency coded OFDM system for multi-wire power line communications," in *Proc. IEEE Int. Symp. Power Line Commun.*, pp. 191–195, Apr. 2005.

[7] T. L. Marzetta and B. M. Hochwald, "Capacity of a mobile multiple-antenna communication link in Rayleigh flat fading," *IEEE Trans. Inform. Theory*, vol. 45, pp. 139–157, Jan. 1999.

[8] B. M. Hochwald and T. L. Marzetta, "Unitary space–time modulation for multiple-antenna communications in Rayleigh flat fading," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 543–564, Mar. 2000.

[9] B. M. Hochwald, T. L. Marzetta, T. J. Richardson, W. Sweldens, and R. Urbanke, "Systematic design of unitary space-time constellations," *IEEE Trans. Inf. Theory*, vol. 46, no. 9, pp. 1962–1973, Sep. 2000.

[10] X.-B. Liang and X.-G. Xia, "Some unitary signal constellations for differential space–time modulation," in *Proc. Asilomar Conf.*, Pacific Grove, CA, Oct. 31–Nov. 2, 2000.

[11] D. Middleton, "Statistical-physical models of electromagnetic interference," *IEEE Trans. Electromagn. Compat.*, no. 3, pp. 106–127, 1977.

Ye Tian received the B.S. degree in electronic information of science and technology in 2009 from Harbin Institute Of Technology, Haerbin, China, and M.S. degree with the Department of Electrical and Electronics Engineering from Chiba University in 2014. He is currently pursuing a Ph.D. degree in Electrical and Electronics Engineering in Chiba University, Japan. His research interests include OFDM wireless communications, channel estimation and indoor postioning systems. He is a member of IEEE and IEICE.

Chang-Jun Ahn received the Ph.D. degree in the Department of Information and Computer Science in 2003 from Keio University, Japan. From 2001 to 2003, he was a research associate in the Department of Information and Computer Science, Keio University. From 2003 to 2006, he was with the Communication Research Laboratory, Independent Administrative Institution (now the National Institute of Information and Communications Technology). In 2006, he was on assignment at ATR Wave Engineering Laboratories. From 2003 to 2006, he was at the Faculty of Information Science, Hiroshima City University. Currently, he is working at the Faculty of Engineering, Chiba University as an associate professor. His current research interests include OFDM, digital communication, channel coding, and signal processing for telecommunications. He served as an associate editor for Special Section on Multi-dimensional Mobile Information Network for the IEICE Trans. on Fundamentals. From 2005 to 2006, he was an expert committee member for emergence communication committee, Shikoku Bureau of Telecommunications, Ministry of Internal Affairs and Communications (MIC), Japan. Dr. Ahn received the ICF research grant award for Young Engineer in 2002 and the Funai Information Science Award for Young Scientist in 2003. He is a senior member of IEICE, and IEEE.