Improvement of Transmission Capacity of Visible Light Access Link using Bayesian Compressive Sensing

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***Abstract*— A technical method regarding to the improvement of transmission capacity of an optical wireless orthogonal frequency division multiplexing (OFDM) link based on a visible light emitting diode (LED) is proposed in this paper. An original OFDM signal, which is encoded by various multilevel digital modulations such as quadrature phase shift keying (QPSK), and quadrature amplitude modulation (QAM), is converted into a sparse one and then compressed using an adaptive sampling with inverse discrete cosine transform, while its error-free reconstruction is implemented using a L1-minimization based on a Bayesian compressive sensing (CS). In case of QPSK symbols, the transmission capacity of the optical wireless OFDM link was increased from 31.12 Mb/s to 51.87 Mb/s at the compression ratio of 40 %, while It was improved from 62.5 Mb/s to 78.13 Mb/s at the compression ratio of 20 % under the 16-QAM symbols in the error free wireless transmission (forward error correction limit: bit error rate of 10^{-3}).**

Keywords*— *Bayesian compressive sensing; light emitting diode; transmission capacity; visible light communication

I. INTRODUCTION

Recently, the rapid development in visible light emitting diode (LED) allows researchers to use it in many applications that require illumination, such as displays, and signal devices. Various visible light communication (VLC) systems using visible LED, which can be employed for both illumination and wireless data transmission, have been proposed to support multimedia mobile services such as indoor positioning, broadband wireless multimedia services over 1 Gb/s, and inter-vehicular communication [1].

One of the required technical requirements for these kinds of services in VLC network is to have a wireless broadband channel bandwidth so that access users would transmit or receive flexibly multimedia data irrespective of their data rates. However, it was very difficult to support this because the commercial LED devices have a 3-dB physical bandwidth below 10 MHz. To complement and overcome the drawbacks of the conventional LED, several techniques have been proposed to improve the bandwidth efficiency [2-6]. Gruber et al. reported that the modulation bandwidth of visible LEDs increased from 3 to 20 MHz by removing the yellow phosphor that has a slow time constant with the help of a blue filter [2]. This technique reduces the intensity of the received light because of the insertion of the blue filter. As a result, the wireless-transmission distance reduces, while the received channel noise is also attenuated. Therefore, it is important to optimize the relation between the received optical power and channel noise in order to minimize the noise figure of VLC system using the blue filter. Using an electronic equalizer is also an efficient technique to improve the channel-bandwidth of the wireless channel in a VLC network because the electronic equalizer compensates the signal components with a small frequency response [3]. However, each equalizer requires a different driving circuit because each white LED has its own distinct frequency response. The cost of a VLC module also increases because it takes longer to produce them in a commercial scale when these optical and electrical devices are added. Kottke et al. proposed a 1.25-Gb/s wireless optical transmission technique that uses discrete multi-tones (DMTs) and RGB-LEDs [5]. However, an RGB-LED costs more than a white LED, which discourages commercialization. Moreover, their wireless-transmission distance (10 cm) is too short to use in wireless multimedia services such as Wi-Fi and Bluetooth.

In this paper, the compression and reconstruction of orthogonal frequency division multiplexing (OFDM) signal, which is encoded by multi-level digital modulation, using a Bayesian compressive sensing (CS) is proposed in order to increase the transmission capacity of optical wireless link based on visible LED in terms of Bayesian perspective. Using the Bayesian CS, the error free reconstruction of a sparse signal can be obtained with enough CS measurement taken from a sparse signal, i.e., data that is sampled significantly below the Nyquist/Shannon limit [14]. Figure 1 shows an optical wireless link using the proposed technique. Here, an OFDM signal encoded by quadrature phase-shift keying (QPSK) or different multi-level digital modulation is compressed using adaptive sampling and inverse discrete cosine transform (IDCT) at the VLC transmitter (Tx), and then transmitted wirelessly to the VLC receiver (Rx). The compressed waveform is reconstructed at the VLC Rx using L1-minimization. As shown in Fig. 1, a sparse matrix is used for adaptive sampling, while the IDCT is computed using a domain transformer. To the best of our knowledge, this is the first work to transmit and reconstruct compressed data using a compressive sensing technique in VLC systems.

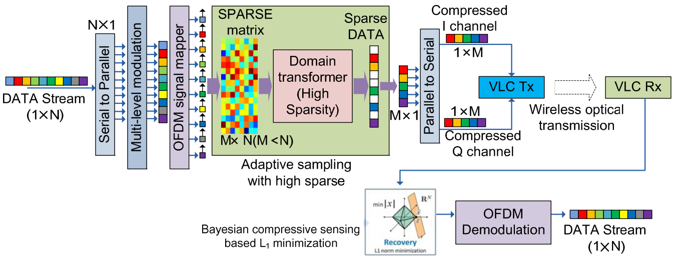


Fig. 1. Compressed optical OFDM signal transmission and reconstruction in a VLC system using adaptive sampling with IDCT domain and L1-minimization based on Bayesian compressive sensing

II. COMPRESSION AND RECONSTRUCTION OF OFDM SIGNAL USING BAYESIAN COMPRESSIVE SENSING

A. Compression of OFDM signal encoded by multi-level digital modulation using adaptive sampling

Our proposed technique, which improves the transmission capacity of optical wireless link based on visible LED, is composed of two steps. In the source, original OFDM data is compressed using adaptive data sampling to efficiently compress the original data by keeping the important OFDM signal. In the receiver, Bayesian CS-based signal reconstruction is applied to exactly/approximately reconstruct the signal. Many suboptimal methods such as basis pursuit and basis marching are proposed in order to reconstruct more exactly the original signal from compressed measurement [7].

It is needed how to efficiently reduce the redundant signal and keep the important signals to improve the transmission capacity in the VLC Tx using data adaptive sampling methodology. It is proposed to reduce the complexity and to increase the channel capacity rate of OFDM data transmission. Generally, random sampling procedure is popularly used, but it has still problem because the samples can be partial toward to certain scope of the given signal. The random sampling-based signal reconstruction generates measurement error by failing to tract the rapid movement of the OFDM signal which includes numerous local maxima and minima. We apply the adaptive signal sampling procedure by regularly extract the samples to prevent the signals to be concentrated to certain part of the original signal and local maxima and minima to successfully tract the complex OFDM signal. The samples are converted into the sparse domain using an inverse discrete cosine transform (IDCT) because it guarantees sparsity in the complicated OFDM signal.

B. Reconstruction of comressed OFDM signal using Bayesian compressive sensing

The compressed data is reconstructed in the part of the receiver using L1-minimization. Basically, CS-based signal reconstruction approach generates a tremendous amount of attention in the signal processing community, which enables a potential large reduction (under Nyquist/Shannon limit) in the sampling and computation cost. The uncompressed given OFDM signal () which is represented as a vectorized column vector with m dimension, can be exactly/approximately recovered from $(x\in\Re^m)$ sampled measurements $(m << n)$. This can be done with certain condition on the $m\times n$ measurement matrix, Φ, and the $m\times m$ basis matrix $\Psi=[\psi_1,\psi_2,\ldots,\psi_m]$, where $\psi_{i=1}^{m}$, is a basis in $\Re^m$, where m is the number of observations. Here, the original signal x is a linear combination of $[\psi_1,\psi_2,\ldots,\psi_m]$, as written in the matrix form as follows:

$$x=\Psi\alpha \tag{1}$$

Only k of the m coefficient entries in α is nonzero, with $k << m$. The general joint Bayesian CS algorithm addressed these shortcomings and fits perfectly to the complex signal. Given the observation matrices $\Psi\in\Re^{k_i\times M}$ with k_i representing the number of *k*-space points sampled for the *i*-th samples and *m* being the number of observations, the linear relationship between the *k*-space data and the unknown signal can be expressed as $y=\Phi x$ is the *k*-space samples belonging to the x. Making the use of CS theory is to solve the inverse problem can be written as shown in Eq.2.

$$\alpha=\arg\min\|\alpha\|_1 \quad \text{s. t. } y=\Phi\Psi\alpha \tag{2}$$

The general approach of Bayesian CS is to find the most likely signal coefficients with the assumptions that the signal is approximately sparse and that the data are corrupted by noise with a known distribution. The sparsity assumption is reflected by the prior defined on the signal coefficients, whereas the noise model is expressed via the likelihood term. This means that it is possible to recover the conventional CS formulation with a Bayesian treatment. As a means to justify, we present a commonly used signal prior and noise distribution. We model the data as being corrupted by additive white Gaussian noise with variation σ^2 via $y=\Phi x+n$. In this case, the probability of observing the data y given the signal x is a Gaussian probability density function (pdf) with mean Φx and variance σ,

$$P(y\,|\,x,\sigma^2)=(2\phi\sigma^2)^m\exp\left(-\frac{1}{2\sigma^2}\|y-\Psi x\|\right) \tag{3}$$

which constitutes the likelihood term. To formalize our belief that the signal *x* is sparse, we place a sparsity-promoting prior on it. A common prior is the separable Laplacian density function.

$$P(x)=(\lambda/2)^2\exp\left(-\lambda\sum_{i=1}^{m}|x_i|\right) \tag{4}$$

From motivated Bayesian formulation, the posterior for the signal coefficients can be related to the likelihood and the prior as

$$P(x\,|\,y)=\frac{P(y\,|\,x)P(x)}{P(y)} \tag{5}$$

We seek the signal that maximizes this posterior probability via maximum a posterior (MAP) estimation. Since the denominator is negative of the logarithm of the numerator:

$$x_{MAP} = \arg\min_x \left\| y - \Phi x \right\|_2^2 + 2\sigma^2 \lambda \left\| x \right\|_1 \qquad (6)$$

This expression in Eq. 6 shows that the reconstructed signal x_{MAP} can be extracted by both optimizing the error and prior characteristics of the OFDM signal with a slightly more complicated prior. Therefore, it is possible to reconstruct the original OFDM signal by estimating with with a Laplacian prior on the signal coefficients.

III. EXPERIMENTAL SETUP

Figure 2 shows the experimental setup which is implemented in order to verify experimentally the proposed technique. The setup was employed to wirelessly transmit and reconstruct an OFDM signal encoded by quadrature phase shift keying (QPSK) that is compressed using the Bayesian CS technique. The comparison of error vector magnitude (EVM) between a compressed OFDM-QPSK signal and the original one was made to investigate the transmission performance of the proposed technique. The original OFDM-QPSK signal was generated and recovered using the route of offline processing 1, while the compressed one was handled using that of an offline processing 2.

At first, a QPSK-encoded OFDM signal was generated by MATLAB®. The size of fast Fourier transform (FFT) was chosen as 2048 in order to optimize the signal quality of the proposed scheme. One frame containing the training sequence was inserted into every 1000 OFDM symbols as the preamble. The size of cyclic prefix (CP) was 224 for all 1200 OFDM subcarriers. After generating the OFDM-QPSK waveform using offline digital processing, it is converted to an analog waveform by an arbitrary waveform generator (AWG: Tektronix 7122C) that sampled at 31.25 Msample/s. The spectrum of the converted analog OFDM-QPSK signal waveform ranged from dc to 15.625 MHz. Before loading the OFDM-QPSK waveform on the AWG, the generated OFDM-QPSK signal was separated into an in-phase (I) and a quadrature-phase (Q) channel with real values in the digital domain. In the experimental setup, the Q channel signal with imaginary values is not loaded to the arbitrary waveform generator (AWG) equipment because all signal are entered into AWG should have real values. Therefore, all the data of the Q-channel, which had only imaginary values, were transformed to purely real values using an imaginary-to-real numerical converter in each offline processing. Then, both the I and Q channel data streams with real values were loaded to the AWG so that they would be transmitted separately.

In the second offline processing, the OFDM/QPSK signal was re-sampled by adaptive sampling and was then transformed into a sparse waveform using IDCT based on the Bayesian CS technique. After the Bayesian CS process, the compressed OFDM/QPSK signal was generated. The original OFDM-QPSK signal and the compressed one from the AWG were equalized and amplified by a 1st order equalizer and a low noise amplifier (LNA: 25 dB gain, 30 MHz 3-dB bandwidth). The 3-dB channel bandwidth of VLC-transmitter (Tx) was 25 MHz for the 1st order equalizer with LNA. This is done to obtain enough bandwidth for the white LED to modulate the OFDM-QPSK signal, which is sampled at 31.25 Msample/s. After being equalized, the two kinds of OFDM-QPSK signals were combined with a dc source (bias current: 300 mA) using a bias-T and then the diffused light of the white LED was modulated. The white LED was operated in the quasilinear region by controlling the bias current as well as the electrical output power of AWG.

The modulated light of the white LED was transmitted wirelessly to a VLC-Rx. It was placed one meter away from the VLC-Tx and aligned to have a direct line-of-sight (LOS) between the Tx and the Rx. The VLC-Rx was made of a dichroic optical bandpass filter (Thorlab, FD2B, FWHM bandwidth: 50 nm), which eliminated the phosphorescent component from the white LED, a biconvex glass lens (Thorlab, LB1723, focal length: 60 mm), and an APD module. The APD module (Hamamatsu C5331) consisted of an avalanche photodiode and an integrated TIA (transimpedance amplifier, 3-dB bandwidth of 100 MHz), which amplified the low-level photocurrent generated by the APD. The illuminance of 120 lux was measured in front of VLC-Rx at 1-m wireless transmission length. The original OFDM-QPSK waveform was sampled by a real-time oscilloscope (DPO: Tektronix 7200B) and the OFDM symbols were recovered by combining the I and Q channels after synchronization. Next, the compressed waveform uncompressed into an OFDM-QPSK signal using L1-minimization, and its OFDM symbol was recovered by the same process as the original OFDM-QPSK signal. The OFDM-QPSK signal and compressed one were transmitted sequentially due to the limitation of AWG input port.

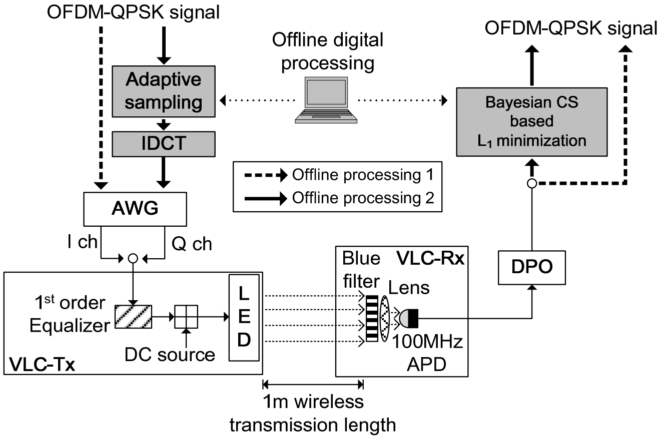


Fig. 2. Experimental setup for reconstruction of the compressed OFDM-QPSK signal in an optical wireless link based on a white LED.

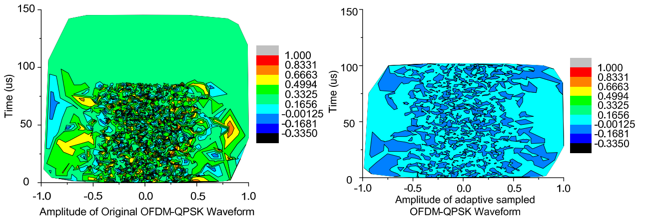
IV. EXPERIMENTAL RESULTS

Figure 3 shows the distribution of signal components which are transformed using IDCT against amplitude of each waveform. A y-axis means how each component transformed by IDCT is changed according to the propagation time. Fig. 3(a) shows how signal components transformed by IDCT are distributed in case of original OFDM-QPSK waveform. Fig. 5(b) shows the result in case of adaptive sampled OFDM-

QPSK waveform at a compression ratio of 30 %. The compression ratio is defined in Eq (7).

$$\text{Compression ratio (\%)} = \left(1 - \frac{\text{Length of compressed data}}{\text{Length of original data}}\right) \times 100 \quad (7)$$

Here, areas with the color of blue and sky shows the signal components with smaller amplitude than that with the color of red, orange, yellow, green, and black. As shown in Fig. 3(a) and (b), the usage of adaptive sampling has more signal components near to zero than using IDCT without adaptive sampling. This result tells us that using IDCT with adaptive sampling allows us to have a high sparse waveform. After the transformation using IDCT, the original OFDM-QPSK signal and the compressed one was transmitted through the air to the VLC-Rx sequentially, and then demodulated or reconstructed using L1-minimization based on Bayesian CS.



(a) (b)

Fig. 3. Contour of signal components transformed by IDCT, (a) in case of original OFDM-QPSK waveform, (b) in case of adaptive sampled OFDM-QPSK waveform.

Figure 4 shows the variation of EVM as well as the transmitted data rate at two kinds of modulation format (QPSK and 16 quadrature amplitude modulation (QAM)) against the compression ratio. Two constellations of 16-QAM symbols and QPSK ones were measured at the compression ratio of 35% and 20% respectively. Transmitted data rate means the transmission capacity of signal which is reconstructed after the compressed signal is received. The filled squares show the EVM of the QPSK symbols, and the open squares correspond to its transmitted data rate. The filled triangles show the EVM of the 16QAM symbols, and the open triangles correspond to its transmitted data rate. As the criteria of transmission performance, It was reported that the EVMs of 16-QAM symbols and QPSK ones were 14 % and 32 %, respectively at the forward error correction (FEC) limit (bit error rate (BER) of 10^{-3}) [12-13]. As shown in Fig. 4, it was observed that the compression ratio of almost 20% and 40% could be obtained in case of 16-QAM and QPSK, respectively. These experimental results tell us that in case of QPSK, transmission capacity can be increased from 31.12 Mb/s to 51.87 Mb/s, while in case of 16-QAM, it can be increased from 62.5 Mb/s to 78.13 Mb/s. In case of high order modulation format more than 16-QAM, it is expected that the transmitted data rate will be reduced due to the decrease in compression ratio as the level of modulation format grow higher because the minimum SNR, which is required for error free transmission, also increased at high order modulation more than 16-QAM.

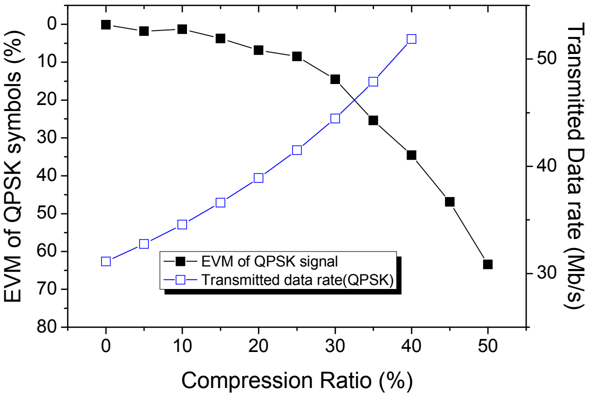


Fig. 4. Variations of EVM and transmitted data rate against the compression ratio. The dotted lines indicate two FEC limits of 16 QAM and QPSK (EVM of 14 % = BER of 10-3, EVM of 32 % = BER of 10-3,).

V. CONCLUSION

A new technique, which can improve the transmission capacity of optical wireless link based on visible LED was proposed in this letter. In the proposed method, the OFDM signal encoded by multi-level digital modulation (QPSK and 16-QAM) was compressed using the adaptive sampling with IDCT and then reconstructed using L1-minimization based on the Bayesian CS technique. In case of QPSK symbols, the transmission capacity was increased from 31.12 Mb/s to 51.87 Mb/s at the compression ratio of 40 %, while It was improved from 62.5 Mb/s to 78.13 Mb/s at the compression ratio of 20 % under the 16-QAM symbols in the error free wireless transmission (FEC limit: BER of 10^{-3}). These experimental results tell us that the shortage of transmission capacity of optical wireless link using the visible LED with narrow channel bandwidth can be resolved using the proposed Bayesian CS technique.

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