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Indoor Sensor Data Transmission for Energy-Saving Buildings

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***Abstract*—Sensor data transmission for indoor sensor network for energy saving buildings can be accomplished by indoor visual light communication (VLC) technology using the white LED originally equipped for energy saving illumination. In this paper, new blind equalization methods are proposed for enhanced data rate and robustness against multipath effect, DC bias and impulsive noise which are crucial obstacles in indoor VLC. Based on the property that the Gaussian kernel of lagged cross-correlation of probabilities (LCCP) method has the inherent immunity against those obstacles, decision feedback (DF) approach is applied for data rate improvement. From the results of the simulation, DF version of LCCP algorithm yielded about 8 dB of MSE performance enhancement showing rapid compensation for multipath effect undisturbed by impulsive and DC bias noise in the indoor VLC environment.**

Keywords—sensor network; indoor VLC; LCCP; decision feedback; DC bias noise; multipath

I. Introduction

Innovations in the design and construction of sustainable green buildings have gained significant interest in recent years. It has been estimated that the deployment of an intelligent monitor and control systems through sensor networks can result in around 20% savings in energy usage and play a crucial role in green buildings [1]. But the cost of running wire for sensors in buildings is 50%-90% of the cost of the sensor network. Wireless communications could eliminate that cost and reduce it further allowing sensors to be embedded in products such as furniture and floor and enabling improved control of the indoor environment with dense wireless sensor networks [2].

For indoor wireless sensor data communication, there can be radio frequency (RF) and optical wireless technology. Recently, owing to the abundance of unregulated bandwidth at the optical frequencies and the usability even in RF-restricted areas such as hospitals, optical wireless is a promising complementary technology for RF. The signal in optical wireless transmission is modulated by the intensity of a light emitting diode (LED).

LEDs are useful in many areas, especially in energy saving green buildings. White LEDs are great options for illumination due to their long lifetimes and energy efficiencies. And also by modulating the white LEDs at high rates sensor information can be carried in a way that is imperceptible to humans. This technology is called visible light communication (VLC) for both lighting and communication [3].

In indoor VLC systems employing LEDs, non-directed links can be classified into line-of-sight (LOS) links and non line-of-sight (NLOS) links. LOS links, depending on the existence of an unobstructed path between the transmitter and receiver, can maintain small path loss, but are susceptible to blockage. NLOS links, utilizing reflected paths of the light from indoor surfaces of wall, ceiling and furniture can be easily used and have strong robustness to blocking, but suffer from multipath effect [4][5]. Multipath effect may result in intersymbol interference (ISI) in the received signal. Besides multipath problems in NLOS links of VLC systems with white LEDs, background solar radiation and incandescent lamps are the main source of DC bias noise seriously affecting the received sensor data [6].

Recently for home sensor networking, new integrated systems of VLC system utilizing white LEDs with power line communication (PLC) system using the ubiquitous wired infrastructure are emerging [7][8]. In the integrated systems some sensor readings on the wireless sensor nodes can be transmitted through the LED lighting on the ceiling or walls and then retransmitted through the PLC to the control system of the building or out to the smart grid.

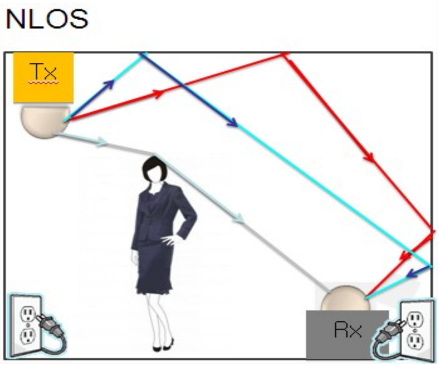
Due to the abrupt power surging on the PLC network, impulsive noise is added to the communication signal and considered the main cause of burst error occurrence in data transmitted over the PLC medium, which makes it even harder for the data to be recovered at the receiver [7][9].

In this paper, improvement of sensor data transmission in the indoor VLC/PLC environment with multipath effects, DC bias and impulsive noise by the use of blind equalization methods is investigated.

II. Multipath Effect and Noise Problems

A. Multipath of NLOS Links

In indoor VLC sensor network, the transmitted light signal goes through reflection, diffusion, and diffraction. The received signal is a summed form of signals that come through many paths as in Fig. 1. This multipath propagation induces ISI, a distortion from overlapping of multipath signals. ISI



a.

Fig. 1. Multipath effect in NLOS links of VLC systems.

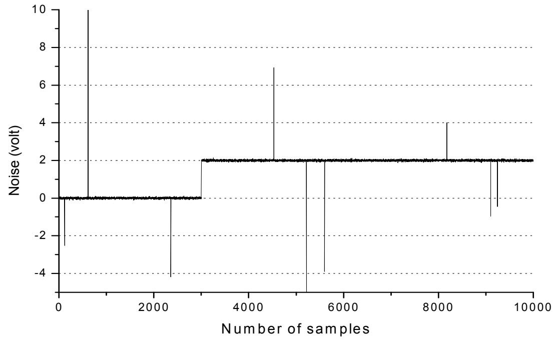


Fig. 2. Generated noise composed of DC bias and impulsive noise for simulation.

makes it difficult to achieve high data date. We can first measure the reference impulse response for the transmitter and the receiver under a direct LOS channel where the channel impulse response can be considered as an ideal delta function. And then we measure the NLOS system impulse response and compare it with the measured reference impulse response, we can gain information about the channel impulse response and the ISI power induced by multipath dispersion. It has been found in [4] that ISI has large influence on data rate performance from above 100 Mb/s and the receiver with larger field-of-view (FOV) is more prone to be affected by ISI.

B. DC Bias and Impulsive Noise

Indoor VLC systems are vulnerable to the sunlight and other illuminations. The illuminations can be abruptly turned on or off by power switches of a room and the sunlight can abruptly come in through the window by curtains or blinds. This abruptly changing ambient light induces DC bias noise that can cause decreased sensitivity and, worst of all, saturation in some types of detectors [10]. It is important to employ appropriate schemes to eliminate the abruptly inflicting DC bias noise component in the received signal [11]

In the integrated system of VLC and PLC, received data from the LED lighting are retransmitted through the sockets of PLC system. The PLC impulsive noise is generated distinguishingly by electrical switch and thermostat ON/OFF events, electrical plug plugging/unplugging, and electrical motor start [12]. The impulsive noise model in this paper is from [13][14]. The distribution of impulsive noise n_{Im} is expressed as

$$f_{IM}(n_{\mathrm{Im}}) = \frac{\varepsilon}{\sqrt{2\pi(\sigma_{GN}^2 + \sigma_{IN}^2)}} \exp\left[\frac{-n_{\mathrm{Im}}^2}{2(\sigma_{GN}^2 + \sigma_{IN}^2)}\right] + \frac{1-\varepsilon}{\sigma_{GN}\sqrt{2\pi}} \exp\left[\frac{-n_{\mathrm{Im}}^2}{2\sigma_{GN}^2}\right]. \qquad (1)$$

where σ_{GN}^2 is the variance of background Gaussian noise and σ_{IN}^2 is that of impulse noise. The impulse noise occurs according to a Poisson process and the average number ε of impulses per information symbol duration.

An example of generated DC bias and impulsive noise according to the distribution model for the integrated system of VLC and PLC is given in Fig. 2.

III. Blind Equalization Criteria with Immunity to DC Bias and Impulsive Noise

For ISI cancellation, adaptive equalizer algorithms are effective and blind algorithms are more useful in VLC systems since they do not require a training sequence to start up or to restart after a communications breakdown. Recently as a correlation function of two probability density functions (PDFs), a lagged cross-correlation of PDFs (LCCP) has been introduced and applied to blind equalization as a performance criterion [14]. LCCP for the PDF of the source symbol set $f_S(x)$ and output PDF $f_Y(x)$ at lag τ is defined as

$$R_{SY}(\tau) = \int f_S(\alpha) \cdot f_Y(\alpha + \tau) d\alpha. \qquad (2)$$

By kernel density estimation with a Gaussian kernel $G_\sigma(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-x^2}{2\sigma^2}\right]$ and a set of M symbols $\{s_1, s_2, ..., s_i, ..., s_M\}$ and $\{y_1, y_2, ..., y_i, ..., y_N\}$ $f_S(x)$ is expressed as $f_S(x) \cong \frac{1}{M}\sum_{i=1}^{M} G_\sigma(x - s_i)$. The calculation of LCCP can be done as

$$R_{SY}(\tau) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} G_{\sigma\sqrt{2}}(s_i - (y_j - \tau)). \qquad (3)$$

Blind algorithms derived by maximizing the criterion (3) have proven superior in multipath channels with impulsive and DC bias noise in [14] so equalization based on LCCP criterion can be considered to be the most desirable candidate for receiver design in indoor VLC/PLC systems. As will be shown in the simulation for the impulse response of a NLOS link in an indoor VLC channel, the linear LCCP algorithm is effective in 100 Mb/s data rate. However in 200 Mb/s rate, the method fails to produce satisfying performance without schemes for further cancelling of residual ISI.

To improve data rate by way of residual ISI cancelation, we can consider decision feedback equalizer (DFE) schemes. One of critical considerations for that approach may be error propagation problem. Since impulsive noise and abruptly added DC bias noise can induce a burst of errors in common systems and such bursts of errors inevitably yield error propagation in DFE. In this perspective, we can convince that LCCP criterion can be employed effectively to DFE since its own inherent robustness against impulsive and DC bias noise.

When we define a biased output $y_{biased,j}$ as $y_{biased,j} = y_j - \tau$ and biased error $e_{biased}(i,j)$ as $e_{biased}(i,j) = s_i - y_{biased,j}$, respectively, the Gaussian kernel in the LCCP criterion in (3) becomes $G_{\sigma\sqrt{2}}(e_{biased}(i,j))$ and is a function of biased error and an exponential decay function so that excessively large biased errors become small and negligible in maximization process of LCCP criterion.

Under the assumption of the receiver is calibrated properly, output y_j can become biased by the inflow of DC bias noise and $y_{biased,j}$ becomes free of DC bias to which the amount of τ is adjusted. Now excessively large errors can be regarded as due to severe multipath effect or strong impulsive noise. This indicates that the Gaussian kernel $G_{\sigma\sqrt{2}}(e_{biased}(i,j))$ has the inherent rejection property of ISI and impulsive noise as well as DC bias noise by adjusting the bias variable τ. This property allows us to employ decision feedback approach under the conviction that error propagation problems can be avoided.

IV. Decision Feedback Approach to LCCP Criterion

The decision feedback structure based on LCCP is composed of feed-forward section and feedback section. Feed-forward section with weight vector $\mathbf{W}_k^F = \left[w_{k,0}^F, w_{k,1}^F, w_{k,2}^F, \ldots, w_{k,P-1}^F\right]^T$ and input vector $\mathbf{X}_{k,P} = \left[x_k, x_{k-1}, x_{k-2}, \ldots, x_{k-P+1}\right]^T$ produces $y_k^F = \left[\mathbf{W}_k^F\right]^T \mathbf{X}_{k,P}^*$ and Feedback section with weight vector $\mathbf{W}_k^B = \left[w_{k,0}^B, w_{k,1}^B, w_{k,2}^B, \ldots, w_{k,Q}^B\right]^T$ and decided vector $\hat{\mathbf{D}}_{k-1} = \left[\hat{d}_{k-1}, \hat{d}_{k-2}, \ldots, \hat{d}_{k-Q-2}, c\right]^T$ produces $y_k^B = \left[\mathbf{W}_k^B\right]^T \hat{\mathbf{D}}_{k-1}^*$ where c is a constant and $\hat{d}_k$ is the decided value of a decision device through which equalizer output $y_k = y_k^F + y_k^B$ goes.

As in [4], when the basic binary modulation technique OOK with NRZ pulses is used in VLC, the PDF of transmitted symbols can be constructed using two Dirac-delta functions $(M = 2)$ as $f_S(\alpha) = \frac{1}{2}[\delta(\alpha - 1) + \delta(\alpha + 1)]$. Then LCCP (2) can be expressed as $R_{SY}(\tau) = \frac{1}{2}(f_Y(1+\tau) + f_y(-1+\tau))$ and calculated with $\{y_k, y_{k-1}, \ldots, y_{k-N+1}\}$ as

$$R_{SY}(\tau) = \frac{1}{2N}\sum_{i=0}^{N-1}[G_\sigma(1+\tau-y_{k-i}) + G_\sigma(-1+\tau-y_{k-i})]. \quad (4)$$

To maximize (4) with respect to each weight vector, each gradient is obtained as

$$\begin{aligned}\frac{\partial R_{SY}(\tau)}{\partial \mathbf{W}^F} &= \frac{1}{2N}\sum_{i=0}^{N-1}\frac{\partial}{\partial \mathbf{W}^F}[G_\sigma(1+\tau-y_{k-i}) + G_\sigma(-1+\tau-y_{k-i})] \\ &= \frac{1}{2\sigma^2 N}\sum_{i=0}^{N-1}[(1+\tau-y_{k-i})\cdot G_\sigma(1+\tau-y_{k-i}) \\ &\quad -(-1+\tau-y_{k-i})\cdot G_\sigma(-1+\tau-y_{k-i})]\mathbf{X}_{k-i,P}^*. \quad (5)\end{aligned}$$

By the steepest ascent method with a step size μ_{LCCP}, we have the weight updating equation for forward section as

$$\begin{aligned}\mathbf{W}_{k+1}^F = \mathbf{W}_k^F &+ \frac{\mu_{LCCP}}{2\sigma^2 N}\sum_{i=0}^{N-1}[(1+\tau-y_{k-i})\cdot G_\sigma(1+\tau-y_{k-i}) \\ &-(-1+\tau-y_{k-i})\cdot G_\sigma(-1+\tau-y_{k-i})]\mathbf{X}_{k-i,P}^*. \quad (6)\end{aligned}$$

Accordingly,

$$\begin{aligned}\mathbf{W}_{k+1}^B = \mathbf{W}_k^B &+ \frac{\mu_{LCCP}}{2\sigma^2 N}\sum_{i=0}^{N-1}[(1+\tau-y_{k-i})\cdot G_\sigma(1+\tau-y_{k-i}) \\ &-(-1+\tau-y_{k-i})\cdot G_\sigma(-1+\tau-y_{k-i})]\hat{\mathbf{D}}_{k-i-1}^*. \quad (7)\end{aligned}$$

For convenience's sake, equation (6) and (7) will be referred to in this paper as LCCP-DF.

Defining $\mathring{y}_k^B$ as $\mathring{y}_k^B = \left[\mathring{\mathbf{W}}_k^B\right]^T \left[\mathring{\mathbf{D}}_{k-1}\right]^*$ with $\mathring{\mathbf{W}}_k^B = \left[w_{k,0}^B, w_{k,1}^B, w_{k,2}^B, \ldots, w_{k,Q-1}^B\right]^T$ and $\mathring{\mathbf{D}}_{k-1} = \left[\hat{d}_{k-1}, \hat{d}_{k-2}, \ldots, \hat{d}_{k-Q-2}\right]^T$, the equalizer output becomes

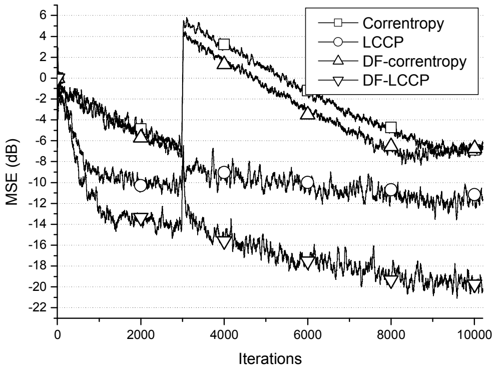


Fig. 3. MSE convergence performance.

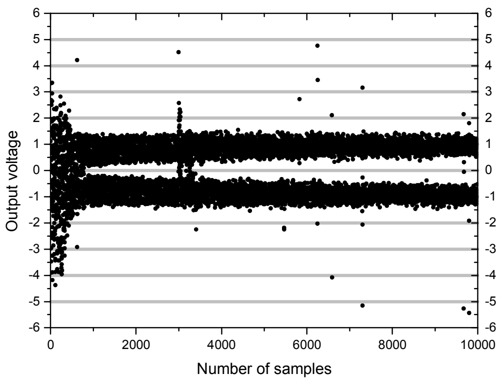


Fig. 4. The convergence of output samples of DF-LCCP.

$y_k = y_k^F + \mathring{y}_k^B + w_{k,Q}^B c$. Then $R_{SY}(\tau)$ in (4) can be rewritten as

$$R_{SY}(\tau) = \frac{1}{2N}\sum_{i=0,}^{N-1}[G_\sigma(1 - y_{k-i}^F - \mathring{y}_k^B + \tau - w_{k-i,Q}^B \cdot c) + G_\sigma(-1 - y_{k-i}^F - \mathring{y}_k^B + \tau - w_{k-i,Q}^B \cdot c)] \quad (8)$$

When the criterion (8) is maximized, the arguments of Gaussian kernel are minimized, in effect, three operations are carried out. One is that excessively large argument values by impulsive noise are cut out due to the exponentially decaying function of Gaussian kernel. Another operation is that $y_{k-i}^F + \mathring{y}_k^B$ produced with received signal approaches the symbol points 1 or -1, and ISI in forward section and residual ISI in feedback section are removed in each section output y_{k-i}^F and $\mathring{y}_k^B$, respectively. Finally we can notice that as DC bias noise makes output y_k biased by the amount of τ, $w_{k-i,Q}^B \cdot c$ approaches τ so that DC bias noise is cancelled.

V. Results and Discussions

Impulse response of NLOS links in VLC systems may vary largely from room to room. As an example to measure the impulse response the authors in [4] took an empty typical office room with a transmitter and two FOV receivers $Rx1$ (40°) and $Rx2$ (132°), where 132° FOV is more prone to be affected by ISI. They also found that ISI has large influence on data rate performance from 100 Mb/s, we opted to use the following normalized impulse response for 200 Mb/s data rate and FOV 132° for this simulation.

$$H(z) = 0.3041 + 0.6595z^{-1} + 0.5512z^{-2} + 0.3497z^{-3} + 0.1711z^{-4} + 0.1064z^{-5} + 0.0608z^{-6} + 0.0418z^{-7} + 0.0190z^{-8} + 0.0076z^{-9} \quad (9)$$

As in [4] for VLC, binary symbol {+1,-1} is transmitted through the channel. The random impulsive and abrupt DC bias noise as in Fig. 2 is added to the received signal where $\varepsilon = 0.0012$, $\sigma_{GN}^2 = 0.001$, $\sigma_{IN}^2 = 50$, DC=2 (abruptly added to the background Gaussian noise from the sample number 3000). For DF $P = 11$ and $Q = 4$ while $L = 15$ for the linear counterpart. The constant c for $\hat{\mathbf{D}}_{k-1}$ is set to 3. We use the data-block size $N = 2$ and the kernel size $\sigma = 0.6$. The convergence parameter $\mu_{LCCP} = 0.01$ is used. Performance comparison is carried out with correntropy algorithm introduced in [13] that has been developed recently based on the generalized correlation function in a kernel-transformed space and known to have impulsive noise immunity.

From the results of MSE learning curves as shown in Fig. 3, the linear and DF version of correntropy algorithm suffer seriously from the abrupt DC bias noise under the NLOS/VCL channel with impulsive noise recovering the steady state MSE (-7 dB) with very slow convergence of about 600 samples from the sample time 3000. On the other hand, linear and DF version of LCCP rapidly converge again within 200 samples right after DC noise addition and reach -12 dB and -20 dB, respectively. The result indicates that DF-LCCP can enable the VLC system to achieve double the data rate of current speed 100 Mb/s.

The immunity performance against impulsive and DC bias noise can be more clearly observed in Fig. 4, where the output samples of the DF-LCCP are concentrated and quickly returned to the symbol points -1 and 1 after the addition time of DC bias. It is also noticed that the outlying output samples do not have influence on the following output samples. This implies that due to the Gaussian kernel, the weight updating process of LCCP-type algorithms is undisturbed by outliers such as impulsive noise.

VI. CONCLUSION

In this paper, blind equalization methods are investigated for sensor data transmission in indoor VLC/PLC environment with NLOS multipath links, DC bias and impulsive noise. Based on the property that error propagation problems can be avoided since the Gaussian kernel of LCCP method has the inherent immunity against ISI and impulsive noise as well as DC bias noise, decision feedback approach is applied to the indoor sensor data transmission for data rate improvement. From the results of the simulation in the 200 Mb/s NLOS/VCL channel environment with DC bias and impulsive noise, the DF version of LCCP algorithm yielded about 8 dB of MSE performance enhancement showing rapid cancellation of abruptly added DC bias noise and ISI cancellation capability undisturbed by impulsive noise. These results indicate that the proposed method can be an excellent candidate for blind data communication for indoor sensor network for energy saving buildings.

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