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Reducing Environmental Noise Light Interference in Visible Light Communication Using a Solar Cell

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Abstract: In this study, we introduce a new method to reduce the interference of environmental noise light in a Visible Light Communication (VLC) system, using a solar cell. In the VLC transmitter a Light Emitting Diode (LED) array was used for the light source and in the VLC receiver a differential detector with a photodiode and a solar cell was used for the light detector. By subtracting the solar cell voltage from the photodiode voltage using a differential amplifier, we removed the noise contained in the photodiode voltage. In the experiment, the Signal-to-Noise Ratio (SNR) was improved by about 15 dB using the solar cell. This configuration is useful for constructing a VLC link without noise light interference in an environment where the noise light interference from a conventional fluorescent lamp or incandescent lamp is severe.

Key words: Visible light communication, LED, environmental noise light, noise reduction, constructing, incandescent

INTRODUCTION

Recently, LED manufacturing technology has been rapidly developing and high-power visible LEDs of several W or more are being mass-produced and widely used as a light source for illumination. Visible LEDs have higher power conversion efficiency than conventional fluorescent lamps or incandescent lamps and the LED illumination is easily controlled by changing the injection current, so the use of visible LEDs is steadily increasing. Since, LED light can be modulated at a speed faster than the human eye can detect, Visible Light Communication (VLC) technology which uses LED light to perform simultaneous illumination and communication is steadily developing (Komine and Nakagawa, 2004; Cheong *et al*., 2013).

Since, VLC performs both the functions of lighting and communication at the same time, the system must be designed so that the lighting and communication are not affected by each other. In order to keep flicker-free lighting during data transmission, LED modulation using Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), manchester coding or Pulse Position Modulation (PPM) has been widely used. These are efficient ways of keeping the average LED power constant during data transmission, thus, preventing the LED light from perceptively flickering (Ma *et al*., 2012; Rajagopal *et al*., 2012).

Since, the VLC usually transmits data through a free space between the LED and the photodetector, the transmission condition can be affected by interference from noise light from adjacent lighting facilities such as fluorescent lamps and incandescent lamps. Adopting an optical filter or an electrical filter in the VLC receiver is an efficient way to reduce the influence of noise light (Kahn and Barry, 1997). When the noise frequency is near to that of the signal or when the noise wavelength overlaps the signal wavelength, it may be difficult to prevent noise interference with optical or electrical filters. In that case a differential detection can be an efficient way to reduce the noise light interference (Street *et al*., 1997). Differential detection is a method of using two detectors with different coupling coefficients to noise and remove noise components by subtracting one detector voltage from the other.

In this study, we newly introduce a differential detection method that removes the interference of low-frequency noise light using a solar cell. In this structure we use two light-detecting components with different bandwidths: one is a high-speed photodiode and the other is a low speed solar cell. The solar cell has the bandwidth of a few tens kHz which is much lower than the photodiode bandwidth, due to its wide receiving area (Lee, 2015). Although, the response speed of a solar cell is very low compared to that of a photodiode, the solar cell detects 120 Hz noise from fluorescent lamps or incandescent lamps that are driven by an AC power source of 60 Hz.

If we use a signal frequency that is lower than the photodiode bandwidth and higher than the solar cell, the photodiode will detect the signal light mixed with noise light while the solar cell detects only noise light. In this configuration the solar cell is used for two purposes: the AC component of the solar cell voltage is used as a differential input for removing the noise component in the photodiode and the DC component is used as a power supply for biasing the photodiode. This structure is very useful for constructing a noise-free VLC link using LED light in an environment where the interference of noise light due to a conventional fluorescent lamp or incandescent lamp is severe.

MATERIALS AND METHODS

The VLC system is composed of a transmitter and a receiver. The system configuration of the transmitter and a receiver are as follows.

VLC transmitter: The VLC transmitter is illustrated in Fig. 1. It is composed of an Amplitude-Shift-Keying (ASK) modulator, a Field Effect Transistor (FET) and an LED array. Input data is ASCII code generated by a microprocessor and applied to the input of the ASK modulator. The ASK modulated voltage is applied to the gate of the FET. The FET is biased to operate in the linear region using two resistors Ra and Rb.

The drain current of the FET is proportional to the gate voltage and flows to the LED array and as a result the LED output light is proportional to the ASK modulated input data. The LED output light is radiated to the free space and a part of the light reaches the VLC receiver. The optical power of the LED array can be expressed as follows:

$$P(t) = \begin{cases} P_0 + P_s \sin \omega t & \text{when } V_{in} = 1 \\ P_0 & \text{when } V_{in} = 0 \end{cases} \quad (1)$$

Where:

P_0 = The DC optical power

P_S = The optical amplitude of the ASK modulated signal

ω = The subcarrier frequency

V_{in} = The input voltage that is applied to the input port of the VLC transmitter

The devices used in the VLC transmitter were as follows. Input data was generated by an Atmega 32 microprocessor and the ASK modulator was made using a 200 kHz oscillator and ADG 417 analog switch. The LED array was made of six identical LEDs in the form of a 2H3 array, each LED was a 1 W white LED.

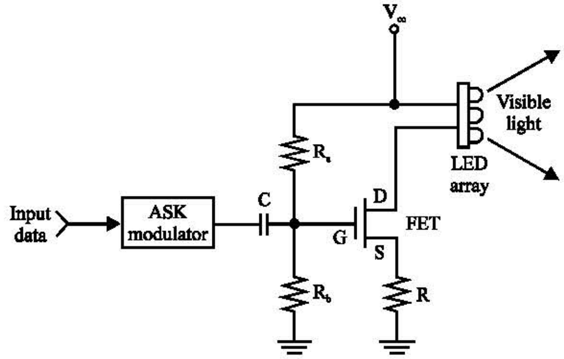

Fig. 1: VLC transmitter

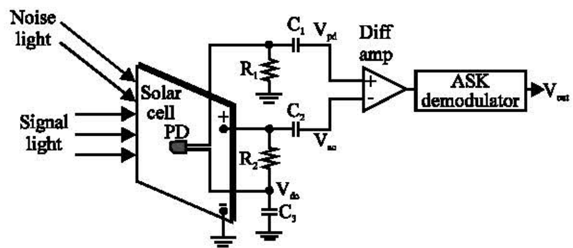

Fig. 2: VLC receiver

VLC receiver: The VLC receiver is schematically shown in Fig. 2. The VLC receiver is composed of a PhotoDiode (PD), a solar cell, a differential amplifier and an ASK demodulator. In Fig. 2, both the photodiode and the solar cell are used for light detection, however, the solar cell has a bandwidth that is much lower than that of the photodiode. R_1 and R_2 are the load resistances of the photodiode and the solar cell, respectively. C_1 and C_2 are the capacitors for AC detection and capacitor C_3 was used to supply DC power to the photodiode using the solar cell voltage. Therefore, in this configuration, the solar cell is used for noise light detection and at the same time supplying DC power to the photodiode.

The photodiode and the solar cell detect the signal light from the VLC transmitter. At this time, noise light from a nearby lighting facility such as a fluorescent lamp or an incandescent lamp may exist at the position of the photodetector. In this environment, the signal light from the VLC transmitter and the noise light from other nearby lighting facilities enter the photodiode and the solar cell at the same time. In general, the receiving bandwidth of a solar cell is significantly lower than that of a photodiode. When the ASK modulation subcarrier frequency in the VLC transmitter is lower than the photodiode receiving bandwidth and higher than that of the solar cell, the AC voltages generated in the photodiode and the solar cell can be expressed as follows:

$$V_{pd}(t) = \begin{cases} \rho_1 R_1 \left[k_{1,S} P_S \sin\omega t + k_{1,N} P_N(t)\right] & \text{when } V_{in} = 1 \\ \rho_1 R_1 k_{1,N} P_N(t) & \text{when } V_{in} = 0 \end{cases} \quad (2)$$

$$V_{solar}(t) = \rho_2 R_2 k_{2,N} P_N(t) \quad (3)$$

Where:

- $V_{pd}(t)$ and $V_{solar}(t)$ = The output voltages of the photodiode and solar cell, respectively
- $P_N(t)$ = The noise light power
- ρ_1 and ρ_2 = The responsivities of the photodiode and the solar cell, respectively
- R_1 and R_2 = The load resistances of the photodiode and the solar cell, respectively
- $k_{1,S}$ and $k_{1,N}$ = The coupling coefficient from the VLC transmitter and the noise source to the photodiode, respectively
- $k_{2,N}$ = The coupling coefficient from the noise source to the solar cell

In Eq. 2, the first term is the signal voltage from the VLC transmitter and the second is the noise voltage from the environmental noise source such as a fluorescent lamp. In Eq. 3, the solar cell voltage only has the noise term because the solar cell bandwidth is lower than the ASK carrier frequency and it does not detect the ASK carrier frequency. As shown in Fig. 2, the photodiode voltage and the solar cell voltage are applied to the positive and negative input terminals of a differential amplifier, respectively. The output voltage of the differential amplifier is:

$$V_{pd}(t) = G(V_{pd} - V_{solar}) = \begin{cases} G[\rho_1 R_1 k_{1,S} P_S \sin\omega t + \rho_1 R_1 k_{1,N} P_N(t) - \rho_2 R_2 k_{2,N} P_N(t) \text{ when } V_{in} = 1] \\ G[\rho_1 R_1 k_{1,N} P_N(t) - \rho_2 R_2 k_{2,N} P_N(t)] \text{ when } V_{in} = 0 \end{cases} \quad (4)$$

where, G is the voltage gain of the differential amplifier. If we set $\rho_1 R_1 k_{1,N} = \rho_2 R_2 k_{2,N}$ by adjusting the ratio R_1/R_2, in Eq. 3) the noise term disappears and only the signal term remains. That is:

$$V_{out}(t) = \begin{cases} G\rho_1 R_1 k_{1,S} \sin\omega t & \text{when } V_{in} = 1 \\ 0 & \text{when } V_{in} = 0 \end{cases} \quad (5)$$

As a result when the input data is “1” in the transmitter, only the subcarrier signal exists in the receiver and when the input data is “0”, the receiver voltage is 0 V, so that, the ASK signal is normally received without being influenced by the noise light.

The devices used in the VLC receiver were as follows. We used an M11080-12 V silicon solar cell, BPW34 PIN photodiode for light detection and used an opa228 op-amp for the differential amplifier. The ASK demodulator was composed of an envelope detector and

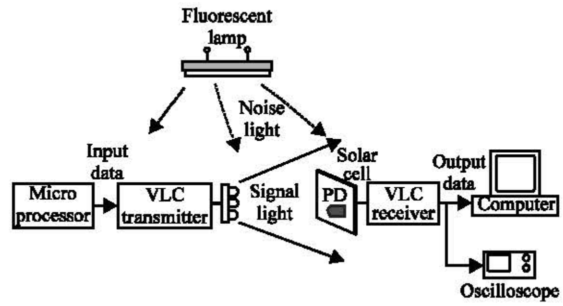

Fig. 3: Experimental setup

a comparator. The envelope detector was made of a diode and RC circuit and an LM7171 op-amp was used for the comparator. The load resistances R_1 and R_2 were 1 k and 2 kΩ, respectively. Capacitors C_1-C_3 were 0.1, 0.1 and 100 uF, respectively.

Experimental setup: Figure 3 is a schematic diagram of the experimental setup. A VLC transmitter and an LED array were installed on a table. The VLC transmitter circuit was configured as described in Fig. 1. The LED array was made of six identical LEDs in the form of a 2H3 array, each LED was a 1 W white LED. An Atmega 8 microprocessor was connected to the input port of the VLC transmitter and used as a data generator. A 60 W fluorescent lamp was installed on the ceiling of the laboratory for indoor illumination. The fluorescent lamp showed 120 Hz noise and it induced noise voltage in the VLC receiver.

At a distance of about 2 m from the LED array, a VLC receiver with a solar cell and a PIN photodiode was placed. The solar cell was an M11080-12 V and the photodiode was BPW34. The VLC receiver circuit was configured as shown in Fig. 2. The output of the VLC receiver was sent to a computer to see the transmitted character data. We used an HP 52615B oscilloscope to observe the waveforms in the VLC transmitter and the receiver.

Observed waveforms: We programmed the microprocessor to generate ASC2 characters “A\tVLC-CH\r\n” and applied the data to the input port of the ASK modulator whose carrier frequency was 200 kHz. The data rate was 9.6 kbps and the data was in Non-Return-to-Zero (NRZ) code format. The ASK modulated input data was applied to the gate of an FET as shown in Fig. 1. The FET was biased to operate in the linear region and the drain current was proportional to the gate voltage. The drain current flowed to the LED array and it radiated visible light into free space.

Figure 4 shows the waveforms observed with an oscilloscope in the VLC transmitter. Figure 4a shows the

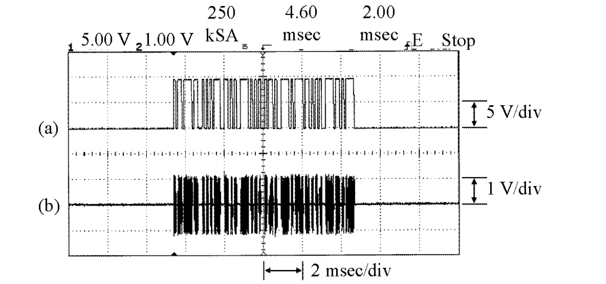

Fig. 4: Waveforms in VLC transmitter: a) Input data waveform and b) ASK modulated waveform

voltage waveform of the data going from the microprocessor to FET gate in the VLC transmitter. The data waveform corresponds to a character string "A\tVLC-CH\r\n" in NRZ code. Figure 4b is the output voltage of the ASK modulator. The black region is a 200 kHz carrier signal and the envelope is the same as the transmitted data. The ASK modulated light from the LED array radiated toward the direction of the VLC receiver. The photodiode and the solar cell in the VLC receiver have different bandwidths. In separate experiments, we measured the bandwidths of the PIN photodiode and the solar cell. In order to measure the bandwidths, we modulated the LED with a sine wave of 1Vpp amplitude and measured the voltages of the photodiode and the solar cell while increasing the modulation frequency.

Figure 5 shows the measured AC responses of the photodiode and the solar cell. Figure 5a is the normalized AC response of the PIN photodiode and Fig. 5b is that of the solar cell. The 3 dB receiving bandwidth is the frequency at which the AC response falls to $1/\sqrt{2}$ of its maximum. As shown in Fig. 5, the 3 dB bandwidth of the PIN photodiode and the solar cell were measured to be about 500 kHz and about 8 kHz, respectively. Thus, the carrier frequency 200 kHz in the ASK modulator of the VLC transmitter was lower than the PIN photodiode bandwidth and higher than the solar cell bandwidth. The differential amplifier in the VLC receiver subtracts the solar cell voltage from the PIN photodiode voltage and detects only the signal voltage as shown in the circuit of Fig. 2.

Figure 6 shows the waveforms observed in the VLC receiver. Figure 6a shows a PIN photodiode voltage in which the ASK modulated signal is mixed with the 120 Hz noise from the fluorescent lamp. The peak-to-peak ASK signal amplitude was about 0.13 V, the peak-to-peak noise voltage was about 0.14 V and the Signal-to-Noise Ratio (SNR) was 0.93 (-0.63 dB). Figure 6b is the solar cell voltage in which only 120 Hz noise is detected. Figure 6c denotes the output voltage of the differential amplifier in

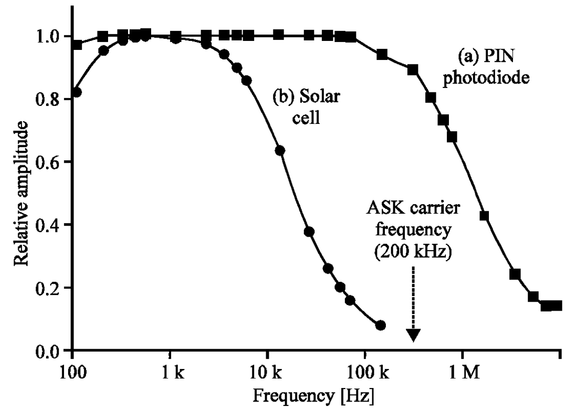

Fig. 5: AC response characteristics: a) PIN photodiode and b) A solar cell

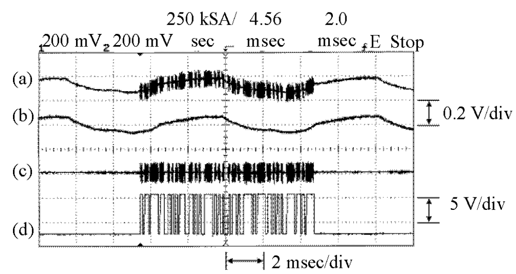

Fig. 6: Waveforms observed in VLC receiver: a) Photodiode voltage; b) Solar cell voltage; c) differential amplifier output and d) ASK demodulated output

the VLC receiver. In this waveform, the 120 Hz noise almost disappeared and only the ASK modulated signal was detected. In this waveform, the peak-to-peak ASK signal voltage was about 4.4 V while the peak-to-peak noise voltage was about 0.8 V and SNR was 5.5 (14.8 dB). Comparing the two waveforms of Fig. 6a and c, the SNR in the photodetector was improved by 15.43dB by using a solar cell. Figure 6d is the recovered NRZ digital waveform observed at the output of the ASK demodulator in the VLC receiver. This waveform was the same as the input data "A\tVLC-CH\r\n" in Fig. 4a.

To check the transmission condition of the characters, we connected this waveform to the serial port of a computer and observed the characters on the monitor. Figure 7 shows the characters displayed on the computer monitor. As shown in Fig. 7, the character string "VLC-CH" was displayed on the monitor. Among the characters sent by the VLC transmitter, "\t" (horizontal tab), "\r" (carriage return), "\n" (line feed) do not appear on the monitor because they are special characters indicating the positions of the characters on the screen.

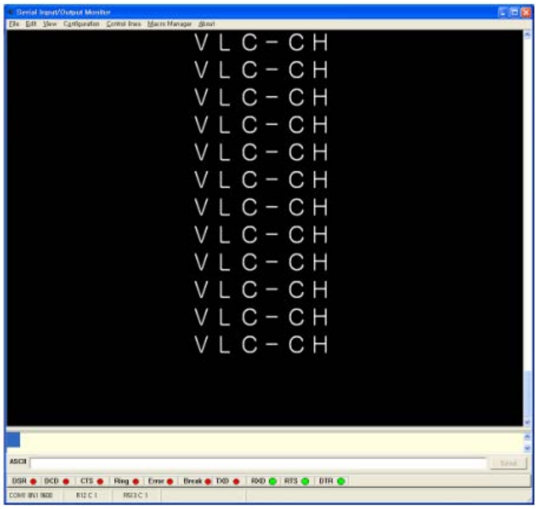

Fig. 7: Characters displayed on a monitor

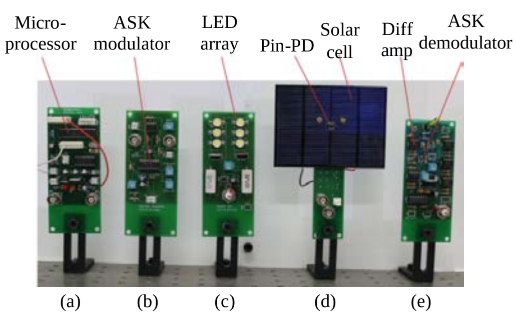

Fig. 8: Circuit boards used in experiments: a) microprocessor; b) ASK modulator; c) LED array; d) PIN photodiode and solar cell circuit and e) Differential amplifier and ASK demodulator

Thus, we experimentally confirmed that the interference of noise light can be prevented by using a solar cell in an environment where noise light could affect the VLC transmission.

Figure 8 shows the circuit boards used in the experiments. Figure 8a is the microprocessor circuit that was used for a data generator in VLC transmitter. Figure 8b is the ASK modulator in the VLC transmitter. Figure 8c shows the 2×3 LED array with FET circuit. Figure 8d shows a PIN photodiode and a solar cell. Figure 8e is the differential amplifier and the ASK demodulator circuit.

RESULTS AND DISCUSSION

We have experimentally demonstrated that we can reduce the interference of environmental noise light using differential detection with a photodiode and a solar cell in the VLC receiver. We measured their bandwidths and determined the PIN photodiode bandwidth was about 500 kHz and the solar cell bandwidth was about 8 kHz, respectively. The noise frequency from a fluorescent lamp was 120 Hz which is twice the power line frequency of 60 Hz. Therefore, the noise could be detected by the PIN photodiode and the solar cell simultaneously. By setting the ASK carrier frequency higher than the solar cell bandwidth, we could reduce the noise interference by subtracting the solar cell voltage from the photodiode voltage. In experiments we set the ASK modulation carrier frequency at 200 kHz which is between the bandwidths of the PIN photodiode and the solar cell.

In the VLC receiver, we placed the photodiode at the center of the solar cell surface in order to ensure the noise light intensity at the photodiode and at the solar cell would be the same. When the photodiode and the solar cell were exposed to the ASK signal light from the VLC transmitter and the noise light from a fluorescent lamp simultaneously, the photodiode detected the signal mixed with the noise while the solar cell detected the noise only. This is because the photodiode bandwidth was higher than the ASK carrier frequency while the solar cell bandwidth was lower than the ASK carrier frequency. By subtracting the solar cell voltage from the photodiode voltage using a differential amplifier we could detect the signal with the noise almost entirely removed.

CONCLUSION

In experiments we improved the SNR in the VLC receiver by about 15 dB using the solar cell. In this configuration the solar cell was used for two functions: for noise reduction as well as to supply DC power to the photodiode. This configuration is very useful for constructing a noise-free VLC link using LED light in an environment where noise light interference from a conventional fluorescent lamp or incandescent lamp is severe.

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