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Transmitting ECG waveforms by means of optical antennas

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***Abstract*—We present the characterization of electrocardiogram (ECG) signals transmitted using optical wireless communication (OWC). The system used a light-emitting-diode (LED) and silicon photodiode as optical wireless antennas. OWC system transmitted the optical signal within the distance of 50 cm to 1 m with line-of-sight (LOS) configuration. After the transmission, the received ECG signal was filtered using Gaussian filter and analyzed using Shannon energy to obtain signal peaks. Accuracy, sensitivity, detection error rate and positive predictive values were evaluated to qualify the signal that is transmitted using OWC system. We carefully characterize the electrocardiogram signals after transmission and found that they present high accuracy. Heart rate variability was analyzed to provide the heart rate condition from ECG signals after the optical wireless transmission.**

Keywords*—*electrocardiogram, heart rate, optical wireless communication

I. INTRODUCTION

Medical technology plays a significant role to monitor health information of patients, such as glucose level, heart rate, blood pressure [1]. However, the cabling in medical devices for health monitoring can interfere with the operation process and nursing, especially in the intensive care unit and operating rooms [2]. Medical devices using wireless technology such as radio frequency (RF) has been proposed to monitor medical data for elderly [3], to monitor vital signs of patients such as respiration rate, blood pressure heart rate pulse and body temperature [4], and to analyze biomedical data for diagnostic [5]. Although RF is beneficial in medical applications, the electromagnetic radiation can potentially cause harm to patient health because of the long-term negative effects of being exposed by RF radiation [6]. Furthermore, medical devices using RF and metals equipment in the operating room can generate multipath interference, which can decrease the performance and the transmission range [5]. Other wireless devices located near medical devices also induce electromagnetic interference [7], which can cause fault in medical devices for patients diagnoses [8].

Recently, optical wireless communication (OWC) has been proposed to overcome the problem of electromagnetic interference from RF in medical devices [9], [10]. OWC for medical has been introduced for wearable medical devices [11] and implantable medical devices [12], [13]. The key benefit of OWC for medical health monitoring is that it does not cause electromagnetic interference. Most of the OWC in medical applications uses indoor systems in the hospital. Infrared and visible light have higher frequency than RF: this can be also advantageous for medical data transmission because of the higher bandwidth.

OWC system using infrared LED has been proposed to transmit medical data such as ECG, body temperature and blood pressure [11]. However, long exposure to IR might be harmful for human eyes. Therefore, Visible Light Communication (VLC) is preferable for wearable medical device because visible light is safer than infrared. VLC could transmit medical signals using LED in visible light region [14], [15]. VLC for health monitoring has also been proposed to monitor heart rate and temperature without causing electromagnetic interference [16]. ECG transmission using VLC in line-of-sight (LOS) configuration within the distance of 50 cm has been performed to provide heart rate data of the patient [17]. Another approach of OWC using visible light Optical Camera Communication (VL-OCC) has been demonstrated to transmit medical data [18]. Several research in ECG signal transmission using OWC have been introduced. However, biomedical characterization of the OWC systems transmitting ECG signals has not been introduced. The evaluation on biomedical signal, which is received after optical wireless transmission, are crucial to prevent any misdiagnosis of the patient.

The characteristic of biomedical data in OWC is one of the important parameters for medical health monitoring. Noise in biomedical signal called artifacts is one of the issues in wireless technology for medical application. Characterization of biomedical data especially ECG is crucial for medical purpose to analyse the heart rate. ECG is an electrical measurement to collect a pattern of the electrical activity in the heart tissue which is recorded by a medical device. Generally, ECG signals are corrupted by the noises from various sources during ECG measurement by medical devices. Artifacts in the ECG signal affect the waveform pattern of the signal. The presence of artifacts would lead to misdiagnose of R peaks detection and heart rate variability (HRV) analysis. Noiseless ECG signal is required to achieve reliable and accurate diagnosis of heart rate conditions.

In this paper, we present the transmission experiment of direct analogue ECG waveforms using OWC; we perform the quantitative characterization of the ECG signal at the receiver end and evaluate the accuracy of the solution for medical applications. Analysis of received ECG signal after the

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transmission was also performed using digital signal processing to obtain HRV and heart rate. We directly transmitted the analogue ECG signals: this avoids the need to convert the analogue signal to digital signals before transmission, thus the scheme works without any analogue to digital converter (ADC) unit at the transmitter, and without any digital to analogue converter (DAC) at the receiver. Using a ADC and a DAC would be more complex if the OWC system is applied in the medical application at the hospital.

II. EXPERIMENTAL SETUP

The experimental setup for this measurement is reported in Figure. 1. The tests were realized in indoor with LOS configuration.

This experiment used ECG data recording of Apnea-ECG signals [19] and congestive heart failure signals [20] which were obtained from PhysioNet database [21]. ECG waveforms recording from PhysioNet database were imported into MATLAB. This last was used to drive an Arbitrary Waveform Generator (AWG). The AWG generated the electrical ECG waveform to be transmitted. The output of the AWG is sent to a LED driver and then to a LED, which was used as an optical antenna to transmit over free space. The LED emits light in the wavelength range from 380 to 780 nm. The received optical power was measured by spectrometer, which was placed in front of photodiode (PD). The intensity of the received light in lux, measured by a luxmeter, was converted into radiometer units to obtain the optical power in dBm. The received optical power was -19 dBm for 1 m distance of OWC system. The transmission distance spans from 50 cm to 1 meter.

On the other side, a silicon PD with active area of 18x18 mm^2 and detection of spectral range from 340 nm to 1100 nm received (with the peak sensitivity at 960 nm) the optical signal and converted it back into an electrical waveform. The PD was located on axis with the LED. The PD and the LED driver was developed for a general purpose and better results can be obtained using ad-hoc circuits. A Real-Time Oscilloscope (RTO) recorded the electrical signal after the PD. Finally, the received ECG signals were analysed using an home-made MATLAB script for ECG signal characterization.

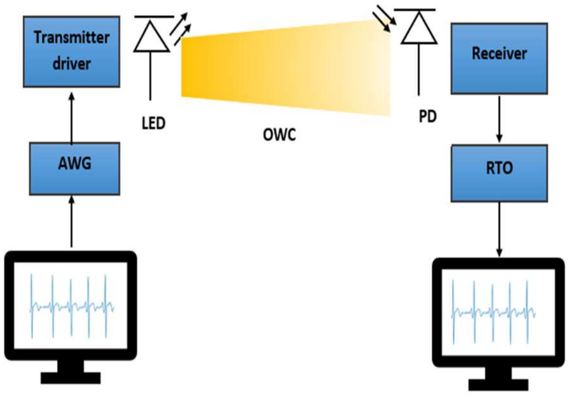

Fig. 1. Experimental setup for ECG signal transmission; AWG: Arbitary Waveform Generator; LED: Light-Emitting-Diode; OWC: Optical-Wireless Communication; PD: Photo-Diode; RTO: Real-Time Oscilloscope

Let us recall that one cycle of a normal ECG signal has waveforms of P-wave, Q-wave, R-wave or R peak, S-wave, and T-wave as shown in Figure 2. ECG signal gives heart rate information by measuring the duration of electrical waves from one cycle to another cycle. Artifacts were removed to obtain clean ECG signals after ECG recording was received by the computer. Artifacts should be removed to prevent misleading for heart rate diagnosis.

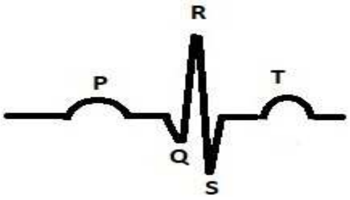

Fig. 2. Scheme of the PQRST waves in normal pattern in a ECG signal

On the received analogue waveforms, we performed signal filtering and processing to analyse the ECG waveforms. The schematic of this processing is shown in Figure 3. The analogue ECG signal in the time domain was converted into the frequency domain by Fourier transform. Then, a Gaussian filter was used to eliminate noise and artifacts in the ECG signal because the ECG signal from PhysioNet database [21] still contained noises. After filtering, the signal in the frequency domain was then converted back into time domain. After filtering, the ECG signal was normalized to simplify R peak detection.

The received ECG waveform has apparently the same pattern as the transmitted ECG signal; as an example, we report in Figure 4 the transmitted signal (blue curve) and after the received signal was filtered (red curve). The apparent similarity of the two patterns shows that the OWC antennas are a reliable means for transmitting ECG signal.

For a detailed characterization, Shannon energy envelope is the mostly used method to obtain R peak in the ECG signal by measuring energy of the signal spectrum in each sample. Shannon energy attenuating low intensities and amplifying high intensities in the ECG signal. Then, R peaks were detected by applying threshold in the Shannon energy envelope signal.

The amount of the detected R peaks in the ECG signal were calculated for characterization of the ECG signal to obtain the accuracy of the OWC system. We recall that ECG signals have Q wave, R wave and S wave which can be categorised as QRS complex (central part), and P and T wave (side). The distances between R peaks in each QRS waves in time domain were calculated to obtain the values of RR intervals. Heart rate was calculated from the duration of RR intervals. The average of RR intervals in ECG signal were multiplied by 60 to obtain heart rate in beat per minute (bpm). The analysis of HRV and of heart rate condition can also be obtained from RR intervals.

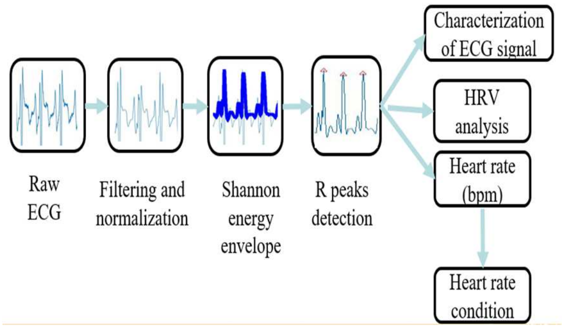

Fig. 3. Digital signal processing for electrocardiogram characterization; ECG: electrocardiogram; HRV: Heart Rate Variability; bpm: beat-per-minute

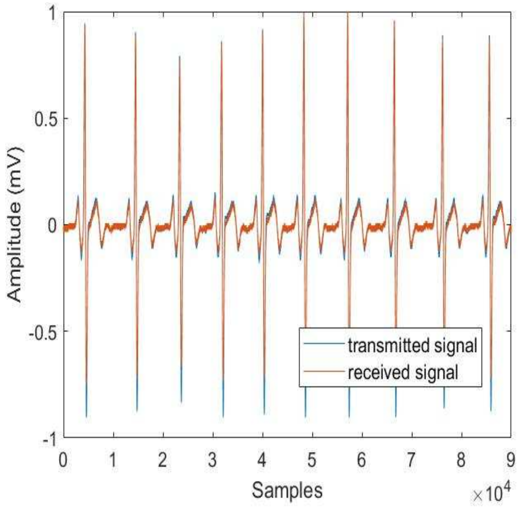

Fig. 4. Transmitted and received ECG signals; mV: mili Volts

The result of heart rate measurement in bpm was then categorized as normal or abnormal heart beats. The normal standard of the heart rate is between 60 bpm and 100 bpm. The abnormal condition is defined if the heart rate is below 60 bpm or above 100 bpm. This system measured heart rate and evaluated heart rate condition to detect abnormal heart rate from ECG signals before and after OWC. The information about heartbeat detection performance in ECG waveform was investigated using HRV analysis.

III. RESULTS

A. Heart Rate Variability analysis

Three key parameters of HRV analysis were measured in order to characterize the transmitted ECG waveforms and the received ECG waveforms. Standard deviation of average normal-to-normal (SDNN) intervals is the standard deviation of normal sinus beats as a standard of cardiac risk that predict mortality and morbidity. Normal-to-normal (NN) intervals for SDNN is calculated based on intervals between normal R peaks of two heart beats. The root mean square of successive difference (RMSDD) can be used to identify parasympathetic nervous system which can be performed later by a doctor. Coefficient of variance of RR (CVRR) intervals was measured from the value of SDNN and RMSDD. These three parameters play an important role to assess the heartbeat condition of the patient.

Table I shows the result of the HRV measurements of 10 seconds of ECG recording from PhysioNet database [20]. Each line refers to a specific waveform. ECG waveforms were transmitted using OWC system over 1 meter. As we can see in Table I, there were small different values of RMSDD and CVRR between the transmitted signals and the received signals in few ECG recordings. These small differences could be caused by the slight decrease of quality during optical wireless transmission. The value of SDNN, RMSDD and CVRR will later be used for diagnosing heart condition of patients by doctors.

TABLE I. HEART RATE VARIABILITY ANALYSIS OF ECG SIGNALS

Data	**SDNN**		**RMSSD**		**CVRR**	
	Transmit	***Received***	***Transmit***	***Received***	***Transmit***	***Received***
1	0.90	0.90	28.7	28.7	77	77
2	0.77	0.77	24.3	24.3	39	39
3	0.99	0.99	31.9	31.8	99	110
4	0.55	0.55	17.7	17.6	91	91
5	0.71	0.71	22.6	22.7	56	56
6	0.91	0.91	28.9	28.9	66	66
7	0.99	0.99	31.5	31.5	40	40
8	0.82	0.82	26.4	26.4	120	120
9	0.77	0.77	24.5	24.5	130	130

B. Characterization of ECG signal

Four parameters were measured to characterize OWC system from the ECG signal for the quantitative performance evaluation. We measured accuracy (1), sensitivity (2), positive predictive value (3). These parameters were calculated from the True Positive (TP), False Negative (FN) and False Positive (FP) of R peaks in the transmitted ECG signal and the received ECG signal. TP is the ratio of the number of correctly detected R peaks over the total number of transmitted signals. FP is a similar ratio but refers to the number of detected R peaks in the received signal but missed in the transmitted signal. FN is the ratio number of detected R peaks in the transmitted signal but missed in the received signal. The following definitions can be given:

$$Accuracy\ (\%) = (TP / (TP+FP+FN)) \times 100 \qquad (1)$$

$$Sensitivity\ (\%) = (TP / (TP+FN)) \times 100 \qquad (2)$$

$$Positive\ predictive\ value\ (\%) = (TP/(TP+FP)) \times 100 \qquad (3)$$

Each 10 seconds of ECG recording from PhysioNet database contained different amount of R peaks because the recording not only captured the normal heart rate but also abnormal heart rate. Therefore, TP has different value for each ECG signal. Characterization from the ECG signal evaluated the performance of OWC system in this experiment. Table II shows that 10 ECG recordings reached the accuracy of 100% after the OWC transmission.

TABLE II. CHARACTERIZATION FROM ECG SIGNALS

Data	TP	FP	FN	Accuracy (%)	SSE (%)	PPV (%)
1	12	0	0	100	100	100
2	16	0	0	100	100	100
3	11	0	0	100	100	100
4	18	0	0	100	100	100
5	18	0	0	100	100	100
6	11	0	0	100	100	100
7	19	0	0	100	100	100
8	20	0	0	100	100	100
9	13	0	0	100	100	100
10	10	0	0	100	100	100

TP: True Positive; FP: False Positive; FN: False Negative; SSE: Sensitivity; PPV: Positive Predictive Value

C. *Receiver sensitivity measurement*

Finally, we tested the system by placing an optical attenuator in front of the transmitter to measure the impact of the signal attenuation. 1 dB to 21 dB attenuators were used to test the receiver sensitivity. A spectrometer was placed in front of the PD and was used to measure the received optical power when the attenuator was applied to the system setup. The accuracy of the system was evaluated under the variation of the received optical power from -21.3 dBm to -39 dBm. The accuracy of the system started to decrease when the received optical power was lower than -30 dBm (reaching less than 80% at power lower than -32 dBm). Minimum optical power of -30 dBm was required the reach the high performance of the system.

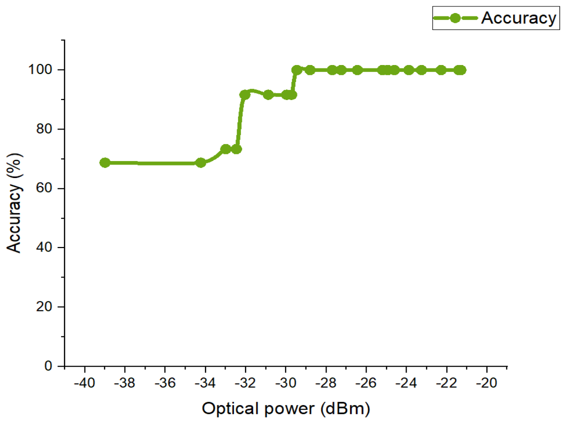

Fig. 5. Receiver sensitivity measurement; dBm: decibels per miliwatt

IV. CONCLUSION

We experimentally demonstrated that optical antennas could transfer analogue ECG signals with good accuracy. We obtained the required values for the sensitivity, the positive predictive value, and the accuracy for 1 m transmission distance with line-of-sight configuration.

A detailed HRV analysis was successfully performed to obtain the values of SDNN, RMSDD, CVRR, mean RR peak and heart rate. HRV values in transmitted signals were compared to received signals to evaluate the performance of the OWC system for medical application. HRV analysis will be useful for medical diagnosis which can be done by doctors or cardiologists. Receiver sensitivity measurement was also performed to evaluate the minimum optical power for the system. The minimum optical power of the system in this experiment was -30 dBm to reach the accuracy of 92%. Further improvements can allow to reach higher accuracy at lower power.

This first system demonstration proves the feasibility of analogue ECG signal transmission using VLC. Clearly, the present scheme is not yet suitable for mobility of the user, because the transmitter and the receiver must have a fixed position to obtain the direct sight in LOS configuration. Moreover, the perfect transmission cannot be achieved if there is any obstacle between the transmitter and the receiver. Therefore, further optimization and improvement will be required to achieve a good degree of user mobility. As example, improved performance can be achieved by optimizing the transmitter and receiver devices.

REFERENCES

[1] M. AlGhatrif and J. Lindsay, “A brief review: history to understand fundamentals of electrocardiography,” *Journal of Community Hospital Internal Medicine Perspectives*, vol. 2, no. 1, p. 14383, 2012, doi: 10.3402/jchimp.v2i1.14383.

[2] M. Paksuniemi, H. Sorvoja, E. Alasaarela, and R. Myllyla, “Wireless sensor and data transmission needs and technologies for patient monitoring in the operating room and intensive care unit,” in *2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*, 2005, pp. 5182–5185. doi: 10.1109/IEMBS.2005.1615645.

[3] S. G., R. R. Chittal, and K. Kumar, “Medical Applications of Wireless Networks,” in *2007 Second International Conference on Systems and Networks Communications (ICSNC 2007)*, 2007, p. 82. doi: 10.1109/ICSNC.2007.51.

[4] E. Teaw *et al.*, “A wireless health monitoring system,” *ICIA 2005 - Proceedings of 2005 International Conference on Information Acquisition*, vol. 2005, pp. 247–252, 2005, doi: 10.1109/icia.2005.1635090.

[5] M. Mahfouz, G. To, and M. Kuhn, “No Strings Attached,” *IEEE Microwave Magazine*, vol. 12, no. 7, pp. S34–S48, 2011, doi: 10.1109/MMM.2011.942729.

[6] Y.-K. Cheong, X.-W. Ng, and W.-Y. Chung, “Hazardless Biomedical Sensing Data Transmission Using VLC,” *IEEE Sensors Journal*, vol. 13, no. 9, pp. 3347–3348, 2013, doi: 10.1109/JSEN.2013.2274329.

[7] H. Karvonen, K. Mikhaylov, M. Hämäläinen, J. Iinatti, and C. Pomalaza-Ráez, “Interference of wireless technologies on BLE based WBANs in hospital scenarios,” in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and*

Mobile Radio Communications (PIMRC), 2017, pp. 1–6. doi: 10.1109/PIMRC.2017.8292333.

[8] K.-S. Tan, I. Hinberg, and J. Wadhwani, "Electromagnetic interference in medical devices: Health Canada's past and current perspectives and activities," in *2001 IEEE EMC International Symposium. Symposium Record. International Symposium on Electromagnetic Compatibility (Cat. No.01CH37161)*, 2001, vol. 2, pp. 1283–1288 vol.2. doi: 10.1109/ISEMC.2001.950631.

[9] S. Riurean, T. Antipova, Á. Rocha, M. Leba, and A. Ionica, "VLC, OCC, IR and LiFi Reliable Optical Wireless Technologies to be Embedded in Medical Facilities and Medical Devices," *Journal of Medical Systems*, vol. 43, no. 10, p. 308, 2019, doi: 10.1007/s10916-019-1434-y.

[10] O. Haddad and M. A. Khalighi, "Enabling Communication Technologies for Medical Wireless Body-Area Networks," in *2019 Global LIFI Congress (GLC)*, 2019, pp. 1–5. doi: 10.1109/GLC.2019.8864122.

[11] D. R. Dhatchayeny, S. Arya, and Y. H. Chung, "Infrared-Based Multiple-Patient Monitoring in Indoor Optical Wireless Healthcare Systems," *IEEE Sensors Journal*, vol. 19, no. 14, pp. 5594–5599, 2019, doi: 10.1109/JSEN.2019.2906898.

[12] I. Sohn, Y. H. Jang, and S. H. Lee, "Ultra-Low-Power Implantable Medical Devices: Optical Wireless Communication Approach," *IEEE Communications Magazine*, vol. 58, no. 5, pp. 77–83, 2020, doi: 10.1109/MCOM.001.1900609.

[13] P. Johari, H. Pandey, and J. M. Jornet, "Interconnecting wearable devices with nano-biosensing implants through optical wireless communications," in *Optical Diagnostics and Sensing XVIII: Toward Point-of-Care Diagnostics*, 2018, vol. 10501, pp. 281–292. doi: 10.1117/12.2288779.

[14] D. R. Dhatchayeny, A. Sewaiwar, S. V. Tiwari, and Y. H. Chung, "Experimental Biomedical EEG Signal Transmission Using VLC," *IEEE Sensors Journal*, vol. 15, no. 10, pp. 5386–5387, 2015, doi: 10.1109/JSEN.2015.2453200.

[15] D. R. Dhatchayeny, A. Sewaiwar, S. V. Tiwari, and Y. H. Chung, "EEG biomedical signal transmission using visible light communication," in *2015 International Conference on Industrial Instrumentation and Control (ICIC)*, 2015, pp. 243–246. doi: 10.1109/IIC.2015.7150746.

[16] N. V. P. M.R.Ezilarasan ., "Health Care Monitoring System Using Visible Light Communication," *European Journal of Molecular & Clinical Medicine*, vol. 7, no. 3, pp. 4358–4363, 2020, [Online]. Available: https://ejmcm.com/article_4514.html

[17] Y. Y. Tan, S.-J. Jung, and W.-Y. Chung, "Real time biomedical signal transmission of mixed ECG Signal and patient information using visible light communication," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2013, pp. 4791–4794. doi: 10.1109/EMBC.2013.6610619.

[18] G. Aggarwal, X. Dai, R. Binns, and R. Saatchi, "Real-time wireless healthcare system for angular transmission of EEG signal using VL-OCC," in *Procedia Computer Science*, 2019, vol. 152, pp. 28–35. doi: 10.1016/j.procs.2019.05.023.

[19] T. Penzel, G. B. Moody, R. G. Mark, A. L. Goldberger, and J. H. Peter, "Apnea-ECG database," *Computers in Cardiology*, pp. 255–258, 2000.

[20] D. S. Baim *et al.*, "Survival of patients with severe congestive heart failure treated with oral milrinone," *J Am Coll Cardiol*, vol. 7, no. 3, pp. 661–670, 1986, doi: 10.1016/S0735-1097(86)80478-8.

[21] A. L. Goldberger *et al.*, "Current Perspective," 2000.