Performance Analysis of the SLIPT Architectures

Sumali S. Morapitiya[1,2,3], T.W.W. Leelarathna[4], Dushantha Nalin K. Jayakody[2,5] and R.U.Weerasuriya[3]
[1]Dept. of Electrical, Electronics and Telecommunication Engineering, General Sir John Kotelawala Defence University, Sri Lanka.
[2]Centre of Telecommunications Research, School of Engineering, Sri Lanka Technological Campus, Padukka, Sri Lanka.
[3] Faculty of Engineering, University of Moratuwa, Sri Lanka.
[4] Directorate of Electrical and Electronics Engineering, Sri Lanka Navy, Colombo, Sri Lanka.
[5] School of Computer Science and Robotics, National Research Tomsk Polytechnic University, Tomsk 634050, Russia.
Email:morapitiyas@kdu.ac.lk, leelarathna@hotmail.com, dushanthaj@sltc.ac.lk, ruwanu@uom.lk.

***Abstract*—Recently, The study builds on Simultaneous Lightwave Information and Power Transfer (SLIPT) has become a hot topic among the research community. The importance of the SLIPT is to harvest energy using light sources while decoding the information. In this approach, we present the mathematical framework for the Power Splitting (PS) based SLIPT system and study the performance of the PS-SLIPT and time switching (TS)-SLIPT architectures. Moreover, we quantitatively studied the harvested energy with different Field of View (FoV) angles of the Light Emitting Diode (LED) and the Photodiode (PD). In addition, we considered the amount of harvested energy for different Direct Current (DC) values. Overall, this paper concludes that the FoV and DC bias signals are directly affected by SLIPT systems. Using numerical simulations, we demonstrated the performance of the both architectures to enhance the QoS of data rate, amount of harvested energy and trustworthiness of the information.**

***Index Terms*—Energy Harvesting (EH), Light emitting Diode (LED),Information Decoding (ID), Simultaneous Lightwave Information and Power Transfer (SLIPT) and Visible Light Communication (VLC).**

I. Introduction

VLC is a new technology in Optical Wireless Communication (OWC) that provides high-speed wireless communication in an indoor environment as well as an outdoor environment. There are limitations of the Radio Frequency (RF) technology and to conquer the restraint of RF, introduce the VLC technology. This is a comparatively inexpensive, high security, high bandwidth, low energy consumption and can use existing light infrastructure [1].

In VLC system contributes three functions at the same time such as lighting, transmission data and energy harvesting. A new concept named SLIPT that Simultaneous Lightwave Information and Power Transfer [2] provides the above three functions simultaneously. Particularly, LED selected for transmitter functions and PD or solar cell selected for the receiver. The electrical power converts to optical power using LED and optical power converts to electrical power using PD or solar cell [3]. Also, one LED can transmit data at 3 Gbps speed and the lifetime of LED is high [4]. There are more advantages in the SLIPT system in VLC namely wide range of bandwidth, reuse of bandwidth, energy-saving and no interference with Electro-Magnetic (EM) sources [5] [6]. Furthermore, there are few challenges recognized in the literature such as line of sight requirement, light cannot pass through objects, interfere with external sources,etc [7].

The SLIPT system realizes the practice in some applications in EH such as Wireless Sensor Networks (WSNs), power electronic, electromagnetic and solid-state lighting applications [8]. Moreover, identified the weaknesses of the conventional EH methods. All the EH resources depend on natural resources such as wind and solar. Also, most of the natural resources are uncontrollable [9].

The evolution of the SLIPT technology introduced three-receiver designed architectures namely TS, Signal Component Separation (SCS) or PS and Photoelectric Converter (PEC) grouping receiver design. TS receiver architecture is working on the time domain. Also, there are two functions provide that EH and Information Decoding (ID) in discrete time zone. PS receiver architecture is functioning on the power domain. Further, the received signal split into two parts and one portion support EH and the other portion support to ID. PEC grouping receiver design has a group of PECs at the receiver side. At the same time, a subgroup of PECs are used for EH and the other PECs are used for ID [10].

Recently,the literature expanded to the comparison between Simultaneous Wireless Information and Power Transfer (SWIPT) and SLIPT for indoor communication. Also, explore the study that Bit Error Rate (BER), outage probability and amount of harvested energy [12] [11] [1]. In particular, the application is used multiple LEDs and multiple users and average illumination with dimming control. Also, explored the literature about output voltage, output current and power amplifier [13].

Most of the articles are based on the TS SLIPT architectures in recent literature. However, there are few works based on the PS SLIPT system. In SLIPT based indoor wireless communication systems is used for ID and EH using received optical signal. To enhance energy efficiency and minimize path loss, the SLIPT system focuses on the LoS condition. The received optical power converted into electrical power and it is divided into two currents such as Alternating Current (AC) and DC. Further, DC stored in a battery and AC used to detect the information. There are many research proposals are on the EH and ID. However, few works are identified of the SLIPT. [12]

To enhance the Quality of Service (QoS) of data rate, amount

of harvest energy and trustworthiness of the information. The main contribution of this works are listed as follows:
1. Measured the amount of harvested energy for PS and TS SLIPT receiver architectures.
2. Harvested energy vs data rate for discrete FoV angles in PS SLIPT architecture and PS SLIPT architecture for direct LoS single LED.
3. Harvested energy vs data rate for discrete B values in PS SLIPT architecture and PS SLIPT architecture for direct LoS single LED.
4. Observed the behaviour of PS and TS receiver architectures with SNR and BER.
The rest of the paper is organized as follows. Section II reveal the PS system model and mathematical expressions of the system model. Numerical results are discussed in Section III, while Section IV concludes the paper.

II. System Model

The SLIPT system builds on VLC technology and a diagram shown in Fig. 1. The diagram shows the downlink SLIPT system with the transmitter, channel and receiver. On the receiving side, there are two functions as EH and ID. Further, the received signal divided into two portions: AC component and the DC component. The modulated signal gives an AC component and its support to transmit the information. Also, the DC component helps with energy harvesting. In Fig.2 shows the transmission block diagram of the PS and TS architectures. Moreover, ρ is the power splitting coefficient and τ is the time splitting coefficient and P_r is total received power and T_s is the total time taken to transmit data.

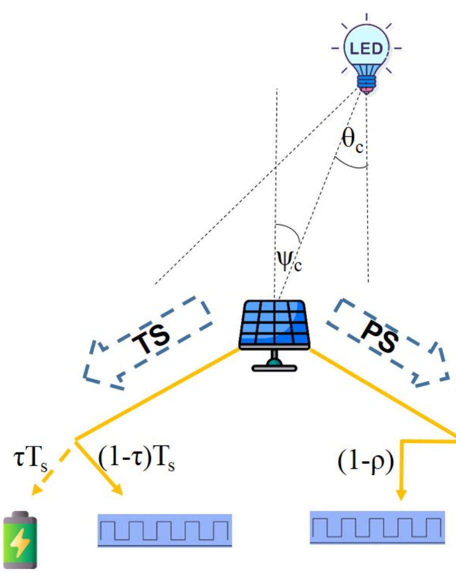

Fig. 1. overall system model of SLIPT system with PS receiver architecture and TS receiver architecture.

The system model can be defined mathematically as follows. Transmitted optical power is given as follows [9]

$$P_t(t) = P_{LED}[B + m(t)], \tag{1}$$

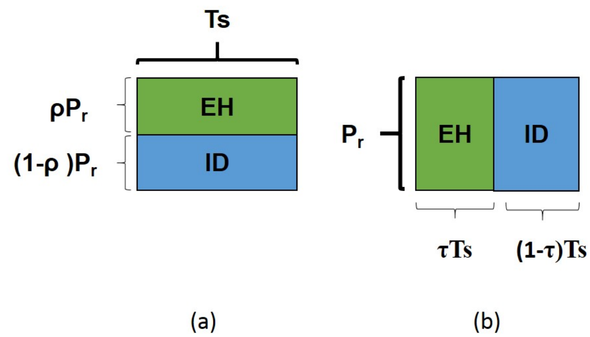

Fig. 2. (a) PS SLIPT architecture shows the concept of dividing power for EH and ID. (b) TS SLIPT architecture shows the concept of dividing time for EH and ID.

where P_{LED} denotes the LED power and it gives in W/A. B is the adding DC and m(t) is the information signal that modulated electrical signal. The (1) contains two components of the signal such as the AC component (m(t)) and amplitude of the DC component and it gives in B.
We can express the channel gain of the system as in [15],

$$h = \frac{Ar(m+1)(cos^m(\theta_c)T(\Psi_c)g(\Psi_c)(cos(\Psi_c)}{2(\pi)(d^2)},\ 0 \leq \Psi_c \leq \Psi \tag{2}$$

where the distance between the transmitter and the receiver denotes as d, optical filter gain denotes as $T(\Psi_c)$ and A_r denotes the surface area of the receiver. According to equation (5), channel gain depend on the physical area of the solar and optical concentrator gain.
Here, the free space channel between transmitter and receiver as in [14],

$$m = \frac{-ln(2)}{ln(cos(\theta_c))}, \tag{3}$$

where m denotes the Lambertian's mode number and it gives the direction of the transmitter. θ is the FoV of LED and θ_c ($0 < \theta_c < \theta$) represents the angle of irradiance.
Optical concentrator gain is given by [15],

$$g(\Psi_c) = \frac{n^2}{sin^2(\Psi_c)}, \tag{4}$$

where n parameter is the refractive index and $g(\Psi_c)$ denotes the concentrator gain or coating factor, where Ψ_c is the incidence angle and Ψ is the FoV of the receiver when $0 < \Psi_c < \Psi$.

Received electrical signal as originally given in [11]

$$i_r(t) = \eta h P_t(t) + n(t), \tag{5}$$

where P_0 is the received optical signals from neighbouring LEDs. η denotes the photodetector responsivity.

$$i_r(t) = I_{DC}(t) + i(t) + n(t), \tag{6}$$

where I_{DC} denotes the DC portion of the received signal and $i(t)$ is the AC signal of the received signal. Also, Additive

White Gaussian Noise (AWGN) denotes as $n(t)$. AWGN creates the background thermal noise and shot noise.

A. AC component of the received electrical signal $i(t)$ - information decoding

$$i(t) = i_1(t) + i_2(t), \tag{7}$$

where $i_1(t)$ denote the current from dedicated LED and $i_2(t)$ represent the other interfering sources.Therefore,

$$i_1(t) = \eta h(1-\rho)P_{LED}m(t), \tag{8}$$

The Signal to Noise Ratio (SNR) for PS SLIPT system can be expressed as ,

$$\gamma_{PS} = \frac{(\eta h(1-\rho)P_{LED}A)^2}{P_I + \sigma^2}, \tag{9}$$

where the amplitude of the transmitted signal denotes A and ρ is the PS coefficient. P_I is the electrical power of received interference and σ^2 denotes the noise power (thermal noise and shot noise).
Also, the SNR for TS SLIPT system can be expressed as follows ,

$$\gamma_{TS} = \frac{(\eta h P_{LED}A)^2}{P_I + \sigma^2}, \tag{10}$$

The throughput of channel using PS SLIPT system is expressed as,

$$R_{PS} = T_s log(1 + \frac{e(\eta h(1-\rho)P_{LED}A)^2}{2\pi(P_I + \sigma^2)}), T \tag{11}$$

Also, throughput of channel using TS SLIPT system is expressed as,

$$R_{TS} = (1-\tau)T_s log(1 + \frac{e(\eta h P_{LED}A)^2}{2\pi(P_I + \sigma^2)}), \tag{12}$$

B. DC component of the received electrical signal I_{DC} - energy harvesting

The Amount of harvested energy is given by [5],

$$E = f I_{DC} V_{oc}, \tag{13}$$

where f is the Fill Factor (FF). This is defined the overall behaviour of a solar cell and it is measure the quality of a cell.

$$I_{DC} = I_1 + I_2, \tag{14}$$

where I_1 is the current of dedicated LED and I_2 is the current of neighbouring LEDs.

$$I_1 = \eta h \rho P_{LED} B, \tag{15}$$

The open circuit of voltage is given by,

$$V_{oc} = V_t ln(1 + \frac{I_{DC}}{I_0}), \tag{16}$$

where V_{oc} denotes the open circuit voltage of solar cell and V_t denotes the thermal voltage. Also, I_0 is the dark saturation current of the photo diode.

Therefore energy harvesting for PS system equation is expressed as,

$$E_{PS} = f T_s(\eta h \rho P_{LED} B + I_2) V_t ln(1 + \frac{\eta h \rho P_{LED} B + I_2}{I_0}), \tag{17}$$

where E_{PS} denotes the harvested energy from PS SLIPT architecture while decode the information.
The energy harvesting for TS is expressed as,,

$$E_{TS} = f \tau T_s(\eta h P_{LED} B + I_2) V_t ln(1 + \frac{\eta h P_{LED} B + I_2}{I_0}), \tag{18}$$

where E_{TS} denotes the harvested energy for TS receiver architecture.
For consider the neighbouring LEDs that mathematical expressions are given by,

$$P_I = \sum_{n=1}^{N} (\eta h_n P_{LED} A_n^{'})^2, \tag{19}$$

$$I_2 = \sum_{n=1}^{N} (\eta h_n P_{LED} B_n^{'}), \tag{20}$$

where DC bias denoted by $B_n^{'}$ and $A_n^{'}$ is peak amplitude of the neighbouring LEDS. h_n is the channel between neighbouring LEDs and receiver. n ϵ 1.....N.

III. Numerical and Simulation Results

In this section, the amount of harvested energy and the behaviour of the PS and TS receiver architecture of the system model are analyzed to enhance the QoS of the proposed architecture.

TABLE I
Numerical Details

Parameters	Value	Parameters	Value
n	1.5	A_r	0.04 m^2
$T(\phi_c)$	1	P_t	30 dBm
f	0.75	η	0.85 A/W
I_o	$3x10^{-9}A$	V_t	25mV
$g(\phi_c)$	1	d	2m

In figure 3 shows the effect of the energy harvesting with the achievable data rate of the receiver. The two systems are in LoS condition and used 1 LED for 5 seconds. As we notice, the harvested energy has a small difference in the achievable data rate is less than 21 dB for PS systems. Also, the harvested energy has a slight difference in the achievable data rate is less than 24 dB for TS systems. We observe that the amount of harvested energy decreases speedily after reaching 21dB for PS and 24dB for TS of achievable data rate. The importance of the PS SLIPT architecture is two functions are progressing at the same time. However, the TS SLIPT architecture is progressing only one function at a time. Therefore PS SLIPT architecture performs well than TS SLIPT architecture for ID and EH. However, the PS system is able to harvest more energy than the TS system.

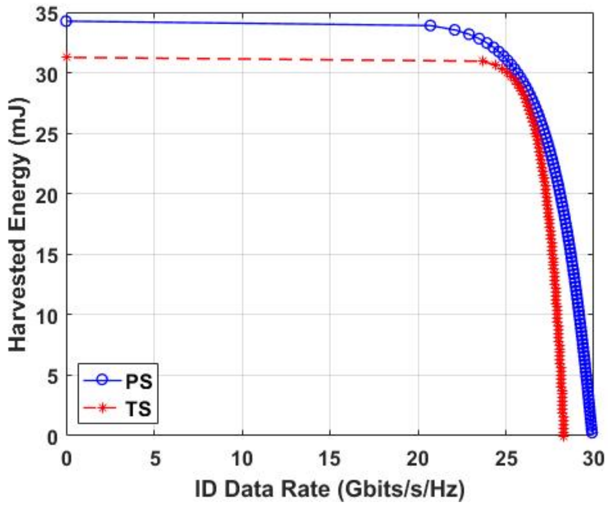

Fig. 3. Amount of harvested energy vs achievable data rate for TS and PS receiver architectures.

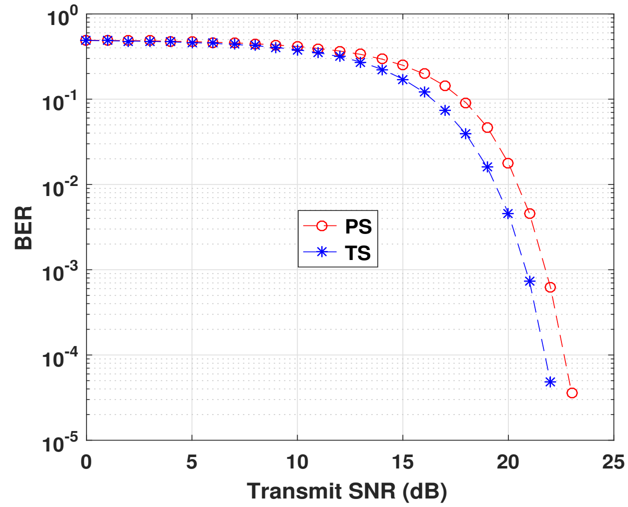

Fig. 5. BER vs SNR for PS SLIPT architecture and TS SLIPT architecture.

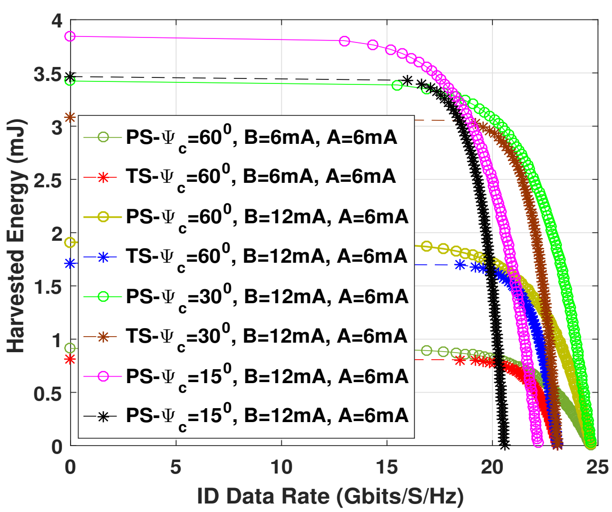

Fig. 4. Harvested energy vs data rate for different B values and FoV values for PS and TS SLIPT receiver architectures.

The amount of harvested energy vs Information decoding data rate in PS and TS SLIPT architectures is shown in Fig. 4. Here, we considered only direct LED with LoS. Further, the FoV of LED (θ_c) is the constant value (30^0) and used the different values of FoV for solar cells (ψ_c). Moreover, we considered ψ_c = 60^0, 30^0, 15^0 and B=12mA, 6mA. With the effect of the different values of the (ψ_c) and the different values of the B values, we can observe the significant difference between each output waveform for both systems. As we notice the maximum amount of harvested energy given at FoV is 15^0 for (ψ_c) and the B is 12mA in both systems.

In Fig. 5, we plot the BER of TS and PS SLIPT architectures with transmitting SNR. As we notice the TS SLIPT architecture shows the lower BER compared with PS SLIPT architecture. The reason for that the SNR is the ratio of signal power to noise power. Since the PS SLIPT architecture divided power into two parts for ID and EH. Hence, the signal power reduces for ID. However, the TS SLIPT architecture uses the total power to send the signal within the time duration. Therefore, TS SLIPT architecture showed superior performance than PS SLIPT architecture for ID function.

IV. Conclusion

The purpose of the research was a performance analysis of the PS SLIPT architecture as well as the TS SLIPT architecture. Moreover, measured the amount of harvested energy and data rates of both systems using numerical results and simulation results. Also, understand the factors that affected the systems to improve the QoS and efficiency. According to the results, the FoV of the transmitter is 30^0 and the receiver is 15^0 for 1 LED in both architectures to enhance the harvested energy with maintaining a good quality of data rate. Further, to enhance the amount of harvested energy, we can increase the DC bias signal (B) in the both architectures. Also, compared the BER of both SLIPT systems and presented results verified the PS receiver architecture performs better than the TS receiver architecture for EH and TS receiver architecture performs better than the PS receiver architecture for ID. Therefore, we showed the performance of the both architectures to enhance the QoS of data rate, amount of harvested energy and trustworthiness of the information.

TABLE II
ABBREVIATIONS

Acronym	Definition
AWGN	Additive White Gaussian Noise
AC	Alternative Current
BER	Bit Error Rate
DC	Direct Current
EH	Energy Harvest
EM	Electromagnetic
FoV	Field of View
FF	Fill Factor
ID	Information Decoding
LoS	Line of Sight
M-PAM	M-Pulse Amplitude Modulation
OWC	Optical Wireless Communication
PEC	Photoelectric Converter
PS	Power Splitting
QoS	Quality of Service
RF	Radio Frequency
SLIPT	Simultaneous Lightwave Information and Power Transfer
SWIPT	Simultaneous Wireless Information and Power Transfer
SCS	Signal Component Separation
SNR	Signal to Noise Ratio
VLC	Visible Light Communication
WSN	Wireless Sensor network

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