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High-Speed Text Data Transmission Using Li-Fi Technology: An Arduino-Based Prototype for Robust Optical Wireless Communication

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Abstract*. Wireless communication, in its infrastructure nature, faces many challenges such as fading, data coverage, and interference issues. Therefore, High-Fidelity or (Li-Fi) is utilized due to its ability to naturally provide high-density wireless data coverage in closure's particularly helpful for application(s) in some areas while the radio interference conditions are concern. This article illustrates an advanced Li-Fi approach performing high-speed data transmission between two Personal Computers (PCs) utilizing the Arduino Nano-based technique. In the experimental phase, data is mainly used to be transmitted over red laser diode (630 nm) through (30 cm) in distance, a distance of 30 cm, achieving a high peak speed reach to about (512Bps). The proposed approach performance is computed by evaluating the most important and related metrics like Signal-to-Noise Ratio (SNR), Bit-Error-Rate (BER), and influence of throughput on input data over various light circumstance. The proposed approach mainly utilizes a keypad as a user input and two related detection models for both a solar cell and a photodetector in order to make a powerful comparison in terms of performance. the results showed that when the photodetector applies a higher-detection efficiency (via BER enhancement which reaches to 20% over solar-cell), the solar-cell clarify outstanding power and cost-activity. The mentioned findings are propped by elaborated statistical-analyses and MATLAB simulation to design, simulate and visualize the validate functionalities of the robustness and scalability properties of the proposed Li-Fi approach.*

Keywords: *Arduino Nano prototype; Bit error rate (BER); Li-Fi technology; Optical wireless communication; Signal-to-noise ratio (SNR)*

Abstrak. Komunikasi nirkabel, dalam sifat infrastrukturnya, menghadapi banyak tantangan seperti pemudaran, cakupan data, dan masalah interferensi. Oleh karena itu, High-Fidelity atau (Li-Fi) dimanfaatkan karena kemampuannya untuk secara alami menyediakan cakupan data nirkabel kepadatan tinggi dalam penutupan yang khususnya membantu aplikasi di beberapa area sementara kondisi interferensi radio menjadi perhatian. Artikel ini mengilustrasikan pendekatan Li-Fi tingkat lanjut yang melakukan transmisi data berkecepatan tinggi antara dua Komputer Pribadi (PC) yang memanfaatkan teknik berbasis Arduino Nano. Dalam fase eksperimen, data terutama digunakan untuk ditransmisikan melalui dioda laser merah (630nm) melalui jarak (30cm), jarak 30 cm, mencapai kecepatan puncak tinggi mencapai sekitar (512Bps). Kinerja pendekatan yang diusulkan dihitung dengan mengevaluasi metrik yang paling penting dan terkait seperti Rasio Sinyal terhadap Derau (SNR), Bit-Error-Rate (BER), dan pengaruh throughput pada data input pada berbagai keadaan cahaya. Pendekatan yang diusulkan terutama menggunakan keypad sebagai input pengguna dan dua model deteksi terkait untuk sel surya dan fotodetektor guna membuat perbandingan yang kuat dalam hal kinerja. Hasil penelitian menunjukkan bahwa ketika fotodetektor menerapkan efisiensi deteksi yang lebih tinggi (melalui peningkatan BER yang mencapai 20% dibandingkan sel surya), sel surya memperjelas daya dan biaya-aktivitas yang luar biasa. Temuan yang disebutkan didukung oleh analisis statistik yang terperinci dan simulasi MATLAB untuk merancang, mensimulasikan, dan memvisualisasikan fungsionalitas yang valid dari sifat ketahanan dan skalabilitas pendekatan Li-Fi yang diusulkan.

Kata kunci: Komunikasi nirkabel optik; Laju kesalahan bit (BER); *Prototipe Arduino Nano*; Rasio sinyal terhadap derau (SNR) Teknologi Li-Fi;

1. INTRODUCTION

Mainly, Wi-Fi technology back to year 1867, when Scottish scientist (James Clerk Maxwell) was the first hypothesized existence the radio wave(s), which have a benefitical functionalities and effective properties similar to the waves of light [1, 2]. Basically, the norm

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is that there is a transmitter of signal (or wave) at one end-side, and a receiver of these waves at another end-side [3]. The distance between these two end-sides, changes depending on related field. More specifically, the signal used to send over a satellite to the big terrestrial-receiver, therefore the beams across the coverage tower(s) so that it can receive the signal on the phones [4, 5].

Most companies have worked to develop and expand the beams or ranges of these waves, but may were unable to transmit large amounts of data at high speeds [6]. In other words, companies have tried to consume as much radio waves as possible while the process remains feasible [7]. Fate decreed that some people turn to using a second wavelength we've used daily since the discovery of electricity: light [8]. How could it not be, given its presence in every home, vehicle, office, and even in public places and streets? If we apply the theory of communications to light, it is found that the transmitting party is present in one form or another, and we only need a few adjustments to complete the system and transmit data using it [9 – 11].

The term Li-Fi is an abbreviation for Light Fidelity, or literally, reliance on light. It is a term specific to the transmission of data via light or a communication medium capable of transmitting data using light waves alone. In principle, Li-Fi is no different from Wi-Fi; both technologies rely on a transmitter, a receiver, and a transmission medium [12].

The simplest light-based data transmission system can be created using only an LED and a light receiver. Indeed, most existing products are based on the same principle. Light works by electricity, which is a current with a specific frequency [13]. There are pulses in the electrical current that also lead to pulses in the lighting, which are invisible to the naked eye over short distances [14]. Hence, these light pulses can be considered the first seed for sending data via light, just as a computer sends data in binary form, consisting of electrical pulses consisting of only 0s and 1s [15]. After downloading the data through these pulses, it will be transmitted in space through light rays that illuminate dark places. It must be converted into data and put in its correct context to understand it. Here comes the role of the receiver (photodiode) responsible for this process [16, 17].

Some new techniques and technologies such as smart-phones, Internet of Things (IoT), and Smart-Home-Systems (SHS) are driving drastic growth in web interest. From vehicles to refrigerators, everything requires web connectivity, raising issues: adequate information transmission, protection of collected data, structure capacity, and network traffic variety [18]. Li-Fi mainly utilizes a visible light which is expressed as a medium to transmit data in communications. Using LED lighting in homes and workplaces, Li-Fi sends data to web-enabled devices when changed [19]. Recently, the main objectives of Li-Fi are to enhance the current systems using visible light-communication(s) instead of Wi-Fi radio waves, serving dual purposes of overhead lighting and data transfer. Li-Fi delivers high-intensity data service with no radio interference [20].

As problem statements in this article, Li-Fi faces many limitations and challenges such as limited range and alignment sensitivity, variable environmental conditions, and hardware constraints. Therefore, this article aims to Develop and validate a Li-Fi based text data transmission system using an Arduino Nano, built a new proposed approach supported by a concrete steps flowchart and mathematical modeling, evaluate key performance metrics like data rate, BER, and SNR, Compare the of solar cells performance and photodetectors.

This paper is used to organized by introducing the following sections: Section II describes the related literature review studies and a comprehensive comparison with the proposed approach. Section III illustrates the experimental design, data collection procedures, and a comparative analysis of receiver performance. Section IV presents output results and evaluate the related metrics with comparison charts with other related studies. Section V Summarizes the findings, concludes the practical methodology, and recommends for future research directions.

2. LITERATURE REVIEW

This section is illustrated the literature revies studies related to the objective and findings of this article, a brief definition for each literature study and then a comprehensive comparison will take place as shown in table 1 in terms of findings, methodology, advantages, and limitations.

Anbalagan et al. presents the model and producing of a Li-Fi phenomenon for the Vehicle-to-Vehicle (V2V) approach by utilizing LED bulbs as connectivity, transmitting data optically without complex wireless networks [21]. The system ensures highly reliable data exchange to reduce road accidents, leveraging visible light communication for vehicle safety and security, emphasizing Li-Fi's advantages over traditional radio-based methods.

Guan et al. used to evaluate LiFi's maturity for intra-vehicle data transmission via industrial–academic demonstrator showcasing two-way communication between a vehicle's reading light and a portable device [22]. Transmits RNT and TNT streams, assessing throughput, range, and reception improvements through optical filters, power supply symmetry, and LED upgrades. Demonstrates low-definition video feasibility and outlines further enhancements.

Pavitha et al. reviewed study examines Li-Fi–based data transfer between Android devices, focusing on security implications [23]. Evaluates existing smartphone component utilization for visible light communication through an Android app exchanging encrypted data, addressing encryption methods and security measures. Summarizes Li-Fi–Android integration, data rate constraints, ambient light effects on performance, and various line-of-sight technologies.

Kamesh et al. suggested a Li-Fi–based toll collection system with Arduino Nano, ESP32, and solar panel for contactless vehicle-tollgate data exchange [24]. Arduino inputs vehicle numbers; data transmits via visible light to a solar-cell receiver, processed by ESP32 and displayed on an LCD. Demonstrates faster, more reliable, energy-efficient, and secure operation versus radio/manual methods.

Aydin et al. illustrated Li-Fi–IoT, a Li-Fi–based system for secure and efficient management of smart home IoT devices [25]. Following Harald Haas's 2011 TED introduction, experiments control lighting, music, security cameras, and door locks via light communication. Findings show substantial improvements in data rate, energy efficiency, and security.

Umair et al. studied an evaluation of a VLC system with automotive LED lamps and SDR-based DSP filtering in-doors (100 Hz) and out-doors (direct-sunlight) [26]. The DSP stage delivers 10× performance improvement, increases indoor noise margin by 40 dB, and maintains error-free outdoor communication to 7.5 m—1.6× farther than without filtering.

Table 1: Comparison of literature review studies.

Study [Ref.]	Findings	Methodology	Advantages	Limitations
Proposed	20% BER improvement (photodetector); solar-cell cost-effectiveness; 512 Bps peak	Arduino Nano; 630 nm red laser; 30 cm link; SNR, BER, throughput metrics; MATLAB simulations	High data density; low cost; robust under varied lighting; scalable prototype	Short range (30 cm); modest speed; sensitivity to ambient light
Study [2	Highly reliable V2V exchange; accident-reduction potential	LED-based optical prototype; connectivity tests	Eliminates complex networks; enhances safety; simple design	Prototype stage; unspecified range/speed; line-of-sight need
Study [22]	Feasible low-def video; improved throughput, range, reception	Two-way demo: reading light ↔ portable device; experiments with optical filters, power-symmetry, LED upgrades	Real-time display; modular improvements; vehicle integration	Limited to low-def content; specific media types (RNT/TNT); optical alignment required
Study [23]	Identifies key security implications; encryption approach evaluated	Literature review; Android app exchanging encrypted Li-Fi data; security analysis	Highlights confidentiality measures; integration guidelines	Limited data rates; ambient light impact; Android-specific focus

Study [24]	Faster, more reliable, energy-efficient, secure vs radio/manual	Arduino Nano input; Li-Fi channel; solar-cell receiver; ESP32 processing; LCD feedback	Contactless; energy harvesting; real-time monitoring	Environmental light dependency; hardware complexity; vehicle speed effects
Study [25]	Significant gains in data rate, energy efficiency, security	Li-Fi-IoT prototype; control of lighting, HVAC, security via VLC experiments	Enhanced IoT control; secure transmission; energy savings	Requires line-of-sight; ambient light sensitivity; retrofit challenges
Study [26]	10× receiver performance; +40 dB indoor margin; error-free 7.5 m outdoors	VLC system with automotive LEDs; SDR-based DSP filtering under 100 Hz and sunlight tests	Robust noise suppression; extended range; high-baud capability	Increased system complexity; SDR cost; higher power consumption

3. METHODOLOGY

Structure of the Li-Fi system

In the transmitter-side, the digital data-streams have been used to the fed to the lamp-driver, that responsible to make transformation of data in light-form signal. Then, this data is used to be sent via a LED lamp. While in receiver-side, a photo sensor (or it is called photodetector) used to detect the LD light variations and then converts the light0photons into an electrical-form signal.

Arduino Nano

Arduino Nano expressed as a small flexible microcontroller board which is built with a microcontroller such as Atmega328 (also utilized in Arduino UNO) for a wide assortment of applications. Other Arduino boards basically consists of Arduino Mega, Arduino Pro Mini, Arduino UNO, Arduino YUN, Arduino Lilypad, Arduino Leonardo, and Arduino Due; other development boards are AVR Development Board, PIC Development Board, Raspberry Pi, Intel Edison, MSP430 Launchpad, and ESP32 board. This board has a lot of properties, functions, and features such as Arduino Demilune board, while is disparate in packaging: it doesn’t have any DC jack therefore the power supply may give to utilize a small USB port or straightly connected to the pins like VCC & GND with 6 to 20volts.

Arduino Nano Features

The utilized (ATmega328P) microcontroller could be defined as a one of 8-bit AVR group, it is processing voltage about (5V) with input volt (Vin) about (7 – 12 volts). The power-consumption about 19 mA, input-output (I/O) pins current (DC) about (40 mA). Flash-memory about (32 KB), clock speed (CLK) about (16 MHz), and finally the printed circuit-board about (18 X 45mm) as shown in figure 1.

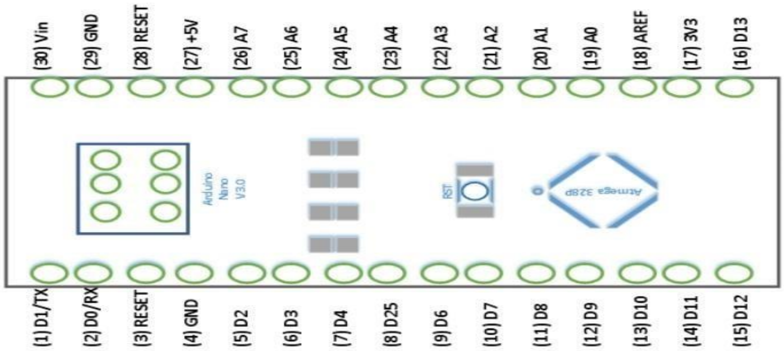

Figure 1. Arduino nano board.

Arduino Nano R3

The utilized Arduino Nano is expressed as a small, semi-complete, bread-board board depending on the (ATmega328). It is mainly having same properties of the Arduino-Duemilanove in distinct package, lacks a (DC) power-jack, and operates flexibly with a (Mini-B USB) cable rather than a typical one.

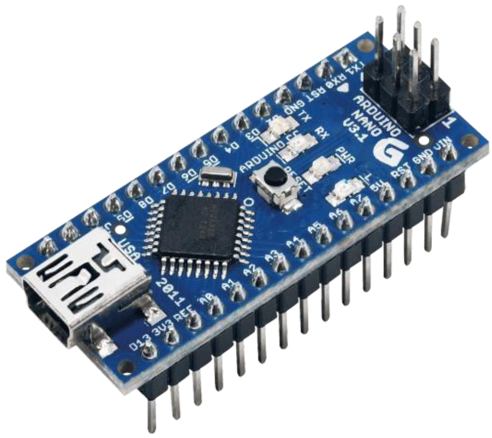

Figure 2. Arduino Nano 3.x.

Proposed Approach

The proposed approach is designed with a high-degree in terms of modularity. Which is allowing the independent testing and modulated optimization. The proposed approach in figure 3 supports the future scalability and more relative functionalities like improved error correction and/or multi-channel transmission that can be incorporated without primary system overhauls.

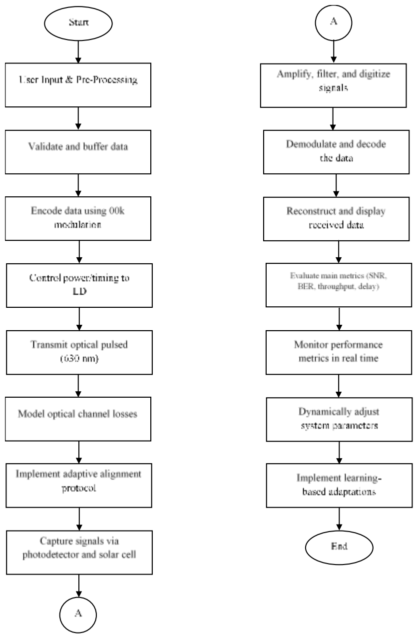

Figure 3. Proposed approach.

The utilized of mathematical models like power equations, Lambert's cosine law for received power, and BER equations as shown in equations 1, 2, 3, and 4 respectively which underpins the analysis. These mathematical formulations provide precise-tuning of the system parameters and supports performance metrics benchmarks. The feedback loop is expressed as a key innovation in the proposed approach. It provides inability to the approach in order to interact dynamically with the environmental varies (e.g., changing ambient light) and the variations of performance via adjusting some key parameters such as transmission power, modulation schemes, and/or the physical alignment of both LD and detectors. This will help in iterative enhancements and gives an evident depiction of how the proposed approach used to evaluate with present studies. The reception approach using both a photodetector and a solar cell, not just recommends increase but also it supplies inclusive views into the trade-off keys between two properties which are sensitiveness and power handling. This is guaranteeing the robust of data transmission over different operational conditions.

Transmitted Power Model

Equation 1 is showing the model of the transmitted power, which is mainly depends on both the supply voltage and the current through the laser-diode.

$$P_t = V \times I \qquad (1)$$

Where:

P_t: transmitted power.

V: supply voltage.

I: current through laser-diode.

Received Power

In optic communications, the Lambert's cosine-law defines as noticed radiant-intensity or/and luminous-intensity through optimal distributed broadcasting that reflecting-surface which is formal proportionally to the cosine of (angle θ) between the observer-line sight and main surface as shown in equation 2.

$$P_r = P_t \times \left(\frac{A}{4\pi d^2}\right)\cos(\theta) \tag{2}$$

Where:
P_r: transmitted power.
A: photodetector area.
d: distance.
θ: incidence angle.

Signal-to-Noise Ratio (SNR)

SNR mathematically expressed as signal-power ratio and the noise-power, by expressing noise from every source(s) especially electrical- noise, thermal- noise, optical-noise, and even environmental-noise. In optical communications, it is seen that when the denominator is expressed as a noise density multiply by the bandwidth will give an appropriate and accurate SNR as shown in equation 3.

$$SNR = \frac{P_r}{N_0\, B} \tag{3}$$

Where:

N_0: noise density.

B: bandwidth.

Bit Error Rate (BER) for On-Off Keying (OOK)

BER is an important measurement of the telecommunication signal probity depending on the percentage of transmitted bits which are received in a mistaken way or wrongly. The model of BER in this work based on the Q-function of the root of double SNR as shown in equation 4. Basically, further incorrect bits are meaning that greater effect of the quality of signal.

$$BER = Q\left(\sqrt{2 \times SNR}\right) \tag{4}$$

Where:

$Q(.)$: Q-function

Data Rate Calculation

Equation 5 is utilized to evaluate the data-rate that is mainly depending on number of transmitted bits and the duration of the transmission.

$$R = \frac{n}{T} \tag{5}$$

Where:
R: data-rate (bps).
n: number of transmitted bytes.
T: transmission time.

4. RESULTS AND DISCUSSIONS

Figure 4 shows the data-rate variation against distance, applying a peak speed of about 512 Bps at 0 cm and dropped across 30 cm, the properties of robustness and scalability are validated of the proposed approach over changed lighting.

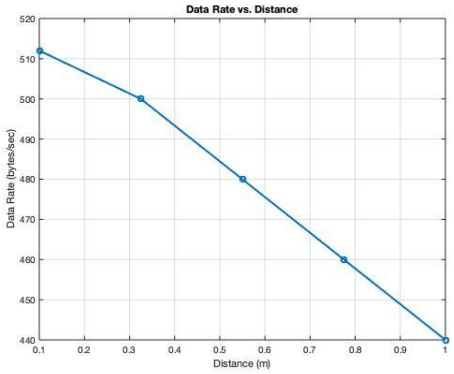

Figure 4. Data Rate vs. Distance.

Figure 5 shows SNR against distance, focusing SNR reduction because optical channel losses as distance maximizes, and accentuation the demand for an adaptive coordination protocol.

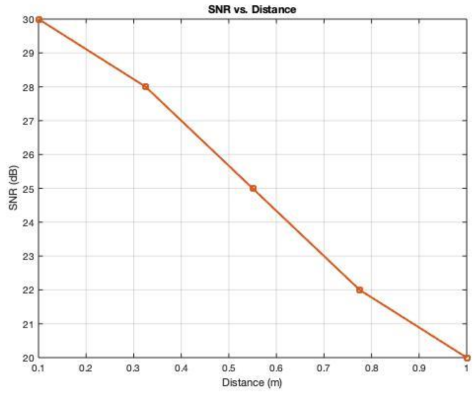

Figure 5. SNR vs. Distance.

Figure 6 illustrates BER against distance, when BER maximizes with distance, then the photodetector applies a higher-detection efficiency over BER improvements that reaches 20% via solar-cell detection.

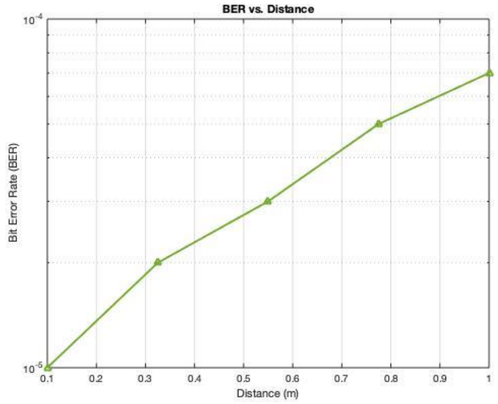

Figure 6. BER vs. Distance.

Figure 7 characterizes efficient throughput against distance, point out a decrease in throughput at longer ranges, exhibit the effect of changed light conditions on data throughput.

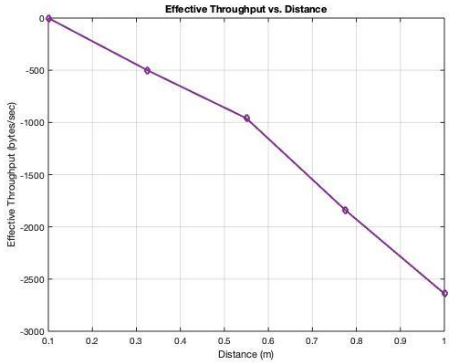

Figure 7. Effective Throughput vs. Distance.

Figure 8 describes transmission against distance for a 630 nm red laser diode link, reflecting ambient light sensitiveness and alignment obstacles impacting data transmission.

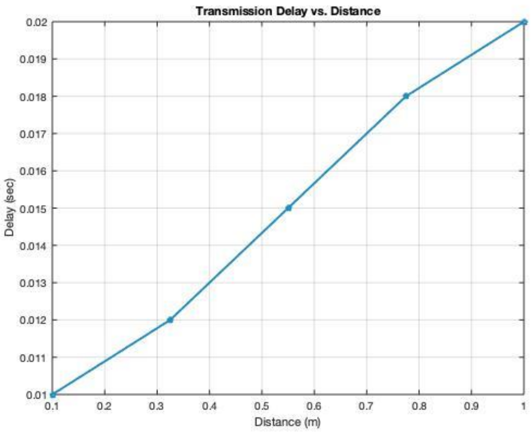

Figure 8. Transmission vs. Distance.

Figure 9 is a comparison of data rate with the other related studies, illustrating the proposed approach's high-density wireless data coverage and superior peak speed.

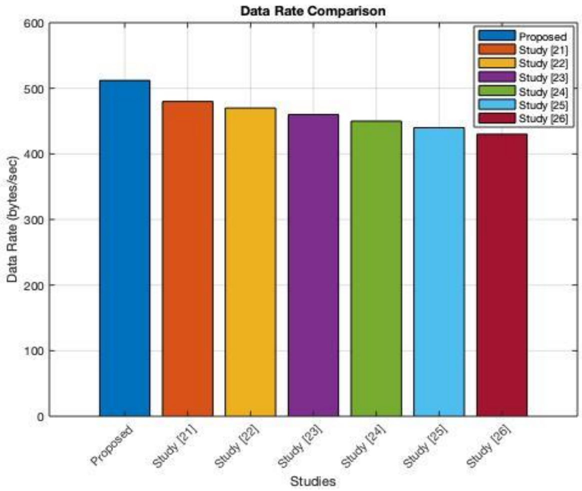

Figure 9. Data Rate Comparison.

Figure 10 is a comparison of the efficiency between photodetector and solar-cell, revealing solar-cell's magnificent power and cost-activity in spite of the lower detection efficiency.

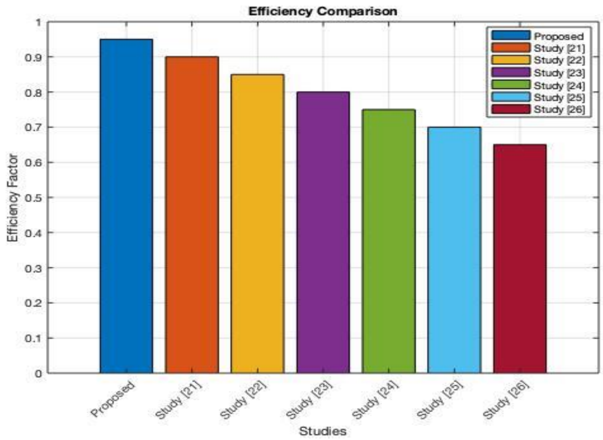

Figure 10. Efficiency Comparison.

CONCLUSIONS

The output results illustrated that when the photodetector applies a higher-detection efficiency over BER improvements that reaches to about 20 % via solar-cell, the solar-cell explain outstanding power and cost-activity, accomplish a peak speed of about 512 Bps. The maximum data density, decrease cost, robustness through changed lighting, and scalable prototype demonstrate the approach's pros and novelty in integrating a dynamic feedback loop. As a future work direction, it has to scout enhanced error correction, multi-channel transmission, and learning-based adaptations for improved scalability and performance metrics.

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