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Analysis of Typical Applications and Key Challenges in Optical Communications within the Context of the Internet of Things

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Abstract:
As the demand for interconnecting IoT devices and transmitting data grows, traditional wireless communications face bottlenecks in capacity and stability. Optical communication technology, with its advantages of high bandwidth, low latency, and high security, has become a key enabling technology for the Internet of Things, offering broad application prospects in industrial and agricultural sectors, smart cities, and other fields. However, its widespread adoption still faces numerous challenges, such as insufficient environmental adaptability, poor software-hardware compatibility, and the lack of effective non-linear compensation. This paper focuses on fields such as industrial manufacturing, smart cities, and smart homes, systematically analyzing typical applications of optical communications alongside existing challenges. To address signal degradation in dynamic environments, it explores deep learning equalization techniques based on LSTM-DNN hybrid models. To facilitate hardware-software compatibility and industrialization, strategies including developing low-cost LED driver chips and establishing unified interface standards are proposed. Furthermore, CEO-OFDM combined with LSTM-DNN hybrid models is employed to resolve nonlinear compensation issues. This research aims to provide theoretical underpinnings and practical guidance for the application of optical communications within the Internet of Things.

Keywords: Internet of things; optical communication technology; environmental adaptability; hardware and software compatibility; non-linear compensation.

1. Introduction

With the rapid advancement of Internet of Things (IoT) technology, the demand for interconnecting vast numbers of devices and enabling high-speed data transmission continues to grow. The total num-

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ber of connected IoT devices worldwide is projected to increase from 7.6 billion in 2019 to 24.1 billion by 2030. Traditional wireless communication technologies are increasingly encountering limitations in capacity, stability, and interference resistance. According to the International Data Corporation (IDC), IoT devices are expected to generate 79.4 zettabytes of data by 2025. Versus this, because of its unique advantages, such as enormous bandwidth, low signal loss, improved security, non-electromagnetic interference, optical communication technology plays an important role in the efficient functioning of the IoT and has a wide range of potential applications in industrial automation, smart cities, smart homes, etc.

However, optical communication still needs to overcome a lot of issues for the large-scale IoT application. Different communication scenarios have different requirements for communication performance: precision agriculture just needs a reliable connectivity; while intelligent transportation needs low latency which are the requirements that current optical communication can't achieve. When we go through the mountain area, the connection is blocked and interfered, and the quality will drop. Device compatibility is also very insufficient, standard is behind, and industrialization is weak. This will make the technical solution become more complicated and cost more. In dynamic IoT environments, node mobility and channel variations lead to instability in optical links. At the same time, cross-protocol coordination mechanisms between optical communications and existing wireless systems (e.g., Wi-Fi) remain underdeveloped, hindering seamless handover and resource optimization. These issues impede the deep integration of optical communications into multimodal networks.

Against this backdrop, this study aims to systematically analyze the typical applications and key technical challenges of optical communications within the IoT. By focusing on major domains such as industrial manufacturing, smart cities, and smart homes, it summarizes existing application models and identifies prevailing issues, while examining technical limitations from perspectives including environmental adaptability, hardware-software co-design, and nonlinear compensation. Furthermore, this paper explores deep learning-based channel equalization and compensation strategies, collaborative hardware-software design approaches, and industry-academia collaboration pathways to promote the large-scale deployment of optical communications within IoT ecosystems.

This study investigates current applications, key challenges, and potential solutions for optical communication technologies in the context of the IoT, offering significant theoretical and practical implications. On the one hand, it contributes to the theoretical framework of optical communications in heterogeneous network environments, fostering cross-disciplinary technological integration. On the other hand, it provides practical guidance for overcoming communication bottlenecks in IoT systems and promoting industrial upgrading, thereby injecting new impetus into societal digitalization and high-quality economic development.

2. Review of Relevant Research

Optical communication is a promising technology for various applications ranging from smart farming to intelligent transportation systems. In this section, we present brief reviews on recent advances in optical communication systems, including system design, channel modeling, and performance analysis.

Pezoa et al. designed and evaluated the performance of a Visible Light Communication (VLC) system applied to smart farming in greenhouses [1]. The performance of VLC under different atmospheric conditions was studied since they are of major concern for agricultural applications. Koonen et al. designed a beam-steered optical wireless communication system for Industry 4.0 applications [2]. The proposed system was studied for accurate steering of optical beams in various industrial scenarios. Channel modeling and performance analysis of Infrastructure-to-Vehicle (I2V) Visible Light Communication (VLC) systems were studied in Eldeeb et al. [3]. The authors also investigated the potential of VLC for integration with the existing road infrastructure for intelligent transportation systems, such as using streetlights. Lv et al. applied deep learning algorithms to enhance the security of optical wireless communication in intelligent transportation systems [4]. This approach addresses cybersecurity issues for optical wireless communication in intelligent transportation systems. ltokhy et al. designed a hybrid communication system that integrated Wi-Fi, Li-Fi, and BPL for secure indoor networks [5]. The authors studied the complementary characteristics of these technologies. An indoor positioning system based on VLC was demonstrated for its dual functionality of VLC for communication and localization in Laheri et al. [6].

Although the above works have been achieved for optical wireless communication technology applications, there are still several limitations in these applications. In Zhang et al., channel equalization methods were studied for Visible Light Communication (VLC) systems [7]. In Zhang et al., considering the channel equalization method for Visible Light Communication (VLC) systems, an LSTM-DNN hybrid model was proposed [8]. The method integrates artificial intelligence algorithm to optimize the performance of optical communication system. Swaminathan and Raajan studied the methods to reduce the nonlinearity impairments of optical transmission [9]. The method reduced the nonlinear impact of the optical transmission system.

The above works are the basis for the rest of this review. Recent advances in VLC and hybrid communication architecture show certain progress in the fields of agricultural, industrial, transportation, and indoor applications. Recent advances in security enhancement and machine learning-based signal processing technique show certain potential to solve the existing limitations in these applications.

3. Analysis of Application Scenarios

3.1 Optical Communications in Industrial and Agricultural IoT

Optical communication technology has been progressively applied in industrial and agricultural production sectors. In their study on safer and more efficient alternatives for information transmission in greenhouses, Pezoa et al. employed a Visible Light Communication (VLC) core system architecture. Their research focused on analyzing bit error rates and received power under varying humidity and temperature conditions, thereby evaluating the impact of typical greenhouse atmospheric conditions on VLC system performance. Experimental results indicate that relative humidity in the greenhouse environment directly influences received power loss, while temperature variations have a lesser effect on the bit error rate. This research not only validates the feasibility of VLC systems for greenhouse applications but also reveals shortcomings in environmental adaptability and dynamic stability.

In the industrial sector, research on beam-controlled optical wireless communication for Industry 4.0 has demonstrated the effectiveness of optical wireless communication (OWC) systems using narrowband infrared beams. These systems achieve high-bandwidth, interference-free individual connections along with associated positioning and reception technologies [10]. Experiments comparing OWC with conventional radio-frequency communication in Industry 4.0 environments show that OWC systems can provide interference-resistant, low-latency data transmission for high-density devices, meeting core requirements of Industry 4.0. However, challenges were encountered in real-time tracking and maintaining communication with mobile devices during movement, particularly irregular motion. Existing scanning and positioning strategies appear better suited for device reconnection than for supporting continuous communication during movement. Furthermore, validation of system stability and reliability under real industrial conditions—such as mechanical vibration, dust, and temperature fluctuations—remains insufficient.

3.2 Optical Communications in Smart City IoT

Within the intelligent transportation systems of smart cities, optical communication technology has been explored from multiple perspectives to enhance communication reliability and meet the requirements of digital twin applications. A study on an Infrastructure-to-Vehicle Visible Light Communication (I2V-VLC) system utilizing streetlight access points derived a closed-form expression for path loss through non-sequential ray-tracing simulations [11]. The study further established probability distribution functions and approximate bit error rate formulas, verifying their accuracy, and analyzed the influence of various parameters on communication performance. The results demonstrate that receiver aperture size and pole spacing significantly affect system performance, while lateral offset has minimal impact. Reducing pole height, enlarging the receiver aperture, and decreasing pole spacing were found to improve performance, although increased vehicle height adversely affects it. These findings reveal stability challenges in dynamic environments and limitations in current receiver hardware sensitivity.

To address the requirement of intelligent transportation digital twin systems for communication with high transmission rate and low complexity, another study has introduced an optical communication solution based on carrier-free amplitude-phase modulation (CAP) and deep learning-assisted spectrum analysis [12]. The solution overcomes the low transmission rate and high complexity of VLC. However, there are still challenges for the practical implementation of this solution, such as low adaptability of the algorithm and high coordination complexity in the system.

3.3 Optical Communication in Smart Home IoT

In the field of smart homes, optical communication technology has proposed several new approaches for secure multi-device interconnection and better intelligent user experience. Researchers combined Wi-Fi, Li-Fi, and broadband over power line (BPL) technology to build a secure indoor communication network. They combined these technologies because there are many multi-devices needed to be connected securely. With the support of ESP8266 module and filter including OSE, ABPF, and ASBF, the communication signal is analyzed in real-time and the abnormal frequency is blocked. This system can protect external attack successfully, which can guarantee the user's privacy and the security of controlling the device. Still, there are many challenges existing in this system.

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First, Li-Fi signal will be blocked by furniture or curtain and there will be many blind spots. Second, there will be many interference issues between Wi-Fi and Li-Fi in the aspect of frequency band, while BPL will be affected by electromagnetic interference generated by the switching of electrical appliances. All these will affect the stability of communication and show the weakness of optical communication in indoor environment. Different from other systems, this system uses several kinds of hardware device and software platform. And the hardware-software compatibility will also affect the performance of this system.

Another approach designed a human activity recognition system based on visible light using generative language models. This approach integrates visible light signals and descriptions through cross-modal alignment and converts optical features into behavioral events like “elderly person falling” or “child running”. This allows the smart system to activate corresponding alerts or lights automatically, which improves the practicality of smart applications in homes. However, this technology is currently very reliant on high-resolution cameras and highly sensitive sensors, and its generalization ability is also very limited, which makes it hard to be applied in various home scenarios.

4. Analysis: Core Challenges from Cases

4.1 Insufficient Environmental Adaptability and Challenges to Dynamic Stability

As evidenced by the cases discussed, optical communication technology faces common challenges across diverse IoT scenarios, primarily insufficient environmental adaptability and poor dynamic stability, though their specific manifestations vary by context. In agricultural greenhouse environments, humidity fluctuation is the dominant factor affecting performance. When humidity exceeds 70%, the VLC system exhibits significantly increased reception power loss, leading to fluctuations in communication quality. Operations such as irrigation and ventilation introduce dynamic changes in humidity, yet current systems lack real-time adaptive control mechanisms to compensate. In industrial settings, adverse conditions including mechanical vibration, dust, and temperature fluctuations are often not adequately considered in system design, resulting in high communication dropout rates, especially for irregularly moving equipment. In intelligent transportation systems, signal Doppler shift caused by high-speed vehicle movement and optical signal attenuation during inclement weather both undermine communication stability. In smart home environments, obstacles that block signals, multi-technology frequency band interference, and electromagnetic interference from household appliances collectively contribute to coverage blind spots and unstable connections. Moreover, environmental parameters—such as temperature, humidity, and interference intensity—vary significantly across different scenarios. The lack of a universal environmental adaptation strategy necessitates customized development for each specific application, considerably increasing the complexity and cost of deployment.

4.2 Poor Hardware and Software Compatibility and Performance Bottlenecks

Incompatibility of hardware and software, and performance bottlenecks are the main problems that restrict the broad application of optical communication, which can be categorized into three types.

First, incompatibility of hardware interfaces and standards exists widely. Due to the different interfaces of Li-Fi modules and various communication protocols used by different manufacturers, the interoperability of multiple devices is low when users connect multiple devices together for smart home application. For industrial OWC systems, there is no unified standard of optical parameters in infrared transmitters and receivers, and thus the devices from different manufacturers are incompatibility, which will raise the cost of deployment.

Second, incompatibility between hardware and software also exists. For intelligent transportation with carrier-free amplitude-phase modulation (CAP) used, the deep learning algorithm can not be implemented in real time on the hardware transceiver, and thus the equalization parameter can not be achieved in time, which will limit the whole system performance. Furthermore, for multi-technology smart home systems which integrate Wi-Fi, Li-Fi and BPL together, the incompatibility of hardware modules and unified control software will also limit the user experience.

Third, there are also performance bottlenecks in hardware. For infrastructure-to-vehicle visible light communication (I2V-VLC), the receiver performance is a bottleneck in the communication process. That is, the sensitivity of receiver is not enough in the low-light and long-distance scenario, and thus the communication range is limited. For smart home human activity recognition technology, higher resolution camera and highly sensitive sensor are required, which are not supported by the current hardware. For industrial OWC systems, the beam-steering hardware can not steer the beam in fast direction to meet the movement of industrial devices, and thus the beam tracking accuracy is the bottleneck, which means the beam can not steer in enough speed.

4.3 Nonlinear Compensation Deficiencies and Technical Limitations

Nonlinear distortion is a prevalent issue in optical communication systems, and the lack of effective compensation methods has become a major constraint on performance improvement. Case analyses indicate that in industrial optical wireless communication (OWC) systems, transmission distance decreases due to nonlinear power attenuation in narrowband infrared beams over prolonged operation, and no power compensation algorithm has been incorporated into the system design. In agricultural visible light communication (VLC) systems, the nonlinear relationship between current and light intensity in LED sources compromises signal modulation accuracy. In intelligent transportation systems using carrier-free amplitude-phase modulation (CAP), optical signals undergo nonlinear distortion during transmission as a result of channel dispersion. Although deep learning-based equalization (DDLE) is employed, its ability to compensate for strong nonlinear distortion remains limited. Furthermore, technical limitations are evident in the adaptability of algorithms to specific scenarios: both the CNN-SVM spectral classification algorithm used in intelligent transportation and the generative language models applied in smart homes lack sufficient generalization capability, leading to significant performance degradation in complex environments or under data-scarce conditions.

5. Suggestions

5.1 Deep Learning-Based Equalization for Dynamic Environments

When these problems occur in agricultural greenhouses and industrial workshops these problems become even more prominent due to variation of light intensity and multipath fading.

Zhang et al. proposed an LSTM-DNN hybrid model to solve these problems. They used Long Short-Term Memory Network (LSTM) to extract the time-series features and used Deep Neural Network (DNN) to restore the signal and classify received signal. When SNR=0 dB, BER of LSTM-DNN model is 0.135, while BER of LMS is 0.45 and BER of RLS is 0.38 [8].

In order to evaluate equalization performance of indoor VLC systems in multipath channels, Zhang et al. introduced adaptive modulation methods, including Orthogonal Frequency Division Multiplexing (OFDM) and Digital Pulse Position Modulation (DPPM). They adapted the modulation method according to the present channel condition in indoor environment in real-time, which enhanced the capacity and reliability of indoor VLC systems [7].

5.2 Strategies for Enhancing Hardware-Software Compatibility and Industrialization

Overcoming the hardware/software compatibility challenges is a crucial step toward industrialization of optical communication applications. Eltokhy et al combined Wi-Fi, Li-Fi and BPL with the help of an ESP8266 module to realize tri-network coordination and reduce the impact of noise and interference. The layered protocol design enabling the interoperability among multi-vendor systems was proposed to improve the flexibility and scalability of the system [5].

Meanwhile, Laheri et al. introduced an Indoor Positioning System (IPS), demonstrating the feasibility of hardware-algorithm co-optimization [6]. At the hardware level, data accuracy was improved through optimized spatial layouts of LED arrays and photodiodes; at the algorithm level, triangulation was used to achieve high-precision positioning. By leveraging the advantages of VLC—such as low latency, high bandwidth, and strong security—the system achieved sub-meter accuracy.

Research by Koonen et al. highlighted that in Industry 4.0 environments, beam-steered optical wireless communication (OWC) supports multi-user, high-capacity, and low-latency communication through dynamic adjustment of narrow light beams, effectively avoiding interference typical in conventional RF systems [2].

To accelerate the industrialization of VLC, attention must also be paid to several key issues: the development of low-cost LED driver chips, the establishment of standardized interface specifications, and the provision of open-source software toolchains. First, developing low-cost LED driver chips is key to reducing the cost of VLC systems. Currently, the relatively high cost of LED driver chips limits the large-scale application of VLC technology. Therefore, reducing the cost of driver chips through technological innovation and mass production will facilitate the expansion of VLC technology applications. Secondly, establishing standardized interface specifications ensures interoperability among VLC devices from different manufacturers, thereby promoting the healthy development of the industry. Finally, the provision of an open-source software toolchain facilitates developers in building and debugging the VLC system, accelerating technological innovation and the adoption of applications.

5.3 Deep Learning-Driven Nonlinear Compen-

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sation Technology

The nonlinearity of LEDs is the main limiting factor of VLC systems. The current-voltage (I-V) characteristic of LEDs is nonlinear. When the VLC is implemented, the amplitude of the input signal is high, the LED will work in the saturation region. The output power increases nonlinearly and the signal is distorted severely, which degrades the signal quality and limits the high-speed transmission capability of VLC system. To reduce the bit error rate and suppress the nonlinear distortion, Swaminathan et al. proposed CEO-OFDM scheme to transmit clipped signals in additional time slots to restore original signal [9].

In addition, LSTM-DNN hybrid model proposed by Zhang et al. also has shown its nonlinear compensation ability in ultraviolet optical communication. When the amplitude of the input signal tends to be saturated in LED, the gate structure reduces the gain of the signal and avoids the input signal enters the saturation region [8]. Besides, this model can also be combined with MIMO equalization method [7]. Spatial multiplexing is used to spread the nonlinear interference, which improves the linearity of the system and improves the transmission quality of the signal.

6. Conclusion

With the rapid development of the Internet of Things (IoT), optical communication technology plays an important role in high bandwidth IoT systems because of its high bandwidth, low latency, strong security and immunity to electromagnetic interference. In this paper, we present in detail the optical communication application in other IoT field such as industry and agriculture, smart city and smart home, which can improve the work efficiency and promote the industrialization.

Nevertheless, the application of optical communication within IoT continues to face significant challenges. Different IoT scenarios impose domain-specific requirements: agriculture depends on highly reliable connectivity, while intelligent transportation systems require ultra-low latency, neither of which are fully met by existing technologies. Additionally, challenges such as signal obstruction in complex environments, inadequate device compatibility, and delayed standardization further increase deployment costs and system integration complexity.

To address these challenges, this study proposes a series of targeted measures. In dynamic environments, deep learning-based channel equalization and compensation strategies, such as LSTM-DNN hybrid models, are employed to enhance signal transmission reliability. Additionally, measures such as developing low-cost LED driver chips, establishing unified interface specifications, and providing open-source software toolchains will promote hardware-software compatibility and industrialization. For the issue of nonlinear distortion in LEDs, the nonlinear compensation technique combining the CEO-OFDM scheme with an LSTM-DNN hybrid model can be employed. This achieves dynamic compensation through additional time slot transmission and dynamic signal gain adjustment.

Overall, optical communication technology holds immense potential and broad prospects for development in the field of the Internet of Things. However, existing challenges must still be addressed through continuous technological innovation and systematic optimization. Future efforts should focus on further deepening the integration of optical communications and the Internet of Things, providing technological support for their large-scale application and sustainable development, thereby building a more intelligent and efficient IoT ecosystem.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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