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Development of a Connection Node in a Li-Fi Network for Smart Environment Systems

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Abstract

The article presents the development of a connection node in a Li-Fi/Wi-Fi hybrid network designed for smart environment monitoring and management systems. Transmitter and receiver nodes are implemented using optical communication modules. The On-Off Keying (OOK) modulation scheme is applied in combination with the UART 8N1 protocol and an adaptive two-level calibration method to reduce the impact of varying ambient lighting conditions. The system ensures a complete data exchange cycle, including transmission, reception, and acknowledgment mechanisms. The proposed architecture demonstrates effective performance in terms of reliable communication and stable signal transmission. The architecture is designed as a scalable structure supporting multi-node networks and routing capabilities. This approach enables Li-Fi technology to be used locally for high-speed optical data exchange between neighboring nodes, while Wi-Fi provides global integration with external networks and cloud services. Thus, the system ensures efficient and flexible operation within a hybrid communication environment. The proposed prototype is built on microcontroller-based components and offers a cost-effective implementation. Furthermore, the system can be extended for use in more complex IoT infrastructures. The study shows that Li-Fi-based hybrid approaches have strong potential in smart systems and serve as a foundation for future developments in this field.

Keywords: Li-Fi, connection node, OOK modulation, adaptive calibration, optical communication, IoT, smart environment systems.

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Ağıllı mühit sistemləri üçün Li-Fi şəbəkəsində əlaqə qovşağının hazırlanması

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Xülasə

Məqalədə ağıllı ətraf mühitin monitorinqi və idarəetmə sistemləri üçün nəzərdə tutulmuş Li-Fi/Wi-Fi hibrid şəbəkəsində əlaqə qovşağının inkişafı təqdim olunur. Optik əlaqə modullarından istifadə edilərək ötürücü və qəbuledici node-lar reallaşdırılmışdır. On-Off Keying (OOK) modulyasiyası dəyişən xarici işıqlandırma şəraitinin təsirini azaltmaq məqsədilə adaptiv iki səviyyəli kalibrləmə ilə birlikdə UART 8N1 protokolu əsasında tətbiq edilmişdir. Sistem məlumatların ötürülməsi, qəbul edilməsi və təsdiqlənməsi daxil olmaqla tam bir məlumat mübadiləsi dövrünü təmin edir. Təklif olunan arxitektura etibarlı rabitə və sabit siqnal ötürülməsi baxımından effektiv nəticələr göstərir. Arxitektura çoxqovşaqlı şəbəkələrə genişləndirilə bilən və marşrutlaşdırma imkanlarını dəstəkləyən struktur kimi layihələndirilmişdir. Bu yanaşma Li-Fi texnologiyasından lokal səviyyədə qonşu qovşaqlar arasında yüksək sürətli optik məlumat mübadiləsi üçün, Wi-Fi isə xarici şəbəkələr və bulud xidmətləri ilə qlobal inteqrasiya üçün istifadə olunmasını təmin edir. Beləliklə, sistem hibrid kommunikasiya mühitində səmərəli və çevik işləmə imkanı yaradır. Təklif olunan prototip mövcud mikrokontroller əsaslı komponentlər üzərində qurulmuşdur və aşağı qiymətli implementasiya baxımından əlverişlidir. Eyni zamanda sistemin gələcəkdə genişləndirilərək daha kompleks IoT infrastrukturlarında tətbiqi mümkündür. Aparılan tədqiqat göstərir ki, Li-Fi əsaslı hibrid yanaşmalar smart sistemlərdə yüksək potensial nümayiş etdirir və bu sahədə yeni inkişaf istiqamətləri üçün baza rolunu oynayır.

Açar sözlər: Li-Fi, əlaqə qovşağı, OOK-modulyasiya, adaptiv kalibrləmə, optik rabitə, IoT, ağıllı ətraf mühit sistemləri.

Разработка узла соединения в Li-Fi сети для систем умной среды

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Аннотация

В статье представлена разработка узла соединения в гибридной сети Li-Fi/Wi-Fi, предназначенной для систем мониторинга и управления интеллектуальной средой. Передающие и принимающие узлы реализованы с использованием оптических коммуникационных модулей. Применена модуляция On-Off Keying (OOK) в сочетании с протоколом UART 8N1 и адаптивной двухуровневой калибровкой для снижения влияния изменяющихся условий внешнего освещения. Система обеспечивает полный цикл обмена данными, включая передачу, прием и механизм подтверждения доставки. Предложенная архитектура демонстрирует эффективную работу с точки зрения надежности связи и стабильности передачи сигнала. Архитектура спроектирована как масштабируемая структура, поддерживающая многоузловые сети и функции маршрутизации. Такой подход позволяет использовать технологию Li-Fi на локальном уровне для высокоскоростного оптического обмена данными между соседними узлами, в то время как Wi-Fi обеспечивает глобальную интеграцию с внешними сетями и облачными сервисами. Таким образом, система обеспечивает эффективную и гибкую работу в гибридной среде связи. Предложенный прототип построен на базе микроконтроллерных компонентов и отличается низкой стоимостью реализации. Кроме того, система может быть расширена для применения в более сложных IoT-инфраструктурах. Исследование показывает, что гибридные подходы на основе Li-Fi обладают высоким потенциалом в интеллектуальных системах и служат основой для дальнейшего развития данной области.

Ключевые слова: Li-Fi, узел соединения, OOK-модуляция, адаптивная калибровка, оптическая коммуникация, IoT, системы умного окружении.

Introduction

Modern IoT and smart environment systems rely heavily on radio-frequency technologies, primarily Wi-Fi and Bluetooth, operating in the 2.4 GHz and 5 GHz bands [1, 2, 6]. However, the continuous growth in the number of connected devices leads to congestion of this spectrum, increases the level of interference, and makes it more difficult to ensure reliable data delivery. In addition, in a number of applications, such as industrial automation, medical institutions, and scientific laboratories, the use of radio-frequency communication is restricted by electromagnetic compatibility requirements.

Optical Wireless Communication (OWC), and in particular Li-Fi (Light Fidelity) technology, provides an attractive alternative [1–5]. The advantages of Li-Fi include:

- the directionality of the optical beam, which enhances security and reduces interference between nodes;
- the absence of competition for the radio-frequency spectrum;
- compatibility with electromagnetically sensitive environments.

These advantages make Li-Fi especially relevant for indoor smart environment systems, electromagnetically sensitive areas, and local optical data exchange scenarios [1, 2, 5].

Purpose of the Study

The purpose of this study is to develop and demonstrate a practical connection node for a Li-Fi-based smart environment system. The node is designed to provide local optical data exchange between neighboring devices while maintaining integration with external infrastructure through Wi-Fi/Ethernet communication.

Problem Statement

Modern smart environment and IoT systems mainly depend on radio-frequency communication, which can suffer from spectrum congestion, interference, and limitations in electromagnetically sensitive environments. Therefore, there is a need for an alternative short-range communication solution that is reliable, low-cost, and suitable for local data exchange.

Problem Solution

To solve this problem, a hybrid Li-Fi/Wi-Fi connection node was developed using microcontroller-based optical transmitter and receiver modules. The proposed prototype applies OOK modulation, UART 8N1 framing, adaptive two-level calibration, checksum validation, and ACK-based (Acknowledgement) confirmation to ensure stable optical data transmission under changing lighting conditions.

Hardware Architecture and Components. Both nodes are built based on microcontrollers. For a realistic representation of the system state, the following modules have been added:

- Central nodes will be present in the system to monitor the overall system state and to maintain communication with the external infrastructure through wired and wireless connections [6, 7, 10]. For this purpose, a Wi-Fi/Ethernet module is installed.

- For establishing optical communication, a laser module is used for transmission, while a photodiode is used for signal reception. This configuration will be installed on each node of the system to ensure uninterrupted communication between the system nodes. Using these modules, at least a peer-to-peer connection will be implemented. In nodes where necessary, the number of connections may be increased [8, 9].

- The useful information to be transmitted will consist of data obtained from peripheral modules. As the simplest example, a combined temperature/humidity/pressure module can be considered. In general, this category may include modules that perform various measurements required for further processing and automatic decision-making.

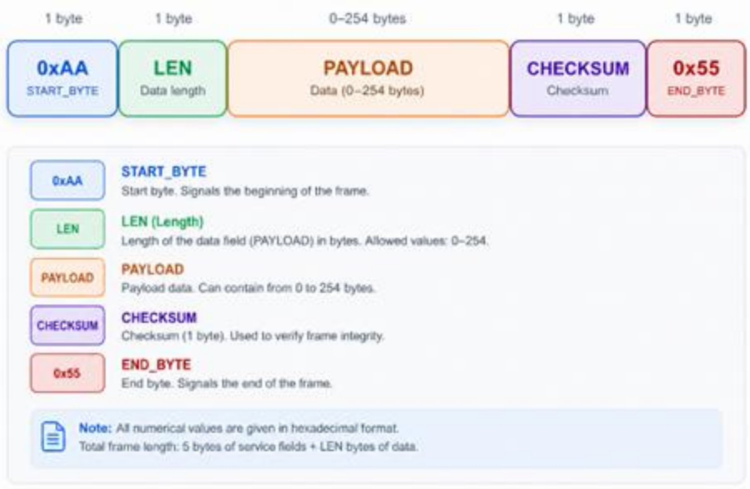
Transmission Protocol and Encoding Methods. The system uses On-Off Keying (OOK) amplitude modulation, in which a logical one is encoded by the switched-on state of the laser, where radiation is present (HIGH), while a logical zero is encoded by the switched-off state, where radiation is absent (LOW) [2, 3].

The advantages of OOK for this application include its simple implementation, since only digital control of the microcontroller output is required, its limited sensitivity to channel nonlinearities, and its compatibility with available optical components.

Bit-level encoding is implemented using an asynchronous universal UART interface with the following structure: one start bit, eight data bits, and one stop bit (Fig. 1). This simplified implementation is used as a prototype-level realization of short-range optical data transmission [3].

At a baud rate of 300 baud, each bit is transmitted for 3333 microseconds, while a complete character consisting of 10 bits takes 33.3 milliseconds to transmit.

The checksum is calculated using a bitwise XOR operation applied to all bytes of the payload. This method provides a simple and computationally lightweight mechanism for detecting transmission errors, which is especially important for microcontroller-based systems with limited processing resources. During packet formation, the transmitting node calculates the XOR value of the payload bytes and appends it to the packet as a checksum field. After receiving the packet, the receiving node performs the same XOR operation over the received payload and compares the result with the transmitted checksum (Fig. 1). If the two values match, the packet is considered valid; otherwise, the packet is rejected as corrupted.



START_BYTE
Start byte. Signals the beginning of the frame.

LEN (Length)
Length of the data field (PAYLOAD) in bytes. Allowed values: 0–254.

PAYLOAD
Payload data. Can contain from 0 to 254 bytes.

CHECKSUM
Checksum (1 byte). Used to verify frame integrity.

END_BYTE
End byte. Signals the end of the frame.

Note: All numerical values are given in hexadecimal format.
Total frame length: 5 bytes of service fields + LEN bytes of data.

Figure 1 – Format of the transmitted frame

Although XOR checksum verification is not as powerful as CRC-based error detection, it is sufficient for the proposed prototype because of its simplicity, low memory requirements, and fast execution. It allows reliable detection of single-bit errors and can also detect many types of multi-bit errors, depending on their distribution within the packet.

The START_BYTE and END_BYTE markers are used to define the beginning and the end of each transmitted packet. This structure supports synchronization and error control in the proposed short-range optical communication prototype [3]. These markers play an important role in maintaining synchronization between the transmitting and receiving nodes. If noise, signal interruption, or incorrect bit detection causes part of the packet to be lost or corrupted, the receiver can ignore invalid data and wait for the next valid START_BYTE. This mechanism enables fast re-synchronization and prevents the system from interpreting random or incomplete data as a valid message.

The maximum payload size is limited to 254 bytes. This value is sufficient for typical IoT and smart environment applications, where transmitted messages are usually short and contain sensor readings, device status information, or simple control commands. For example, a single temperature measurement generally requires only 10–15 characters, while a combined message containing temperature, humidity, and pressure values can also be transmitted within this payload limit. Therefore, the selected packet structure provides an appropriate balance between data capacity, transmission reliability, and implementation simplicity.

Figure 2 illustrates the operation algorithm of a node acting as the transmitting side of the proposed Li-Fi communication system. The process begins with data collection from the connected peripheral modules, such as temperature, humidity, pressure, or other environmental sensors. The acquired data are then validated to exclude incorrect or incomplete measurements and formatted into a structured packet. The presented algorithm reflects a practical implementation of local optical data exchange within a Li-Fi-based smart environment node [1, 2].

After formatting, the packet is encoded according to the selected transmission method. In the proposed system, data transmission is performed using On-Off Keying modulation, where the laser is switched on or off depending on the logical value of each bit. The encoded packet is then sent through the optical module under the control of the microcontroller.

In the experimental implementation, the transmitting node is organized as a compact microcontroller-based unit that combines sensing, packet formation, optical modulation, and feedback processing within a single functional block. The sensor module provides the input data, while the microcontroller validates the measured value, converts it into a text-based payload, calculates the checksum, and controls the laser module according to the selected OOK/UART transmission logic. After sending the optical frame, the same node switches to the acknowledgment waiting mode and analyzes the response received through the photodiode channel. This allows the transmitter not only to generate optical data packets, but also to verify whether the transmitted information has been successfully delivered to the receiving side.

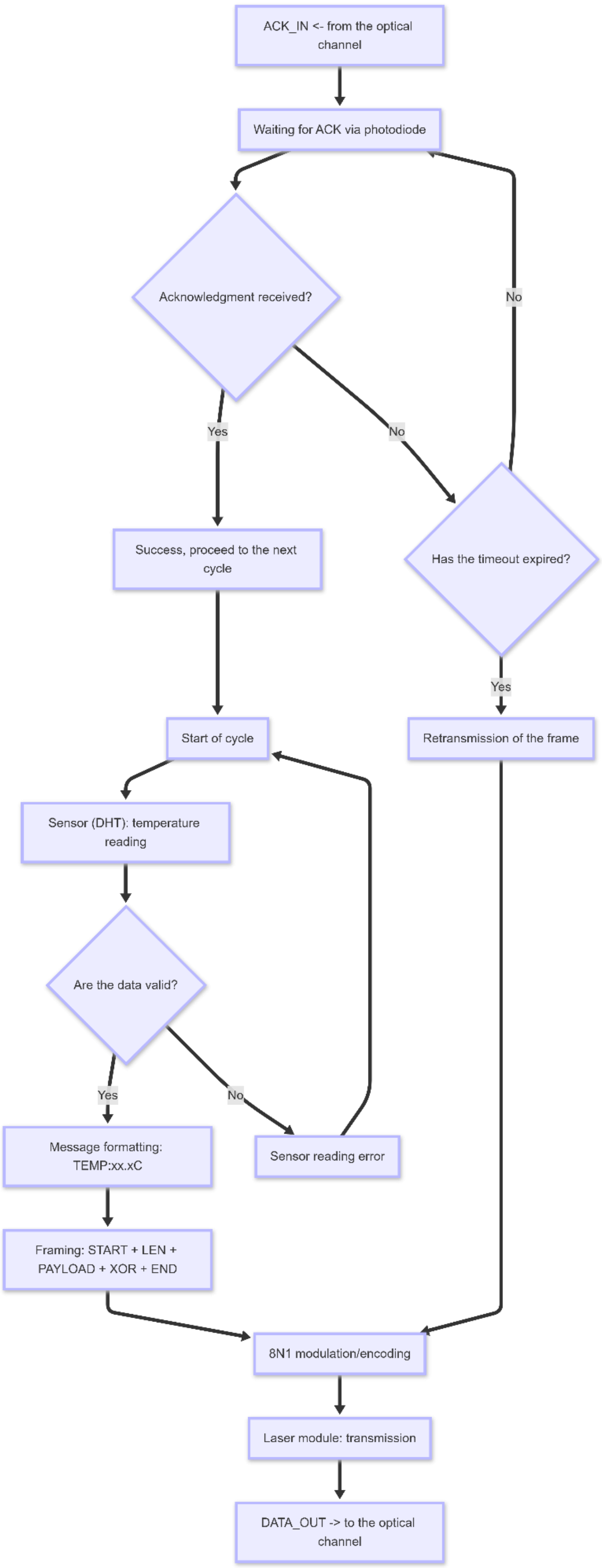


Figure 2 – Experimental node of the transmitting side

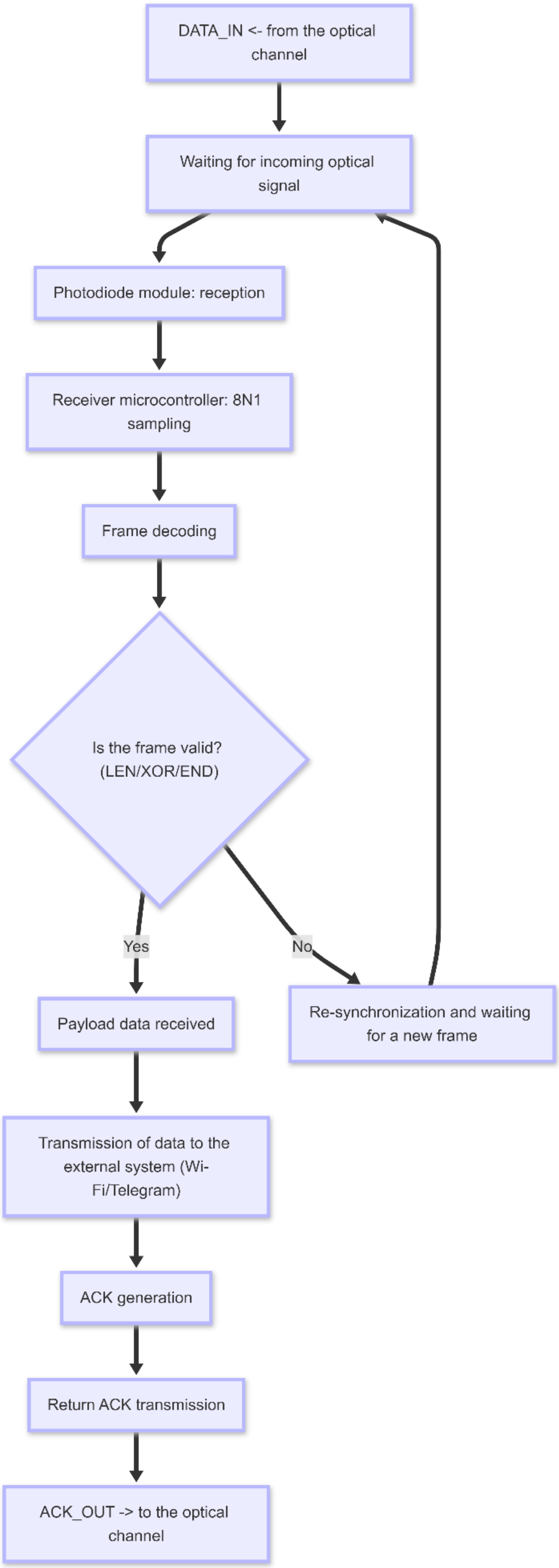


Figure 3 – Experimental node of the receiving side

Figure 3 shows the opposite side, namely the receiving side, where optical signal detection, decoding, validation, and acknowledgment generation are performed according to the logic of short-range optical communication [2, 3]. Here, the reverse process is performed: signal sampling, decoding into a readable packet, integrity validation using the checksum and packet length, further data processing, and finally sending a reception confirmation back through the optical channel.

Adaptive Two-Level Calibration of the Optical Channel. The quality of a Li-Fi optical channel is largely dependent on the background illumination of the room. Sunlight, fluorescent lamps, and LED luminaires generate background noise, which increases the detection thresholds for logical zeros and ones. A simple comparator with a fixed threshold is unable to adapt to slow changes in lighting conditions.

At each system startup, an initial calibration is performed: the analog value V at the photodiode input is measured by the microcontroller under dark conditions, that is, without laser radiation, by averaging 250 samples with an interval of 4 ms to improve reliability. The obtained value is stored as the baseline. Then, the laser beam is directed at the photodiode by the operator, the system waits for 3 seconds, and the measurement of the illuminated state is repeated.

Based on the difference between the illuminated and dark levels, threshold values with hysteresis are calculated:

$$T_{\mathrm{Hi}} = \max\left(6, \frac{\Delta}{3}\right)$$

as the upper threshold for the 0 → 1 transition, and

$$T_{\mathrm{Lo}} = \max\left(3, \frac{\Delta}{6}\right)$$

as the lower threshold for the 1 → 0 transition.

During normal operation, the microcontroller continuously monitors the analog input and slowly adjusts the baseline using an exponential filter:

$$\text{baseline}_{new} = \frac{15 \times \text{baseline}_{old} + V_{\mathrm{Current}}}{16}$$

A critically important aspect is the adaptation condition: the baseline adjustment is applied only when the optical signal is absent, that is, at logical zero when the laser is switched off. This prevents the adaptive filter from affecting the data transmission process itself and allows the system to compensate for slow changes in background illumination, such as switching room lighting on or off, without distorting the received signal.

Conclusion

The proposed optical connection node represents an engineering-feasible and practically accessible solution for local optical networks in the context of Internet of Things and smart environment systems. The work convincingly demonstrates that, even using readily available components, it is possible to create a functional Li-Fi network prototype that is fully integrated into the existing infrastructure, including Wi-Fi and cloud platforms, and is ready for practical deployment and use.

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Conflict of interests

The authors declare there is no conflict of interests related to the publication of this article.

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