Semantic Communication in Visible Light Communication - A Review

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Abstract: The rapid advancement of 6G communication networks has intensified research into intelligent communication paradigms that support semantic-aware information exchange, ultra-low latency, energy-efficient transmission, and AI-driven network optimization. Recent studies have examined semantic communication, Visible Light Communication (VLC), Orthogonal Frequency Division multiplexing (OFDM), Multiple Input Multiple Output,Non-Orthogonal Multiple Access (NOMA, and Reinforcement Learning as the key enabling technologies. However, these technologies have largely been studied in isolation, with limited progress toward a unified AI-native communication framework. This paper reviews recent literature and identifies the research gaps that motivate the proposed work.

Keywords: Semantic Communication; Visible Light Communication (VLC); Artificial Intelligence Native (AI-Native); Q-Learning Semantic Resource Allocation (QL-SRA); Non-Orthogonal Multilple Access (NOMA)

Introduction

Semantic communication has emerged as a transformative paradigm for 6G wireless networks by shifting the objective from accurate bit delivery to a reliable semantic information exchange. In contrast to the conventional Shannon framework, which focuses on minimizing the bit error rates and maximizing the channel capacity, semantic communication transmits only task-relevant information and eliminates semantic redundancy. This approach reduces the communication overhead, improves bandwidth utilization, and enhances transmission efficiency. As a result, semantic communication is particularly advantageous for AI-native systems supporting autonomous vehicles, the industrial Internet of Things (IIoT), digital twins, XR, and intelligent edge computing applications [1]-[2]. The concept of semantic communication has advanced significantly since the foundational work of Shannon and Weaver, who identified semantic communication as one of three communication levels but did not address its practical implementation. Recent advancements in deep learning have enabled the development of practical semantic communication systems through the integration of neural networks with joint source-channel coding (JSCC). This approach facilitates end-to-end optimization of semantic feature extraction, compression, transmission, and reconstruction [1], [2].

In contrast to conventional systems that separately perform source coding, channel coding, modulation, and decoding, semantic communication jointly optimizes these processes to maximize semantic fidelity across varying channel conditions. A significant advancement in this domain is the Deep Semantic Communication (DeepSC) framework proposed by Xie et al. [3], which introduces an end-to-end transformer based architecture for semantic communication in text transmission. Instead of reconstructing the exact transmitted bit sequence, DeepSC focuses on reconstructing the intended semantic meaning by jointly learn ing the semantic representations and channel characteristics. The experimental results indicate that DeepSC substantially outperforms conventional systems under low signal-to-noise ratio (SNR) conditions and requires fewer transmitted symbols. This study establishes the feasibility of integrating deep learning into semantic communication and stimulates further research into semantic-aware communication system design.

Building on DeepSC, several extensions have been developed to address diverse communication modalities. CNN based semantic communication frameworks have been investigated for image transmission, utilizing convolutional feature extraction to preserve perceptual quality and minimize transmission redundancy [4]. Vision Transformer (ViT)-based architectures and diffusion-model-assisted semantic communication systems have improved semantic reconstruction quality, particularly under severe channel impairments . Multi-modal semantic communication, which integrates text, speech, and visual information within a unified semantic representation framework, has also attracted considerable attention. Collectively, these approaches demonstrate that semantic communication can significantly enhance efficiency while maintaining task-specific semantic fidelity. Recent studies have expanded semantic communication to encompass multi-user and scenarios. Federated semantic communication, distributed semantic inference, and edgeassisted semantic communication have been examined to support collaborative artificial intelligence applications in future 6G networks[5]. Furthermore, RL, graph neural networks, and knowledge graph-based semantic representations have been explored to improve semantic decision making in dynamic network environments. These advancements indicate that semantic communication has transitioned from point-to-point transmission toward intelligent semantic networking.

However, despite these advancements, several critical research challenges remain. Most of the existing semantic communication frameworks are tailored to conventional RF systems and do not exploit the distinctive properties of optical wireless communication. Additionally, most studies focus on single-user environments and rarely address semantic communication in multi-user transmission architectures, such as Non-orthogonal Multiple Access (NOMA). Third, while semantic communication reduces redundancy, adaptive semantic-aware resource allocation remains largely unexplored. Current frameworks typically optimize the reconstruction accuracy using fixed transmission strategies, without jointly considering semantic utility, latency, throughput, and energy efficiency during resource allocation [2], [5]. Another significant limitation is the insufficient integration of semantic communication with advanced physical-layer technologies. Most recent studies have evaluated semantic communication performance over additive white Gaussian noise (AWGN), Rayleigh fading, or conventional wireless channels, with limited focus on VLC systems. Consequently, the potential advantages of combining semantic communication with optical OFDM, MIMO, and power-domain NOMA remain largely unexplored. In addition, current semantic communication frameworks generally lack adaptive

intelligence to dynamically adjust transmission policies in response to varying channel conditions and semantic requirements.

In summary, although significant progress has bee made in semantic communication, current studies regarding communication media, network architecture, and intelligent resource optimization remain fregmented. These limitations underscore the need for an integrated AI-native semantic communication framework that jointly leverages semantic feature extraction, VLC-enabled OFDM-MIMO-NOMA transmission, and RL-based adaptive resource optimization. Such a framework can simultaneously enhance the semantic fidelity, spectral efficiency, latency, throughput, and energy efficiency in intelligent indoor 6G communication systems.

Related work

VLC has emerged as a leading optical wireless communication technology for beyond fifth-generation (B5G) and sixth generation (6G) networks because of its extensive unlicensed optical spectrum, high spatial reuse, robust physical-layer security, and resistance to RF electromagnetic interference [6]. By employing commercially available LEDs as optical transmitters, the VLC enables simultaneous illumination and high-speed wireless communication without requiring additional spectrum allocation. The extensive deployment of solid-state LED lighting infrastructure has accelerated the adoption of VLC in smart buildings, intelligent transportation systems, healthcare facilities, industrial automation, under water communication, and IoT applications [6].

Unlike conventional RF communication systems that operate within congested licensed frequency bands, VLC utilizes the visible optical spectrum (approximately 400–800 THz), which provides substantially greater bandwidth and supports multi-gigabit wireless communication. Furthermore, the directional propagation of visible light enhances communication security by confining optical signals to enclosed environments and reducing inter-cell interference through improved spatial reuse [6]. These attributes make VLC particularly suitable for intelligent indoor communication scenarios, where high throughput, low latency, and energy efficiency are essential for future AI-native 6G networks.

Recent research on VLC has focused on improving the physical-layer communication performance through advanced modulation techniques, channel modeling, equalization algorithms, adaptive dimming control, optical MIMO, hybrid RF/VLC architectures, and intelligent receiver design [7]. To increase communication capacity, extensive research has investigated the integration of OFDM into VLC systems. Optical OFDM variants, including direct current-biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM), and flip-OFDM, effectively mitigate frequency-selective optical channel impairments while satisfying the non-negativity constraint required by intensity modulation and direct detection (IM/DD) systems. Recent studies have also proposed hybrid precoding and companding techniques to reduce the peak-to-average power ratio (PAPR) and improve the bit-error rate (BER) performance. MIMO techniques have been extensively investigated to increase the VLC system capacity and communication reliability. By employing multiple LEDs and photodetectors, optical MIMO systems exploit spatial multiplexing and diversity gains to improve the throughput. Sejan et al. conducted a comprehensive survey of MIMO-based VLC systems, classifying the research into imaging MIMO, non-imaging MIMO, angle-diversity receivers, spatial modulation, and machine learning-assisted

MIMO architectures . The survey concluded that, despite significant capacity improvements, practical

implementation is hindered by channel correlation, optical interference, receiver complexity, and the need for accurate channel estimation. AI and machine learning (ML) techniques have recently attracted significant attention for addressing the various challenges in VLC systems. Deep learning has been effectively applied in optical channel estimation, signal detection, modulation recognition, localization, equalization, and interference mitigation. Recent surveys indicate that AI-driven VLC systems exhibit enhanced robustness under nonlinear optical channel conditions and substantially reduce computational complexity compared with traditional optimization techniques [8]. RL has shown considerable potential for adaptive link management and dynamic resource allocation in intelligent optical wireless networks. Despite significant progress, several critical limitations remain in current VLC communication systems. Most VLC architectures rely on conventional bit-level communication models based on Shannon's framework, transmitting complete source information regardless of semantic relevance. Although OFDM and MIMO techniques enhance communication reliability and spectral efficiency, their optimization is largely confined to physical-layer performance, neglecting semantic information representation and fidelity.

Furthermore, recent AI-assisted VLC studies primarily address channel estimation, equalization, and signal detection, with limited focus on semantic communication within optical wireless systems [8]. A further limitation is that most VLC studies focus on point-to-point communication or traditional multi-user transmission strategies, without integrating semantic communication, MIMO, NOMA, and intelligent resource optimization into a unified end-to-end architecture. Although hybrid RF/VLC systems enhance communication reliability by leveraging complementary media, they continue to depend on conventional source and channel coding techniques [9]. Consequently, the benefits of combining semantic feature extraction with VLC-enabled OFDM-MIMO transmission are largely unexplored in current research.

The preceding analysis indicates that, although VLC has matured as a candidate technology for indoor 6G communication systems, research efforts primarily focus on physical layer enhancements. Semantic-aware communication, intelligent multi-user transmission, and adaptive AI-native optimization are comparatively underexplored. These findings underscore the need to integrate semantic communication with VLC-enabled OFDM-MIMO-NOMA architectures to optimize semantic fidelity, communication reliability, latency, throughput, and energy efficiency jointly within a unified intelligent communication framework.

Key Contribution

The primary novelty of this work lies in the first-time integration of CNN-based semantic communication, VLC-enabled OFDM-MIMO-NOMA transmission, and Q-learning-driven semantic resource optimization into a unified AI-native communication framework that jointly maximizes semantic fidelity, throughput, energy efficiency, and latency performance for intelligent indoor 6G networks.

Methodology

This review paper examines recent research on semantic communication and its integration with VLC and emerging 6G communication technologies. Relevant studies covering semantic communication, VLC, OFDM, MIMO, NOMA, and AI/RL-based resource optimization were reviewed and categorized based on

their communication architecture, enabling technologies, and reported objectives. The reviewed

literature was then analyzed to identify current developments, limitations, and research gaps toward integrated AI-native semantic communication systems.

Discussions

The reviewed studies indicate significant progress in semantic communication, VLC, and AI-assisted wireless systems; however, these technologies are largely investigated independently. Existing works provide limited consideration of semantic communication over VLC-enabled OFDM-MIMO systems, multi-user NOMA transmission, and adaptive semantic-aware resource allocation. The review therefore highlights the need for an integrated framework that jointly considers semantic fidelity, throughput, latency, and energy efficiency in intelligent indoor 6G networks.

Conclusions

This review summarizes the recent developments in semantic communication, VLC, OFDM, MIMO, NOMA, and AI-based resource optimization for future 6G networks. The analysis shows that although considerable progress has been achieved in individual technologies, their unified integration remains relatively underexplored. Future research should focus on AI-native semantic communication frameworks that combine VLC-enabled OFDM-MIMO-NOMA transmission with adaptive and semantic-aware resource optimization to improve communication efficiency, reliability, latency, and energy performance.

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