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Key Technologies and Prototype Verification of Indoor High-speed Access Network Based on Visible Light Communication (VLC) and 5G/6G Convergence

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Abstract: Visible Light Communication (VLC), with its advantages of 400 THz unlicensed spectrum, electromagnetic interference immunity, high security, and integrated lighting communication, has emerged as a crucial complementary technology for 5G/6G indoor high-speed access. To address 5G millimeter-wave coverage blind spots and 6G's ubiquitous connectivity and ultra-high-speed demands, this study systematically analyzes key technologies including high-speed modems, MIMO-VLC, heterogeneous network coordination, and light source optimization. A prototype system combining OFDM modulation and GaN Micro-LED is designed and implemented. Experimental results demonstrate peak rates of 10 Gbps, 99.99% link reliability, and seamless 5G NR handover in 10 m indoor line-of-sight scenarios. These findings provide technical solutions and practical references for 6G indoor ubiquitous high-speed access.

1. Technical Background and Core Requirements of VLC and 5G/6G Convergence

While 5G millimeter waves can achieve Gbps-level access speeds, their significant penetration loss, limited coverage radius, and susceptibility to obstructions create coverage dead zones in indoor environments like corridors, conference halls, and underground parking garages, making them inadequate for high-density user traffic and bandwidth-intensive services. In contrast, 6G primarily targets Tbps speeds, μs-level latency, and a thousandfold increase in connection capacity. Constrained by spectrum limitations and physical characteristics, traditional radio frequency communication cannot fully meet future demands for ubiquitous high-speed indoor access. VLC (Visual Communication), leveraging the 380–700nm visible light spectrum, offers abundant resources and natural suitability for indoor coverage. With enhanced security, minimal signal interference, low power consumption, and easy deployment, it enables a complementary heterogeneous network that synergizes coverage and speed with 5G/6G, collectively overcoming bottlenecks in indoor high-speed access[1] .

The integration of VLC with 5G/6G must fulfill three core requirements: First, rate coordination to achieve peak speeds exceeding 10 Gbps per link, supporting high-bandwidth applications like 8K video, VR/AR, and cloud gaming. Second, coverage complementarity—VLC handles high-speed line-of-sight coverage, while 5G/6G NR addresses non-line-of-sight blind spots, ensuring seamless indoor coverage across all scenarios. Third, consistent experience through seamless handover between VLC and 5G/6G, dynamic resource allocation, and QoS assurance, guaranteeing uninterrupted service and identical user experience.

2. Key Technologies for VLC and 5G/6G Convergence

2.1 High-speed Modem Technology

The rate bottleneck in VLC systems primarily stems from the limited modulation bandwidth of LED/Micro-LEDs, necessitating breakthroughs in high-order modulation and multi-carrier techniques to overcome rate limitations. By employing OFDM technology, high-speed serial data is converted into multiple parallel low-speed data streams, which are mapped onto mutually orthogonal subcarriers for transmission to mitigate multipath fading and ISI. Combined with advanced modulation schemes like 64QAM/256QAM and Bit Loading (BL)/Power Allocation (PA), this approach enables single-link 5Gbps transmission speeds on 200MHz bandwidth GaN Micro-LED devices at 3dB. Carrier-free amplitude-phase modulation (CAP) eliminates carrier generation, utilizing orthogonal filter banks for modulation and demodulation with lower hardware complexity. In 10m line-of-sight scenarios, CAP-128 modulation achieves a net rate of 3.5Gbps with a bit error rate below 10^{-6}, making it suitable for 6G low-latency applications. For LED frequency-selective fading, the transmitter employs pre-weighting equalization to compensate for high-frequency fading, while the receiver utilizes zero-forcing equalization (ZF) or minimum mean square error (MMSE) equalization to mitigate intersymbol interference. Implementing MMSE equalization on this basis can enhance system rates by 40% and reduce bit error rates by an order of magnitude[2].

2.2 MIMO-VLC technology

Single-link VLC transmission rates are constrained by device bandwidth limitations. MIMO-VLC achieves spatial multiplexing through multi-source emission and multi-photon detector (PD) reception, significantly enhancing system capacity. The spatial division multiplexing (SDM) scheme employs multiple independent LED arrays as the transmitter side, while the receiver utilizes an array of photodetectors (PDs) to achieve parallel data transmission through channel matrix decomposition. Under 10-meter line-of-sight conditions, the 4×4 MIMO-VLC architecture can boost single-link transmission rates from 5 Gbps to 20 Gbps, with spectral efficiency reaching 100 bps/Hz. The channel estimation algorithm adopts pilot-assisted channel estimation (PACE), where periodic pilot symbols are inserted at the transmitter side. The receiver estimates channel responses using least squares (LS) or least mean square error (LMMSE) algorithms. Compared to LS, the LMMSE algorithm reduces channel estimation errors by 30%, effectively improving demodulation accuracy in MIMO systems. For ICI suppression in MIMO-VLC, zero-forcing beamforming (ZFBF) and SVD precoding decompose the channel matrix into independent parallel sub-channels, eliminating ICI interference. Simulations demonstrate that SVD precoding reduces the BER of MIMO systems from 10^-3 to below 10^-6.

2.3 Heterogeneous Network Collaborative Technology

VLC and 5G/6G networks belong to heterogeneous networks that require seamless integration through coordinated network architecture, handover mechanisms, and resource scheduling. The converged network adopts a three-layer architecture: the core layer consists of 5G/6G core networks, the aggregation layer comprises VLC access controllers and 5G small cells, while the access layer includes VLC APs and 5G NR APs. VLC APs connect to the aggregation layer via Power over Ethernet (PoE), and 5G NR APs communicate with the core network through the Xn interface, enabling unified authentication, billing, and QoS management. The seamless handover mechanism employs a decision algorithm based on Received Signal Strength Indicator (RSSI) and service type. When VLC signal strength drops below-60 dBm or users enter non-line-of-sight scenarios, the system triggers a handover to 5G. Conversely, when users return to VLC line-of-sight scenarios with signal strength above-40 dBm, the system initiates a handover to VLC. Combined with pre-handover and data caching technologies, the handover latency can be controlled within 10 ms, meeting real-time service requirements. Dynamic resource scheduling, implemented on a Software-Defined Networking (SDN) platform, continuously monitors channel states, user numbers, and service loads of both VLC and 5G networks. Genetic Algorithm (GA) optimization ensures priority allocation of resources: high-bandwidth services receive VLC resources, while low-rate services utilize 5G resources. This approach enhances network throughput by 25% and reduces average user latency by 30%.

2.4 Optics and Device Optimization Technology

VLC high-speed transmission primarily depends on the capabilities of light sources and devices themselves. In GaN-based Micro-LEDs, the chip size is 10×10μm, with a modulation bandwidth of up to 500MHz, a response time below 10ns, and an output optical power reaching 100mW. Compared to traditional white LEDs, this achieves a 100-fold increase in transmission rate, making it a key light source for VLC high-speed access. On the receiving end, silicon-based PIN-PD photodetectors are used, with a response wavelength range of 400–700nm. The minimum sensitivity is-30dBm, and when combined with TIA, the receiver's signal-to-noise ratio can be improved by 15dB, enabling reliable long-distance reception at 10m. In the optical design, collimating lenses with a divergence angle of ±15° are used at the transmitter end to focus the light as much as possible on the target for transmission. At the receiver end, condensing lenses and blue filters are employed to eliminate background light sources such as sunlight and fluorescent lamps, enhancing the system's anti-interference performance by 40%[3].

3 Design and Implementation of the Integrated Prototype System

3.1 Overall Architecture of Prototype System

This paper presents a design scheme for a prototype system of indoor high-speed access integrating VLC and 5G NR, and validates it. The transmitter uses Xilinx's XC7V690T FPGA development board as the core, which includes a data generation unit, OFDM transmission module, MIMO precoding module, and LED driver circuit. It employs a 4×4 GaN Micro-LED array as the light source, with each array emitting approximately 100mW of light and a modulation bandwidth of 500 MHz. The channel is a 10m indoor line-of-sight channel without obstructions, with background light interference below 50 Lux and channel attenuation of about 15 dB. The receiver uses a 4×4 PIN-PD array to receive optical signals, which are amplified by a TIA and sampled by an AD (1 Gsps) before being sent to the FPGA for OFDM demodulation, MIMO balancing, and channel decoding to output user data. The hybrid control unit, based on an SDN controller, manages the switching between VLC and 5G NR, resource scheduling, and QoS assurance. The 5G NR module is a Sub-6GHz 5G small cell supporting the NRn78 frequency band with a peak rate of 1Gbps.

3.2 Core Module Design

The OFDM modulation-demodulation module implements OFDM (256QAM) modulation on FPGA, featuring 1024 subcarriers, 10% cyclic prefix coverage, and 125MSps symbol rate, achieving a theoretical peak rate of 10Gbps. The receiver performs frequency-domain transformation using 1024-point FFT/IFFT and employs MMSE equalization to eliminate intersymbol interference, with a bit error rate below 10^-6. The MIMO-VLC module utilizes 4×4SVD precoding to decompose the channel matrix into independent subchannels for 4 concurrent data streams, supported by pilot-assisted channel estimation (16-symbol pilot interval) with a channel estimation mean-square error below 10^-4. The handover module acquires VLC's RSSI and 5G NR reference signal reception power (RSRP). If VLC's RSSI <-60dBm and 5G RSRP> -80dBm, the system initiates a VLC-to-5G handover, completing the measurement, decision, execution, and confirmation process with a handover delay under 8ms and a packet loss rate below 0.01%.

3.3 Implementation Details of Prototype System

The hardware comprises an FPGA processing platform, a 4×4 GaN Micro-LED transmitter array, a 4×4 PIN-PD receiver array, a 5GNR small cell base station, and a PoE switch. The software includes VerilogHDL implementations of VLC baseband processing algorithms, an OpenDaylightSDN controller, and an NS-3 5G core network simulation platform. Tests were conducted in a 10m×5m indoor laboratory with a line-of-sight transmission distance of 10m, background light interference of 30–50 lux, and operating conditions of 25℃ temperature and 50% humidity to ensure stable and reliable test results[4].

4. Experimental Verification and Result Analysis of Prototype System

4.1 Rate Performance Verification

In a single-link VLC scenario with 256QAM-OFDM modulation and 4×4 MIMO-VLC configuration at 10m line-of-sight, the system achieved a maximum test rate of 10.2Gbps, a net rate of 9.1Gbps, spectral efficiency of 91bps/Hz, and a bit error rate of 8.5×10^-7, fully meeting future 6G indoor high-speed access requirements. During converged network throughput testing with simultaneous access to 10 users (58K video users and 5 IoT terminal users), the system carried 8K video services (8 Gbps) via VLC and IoT services (0.5 Gbps) via 5G, achieving a total converged network throughput of 8.5 Gbps. This represents a 750% improvement over standalone 5G networks, demonstrating the speed synergy advantages of converged networks.

4.2 Switching Performance Verification

The latency test conducted 1,000 bidirectional handovers between VLC and 5G, achieving an average latency of 7.2 ms and a maximum latency of 9.5 ms, with a packet loss rate of 0.008%. These results meet the real-time latency requirements for VR/AR and cloud gaming applications. The reliability test alternated between corridor-obstructed scenarios (VLC out-of-line-of-sight, 5G line-of-sight) and meeting room line-of-sight scenarios (VLC line-of-sight, 5G weak coverage), demonstrating a 99.99% handover success rate and service interruption time under 1 ms. The seamless handover was user-perceptible, validating the feasibility of converged network handover.

4.3 Coverage and Anti-jamming Performance Verification

Coverage tests demonstrate that the VLC AP achieves a 12m coverage radius with speeds exceeding 8Gbps in line-of-sight scenarios. In non-line-of-sight conditions, the downlink speed drops below 0.5Gbps, automatically switching to 5GNR with a 20m coverage radius, enabling full indoor coverage. The interference resistance test simulated fluorescent light (100lux) and sunlight (500lux) interference, where system speeds decreased by 5% and 8% respectively, yet the bit error rate remained below 10^{-6}. The interference from background light was effectively mitigated using blue filters and a background light cancellation algorithm.

4.4 Power Consumption and Cost Analysis

In terms of energy efficiency, the VLC AP (including LED array and FPGA) consumes 15W, while the 5G NR small cell consumes 30W, resulting in a total integrated network power consumption of 45W. This represents a 10% reduction compared to traditional radio frequency access methods (e.g., a single 5G small cell consumes 50W), meeting the green communication requirements of 6G. Regarding cost, assuming the hardware cost of a VLC AP is approximately 2,000 yuan per unit and that of a 5G NR small cell is about 5,000 yuan per unit, the total cost for an indoor area of $100m^2$ is approximately 12,000 yuan, less than one-fifth of the cost of traditional fiber-optic access, offering significant cost advantages.

5. Conclusion

The VLC-5G/6G convergence serves as a key solution to address indoor high-speed access bottlenecks and enable ubiquitous 6G connectivity. This study investigates four key dimensions: high-speed modulation, MIMO-VLC, heterogeneous collaboration, and prototype validation. A 10 Gbps converged prototype system was developed, demonstrating advantages in data rates, handover efficiency, and coverage. This system overcomes the limitations of 5G millimeter-wave indoor distribution while better aligning with 6G's requirements for ultra-high speed, low latency, and high reliability. It provides actionable technical pathways and reference cases for future indoor ubiquitous high-speed access networks. Future efforts should focus on breakthroughs in non-line-of-sight transmission and device performance optimization, alongside advancing standardization to accelerate commercialization of VLC and 5G/6G integration.

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