

VoLiFi as the Next Generation Voice Service over LiFi

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Abstract: The radio frequency (RF) based wireless systems are at fundamental limits due to the exponential growth of mobile data and the increasing need for high quality and low latency voice services. Light Fidelity (LiFi), a high-speed, two-way, and networked optical wireless communication (OWC) system, is a technology utilizing visible and infrared light as its medium and providing many benefits over traditional WiFi and cellular systems, including orders-of-magnitude greater unlicensed spectrum, natural spatial confinement, resistance to RF interference, and greater physical-layer security. In this regard, the idea of Voice over LiFi (VoLiFi) appears to be a promising paradigm that is based on the utilization of LiFi access networks to provide next-generation real-time voice and audio services. Pioneering projects of audio and voice communication over LiFi indicate that it is possible to transmit continuous-time audio streams with satisfactory quality over intensity modulation and direct detection (IM/DD) links. This paper gives a comprehensive system level view of VoLiFi as next generation voice service, its architecture, protocol stack, quality of service (QoS) requirements, the technologies that enabled it, and research challenges. We propose VoLiFi based on the IP-based voice services and hybrid RF-optical networks can offer very secure, low latency, and spectrum efficient voice connectivity to smart buildings, healthcare, industry, and mission-critical systems.

Keywords: LiFi; Visible Light Communication; Optical Wireless Communication; VoIP; VoLiFi; Quality of Service; Next-Generation Networks.

Introduction

The global proliferation of wireless devices and bandwidth-intensive applications has led to severe congestion of the RF spectrum, especially in unlicensed bands used by WiFi and other short-range systems [4], [6]. With mobile data traffic continuing to grow rapidly, RF-based networks face capacity, interference, and energy-efficiency challenges. At the same time, the Internet Protocol (IP) has become the universal convergence layer for multimedia services, and Voice over IP (VoIP) has replaced circuit-switched telephony in many scenarios. Future voice services must therefore be tightly integrated with high-capacity access networks that provide low delays, low jitter, and high reliability.

LiFi is a new form of optical wireless communication technology [4]–[6], where the light-emitting diodes (LEDs) or laser diodes are used to transmit data faster by modulating the level of optical intensity at

frequencies that cannot be perceived by the human eye, which is hundreds of thousands of times larger than the RF spectrum.

Preliminary experiments have already demonstrated the use of LiFi-based audio and voice transmission systems with comparatively simple analog and digital modulation schemes, using commercial-off-the-shelf LEDs, photodiodes and inexpensive circuit boards. On these premises, this paper constructs the VoLiFi: an upcoming voice service that leverages LiFi access networks to deliver voice over IP with a high-quality assurance of QoS [7]–[10].

The contributions of the article are as follows:

- Present a thorough introduction to LiFi basics and what they mean to real time voice services.
- Recommend a reference architecture and protocol stack of VoLiFi combined with IP-based voice systems.
- QoS requirements (latency, jitter, packet loss): Analyze and map them to LiFi link- and MAC-layer mechanisms.
- Talk about some of the important enabling technologies, such as modulation, coding, multiple access, handover, and hybrid RF-LiFi integration.
- Determine the open research opportunities and promising usage areas of VoLiFi.

Related work

The LiFi (Light wireless) is a type of optical wireless communication that uses solid-state lighting infrastructure by modulating an electrical signal applied on top of a DC bias current to create intensity modulation of the light emitted. Direct detection is done at the receiver by a photodiode that produces a current proportional to the optical power and it is then processed to retrieve the transmitted data.

The main features about LiFi that are relevant in voice services are:

- Fully featured the visible-light band spans approximately 400 to 800 Th, with orders of magnitude of spectrum available compared to standard RF allocations.
- High data rates: Recent future state-of-the-art LiFi systems have already shown fixtures of gigabit-per-second scale data rates with advanced modulation scheme and multiple-input multiple-output (MIMO) designs.
- Spatial confinement and security Light does not travel through walls, which means that LiFi transmissions are automatically enclosed in a room, which reduces the vulnerability to eavesdropping and allows high spatial reuse.
- Low interference and EMI immunity LiFi does not interfere with RF systems, and is not influenced by RF interference, which makes it a potentially suitable solution to RF-sensitive environments (such as hospitals and aircraft cabin) that might be impacted by other electronics in the vicinity.
- (Real-time capability): Proven LiFi systems can use microsecond-level latency, supporting real-time communication and control.

Audio and Voice over LiFi: Past Research. Several experiments have been done on the transmission of audio and voice over LiFi links as an initial step to full-fledged data communications systems. A LiFi voice experimental platform was built in an article authored by lifi (2017) (refer to image LiFi voice) to transmit audio signals using visible-light channels and analyze quality indicators including signal-to-noise ratio (SNR) and distortion. The system used the intensity modulation process with the input of the analog audio and proved intelligent audio in the short distance.

The article contained in the publication of [8] has been dedicated to the creation of the LiFi-based system, which can provide simultaneous voice and data transmission and has compared its operation to the WiFi one regarding the throughput and the reliability. Similarly, audio transfers and voice directing systems with LiFi LED links, as reported by the authors, could produce voice-like audio over relatively short distances, in addition, to being more secure at lower RF levels and less disruptive.

These early experiments usually simulate the LiFi system link as a baseband analog channel in which continuous-time audio data are transmitted, and nothing more. However, they confirm the practicality of optical voice communication and demonstrate the benefits of high-speed LiFi communication to provide high-speed services of low latency and interference-free audio services.

Concept and Architecture of VoLiFi

A. Definition and Service Model

VoLiFi can be defined as a voice communication service in which the access link between user equipment (UE) and the local access network is provided by LiFi, while the end-to-end voice transport uses IP-based protocols similar to VoIP. In a VoLiFi system, voice packets generated by an IP telephony stack (e.g., SIP/RTP-based) are mapped onto LiFi frames at the link layer, transmitted over optical channels, and then forwarded via wired or RF backhaul to remote endpoints or application servers.

The VoLiFi service model may include:

- On-net VoLiFi calls: Both endpoints are connected via LiFi access networks within the same building or campus, enabling end-to-end optical access for the voice path.
- Hybrid VoLiFi–RF calls: One endpoint uses a LiFi access network, while the other uses WiFi or cellular access; LiFi serves as the downlink or both uplink and downlink in the first hop.
- Local voice broadcast or group calls: A LiFi access point (AP) provides multicast voice services (e.g., public address or guidance) to multiple users within a cell [9].

B. Reference Architecture

Fig. 1 conceptually illustrates a reference architecture for VoLiFi in an indoor environment. Ceiling-mounted LiFi APs provide illumination and bidirectional data connectivity within optical attocells. [2], [3] User devices, such as smartphones, headsets, or dedicated VoLiFi handsets, are equipped with LiFi transceivers comprising photodiodes (for downlink) and modulated LEDs or infrared emitters (for uplink) [2], [5].

Each LiFi AP connects via Ethernet or power line communication (PLC) to a central LiFi controller that performs resource management, mobility handling, and IP routing [2], [5]. A session initiation protocol (SIP) server or IP PBX handles call signaling, registration, and service logic for VoIP sessions. The core network may interconnect with enterprise IP networks, the public switched telephone network (PSTN) via gateways, or external VoIP service providers.

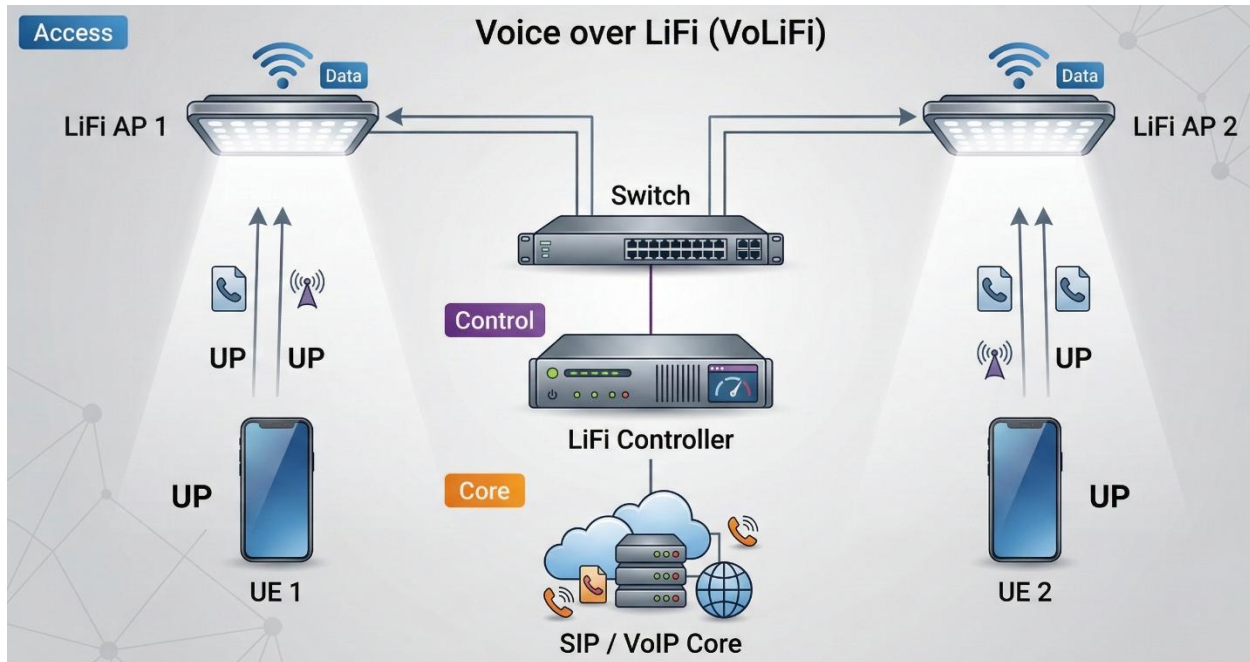


Fig. 1. Conceptual VoLiFi architecture with LiFi access, LiFi controller, and SIP/VoIP core.

The main functional blocks in a VoLiFi architecture are:

- LiFi physical (PHY) and MAC layers implementing optical modulation, coding, and medium access control.
- A LiFi convergence layer that encapsulates IP packets (including RTP voice payloads) into LiFi frames.
- QoS management functions that prioritize voice traffic and perform scheduling, admission control, and rate adaptation.
- A VoIP stack (SIP, RTP/RTCP) providing signaling and media transport.
- Mobility and handover mechanisms across LiFi cells and between LiFi and RF networks [2], [5].

C. Protocol Stack for VoLiFi

The protocol stack for VoLiFi can be layered as follows:

- Application layer: Voice codecs (e.g., G.711, G.722, Opus), voice activity detection (VAD), echo cancellation.
- Transport and session layer: Real-time Transport Protocol (RTP) over UDP, Real-time Control Protocol (RTCP) for QoS feedback, SIP for call control.

- Network layer: IP for packet forwarding and addressing, with optional Differentiated Services (DiffServ) for QoS marking.
- Data link and MAC layer: LiFi MAC with service differentiation, frame aggregation, and ARQ mechanisms designed to meet voice delay and loss constraints [2].
- Physical layer: IM/DD-based LiFi PHY with modulation schemes such as on-off keying (OOK), pulse-amplitude modulation (PAM), orthogonal frequency-division multiplexing (OFDM), and spatial multiplexing [1], [2].

The interaction between RTP/UDP/IP and the LiFi MAC closely resembles VoIP over WiFi, but with key differences in channel characteristics, interference patterns, and mobility behavior that must be taken into account for VoLiFi service design [2], [6].

QoS Requirements for Voice Over LiFi

A. Delay, Jitter, and Packet Loss Constraints

Voice services impose stringent QoS requirements on the underlying network. For acceptable conversational quality, the end-to-end one-way delay is typically recommended to be below 150 ms, with delays up to 400 ms being marginally acceptable [11], [12]. Jitter must be controlled within tens of milliseconds, often mitigated by playout buffers at the end-points. Packet loss rates above 1–3% can significantly degrade perceived quality, although modern codecs are more robust and can tolerate somewhat higher losses with concealment [12].

In a VoLiFi system, the access link provided by LiFi constitutes one segment of the end-to-end path, and its contribution to latency and jitter must be minimized to leave budget for processing and backbone delays. Experimental LiFi systems exhibit very low PHY-layer latencies on the order of microseconds, and MAC-layer delays can be kept in the millisecond range with appropriate scheduling [2], [3]. Thus, LiFi is inherently well-suited for low-latency voice traffic, provided that MAC contention, ARQ retransmissions, and handover procedures are carefully engineered.

B. Mapping Voice QoS to LiFi MAC and PHY

The LiFi MAC layer must support traffic differentiation to ensure real-time voice traffic is prioritized over best-effort data.

Possible mechanisms include:

- Priority queues: Greater priority is assigned to voice packets such that there is less waiting time to be transmitted in the buffer.
- Contention-based access with differentiated parameters: Mechanisms similar to that of IEEE 802.11e Enhanced Distributed Channel Access (EDCA), but specific to optical channels.
- Scheduled access: Collisions can be avoided and delays can be bounded using time-division multiple access (TDMA) slots allocated to voice flows [2].

At the PHY layer, the chosen modulation and coding schemes should find an equilibrium between robustness and spectral efficiency. For VoLiFi, operating in a more robust regime, where some throughput is sacrificed in exchange for greater SNR and reduced packet error rates, is likely to be more advantageous considering voice is less bandwidth demanding than video or other large data. Techniques such as adaptive modulation and coding (AMC) and link adaptation (based) to the state of the channel can effectively manage the channel and mobility to meet the desired packet loss threshold [2], [5].

C. Comparison with Voice over WiFi

Table I provides a high-level comparison between VoWiFi and VoLiFi for indoor scenarios. The table highlights that VoLiFi can provide improved security, lower interference, and potentially lower latency compared to VoWiFi, at the cost of stricter coverage constraints and additional deployment requirements [2]-[5].

Key Enabling Technologies for VoLiFi

A. Modulation and Coding Schemes

LiFi systems employ IM/DD and therefore require real-valued, non-negative intensity waveforms. [2], [4] Conventional schemes for LiFi include:

- On-Off Keying (OOK): Simple binary intensity modulation, suitable for low-complexity implementations but with limited spectral efficiency [4].
- Pulse-amplitude modulation (M-PAM): Multi-level intensity signaling providing higher data rates at the cost of tighter SNR requirements [2].
- DC-biased optical OFDM and related multicarrier schemes: Offering high spectral efficiency and robustness to multipath, used in high-speed LiFi prototypes [2], [3].

For VoLiFi, the choice of modulation and coding is driven by the required robustness, latency, and complexity constraints rather than maximizing throughput. Lower-order M-PAM or OOK with strong forward error correction (FEC) may be sufficient to support multiple simultaneous voice calls in a LiFi cell, while OFDM-based solutions can multiplex voice and data services on different subcarriers with flexible resource allocation [2], [3].

B. Multiple Access and Resource Allocation

The optical medium among multiple users in multi-user LiFi networks requires multiple access techniques. These techniques can include:

- TDMA: Time assigned to users or individual data streams; works well for deterministic guarantees of Quality of Service.
- OFDMA: Flexible frequency domain scheduling. Users are assigned portions of the subcarrier sets.
- Using multiple LEDs and multiple receivers to form spatially separated beams for Spatial Division Multiple Access (SDMA) [2].

In VoLiFi, resource allocation algorithms should focus on voice flows and guarantee the reservation of adequate intervals and/or frequency streams to satisfy their delay and loss needs.

This can be done by admission control, which limits the active calls in a LiFi cell, and by dynamically adaptable scheduling policies to the active traffic load and the set of available channels [2], [5].

C. Multiple Access and Resource Allocation

The gain experienced by a channel is highly dependent on line-of-sight and the angle of the receiver and, hence, changes in device orientation or user movement are difficult to manage in a LiFi network [2], [5].

For VoLiFi, handover must be seamless enough to avoid noticeable audio glitches.

This involves:

- Link-layer handover that is quick and involves pre-authentication as well as context transfer between LiFi APs.
- Advanced techniques at the packet level to buffer and mask losses transitorily and utilize duplication.
- Optional integration with RF (e.g., WiFi) as a back-up path and therefore allow make-before-break handover with multi-homing.

It has been demonstrated that a hybrid approach in other VLC systems is possible and can be applied in VoLiFi. [2]

D. Hybrid RF-LiFi Integration for Voice

The combination of WiFi or cellular with LiFi is more practical due to coverage restrictions and the need for line-of-sight with LiFi [2], [5], [6]. In a VoLiFi context, hybrid integration can take the following:

- LiFi downlink, RF uplink: Using LiFi for high-capacity downlink data and voice and still using RF for uplink and control intentionally to simplify the device [2].
- Dual connectivity: Maintain simultaneous LiFi and WiFi connections, dynamically routing voice packets over the better link based on QoS metrics.
- LiFi offloading: Offloading voice and data traffic from congested WiFi to LiFi in densely populated indoor scenarios [6], [8].

Such hybrid architecture can enhance robustness, coverage, and user experience while still reaping the benefits of LiFi for voice services.

Performance Evaluation: Insights from existing Prototypes

Although in-depth VoLiFi systems are still an ongoing field of research, knowledge can be obtained based on accessible LiFi voice and audio prototypes. The LiFi-Voice of [7] establishes that low signal-to-noise ratios and low distortion at ranges of some meters can be achieved with a LiFi link under direct line-of-sight with the quality of the received signal depending on the nature of the LED drivers, noise in ambient light, and the receiver orientation. This has been reported, together with the use of a simple LED source and solar-cell receiver, in the paper of Iijert audio lifi which also demonstrates clear audio reception with

no more than a few seconds delay, confirming that LiFi can be used with real-time audio over a controlled setting.

A study of voice and data communication over LiFi at Work highlights that LiFi can perform equal or better than WiFi under some indoor deployment in terms of both throughput and RF in addition to better physical-layer security and lower RF interference. Papers that discuss the LiFi technology at study level [4], [6] and systems level on VLC discuss the data rate, coverage, and mobility behaviour that can be achieved and those can be tens of megabits per second to many gigabits per second in indoor cells with low latency and flexible cells planning.

Such observations suggest that, physically and regarding link-layers, LiFi can host several simultaneous voice calls with considerable capacity, assuming that any practical challenges, e.g., the dynamics of line-of-sight, lighting, and mobility of users are properly carefully considered (at a higher implementation level) (vlc system perspective, fraunhofer lifigroup).

Applications and Use Cases

VoLiFi is especially appealing in places where RF interference, security or spectrum limitations are significant factors.

Examples of representative cases are:

- Hospitals and medical supplies: RFs can disrupt large sensitive machinery, but LiFi can offer interference-free and secure voice calls to staff when communicating with their supervisors and patients.
- Aviation and transportation: Voice and data services based on LiFi can be provided in aircraft cabins and trains without RF congestion, which combines with the current lighting infrastructure.
- Industrial and mission critical applications: VoLiFi can be used to support operator communications in manufacturing plants and control rooms where determinism and RF noise immunity are required (VoLiFi) in industries and mission critical environments.
- Smart offices and buildings: The overcrowded office spaces may install LiFi enabled lighting to deliver safe
- and high density voice and data connection, discharging WiFi and enhancing the user experience experience.
- Assistive and guidance systems: as shown in voice guidance over LiFi voice guidance over LiFi can be extended to context-aware services in museums, shopping malls and buildings open to the public.

Challenges and Research Directions

VoLiFi is, however, in spite of this promise, exposed to various practical and research challenges:

- Standardisation: although a number of LiFi and VLC standardisation efforts are underway, including work on IEEE 802.15.7 and other organizations, there is no standard that is widely adopted as specific to real time voice services at present.
- Device integration: LiFi transceivers need removal of this by miniature, low-power optical front-ends and industrialisation to be integrated into consumer devices like smartphones and headsets.
- Illumination constraints: LiFi luminaires should be capable both of fulfilling illumination needs (e.g. flicker-free lighting, colour rendering) and of providing communication services; such a dual-purpose design puts a limit on modulation depth and waveform design.
- Channel dynamics: Users move about, shadow their body and change device orientation leading to sudden changes in channel gain that may demand strong link adaptation, diversity, and handover techniques.
- Hybrid control: The seamless, QoS-friendly integration of LiFi and RF in voice services, such as the collaborative, intelligent resource usage and intelligent selection of the path to voice devices is a rather challenging issue to design.
- Security and privacy: LiFi is offering more physical-layer security that comes consuming the fact that the space is limited; however, more layer security is needed to safeguard signalling and stream media streams [5], [6].

The research directions include:

- Cross-layer optimisation of LiFi MAC and VoIP protocols to achieve smallest latency and jitter inVoLiFi.
- Proactive handover and resource allocation with machine learning based link adaptation and mobility prediction.
- VoLiFi on real conditions: prototyping and field tests including LiFi-WiFi hybrids.
- Formulation of open, interoperable voice-centric LiFi network standards and testbeds.

Conclusion

LiFi provides a strong substitute and supplement RF-based wireless access on the next-generation voice services. Massive unlicensed spectrum, spatial confinement, resistance to RF interference, and low latency make it especially efficient with regard to real-time voice communication within an indoor setting. Expanding on some of the early audio and voice over LiFi prototypes, VoLiFi is a logical extension of the IP-based voice services into the LiFi access networks. A VoLiFi architecture with LiFi PHY/MAC and QoS-aware link and network layers with standard VoIP stacks can offer highly secure, low-latency, and spectrum-efficient voice services in smart buildings, in healthcare, transport and industrial usage. It will be important to address issues of standardisation, device integration, mobility and hybrid RF -LiFi control in order to make VoLiFi a mainstream next generation voice service.

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