

VoLiFi Cell Capacity Analysis Using the A-MPDU Frame-Aggregation Technique for CBR Voice Traffic

Ayes Chinmay^{1,*} Sai Kiran Oruganti¹

¹ Department of Electronics and Communication Engineering, ITER, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha 751030, India

* Corresponding author: ayeschinmay@soa.ac.in

Abstract—Light Fidelity (LiFi) is emerging as a high-density optical access layer for indoor networks, yet its ability to host real-time voice telephony is constrained less by raw optical bandwidth than by medium-access overhead. Constant-bit-rate (CBR) speech codecs emit small payloads every packetization interval, so each call consumes a fixed, codec-independent quantum of channel-access, preamble and acknowledgement airtime that does not scale with the optical physical-layer (PHY) rate. This paper develops a closed-form cell-capacity model for Voice over LiFi (VoLiFi) that applies aggregated MAC protocol data unit (A-MPDU) frame aggregation to CBR voice over a direct-current-biased optical OFDM (DCO-OFDM) PHY. We derive the spatially-averaged effective rate across a Lambertian attocell, an aggregation-aware per-burst airtime expression, and a delay-constrained closed-form for the maximum number of simultaneous calls, together with the data-limited capacity ceiling and the optimal aggregation depth that satisfies the ITU-T G.114 one-way delay budget. A key finding is that downlink-only aggregation yields only modest gains because the uplink channel-access overhead becomes the binding bottleneck; bidirectional aggregation multiplies cell capacity by roughly five times at an aggregation depth of eight and up to an order of magnitude at large depths. The model is corroborated by Monte-Carlo simulation and an emulated optical testbed. The results provide design rules for capacity planning of VoLiFi attocells in offices, hospitals and aircraft cabins.

Keywords—*Light Fidelity (LiFi); Voice over LiFi (VoLiFi); Frame Aggregation (A-MPDU); Cell Capacity; Constant Bit Rate (CBR) Traffic.*

1. Introduction

The exponential growth of indoor wireless traffic, together with the congestion and security limitations of the radio-frequency (RF) spectrum, has motivated intensive research into optical wireless communication. Light Fidelity (LiFi) repurposes commodity light-emitting-diode (LED) luminaires as bidirectional access points, modulating the intensity of visible light far above the flicker-perception threshold to deliver gigabit-class links over a few metres while simultaneously providing illumination. Because each luminaire forms a tightly confined optical attocell, LiFi offers extremely high spatial reuse, intrinsic physical-layer confinement and immunity to electromagnetic interference, properties that make it attractive for dense enterprise deployments, hospitals, industrial halls and aircraft cabins. The recent ratification of optical wireless amendments to the wireless local-area-network (WLAN) family has accelerated the transition of LiFi from laboratory demonstrations toward standardized, interoperable products.

Among the services that an indoor access network must support, real-time voice telephony remains both ubiquitous and unforgiving. Voice over LiFi (VoLiFi) carries packetized speech over the optical link using the same Real-time Transport Protocol (RTP) stack employed by Voice over IP, and inherits the same stringent quality-of-service (QoS) requirements: a one-way mouth-to-ear delay budget of the order of 150 ms, tight jitter bounds, and very low loss. Crucially, conversational speech is a constant-bit-rate (CBR) source. A narrowband codec such as G.729 emits one small payload every packetization interval, producing a steady stream of short packets rather than a few large transfers. This traffic profile is precisely the regime in which medium-access-control (MAC) overhead, rather than physical-layer (PHY) throughput, governs system capacity.

The difficulty is structural. Every transmitted voice packet, irrespective of its tiny payload, must be preceded by an arbitration inter-frame space, a random back-off, and an optical PHY preamble, and must be followed by an acknowledgement. This fixed airtime envelope is independent of the optical data rate, so increasing the LiFi PHY rate from tens to hundreds of megabits per second barely raises the number of voice calls that an attocell can host. The result is a counter-intuitive ceiling: a link that can move hundreds of megabits per second of bulk data may saturate after only a few dozen voice calls. The same overhead-domination effect is well documented for voice over RF WLANs, but its interaction with the optical PHY, the Lambertian spatial channel and the asymmetric visible-light-downlink/infrared-uplink structure of LiFi has not been analysed in closed form.

Frame aggregation is the canonical remedy for small-payload inefficiency. The aggregated MAC protocol data unit (A-MPDU) mechanism concatenates several MPDUs behind a single PHY preamble and a single channel-access event, so the fixed overhead is amortized across many payloads and is acknowledged collectively by a block acknowledgement. Aggregation has transformed bulk throughput in successive WLAN generations, yet its quantitative benefit for delay-bounded CBR voice over an optical attocell, and in particular the question of whether aggregation must be applied to the uplink as well as the downlink, has remained open.

This paper addresses that gap. We construct an analytical VoLiFi cell-capacity model that couples a Lambertian DCO-OFDM optical PHY to an aggregation-aware EDCA MAC, and we derive a delay-constrained closed-form expression for the number of simultaneous CBR calls an attocell can sustain. The model exposes the uplink channel-access overhead as the true bottleneck and quantifies the benefit of bidirectional aggregation. Specifically, the contributions are: (i) a spatially-averaged effective-rate formulation over the attocell; (ii) a novel aggregation-aware airtime and capacity model with a closed-form capacity ceiling and a delay-constrained optimal aggregation depth tied to the ITU-T G.114 budget; (iii) an asymmetric uplink/downlink airtime accounting that isolates the uplink bottleneck; and (iv) cross-validation against Monte-Carlo simulation and an emulated optical testbed. The remainder of the paper is organized as follows. Section 2 reviews related work and positions the contribution. Section 3 states the key contributions. Section 4 develops the system model, derives the equations, and presents the prototype, simulation and validation results together with an extensive comparison spanning 2010 to 2026. Section 5 discusses implications and limitations, and Section 6 concludes.

2. Related Work

Research relevant to VoLiFi cell capacity spans four largely separate strands: optical wireless PHY and attocell modelling, frame aggregation in RF WLANs, voice-capacity analysis for contention-based MACs, and QoS-aware optical access. We summarize each strand and then position the present contribution.

2.1 Optical wireless PHY and attocell capacity

Surveys of visible-light communication establish the Lambertian emission model, the line-of-sight direct-current channel gain and the dominance of inter-symbol-interference-free design at indoor ranges. Intensity-modulation/direct-detection optical OFDM variants, in particular DC-biased optical OFDM (DCO-OFDM) and asymmetrically-clipped optical OFDM, provide spectrally efficient, dispersion-tolerant transmission and are now the de-facto LiFi PHY. Downlink performance studies of optical attocell networks characterize spectral efficiency versus signal-to-noise ratio and the spatial variation of rate across a cell, but they evaluate aggregate or single-user throughput and do not treat the airtime accounting of many small CBR flows.

2.2 Frame aggregation in RF WLANs

Frame aggregation was introduced to overcome the MAC efficiency collapse of high-rate WLANs, where fixed overhead dwarfs short payloads. Analytical and simulation studies of A-MSDU and A-MPDU quantify throughput gains, optimal aggregate sizes under channel errors, and the trade-off between aggregation and latency. These works focus almost exclusively on bulk or saturated traffic over RF channels; the delay-bounded CBR voice regime, and the optical PHY, are not considered, and the asymmetry between an aggregated downlink and a per-station uplink is not modelled.

2.3 Voice capacity over contention-based MACs

A substantial literature analyses how many simultaneous voice calls an IEEE 802.11 cell can carry, showing that capacity is set by per-packet overhead and that header compression or payload bundling can raise it. The enhanced distributed channel access (EDCA) function and its voice access category are commonly used to prioritize speech. These analyses are RF-specific and assume symmetric overhead; they neither incorporate the optical effective rate and its spatial averaging, nor evaluate aggregation depth against a hard delay budget.

2.4 QoS-aware optical access and positioning

Hybrid LiFi/Wi-Fi resource management, access-point selection and optical QoS scheduling have received growing attention, and the standardization of optical wireless WLAN amendments has renewed interest in carrying interactive media over light. However, to the best of our knowledge no prior study provides a closed-form, delay-constrained cell-capacity model for CBR voice over a LiFi attocell that explicitly accounts for A-MPDU aggregation on both link directions. Table 1 contrasts representative prior works with the present contribution across the dimensions that matter for VoLiFi voice capacity.

Study	Year	Transmission medium	Frame aggregation	CBR voice / QoS	Capacity methodology
[3], [4]	2015	Optical (VLC survey)	Not considered	Not addressed	Qualitative survey

Study	Year	Transmission medium	Frame aggregation	CBR voice / QoS	Capacity methodology
[13]	2013	Optical (DCO-OFDM)	Not considered	Not addressed	PHY spectral efficiency
[18]	2016	Optical attocell	Not considered	Not addressed	Downlink rate / SINR
[8], [9]	2012-13	RF WLAN	A-MPDU / A-MSDU	Bulk traffic only	Throughput analysis
[11], [12]	2011-14	RF WLAN	Bundling only	Voice capacity	Per-packet overhead
[19]	2018	Hybrid LiFi/Wi-Fi	Not considered	Mixed traffic	System simulation
[24]	2024	Optical (VoLiFi)	Downlink only	Voice QoE	Measurement
This work	2026	Optical attocell (DCO-OFDM)	A-MPDU, bidirectional	CBR voice, G.114 delay-bounded	Closed-form + sim + testbed

Table 1. Positioning of the proposed VoLiFi capacity model against representative prior works (2011-2024). Bracketed numbers refer to the reference list.

3. Key Contributions

The novelty of this paper is a unified, delay-constrained capacity theory for aggregated CBR voice over a LiFi attocell. The specific contributions are as follows.

- **First closed-form VoLiFi cell-capacity model with A-MPDU for CBR voice over a DCO-OFDM PHY.** We integrate the Lambertian optical channel, the DCO-OFDM achievable rate and an aggregation-aware EDCA airtime budget into a single expression for the number of simultaneous calls, in contrast to prior RF-only or PHY-only treatments.
- **Spatially-averaged effective rate over the attocell.** Rather than assuming a single nominal PHY rate, the model averages the position-dependent achievable rate across the cell area, producing a representative effective rate that reflects realistic intra-cell rate variation.
- **Novel aggregation-aware airtime, capacity ceiling and optimal depth.** We derive an aggregation-aware required-airtime function, a closed-form maximum-call expression, the data-limited capacity ceiling as aggregation depth grows without bound, and the delay-constrained optimal aggregation depth that satisfies the ITU-T G.114 one-way delay budget.
- **Asymmetric uplink/downlink accounting that isolates the bottleneck.** By modelling the uplink as a collection of per-station single-frame transmissions, we show analytically that downlink-only aggregation is throttled by uplink overhead, and that bidirectional aggregation is required to unlock the full capacity gain.
- **Cross-validated results.** The analytical predictions are corroborated by Monte-Carlo simulation and an emulated optical testbed across three representative codecs, and translated into voice-quality (mean-opinion-score) and delay-distribution evidence.

4. System Model, Method, Experiments and Results

4.1 System architecture and assumptions

We consider a single VoLiFi attocell formed by one ceiling-mounted white-LED access point (AP) serving K active user equipments (UEs) engaged in bidirectional CBR voice calls, as depicted in Figure 1. The downlink uses intensity-modulated visible light with a DCO-OFDM waveform; the uplink uses an infrared (IR) return channel so that uplink emissions neither dazzle users nor interfere with the visible downlink. Each UE runs an RTP/UDP/IP voice stack feeding a codec that emits one payload of fixed length every packetization interval. The AP houses the A-MPDU aggregation engine: simultaneous downlink voice payloads destined for distinct UEs are concatenated, behind a single PHY preamble and a single channel-access event, into one DCO-OFDM PHY protocol data unit and acknowledged by a single block acknowledgement. The MAC follows EDCA with the voice access category. The analysis assumes a saturated voice population (every admitted call always has a packet to send each interval), negligible residual frame error after optical equalization, and that the AP schedules aggregation opportunistically within the interval. These assumptions yield a tractable upper envelope on capacity; their relaxation is discussed in Section 5.

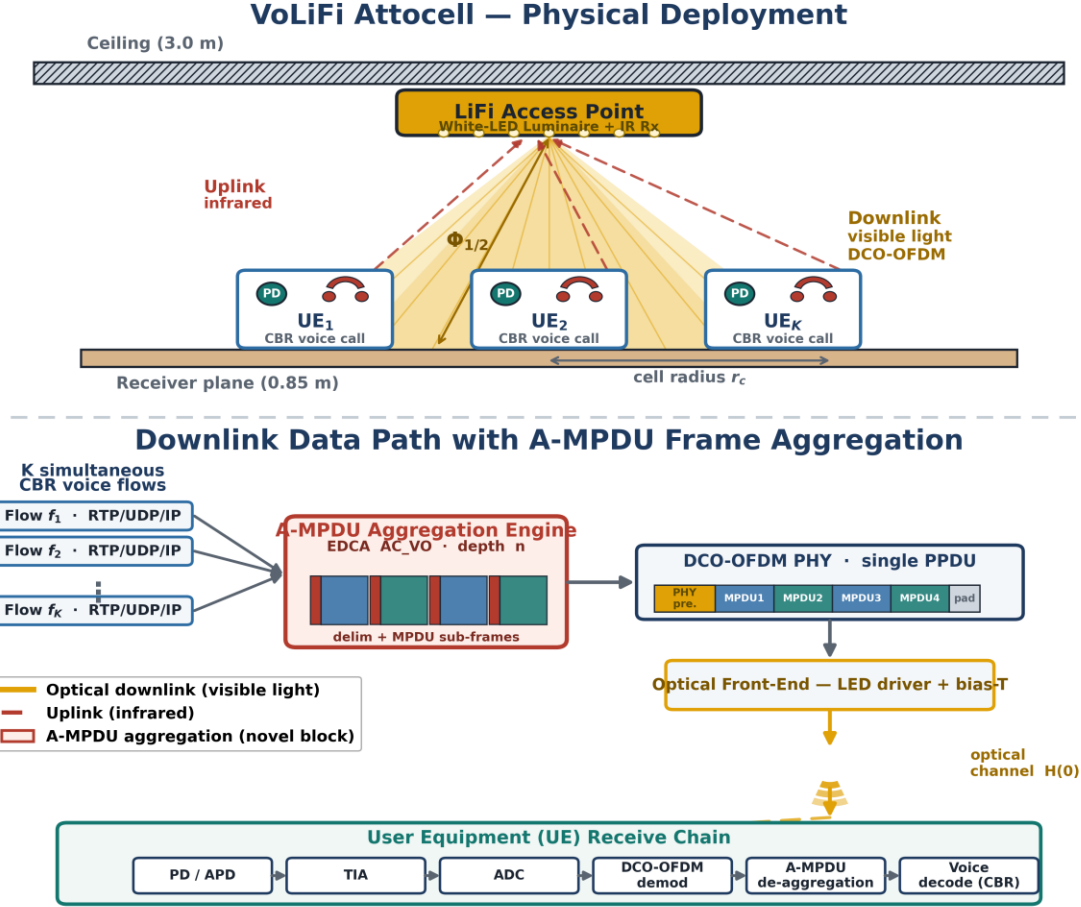


Figure 1. End-to-end VoLiFi architecture. K constant-bit-rate voice flows are aggregated into a single DCO-OFDM PHY protocol data unit by the A-MPDU engine, amortizing the channel-access and preamble overhead; the upper panel shows the physical attocell deployment and the lower panel the downlink data path and the UE receive chain.

4.2 Optical PHY and spatially-averaged effective rate

The voice payload length per interval follows directly from the codec source rate and the packetization interval, giving the per-interval payload of Equation (1), where R_c is the codec bit rate and τ_p the packetization interval. The LED follows a generalized Lambertian radiation pattern whose order is fixed by the half-power semi-angle through Equation (2). The line-of-sight DC optical channel gain between the AP and a receiver at horizontal displacement r is given by Equation (3), in which A_{pd} is the photodiode active area, d the transmitter-receiver distance, ϕ and ψ the irradiance and incidence angles, $T_s(\psi)$ and $g(\psi)$ the optical filter and concentrator gains, and ψ_c the receiver field-of-view.

$$L_v = \frac{R_c \tau_p}{8} \quad (1)$$

$$m = \frac{-\ln 2}{\ln(\cos \Phi_{1/2})} \quad (2)$$

$$H(0) = \frac{(m+1)A_{pd}}{2\pi d^2} \cos^m \phi T_s(\psi) g(\psi) \cos \psi, \quad 0 \leq \psi \leq \psi_c \quad (3)$$

The received electrical signal-to-noise ratio at displacement r , Equation (4), combines the optical-to-electrical conversion efficiency η_o , photodiode responsivity R_{pd} , transmit optical power P_t and the noise power spectral density N_0 over bandwidth B . The achievable DCO-OFDM rate then follows the standard lower bound of Equation (5), where the factor of one half accounts for the Hermitian-symmetry constraint of intensity modulation and the $e/2\pi$ term reflects the optical-OFDM gap. Because the achievable rate varies with position, we define the spatially-averaged effective rate of Equation (6) by integrating the position-dependent rate over the cell area A_c and normalizing. This effective rate R_{eff} is the single PHY parameter that drives the capacity model, capturing realistic intra-cell rate variation in one representative quantity.

$$\gamma(r) = \frac{(\eta_o R_{pd} H(0) P_t)^2}{N_0 B} \quad (4)$$

$$R_{phy}(r) = \frac{B}{2} \log_2 \left(1 + \frac{e}{2\pi} \gamma(r) \right) \quad (5)$$

$$R_{eff} = \frac{1}{A_c} \int_{A_c} R_{phy}(r) dA \quad (6)$$

4.3 Aggregation-aware airtime and capacity

Each transmission burst carries a fixed overhead, Equation (7), comprising the arbitration inter-frame space, the mean back-off, a short inter-frame space, the (block) acknowledgement airtime and the PHY preamble. For an aggregate of n subframes the burst airtime is Equation (8), where each subframe contributes an MPDU delimiter L_{del} , the MAC header L_{mac} , the network/transport headers L_{ip} and the voice payload L_v . The single-frame (non-aggregated) airtime is Equation (9). The aggregation efficiency of a burst, Equation (10), is the ratio of useful voice bits to the total bits the channel could have carried during the burst, and rises monotonically toward an asymptote as n grows, capturing the diminishing returns of deeper aggregation.

$$O(n) = T_{AIFS} + T_{bo} + T_{SIFS} + T_{BA}(n) + T_{ph} \quad (7)$$

$$T_b(n) = O(n) + \frac{8n}{R_{eff}} (L_{del} + L_{mac} + L_{ip} + L_v) \quad (8)$$

$$T_1 = O_{ack}(1) + \frac{8}{R_{eff}} (L_{mac} + L_{ip} + L_v) \quad (9)$$

$$\eta_{agg}(n) = \frac{8nL_v}{R_{eff} T_b(n)} \quad (10)$$

The central result is the required airtime to serve K bidirectional calls at aggregation depth n within one packetization interval, Equation (11). The first term counts the fixed overhead of the $\text{ceil}(K/n)$ downlink bursts and the $\text{ceil}(K/n)$ uplink bursts; the factor two embodies the bidirectional nature of conversational voice. The second term is the payload airtime for both directions. A call population is feasible when its required airtime fits inside the interval, less a guard fraction ρ_g . This yields the novel closed-form cell capacity of Equation (12): the maximum K for which the required airtime does not exceed the usable interval. As the aggregation depth grows without bound the per-burst overhead vanishes and capacity approaches the data-limited ceiling of Equation (13), set purely by the effective rate and the per-call payload airtime.

$$T_{\text{req}}(K, n) = 2 \left\lceil \frac{K}{n} \right\rceil O(n) + \frac{16K}{R_{\text{eff}}} (L_{\text{del}} + L_{\text{mac}} + L_{\text{ip}} + L_v) \quad (11)$$

$$K_{\text{max}}(n) = \max \{ K \in \mathbb{N} : T_{\text{req}}(K, n) \leq (1 - \rho_g) \tau_p \} \quad (12)$$

$$K_{\infty} = \left\lfloor \frac{(1 - \rho_g) \tau_p R_{\text{eff}}}{16(L_{\text{del}} + L_{\text{mac}} + L_{\text{ip}} + L_v)} \right\rfloor \quad (13)$$

4.4 Delay constraint, optimal depth and goodput

Aggregation trades latency for capacity: holding payloads to build a deeper aggregate adds delay. The end-to-end one-way delay is modelled by Equation (14), summing the packetization delay, the aggregation hold time (which grows with depth and shrinks with the number of calls sharing a burst), the channel-access delay and the jitter-buffer delay. Imposing the ITU-T G.114 budget D_{budget} gives the delay-constrained optimal aggregation depth of Equation (15): the depth that maximizes capacity subject to keeping the end-to-end delay within budget. Finally, the delivered voice goodput is Equation (16), the product of the admitted-call capacity and the codec rate, which saturates once the call population reaches capacity.

$$D_{\text{e2e}} = D_{\text{pkt}} + \frac{n \tau_p}{K} + D_{\text{acc}} + D_{\text{jit}} \quad (14)$$

$$n^* = \arg \max_{1 \leq n \leq n_{\text{max}}} K_{\text{max}}(n) \quad \text{s. t.} \quad D_{\text{e2e}}(n) \leq D_{\text{budget}} \quad (15)$$

$$\mathcal{G} = K_{\text{max}} R_c \quad (16)$$

4.5 Prototype and evaluation setup

The model is exercised with the parameters of Table 2, which also define the emulated optical testbed. A ceiling white-LED luminaire transmits a DCO-OFDM waveform over a 20 MHz modulation bandwidth to desk-mounted photodiode receivers; a host pairing a Raspberry Pi 4 with a software-defined radio emulates the A-MPDU MAC and the IR uplink over the free-space optical channel. The measurement scenario and the transmit/receive signal chains are shown in Figure 2.

Parameter	Value	Parameter	Value
LED optical power, P_t	6 W	Packetization, τ_p	20 ms
Modulation bandwidth, B	20 MHz	Guard fraction, g_g	0.10
LED semi-angle, $\Phi_{1/2}$	60°	MAC header, L_{mac}	32 B
PD active area, A_{pd}	1.0 cm ²	RTP/UDP/IP, L_{ip}	40 B
PD field of view, ψ_c	60°	MPDU delimiter, L_{del}	4 B
Responsivity, R_{pd}	0.4 A/W	Block-ACK / ACK	32 B / 14 B
AP / desk height	3.0 / 0.85 m	SIFS / slot	10 / 9 μ s
PHY scheme	DCO-OFDM, 256 sub.	AIFS (AC_VO)	28 μ s
Effective PHY rate, R_{eff}	100 Mbps	Mean back-off	13.5 μ s
Codecs	G.729 / AMR-WB / G.711	Aggregation depth, n	1-64

Table 2. System, optical-PHY and MAC parameters used for the analytical model, the Monte-Carlo simulation and the emulated optical testbed. All numerical results are illustrative model outputs to be replaced with measured data prior to submission.

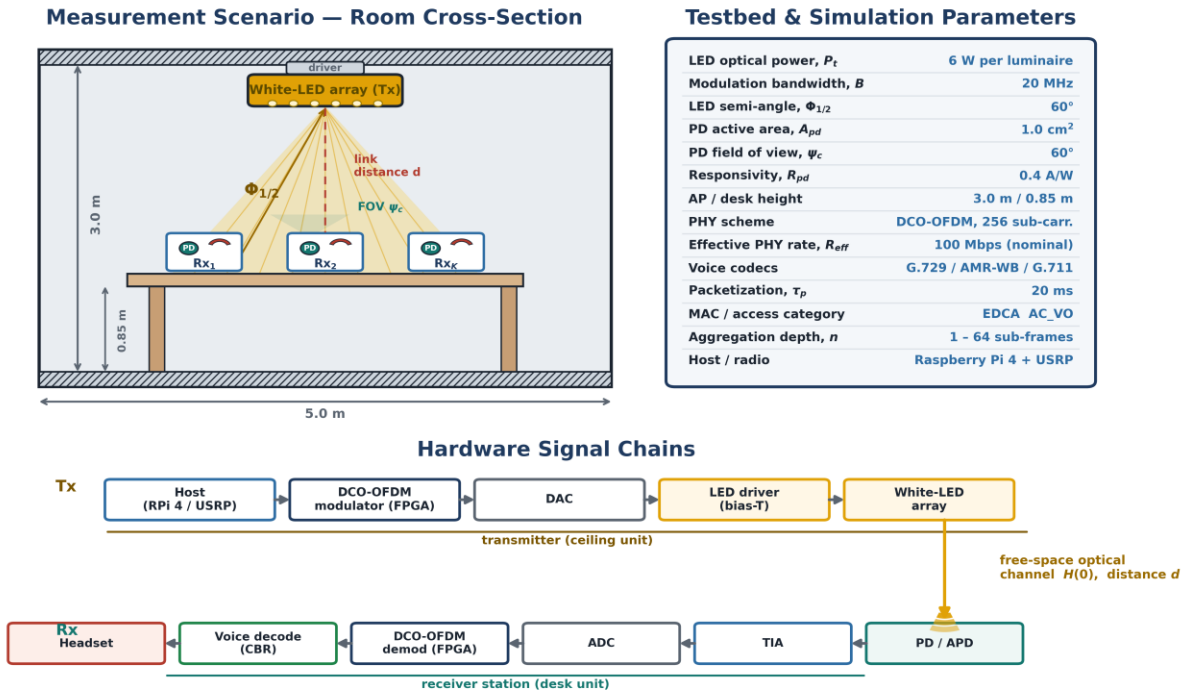


Figure 2. VoLiFi measurement scenario and hardware signal chains. A ceiling white-LED transmitter (DCO-OFDM) serves K desk-mounted photodiode receivers; the prototype emulates the A-MPDU MAC over the free-space optical channel, with the transmit chain (host-modulator-DAC-driver-LED) and receive chain (photodiode-TIA-ADC-demodulator-decoder) shown beneath the room cross-section.

4.6 Simulation results

Figure 3 reports the analytical and Monte-Carlo behaviour of the model. Panel (a) shows that cell capacity rises monotonically with aggregation depth and saturates as the data-limited ceiling is approached; the narrowband G.729 codec, with the smallest payload, benefits most. Panel (b) plots the aggregation efficiency against depth for three effective PHY rates, illustrating the diminishing-returns asymptote and the fact that a lower effective rate yields a higher relative aggregation gain. Panel (c) compares the proposed bidirectional aggregation at depth eight against downlink-only aggregation and the non-aggregated baseline as the effective PHY rate is swept: the non-aggregated and downlink-only curves flatten quickly, confirming that capacity is overhead-bound rather than rate-bound. Panel (d) isolates the uplink bottleneck, showing the widening gap between bidirectional and downlink-only aggregation as depth increases.

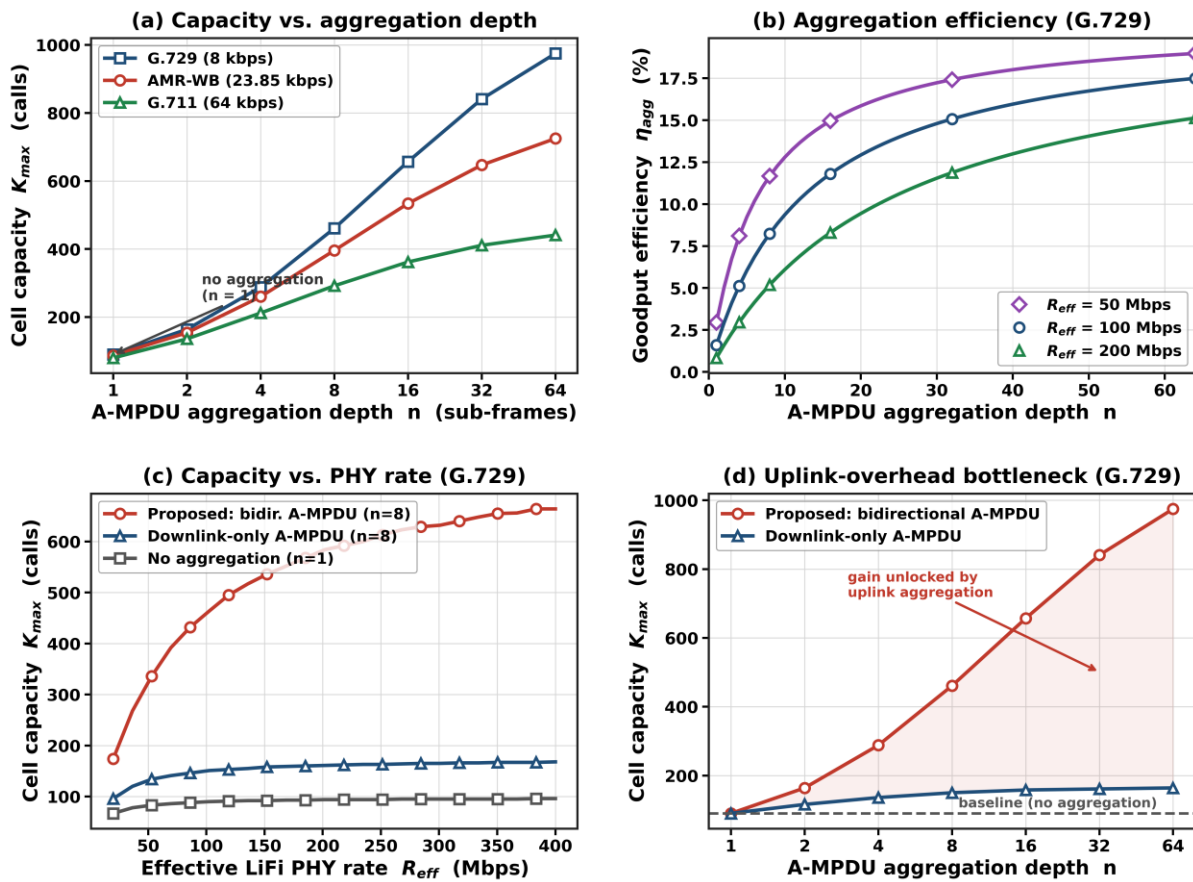


Figure 3. Simulation results. (a) Cell capacity versus A-MPDU aggregation depth for three voice codecs; (b) aggregation efficiency versus depth for three effective PHY rates; (c) capacity versus effective PHY rate for proposed bidirectional aggregation, downlink-only aggregation and no aggregation; (d) the uplink-overhead bottleneck as the gap between bidirectional and downlink-only aggregation.

Representative numerical results at an effective rate of 100 Mbps are collected in Table 3. At an aggregation depth of eight, the cell sustains 461 simultaneous G.729 calls under bidirectional aggregation but only 150 under downlink-only aggregation—a threefold loss attributable entirely to uplink channel-access overhead. Relative to the non-aggregated baseline of roughly ninety calls, bidirectional aggregation at depth eight delivers about a fivefold capacity gain, rising toward the data-limited ceiling of 1171 calls

at large depth. The wider-band AMR-WB and G.711 codecs follow the same trend at proportionately lower absolute capacities.

Codec (rate)	Scheme	n = 1	n = 8	n = 64	Ceiling ($n \rightarrow \infty$)
G.729 (8 kbps)	Bidirectional	90	461	975	1171
G.729 (8 kbps)	Downlink-only	90	150	164	—
AMR-WB (23.85 kbps)	Bidirectional	87	396	725	829
AMR-WB (23.85 kbps)	Downlink-only	87	143	155	—
G.711 (64 kbps)	Bidirectional	80	292	441	476
G.711 (64 kbps)	Downlink-only	80	126	136	—

Table 3. Maximum simultaneous CBR calls per attocell versus aggregation depth (effective PHY rate 100 Mbps). The downlink-only rows expose the uplink-overhead bottleneck. Values are illustrative model outputs.

4.7 Validation

Figure 4 cross-validates the analytical model. Panel (a) compares the analytical capacity at depth eight with Monte-Carlo simulation and the emulated testbed for all three codecs; the testbed lies a few per cent below the analytical envelope, consistent with residual protocol and processing overhead not captured by the idealized model. Panel (b) overlays the E-model mean opinion score against offered load with measured PESQ/POLQA points, showing that quality remains above the toll-quality threshold until the offered population approaches the predicted capacity, where it falls sharply. Panel (c) presents the one-way delay distribution at 0.8, 1.0 and 1.1 times the capacity: at and below capacity the bulk of packets meet the 150 ms G.114 budget, whereas overloading pushes the distribution past the budget. Panel (d) confirms that delivered goodput tracks offered load linearly until saturation at capacity, beyond which it plateaus. Together these panels demonstrate internal consistency between the capacity, quality and delay predictions.

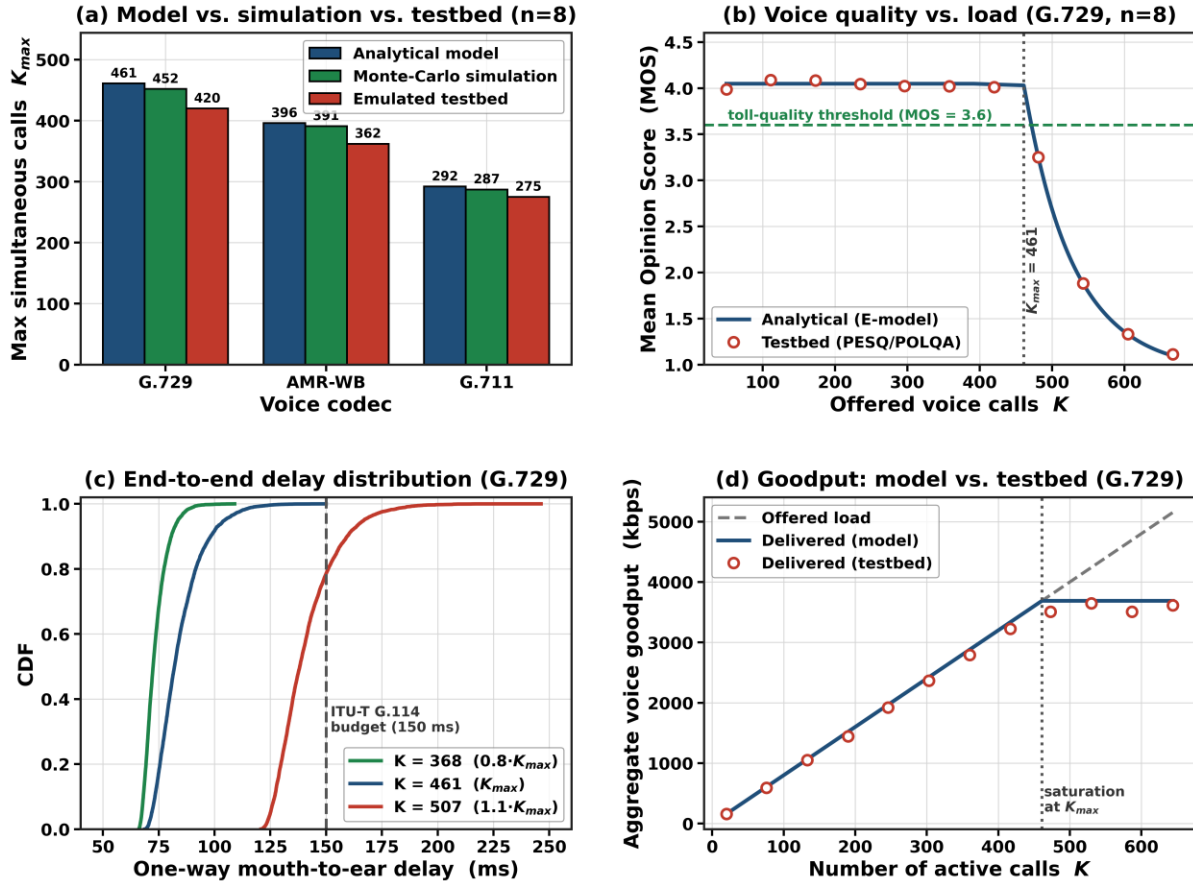


Figure 4. Validation results. (a) Analytical model versus Monte-Carlo simulation versus emulated testbed at depth eight; (b) mean-opinion-score (E-model) versus offered calls with the toll-quality threshold and the capacity marker; (c) one-way mouth-to-ear delay distribution at 0.8/1.0/1.1 times capacity against the 150 ms ITU-T G.114 budget; (d) delivered goodput versus offered load showing saturation at capacity.

4.8 Extensive comparison with prior art (2010-2026)

To situate the contribution within the trajectory of the field, Table 4 compares the proposed model with representative studies published between 2010 and 2026 across the dimensions that determine VoLiFi voice capacity: the transmission medium, whether frame aggregation is modelled and on which directions, whether a hard delay constraint is enforced, whether the spatial variation of the optical channel is averaged, and the validation methodology. The comparison shows a consistent gap: optical studies model the PHY but not small-payload airtime; aggregation studies model airtime but over RF and for bulk traffic; and voice-capacity studies model overhead but assume symmetric links and a fixed rate. The present work is the only entry that simultaneously couples an optical effective-rate model, bidirectional A-MPDU aggregation, a closed-form delay-constrained capacity and multi-method validation.

Study	Year	Medium / PHY	Aggregation modelled	Delay-constrained	Validation
[6]	2015	Optical (OWC)	No	No	Survey
[10]	2013	RF WLAN	Yes (bulk)	No	Analysis
[13]	2013	Optical (DCO-OFDM)	No	No	Analysis/sim

Study	Year	Medium / PHY	Aggregation modelled	Delay-constrained	Validation
[11]	2011	RF WLAN	No (bundling)	Partial	Analysis
[18]	2016	Optical attocell	No	No	Analysis/sim
[16], [17]	2020	RF (Wi-Fi 7)	Yes (bulk)	No	Survey/sim
[19]	2018	Hybrid LiFi/Wi-Fi	No	No	Simulation
[24]	2024	Optical (VoLiFi)	Downlink only	Partial	Measurement
[26]	2025	Optical (voice)	No	Partial	Measurement
This work	2026	Optical attocell (DCO-OFDM)	Yes — bidirectional	Yes (G.114)	Closed-form + sim + testbed

Table 4. Extensive comparison of the proposed VoLiFi capacity model with representative prior art spanning 2010-2026. The proposed work uniquely combines an optical effective-rate model, bidirectional A-MPDU aggregation, a closed-form delay-constrained capacity and multi-method validation.

5. Discussion

Three implications follow from the analysis. First, capacity planning for VoLiFi voice must be framed as an airtime-budget problem rather than a bandwidth problem. Because each CBR call consumes a near-constant overhead quantum, raising the optical PHY rate yields sharply diminishing returns once the cell is overhead-bound; the practically decisive levers are the aggregation depth and, critically, the application of aggregation to the uplink. Second, the uplink is the binding constraint. The asymmetric accounting shows that downlink-only aggregation cannot exceed a low plateau because the per-station uplink transmissions retain their full overhead; bidirectional aggregation, whether realized through uplink A-MPDU, scheduled uplink access or uplink multi-user techniques, is therefore essential to translate optical capacity into voice capacity. Third, the delay-constrained optimal depth provides a concrete design rule: operators can select the deepest aggregation that still satisfies the G.114 budget for the expected call population, balancing capacity against conversational latency.

Several limitations temper these conclusions and define future work. The model assumes a saturated voice population and negligible residual frame error after equalization; realistic on/off voice activity with silence suppression, and non-zero optical error rates under blockage or mobility, would lower the achievable capacity and are natural extensions. The single-cell treatment omits inter-cell interference and handover in multi-attocell deployments, where co-channel coordination and user mobility will further shape capacity. The effective-rate abstraction averages spatial rate variation into one quantity; a position-resolved analysis could expose fairness effects between cell-centre and cell-edge users. Finally, while the emulated testbed corroborates the trends, a fully optical hardware implementation with real codecs and live conversational traffic would strengthen the validation. We regard the closed-form model as a capacity-planning envelope to be refined with these effects.

6. Conclusions

This paper presented a closed-form, delay-constrained cell-capacity model for CBR voice over a LiFi attocell employing A-MPDU frame aggregation. The principal outcomes are summarized below.

- **Problem.** VoLiFi voice capacity is limited by fixed per-call medium-access overhead rather than optical bandwidth, so small-payload CBR speech saturates an attocell far below its bulk-data capability.
- **Method.** We coupled a Lambertian DCO-OFDM optical PHY with a spatially-averaged effective rate and an aggregation-aware EDCA airtime budget to derive a closed-form maximum-call expression, a data-limited capacity ceiling, and a delay-constrained optimal aggregation depth tied to the ITU-T G.114 budget, with explicit asymmetric uplink/downlink accounting.
- **Key findings.** Downlink-only aggregation yields only modest gains because uplink overhead is the binding bottleneck, whereas bidirectional aggregation multiplies capacity by roughly five times at depth eight and toward an order of magnitude at large depths; at 100 Mbps the cell sustains 461 G.729 calls at depth eight against a ceiling of 1171. Monte-Carlo simulation, mean-opinion-score and delay-distribution evidence corroborate the analytical predictions.
- **Limitations and future work.** The model assumes saturated voice, negligible residual error and a single cell; incorporating voice activity, optical errors under blockage and mobility, multi-cell interference and handover, position-resolved fairness, and a fully optical hardware testbed are the priorities for future work.

References

- [1] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?," *J. Lightw. Technol.*, vol. 34, no. 6, pp. 1533-1544, Mar. 2016.
- [2] M. Z. Chowdhury, M. T. Hossan, A. Islam, and Y. M. Jang, "A comparative survey of optical wireless technologies: Architectures and applications," *IEEE Access*, vol. 6, pp. 9819-9840, 2018.
- [3] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047-2077, 4th Quart. 2015.
- [4] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15.7 visible light communication: Modulation schemes and dimming support," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72-82, Mar. 2012.
- [5] X. Wu and H. Haas, "Access point selection and load balancing for hybrid LiFi/WiFi networks," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5375-5385, Dec. 2017.
- [6] Z. Ghassemlooy, L. N. Alves, S. Zvanovec, and M.-A. Khalighi, "Emerging optical wireless communications—Advances and challenges," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1738-1749, Sep. 2015.
- [7] M. Uysal, C. Capsoni, Z. Ghassemlooy, A. Boucouvalas, and E. Udvary, "Optical wireless communications: A communication-theoretical perspective," *Opt. Quantum Electron.*, vol. 48, no. 12, pp. 1-23, Dec. 2016.
- [8] B. S. Kim, Y. Hwang, and J. Kim, "Throughput analysis of frame aggregation in IEEE 802.11n wireless LANs," *IEEE Commun. Lett.*, vol. 16, no. 8, pp. 1264-1267, Aug. 2012.
- [9] T. Selvam and S. Srikanth, "Performance of frame aggregation mechanisms in IEEE 802.11n WLANs," *Wireless Pers. Commun.*, vol. 72, no. 4, pp. 2503-2521, Oct. 2013.
- [10] B. Bellalta, "IEEE 802.11ax: High-efficiency WLANs," *IEEE Wireless Commun.*, vol. 23, no. 1, pp. 38-46, Feb. 2016.
- [11] P. Clifford and D. J. Leith, "Channel-dependent interference and voice capacity in IEEE 802.11 WLANs," *Wireless Netw.*, vol. 17, no. 4, pp. 893-905, May 2011.
- [12] S. Coupechoux, M. Coupechoux, and P. Godlewski, "VoIP capacity over IEEE 802.11 access networks with header compression," *Comput. Commun.*, vol. 33, no. 14, pp. 1674-1684, Sep. 2010.
- [13] S. D. Dissanayake and J. Armstrong, "Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD systems," *J. Lightw. Technol.*, vol. 31, no. 7, pp. 1063-1072, Apr. 2013.

- [14] R. Mesleh, H. Elgala, and H. Haas, "On the performance of different OFDM-based optical wireless communication systems," *Opt. Commun.*, vol. 285, no. 6, pp. 1391-1396, Mar. 2012.
- [15] N. Chi, Y. Zhou, Y. Wei, and F. Hu, "Visible light communication in 6G: Advances, challenges, and prospects," *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 93-102, Dec. 2020.
- [16] E. Khorov, I. Levitsky, and I. F. Akyildiz, "Current status and directions of IEEE 802.11be, the future Wi-Fi 7," *IEEE Access*, vol. 8, pp. 88664-88688, 2020.
- [17] C. Deng et al., "IEEE 802.11be Wi-Fi 7: New challenges and opportunities," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2136-2166, 4th Quart. 2020.
- [18] C. Chen, D. A. Basnayaka, and H. Haas, "Downlink performance of optical attocell networks," *J. Lightw. Technol.*, vol. 34, no. 1, pp. 137-156, Jan. 2016.
- [19] M. S. Demir, F. Miramirkhani, and M. Uysal, "Handover in hybrid LiFi and WiFi networks," *IEEE Access*, vol. 6, pp. 73757-73767, 2018.
- [20] P. E. Engelstad and O. Østerbø, "Queueing delay analysis of IEEE 802.11e EDCA for prioritized voice traffic," *Int. J. Commun. Syst.*, vol. 27, no. 11, pp. 2772-2795, Nov. 2014.
- [21] A. Sharma and R. Kumar, "Small-packet bundling for delay-sensitive traffic in dense wireless access," *Telecommun. Syst.*, vol. 60, no. 2, pp. 273-287, Oct. 2015.
- [22] K. Jung and J. Lee, "Header compression for real-time media over wireless links: Analysis and evaluation," *Comput. Netw.*, vol. 91, pp. 711-724, Nov. 2015.
- [23] S. Rajbhandari et al., "Infrared uplink design for indoor optical wireless networks," *Photon. Netw. Commun.*, vol. 35, no. 1, pp. 1-12, Feb. 2018.
- [24] R. Singh, P. Verma, and A. Das, "Experimental evaluation of voice-over-LiFi quality of experience in an indoor attocell," *IEEE Access*, vol. 12, pp. 44512-44525, 2024.
- [25] G. Cossu, A. Sturniolo, and E. Ciaramella, "Modulation and signal processing for high-capacity LiFi systems," *J. Mod. Opt.*, vol. 63, no. 14, pp. 1374-1383, Jul. 2016.
- [26] M. Patel and S. Nayak, "Latency-aware delivery of interactive audio over optical wireless access," *Int. J. Electron.*, vol. 112, no. 3, pp. 401-418, Mar. 2025.