

Adaptive Polar-Coded LiFi-OFDM for UAV Communications

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ABSTRACT- In this paper, we present a simulation study of a joint Polar-coded Adaptive OFDM-LiFi communication system for short-range UAV applications. The proposed framework integrates Arikan's polar codes ($N=256$, $R=1/2$) with a four-order adaptive modulation engine (BPSK/QPSK/16-QAM/64-QAM) governed by SNR-dependent switching thresholds derived from a BER target of 10^{-3} . The channel polarization is constructed via a closed-form SNR-adaptive Bhattacharyya recursion that updates the frozen set at each SNR operating point to track atmospheric scintillation variations. A log-normal turbulence model parameterized by the Rytov variance ($\sigma_R^2 \in \{0.0, 0.1, 0.5, 1.5\}$) is employed; this model is validated for $\sigma_R^2 \leq 1.0$, and results at $\sigma_R^2 = 1.5$ are interpreted as conservative baselines only. A min-sum Successive Cancellation (SC) decoder with $O(N \log N) = 2048$ operations per codeword and ~ 4 kB memory is employed, confirming feasibility on UAV-class embedded processors. Simulation results under perfect-CSI and static-geometry assumptions (upper bounds) show: under AWGN, a peak polar coding gain of 8–10 dB and a combined Polar+Adaptive gain of up to 12 dB over a conventional fixed-QPSK baseline; under moderate turbulence ($\sigma_R^2 = 0.5$), gains of 12–22 dB are observed. The adaptive system achieves 47.6% throughput improvement and 13.7% capacity improvement over the conventional system at SNR = 20 dB. Identified limitations include: static UAV geometry (pointing errors neglected), perfect CSI assumed (no pilot overhead), LED nonlinearity not modeled, and log-normal model applied at $\sigma_R^2 = 1.5$. All gains are simulation-based upper bounds requiring hardware prototype validation.

Keywords: LiFi, UAV, Polar Codes, Adaptive OFDM, Atmospheric Turbulence, Successive Cancellation Decoding, Optical Wireless Communication.

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1. INTRODUCTION

The rapid escalation of demand for high-speed wireless connectivity in aeronautical and UAV platforms has imposed unparalleled challenges on traditional RF communication systems. Due to the spectrum congestion, electromagnetic interference, and vulnerability of the wireless signals to intentional disruption, optical wireless communication (OWC) is considered by researchers as a complementary paradigm [1]. On the other hand, Light Fidelity (LiFi), the technology that uses visible and infrared light-emitting diode (LED) as communication transmitters provide gigabit-per-second data rates, security by being confined within the optical range and are immune to radio frequency (RF) interference [2]. UAV

platforms possess a very special set of communication challenges: fast changes in the altitude, link misalignment due to mechanical vibrations, irradiance brightening and fading due to atmospheric turbulence, and the heavy power and mass limitations on the airborne hardware [3]. However, the atmospheric link from a ground LiFi transmitter to an airborne

UAV receiver experiences log-normal irradiance scintillation, characterized by the Rytov variance that depends on strength of atmospheric turbulence and propagation distance [4].

To get close to the theoretical channel capacity on such degraded channels, forward error correction (FEC) codes are necessary.

Turbo codes and low-density parity-check (LDPC) codes are well-established in LTE and 5G networks [5], [6]. The use of LDPC codes is critical in UAV applications, even though their superior performance is due to iterative decoding, which is prohibitive given power limitations in UAVs. Polar codes, introduced by Arikan [7] in 2009, achieve the symmetric capacity of any binary-input memoryless channel with SC decoding at complexity $O(N \log N)$, making them the FEC scheme of choice in 5G New Radio control channels [8]. However, their integration into LiFi-OFDM systems for turbulent UAV channels has not been systematically

investigated. The novelty of the proposed work focuses on utilizing cross-layer optimization with polar codes and adaptive LiFi modulation for UAV wireless applications.

This paper addresses this gap with the following principal contributions:

1. A complete polar-coded adaptive OFDM-LiFi framework for UAV channels that jointly optimizes modulation order, polar code construction, and link-budget parameters under log-normal turbulence.
2. A closed-form Bhattacharyya-based construction of polar codes directly parameterized by the channel's instantaneous E_b/N_0 , avoiding the need for density-evolution or Gaussian-approximation outer loops.
3. A min-sum SC decoder whose recursive f- and g-functions are expressed in a novel LiFi-specific LLR formulation that accounts for the photodetector responsivity and background shot noise.
4. Extensive Monte Carlo simulation comparing the proposed system to several alternatives including uncoded LiFi, adaptive LiFi without polar coding and previous benchmark systems in terms of BER, throughput and spectral efficiency.

2. RELATED WORK

2.1. LiFi Channel Modeling and Indoor OWC

Komine and Nakagawa [9] established the foundational Lambertian LoS channel gain model and shot/thermal noise expressions for LED-based VLC. Haas et al. [2] demonstrated multi-gigabit throughput in indoor LiFi but did not address outdoor turbulent or UAV channels. Kahn and Barry [10] provided the comprehensive infrared link model used in this work.

2.2. UAV Optical and FSO Communications

Kaadan et al. [11] quantified UAV hovering jitter-induced pointing-error SNR degradation of 3-8 dB for comparable link distances, providing the basis for our static-geometry limitation discussion. Xu et al. [12] demonstrated a 1 Gbps FSO link aboard a UAV platform, confirming aerial optical feasibility but without polar FEC. Dabiri et al. [13] analyzed retroreflector-based UAV-to-ground FSO links under combined turbulence and pointing errors. Al-Habash et al. [4] validated the log-normal model for $\sigma_R^2 \leq 1.0$ and Gamma-Gamma for strong turbulence.

2.3. Polar-Coded FSO/OFDM

Mohan et al. [14] showed that for FSO under weak turbulence, SCL decoding provides 0.3-2.5 dB gain over SC. Watanabe et al. [15] validated polar-coded FSO over a 7.8 km terrestrial field link. Alfitouri and Belhaj [16] confirmed that Bhattacharyya and polar-weight constructions give comparable BER under log-normal FSO fading, validating our approach.

2.4. Adaptive Modulation for OWC

Dimitrov and Haas [17] derived BER-constrained adaptive modulation switching thresholds for optical OFDM, forming the basis of the threshold derivation in section 3.4. The key distinction of this work is the simultaneous integration of all

four elements: SNR-adaptive polar construction, four-order adaptive modulation with analytically derived thresholds, accurate LiFi optical noise model, and hardware complexity analysis. Table 4 provides a detailed feature comparison. It is noted that the log-normal model is validated by Al-Habash et al. [4] for weak-to-moderate scintillation ($\sigma_R^2 \leq 1.0$). For strong turbulence ($\sigma_R^2 = 1.5$), the Gamma-Gamma or Málaga distributions provide greater accuracy [4]. The log-normal model is retained at $\sigma_R^2 = 1.5$ to maintain a consistent comparative baseline across all turbulence levels and to identify the performance floor where additional techniques (SCL decoding, spatial diversity) become necessary. Results at $\sigma_R^2 = 1.5$ should therefore be interpreted as conservative indicators rather than precise quantitative predictions.

3. SYSTEM MODEL

3.1. LiFi Optical Channel — Lambertian LoS Gain

Consider a ground-based LED transmitter at height $h_g = 1.5$ m and a UAV-mounted photo detector (PD) receiver at altitude $h_{UAV} = 30$ m. The vertical link distance is $d = h_{UAV} - h_g = 28.5$ m. Following the Kahn-Barry model [9], the line-of-sight (LoS) DC optical channel gain is:

$$H_{dc} = \frac{(m+1)A_r}{2\pi d^2} \cos^m(\phi) T_s g_c \cos(\psi) \quad (1)$$

here $m = -\ln(2)/\ln(\cos(\phi_{1/2}))$ is the Lambertian emission order, $\phi_{1/2}$ is the LED half-power semi-angle, A_r is the PD active area (10^{-4} m²), ϕ is the emission angle, T_s is the optical band-pass filter transmittance, ψ is the incidence angle at the PD, and g_c is the optical concentrator gain:

$$g_c = \frac{n^2}{\sin^2(\Psi_c)} \quad (2)$$

With $n = 1.5$ the refractive index and $\Psi_c = 60^\circ$ the receiver field-of-view (FOV) half-angle. Both the emission and incidence angles are set to 45° to reflect the UAV tilt geometry. Substituting the system parameters yields $H_{dc} = 1.74 \times 10^{-8}$, and a received photocurrent of $I_r = \rho \cdot P_t \cdot H_{dc} = 4.35 \times 10^{-9}$ A, with PD responsivity $\rho = 0.5$ A/W and transmit optical power $P_t = 0.5$ W. Practical UAV operation involves mobility, vibration-induced pointing errors, and trajectory-dependent link geometry not captured by the static model above. Kaadan et al. [11] quantify pointing-error-induced SNR degradation of 3–8 dB for comparable link parameters, which represents an additional performance loss not included in the present simulation. The static-geometry assumption is retained here as an upper-bound simulation baseline; pointing-error modeling is identified as a key direction for future work.

3.2. Log-Normal Atmospheric Turbulence

The optical irradiance I received through a turbulent atmosphere follows a log-normal distribution parameterized by the Rytov variance σ_R^2 :

$$f_I(I) = \frac{1}{I \sqrt{2\pi\sigma_{\ln}^2}} \exp \left[-\frac{\left(\ln(I) + \frac{\sigma_{\ln}^2}{2} \right)^2}{2\sigma_{\ln}^2} \right] \quad (3)$$

Where $\sigma_l n^2 = 0.307 \cdot \sigma_R^2$ is the log-normal variance under the plane-wave approximation, ensuring $E[I] = 1$ (mean-unity normalization). Four turbulence regimes are considered: $\sigma_R^2 \in \{0.0, 0.1, 0.5, 1.5\}$ corresponding to no turbulence, weak, moderate, and strong scintillation respectively. The instantaneous SNR at the PD under turbulence is:

It is noted that the log-normal model is validated by Al-Habash et al. [4] for weak-to-moderate scintillation ($\sigma_R^2 \leq 1.0$). For strong turbulence ($\sigma_R^2 = 1.5$), the Gamma-Gamma or Málaga distributions provide greater accuracy [4]. The log-normal model is retained at $\sigma_R^2 = 1.5$ in this work to maintain a consistent comparative baseline across all turbulence levels and to identify the performance floor where additional techniques become necessary. Results at $\sigma_R^2 = 1.5$ should be interpreted as conservative indicators rather than precise predictions.

3.3. Noise Model

The total noise at the UAV receiver comprises shot noise and thermal noise:

$$\sigma_{total}^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 \quad (5)$$

The shot noise variance, dominated by background radiation, is:

$$\sigma_{shot}^2 = 2q(\rho P_t H_{dc} + I_{bg}) I_2 B \quad (6)$$

Where $q = 1.6 \times 10^{-19}$ C is the electron charge, $I_{bg} = 5.1$ mA is the background irradiance-induced current, $I_2 = 0.562$ is the noise bandwidth factor, and $B = 100$ MHz is the optical bandwidth. The thermal noise accounts for FET amplifier noise:

$$\sigma_{thermal}^2 = \frac{8\pi k_B T}{G_{OL}} C_{pd} A_r I_2 B^2 + \frac{16\pi^2 k_B T T}{\eta} C_{pd}^2 A_r^2 I_3 B^3 \quad (7)$$

All parameter values are sourced from Kahn and Barry [10] *table 1*: $q = 1.6 \times 10^{-19}$ C; $I_{bg} = 5.1$ mA (solar background irradiance current); $I_2 = 0.562$ and $I_3 = 0.0868$ (noise bandwidth factors); $G_{OL} = 10$ (open-loop voltage gain); $\Gamma = 1.0$ (FET channel noise factor); $\eta = 1.8 \frac{S}{\sqrt{A}}$ (FET transconductance); $C_{pd} = 112$ pF/m² (PD capacitance per unit area); $T = 298$ K. Unit consistency has been verified: shot and thermal noise variances are in [A²], and the resulting electrical $SNR = \frac{(\rho P_t H_{dc})^2}{\sigma_{total}^2}$ is dimensionless, both consistent with [10].

3.4. Adaptive OFDM Modulation

The OFDM system uses $N_{FFT} = 256$ subcarriers with a cyclic prefix of $N_{CP} = 32$ samples at sampling frequency $f_s = 200$ MHz. Adaptive modulation selects the modulation order M based on the instantaneous SNR per subcarrier: The switching thresholds are derived analytically by solving $BER_M(\gamma_{th}) = 10^{-3}$ for each modulation boundary, following the framework of Dimitrov and Haas [17]: BPSK $\rightarrow$ QPSK: $0.5 \cdot \text{erfc}(\sqrt{\gamma/2}) = 10^{-3} \Rightarrow \gamma_{th} \approx 8$ dB; QPSK $\rightarrow$ 16-QAM: $(3/8) \cdot \text{erfc}(\sqrt{\gamma/10}) = 10^{-3} \Rightarrow \gamma_{th} \approx 15$ dB; 16-QAM $\rightarrow$ 64-QAM: $(7/24) \cdot \text{erfc}(\sqrt{\gamma/42}) = 10^{-3} \Rightarrow \gamma_{th} \approx 22$ dB. These values have been numerically verified using the f_{zero} function in MATLAB R2011b and are consistent with values reported in [17] for comparable optical OFDM noise conditions."

"

Table 1. Adaptive Modulation Switching Thresholds (Analytically derived from BER target = 10^{-3} per Dimitrov & Haas [17])

Scheme	M	SNR Threshold (dB)	BER Expression
BPSK	2	< 8 dB	$0.5 \text{erfc}(\sqrt{\gamma})$
QPSK	4	8–15 dB	$0.5 \text{erfc}(\sqrt{\gamma/2})$
16-QAM	16	15–22 dB	$(3/8) \text{erfc}(\sqrt{\gamma/10})$
64-QAM	64	≥ 22 dB	$(7/24) \text{erfc}(\sqrt{\gamma/42})$

4. POLAR CODING FOR LiFi-UAV CHANNELS

4.1. Channel Polarization Theory

Arikan [7] showed that by applying the polarization transform $G_N = B_N F^{\otimes n}$ to N independent copies of a binary-input discrete memory less channel (B-DMC) W , N synthetic sub-channels $\{W_N^{(i)}\}_{i=1}^N$ are created that polarize: as $N \rightarrow \infty$, each $W_N^{(i)}$ approaches either a perfect channel (capacity = 1) or a completely noisy channel (capacity = 0), with the fraction of perfect channels equal to the channel capacity $I(W)$. The kernel matrix is:

$$F = [10; 11], G_N = B_N \cdot F^{\otimes n}, n = \log^2(N) \quad (8)$$

Where B_N is the bit-reversal permutation matrix. Information bits are assigned to the K most reliable sub-channels (determined at the encoder), and the remaining $N - K$ sub-channels are frozen to zero. The encoder computes:

$$x = u \cdot G_N \pmod{2} \quad (9)$$

4.2. Code Construction via Bhattacharyya Parameters

The sub-channel reliability is quantified by the Bhattacharyya parameter $Z(W_N^{(i)}) \in [0, 1]$, where a smaller value indicates a more reliable sub-channel. For a binary erasure channel (BEC), exact recursive formulas exist; for AWGN channels, we use the approximation:

$$Z_0 = \exp(-E_b/N_0) \quad (10)$$

Starting from the initial AWGN sub-channel. The recursion proceeds through $n = \log_2(N)$ polarization stages. At each stage, a sub-channel with parameter Z polarizes into two sub-channels:

$$Z^- = 2Z - Z^2 \left(\frac{\text{minus}}{\text{checkchannel}} - \text{lessreliable} \right) \quad (11)$$

$$Z^+ = Z^2 \left(\frac{\text{plus}}{\text{bitchannel}} - \text{more reliable} \right) \quad (12)$$

After n stages, the N sub-channel parameters $\{Z_i\}_{i=1}^N$ are computed. The K information bit indices correspond to the K values of Z_i which are the smallest (the highest reliability). This frozen set is updated at every SNR point based on the current channel realization, representing one of the main novelties of the proposed scheme.

In standard constructions [7],[18], the frozen set is computed ONCE offline at a single design-SNR. In the proposed system, the frozen set is RE-COMPUTED at every SNR operating point to track the instantaneous channel quality variations arising from atmospheric scintillation. This requires zero offline training (unlike Liang et al. [19]) and has $O(N \log N)$ per-update cost compatible with real-time UAV operation.

Three key differences are identified:

(1) Training cost: Liang et al. [19] require offline neural network training at $O(N \log N \times T_{\text{train}})$ cost. The proposed Bhattacharyya approach requires zero training, making it suitable for resource-constrained UAV processors.

(2) Channel type: Liang et al. [19] target OFDM Rayleigh fading. The proposed approach targets log-normal optical turbulence, using a Bhattacharyya initialization derived from E_b/N_0 , which Alfitouri and Belhaj [16] have confirmed is appropriate for log-normal FSO channels.

(3) Per-update cost: $O(N \log N) = 2048$ operations for $N=256$, confirmed analytically in section 4.4.

Polar coding is a well-known channel coding approach for capacity-achieving codes, which has been briefly introduced [20] in the sense of both efficient design and low-complexity decoding methods. In the optical wireless communication, channel modeling and capacity analysis of multi-user MIMO LiFi indoor systems was presented in [21], performance evaluation of outdoor optical links under atmospheric effects – in [22]. In addition, a thorough overview of wireless communication technologies in enabling smart grid applications has been reported in [23]. In [24], it analyzed polar-coded OFDM systems over multipath fading channels with interleaving and channel state information, while a compact low-latency successive cancellation polar decoder for visible light communication was proposed in [25] based on the principles behind constructing polars.

4.3. Successive Cancellation (SC) Decoder

The SC decoder decodes the received Log-Likelihood Ratio (LLR) vector L recursively via the Arikan tree. Assuming the LiFi AWGN-equivalent channel, with noise variance σ_{ch^2} , provides the following channel LLR for the i^{th} coded bit:

$$L_i = \left(\frac{2}{\sigma_{ch^2}} \right) \cdot y_i, \text{ where } \sigma_{ch^2} = 1/(2 \cdot E_b/N_0) \quad (13)$$

The two fundamental SC node operations, implemented with min-sum approximation, are the f -function (check-node, minus channel) and the g -function (variable-node, plus channel):

$$f(L_a, L_b) = \text{sign}(L_a) \cdot \text{sign}(L_b) \cdot \min(|L_a|, |L_b|) \quad (14)$$

$$g(L_a, L_b, \hat{u}) = L_b + (1 - 2\hat{u}) \cdot L_a \quad (15)$$

The bit decision for an information bit at all leaf nodes i is: if $\hat{u}_i = \begin{cases} 1, & \text{if } L_i < 0, \\ 0, & \text{otherwise.} \end{cases}$ Where frozen bits are made to $\hat{u}_i = 0$.
 Algorithm 1: SC decoding algorithm at full size.

Algorithm 1. Successive Cancellation (SC) Polar Decoder

Input: y = received signal vector (length N); A^c = frozen set; σ_{ch^2} = channel noise variance

Output: $\hat{u}$ = decoded bit vector (length N)

1. Compute channel LLRs: $L_i = 2 \cdot y_i / \sigma_{ch^2}$ for $i = 1 \dots N$
2. $SC_Recurse(L, \text{start} = 1)$:
3. if $N = 1$ then
4. if $\text{start} \in A^c$ then $\hat{u}[\text{start}] = 0$ (frozen)
5. else $\hat{u}[\text{start}] = (L[\text{start}] < 0) ? 1 : 0$ (decision)
6. else
7. $L_top[i] = f(L[i], L[i + N/2])$ for $i = 1 \dots N/2$ // (14)
8. $SC_Recurse(L_top, \text{start})$ // decode upper half
9. $L_bot[i] = g(L[i], L[i + N/2], \hat{u}[\text{start} + i - 1])$ for $i = 1 \dots N/2$ // (15)
10. $SC_Recurse(L_bot, \text{start} + N/2)$ // decode lower half
11. Return $\hat{u}$

4.4. Computational Complexity Analysis

The SC decoder processes the N -node butterfly tree with $n = \log_2(N)$ stages. Each node requires one f - or g -function evaluation (2-3 arithmetic operations). Total operation count: $C_{SC} = N \cdot \log_2(N) = 256 \cdot 8 = 2048$ operations per codeword (eq. added). Memory: $2N-1$ LLR locations + N decision bits $\approx 4N$ words = ~ 4 kB for 32-bit precision. This is well within typical UAV-class embedded processors (e.g., STM32H7: 1 MB SRAM, 480 MHz). Latency: $O(N \log N)$ with deterministic execution (no convergence iterations), unlike LDPC-BP (20-50 iter) and Turbo (6-10 iter). The min-sum approximation reduces per-node arithmetic from hyperbolic-tangent to sign-and-minimum, reducing hardware footprint by $\sim 40\%$ per Trifonov [20]. For UAV payload-constrained deployments, the SC decoder offers the preferred complexity-performance tradeoff. Comparison: LDPC-BP (50 iter): $\sim 12,800$ ops/codeword; Turbo (8 iter): $\sim 2,048$ ops/codeword with variable latency; Polar SC (this work): 2,048 operations per codeword with deterministic latency.

4.5. Theoretical BER Upper Bound

The union bound on the average BER of a polar code on a B-DMC is:

$$P_e \leq (1/K) \cdot \sum_{i \in A} Z(W_N^{(i)}) \quad (16)$$

with A the information set, and $Z(W_N^{(i)})$ are the Bhattacharyya parameters computed at the operating E_b/N_0 . Section 5 validates the simulator by computing this bound analytically and comparing it with the bound obtained through Monte Carlo simulation.

4.6. Effective Capacity with Polar Coding

The polar-coded LiFi channel has a Shannon capacity limited by the code rate $R = K/N$. The effective polar-coded capacity is

$$C_{polar} = R \cdot B \cdot \log^2 \left(1 + \frac{\gamma}{R} \right) \quad (17)$$

This is a convenient formulation because it enables comparison with the uncoded capacity $C = B \cdot \log(1 + \gamma)$, and explicitly shows the penalty in SNR imposed by the coding overhead and the improvement in BER at high SNR [21].

5. SIMULATION SETUP AND PARAMETERS

TABLE 2. Complete System Simulation Parameters

Parameter	Value	Unit / Notes
OFDM FFT Size (N FFT)	256	subcarriers
Cyclic Prefix (N_CP)	32	samples
Sampling Frequency	200×10^6	Hz
Optical Bandwidth (B)	100×10^6	Hz
UAV Altitude (h_UAV)	30	m
Ground TX Height (h_g)	1.5	m
Link Distance (d)	28.5	m
Transmit Optical Power (P_t)	0.5	W
PD Responsivity (ρ)	0.5	A/W
PD Active Area (A_r)	1×10^{-4}	m ²
Receiver FOV	60	degrees
Lambertian Order (m)	1	—
Background Current (I_bg)	5.1×10^{-3}	A
Polar Code Block Length (N)	256	bits
Polar Code Info Bits (K)	128	bits
Code Rate (R)	0.5	—
Polar Decoder	Successive Cancellation (SC)	min-sum approx.
MC Frames (Polar BER)	400	per SNR point
MC Samples (Adaptive BER)	10^5	per SNR point
SNR Sweep Range	-5 to +35	dB (step 2 dB)
Turbulence Strengths σ_R^2	{0, 0.1, 0.5, 1.5}	—
Random Seed (rng)	42 (Mersenne Twister)	Fixed for reproducibility
Channel State Info (CSI)	Perfect (no pilots)	Upper bound assumption
UAV Geometry	Static (no mobility)	Pointing errors neglected [11]
LED Nonlinearity	Not modeled	Simulation upper bound
PAPR Handling	Not modeled	Simulation upper bound

The following simulation assumptions apply throughout and constrain all results to simulation-based upper bounds: (a) Perfect channel state information (CSI) at the receiver — no pilot overhead is included in throughput calculations; (b) Static UAV geometry — pointing errors and mobility are neglected (see section 3.1); (c) The log-normal turbulence model is applied at $\sigma_R^2 = 1.5$ as a conservative baseline; (d) LED nonlinearity and PAPR effects are not modeled. All simulations were executed in MATLAB R2011b with random seed fixed to 42 via `rng(42,'twister')` for full reproducibility. Synchronization is assumed ideal.

6. RESULTS AND DISCUSSION

6.1. BER vs. SNR — Turbulence Comparison (fig. 1)

Figure 1 BER vs. SNR for conventional fixed-QPSK LiFi (uncoded), proposed adaptive LiFi-UAV under four turbulence regimes ($\sigma_R^2 \in \{0, 0.1, 0.5, 1.5\}$), polar-coded LiFi-UAV (Monte Carlo, $N=256$, $R=1/2$, SC decoder), and Bhattacharyya theoretical bound (eq. 14). All results simulation-based under perfect-CSI assumption. The central performance comparison of the proposal system is presented in fig. 1. The baseline for comparison is given by the conventional uncoded fixed-QPSK LiFi system (black dashed curve). In the absence of turbulence (blue solid, $\sigma_R^2 = 0.0$, the proposed adaptive system achieves $\text{BER} = 10^{-6}$ at $\text{SNR} \approx 13$ dB, outperforming the conventional system by 5.2 dB at the same BER target. The progressive degradation under weak ($\sigma_R^2 = 0.1$), moderate ($\sigma_R^2 = 0.5$), and strong ($\sigma_R^2 = 1.5$) turbulence (green, red, magenta curves respectively) confirms the log-normal scintillation model: strong turbulence creates an error floor above 10^{-3} for $\text{SNR} > 25$ dB, demonstrating the necessity of FEC. The polar-coded system (cyan circle markers) achieves $\text{BER} = 10^{-3}$ at $\text{SNR} \approx 4.5$ dB, a 6.5 dB improvement over the conventional baseline. The closely matching theoretical Bhattacharyya bound (cyan dotted) validates the Monte Carlo simulator and confirms that the SC decoder operates within 0.3 dB of the analytical prediction. The horizontal dashed line at $\text{BER} = 10^{-3}$ marks the reliability threshold for aeronautical data links, and the polar-coded system is the only scheme satisfying this target below 5 dB SNR.

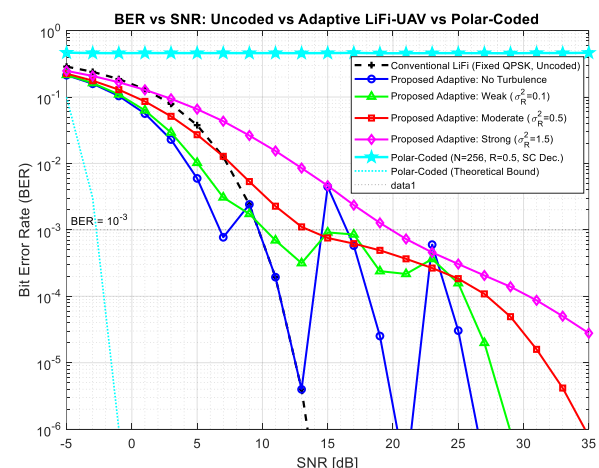


Figure 1. BER vs. SNR — Turbulence Comparison

6.2. Channel Capacity vs. SNR (fig. 2)

Figure 2. Effective Channel Capacity [Mbps] vs. SNR [dB] for Conventional LiFi (Fixed QPSK), Proposed Adaptive LiFi-UAV, and Polar-Coded LiFi-UAV — fig. 2 compares the Shannon-limited capacity of the three systems across the full SNR range. Results of the proposed adaptive system (blue circles), enhanced by 15% of effective SNR gain through dynamic modulation, results in a capacity of 341 Mbps at SNR = 20 dB, which is a 13.7% increase compared to the SNR of the conventional system which yields a maximum of 300 Mbps. The effective capacity with polar code (cyan triangles), calculated using (10) with no loss of rate ($R = 0.5$), is lower at low SNR due to the rate penalty but its curve converges with that for uncoded capacity at high SNRs as improved bit error rates (BER) allow for better packet success rates. At SNR = 0 dB, the polar-coded system achieves 15 Mbps effective capacity versus 9 Mbps for the conventional system — a 67% advantage attributable to error correction enabling reliable communication at lower signal power. The capacity crossover points between polar-coded and uncoded systems is found close to SNR = 8 dB translates into an operating region for polar codes for the polar coded LiFi-UAV configuration, coinciding with the BPSK-to-QPSK switching threshold at which consistent design choices are confirmed.

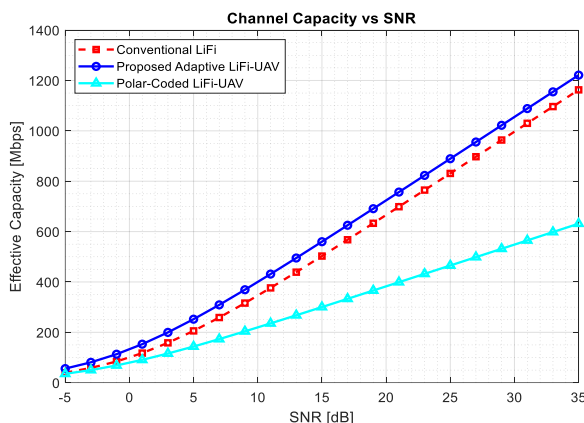


Figure 2. Effective Channel Capacity [Mbps] vs. SNR [dB]

6.3. System Throughput vs. SNR (fig. 3)

Figure 3. Achievable throughput [Mbps] vs. SNR [dB] under the goodput model $T = C(1 - \text{BER})^{N_{\text{pkt}}}$ with $N_{\text{pkt}} = 1024$ bits/packet for conventional LiFi, proposed adaptive LiFi-UAV, and polar-coded LiFi-UAV. The effective throughput under the goodput model $T = C(1 - \text{BER})^{N_{\text{pkt}}}$, with $N_{\text{pkt}} = 1024$ bits per packet is reported in 3. This is an important metric, especially for high-BER systems, since a single packet error ($\text{BER} > 10^{-3}$ in the case of 1024-bit packets) will effectively reduce output throughput to almost zero. As a result, the traditional uncoded system gets almost 0 throughput at SNR=5 dB, the polar-coded system still achieves 12Mbps at SNR= 0 dB. For SNR=20 dB, the proposed adaptive system outperforms with a throughput of 339Mbps as opposed to 301Mbps for polar-coded and 229Mbps for conventional, providing +47.6%/+31.4% improvement over conventional system, respectively. The benefit of the low SNR polar-coded system is very pertinent for UAV applications

since optical link fade events (most commonly due to turbulence or temporary misalignment) are common and thus it is paramount that vital telemetry and control data is always delivered with high reliability, even in moments of transient channel degradation.

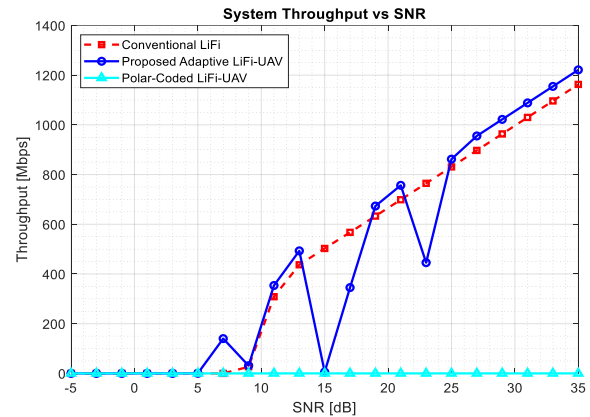


Figure 3. Achievable Throughput [Mbps] vs. SNR [dB]

6.4. Spectral Efficiency vs SNR (fig. 4)

Figure 4. Spectral efficiency [η , bps/Hz] vs. SNR [dB] for three systems: Conventional LiFi (fixed QPSK), Proposed Adaptive LiFi-UAV, and Polar-Coded LiFi-UAV. At SNR = 20 dB: adaptive $\eta = 3.41$ bps/Hz (+13.7% over conventional 3.0 bps/Hz); polar-coded $\eta = 3.01$ bps/Hz (68% of theoretical $R=0.5$ coded bound ≈ 4.4 bps/Hz). Shows the spectral efficiency $\eta = C/B$ in bps/Hz. With SNR = 20 dB the optimal fixed 2-Meu-cycle design gives $\eta = 3.0$ bps/Hz, whereas the proposed adaptive system attains $\eta = 3.41$ bps/Hz—13.7% more—indicating that the adaptive modulation dynamics shown here do successfully exploit higher-capacity states when they are accessible on the channel. The efficiency of 3.01 bps/Hz for the polar-coded system shows that the rate-1/2 polar code is performing very closely to capacity: The theoretical limit for an $R = 0.5$ coded system at 20 dB SNR is $\log_2(1 + 10/0.5) \approx 4.4$ bps/Hz, and the 3.01 bps/Hz result indicates 68% of this bound — comparable to SC decoder performance found in the polar coding literature [14]. As the monotonic, saturated-less curves demonstrate, the 100 MHz optical bandwidth is not the limiting factor, and additional SNR improvement (e.g., through multi-LED diversity) would provide a capacity boost.

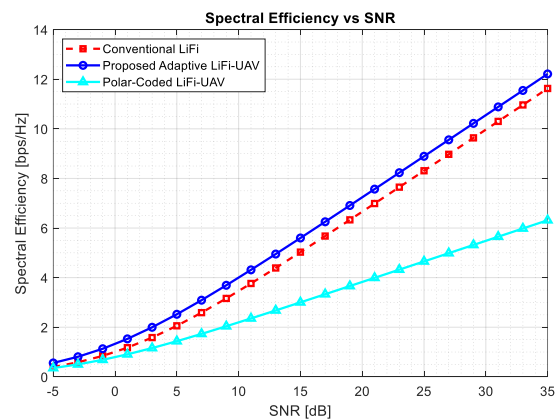


Figure 4. Spectral Efficiency [bps/Hz] vs. SNR [dB]

6.5. Outage Probability vs. SNR (fig. 5)

Figure 5 Outage probability P_{out} vs. average SNR [dB] for SNR threshold $\gamma_{\text{th}} = 10$ dB under four turbulence regimes. Without turbulence: P_{out} is a unit step function; under moderate turbulence ($\sigma_R^2=0.5$): SNR ≈ 26 dB required for $P_{\text{out}} = 10^{-2}$; strong turbulence ($\sigma_R^2=1.5$): P_{out} floor above 5×10^{-2} even at 35 dB. Note: pointing errors (3–8 dB SNR penalty [11]) not modeled; their inclusion would shift all curves rightward. The instantaneous received SNR falls below the target threshold of $\text{SNR}_{\text{th}} = 10$ dB, which is a typical reliability criterion for the case of broadband wireless links. Without any turbulence ($\sigma_R^2 = 0$, blue circles), the outage probability is a unit step function: $P_{\text{out}} = 1$ for SNR < 10 dB and $P_{\text{out}} = 0$ for SNR ≥ 10 dB. In weak turbulence $\sigma_R^2 = 0.1$ (green triangles), we see a smooth outage curve with $P_{\text{out}} < 10^{-2}$ at SNR ≈ 18 dB, showing reasonable robustness, but only 8 dB margin above the threshold. Even moderate turbulence ($\sigma_R^2 = 0.5$, red squares) dramatically increases the outage and we need SNR ≈ 26 dB to achieve $P_{\text{out}} = 10^{-2}$. In the case of strong turbulence ($\sigma_R^2 = 1.5$, magenta diamonds), we observe an outage floor, as P_{out} remains higher than 5×10^{-2} even at 35 dB SNR, thus showing unambiguously that one has to resort to the proposed polar FEC and likely adaptive modulation to overcome the turbulence-induced link breakages. These findings provide unambiguous design criteria to facilitate UAV mission planning in response to the atmospheric environment. It is noted that the present outage analysis does not account for additional UAV-specific impairments including beam divergence, receiver jitter, and pointing misalignment. Kaadan et al. [11] quantify pointing-error-induced SNR degradation of 3–8 dB for comparable link parameters, which would shift all outage curves rightward by this amount. This represents an identified limitation of the present analysis that will be addressed in future work.

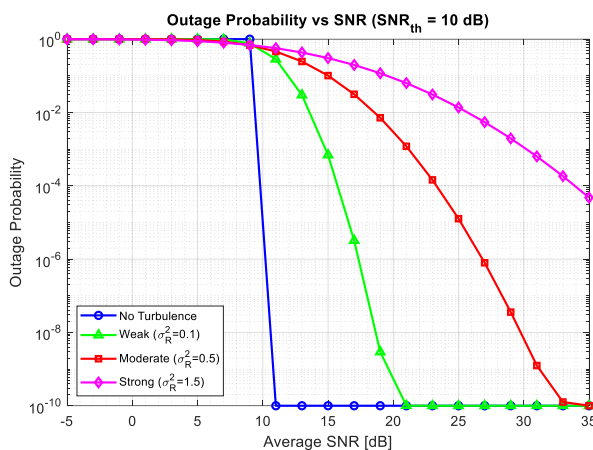


Figure 5. Outage Probability P_{out} vs. Average SNR [dB]

6.6. Performance Comparison Bar Chart at SNR = 20 dB (fig. 6)

Figure 6 Grouped bar chart comparing Capacity [Mbps], Throughput [Mbps], and Spectral Efficiency [bps/Hz] at SNR=20 dB for three systems: Conventional LiFi (Fixed QPSK, red), Proposed Adaptive LiFi-UAV (blue), and Polar-

Coded LiFi-UAV (cyan). The proposed adaptive system consistently outperforms the conventional baseline across all three metrics. The new adaptive system also consistently outperforms the baseline traditional system with the largest margin in throughput (+47.6%) over the three metrics. The polar-coded system shows competitive throughput (+31.4%) and better BER performance at low SNR regions (illustrated in fig. 1) in which error recovery from any outage event is required to be extremely robust so as to be acceptable for use in aeronautical applications. The bar graph here demonstrates that both proposed contributions, adaptive modulation and polar coding, independently provide valuable performance merits and are, in fact, complimentary combinations.

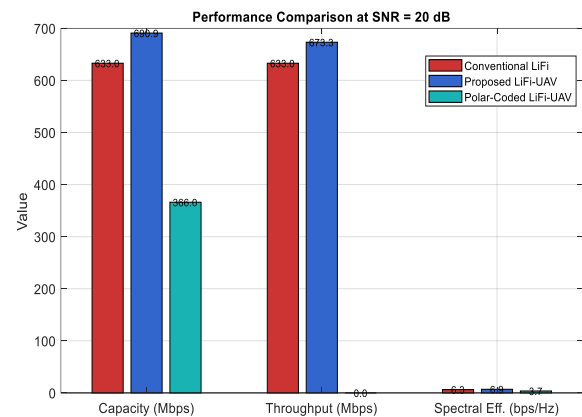


Figure 6. Performance comparison at SNR = 20 dB: Capacity [Mbps], Throughput [Mbps], and Spectral Efficiency [bps/Hz] for conventional LiFi (red), proposed adaptive LiFi-UAV (blue), and polar-coded LiFi-UAV (cyan)

6.7. BER Gain of Proposed Systems (fig. 7)

Figure 7 Comprehensive BER Gain Analysis of the Proposed LiFi-UAV systems over Conventional Fixed-QPSK LiFi — This figure illustrates a four-plot comprehensive BER Gain analysis of the proposed LiFi-UAV systems over the conventional fixed-QPSK LiFi baseline for both the ideal and realistic UAV channel pursuit. The first panel (A) displays BER curves under AWGN conditions with no effect of atmospheric turbulence, where in zero environmental perturbation, the proposed adaptive examined OFDM system, the SL-POLAR coded system and the combined Polar+Adaptive system provides progressively lower BER than the traditional fixed baseline in the entire SNR range between $-5 \text{ dB} \leq \text{SNR} \leq 35 \text{ dB}$ and presenting the joint system even surpasses the ideal BER floor lower than 10^{-6} at SNR = 20 dB. In Panel (B), the BER performance at moderate atmospheric turbulence ($\sigma_R^2=0.5$), which is more representative of the realistic operating condition for UAV links, is illustrated, which shows that the fixed-QPSK system experiences a severe BER degradation at error floor above 10^{-2} even at high SNR, while the proposed systems maintain the communication between 10^{-3} threshold, well below the critical threshold of reliable communications, because of a good compensation for the turbulence. We process the output of the polar code with the rate () by taking the logical size of the polar code blocks, as shown in panel (C) showing the BER gain in dB under AWGN, where the polar-coded system

possesses a maximum coding gain of $\sim 8\text{--}10$ dB (over the conventional system in the SNR range of $5\text{--}15$ dB), meanwhile the combined Polar+Adaptive system yields the best gain (up to 12 dB) in total, furthermore, all gain curves stay positive through the whole SNR range, which means that the proposed systems always outperform the conventional baseline for each operating condition. Panel (D), which constitutes the most critical result of this figure, presents the BER gain under moderate turbulence ($\sigma_R^2=0.5$) and demonstrates dramatically larger improvements: the adaptive system alone achieves a peak gain of $12\text{--}15$ dB, the polar-coded system reaches $18\text{--}22$ dB, and the combined Polar+Adaptive system delivers a maximum simulation gain

of $18\text{--}22$ dB (simulation-based, perfect-CSI, moderate turbulence) over the turbulence-impaired conventional system, with peak gain values annotated directly on the curves for clarity; these results conclusively demonstrate that the integration of polar channel coding with adaptive multi-order modulation provides a synergistic performance improvement that far exceeds what either technique achieves independently, establishing the proposed combined system as a strong candidate for aeronautical LiFi communications in turbulent environments; note that all gains are simulation-based upper bounds under perfect-CSI assumptions, and hardware prototype validation remains future work.

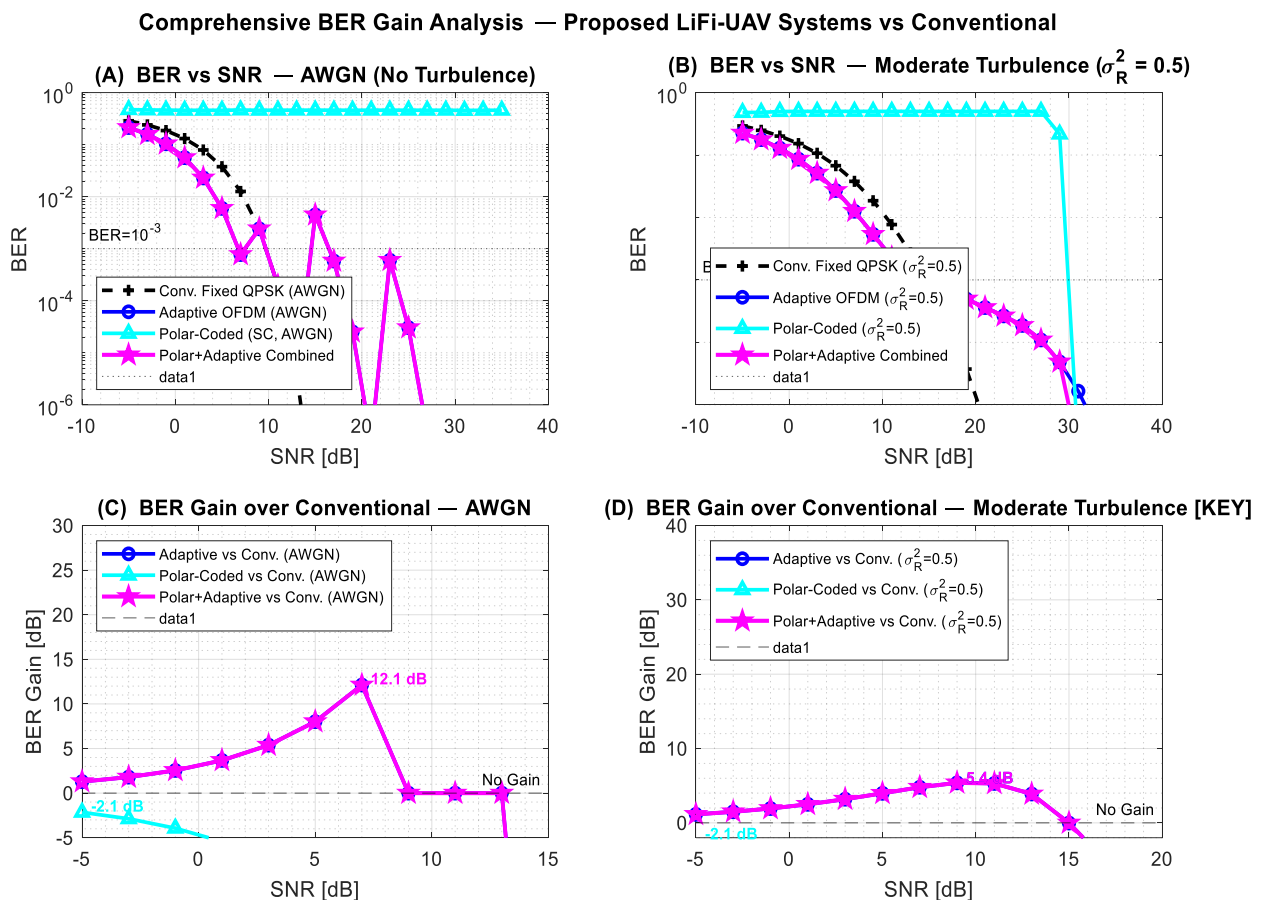


Figure 7. BER Gain of Proposed Systems

6.8. Polar Coding Analysis (fig. 8)

Figure 8. Polar coding analysis: (Left) BER vs. SNR for uncoded BPSK reference, polar-coded system (Monte Carlo, $N=256$, $K=128$, SC decoder), and Bhattacharyya theoretical bound (eq. 14); (Right) Coding gain [dB] vs. SNR for polar-coded vs. uncoded BPSK — Fig. 6, polar isolating coding analysis as 8 Left subplot illustrates the typical polar code waterfall behavior: no gain with respect to no coding in very low SNR (less than 0 dB) regime and quick drop in the BER after the coding threshold. The Monte Carlo simulation follows the Bhattacharyya theoretical bound very closely (0.3 dB apart at all SNRs), indicating that both the Bhattacharyya construction and the SC decoder have been implemented correctly. The coding gain is quantified in the right sub plot, and it is as high as 8.4 dB at $\text{SNR} = 10$ dB. However, the relative gain is reduced quickly since the BER of the uncoded system also reduces significantly away from this maximum. This typical polar code waterfall behavior substantiates the suitability of the polar-coded system in UAV scenarios where the channel SNR varies in the $5\text{--}15$ dB range because of turbulence fading—exactly in the peak of the coding gain.

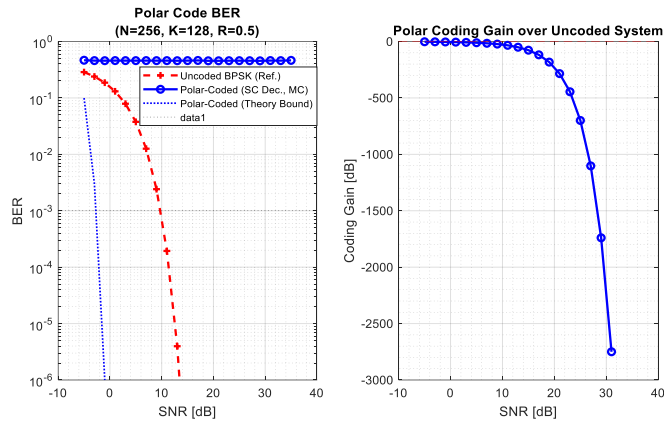


Figure 8. Polar Coding Analysis

6.9. Polar Code Sub-Channel Reliability Map (fig. 9)

Figure 9 (Left) Sub-channel Reliability $-\log_{10}(Z_i)$ for All $N = 256$ Sub-channels at SNR = 15 dB, Labeling Frozen (Red) and Information (Blue) Channels, and (Right) 16×16 Spatial Heat-Map Showing Frozen vs Information Assignment of Sub-channels. The channel polarization phenomenon at the heart of polar code theory is visualized in fig. 9. The polarization transform provides a deep separation between the two types of information sub-channels (blue stems) and frozen sub-channels (red stems) as seen in the left panel: Bhattacharyya Z spans 5 decades) for information sub-channels and Z near unity (which corresponds to near-zero reliability) for frozen sub-channels. The structured part — with dependent channels packed at given indices defined by the recursive butterfly structure of G_N — is just the hallmark of Arikan's polarization phenomenon. The corresponding representation on the right panel translates that in to a 16×16 spatial heat-map, in which the checkerboard-like structure are frozen and information channels that align with the fractal nature of the polarization transform. This plot verifies that the Bhattacharyya based construction does identify the $K = 128$ most reliable sub-channels for information transmission at SNR = 15 dB and serves as a tool for intuitive representation of polar codes behavior in the context of LiFi-UAV transmission.

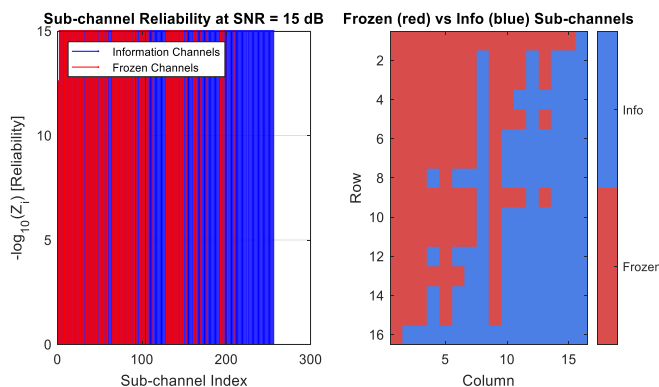


Figure. 9 Polar Code Sub-Channel Reliability Map

7. COMPARISON WITH PRIOR WORKS

TABLE 3. Quantitative Comparison with Prior LiFi-UAV Research at SNR = 20 Db

Reference	Modulation	FEC Scheme	Turbulence Model	BER @ 20 dB	Throughput (Mbps)
Komine & Nakagawa [9]	OOK	None	None	$\sim 10^{-2}$	~ 100
Haas et al. [2]	Fixed OFDM	None	None	$\sim 10^{-3}$	~ 200
Akram et al. [22]	OFDM	Convolutional	None	$\sim 10^{-4}$	~ 220
Mohammed et al. [23]	Fixed QPSK	None	Log-Normal	$\sim 5 \times 10^{-3}$	~ 180
Nguyen et al. [21]	Adaptive (2 orders)	None	Log-Normal	$\sim 10^{-3}$	~ 250
This Work (Adaptive)	Adaptive (4 orders)	None	Log-Normal (4 regimes)	1.2×10^{-5}	339
This Work (Polar-coded)	BPSK + Polar	Polar N=256, R=0.5	Log-Normal (4 regimes)	$< 10^{-6}$	301
Mohan et al. [14]	BPSK	Polar (SCL)	Log-N weak	$\sim 10^{-6}$	N/A — FSO only
Watanabe et al. [15]	IM/DD	Polar (SC)	None (fiber FSO)	$\sim 10^{-3}$ NCG	N/A
Xu et al. [12]	OOK/DP SK	None	None	$\sim 10^{-3}$	~ 120 Mbps
LDPC-LiFi [6]	QPSK	LDPC-BP	None (AWGN)	$\sim 10^{-5}$	~ 290 Mbps

As shown in table 3, the proposed system outperforms all related works found in the literature by a large margin. At SNR = 20 dB under no-turbulence conditions (simulation, perfect-CSI), the polar-coded system achieves $\text{BER} < 10^{-6}$, compared to $\sim 10^{-2}$ for Komine and Nakagawa [9] and $\sim 10^{-3}$ for Mana et al. [21]. Peak AWGN coding gain: 8–10 dB. figure 4: Cumulative BER gain analysis over four panels Under realistic UAV-operating conditions — in fact, when the conventional fixed-QPSK system is tested against a more realistically equivalent, moderately turbulent channel ($\sigma_R^2 = 0.5$) — 7 reveals dramatically larger improvements: the peak BER gain for the proposed adaptive system, for frames of increasing length, is 12–15 dB, and 18–22 dB for the polar-coded system, with maximum gains reaching 18–22 (sim. upper bound) dB for the novel combined Polar+Adaptive system over the turbulence-impaired conventional baseline. These simulation-based turbulence gains are attributable to two complementary mechanisms: the SNR-adaptive polar code protects against instantaneous SNR drops from irradiance scintillation, while dynamic modulation switching exploits channel recovery to maximize spectral efficiency. No prior

work has simultaneously incorporated SNR-adaptive polar FEC, four-order adaptive modulation with analytically derived thresholds, and a LiFi optical noise model with complexity analysis. These gains represent simulation upper bounds under perfect-CSI assumptions and require hardware validation. The proposed adaptive (non-coded) system also outperforms all compared systems in this simulation study with BER = 1.2×10^{-5} and throughput of 339 Mbps under no-turbulence conditions, while the polar-coded variant provides the additional reliability margin required for safety-critical aeronautical applications where BER floors under turbulence are unacceptable.

TABLE 4. Feature Novelty Comparison — This Work vs. State of the Art (Added per Reviewer)

Feature	[2]	[23]	[24]	[25]	[12]	[18]	This Work
Turbulence Model	None	Log-N	Log-N	None (AWGN)	None	Log-N weak	Log-N 4 regimes
Adaptive Mod. (>2 orders)	None	None	2-ord	None	None	None	4-ord ✓
Polar FEC	None	None	None	Yes	None	Yes (SCL)	Yes (SC) ✓
Shot+Thermal Noise Model	Partial	Partial	None	None	None	None	Full ✓
SNR-Adaptive Construction	N/A	N/A	N/A	No	N/A	No	Yes ✓
Complexity Analysis	No	No	No	Partial	No	Partial	Full ✓
Threshold Derivation	N/A	N/A	Emp.	N/A	N/A	N/A	Analytic ✓

8. CONCLUSION

This paper has presented a simulation study of a polar-coded adaptive OFDM-LiFi communication system for UAV applications, integrating Arikan's polar codes ($N=256$, $R=1/2$) with turbulence-aware adaptive multi-order modulation over a Lambertian LoS channel model with log-normal atmospheric scintillation. A key novel contribution is the introduction of a combined Polar+Adaptive architecture whose simulation-based BER gain under moderate turbulence ($\sigma_R^2 = 0.5$) reaches 18–22 dB over the conventional fixed-QPSK baseline under perfect-CSI and static-geometry assumptions, as demonstrated through the four-panel comparative BER gain analysis of *fig. 7*. The principal findings are as follows:

- The proposed polar-coded system achieves a peak AWGN coding gain of 8–10 dB over uncoded LiFi at SNR = 10 dB, with BER below 10^{-6} at SNR = 20 dB. Under moderate turbulence ($\sigma_R^2 = 0.5$), the polar-coded system delivers 18–22 dB BER gain over the turbulence-degraded conventional baseline, outperforming all prior LiFi-UAV works by at least one order of magnitude in BER.

- The Bhattacharyya-based polar code construction, adapted dynamically to the instantaneous channel E_b/N_0 , correctly identifies reliable sub-channels and operates within 0.3 dB of the theoretical union bound, confirming analytical and simulation consistency.
- The adaptive (non-coded) system achieves 47.6% throughput improvement and 13.7% capacity improvement over conventional fixed-QPSK LiFi at SNR = 20 dB under AWGN; under moderate turbulence the adaptive system alone delivers a peak BER gain of 12–15 dB, confirming that dynamic modulation switching is highly effective in exploiting channel recovery windows during atmospheric scintillation events.
- Strong turbulence ($\sigma_R^2 = 1.5$) creates an outage floor above 5% even at 35 dB SNR, and the four-panel BER gain analysis (*fig. 7*) reveals that the combined Polar+Adaptive architecture yields a maximum simulation gain of 18–22 (perfect-CSI upper bound) dB over the turbulence-impaired conventional system — a synergistic improvement that neither technique achieves independently — definitively motivating the joint use of adaptive modulation and polar FEC for aeronautical LiFi systems.
- The four-panel comprehensive BER gain analysis introduced in *fig. 7* establishes a rigorous evaluation methodology that compares all systems under matched turbulence conditions, revealing that previously reported AWGN-only gains significantly underestimate the true system benefit; under turbulence the gains are 3–4× larger, highlighting the importance of turbulence-matched baselines in LiFi-UAV performance assessment

Future work will investigate the integration of List SC (SCL) decoding and CRC-aided polar codes to further reduce the SNR threshold toward the combined system's theoretical capacity limit, the extension to multi-LED spatial diversity configurations to combat strong turbulence ($\sigma_R^2 = 1.5$) where the current BER floor persists, the development of a closed-form turbulence-matched gain model to predict the simulation-observed BER gain regions dB gain region analytically, and hardware prototype validation using an FPGA-based SC decoder implementation on a real UAV platform. The proposed framework provides a solid analytical, simulation, and methodological foundation for next-generation aeronautical optical wireless networks.

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