

Joint Acquisition and High-Rate Data Transmission Using Laser Arrays for Optical Inter-Satellite Links

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ABSTRACT

High-rate optical inter-satellite links require broad angular coverage during acquisition, but high irradiance and tight pointing during data transfer. A fixed single beam cannot independently satisfy these competing requirements. This paper proposes and models a laser-array terminal in which the wavelength, full-angle divergence, and relative beam geometry remain fixed. A common fast-steering mirror translates the complete beam topology, and a single quadrant avalanche photodiode provides both angle-of-arrival observables and the on-off keying data statistic. The fixed total optical power is divided equally among the beams during acquisition and recovery, but is concentrated on the selected beam during tracking and data transmission. A unified framework is developed for Gaussian-beam coupling, stochastic spiral acquisition, communication outage, and conditional one-step recovery after loss of track. For the considered 1000 km, 100 Mbit/s link, 10^5 independent acquisition runs show that a five-beam topology with $175\ \mu\text{rad}$ full-angle divergence gives a conditional mean acquisition time of approximately 2.94 s, an acquisition success probability of 99.5%, and a conditional recovery probability of 0.920. At the same divergence, the single-beam values are approximately 4.38 s, 79%, and 0.326, respectively. The selected five-beam point also gives an outage probability of about 4.4×10^{-4} for a $15\ \mu\text{rad}$ per-axis tracking error.

Keywords: optical inter-satellite links, pointing acquisition and tracking, laser arrays, multibeam transmission, fast recovery, low-SWaP terminal

1. INTRODUCTION

Optical inter-satellite links (OISLs) can provide high-throughput connectivity with compact apertures, but their narrow beams make link availability strongly dependent on pointing, acquisition, and tracking (PAT).¹ Random pointing errors reduce the collected power and create a fundamental trade-off between beam directivity and robustness.² Recent flight demonstrations show that high-rate space laser communication is possible, but also illustrate the required angular precision: the TeraByte InfraRed Delivery (TBIRD) CubeSat demonstrated 100/200 Gbit/s downlinks with measured closed-loop errors of approximately 20–35 μrad root-mean-square (RMS) per axis.³ Link establishment nevertheless involves more than maintaining this closed-loop accuracy. Before data transfer, the partner terminal must be found over a much larger uncertainty region and mutual detection must be confirmed; after loss of track, a rapid local recovery is preferable to restarting the complete search. Acquisition therefore favours angular coverage, tracking/data favours concentrating the available power, and recovery favours local angular diversity around the last valid pointing command.

Compact PAT terminals commonly combine spacecraft body pointing with a fine steering stage. The CubeSat Laser Infrared Crosslink (CLICK), for example, uses the spacecraft attitude-control system for coarse pointing and a microelectromechanical system (MEMS) fast-steering mirror (FSM) for fine transmit/receive alignment.⁴ CubeISL work at the German Aerospace Center (DLR) developed an inter-CubeSat terminal and a partner-search concept,⁵ while Rüddenklau and Schitter compared pairs of spiral, rose, and Lissajous search patterns through Monte Carlo optimisation. Safi et al. jointly optimise the scanning-beam width and successive-track overlap under beam jitter to minimise acquisition time subject to acquisition-failure-probability and power constraints.^{6,7} These studies advance terminal control and search-trajectory design, but treat the transmitted beam configuration as a given and do not jointly design the post-acquisition communication and recovery phases.

Likewise, the on-orbit OSIRIS4CubeSat demonstration validates open-loop acquisition and active fine tracking in a highly miniaturised terminal,⁸ but does not address a multibeam OISL topology that changes its power allocation across operational phases.

Laser arrays and multibeam transmitters offer a complementary route to wider angular coverage. Goorjian uses a vertical-cavity surface-emitting laser (VCSEL)/photodetector array to select an outgoing beam according to the detected incident direction, thereby providing electronic fine pointing without a mechanical steering stage.⁹ Spaander et al. study multibeam satellite terminals mainly for simultaneous links to multiple targets and compare candidate beam-steering technologies.¹⁰ More directly, Apoorva et al. derive acquisition probability and outage for a hybrid radio-frequency (RF)/free-space optical (FSO) inter-satellite link with multiple independently pointed optical sources and best-beam selection.¹¹ That work is the closest multibeam link-level precedent, but it selects one of independently controlled sources and uses RF as a fallback; it does not model a rigid beam cluster scanned by one FSM, continuous threshold confirmation, phase-dependent sharing of a fixed optical-power budget, or optical fast recovery after loss of track.

Related array-based studies also address coverage or robustness after optical power has entered the receiver field of view. Safi et al. optimise divergence and VCSEL allocation for three-dimensional indoor optical coverage,¹² and use an avalanche-photodiode array to enlarge the receiver field of view and jointly perform data detection and fine beam tracking for a CubeSat FSO link.¹³ The authors of another study¹⁴ jointly optimise communications and tracking for an array-based modulating-retroreflector satellite-to-ground link. These studies improve coverage or post-acquisition robustness, but do not model the temporal search required to find an initially unknown line of sight or the transition from link loss to local recovery and, if that fails, full reacquisition. Common-path quadrant photodetector (QPD)-based terminals have also demonstrated that beacon and tracking functions can be integrated with high-rate data transmission,¹⁵ although the reported architecture retains separate QPD and avalanche photodiode (APD) receivers and changes the beam divergence between coarse and fine operation.

The reviewed literature therefore treats search-pattern design, laser-array pointing, multibeam selection, joint tracking/data reception, and recovery largely as separate problems. To the best of our knowledge, no existing study unifies: (i) a fixed co-boresighted multibeam cluster translated by one common FSM; (ii) equal division of a fixed total optical power during acquisition and recovery, followed by concentration of the full power on one selected beam during tracking/data; (iii) one quadrant avalanche photodiode (QAPD) for angular feedback and on-off keying (OOK) detection; and (iv) joint evaluation of confirmed acquisition time and success, communication outage, and conditional fast recovery. This is an operational, not merely geometric, gap because the three phases occur sequentially in the same physical terminal.

The contributions of this paper are threefold:

- We propose a phase-reconfigurable terminal with low size, weight, and power (SWaP), comprising one fixed laser array, one common FSM, and one QAPD. The wavelength, divergence, and relative beam geometry remain unchanged; only emitter activation and per-beam power are reconfigured between phases.
- We develop a common mathematical framework for the overlapping Gaussian beam pattern, fixed-total-power allocation, QAPD-based feedback, stochastic spiral acquisition, data outage, and recovery conditioned on loss of the selected tracking beam.
- We evaluate the beam count and static divergence using 10^5 independent acquisition runs together with analytical outage and conditional-recovery calculations. The resulting design is selected from all three phase metrics rather than from acquisition or closed-loop communication alone.

2. SYSTEM MODEL AND OPERATIONAL PHASES

2.1 Low-SWaP terminal architecture

Consider a bidirectional optical inter-satellite link between two identical terminals, denoted by $\mathcal{T}_A$ and $\mathcal{T}_B$. Each terminal comprises an N -element laser array, an electronically controlled power-allocation stage, one FSM shared

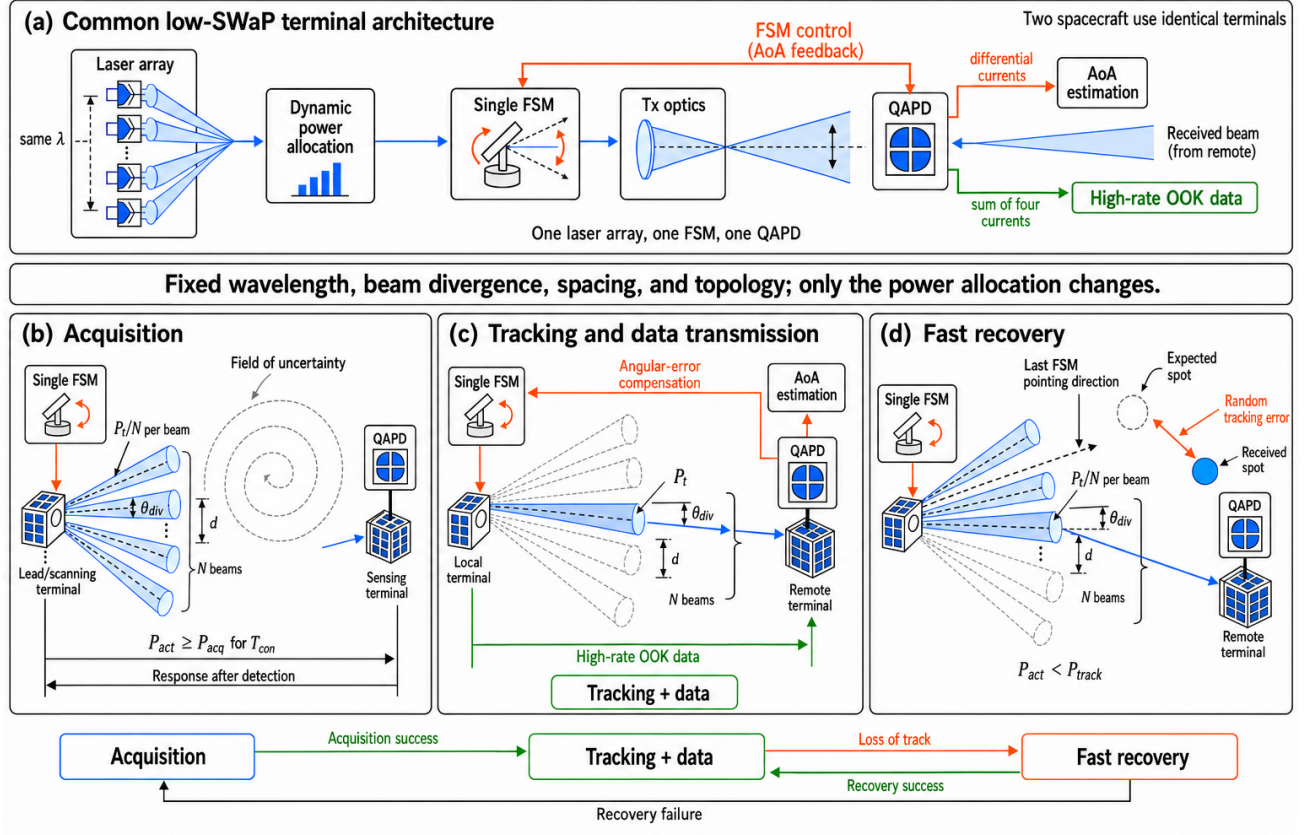


Figure 1. Common low-SWaP terminal architecture and its operational states. The common FSM translates the rigid beam topology, while the electronic allocation stage sets the state-dependent per-beam powers. The QAPD sum and difference channels support data detection and angular tracking, respectively.

by all transmitted beams, transmit optics, and one QAPD. The emitters have a common wavelength λ and full-angle divergence θ_{div} , while their relative angular offsets are fixed by the array geometry. The FSM therefore translates the complete angular pattern without changing its internal geometry. The same received optical signal is used for both functions: the QAPD sum current is the OOK data statistic, and its normalised differential currents provide angle-of-arrival (AoA) observables. Thus, neither a separate beacon wavelength nor a dedicated tracking detector is required.

Figure 1 shows the common terminal architecture. Since the two terminals have identical optical and control chains, their lead and responding roles can be interchanged without changing the model.

2.2 Fixed multibeam geometry and transmit-power variables

Let $\vartheta = [\vartheta_x, \vartheta_y]^T$ denote an angular coordinate in the terminal reference frame, and let the common FSM command be $\mathbf{s}(t) = [s_x(t), s_y(t)]^T$. The fixed offset of beam i from the topology centre is δ_i . For the central-plus-ring topology with $N \geq 4$,

$$\delta_1 = \mathbf{0}, \quad \delta_i = d \begin{bmatrix} \cos\left(\phi_0 + \frac{2\pi(i-2)}{N-1}\right) \\ \sin\left(\phi_0 + \frac{2\pi(i-2)}{N-1}\right) \end{bmatrix}, \quad i = 2, \dots, N, \quad (1)$$

where d is the centre-to-ring angular separation and ϕ_0 is the topology rotation. Both are model variables; no numerical relationship between d and the common full-angle beam divergence θ_{div} is imposed here. For $N = 1$,

$\delta_1 = \mathbf{0}$. The vector $\mathbf{s}(t)$ represents the common FSM steering command, expressed as the instantaneous angular position of the topology centre. Accordingly, the instantaneous centre of beam i is obtained by adding its fixed topology offset δ_i :

$$\beta_i(t) = \mathbf{s}(t) + \delta_i, \quad i = 1, \dots, N. \quad (2)$$

Let $P_{t,i}(t) \geq 0$ be the optical power assigned to beam i , and collect the per-beam powers in

$$\mathbf{P}_t(t) = [P_{t,1}(t) \ \cdots \ P_{t,N}(t)]^\top, \quad \mathbf{1}_N^\top \mathbf{P}_t(t) = P_t, \quad (3)$$

where P_t is the total available optical power. Let $\mathcal{S}(t) \in \{\text{ACQ}, \text{TRK/DATA}, \text{REC}\}$ denote the terminal state, where ACQ, TRK/DATA, and REC represent acquisition, simultaneous tracking and data transmission, and fast recovery after loss of track, respectively. Let $i^*(t)$ denote the selected tracking beam. The state-dependent allocation is

$$P_{t,i}(t) = \begin{cases} P_t/N, & \mathcal{S}(t) \in \{\text{ACQ}, \text{REC}\}, \\ P_t, & \mathcal{S}(t) = \text{TRK/DATA}, \ i = i^*(t), \\ 0, & \mathcal{S}(t) = \text{TRK/DATA}, \ i \neq i^*(t), \end{cases} \quad i = 1, \dots, N. \quad (4)$$

Thus, the total-power constraint in Eq. (3) is satisfied in every state. The same allocation rule is stated explicitly among the numerical settings in Table 1. If $g(\boldsymbol{\vartheta}; \theta_{\text{div}})$ denotes the normalised angular pattern of one emitter, the composite transmitted angular power distribution is

$$\mathcal{P}_{\text{tx}}(\boldsymbol{\vartheta}, t) = \sum_{i=1}^N P_{t,i}(t) g(\boldsymbol{\vartheta} - \beta_i(t); \theta_{\text{div}}). \quad (5)$$

The constituent emitters are assumed mutually incoherent, so their received powers, rather than their optical fields, add.

2.3 Operational state model

Let $\mathcal{C}_{\text{acq}}[k]$ denote confirmed acquisition, $\mathcal{L}[k]$ loss of track, and $\mathcal{C}_{\text{rec}}[k]$ confirmed recovery at discrete control epoch k . The terminal state evolves according to^{4,5,8}

$$\mathcal{S}[k+1] = \begin{cases} \text{TRK/DATA}, & \mathcal{S}[k] = \text{ACQ}, \ \mathcal{C}_{\text{acq}}[k] = 1, \\ \text{REC}, & \mathcal{S}[k] = \text{TRK/DATA}, \ \mathcal{L}[k] = 1, \\ \text{TRK/DATA}, & \mathcal{S}[k] = \text{REC}, \ \mathcal{C}_{\text{rec}}[k] = 1, \\ \text{ACQ}, & \mathcal{S}[k] = \text{REC}, \ k - k_L > K_{\text{rec}}, \\ \mathcal{S}[k], & \text{otherwise}, \end{cases} \quad (6)$$

where k_L is the loss-of-track epoch and K_{rec} is the allowed recovery window. In acquisition, terminal $\mathcal{T}_A$ acts as the lead terminal and its FSM scans the rigid topology while $\mathcal{T}_B$ tests $\mathcal{C}_{\text{acq}}$. After confirmation, B estimates the incident AoA and transmits an optical response towards A; detection of this response closes the reciprocal tracking loops and initiates simultaneous tracking and data transfer. If lock is lost, recovery is performed around the last valid command $\mathbf{s}[k_L - 1]$. Failure to confirm recovery within K_{rec} returns the terminal to full acquisition. The power-threshold events associated with acquisition, loss of track, and recovery are quantified in Sec. 3.

2.4 Joint QAPD reception and FSM feedback

Let $P_{r,q}(t)$ be the optical power incident on QAPD quadrant $q \in \{1, 2, 3, 4\}$. Its current is modelled as

$$i_q(t) = \mathcal{R}_{\text{APD}} P_{r,q}(t) + n_q(t), \quad (7)$$

where $\mathcal{R}_{\text{APD}}$ is the effective APD responsivity, including multiplication gain, and $n_q(t)$ represents the aggregate receiver noise. The sum statistic and normalised angular observables are

$$i_{\Sigma}(t) = \sum_{q=1}^4 i_q(t), \quad (8)$$

$$u_x(t) = \frac{i_R(t) - i_L(t)}{i_{\Sigma}(t)}, \quad u_y(t) = \frac{i_T(t) - i_B(t)}{i_{\Sigma}(t)}, \quad (9)$$

$$\hat{\alpha}(t) = \mathbf{K}_Q [u_x(t) \quad u_y(t)]^T. \quad (10)$$

Here, $u_x(t)$ and $u_y(t)$ are the normalised differential outputs along the x and y axes, respectively, and $\hat{\alpha}(t)$ is the estimated AoA vector. where i_R , i_L , i_T , and i_B are the right, left, top, and bottom two-quadrant sums, respectively, and $\mathbf{K}_Q$ is the calibrated angular-response matrix. For bit interval T_b , an integrate-and-threshold OOK detector can be written as

$$z_j = \int_{jT_b}^{(j+1)T_b} i_{\Sigma}(t) dt, \quad \hat{b}_j = \begin{cases} 1, & z_j \geq \gamma_{\text{OOK}}, \\ 0, & z_j < \gamma_{\text{OOK}}, \end{cases} \quad (11)$$

Here, j is the bit index, z_j is the integrated sum-current statistic for bit interval j , and $\hat{b}_j$ is the detected bit. where γ_{OOK} is the receiver decision threshold. The use of quadrant-detector sums and differences for simultaneous tracking and data reception is supported by prior receiver studies.^{16,17} A sampled local FSM controller compensates the estimated AoA according to^{4,15}

$$\mathbf{s}_{k+1} = \mathbf{s}_k - \mathbf{K}_{\text{FSM}} \hat{\alpha}_k, \quad (12)$$

Here, k is the control-epoch index, $\mathbf{s}_k$ is the FSM steering command at epoch k , $\hat{\alpha}_k$ is the corresponding sampled AoA estimate, and $\mathbf{K}_{\text{FSM}}$ is the FSM controller-gain matrix. where the sign convention and controller gains are fixed by terminal calibration. The FSM acts on the local outgoing pattern through Eq. (2); it does not alter the QAPD measurement itself. Equations (8)–(12) therefore formalise the joint use of one detector for data recovery and closed-loop angular tracking.

3. MULTIBEAM PERFORMANCE MODEL

3.1 Received active-area power

At link range R , the $1/e^2$ beam radius associated with the full-angle divergence is

$$w(R) = R \tan\left(\frac{\theta_{\text{div}}}{2}\right). \quad (13)$$

For a Gaussian beam and a receive aperture that is small relative to $w(R)$, the active QAPD power is approximated by the aperture area multiplied by the irradiance at its centre, consistent with standard pointing-loss models for optical inter-satellite links.^{1,2}

$$P_{\text{act}}(t) = C(\theta_{\text{div}}) \sum_{i=1}^N P_{t,i}(t) \exp\left[-2 \left(\frac{\rho_i(t)}{w(R)}\right)^2\right], \quad (14)$$

$$C(\theta_{\text{div}}) = \frac{2A_r \eta_{\text{tx}} \eta_{\text{rx}} \eta_{\text{act}}}{\pi w^2(R)}, \quad \rho_i(t) = R \tan(\|\mathbf{e}(t) - \mathbf{s}(t) - \boldsymbol{\delta}_i\|_2), \quad (15)$$

where A_r is the aperture area, η_{tx} and η_{rx} represent fixed optical efficiencies, and η_{act} is the QAPD active-area efficiency. Equation (14) preserves the fixed total transmitted power in every state and explicitly accounts for overlap between constituent beams.

3.2 Acquisition model

The initial two-axis coarse-pointing error is modelled as²

$$\mathbf{e}_0 \sim \mathcal{N}(\mathbf{0}, \sigma_0^2 \mathbf{I}_2), \quad r_0 = \|\mathbf{e}_0\|_2 \sim \text{Rayleigh}(\sigma_0). \quad (16)$$

Consequently, a circular field of uncertainty (FOU) with scan radius R_s contains the initial line of sight with probability

$$P_{\text{FOU}} = \Pr(r_0 \leq R_s) = 1 - \exp\left(-\frac{R_s^2}{2\sigma_0^2}\right). \quad (17)$$

The coarse-error and scan-radius scale are informed by compact laser-communication terminals such as CLICK and by inter-CubeSat acquisition studies, while closed-loop pointing values are informed by systems such as TBIRD.^{3,4,7} These values are used here as literature-informed design assumptions rather than hardware requirements.

The common FSM follows a repeated outward/inward Archimedean scan.^{5,7} Defining a monotonic normalised path variable $u = u(t) \in [0, 2]$,

$$q(u) = 1 - |\text{mod}(u, 2) - 1|, \quad r_s(u) = r_{\min} + (R_s - r_{\min})q(u), \quad (18)$$

$$\psi(u) = \psi_0 + 2\pi N_{\text{turn}}u, \quad \mathbf{s}(u) = r_s(u) [\cos \psi(u) \quad \sin \psi(u)]^T. \quad (19)$$

The time parameterisation is limited by the FSM amplitude-frequency envelope. The residual angular rate and pointing jitter are represented by first-order Gauss-Markov processes,

$$\mathbf{v}_{k+1} = a_v \mathbf{v}_k + \sigma_v \sqrt{1 - a_v^2} \boldsymbol{\xi}_k, \quad a_v = e^{-\Delta t / \tau_v}, \quad (20)$$

$$\mathbf{j}_{k+1} = a_j \mathbf{j}_k + \boldsymbol{\zeta}_k, \quad a_j = e^{-\Delta t / \tau_j}, \quad (21)$$

$$\mathbf{e}_{k+1} = \mathbf{e}_k + \Delta t \mathbf{v}_k + \mathbf{j}_{k+1} - \mathbf{j}_k, \quad (22)$$

where $\boldsymbol{\xi}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_2)$ and the innovation covariance of $\boldsymbol{\zeta}_k$ fixes the specified stationary jitter.

Acquisition is confirmed only if the active-area power remains above the acquisition threshold for a continuous confirmation interval:

$$t_{\text{conf}} = \inf \left\{ t : \min_{\tau \in [t - T_{\text{con}}, t]} P_{\text{act}}(\tau) \geq P_{\text{acq}} \right\}. \quad (23)$$

With a reliable optical acknowledgment (ACK), the lead transmitter stops at

$$T_{\text{acq}} = t_{\text{conf}} + \frac{2R}{c} + T_{\text{proc}}, \quad (24)$$

where t_{conf} is referenced to the corresponding emission epoch. The two reported metrics are

$$P_{\text{acq},s} = \Pr(T_{\text{acq}} \leq T_{\text{max}}), \quad \bar{T}_{\text{acq}} = \mathbb{E}[T_{\text{acq}} \mid T_{\text{acq}} \leq T_{\text{max}}]. \quad (25)$$

3.3 Communication outage

During tracking/data operation, one beam carries the entire terminal power. For independent zero-mean Gaussian pointing errors with standard deviation σ_c per axis, the radial error is Rayleigh distributed.^{1,2} Let

$$P_0 = C(\theta_{\text{div}})P_t \quad (26)$$

denote the on-axis active-area power. If $P_0 > P_{\text{com}}$, the angular radius at which the received power equals the OOK communication threshold is

$$r_{\text{com}} = \tan^{-1} \left[\tan\left(\frac{\theta_{\text{div}}}{2}\right) \sqrt{\frac{1}{2} \ln\left(\frac{P_0}{P_{\text{com}}}\right)} \right]. \quad (27)$$

The communication-outage probability is therefore

$$P_{\text{out}} = \begin{cases} \exp[-r_{\text{com}}^2 / (2\sigma_c^2)], & P_0 > P_{\text{com}}, \\ 1, & P_0 \leq P_{\text{com}}. \end{cases} \quad (28)$$

This expression exposes the divergence trade-off: a narrow beam gives high on-axis power but greater sensitivity to angular error, whereas an excessively wide beam becomes power limited.

3.4 Conditional fast recovery and design selection

For $P_0 > P_{\text{tr}}$, the radial loss-of-track boundary for the full-power central beam is

$$r_{\text{tr}} = \tan^{-1} \left[\tan \left(\frac{\theta_{\text{div}}}{2} \right) \sqrt{\frac{1}{2} \ln \left(\frac{P_0}{P_{\text{tr}}} \right)} \right], \quad \mathcal{L} = \{\|e\|_2 > r_{\text{tr}}\}. \quad (29)$$

Before restarting the full acquisition scan, the terminal performs one recovery attempt around the last FSM command. For $N \geq 4$, Eq. (1) is reactivated and the total power is divided equally. For the single-beam baseline, the beam is repointed once by angular distance d in a uniformly random direction. Hence, the recovery offsets are

$$\delta_i^{(\text{rec})} = \begin{cases} d[\cos \Phi, \sin \Phi]^\top, & \Phi \sim \mathcal{U}[0, 2\pi), \quad N = 1, \quad i = 1, \\ \delta_i, & N \geq 4, \quad i = 1, \dots, N. \end{cases} \quad (30)$$

The recovery power for angular error e is

$$P_{\text{rec}}(e) = \frac{C(\theta_{\text{div}})P_t}{N} \sum_{i=1}^N \exp \left[-2 \left(\frac{R \tan \|e - \delta_i^{(\text{rec})}\|_2}{w(R)} \right)^2 \right]. \quad (31)$$

The conditional fast-recovery probability is

$$P_{\text{FR}} = \Pr(P_{\text{rec}} \geq P_{\text{tr}} \mid \mathcal{L}). \quad (32)$$

If the recovery error has per-axis deviation σ_r , this probability is equivalently

$$P_{\text{FR}} = \frac{1}{2\pi} \int_{r_{\text{tr}}}^{\infty} \int_0^{2\pi} \mathbb{I}\{P_{\text{rec}}(r, \varphi) \geq P_{\text{tr}}\} f_{r|r>r_{\text{tr}}}(r) d\varphi dr, \quad (33)$$

$$f_{r|r>r_{\text{tr}}}(r) = \frac{r}{\sigma_r^2} \exp \left[-\frac{r^2 - r_{\text{tr}}^2}{2\sigma_r^2} \right]. \quad (34)$$

If recovery succeeds, tracking/data operation resumes; otherwise, the state machine returns to acquisition.

The design variables are the integer beam count and the static divergence. In the absence of arbitrary scalar weights, they are selected as

$$N^* = \min \{N : \exists \theta_{\text{div}} \text{ satisfying the chosen bounds on } P_{\text{acq,s}}, \bar{T}_{\text{acq}}, P_{\text{out}}, P_{\text{FR}}\}. \quad (35)$$

The numerical results are therefore interpreted as a Pareto trade-off, and the lowest beam count that performs well in all three phases is retained.

4. SIMULATION RESULTS AND DISCUSSION

Table 1 lists the numerical parameters used for the reported results. The QAPD is modelled generically through active-area power thresholds. The First Sensor QA4000-9 is cited only as a representative quadrant-APD candidate;¹⁸ the thresholds in Table 1 are receiver-level design inputs and are not manufacturer sensitivity specifications. The detector data sheet specifies its main near-infrared performance up to 910 nm; consequently, operation at 940 nm requires separate device characterisation. The link and pointing parameters are literature-informed assumptions consistent with compact optical terminals and acquisition studies,^{3,4,7} rather than requirements copied from those missions.

For $R_s = 4\sigma_0$, Eq. (17) gives $P_{\text{FOU}} = 1 - e^{-8} = 99.966\%$. Acquisition is evaluated with common random target trajectories for all optical candidates, so differences between beam counts and divergences are not caused by different Monte Carlo realisations.

Figure 2(a) shows the conditional mean acquisition time. The single beam improves gradually as the divergence increases and reaches its broad minimum near 350–400 μrad . In contrast, the multibeam topologies achieve

Table 1. Simulation parameters. Angular standard deviations and angular-rate statistics are specified per axis.

Parameter	Value	Use or definition
Wavelength, λ	940 nm	All operating phases
Link range, R	1000 km	Inter-satellite link
Total optical power, P_t	1 W	Before transmitter loss
Receive-aperture diameter	60 mm	Clear aperture
Additional Tx/Rx losses	1 and 4.0103 dB	Fixed optical losses
Active-area efficiency, η_{act}	0.8	Applied in all phases
Beam profile/order	Gaussian, $m = 1$	$1/e^2$ intensity convention
Full-angle divergence sweep	50:25:500 μrad	Static candidate designs
Topology spacing	$d = 0.5\theta_{\text{div}}$	Centre-to-ring separation
Acquisition/recovery allocation	$P_{t,i} = P_t/N$	Equal power among active beams
Tracking/data allocation	$P_{t,i^*} = P_t$; $P_{t,i} = 0$, $i \neq i^*$	Full power on selected beam
Initial coarse error, σ_0	1.5 mrad	Gaussian uncertainty
Scan radius, R_s	0–6 mrad	$P_{\text{FOU}} = 99.966\%$
Maximum FSM scan frequency	20 Hz	Amplitude dependent
Confirmation interval, T_{con}	1.5 ms	Continuous exceedance
Acquisition timeout, T_{max}	20 s	Success horizon
Independent acquisition runs	10^5 per case	Monte Carlo evaluation
Data rate/modulation	100 Mbit/s, OOK	Tracking/data state
OOK threshold, P_{com}	26.30 nW	Active QAPD power
Communication pointing deviation	15, 20, 25, 30 μrad	Outage sweep
Tracking/recovery threshold, P_{tr}	5 nW	Loss/recovery event

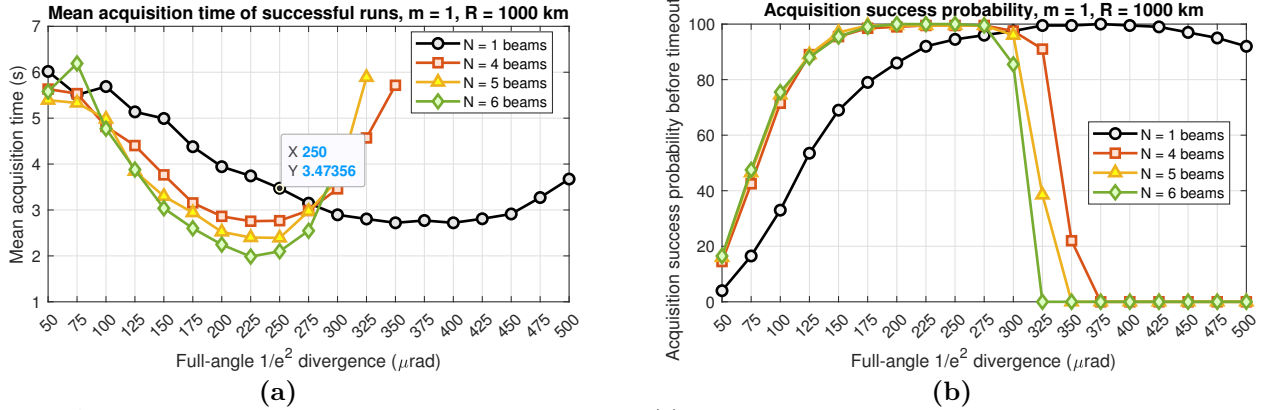


Figure 2. Acquisition performance versus full-angle divergence: (a) mean transmitter-stop time conditioned on successful acquisition; (b) probability of confirmed acquisition before the timeout. The total transmit power is divided equally among the active beams, and each point in (b) is obtained from 10^5 independent runs.

their shortest acquisition times at substantially smaller divergences. At 175 μrad , the five-beam topology gives approximately 2.94 s, compared with 4.38 s for one beam and 3.15 s for four beams. Six beams reduce this value to about 2.60 s. The abrupt termination of the multibeam curves at large divergence is power limited: equal division of a fixed P_t eventually prevents the summed received power from satisfying the acquisition threshold.

The corresponding success probability is shown in Fig. 2(b). For $N = 4, 5$, and 6 , the probability approaches 100% between approximately 175 and 275 μrad , whereas the single-beam topology needs a wider beam to achieve comparable coverage. At 175 μrad , the probabilities are approximately 79%, 98.5%, 99.5%, and 99% for $N = 1, 4, 5$, and 6 , respectively. Above the useful multibeam interval, success collapses rapidly because of the per-beam power penalty. Thus, the divergence that favours single-beam acquisition is far from the range favoured by high-power tracking/data operation.

Figure 3(a) quantifies the second side of this conflict. For each pointing-error standard deviation, the outage probability is U-shaped until the link becomes power limited. At 175 μrad , P_{out} is approximately 4.4×10^{-4} ,

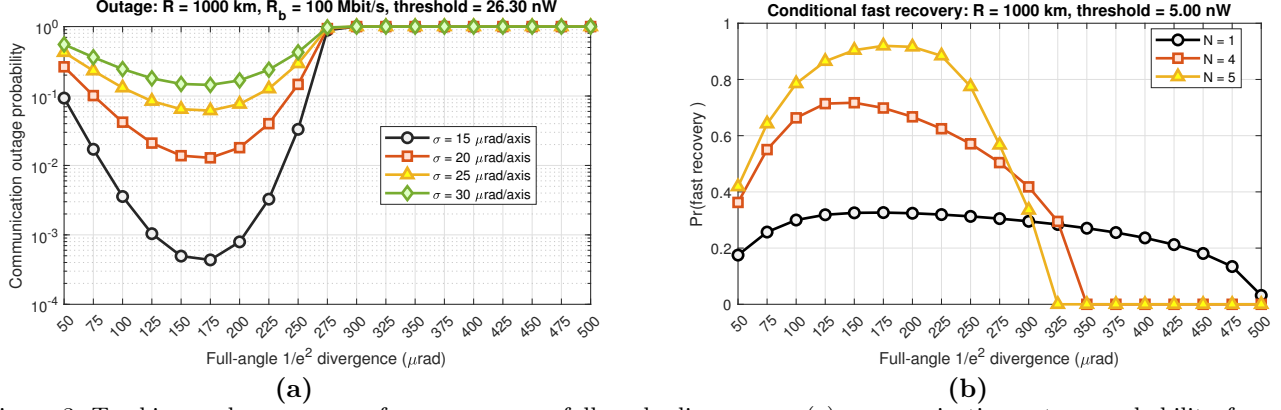


Figure 3. Tracking and recovery performance versus full-angle divergence: (a) communication-outage probability for a full-power selected beam at 100 Mbit/s OOK; (b) conditional fast-recovery probability after loss of the central tracking beam. The pointing-error standard deviation in (a) is specified per axis.

1.3×10^{-2} , 6.2×10^{-2} , and 0.144 for $\sigma_c = 15, 20, 25$, and $30 \mu\text{rad}/\text{axis}$, respectively. Once the divergence reaches approximately $275 \mu\text{rad}$, the on-axis active power is itself insufficient for the 100-Mbit/s OOK threshold and outage becomes unity. Hence, the broad single-beam acquisition optimum near $350\text{--}400 \mu\text{rad}$ cannot support the required data link.

The conditional one-step recovery results in Fig. 3(b) provide the decisive beam-count comparison. A random single-beam repointing reaches only about 0.33 at its maximum. Four beams improve the maximum to about 0.72, but five beams exceed 0.9 around $150\text{--}200 \mu\text{rad}$ because their fixed central-plus-ring topology provides greater angular diversity. At $175 \mu\text{rad}$, the respective recovery probabilities are approximately 0.326, 0.698, and 0.920. Recovery again vanishes at large divergence when the per-beam peak power falls below the tracking threshold.

Taken together, the results show that one fixed single beam cannot simultaneously retain the divergence preferred by acquisition, low-outage data transmission, and fast recovery. Among the topologies evaluated in all three phases, $N = 5$ is the smallest beam count that combines near-unity acquisition success with conditional recovery above 0.9 in the same low-outage region. A full-angle divergence near $175 \mu\text{rad}$ is therefore selected as the strongest figure-supported static design point for the 1000-km, 100-Mbit/s link. It lies near the five-beam recovery maximum, retains approximately 99.5% acquisition success, and avoids the severe communication-outage increase at larger divergences. Values around $200\text{--}225 \mu\text{rad}$ offer shorter conditional acquisition time but trade away recovery probability and outage margin. This point is a phase-consistent multi-criteria choice, not a unique unconstrained optimum. Since six-beam recovery was not evaluated, no recovery-based comparison with $N = 6$ is claimed.

5. CONCLUSION

This paper developed an end-to-end model for acquisition, tracking/data transmission, and fast recovery using a fixed laser-array topology. The same wavelength, full-angle divergence, and relative beam offsets are retained in all phases. The total power is shared equally across the array during acquisition and recovery and is transferred to the selected beam during tracking/data; a common FSM steers the complete topology and one QAPD supplies the angular and OOK observables. The resulting framework connects stochastic scan dynamics and confirmed acquisition with Gaussian pointing loss, communication outage, and recovery conditioned on loss of track.

For the simulated 1000 km, 100 Mbit/s link, the five-beam topology at $175 \mu\text{rad}$ full-angle divergence provides a conditional mean acquisition time of about 2.94 s, 99.5% acquisition success, and 0.920 conditional one-step recovery probability. The corresponding single-beam values are about 4.38 s, 79%, and 0.326. The five-beam point also retains an outage probability of 4.4×10^{-4} at a $15 \mu\text{rad}$ per-axis communication pointing deviation. Thus, among the topologies evaluated in all three phases, five beams are the smallest count that simultaneously provides high acquisition success, low outage in the stated pointing regime, and recovery probability above 0.9.

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