QAI for QFT based Communication framework-Notes

We have QFT that is a great new paradigm for the new age communications. However it has various cavets, doubts and non so clear or very difficult to understand equation based systems design challenges. This is something that our proposed framework tries to address.

There are various theories and hypothesis related to space-time, quantum particles, quantum fields, and some of these are also related to black hole theory, Hawking radiation, worm hole teleportation, quantum gravity etc

Quantum field theory explains particle interactions by treating particles not as discrete units but as energy excitations, or "field quanta,". Quantum field theory (QFT) is a theoretical framework that combines field theory and the principle of relativity with ideas behind quantum mechanics.

QFT encompasses various fundamental forces, with quantum electrodynamics (QED) governing electromagnetic interactions, and quantum chromodynamics (QCD) addressing the strong interactions among quarks and gluons, which come together to form hadrons.

QFT is related to Quantum Chromodynamics (QCD) which is a specific type of Quantum Field Theory (QFT) that describes the strong nuclear force and the interactions between quarks and gluons. QCD is one of its fundamental applications, alongside others like Quantum Electrodynamics (QED). QFT is the broad theory; QCD is an important and successful example of that theory in action, explaining the fundamental forces that hold atomic nuclei together

We also have various master equations related to the QFT and the practical field equations of the QCD. So there are various derivations, map from the theory to the practical master equations

https://www.ebsco.com/research-starters/physics/quantum-field-theory

A notable subtype of QFT is conformal field theory (CFT), which is scale-invariant and exclusively supports massless excitations.

Because fields are continuous, they have an effectively infinite number of degrees of freedom. Moreover, quantum fields can support any number of particles. One way to avoid dealing with these infinities is **renormalization**. This involves "integrating out," or removing from consideration, any parameters that do not apply to the length and energy scales being studied. Renormalization allows for the creation of an effective field theory, which is an approximation of a field theory that holds true for the lengths and energies of interest. . Because the equation is linear, any combination of linear solutions is also a linear solution of the appropriate wave equation. The entire range of linear solutions to a particular wave equation represents the field corresponding to that wave equation.

As yet, there is no complete quantum field theory describing gravity. A model has been proposed, but it relies on hypothetical particles called gravitons, the existence of which has yet to be confirmed.

There are practical tools like the Feynman path integral, that help in solving and finding the best path of the particle signal transmitted and movement from a starting point to an end point

https://forumscience.com/the-5-plet-a-new-particle-that-could-rewrite-physics-and-explain-dark-matter/

Topological Quantum Field Theory (TQFT) relates to Hawking radiation primarily through the study of the topology of black hole horizons and the use of topological invariants to classify these horizons. In theories like string theory, where higher-dimensional black holes or black rings can have complex topologies, TQFT provides tools like the Euler characteristic to study the structure of these horizons.

Understanding various types of space time invariants/gauges, various types of quantum fields due to generation of different types of particles (fermions, bosons, anyons, neutrinos, positron etc) based on energy emission, absorption, decay and noise etc is very useful in understanding quantum mechanics that we see in our lab environments. More over we have dark energy and matter, quantum gravity that needs to be accounted into our existing master equations. Topological anyons offer noise immunity that is interesting to understand and that may be related to Hawking radiation of the black hole theory.

Here is an interesting research in the area of grand unified theory. The Topological Unified Field Theory (TUFT) is a theoretical framework proposed by Jenny Lorraine Nielsen that attempts to unify all fundamental forces of nature—including gravity—within a single mathematical structure using complex topology. It does so by describing spacetime and all fundamental particles and forces as an emergent phenomenon of the geometry and topology of a complex Hopf fibration, paper link: https://philarchive.org/rec/NIETTU

At our startup we plan to leverage your skills in these areas and allow us to help clients in modernizing the classical communication systems, devices, transmitters, receivers, encoders/ decoders, modulators, demodulators, use of quantum protocols or hybrid mode of communications.

This framework will be like a playground trial-and error development using various innovative agile methods, brainstorming, getting the pieces of theories and equations together and referring to GenAI tools like Agents, prompts to refine and get final conclusions

QAI principles, hybrid circuits, algorithms are to be applied and used as done with other in house products. Now this is focused on communication, repeater station devices, distillation of signals, quantum internet, satellite communication, space communication, quantum sensors, quantum radar, military and defense purpose dual purpose build products, antennas, quantum qubit reservoirs, emitters quantum channels, quantum cryptography, quantum key distribution, etc. Also there is a need of various helper AI Agents, for offloading real time tasks like identification, key generation, ciphers etc. Various Radio area NW (RAN) protocols, support for quantum cellular communication, that can scale from one lab to external labs or far off areas in terms of LAN, MAN, WAN topologies that can be connected in various configurations like star, ring, bus, mesh etc.

Various industry standards from NIST, IEEE, ANSI, Cyber Physical systems, Cyber security, RAN, cellular security protocols, etc that needs to be used for hybrid RAN design where say there I a need of side by classical channel for verification purpose.

QAI can help in this newer paradigm design and technology improvement by leveraging the intelligent AI agents and speed of computation and operations using quantum qubits and principles like entanglement and superposition. Our startup products like QAI Processor, OS, Data center etc all can be made use of when designing this newer framework.

We need to accommodate various emerging theories, need placeholders for various configurations, ansatz, templates for different communication modes, use cases, and based on allotted frequency channels, secret keys, hardware modules etc. So we need various types of adoptive and field configurable systems that can adopt to user needs, options, and configure a slice of the equipments, hardware, virtual slice of QAI assets, network etc that can be dedicated or shared based on the type of setup. Also we need software configured asset provisioning that will allow intelligent agents to handle to on boarding, authentication, allocation and deployment of the user's account and related assets. We also need some setup to leverage the old systems like 5G and new spectrum like 6G that will be optional plugins to the core system.

All of these can be placed across our Enterprise onion framework in various layers that you recently generated for us.

Details:

1 Executive Summary

Your QAI–QFT Communication Framework reimagines communications by treating information as excitations of quantum fields and applying Quantum Field Theory (QFT) and Topological QFT (TQFT) concepts to design hybrid classical–quantum communications. The framework couples these physics concepts with the startup's QAI stack — **QAI Processor, QAI OS, QAI Datacenter, QAI Ops, QAI Repeater appliances and QAI Agents** — to enable modular, stageable, and deployable systems for QKD, satellite and space links, quantum-enhanced sensing, and secure RAN slices in 5G/6G.

Goals:

- Provide practical engineering mappings from QFT concepts (QED, CFT, TQFT) to devices: modulators, transducers, quantum memories, repeaters, detectors.
- Enable adaptive, agent-driven orchestration for real-time channel estimation, encoding selection, entanglement management, and key lifecycle.
- Offer staged experimental path (lab → repeater chain → network emulation → field trials) with reproducible telemetry, IP strategy, and compliance guidance.

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2 High-Level Architecture (Layered Flow)

A short description of the flow (client → encoding → channel/repeater → decoding → post-processing). The components are orchestrated by **QAI OS & Orchestrator** and supervised by QAI Agents; telemetry and simulation run in the QAI Datacenter.

- **Client Apps / User**: request RAN slice & secure comm service.
- **QAI OS & Orchestrator**: provisioning, attestation, slice policy, agent interface.
- **Encoding Module**: DOFs (polarization, phase, time-bin, frequency, OAM, topological), AI encoder (ReLU NN), QFT processing (DSP / QFT), modulators & transmitters.
- **Quantum Channel**: fiber or free-space path + classical verification side-channel. Channel Estimator Agent provides noise/decoherence mapping.
- **Repeater Node**: quantum memory, heralding, entanglement swapping, distillation/purification, local agent (Entanglement Manager).
- **Decoding Module**: detectors (SNSPD, APD, homodyne), mode analyzers, basis selection, Fault/Anomaly Agent.
- **Post-Processing & Key Management**: error correction (LDPC, Cascade), privacy amplification, secure key vaults & HSM integration.

(A detailed ASCII/text diagram is included later in the document.)

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3 QAI RAN — Core Functions & Policies

Core functions

- Hybrid access plane: supports classical payloads and quantum-mode payloads in same slice.
- Orchestration plane: QAI OS & QAI Ops manage quantum/classical resource slicing, compliance checks, experiment registries.
- Control plane: agents provide real-time decisions (encoding, switching, distillation).
- Verification plane: mandatory classical verification side-channel for security and attestation.

RAN policies

- Every quantum session must register a classical verification fallback.
- Slices track quantum resource tokens (entanglement credits, memory slots).
- Define Q-URLLC (quantum URLLC) classes with coherence budgets and latency SLAs.

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4 Product Portfolio & Technology Stack

Product verticals

- **QAI Processor**: hybrid QPU + classical accelerators for variational solvers, tensor contractions, QFT/DSP, and ML inference.
- **QAI OS**: slice management, secure device drivers for modulators, detectors, transducers; agent runtime.
- **QAI Datacenter**: multi-fidelity simulation (PDE, tensor-network, surrogate ML), telemetry lake.
- **Quantum Repeater Appliance**: hybrid repeater with quantum memory, distillation policies and FPGA controller.
- **QAI Edge Module**: transducer + local agent for low-latency control and sensor fusion.
- **Agents Platform**: catalog of reusable agents, policy registry, A/B experiment support.

Technology stack (summary)

- Hardware: photonic waveguides, superconducting circuits, trapped ions, topological qubits, cryo systems, modulators (EOM/AOM), SNSPDs.
- Runtime: QAI OS (containerized slices), secure attestation, device drivers.
- Compute: QPUs (as available), GPUs/TPUs, ASICs for FFT & tensor ops.
- Simulation: FEA EM solvers, Lindblad/density-matrix solvers (QuTiP), tensor-network libs.
- ML/QAI: PyTorch/TensorFlow, RL agents, surrogate models.
- Orchestration: QAI Ops, instrumentation & provenance (experiment registry).
- Security: QKD primitives, classical side-channel verification, HSMs for key storage.

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5 QAI Agents Roster & Responsibilities

Agent	Role	Inputs	Outputs
Channel Estimator	Online channel & noise model inference	Probe telemetry, pilot pulses	Noise estimates, turbidity, SNR maps
Adaptive Modulator	Select encoding & modulation parameters	Channel estimates, policies	Modulator configs (EOM drive, phase settings)
Entanglement Manager	Repeater orchestration, distillation scheduling	Memory state, link fidelity	Swap/distill commands, thresholds
Key Management	QKD orchestration & key lifecycle	Entanglement/key rates, QBER	Session keys, rotation, attestations
Fault/Anomaly	Hardware & attack detection	Telemetry, spectral anomalies	Quarantine commands, rollback actions

Agent	Role	Inputs	Outputs
Detector			
Provisioning Agent	Slice on-boarding, compliance	User request, inventory	Resource allocation, device attestation

Agents are versioned, policy-driven, and orchestrated via QAI Ops for reproducibility and audit.

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6 Protocols, Encodings & DOF Mapping

Common protocols

- **DV QKD** (BB84, entanglement-based) — polarization, time-bin or frequency-bin encodings.
- **CV QKD** (coherent/squeezed states) — quadrature encoding + homodyne detection.
- **Entanglement-swapping & Repeater protocols** — heralded entanglement, DEJMPS-style purification, distillation procedures.
- **Hybrid verification** — classical side-channel handshake & attestation for authentication.

DOF → channel suitability

- Polarization: fiber (with compensation), satellite (with tracking), sensitive to birefringence.
- Time-bin: robust for fiber and free-space when timing control is good.
- Frequency-bin: resilient to phase drift, good for multiplexing.
- OAM (spatial modes): high-dimension but sensitive to turbulence.
- Topological DOFs (anyons): high resilience to local noise — experimental & material-dependent.

DSP / QFT role

- QFT/DSP can be used to convert modes, perform spectral shaping, filtering, and discrete-QFT-based transformations for encoding/decoding. Use classical DSP chips for near-term deployments; consider QPU-accelerated QFT for research flows.

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7 TQFT & QFT-derived Theories — Features, Merits & Engineering Mapping

Topological Quantum Field Theory (TQFT)

- **Features**: topological invariants, nonlocal degrees of freedom (anyons), braiding-based logical gates.
- **Merits**: noise immunity to local perturbation, potential for lower error overhead if implemented.
- **Mapping**: prototype anyon-supporting materials (FQH, engineered superconducting lattices) → braiding controller microservices in QAI OS → agent-determined braiding schedules.

Topological Orders & Mixed-State Robustness

- **Feature**: some topological observables survive mixed-state conditions.
- **Merit**: useful for noisy or finite-temperature deployments.
- **Mapping**: add mixed-state detectors to Channel Estimator Agent.

TUFT & speculative unified proposals

- **Status**: conceptually interesting; treat as mathematical inspiration. Avoid product claims based on speculative unified theories. Use their constructs (fibrations, topology) as design inspiration only.

CFT, QED, QCD

- **QED**: primary theoretical backbone for photonic carriers and light-matter interactions — used for modeling transducers and channel interactions.
- **CFT**: useful for scale-invariant edge-mode analysis for metamaterials/topological edges.
- **QCD**: mostly mathematical analogues; not directly applicable to photonic hardware but may inspire symmetry-based encodings.

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8 EPR, ER=EPR, Hawking Radiation — Clarifications (Engineering Takeaway)

- **EPR entanglement is not a traversable wormhole** in practical lab contexts. Entanglement provides correlations and enables teleportation of quantum states but teleportation requires LOCC (local operations + classical communication). There is no FTL signaling.
- **ER=EPR** is a theoretical conjecture linking entanglement and spacetime geometry in gravity/holographic models; it is not an engineering mechanism to create space-time tunnels.
- **Hawking radiation** concerns black-hole horizons and curved spacetime quantum fields; it does not apply to ordinary quantum communication devices or repeater appliances.

Engineering implication: treat entanglement as a communication resource that requires classical coordination; do not claim wormhole-based transmission.

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9 Repeaters — Types & How Distillation Works

- **Trusted-node**: node measures and re-sends data; simple but requires trust.
- **Entanglement-swapping repeater**: create entanglement on segments, use entanglement swapping and purification to extend fidelity across distance. Requires quantum memory and heralding detectors.
- **Purification & error-correcting repeaters**: probabilistic distillation or full QEC to correct errors; more resource-heavy.

Practical Repeater Appliance

- Hybrid node: transducer + quantum memory + FPGA timing & heralding + local agents for distillation/swapping.
- Use agent policies to decide when to distill, swap, or invoke fallback.

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10 Experimental Stages, Metrics & Testbeds

Stage 0 — Lab feasibility (weeks)

- Goal: show basic encoding, detection, and channel estimation on short links.
- Setup: single fiber/waveguide; coherent/squeezed/single-photon sources; homodyne/APD detectors.
- Metrics: fidelity, SNR, photon loss, heralding rate, coherence time.

Stage 1 — Repeater tests (1–3 months)

- Goal: entanglement swapping and distillation across 2–4 nodes with quantum memory.
- Metrics: entanglement generation rate (ebit/s), distillation success probability, latency, resource overhead.

Stage 2 — Network emulation & agents (3–9 months)

- Goal: multi-node topologies, agent-led policies, integration with QAI OS.
- Metrics: network reliability, end-to-end key rates (kbit/s), resilience to adversarial noise, orchestration latency.

Recommended measurement devices

- Single-photon counters / SNSPDs, homodyne detectors, OTDR, spectrum analyzer, time-to-digital converters (TDC), oscilloscopes, cryo monitoring sensors.

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11 Sample Use Cases & Demo Ideas

1. **Metro fiber QKD**: polarization/time-bin DV QKD through telecom fiber with classical verification and trusted repeater chain.
2. **Satellite QKD**: time-bin or polarization between satellite and ground, classical side-channel for sifting and attestation.
3. **Quantum Repeater Chain**: lab demonstration of entanglement-swapping + distillation across 3 nodes.
4. **Topological R&D**: braiding experiments on candidate anyonic platforms in partnership with condensed-matter labs.
5. **Quantum-enhanced sensing**: squeezed-state radar/imaging with QAI agent selecting probe waveforms.

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12 Security, Compliance & Ethics

- Classify all use-cases for civilian vs dual-use. Conduct early legal & export-control review.
- Implement secure boot, attestation & audit trails in QAI OS for quantum nodes.
- Use classical verification side-channels to prevent misinterpretation and enable dispute resolution.
- Limit speculative claims (ER=EPR, Hawking) in sales/marketing; mark as theoretical inspiration only.

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13 IP & Patent Strategy

- Focus patents on **system-level** and engineering inventions:
  - Orchestration protocols for hybrid quantum/classical validation channels.
  - Agent-driven adaptive modulation and distillation policies.
  - Interfaces/APIs between QAI OS and transducer drivers, repeaters and memory.
  - Repeater appliance architectures and secure provisioning workflows.
- Avoid claiming pure theoretical physics as patentable subject matter. Use defensive publication for speculative theoretical ideas.

14 Risks & Mitigations

- **Decoherence & material limits** — run per-channel coherence budgets, model with Lindblad, choose encodings that fit.
- **Intractable simulations** — adopt multi-fidelity pipeline (analytic → PDE → tensor networks → surrogate ML).
- **Hardware fabrication** — partner with leading labs for prototyping; start with classical metamaterial emulation for early tests.
- **Regulatory & export-control** — early legal screening, limit dual-use exposure until clear compliance.

15 Roadmap & Priorities (12–18 months)

- **M0 (0–2 months)**: finalize carrier & DOF choice; compile threat & regulatory models.
- **M1 (2–6 months)**: Stage-0 lab demo: single link encoding + detection; QAI Agent channel estimation.
- **M2 (6–12 months)**: Build repeater prototype (1–2 nodes) with entanglement swapping & distillation.
- **M3 (12–18 months)**: Network emulation & multi-node orchestration; integrate hybrid RAN plugin (5G/6G).
- **M4 (18+ months)**: Productization: appliance hardening, IP filing, early field trials.

16 Demo & Code Summary (Colab-ready)

A Colab-ready demo was prepared that simulates the full lifecycle: initialization → encoding (AI encoder + QFT step) → transmission (channel noise including deliberate dip) → repeater distillation → decoding correction → post-processing & key generation. The demo produces:

- fidelity progression plot (dip then recovery)
- artifact JSON (experiment telemetry & results)
- mapping prints to real-world devices

Files & Paths (Colab):

- `qai_qft_fullcycle_artifact.json` — telemetry & experiment summary
- `qai_qft_fullcycle_fidelity.png` — fidelity plot

(If you need the ready-to-copy Colab cell again, include “Colab code” and I’ll paste the full runnable block.)

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17 Device / DSP / Quantum Processor Mapping (Procurement Notes)

Classical DSP / Edge devices

- Analog Devices ADSP family — embedded DSP tasks, low-latency processing.
- Texas Instruments TMS320 — telecom DSP family.
- Qualcomm Hexagon / Snapdragon NPU — low-power ML inference for edge AI encoder.
- Xilinx/AMD Versal / Intel FPGAs — deterministic timing, heralding & control logic.

Quantum / Photonic processors

- IBM Q (Qiskit) — QFT circuits & superconducting QPUs for research QFT.
- Xanadu — photonic processors oriented to CV tasks, boson sampling, photonic DSP.
- PsiQuantum & integrated photonics vendors — photonic transducers & integrated sources.
- Emerging CMOS photonics research — toward integrated transducer modules.

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18 Diagrams & Visuals (text + 2D)

ASCII/text system diagram (copy into docs):

```
[ CLIENT APP / USER ]
    |
    v
+----------------------------------------------------+
|   QAI OS & ORCHESTRATOR                            |
|   - Slice provisioning (quantum/classical)         |
|   - Security, attestation, auth                    |
|   - Protocol stack (QKD, teleportation, RAN)       |
|   - Interface to QAI Agents                        |
+----------------------------------------------------+
                |
====================================================
 STAGE: ENCODING + TRANSMISSION
```

```
=====================================================
+----------------------------------------------------+
|   ENCODING MODULE (QED/QFT based)                   |
|   - DOFs: polarization / phase / time-bin / OAM     |
|   - Modulation: coherent, squeezed, topological     |
|   - AI encoder (ReLU NN) + QFT / DSP                |
|   - QAI Agent: Adaptive Modulator                   |
+----------------------------------------------------+
                |
=====================================================
 STAGE: CHANNEL + REPEATER
=====================================================
+----------------------------------------------------+
|   QUANTUM CHANNEL (fiber/free-space)                |
|   - Medium: fiber (C-band) or optical free-space    |
|   - Classical side-channel for verification         |
|   - QAI Agent: Channel Estimator                    |
+----------------------------------------------------+
                |
+----------------------------------------------------+
|   REPEATER NODE                                     |
|   - Quantum memory, entanglement distillation       |
|   - QAI Agent: Entanglement Manager                 |
+----------------------------------------------------+
                |
=====================================================
 STAGE: DECODING + POST-PROCESSING
=====================================================
+----------------------------------------------------+
|   DECODING MODULE                                   |
|   - Photon detectors / homodyne                     |
|   - QAI Agent: Fault/Anomaly Detector               |
+----------------------------------------------------+
                |
+----------------------------------------------------+
|   POST-PROCESSING & KEY MGMT                        |
|   - Error correction, privacy amplification         |
|   - QAI Agent: Key Manager                          |
+----------------------------------------------------+
```

Additionally, a 2D visual flow (layer boxes + side boxes for Agents, Tech Stack, Errors, Use Cases) was generated earlier — include that PNG in the doc if you want a presentation visual.

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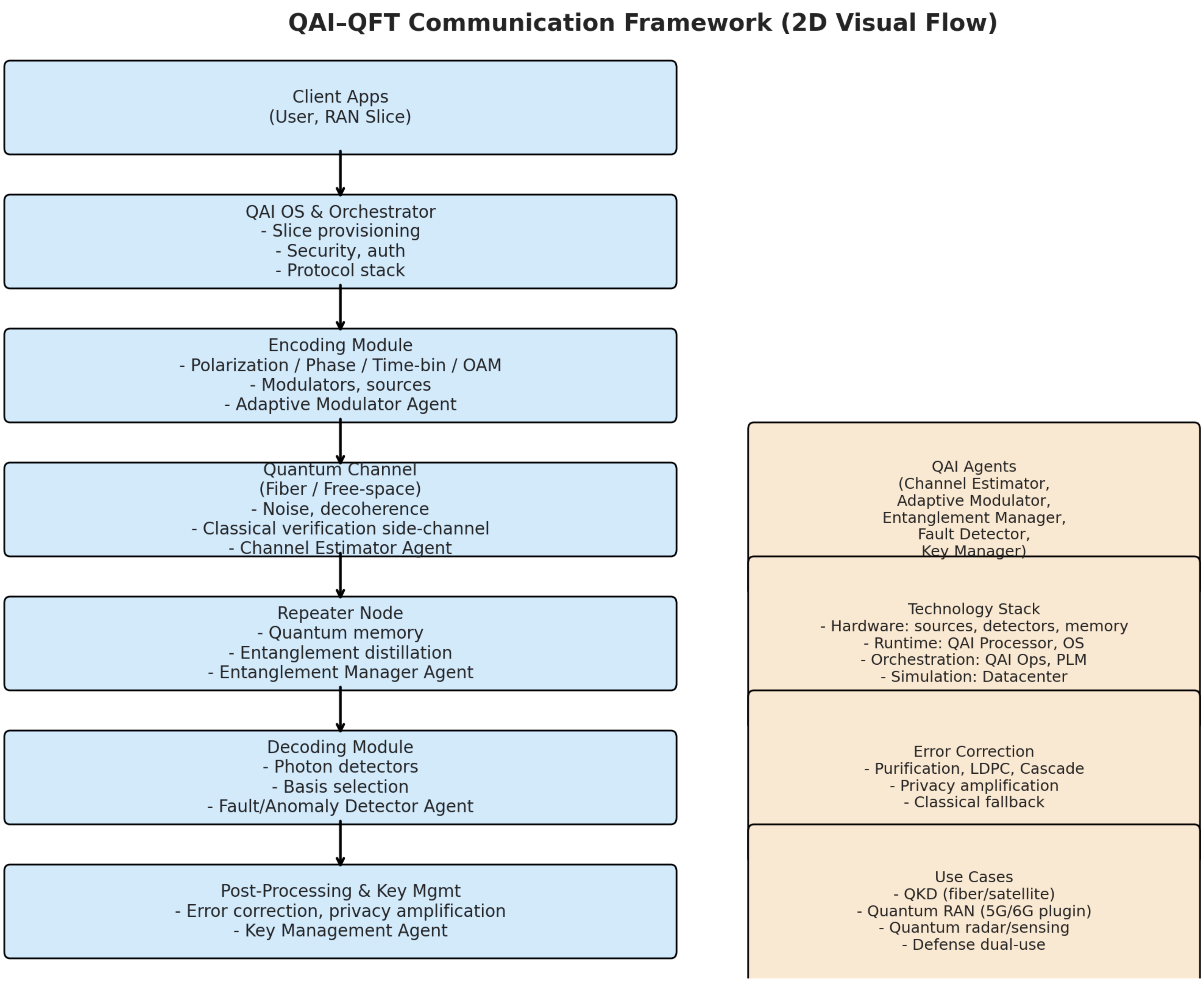
19 Appendices

A — Short checklist for Stage-0 lab

- Select carrier & DOF: e.g., C-band fiber + time-bin or polarization.
- Acquire: pulsed laser / single-photon source, EOM/AOM, SNSPD or APD, timing electronics, FPGA for heralding.
- Prepare QAI stack: QAI OS with slice config, Channel Estimator Agent, Adaptive Modulator Agent.
- Run initial experiment: measure fidelity vs distance & noise; save telemetry.

B — Quick glossary

- DV: discrete-variable quantum communication (single photons).
- CV: continuous-variable communication (quadrature encoding).
- EPR: Einstein–Podolsky–Rosen entanglement pairs.
- LOCC: local operations and classical communication.
- QFT: Quantum Fourier Transform (circuit-level) / also quantum field theory (domain context — careful with abbreviations).
- TQFT: Topological quantum field theory.


QAI–QFT Communication Framework (2D Visual Flow)
Client Apps
(User, RAN Slice)
QAI OS & Orchestrator
- Slice provisioning
- Security, auth
- Protocol stack
Encoding Module
- Polarization / Phase / Time-bin / OAM
- Modulators, sources
- Adaptive Modulator Agent
Quantum Channel
(Fiber / Free-space)
- Noise, decoherence
- Classical verification side-channel
- Channel Estimator Agent
Repeater Node
- Quantum memory
- Entanglement distillation
- Entanglement Manager Agent
Decoding Module
- Photon detectors
- Basis selection
- Fault/Anomaly Detector Agent
Post-Processing & Key Mgmt
- Error correction, privacy amplification
- Key Management Agent
QAI Agents
(Channel Estimator,
Adaptive Modulator,
Entanglement Manager,
Fault Detector,
Key Manager)
Technology Stack
- Hardware: sources, detectors, memory
- Runtime: QAI Processor, OS
- Orchestration: QAI Ops, PLM
- Simulation: Datacenter
Error Correction
- Purification, LDPC, Cascade
- Privacy amplification
- Classical fallback
Use Cases
- QKD (fiber/satellite)
- Quantum RAN (5G/6G plugin)
- Quantum radar/sensing
- Defense dual-use

```
=== INITIALIZATION ===
Slice: slice_qft_fullcycle_v3
QAI Processor: QAIProcessor-v2
QAI OS: QAIOS-QuantumSlice

=== ENCODING ===
AI encoder produced bits (sample): [1 0 1 1 1 0 1 0] len: 64
Chosen encoding: time-bin

=== TRANSMISSION ===
Fidelity after segment1 (with spike): 0.9997
End-to-end fidelity after repeater leg: 0.9996
=== DECODING ===
Measured fidelity after decoding (with correction): 0.9996
=== POST-PROCESSING & KEY MGMT ===
Raw bits len: 64 -> Final key len: 38

=== LIFECYCLE SUMMARY ===
          stage                  slice       processor encoding  f_seg1   f_end distilled  f_decoded  final_key_len
 initialization slice_qft_fullcycle_v3 QAIProcessor-v2      NaN     NaN     NaN       NaN        NaN            NaN
       encoding                    NaN             NaN time-bin     NaN     NaN       NaN        NaN            NaN
   transmission                    NaN             NaN      NaN  0.9997  0.9996     False        NaN            NaN
       decoding                    NaN             NaN      NaN     NaN     NaN       NaN     0.9996            NaN
 postprocessing                    NaN             NaN      NaN     NaN     NaN       NaN        NaN           38.0
```

For more details, email: vijaymohire@gmail.com

// End