

Exploration of Cell-free Quantum Key Distribution: the EXCEL-QKD project

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Background and Objectives

Quantum Key Distribution (QKD) provides information-theoretic security based on quantum physical principles, but conventional implementations predominantly rely on fixed, point-to-point optical links. Such architectures lack spatial redundancy and can suffer significant performance degradation under blocking, misalignment, mobility, and spatially localised attacks—limitations that are particularly relevant for indoor free-space operation [1, 2, 3, 4].

At the same time, advances in multi-pixel single-photon avalanche diode (SPAD) arrays provide spatially resolved photon detection capabilities that remain largely unexplored in QKD [5, 6]. EXCEL-QKD project, approved under the QuantERA Call 2025 [7], proposes a new cell-free QKD paradigm in which multiple spatially distributed quantum emitters cooperatively serve a common receiver equipped with a spatially resolving SPAD array [8]. Rather than relying on a single optical path, the proposed architecture exploits spatial diversity to provide redundancy against localised channel disruptions [9].

The project further introduces space–time QKD protocols, jointly exploiting the spatial origin and temporal information of detected photons, along with reconstruction algorithms capable of discriminating contributions from multiple emitters. The project has three main objectives:

- (i) to demonstrate a cell-free QKD system with coordinated multi-emitter operation;
- (ii) to develop and experimentally validate space–time QKD protocols and spatial–temporal reconstruction techniques;
- (iii) to quantify the security and robustness gains provided by spatial diversity against blocking, perturbations, and spatially localised attacks.

Methodology

The project follows a bottom-up development strategy spanning theoretical modelling, hardware and software development, system integration, and experimental validation. The proposed architecture initially considers two synchronised spatially separated emitters, with scalability toward configurations of up to four emitters. The emitters will be coordinated through a low-latency, LED-based classical signalling layer providing timing distribution, emitter selection, and handover functionality. The target configuration comprises emitters separated by 1–2 m and an indoor free-space link of 2–3 m.

Target configuration	
Synchronised emitters	2 initially; up to 4
Emitter separation	1–2 m
Indoor free-space link	2–3 m
Quantum receiver	2×2 SPAD array
Coordination	Low-latency LED-based classical signalling

The quantum receiver will employ a 2×2 SPAD array combined with dedicated optics for spatial-channel separation. Receiver development includes optical alignment, detector calibration, gating, noise characterisation, and real-time acquisition and preprocessing.

Space–Time Processing and Evaluation

On the algorithmic side, the project will develop spatial–temporal mapping and reconstruction methods for emitter identification, spatial-mode discrimination, and temporal correction in the presence of noise and cross-talk. The experimental campaign will progress from static alignment and dual-emitter operation toward controlled mobility using mechanically steered emitters [10]. The integrated system will subsequently be evaluated through measurements of secret-key rate (SKR), quantum bit error rate (QBER), spatial discrimination accuracy, processing latency, and robustness under controlled blocking, spatially localised intercept–resend attacks, and multi-path interception.

Development and evaluation path			
Theoretical modelling	→	Hardware and software development	→
		System integration	→
		Experimental validation	
Experimental progression: static alignment → dual-emitter operation → controlled mobility.			

Evaluation: SKR; QBER; spatial discrimination accuracy; processing latency; robustness under controlled blocking, spatially localised intercept–resend attacks, and multi-path interception.

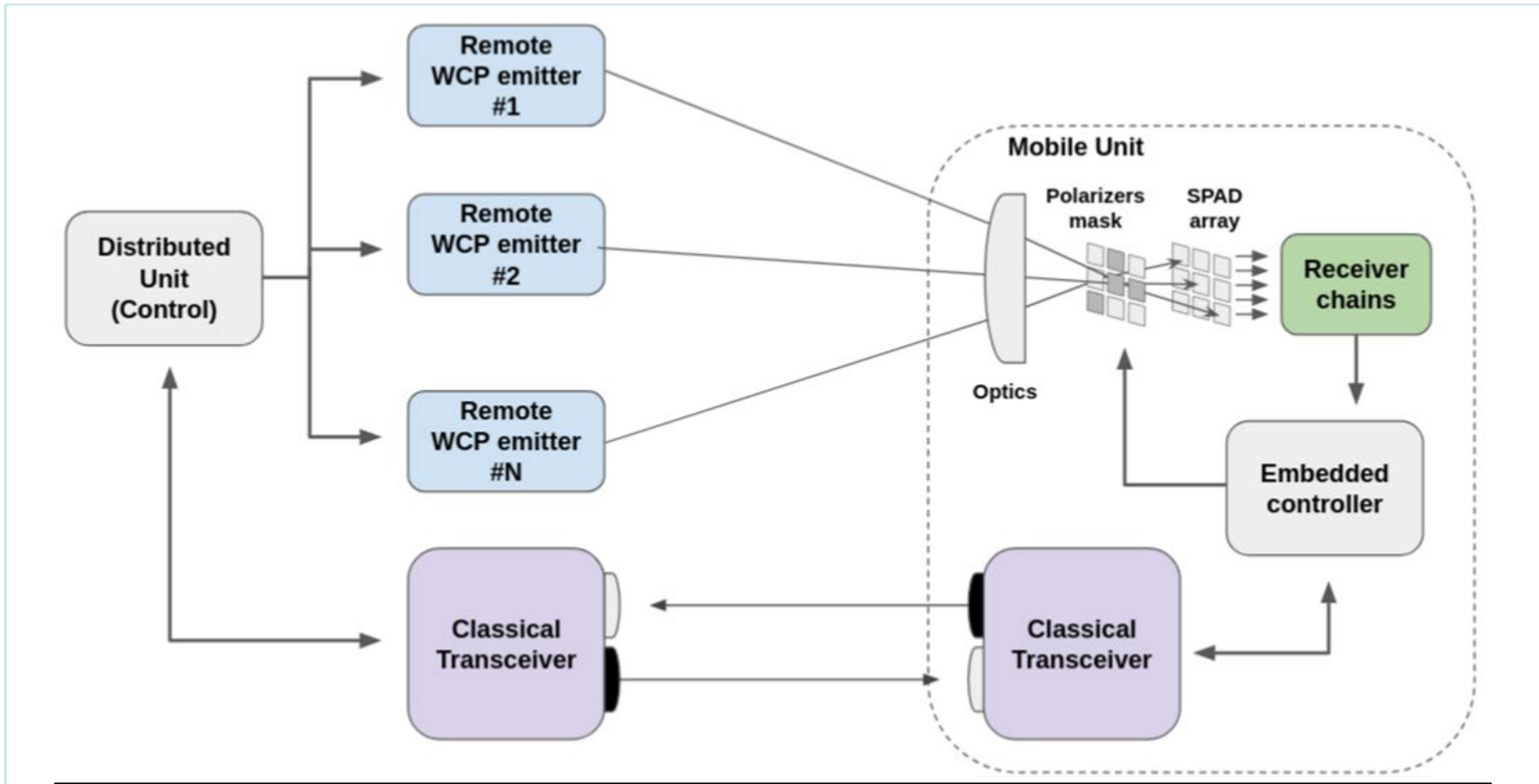


Figure 1. Conceptual EXCEL-QKD architecture: spatially distributed quantum emitters of Weak Coherent Pulses (WCP), jointly serving a spatially resolving SPAD-array receiver, with classical coordination and space–time processing.

Significance and Impact

EXCEL-QKD seeks to establish cell-free QKD as a new architectural approach to indoor quantum-secure communications, moving beyond single-emitter point-to-point links toward distributed and spatially aware quantum communication. By combining multi-emitter coordination, spatially resolved single-photon detection, space–time encoding, and spatial–temporal reconstruction, the project addresses scalability, resilience, and mobility limitations identified for conventional indoor QKD.

Expected outcomes

- first system-level proof of concept;
- reconstruction algorithms;
- synchronisation and calibration methods;
- security models;
- openly accessible datasets.

The outputs are intended to provide reusable foundations for future distributed quantum communication networks, including potential applications in industrial and IoT environments as well as future quantum-secure indoor mobility. The project combines expertise in quantum optics, SPAD-array engineering, communication theory, cryptography, and systems engineering. Its longer-term technological relevance lies in enabling distributed quantum communication architectures with dynamic emitter selection, spatial handover, and enhanced resilience to localised disruptions, contributing to future quantum-secure infrastructures and European initiatives such as EuroQCI [11].

Keywords

Quantum Key Distribution • Cell-free Quantum Communications • SPAD Arrays
Space–Time Encoding • Indoor Free-Space Optical Communications

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