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Digital Modules
Quantum Communication from the Perspective of Electrical Engineering

Quantum technologies have the potential to increase the efficiency and security of communications in network infrastructures in unprecedented ways. In order to profit maximally from this development, a dynamic and active development within the German industry is necessary, for which an intensive education and training of the involved actors is indispensable.

In the project *qp-tech.edu.ee* FAU develops a set of online learning modules. These modules will provide an introduction to Quantum Communication from the perspective of Electrical Engineering. They are specifically created for professionals from the photonic industry. The modules combine insights into quantum physics with an engineering and application perspective on quantum communication. Questions of systems integration and current challenges for photonic implementations of quantum communication and quantum cryptography will be central. Among others we will address questions such as: Which electrical engineering instruments are needed to develop functional products in the field of quantum communication? Which existing technologies are necessary to implement quantum technology-based applications? What further developments in established technologies may be needed?

The modules will be available on the project's Moodle platform: https://www.acp.uni-jena.de/qp-tech-edu. The offer is free of charge and can be accessed after registration on the platform.

Module 1	**Module 2**	**Module 3**	**Module 4**	**Module 5**
APDs for Applications in Quantum Communications	The first QKD protocol: BB84	Entanglement-based QKD protocols	High speed quantum state preparation	Single Photon Sources for Applications in Quantum Communication
Available in Dec. 2023	Available in Apr. 2024	Available in Jul. 2024	Available in Nov. 2024	Available in Jul. 2024

We welcome your questions and feedback.
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Module 1	
Title	APDs for Applications in Quantum Communications
Lecturer/ Responsible	Dr. Angela Pérez, Prof. Dr.-Ing. Bernhard Schmauss
Contents	Avalanche photodiodes (APDs) are photodetectors used in a variety of technological applications. In classical optical communications, for instance, they enable the functioning of high-speed optical receivers. Their advantage consists of converting each detected photon into a large cascade of electron-hole pairs, amplifying weak optical signals that would otherwise be covered by noise, becoming undetectable. The technology behind APDs has also enabled conventional single-photon detection in a reliable way. The expansion of optical quantum information applications, featuring Quantum Key Distribution (QKD) as its most mature innovation, has been the major driver of single-photon detector development. QKD, the most secure form of communication devised so far, benefits from the improvements made in conventional single-photon detection, through the development of single-photon avalanche diodes (SPADs). This module aims to provide a basic understanding of APDs and SPADs as an entry point to develop and deploy commercially viable solutions in the field of optical quantum communications. Technical aspects that are critical to assess their performance will be discussed in this module as well, namely: signal-to-noise ratio, detection efficiency, spectral range and ability to resolve photon number.

Module 2	
Title	The first QKD protocol: BB84
Lecturer/ Responsible	Dr. Angela Pérez, Prof. Dr. Christoph Marquardt
Contents	Quantum Key Distribution (QKD) implies the encoding and transfer of quantum states between two distant parties while guaranteeing the *information-theoretical* security of the established key. On that basis, QKD emerged as a subfield of research inside Quantum Communications. In this field various protocols are being designed with elaborate security-proofs, that employ the unique properties of quantum mechanical systems to achieve secret and authenticated communications. To date, there are in-field technical implementations of QKD prototypes all the way to first deployments of QKD in commercial contexts. This module seeks to introduce QKD using the first quantum key distribution protocol developed in 1984 by Charles Bennett and Gilles Brassard. The original BB84 protocol encodes information using two orthogonal polarization states of single photons along with two conjugate bases, such that an eigenstate in one basis corresponds to an equal superposition of both eigenstates of the other.

Module 3	
Title	Entanglement-based QKD protocols
Lecturer/ Responsible	Dr. Angela Pérez, Prof. Dr. Christoph Marquardt
Contents	Any quantum key distribution (QKD) protocol has the goal of generating a shared secret key between two distant parties over a public communication channel. It is crucial for the key generating protocol to be *provably* secure against decryption attacks. Quantum mechanics guarantees such *information-theoretical* security. The BB84 protocol has been already introduced as an example of a prepare-and-measure protocol. There is a second class of protocols, the *entanglement-based* protocols, where each of the parties hold pairs of entangled states and perform measurements on their respective subsystems to generate the raw key. These kinds of protocols require an (optical) source that provides entangled states for both parties. In this module we examine the steps involved in some of these protocol types and discuss the equivalence between prepare-and-measure protocols and entanglement-based protocols. Additionally, we mention some of the challenges that need to be overcome for wide adoption of QKD in real-life communication networks.

Module 4	
Title	High speed quantum state preparation
Lecturer/ Responsible	Dr. Angela Perez, Prof. Dr.-Ing. Bernhard Schmauss
Contents	QKD faces technical and practical challenges as loss, noise, cost, complexity, security proofs and assumptions. Finding a deployment strategy that makes a good compromise between large distance communications, high transfer rates, good QKD security proofs, robustness, compactness and reasonable costs, requires efficient sources, detectors, repeaters, protocols and error correction schemes. It is thus important to observe that the systems created are compatible with existing communication networks and standards in order to make their deployment realistic without escalating complexity, footprint and power consumption to unmanageable levels. A step forward in this direction is making serious attempts to realize QKD within the technological scope of classical communications, which has accumulated decades of experience in hardware and software development. In this module we explore the preparation of optical quantum states for its usage in QKD protocols under the point of view of electrical engineering. In order to provide optical modulation at high speeds for quantum communications at scale, engineers propose the usage of Mach Zehnder Modulators (MZMs), which play already a key role in classical communications. As the future coexistence of classical and quantum communications might rely on the possibility of achieving chip-scale photonic integration, deployment of QKD using MZMs might be a necessary step to pave the road in this direction.

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Module 5	
Title	Single Photon Sources for Applications in Quantum Communication
Lecturer/ Responsible	Prof. Dr.-Ing. Roland Nagy, Andre Pointner, M.Sc.
Contents	In this module, we will explore the fundamental concepts and technologies behind single photon sources, which are of utmost importance in current research and emerging technologies in the field of quantum communication. Understanding the behavior and statistics of single photons, harnessing their indistinguishability, and generating entanglement are key areas of study for advancing quantum communication protocols. Additionally, the development of efficient single photon sources, such as *color centers*, and the advancements in superconducting nanowire single-photon detectors (SNSPDs) are paving the way for practical implementation of secure quantum communication systems. By learning about cross-polarization detection and its role in analyzing polarization properties, you will gain insights into cutting-edge research on manipulating and utilizing photon states for enhanced quantum communication capabilities.