Research Summary

Laszlo Gyongyosi

1 Previous Work

My research interests are in the theory of quantum information and computation, quantum communications and quantum cryptography.

1.1 Theory of Quantum Computation

1.1.1 Scalable Distributed Gate-Model Quantum Computers

Gate-model quantum computers are fundamental to implement near-term quantum computer architectures and quantum devices. A scalable model for distributed gate-model quantum computers is a challenging problem. In [1], I defined a model of scalable distributed gate-model quantum computation in a near-term setting of the NISQ (noisy intermediate scale quantum) technology era. I proved that the proposed distributed gate-model quantum computers architecture can maximize an objective function of a computational problem in a distributed and scalable manner. I derived the optimal gate parameter values for a distributed setting and analyzed the impacts of decoherence on distributed objective function evaluation.

1.1.2 Circuit Depth Reduction for Gate-Model Quantum Computers

Gate-model quantum computers are essential to implement near-term quantum computer architectures and quantum devices. Since the gate noise and the economic costs of the physical layer implementations are high in practical scenarios, a reduction of these is essential. In [2], I defined a quantum algorithm for the circuit depth reduction of gate-model quantum computers. The proposed solution evaluates the reduced time complexity equivalent of a reference quantum circuit and recovers the reference output quantum state of the reference quantum circuit via quantum operations on the reduced time complexity quantum circuit. I proved the complexity of the proposed quantum algorithm and the achievable reduction in circuit depth. The algorithm provides a tractable solution to reduce both time complexity and the economic cost of implementing quantum computers.

1.1.3 Unsupervised Quantum Gate Control for Gate-Model Quantum Computers

In near-term gate-model quantum computers, the operations are performed by unitary quantum gates. The precise and stable working mechanism of quantum gates is essential for the realization of any complex quantum computations. In [3], I defined a method for the unsupervised control of quantum gates in near-term quantum computers. I modeled a scenario in which a non-stable quantum gate is not controllable in terms of control theory if the quantum gates are unentangled.

I proved that the non-stable quantum gate becomes controllable via our machine learning method if the quantum gates formulate an entangled gate structure. I defined a unit to process the measurement results, which are then fed into the machine learning unit to learn the control function of the entangled gate structure in an unsupervised manner. The machine learning unit achieves the quantum gate calibration by determining an appropriate control function that minimizes a particular cost function defined for the control problem.

1.1.4 Adaptive Problem Solving Dynamics in Gate-Model Quantum Computers

As the development of quantum computers evolves significantly, a fundamental need has arisen to characterize the attributes of problem solving in quantum computers. Gate-based quantum computations represent an essential to realize near-term quantum computer architectures, however, the mathematical description of the dynamical attributes of adaptive problem solving and iterative objective function evaluation in a gate-model quantum computer is currently a challenge. In [4], I defined a mathematical model of adaptive problem solving dynamics in a gate-model quantum computer. I characterized a canonical equation of adaptive objective function evaluation of computational problems and studied the stability of adaptive problem solving in gate-model quantum computers.

1.1.5 Training Optimization for Gate-Model Quantum Neural Networks

A gate-model quantum neural network (QNN) is a QNN implemented on a gate-model quantum computer, realized via a set of unitaries with associated gate parameters. In [5], I defined a training optimization procedure for gate-model QNNs. By deriving the environmental attributes of the gate-model quantum network, I proved the constraint-based learning models. I showed that the optimal learning procedures are different if side information is available in different directions, and if side information is accessible about the previous running sequences of the QNN.

1.1.6 Approximation Method for Optimization Problems in Gate-Model Quantum Computers

In near-term quantum computers, the computations are realized via unitary operators. The optimization problem fed into the quantum computer sets an objective function that is to be estimated via several measurement rounds. In [6], I defined a procedure for objective function approximation in gate-model quantum computers. The proposed solution optimizes the process of objective function estimation for optimization problems in gate-model quantum computers and quantum devices.

1.1.7 Dense Quantum Measurement Theory

Quantum measurement is a fundamental cornerstone of experimental quantum computations. The main issues in current quantum measurement strategies are the high number of measurement rounds to determine a global optimal measurement output and the low success probability of finding a global optimal measurement output. Each measurement round requires preparing the quantum system and applying quantum operations and measurements with high-precision control in the physical layer. These issues result in extremely high-cost measurements with a low probability of success at the end of the measurement rounds. In [7], I defined a novel measurement for quantum computations called dense quantum measurement. The dense measurement strategy aims at fixing the main drawbacks of standard quantum measurements by achieving a significant reduction in the number of necessary measurement rounds and by radically improving the success probabilities of finding global optimal outputs. I provided application scenarios for quantum circuits with arbitrary unitary sequences, and proved that dense measurement theory provides an experimentally implementable solution for gate-model quantum computer architectures.

1.1.8 Objective Function Estimation for Solving Optimization Problems in Gate-Model Quantum Computers

Quantum computers provide a valuable resource to solve computational problems. The maximization of the objective function of a computational problem is a crucial problem in gate-model quantum computers. The objective function estimation is a high-cost procedure that requires several rounds of quantum computations and measurements. In [8], I defined a method for objective function estimation of arbitrary computational problems in gate-model quantum computers. The proposed solution significantly reduces the costs of the objective function estimation and provides an optimized estimate of the state of the quantum computer for solving optimization problems.

1.1.9 State Stabilization for Gate-Model Quantum Computers

Gate-model quantum computers can allow quantum computations in near-term implementations. The stabilization of an optimal quantum state of a quantum computer is a challenge, since it requires stable quantum evolutions via a precise calibration of the unitaries. In [9], I proposed a method for the stabilization of an optimal quantum state of a quantum computer through an arbitrary number of running sequences. The optimal state of the quantum computer is set to maximize an objective function of an arbitrary problem fed into the quantum computer. I also proposed a procedure to classify the stabilized quantum states of the quantum computer into stability classes. The results are convenient for gate-model quantum computations and near-term quantum computers.

1.1.10 Decoherence Dynamics Estimation for Superconducting Gate-Model Quantum Computers

Superconducting gate-model quantum computer architectures provide an implementable model for practical quantum computations in the NISQ era. Due to hardware restrictions and decoherence, generating the physical layout of the quantum circuits of a gate-model quantum computer is a challenge. In [10], I defined a method for layout generation with a decoherence dynamics estimation in superconducting gate-model quantum computers. I proposed an algorithm for the optimal placement of the quantum computational blocks of gate-model quantum circuits. Studied the effects of capacitance interference on the distribution of the Gaussian noise in the Josephson energy.

1.1.11 Quantum Circuit Designs for Gate-Model Quantum Computer Architectures

The power of quantum computers makes it possible to solve difficult problems more efficiently than is possible with traditional computers. Gate-model quantum computers provide an experimentally implementable architecture for quantum circuit computations. In [11], I defined the Quantum Triple Annealing Minimization (QTAM) algorithm, which provides an automated quantum circuit minimization on the physical layout (circuit depth and area), quantum wire length minimization of the quantum circuit, Hamiltonian minimization, and the minimization of the input size and output measurements. I defined a multilayer structure for quantum circuit computations using the hardware restrictions on the connection topology of gate-model quantum computers. The results can be straightforwardly applied to near term gate-model quantum computers.

1.1.12 High-Retrieval-Efficiency Quantum Memory for Near-Term Quantum Devices

Quantum memories are a fundamental of any global-scale quantum Internet, high-performance quantum networking and near-term quantum computers. A main problem of quantum memories is the low retrieval efficiency of the quantum systems from the quantum registers of the quantum memory. In [12], I defined a novel quantum memory called high-retrieval-efficiency (HRE) quantum memory for near-term quantum devices. An HRE quantum memory unit integrates local unitary operations on its hardware level for the optimization of the readout procedure and utilizes the advanced techniques of quantum machine learning. I defined the integrated unitary operations of an HRE quantum memory, prove the learning procedure, and evaluate the achievable output signal-to-noise ratio values. I proved that the local unitaries of an HRE quantum memory achieve the optimization of the readout procedure in an unsupervised manner without the use of any labeled data or training sequences. I showed that the readout procedure of an HRE quantum memory is realized in a completely blind manner without any information about the input quantum system or about the unknown quantum operation of the quantum register. I evaluated the retrieval efficiency of an HRE quantum memory and the output SNR (signal-to-noise ratio).

1.1.13 Quantum State Optimization and Computational Pathway Evaluation for Gate-Model Quantum Computers

A computational problem fed into a gate-model quantum computer identifies an objective function with a particular computational pathway (objective function connectivity). The solution of the computational problem involves identifying a target objective function value that is the subject to be reached. A bottleneck in a gate-model quantum computer is the requirement of several rounds of quantum state preparations, high-cost run sequences, and multiple rounds of measurements to determine a target (optimal) state of the quantum computer that achieves the target objective function value. In [13], I defined a method for optimal quantum state determination and computational path evaluation for gate-model quantum computers. I proved a state determination method that finds a target system state for a quantum computer at a given target objective function value. The computational pathway evaluation procedure sets the connectivity of the objective function in the target system state on a fixed hardware architecture of the quantum computer. The method avoids high-cost system state preparations and expensive running procedures and measurement apparatuses in gate-model quantum computers.

1.2 Quantum Communication

1.2.1 Resource Prioritization and Balancing for the Quantum Internet

In [14], I defined methods and procedures of resource prioritization and resource balancing for the quantum Internet. I defined a model for resource consumption optimization in quantum repeaters, and a strongly-entangled network structure for resource balancing. I studied the resource-balancing efficiency of the strongly-entangled structure. I proved that a strongly-entangled quantum network is two times more efficient in a resource balancing problem than a full-mesh network of the traditional Internet.

1.2.2 Dynamics of Entangled Networks of the Quantum Internet

Entangled quantum networks are a fundamental of any global-scale quantum Internet. In [15] I defined a mathematical model to quantify the dynamics of entangled network structures and entanglement flow in the quantum Internet. The analytical solutions of the model determine the equilibrium states of the entangled quantum networks and characterize the stability, fluctuation attributes, and dynamics of entanglement flow in entangled network structures. I demonstrated the results of the model through various entangled structures and quantify the dynamics.

1.2.3 Routing Space Exploration for Scalable Routing in the Quantum Internet

The entangled network structure of the quantum Internet formulates a high complexity routing space that is hard to explore. Scalable routing is a routing method that can determine an optimal routing at particular subnetwork conditions in the quantum Internet to perform a high-performance and low-complexity routing in the entangled structure. In [16], I defined a method for routing space exploration and scalable routing in the quantum Internet. I proved that scalable routing allows a compact and efficient routing in the entangled networks of the quantum Internet.

1.2.4 Entanglement Concentration Service for the Quantum Internet

In [17], I defined the entanglement concentration service for the quantum Internet. The aim of the entanglement concentration service is to provide reliable, high-quality entanglement for a dedicated set of strongly connected quantum nodes in the quantum Internet. The objectives of the service are to simultaneously maximize the entanglement throughput of all entangled connections and to minimize the hop distance between the high-priority quantum nodes. I proposed a method for the resolution of the entanglement concentration problem and provided a performance analysis.

1.2.5 Theory of Noise-Scaled Stability Bounds and Entanglement Rate Maximization in the Quantum Internet

In [18], I defined a theoretical framework of noise-scaled stability analysis and entanglement rate maximization for the quantum Internet. Crucial problems of the quantum Internet are the derivation of stability properties of quantum repeaters and theory of entanglement rate maximization in an entangled network structure. The stability property of a quantum repeater entails that all incoming density matrices can be swapped with a target density matrix. The strong stability of a quantum repeater implies stable entanglement swapping with the boundness of stored density matrices in the quantum memory and the boundness of delays. I defined the term of entanglement swapping set that models the status of quantum memory of a quantum repeater with the stored density matrices. I determined the optimal entanglement swapping method that maximizes the entanglement rate of the quantum repeaters at the different entanglement swapping sets as function of the noise of the local memory and local operations. I proved the stability properties for non-complete entanglement swapping sets, complete entanglement swapping sets and perfect entanglement swapping sets. I derived the entanglement rates for the different entanglement swapping sets and noise levels.

1.2.6 Entanglement Accessibility Measures for the Quantum Internet

In [19], I defined metrics and measures to characterize the ratio of accessible quantum entanglement for complex network failures in the quantum Internet. A complex network failure models a situation in the quantum Internet in which a set of quantum nodes and a set of entangled connections become unavailable. A complex failure can cover a quantum memory failure, a physical link failure, an eavesdropping activity, or any other random physical failure scenario. I defined the terms entanglement accessibility ratio, cumulative probability of entanglement accessibility ratio, probabilistic reduction of entanglement accessibility ratio, domain entanglement accessibility ratio, and occurrence coefficient. The proposed methods can be applied to an arbitrary topology quantum network to extract relevant statistics and to handle the quantum network failure scenarios in the quantum Internet.

1.2.7 A Poisson Model for Entanglement Optimization in the Quantum Internet

In [20], I defined a nature-inspired model for entanglement optimization in the quantum Internet. The optimization model aims to maximize the entanglement fidelity and relative entropy of entanglement for the entangled connections of the entangled network structure of the quantum Internet. The cost functions are subject of a minimization defined to cover and integrate the physical attributes of entanglement transmission, purification, and storage of entanglement in quantum memories. The method can be implemented with low complexity that allows a straightforward application in the quantum Internet and quantum networking scenarios.

1.2.8 Entanglement Access Control for the Quantum Internet

In [21], I defined a method to achieve controlled entanglement access in the quantum Internet. The proposed model uses different levels of entanglement accessibility for the users of the quantum network. The path cost is determined by an integrated criterion on the entanglement fidelities between the quantum nodes and the probabilities of entangled connections of an entangled path. I revealed the connection between the number of available entangled paths and the accessible fidelity of entanglement and reliability in the end nodes. The scheme provides an efficient model for entanglement access control in the experimental quantum Internet.

1.2.9 Opportunistic Entanglement Distribution for the Quantum Internet

Quantum entanglement is a building block of the entangled quantum networks of the quantum Internet. A fundamental problem of the quantum Internet is entanglement distribution. Since quantum entanglement will be fundamental to any future quantum networking scenarios, the distribution mechanism of quantum entanglement is a critical and emerging issue in quantum networks. In [22], I defined the method of opportunistic entanglement distribution for the quantum Internet. The opportunistic model defines distribution sets that are aimed to select those quantum nodes for which the cost function picks up a local minimum. The cost function utilizes the error patterns of the local quantum memories and the predictability of the evolution of the entanglement fidelities. The method provides efficient entanglement distributing with respect to the actual statuses of the local quantum memories of the node pairs. The model provides an easily-applicable, moderate-complexity solution for high-fidelity entanglement distribution in experimental quantum Internet scenarios.

1.2.10 Adaptive Routing for Quantum Memory Failures in the Quantum Internet

In [23], I defined an adaptive routing method for the management of quantum memory failures in the quantum Internet. In the quantum Internet, the entangled quantum states are stored in the local quantum memories of the quantum nodes. A quantum memory failure in a particular quantum node can destroy several entangled connections in the entangled network. A quantum memory failure event makes the immediate and efficient determination of shortest replacement paths an emerging issue in a quantum Internet scenario. The replacement paths omit those nodes that are affected by the quantum memory failure to provide a seamless network transmission. In the proposed solution, the shortest paths are determined by a base-graph, which contains all information about the overlay quantum network. The method provides efficient adaptive routing in quantum memory failure scenarios of the quantum Internet. The results can be straightforwardly applied in practical quantum networks, including long-distance quantum communications.

1.2.11 Topology Adaption for the Quantum Internet

In the quantum repeater networks of the quantum Internet, the varying stability of entangled quantum links makes dynamic topology adaption an emerging issue. In [24], I defined an efficient topology adaption method for quantum repeater networks. The model assumes the random failures of entangled links and several parallel demands from legal users. The shortest path defines a set of entangled links for which the probability of stability is above a critical threshold. The scheme is utilized in a base-graph of the overlay quantum network to provide an efficient shortest path selection for the demands of all users of the network. Studied the problem of entanglement assignment in a quantum repeater network, prove its computational complexity, and showed an optimization procedure. The results are particularly convenient for future quantum networking, quantum-Internet, and experimental long-distance quantum communications.

1.2.12 Multilayer Optimization for the Quantum Internet

In [25], I defined a multilayer optimization method for the quantum Internet. Multilayer optimization integrates separate procedures for the optimization of the quantum layer and the classical layer of the quantum Internet. The multilayer optimization procedure defines advanced techniques for the optimization of the layers. The optimization of the quantum layer covers the minimization of total usage time of quantum memories in the quantum nodes, the maximization of the entanglement throughput over the entangled links, and the reduction of the number of entangled links between the arbitrary source and target quantum nodes. The objective of the optimization of the classical layer is the cost minimization of any auxiliary classical communications.

1.2.13 Entanglement Availability Differentiation Service for the Quantum Internet

In a quantum Internet scenario where the legal users of the network have different priority levels or where a differentiation of entanglement availability between the users is a necessity, an entanglement availability service is essential. In [26], I defined the entanglement availability differentiation (EAD) service for the quantum Internet. In the proposed EAD framework, the differentiation is either made in the amount of entanglement with respect to the relative entropy of entanglement associated with the legal users, or in the time domain with respect to the amount of time that is required to establish a maximally entangled system between the legal parties. The framework provides an efficient and easily-implementable solution for the differentiation of entanglement availability in experimental quantum networking scenarios.

1.2.14 Decentralized Base-Graph Routing for the Quantum Internet

Quantum repeater networks are a fundamental of any future quantum Internet and long-distance quantum communications. The entangled quantum nodes can communicate through several different levels of entanglement, leading to a heterogeneous, multi-level network structure. The level of entanglement between the quantum nodes determines the hop distance and the probability of the existence of an entangled link in the network. In [27], I defined a decentralized routing for entangled quantum networks. The proposed method allows an efficient routing to find the shortest paths in entangled quantum networks by using only local knowledge of the quantum nodes. I defined bounds on the maximum value of the total number of entangled links of a path. The proposed scheme can be directly applied in practical quantum communications and quantum networking scenarios.

1.2.15 Entanglement-Gradient Routing for Quantum Networks

In [28], I defined the entanglement-gradient routing scheme for quantum repeater networks. The routing framework fuses the fundamentals of swarm intelligence and quantum Shannon theory. Swarm intelligence provides nature-inspired solutions for problem solving. Motivated by models of social insect behavior, the routing is performed using parallel threads to determine the shortest path via the entanglement gradient coefficient, which describes the feasibility of the entangled links and paths of the network. The routing metrics are derived from the characteristics of entanglement transmission and relevant measures of entanglement distribution in quantum networks. The method allows a moderate complexity decentralized routing in quantum repeater networks. The results can be applied in experimental quantum networking, future quantum Internet, and long-distance quantum communications.

1.3 Quantum Cryptography

1.3.1 Multicarrier Continuous-Variable Quantum Key Distribution Protocol

In a CVQKD protocol, the information is conveyed by coherent state carriers. The quantum continuous variables are sent through a quantum channel, where the presence of the eavesdropper adds a white Gaussian noise to the transmission. The amount of tolerable noise and loss is a crucial point in CVQKD, since it determines the overall performance of the protocol, including the secure key rates and transmission distances. In [29], I defined the adaptive multicarrier quadrature division (AMQD) modulation technique for CVQKD. The method granulates the Gaussian random input into Gaussian subcarrier continuous variables in the encoding phase, which are then decoded by a continuous unitary transformation. The subcarrier coherent variables formulate Gaussian sub-channels from the physical link with strongly diverse transmission capabilities, which leads to significantly improved transmission efficiency, higher tolerable loss, and excess noise. I investigated a modulation-variance adaption technique within the AMQD scheme, which provides optimal capacity-achieving communication over the sub-channels in the presence of a Gaussian noise.

1.3.2 Subcarrier Domain of Multicarrier Continuous-Variable Quantum Key Distribution

In [30], I proposed the subcarrier domain of multicarrier CVQKD. In a multicarrier CVQKD scheme, the information is granulated into Gaussian subcarrier CVs and the physical Gaussian link is divided into Gaussian sub-channels. The sub-channels are dedicated for the conveying of the subcarrier CVs. The angular domain utilizes the phase-space angles of the Gaussian subcarrier CVs to construct the physical model of a Gaussian sub-channel. The subcarrier domain injects physical attributes to the description of the subcarrier transmission. I proved that the subcarrier domain is a natural representation of the subcarrier-level transmission in a multicarrier CVQKD scheme. Extended the subcarrier domain to a multiple-access multicarrier CVQKD setting. I demonstrated the results through the adaptive multicarrier quadrature-division (AMQD) CVQKD scheme and the AMQD-MQA (multiuser quadrature allocation) multiple-access multicarrier scheme. The subcarrier domain representation provides a general apparatus that can be utilized for an arbitrary multicarrier CVQKD scenario. The framework is particularly convenient for experimental multicarrier CVQKD scenarios.

1.3.3 Secret Key Rate Proof of Multicarrier Continuous-Variable Quantum Key Distribution

In [31], I proved the secret key rate formulas and derive security threshold parameters of multicarrier CVQKD. In a multicarrier CVQKD scenario, the Gaussian input quantum states of the legal parties are granulated into Gaussian subcarrier CVs (continuous-variables). The multicarrier communication formulates Gaussian sub-channels from the physical quantum channel, each dedicated to the transmission of a subcarrier CV. The Gaussian subcarriers are decoded by a unitary CV operation, which results in the recovered single-carrier Gaussian CVs. Derived the formulas through the AMQD (adaptive multicarrier quadrature division) scheme, the SVD-assisted (singular value decomposition) AMQD, and the multiuser AMQD-MQA (multiuser quadrature allocation). I proved that the multicarrier CVQKD leads to improved secret key rates and higher tolerable excess noise in comparison to single-carrier CVQKD. Derived the private classical capacity of a Gaussian sub-channel and the security parameters of an optimal Gaussian collective attack in the multicarrier setting. I revealed the secret key rate formulas for one-way and two-way multicarrier CVQKD protocols, assuming homodyne and heterodyne measurements and direct and reverse reconciliation. The results reveal the physical boundaries of physically allowed Gaussian attacks in a multicarrier CVQKD scenario and confirm that the improved transmission rates lead to enhanced secret key rates and security thresholds.

1.3.4 Singular Layer Transmission for Continuous-Variable Quantum Key Distribution

In [32], I developed a singular layer transmission model for multicarrier CVQKD. The proposed singular layer uses the singular value decomposition of the Gaussian quantum channel, which yields an additional degree of freedom for the phase space transmission. This additional degree of freedom can further be exploited in a multiple-access scenario. The singular layer defines the eigenchannels of the Gaussian physical link, which can be used for the simultaneous reliable transmission of multiple user data streams. The transmission model also includes the singular interference avoider

(SIA) precoding scheme. I proposed SIA precoding scheme prevents the eigenchannel interference to reach an optimal transmission over a Gaussian link. I demonstrated the results through the adaptive multicarrier quadrature division-multiuser quadrature allocation (AMQD-MQA) CVQKD multiple-access scheme. I defined the singular model of AMQD-MQA and characterize the properties of the eigenchannel interference. I proposed the SIA precoding of Gaussian random quadratures and the optimal decoding at the receiver. I showed a random phase space constellation scheme for the Gaussian sub-channels. The singular layer transmission provides improved simultaneous transmission rates for the users with unconditional security in a multiple-access scenario, particularly in crucial low signal-to-noise ratio regimes.

1.3.5 Multiuser Quadrature Allocation for Continuous-Variable Quantum Key Distribution

In [33], I proposed the adaptive multicarrier quadrature division-multiuser quadrature allocation (AMQD-MQA) multiple access technique for CVQKD. The MQA scheme is based on the AMQD modulation, which granulates the inputs of the users into Gaussian subcarrier continuous-variables (CVs). The subcarrier coherent states formulate Gaussian sub-channels from the physical link with diverse transmittance coefficients. In an AMQD-MQA multiple access scenario, the simultaneous reliable transmission of the users is handled by the dynamic allocation of the Gaussian subcarrier CVs. I proposed two different settings of AMQD-MQA for multiple input-multiple output communication. Introduced a rate-selection strategy that tunes the modulation variances and allocates adaptively the quadratures of the users over the sub-channels. Also proved the rate formulas if only partial channel side information is available for the users of the sub-channel conditions. In an experimental CVQKD scenario, an ideal Gaussian input modulation can only be approximated, which affects the quadrature adaption and the efficiency of the transmission. I showed a technique for the compensation of a nonideal Gaussian input modulation, which allows the users to overwhelm the modulation imperfections to reach optimal capacity-achieving communication over the Gaussian sub-channels. I investigated the diversity amplification of the sub-channel transmittance coefficients and revealed that a strong diversity can be exploited by opportunistic Gaussian modulation.

1.3.6 Multidimensional Manifold Extraction for Multicarrier Continuous-Variable Quantum Key Distribution

In [34], I defined the multidimensional manifold extraction for multicarrier CVQKD. The manifold extraction utilizes the resources that are injected into the transmission by the additional degrees of freedom of the multicarrier modulation. I demonstrated the results through the AMQD (adaptive multicarrier quadrature division) scheme, which granulates the information into Gaussian subcarrier CVs and divides the physical link into several Gaussian sub-channels for the transmission. I proved that the exploitable extra degree of freedom in a multicarrier CVQKD scenario significantly extends the possibilities of single-carrier CVQKD. The manifold extraction allows for the parties to reach decreased error probabilities by utilizing those extra resources of a multicarrier transmission that are not available in a single-carrier CVQKD setting. I defined the multidimensional manifold space of multicarrier CVQKD and the optimal tradeoff between the available degrees of freedom of the multicarrier transmission. Extended the manifold extraction for the multiple-access AMQD-MQA (multiuser quadrature allocation) multicarrier protocol. The additional resources of multicarrier CVQKD allow the achievement of significant performance improvements that are particularly crucial in an experimental scenario.

1.3.7 Post-Processing Optimization for Continuous-Variable Quantum Key Distribution

The performance of a continuous-variable quantum key distribution (CVQKD) protocol depends on the efficiency of the post-processing of measurement results. The post-processing phase is a bottleneck in CVQKD with crucial importance to the efficiency and protocol attributes. Post-processing uses the raw data of the parties generated by the quantum-level transmission and a classical authenticated channel to generate a secret key between the parties. The current reconciliation procedures require high-complexity coding with moderate resulting efficiency. In [35], I defined an optimization method for post-processing in continuous-variable quantum key distribution. The reconciliation method achieves additive Gaussian noise on the random secret for arbitrarily low dimensional blocks. The model consumes all information from the raw data blocks to provide maximal efficiency and security via standard operations. The results can be realized by generic Gaussian coding schemes, allowing an easily implementation for experimental CVQKD protocols.

1.3.8 Secret Key Rates of Free-Space Optical Continuous-Variable Quantum Key Distribution

In [36], I derived the maximal achievable secret key rates for CVQKD over free-space optical (FSO) quantum channels. I provided a channel decomposition for FSO-CVQKD quantum channels and study the SNR (signal-to-noise ratio) characteristics. The analytical derivations focus particularly on the low-SNR scenarios.

1.3.9 Scalar Reconciliation for Gaussian Modulation of Continuous-Variable Quantum Key Distribution

The reconciliation process of correlated Gaussian variables is a complex problem that requires either tomography in the physical layer that is intractable in a practical scenario, or high-cost calculations in the multidimensional spherical space with strict dimensional limitations. To avoid these issues, he proposed an efficient logical layer-based reconciliation method for CVQKD to extract binary information from correlated Gaussian variables. In [37], I proved that by operating on the raw-data level, the noise of the quantum channel can be corrected in the scalar space and the reconciliation can be extended to arbitrary high dimensions. I proved that the error probability of scalar reconciliation is zero in any practical CVQKD scenario, and provides unconditional security. The results allow to significantly improve the currently available key rates and transmission distances of two-way CVQKD. The proposed scalar reconciliation can also be applied in one-way systems as well, to replace the existing reconciliation schemes.

1.3.10 Iterative Secret Key Rate Adapting with Error Minimization for Continuous-Variable Quantum Key Distribution

In [38], I defined an iterative error-minimizing secret key adapting method for multicarrier CVQKD. A multicarrier CVQKD protocol uses Gaussian subcarrier quantum continuous variables (CVs) for the transmission. The proposed method allows for the parties to reach a given target secret key rate with minimized error rate through the Gaussian sub-channels by a sub-channel adaption procedure. The adaption algorithm iteratively determines the optimal transmit conditions to achieve the target secret key rate and the minimal error rate over the sub-channels. The solution requires no complex calculations or computational tools, allowing for easy implementation for experimental CVQKD.

1.3.11 Statistical Quadrature Evolution by Inference for Continuous-Variable Quantum Key Distribution

In [39], I defined the statistical quadrature evolution (QE) method for multicarrier CVQKD. A multicarrier CVQKD protocol uses Gaussian subcarrier quantum continuous variables (CVs) for information transmission. The QE scheme utilizes the theory of mathematical statistics and statistical information processing. The QE model is based on the Gaussian quadrature inference (GQI) framework to provide a minimal error estimate of the CV state quadratures. The QE block evaluates a unique and stable estimation of the non-observable continuous input from the measurement results and through the statistical inference method yielded from the GQI framework. The QE method minimizes the overall expected error by an estimator function and provides a viable, easily implementable, and computationally efficient way to maximize the extractable information from the observed data. The QE framework can be established in an arbitrary CVQKD protocol and measurement setting and is implementable by standard low-complexity functions, which is particularly convenient for experimental CVQKD.

1.3.12 Gaussian Quadrature Inference for Multicarrier Continuous-Variable Quantum Key Distribution

In [40], I proposed the Gaussian quadrature inference (GQI) method for multicarrier CVQKD. A multicarrier CVQKD protocol utilizes Gaussian subcarrier quantum continuous variables (CV) for information transmission. The GQI framework provides a minimal error estimate of the quadratures of the CV quantum states from the discrete, measured noisy subcarrier variables. GQI utilizes the fundamentals of regularization theory and statistical information processing. Characterized GQI for multicarrier CVQKD, and defined a method for the statistical modeling and processing of noisy Gaussian subcarrier quadratures. I demonstrate the results through the adaptive multicarrier quadrature division (AMQD) scheme. I defined direct GQI (DGQI), and proved that it achieves a theoretical minimal magnitude error. Introduced the terms statistical secret key rate and statistical private classical information, which quantities are derived purely by the statistical functions of GQI. I proved the secret key rate formulas for a multiple access multicarrier CVQKD via the AMQD-MQA (multiuser quadrature allocation) scheme.

1.3.13 Distribution Statistics and Random Matrix Formalism of Multicarrier Continuous-Variable Quantum Key Distribution

In [41], I proposed a combined mathematical framework of order statistics and random matrix theory for multicarrier CVQKD. In a multicarrier CVQKD scheme, the information is granulated into Gaussian subcarrier CVs, and the physical Gaussian link is divided into Gaussian sub-channels. The sub-channels are dedicated to the conveying of the subcarrier CVs. The distribution statistics analysis covers the study of the distribution of the sub-channel transmittance coefficients in the presence of a Gaussian noise and the utilization of the moment generation function (MGF) in the error analysis. I revealed the mathematical formalism of sub-channel selection and formulation of the transmittance coefficients, and show a reduced complexity progressive sub-channel scanning method. I defined a random matrix formalism for multicarrier CVQKD to evaluate the statistical properties of the information flowing process. Using random matrix theory, expressed the achievable secret key rates and studied the efficiency of the AMQD-MQA (adaptive multicarrier quadrature division-multiuser quadrature allocation) multiple-access multicarrier CVQKD. The combined framework is particularly convenient for the characterization of the physical processes of experimental multicarrier CVQKD.

1.3.14 Adaptive Quadrature Detection for Multicarrier Continuous-Variable Quantum Key Distribution

In [42], I proposed the adaptive quadrature detection for multicarrier CVQKD. A multicarrier CVQKD scheme uses Gaussian subcarrier continuous variables for the information conveying and Gaussian sub-channels for the transmission. The proposed multicarrier detection scheme dynamically adapts to the sub-channel conditions using a corresponding statistics which is provided by our sophisticated sub-channel estimation procedure. The sub-channel estimation phase determines the transmittance coefficients of the sub-channels, which information are used further in the adaptive quadrature decoding process. I defined the technique called subcarrier spreading to estimate the transmittance conditions of the sub-channels with a theoretical error-minimum in the presence of a Gaussian noise. Introduced the terms of single and collective adaptive quadrature detection. Extended the results for a multiuser multicarrier CVQKD scenario. I proved the achievable error probabilities, the signal-to-noise ratios, and quantified the attributes of the framework.

1.3.15 Algorithmic Analysis of Quantum Key Distribution

In [43], I analyzed the information-theoretical security of the Differential Phase Shift (DPS) QKD protocol. The DPS QKD protocol was introduced for practical reasons. The DPS QKD protocol can be an integrated part of current network security applications, hence it's practical implementation is much easier with the current optical devices and optical networks. The proposed algorithm could be a very valuable tool to answer the still open questions related to the security bounds of the DPS QKD protocol.

1.4 Quantum Information Theory

1.4.1 Quantum Imaging of High-Dimensional Hilbert Spaces with Radon Transform

High-dimensional Hilbert spaces possess large information encoding and transmission capabilities. Characterizing exactly the real potential of high-dimensional entangled systems is a cornerstone of tomography and quantum imaging. The accuracy of the measurement apparatus and devices used in quantum imaging is physically limited, which allows no further improvements to be made. To extend the possibilities, in [44] I introduced a post-processing method for quantum imaging that is based on the Radon transform and the projection-slice theorem. The proposed solution leads to an enhanced precision and a deeper parameterization of the information conveying capabilities of high-dimensional Hilbert spaces. I demonstrated the method for the analysis of high-dimensional position-momentum photonic entanglement. I showed that the entropic separability bound in terms of standard deviations is violated considerably more strongly in comparison to the standard setting and current data processing. The results indicate that the possibilities of the quantum imaging of high-dimensional Hilbert spaces can be extended by applying appropriate calculations in the post-processing phase.

1.4.2 Mathematical Limits of Communication over Zero-Capacity Quantum Channels

In [45], I discovered a mathematical limit in the superactivation effect of quantum channels. I proved that the possibility of superactivation of quantum channel capacities is determined by the mathematical properties of the quantum relative entropy function. Before my result this fundamental and purely mathematical connection between the quantum relative entropy function and the superactivation effect was completely unrevealed.

1.4.3 Partially Degradable Quantum Channels

The quantum capacity of degradable quantum channels has been proven to be additive. On the other hand, there is no general rule for the behavior of quantum capacity for non-degradable quantum channels. In [46], I introduced the set of partially degradable (PD) quantum channels to answer the question of additivity of quantum capacity for a well-separable subset of non-degradable channels. A quantum channel is partially degradable if the channel output can be used to simulate the degraded environment state. PD channels could exist both in the degradable, non-degradable and conjugate degradable family. I defined the term partial simulation, which is a clear benefit that arises from the structure of the complementary channel of a PD channel. I proved that the quantum capacity of an arbitrary dimensional PD channel is additive. I demonstrated that better quantum data rates can be achieved over a PD channel in comparison to standard (non-PD) channels. The results indicate that the partial degradability property can be exploited and yet still hold many benefits for quantum communications.

1.4.4 Private Classical Communication over Partially Degradable Quantum Channels

For a partially degradable (PD) channel, the channel output state can be used to simulate the degraded environment state. The quantum capacity of a PD channel has been proven to be additive. In [47], I showed that the private classical capacity of arbitrary dimensional PD channels is equal to the quantum capacity of the channel and also single-letterizes. I proved that higher rates of private classical communication can be achieved over a PD channel in comparison to standard degradable channels.

1.4.5 Quantum Information Transmission over a Partially Degradable Channel

In [48], I defined a quantum coding for quantum communication over a PD quantum channel. PD channels can be restricted to the set of optical channels which allows for the parties to exploit the benefits in experimental quantum communications. We show that for a PD channel, the partial degradability property leads to higher quantum data rates in comparison to those of a degradable channel. The PD property is particular convenient for quantum communications and allows one to implement the experimental quantum protocols with higher performance. We define a coding scheme for PD-channels and give the achievable rates of quantum communication.

1.4.6 Correlation Conversion Property of Quantum Channels

Transmission of quantum entanglement will play a crucial role in future networks and long-distance quantum communications. Quantum Key Distribution, the working mechanism of quantum repeaters and the various quantum communication protocols are all based on quantum entanglement. On the other hand, quantum entanglement is extremely fragile and sensitive to the noise of the communication channel over which it has been transmitted. In [49], I showed that quantum entanglement can be generated by a fundamentally new idea, exploiting the most natural effect of the communication channels: the noise itself of the link. I proved that the noise transformation of communication links that are not able to transmit quantum entanglement can be used to generate entanglement from classically correlated, unentangled input. I worked out the mathematical background and proved the information theoretic correctness.

1.4.7 Quantum Entanglement with Stimulated Emission for Communication over Zero-Capacity Quantum Channels

In [50], I defined the term quasi-superactivation for classical communication over zero-capacity channels. One of the most surprising recent results in quantum Shannon theory is the superactivation of the quantum capacity of a quantum channel. However, the originally introduced superactivation has many limitations since it is based on the phenomenon of "capacity conversion", which makes no possible to extend it to the classical capacity. I demonstrated a similar effect for the classical capacity of a quantum channel which previously was thought to be impossible. I proved that a nonzero classical capacity can be achieved for all zero-capacity quantum channels and it only requires the combination of an elementary photon-atom interaction process – the stimulated emission, with quantum entanglement. Worked out the mathematical background and proved it's correctness in information theoretic terms.

1.4.8 Algorithmical Solution for Superactivation of Quantum Channels

The superactivation of zero-capacity quantum channels makes it possible to use two zero-capacity quantum channels with a positive joint capacity for their output. Currently, I have no theoretical background to describe all possible combinations of superactive zero-capacity channels; hence, there may be many other possible combinations. In practice, to discover such superactive zero-capacity channel-pairs, we must analyze an extremely large set of possible quantum states, channel models, and channel probabilities. There is still no extremely efficient algorithmic tool for this purpose. In [51], I showed an efficient algorithmical method of finding such combinations. The proposed algorithm can be a very valuable tool for improving the results of fault-tolerant quantum computation and possible communication techniques over very noisy quantum channels.

1.4.9 Capacity Domains of Quantum Channels

In [52], I introduced the term called polaractivation, which makes possible the communication over zero-capacity quantum channels. The result is similar to the superactivation effect, however it is based on a different phenomenon. Polaractivation opens the unreachable capacity domains by a special channel coding technique. I worked out the mathematical background and proved it's correctness in information theoretic terms. The method can be used to transmit private classical and quantum information and for zero-error classical or quantum communication.

1.4.10 Concatenated Capacity-Achieving Quantum Codes

Constructed concatenated capacity-achieving quantum codes for noisy optical quantum channels. In [53], I demonstrated that the error-probability of quantum polar encoding can be reduced by the proposed low-complexity concatenation scheme. In the proposed code concatenation scheme, he combined the quantum polar codes with quantum LDPC CSS (Low-Density-Parity-Check Calderbank-Shor-Steane) codes. The concatenation coding has two important advantages: First, the LDPC CSS codes decrease the error probability of the quantum polar codes. Second, by using quantum polar codes, the error-floor problem of quantum LDPC CSS codes can be completely eliminated.

1.4.11 Information Processing Structure of Quantum Gravity

The theory of quantum gravity is aimed to fuse general relativity with quantum theory into a more fundamental framework. The space of quantum gravity provides both the non-fixed causality of general relativity and the quantum uncertainty of quantum mechanics. In a quantum gravity scenario, the causal structure is indefinite and the processes are causally non-separable. In [54], I provided a model for the information processing structure of quantum gravity.

1.4.12 Entropy Transfer of Quantum Gravity Information Processing

In [55], I introduced the term smooth entanglement entropy transfer, a phenomenon that is a consequence of the causality-cancellation property of the quantum gravity environment. The causality-cancellation of the quantum gravity space removes the causal dependencies of the local systems. Studied the physical effects of the causality-cancellation and show that it stimulates entropy transfer between the quantum gravity environment and the independent local systems of the quantum gravity space. The entropy transfer reduces the entropies of the contributing local systems and increases the entropy of the quantum gravity environment. Discussed the space-time geometry structure of the quantum gravity environment and the local quantum systems. I proposed the space-time geometry model of the smooth entropy transfer. I revealed on a smooth Cauchy slice that the space-time geometry of the quantum gravity environment dynamically adapts to the vanishing causality. I define the corresponding Hamiltonians and the causal development of the quantum gravity environment in a non-fixed causality structure. I proved that the Cauchy area expansion, along with the dilation of the Rindler horizon area of the quantum gravity environment, is a strict corollary of the causality-cancellation of the quantum gravity environment.

1.4.13 Correlation Measure Equivalence in Dynamic Causal Structures

In [56], I proved an equivalence transformation between the correlation measure functions of the causally-unbiased quantum gravity space and the causally-biased standard space. The theory of quantum gravity fuses the dynamic (nonfixed) causal structure of general relativity and the quantum uncertainty of quantum mechanics. In a quantum gravity space, the events are causally nonseparable and all time bias vanishes, which makes it no possible to use the standard causally-biased entropy and the correlation measure functions. Since a corrected causally-unbiased entropy function leads to an undefined, obscure mathematical structure, in our approach the correction is made in the data representation of the causally-unbiased space. I proved that the standard causally-biased entropy function with a data correction can be used to identify correlations in dynamic causal structures. As a corollary, all mathematical properties of the causally-biased correlation measure functions are preserved in the causally-unbiased space. The equivalence transformation allows us to measure correlations in a quantum gravity space with the stable, well-defined mathematical background and apparatus of the causally-biased functions of quantum Shannon theory.

1.4.14 Statistical Communication Model for Black Holes

In [57], I defined a statistical communication model for the phenomenon of quantum information evaporation from black holes. A black hole behaves as a reflecting quantum channel in a very special regime, which allows for a receiver to perfectly recover the absorbed quantum information. The quantum channel of a perfectly reflecting (PR) black hole is the probabilistically weighted sum of infinitely many qubit cloning channels. I revealed the statistical communication background of the information evaporation process of PR black holes. I showed that the density of the cloned quantum particles in function of the PR black hole's mass approximates a Chi-square distribution, while the stimulated emission process is characterized by zero-mean, circular symmetric complex Gaussian random variables. The results lead to the existence of Rayleigh random distributed coefficients in the probability density evolution, which confirms the presence of Rayleigh fading (a special type of random fluctuation) in the statistical communication model of black hole information evaporation.

1.4.15 Low-Redundancy Quantum Error Correction

In [58], I introduced a new quantum error correction scheme, called pilot quantum error correction. Real global-scale quantum communications and quantum key distribution systems cannot be implemented by the current fiber and free-space links. These links have high attenuation, low polarization-preserving capability or extreme sensitivity to the environment. A potential solution to the problem is the space-earth quantum channels. These channels have no absorption since the signal states are propagated in empty space, however a small fraction of these channels is in the atmosphere, which causes slight depolarizing effect. The proposed quantum error-correction technique can be applied to fix the polarization errors which are critical in space-earth quantum communication systems.

1.4.16 Quantum Coding for Quantum Relay Networks

The relay encoder is an unreliable probabilistic device which is aimed at helping the communication between the sender and the receiver. In [59], I showed that in the quantum setting the probabilistic behavior can be completely eliminated. I proved that reliable and capacity-achieving private communication over noisy quantum relay channels can be achieved.

1.4.17 Additivity Analysis of Amplitude Damping Channels

In [60], I developed an information geometric algorithm to analyze the additivity property of the arbitrary dimensional amplitude damping quantum channels.

1.4.18 Quantum-assisted and Quantum-based Solutions in Wireless Optical Systems

In wireless systems there is always a trade-off between reducing the transmit power and mitigating the resultant signal-degradation imposed by the transmit-power reduction with the aid of sophisticated receiver algorithms, when considering the total energy consumption. Quantum-assisted wireless communications exploits the extra computing power offered by quantum mechanics based architectures. In [61], I showed that how the results of quantum computing and the corresponding application areas can be combined in wireless communications.

1.4.19 Intelligent Self-Organizing Quantum Networks and Web-based Applications

The modern networks have an increasing complexity and the Internet – in nowadays construction – is not seem to be suitable for handling the near future's service demands. The autonomic communication could help to gain over these issues. In [62], I defined a Quantum Autonomic Communication Element (QACE) which uses quantum algorithms and processes for the realization of a real-life based network organism. It uses classical language to communicate with the network elements, and uses a closed, non-classical quantum mechanical based language inside the component model. I developed the quantum cellular automata based version of the proposed intelligent self-organizing component.

1.4.20 Quantum Copy Protection

In [63], I developed a quantum copy-protection system which protects classical information in the form of non-orthogonal quantum states. The decryption mechanism of data qubits is realized by secret unitary rotations. I defined an authentication method for the proposed copy-protection scheme and analyzed the success probabilities of the authentication process.

1.4.21 Quantum Singular Value Decomposition Based Approximation Algorithm

In [64], I defined a Quantum-SVD (Singular Value Decomposition) based approach for the computation of Quantum Fourier Transformation coefficients. While the complexity of the proposed scheme is the same as the standard Quantum Fourier Transform, the accuracy of the Quantum-SVD approach is some orders higher.

1.5 Surveys

1.5.1 Survey on Quantum Computing Technology

The power of quantum computing technologies is based on the fundamentals of quantum mechanics, such as quantum superposition, quantum entanglement, or the no-cloning theorem. Since these phenomena have no classical analogue, similar results cannot be achieved within the framework of traditional computing. The experimental insights of quantum computing technologies have already been demonstrated, and several studies are in progress. In [65], I reviewed the most recent results of quantum computation technology and addressed the open problems of the field.

1.5.2 Survey on Quantum Channel Capacities

Quantum information processing exploits the quantum nature of information. It offers fundamentally new solutions in the field of computer science and extends the possibilities to a level that cannot be imagined in classical communication systems. For quantum communication channels, many new capacity definitions were developed in comparison to classical counterparts. A quantum channel can be used to realize classical information transmission or to deliver quantum information, such as quantum entanglement. In [66], I reviewed the properties of the quantum communication channel, the various capacity measures and the fundamental differences between the classical and quantum channels.

1.5.3 Survey on Quantum Key Distribution

Quantum key distribution (QKD) protocols represent an important practical application of quantum information theory. QKD schemes enable legal parties to establish unconditionally secret communication by exploiting the fundamental attributes of quantum mechanics. In [67], I reviewed the principles of QKD systems, the implementation basis, and the application of QKD protocols in the standard Internet and the quantum Internet.

1.5.4 Survey on the Quantum Internet

The quantum Internet utilizes the fundamental concepts of quantum mechanics for networking. The entangled network structure of the quantum Internet formulates a high-complexity network space with several advantages and challenges. In [68], I reviewed the attributes of the quantum Internet, addressing the requirements and proposals, the recent implementation basis, and the open problems.

1.6 Books

1.6.1 Advanced Quantum Communications, Wiley-IEEE Press, New Jersey, USA (2013)

In this book [69], we present the fundamental results of quantum information theory and the details of advanced quantum communication protocols with clear mathematical and information theoretical background.

1.6.2 Quantum Mechanics based Communications, Research University series, Budapest University of Technology and Economics (2012)

This book reviews the fundaments of quantum communications and addresses the open problems [70].

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