Coexisting Raman-Scattering Depolarization Simulation

Overview

This code simulates quantum communication experiments utilizing coexistence with classical signals, such as in fiber optic links carrying both quantum and classical data. This is modelled using the depolarization channel.

For a complete theoretical explanation of the methods employed, read the associated pre-print: "*Simulating Raman Scattering Impairments with Depolarization Noise in Quantum-Classical Links"* [1].

The main entry point is:

`characterized_coex_sim.py`

Verified with Python version: 3.10.0

This script allows the user to run 3 types of coexistence experiments:

1. **Direct Transmission** (`import_coexisting_direct_transmission`)
2. **Entanglement Distribution** (`import_coexisting_entanglement`)
3. **Teleportation** (`import_coexisting_teleportation`)

Both simulate how coexisting **Raman noise**, modeled as **depolarization**, affects coexisting quantum channel fidelity, based on input **visibility** values.

Guidance on Usage

There are two main use cases for this simulator:

1. **Estimating the coexisting fidelity value of a coexisting link configuration (fibre + detector setup).** The user may be interested in comparing the fidelity difference of two hardware configurations (e.g. wavelength channel selections or launch powers and their respective Raman photons received at the detector), perhaps with respect to a minimum fidelity requirement of the protocol.

2. **Simulating larger network protocols in NetSquid with coexisting links.** If the user is intending to include coexisting noise in link or network layer protocol simulation, this simulator can be forked, or subsections utilized, to apply the appropriate coexisting noise to the transmitted qubits to yield the appropriate noisy coexisting density matrix.

Both of these cases will follow a similar workflow:

1. Using the characterized Raman gain spectrum, rho, determine the number of incident Raman photons at the detector. This is from experimental measurements, or from an estimated number.
2. Then**,** calculates the mixing probability of the link based on the incident Raman photons. Applies depolarization with this mixing probability to NetSquid qubit objects.
   a. Note: for teleportation using a midpoint Bell-state Measurement, there will be corresponding mixing probabilities for both fibres utilized (Alice's qubit to be teleported → BSM, Bob's entangled signal photon → BSM)
3. The simulator by default plots input fidelity as a function of launch power for each quantum channel [nm] of interest.

See below for more tailored workflows for each scenario.

---

1. `characterized_coex_sim.py`

Purpose

This is the main runner file that executes the simulation. It lets you specify:

- Type of experiment
- Hardware parameters from `hardware_config.py`
- Optional flags (e.g. verbosity)

Execution

- `python3 characterized_coex_sim.py`
- Modify the file directly to change input parameters or flags.
  - Modify the entangled_hardware_config.py file to modify hardware parameters for entanglement architectures

Output

- Graph of fidelity as function of desired parameters

Usage

Within `characterized_coex_sim`

- Determine the number of incident Raman photons at the detector per second
  - `read_measurement_data()`: Pull measurement data from RAMAN_Charact.xlsx. The 1565 nm characterization using high-power and dual-polarization (i.e. kpol = 2) is the validated experiment.
  - `calculate_rho()`: Calculate Raman gain coefficient, rho, from this data.
  - `calc_raman_photons()`: Calculate Raman photons generated from the classical channel that are detected at the quantum wavelength
  - `simulate()`: simulate coexisting transmission within the desired link
    - **This function can be updated to simulate direct transmission, or teleportation of coexisting qubits.**
    - **Replace** `ent.run_coex_ent_experiment()` with `direct.run_coex_direct_transm_experiment` or `tele.run_coex_tele_experiment()`
- *`Note: The only lines that require modification are below “CONFIGURABLE:...” comments`*

---

2. Interfacing with `import_coexisting_direct_transmission.py`

Purpose

Simulates coexisting **direct quantum transmission** of a single pure qubit from an emitter to a receiver over a fiber with **depolarizing noise**.

Key Functions

- `run_coex_direct_experiment(noisy_visibility, random_seed=1, input_state='0', verbose=False)`

  - Converts incident Raman photons to depolarizing probability.

    - Sets up a network with one coexisting quantum channel.
    - Sends a single pure qubit and retrieves the noisy output.
    - Calculates fidelity of the output vs. the ideal state.
    - Returns: (depolarized fidelity, depolarized state)

---

3. Interfacing with `import_coexisting_entanglement.py`

Purpose

Simulates coexisting **entanglement distribution** through a noisy fiber link. Uses a pure Bell-pair source and characterizes the received state fidelity.

Key Functions

- `run_coex_ent_experiment(noisy_visibility, random_seed=1, bell_state="phi+", verbose=True)`
    - Converts visibility to depolarizing probability.
    - One half of the Bell pair is stored locally; the other travels through the depolarizing fiber.
    - Fidelity is computed between the received (noisy) Bell state and the original.
    - Returns: (depolarized fidelity, depolarized entangled qubit 1, depolarized entangled qubit 2)

Usage

Within `characterized_coex_sim`

- Select your link lengths and wavelengths of choice to sweep
- Determine the number of incident Raman photons at the detector
- Within `simulate()`
    - Using `calc_visibility()` from `import_coexisting_teleportation`, calculate the noisy visibility of the signal photon's fibre based on the number of incident

    - Raman photons at the detector and other hardware parameters listed in the parameter dictionary.
    - **Note**: skip these first 2 steps if noisy visibility is already known
    - **Note:** the transmission parameters may need to be modified to best model your unique hardware setup
- Input noisy visibility to `ent.run_coex_ent_experiment()` to run experiment

---

4. Interfacing with `import_coexisting_teleportation.py`

Purpose

Simulates coexisting **teleportation** through a noisy fiber link. Alice prepares a pure state to teleport. Bob prepares the pure entangled Bell-state. Bob keeps the entangled idler. Both send their signal photons to a midpoint optical Bell-state measurement. Both experience (possibly unique) coexisting noise, with a corresponding amount of detected Raman photons within the BSM component and idler receivers. See [2] for the full setup.

Key Functions

- `run_coex_ent_experiment(noisy_visibility, random_seed=1, bell_state="phi+", verbose=True)`
    - Converts visibility to depolarizing probability.
    - Fidelity of teleportation is computed as function of Alice's qubit's fidelity and the entangled fidelity after coexisting transmission.
    - Returns: (depolarized fidelity, depolarized entangled qubit 1, depolarized entangled qubit 2, depolarized Alice's qubit)

Usage

Within `characterized_coex_sim`

- Determine the number of incident Raman photons at the detector
- Calculate the noisy visibility of each signal photon's fibre based on the number of incident Raman photons at the detector and other hardware parameters listed in the parameter dictionary.
- Within `simulate()`
    - Using `calc_visibility()` from `import_coexisting_teleportation`

    - For teleportation using a midpoint Bell-state Measurement, there will be corresponding mixing probabilities for both fibres utilized (Alice's qubit to be teleported → BSM, Bob's entangled signal photon → BSM)
    - **Note**: skip these first 2 steps if noisy visibility is already known
    - **Note:** the transmission parameters may need to be modified to best model your unique hardware setup
- Input noisy visibility to `tele.run_coex_tele_experiment()` to run experiment

References

1. Smith, J., & Proietti, R. Simulating Raman Scattering Impairments with Depolarization Noise in Quantum-Classical Links. Photonics in Switching and Computing (2025). To Appear.
2. Thomas, J. M., Yeh, F. I., Chen, J. H., Mambretti, J. J., Kohlert, S. J., Kanter, G. S., & Kumar, P. (2024). Quantum teleportation coexisting with classical communications in optical fiber. Optica, 11(12), 1700-1707.