GNU Radio for Quantum Optical Communication

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In this talk, we discuss the implementation of quantum optical communication protocols within the GNU Radio framework. We report on efforts to develop single-photon optical receivers at infrared and visible wavelengths that interface directly with GNU Radio, and our development of a quantum information tool kit for application testing built on top of GNU Radio.

While the physics underlying quantum communication distinguish it from conventional radios, we conclude that GNU Radio provides a convenient means for prototyping research-grade implementations of various quantum applications and, subsequently, for diagnosing relative performance

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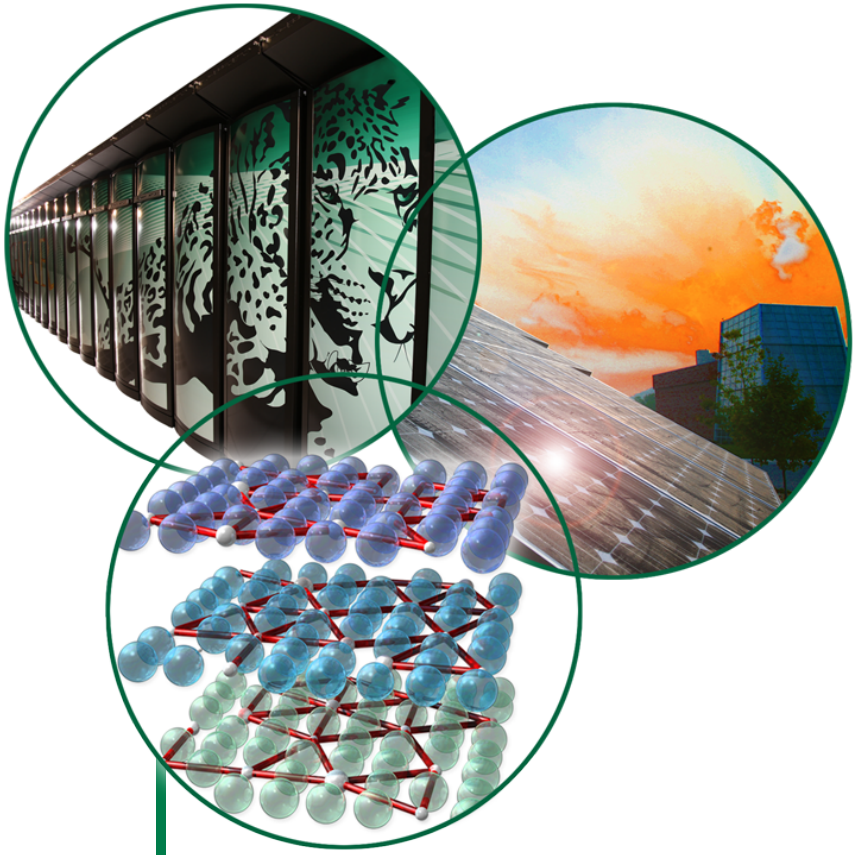

U.S. DEPARTMENT OF ENERGY

GNU Radio Conference
14 Sept 2011 Philadelphia, PA

OAK RIDGE NATIONAL LABORATORY

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GNU Radio for Quantum Optical Communication

- Purpose:
  - Develop a toolkit within the GNU Radio framework for processing quantum communication protocols; prototype quantum applications
  - Develop quantum optical hardware capable of talking with GNU Radio
- Challenges:
  - Interfacing with optical detectors
  - Partitioning quantum communications into GR ‘blocks’
  - Two-way communication
  - Securing the implementation
- Current Status:
  - Prototype optical receivers interface with GR over Ethernet
  - Developed multiple specialty blocks; prototyping simple applications

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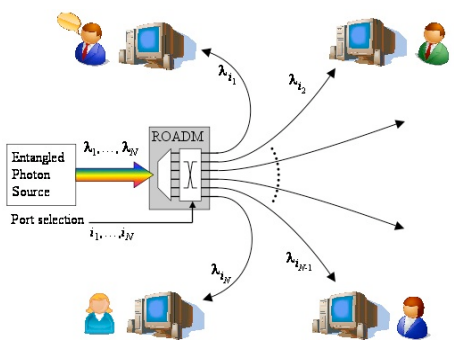
Oak Ridge National Laboratory

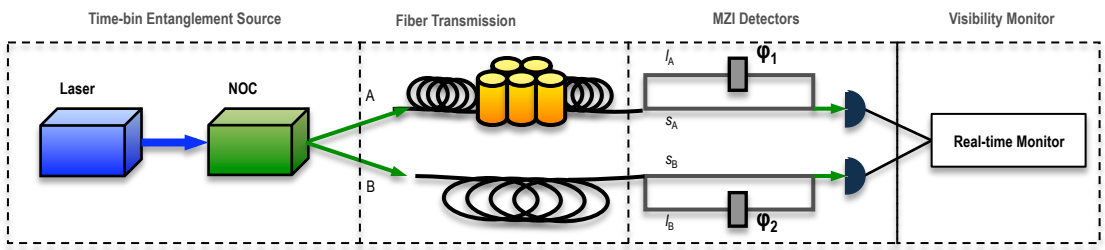
- Department of Energy Research and Development Center
  - Largest DOE open science lab; population 4,800 across 1809 hectares
  - Emphasis in computer science, material science, neutrons, and energy

- Quantum Information Science Working Group
  - Locus of research in quantum information
    - Quantum communication
    - Quantum sensing
    - Quantum computation
    - Quantum imaging

Multi-user Quantum Key Distribution



Quantum Optical Seals



Why GNU Radio?

- Leverage advantages of software-defined radio paradigm
  - Replace traditional, dedicated hardware with software-based systems
  - Advantage of being reusable, replicated at reduced cost
  - Advantage of being reconfigurable, tunable, exploratory

- The advantages for quantum communications
  - Avoid developing research-grade hardware that is quickly obsolete
  - Avoid hardcoding guesses to questions that are not answered yet
  - Rapidly prototype new applications, protocols, and error models
  - Provide a robust research-focused toolkit for enabling discovery

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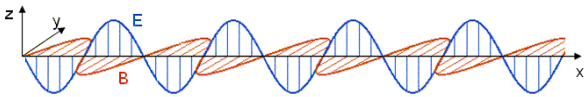
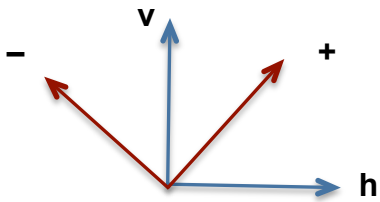
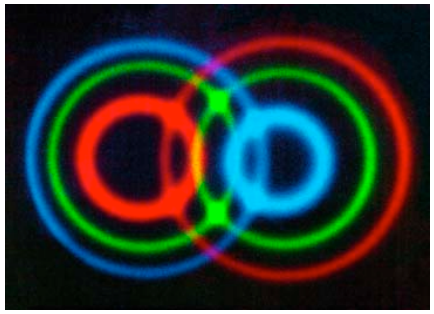
Why Quantum Optical Communication?

- Quantum Optical Communication
  - Encoding information into the quantum state of light
    - polarization
    - angular momentum
    - frequency
    - spatial mode
    - temporal mode
    - field quadratures
  - Special features of quantum information
    - No cloning: cannot be copied
    - Non-local correlations: spooky action at a distance
    - Squeezing: sub-shot noise limited detection



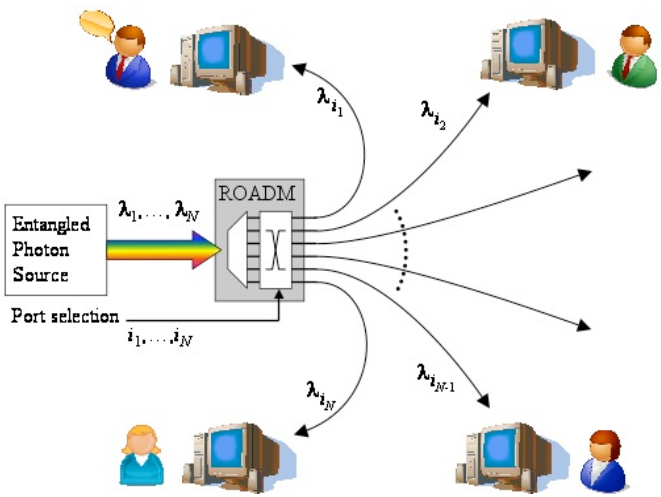


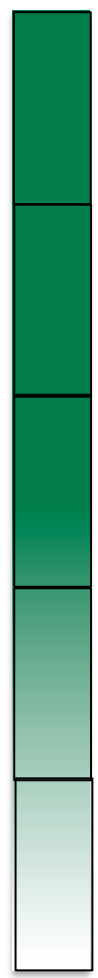


- Promise of Quantum Optical Communication
  - Quantum Key Distribution: Securely distribute cryptographic keys
  - Quantum Teleportation: Relaying quantum information
  - Quantum Optical Seals: Authenticating the integrity of an optical transmission

The Current State of Quantum Optical Communication

- Quantum Communication is relatively young
  - < 20 years of laboratory research
  - Lacks industry standards, but efforts are underway
  - Very few commercial implementations
  - Few commercial users
- Quantum Key Distribution





1911: quantum theory of blackbody radiation

1926: 'photon' invented

1936: quantum logic invented

1957: optical laser invented

1970: conjugate coding invented

1980: entanglement observed

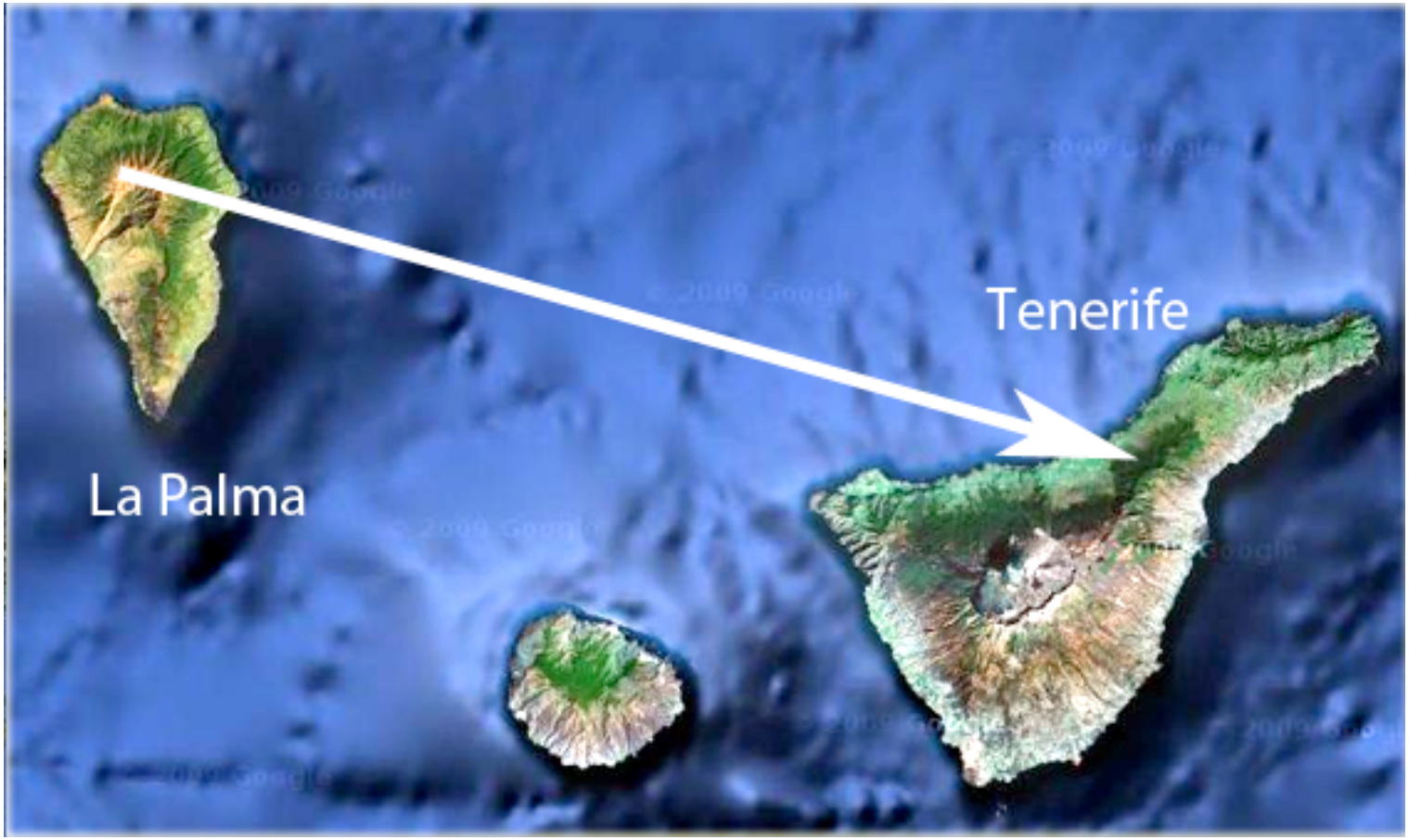
1984: BB84 QKD

1994: Shor's factorization alg.

2003: QKD Network Test beds

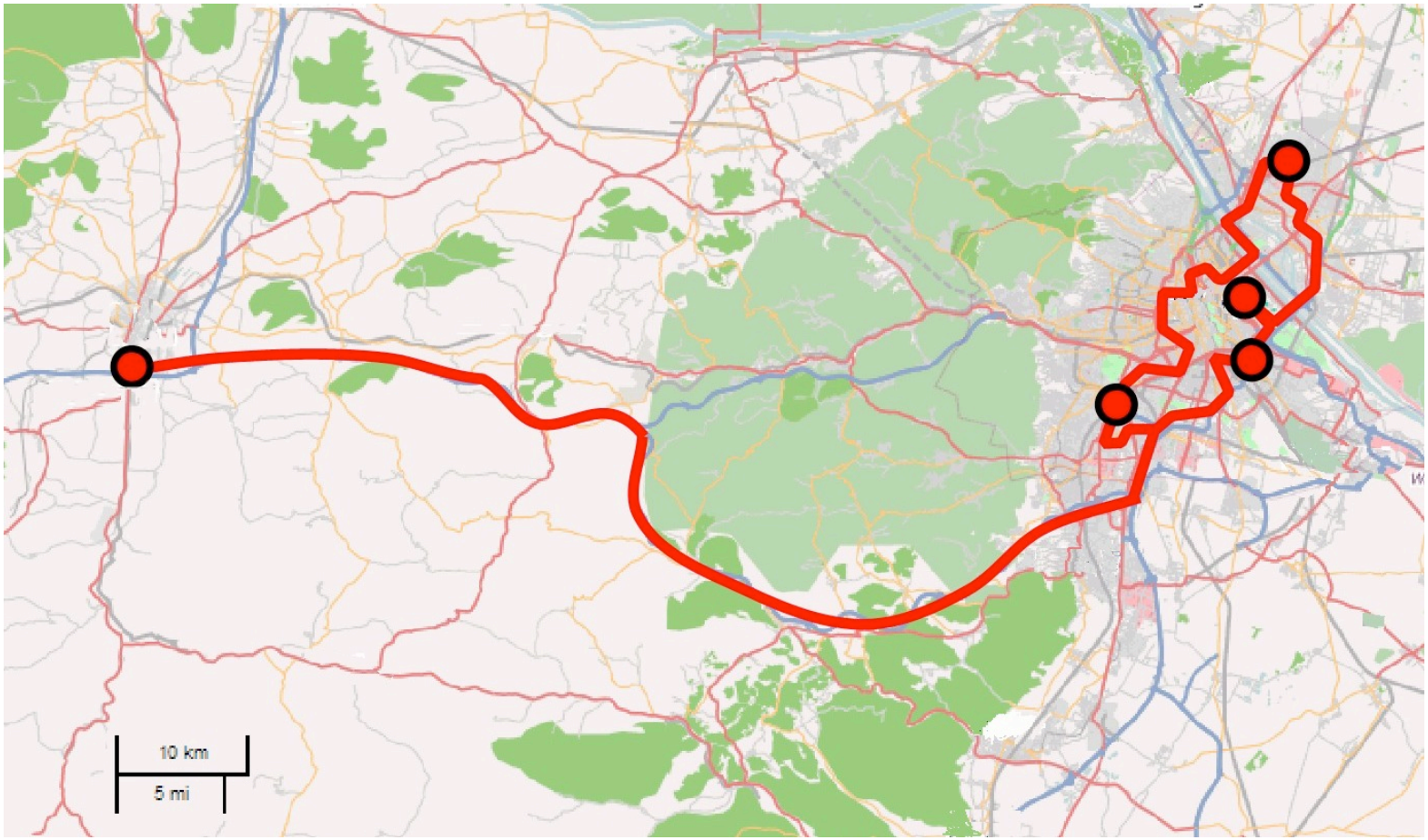
2011

Free-space Optical Channel



Point-to-point free-space QKD over the Canary Islands, 1.8 bit/s @ 144 km by European consortium, 2006-2007

Fiber-based Computer Network



Fiber-ring network in Vienna support QKD base stations, 11kbps @ 20 km by SECOQC consortium, 2004-2010

Fiber-based Commercial System

Quantum Stadium project at 2010 World Cup South Africa,
1kbps @ 25 km by IdQuantique Cerberis

Tokyo QKD Research Network

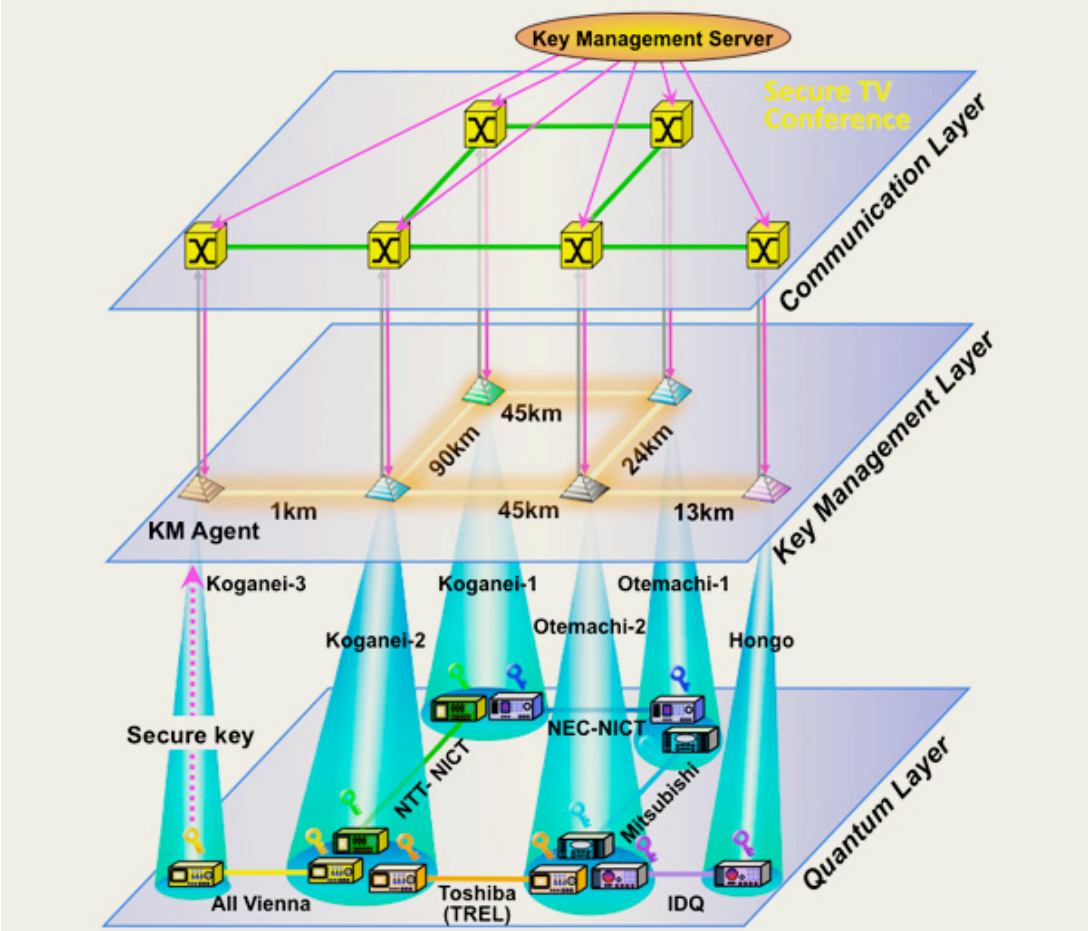
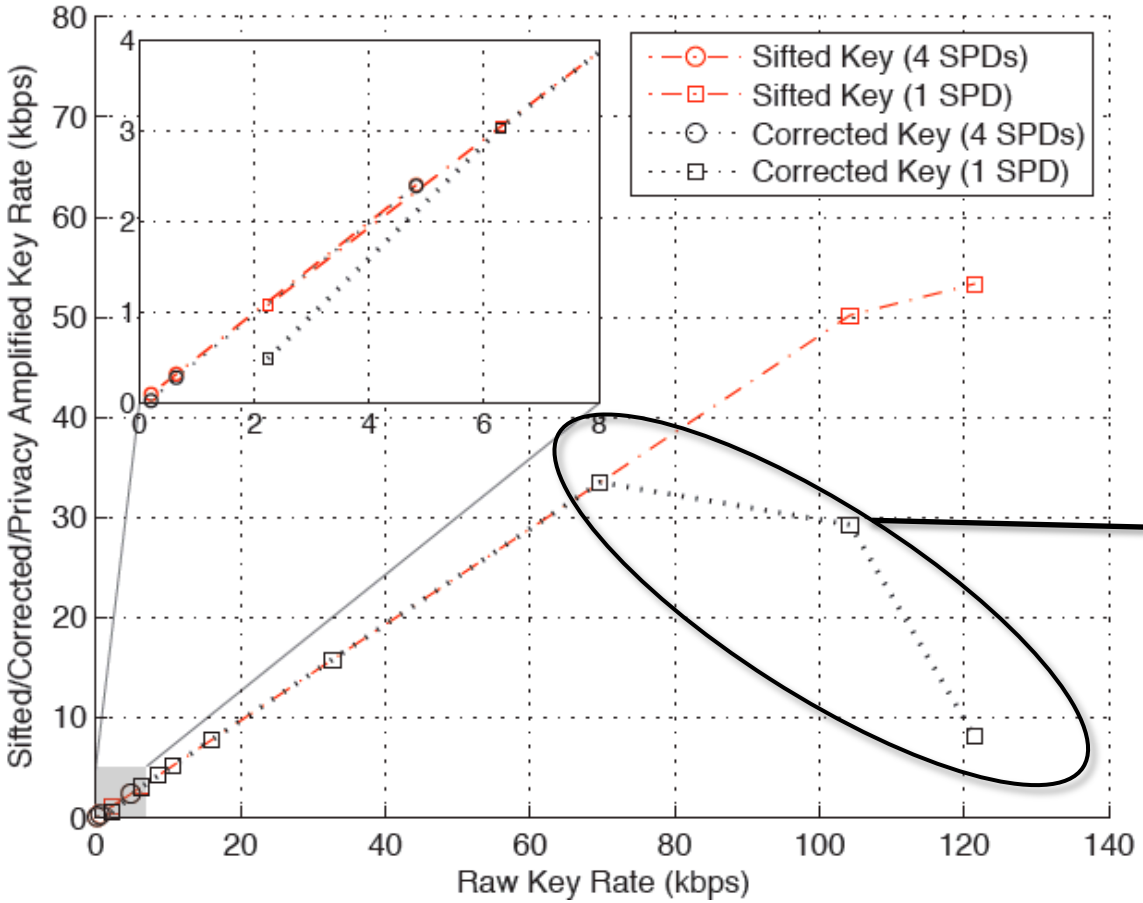


Fig. 2 Network Layer Structure of the Tokyo QKD Network

Metro-area fiber-based network demonstrated by NEC, Mitsubishi, NTT, Toshiba, and others, 40-300 kbps @ 24-90 km

Turn over example

- Figure 3 from “Time-cost analysis of a quantum key distribution system clocked at 100 MHz”, Z. E. Mo et al., Optics Express **19**, 17729-17737 (2011)



Processing can’t keep up with acquisition

Adopting a GNU Radio Paradigm

Hardware Frontend

- Detector converts photons to electrical signals
- Material varies with wavelength

Hardware Backend

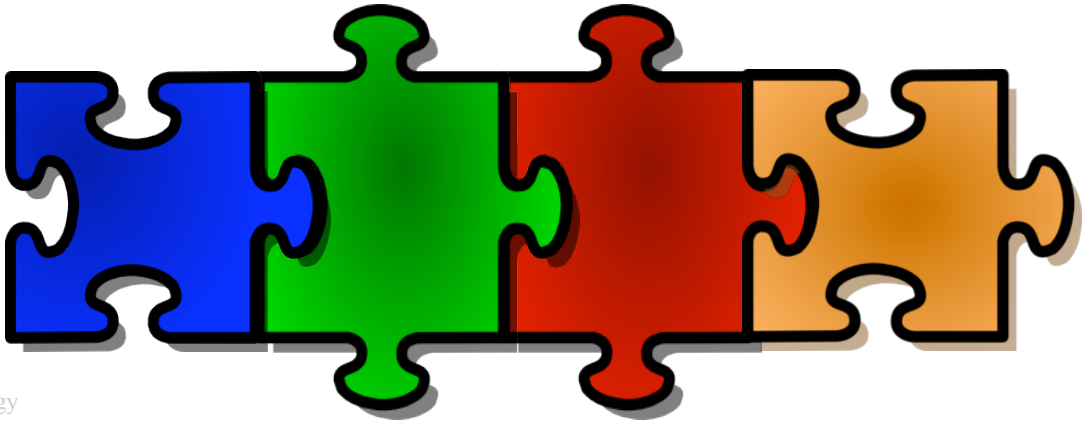
- Process raw electrical signals
- Clocking/synchronization
- Some logic
- Normalizes output

Software backend

- Device driver for hardware backend
- Handle setups, shutdowns, data transfers

Software frontend

- Software-defined signal processing applications
- Standardized API



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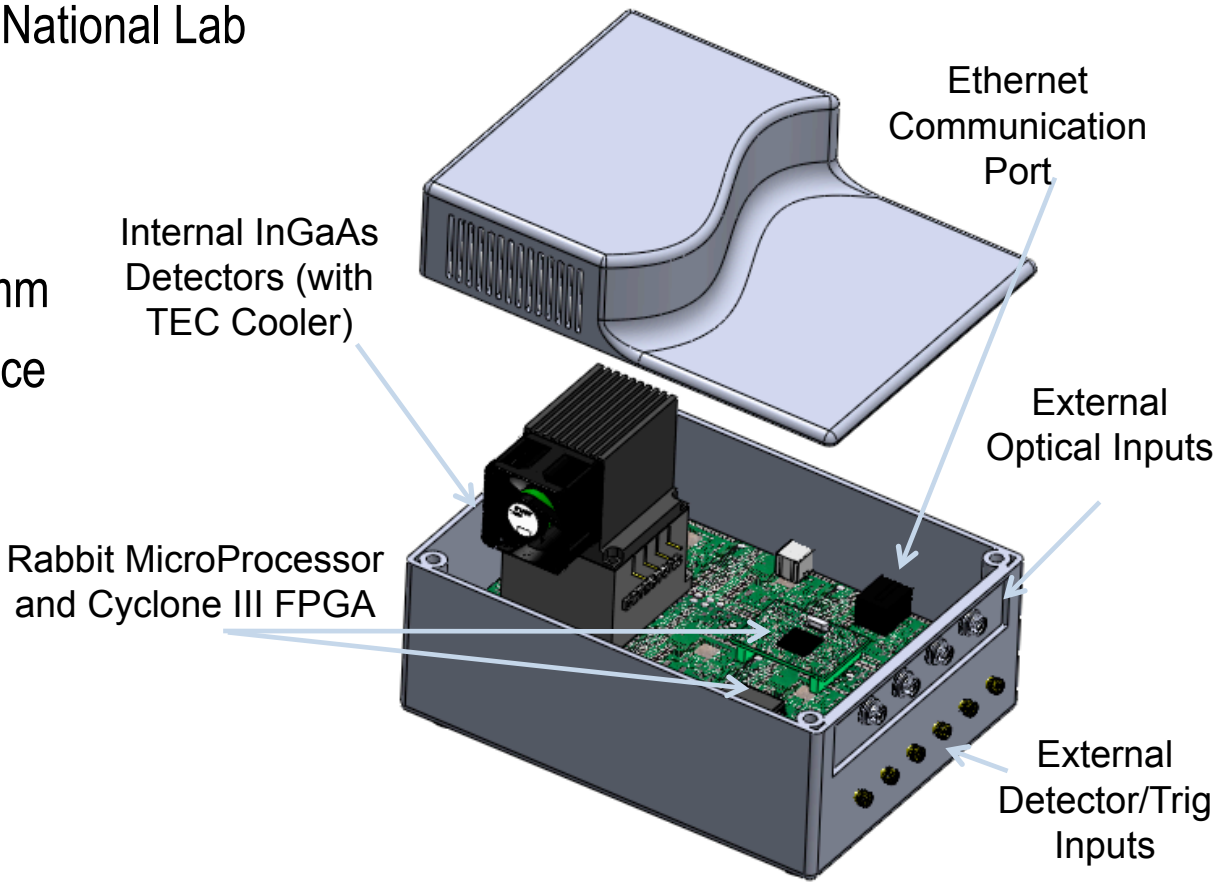
Quantum Optical Hardware

- ORNL single-photon detectors
- DEED: Duncan Earl's Everything Detector
  - Duncan Earl, Oak Ridge National Lab
- Hardware frontend
  - Single-photon detectors
  - InGaAs: Infrared/Telecomm
  - Si-APD: Visible/Free-space
- Hardware backend
  - Self-differencing circuit
  - Amplifier, comparator
  - Coincidence counting
  - Timestamping
  - FPGA+Microcontroller



Software-defined Quantum Comms

- Quantum Information Tool Kit for Application Testing (QITKAT)
  - GNU Radio-based quantum communication library
  - Developed at ORNL, ongoing (10 Months in)
  - Specialty blocks for handling time-stamped data measured in conjugate bases
  - 64-bit data type: 60-bit counter/metadata, 4-bits for measurements
  - Use _q for quad word (unsigned long long int)
  - List of Blocks from `dir(qitkat)`
    - `timestamp_source_q()`
    - `timestamp_sink_q()`
    - `random_symbols_b()`
    - `entangled_symbols_b()`
    - `fpga_source_q()`
    - `timesync_qq()`
    - `entropy_bf()`
    - `ber_bf()`
    - `bsc_bf()`
    - `visibility_ff()`
    - `detection_ff()`
    - `correct_qq()`
    - `encode_qq()`
    - `sendlist_qq()`
    - `fetchlist_qq()`
    - `coset_qq()`
    - `checkbits_qq()`
    - `discard_qq()`

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QITKAT Classes

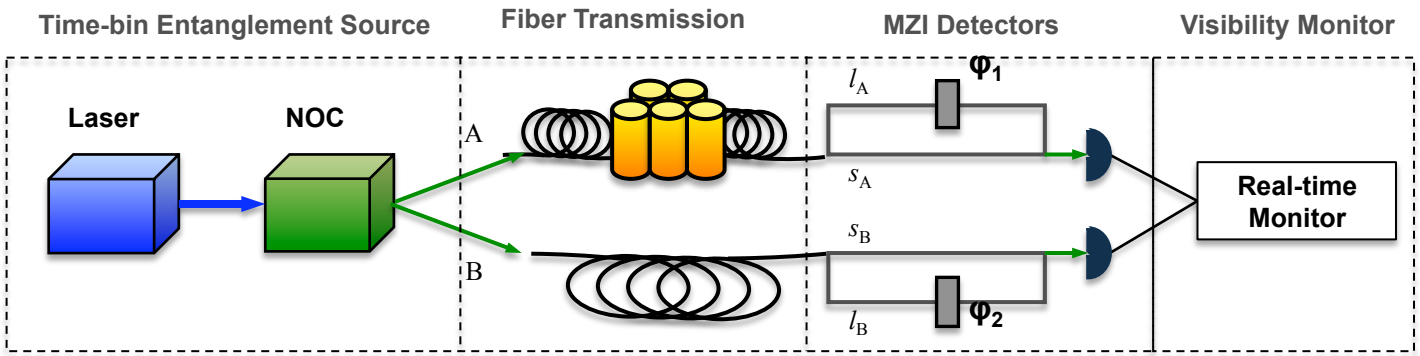
```
// output entries of data as timestamps
timestamp_source_q(uint64_t &data);

// store entries of data as timestamps
timestamp_sink_q(uint64_t &data);

// output uniform random entries of alphabet
random_symbols_b(uint64_t &alphabet, uint32_t seed);

// output uniform random, but correlated entries of alphabet
entangled_symbols_b(uint64_t &alphabet, float correlation, uint32_t seed)

// fetch packetsize data from ipaddr:port using sockets
fpga_source_q(char *ipaddr, char *port, char *packetsize);

// cross-correlate two input streams using sync_length samples every sync_period
timesync_qq(uint sync_length, uint sync_period);

// output either single (joint) entropy of one (two) input stream(s)
entropy_bf(uint32_t num_items);

// output bit error rate between two input streams
ber_bf(uint32_t num_items);

// output result of binary symmetric channel
bsc_bf(float error_rate, uint23_t seed);
```

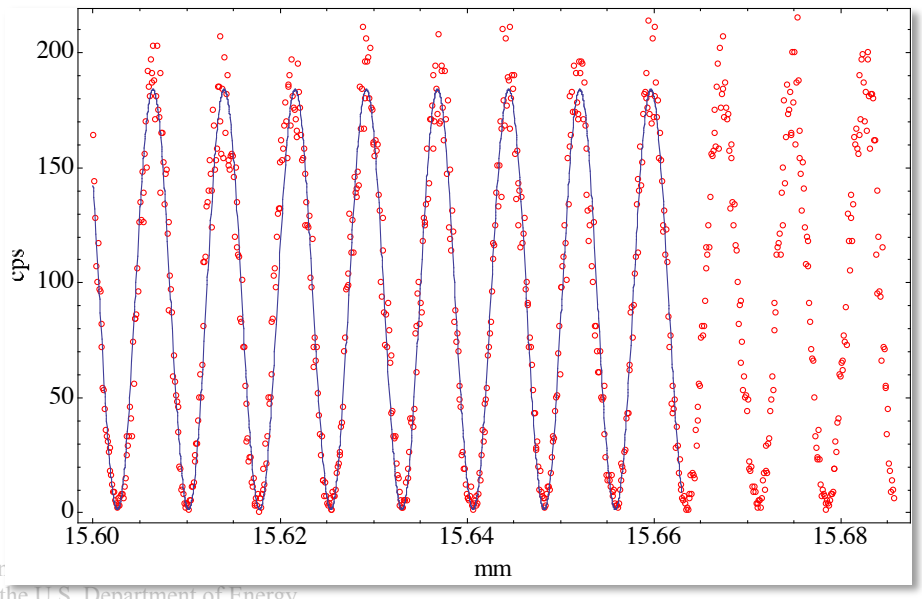
QITKAT Classes

```
// output visibility contrast over window_size samples every step_size samples
visibility_ff(uint32_t window_size, uint32_t step_size);

// output prob. of detection, prob. of false alarm for noise and threshold
detection_ff(float noise, float threshold);

// output error correction using n-by-m generator matrix g
decode_qq(uint32_t n, uint32_t m, uint32_t &g);

// output error encoding using n-by-m generator matrix g
encode_qq(uint32_t n, uint32_t m, uint32_t &g);

// output input after sending list of size element to ipaddr:port
sendlist_qq(char *ipaddr, char *port, uint32_t size);

// output input and list of size elements retrieved from ipaddr:port
fetchlist_qq(char *ipaddr, char *port, uint32_t size);

// output coset of C2 in C1 with input
coset_qq(uint32_t n, uint32_t m, uint32_t &g);

// output unchecked bits after sending errors to ipaddr:port
checkbits_qq(char *ipaddr, char *port);

// output good bits after receiving errors from ipaddr:port
discard_qq(char *ipaddr, char *port)
```

Example: Quantum Optical Seals

- Monitoring integrity of fiber-based transmission of entanglement
  - Absence of non-local correlations indicates intercept-resend attack, intrusion





Presence of entanglement quantified by visibility.

Absence of entanglement signifies an intrusion.

Quantum Seals QITKAT Results

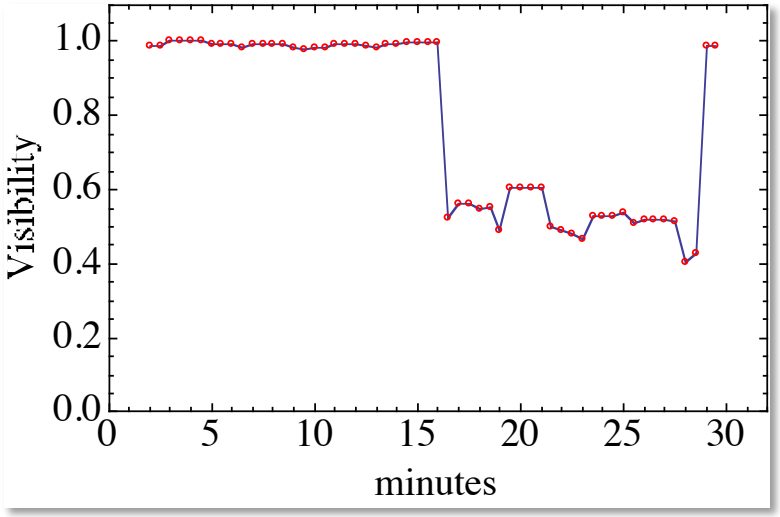
- Entanglement Monitoring: sensing intrusions

fpga_source_q(n) → visibility_qf(n) → detection_ff(n) → alarm_sink_f(n)

visibility.py source code

```
# visibility.py
...
# Source of data
src = gr.vector_source_f(data);

# Compute visibility as (max - min)/(max + min)
vis_window = 120;
vis_step = 30;
vis = qitkat.visibility_ff(vis_window, vis_step);
vissnk = gr.vector_sink_f();

# Compute pdet, pfar
threshold = 1.;
noise = 0.1;
det = qitkat.detection_ff(noise, threshold);

# Sink for running average
snk0 = gr.vector_sink_f();
snk1 = gr.vector_sink_f();
```

Output of visibility.py
running average 120/30

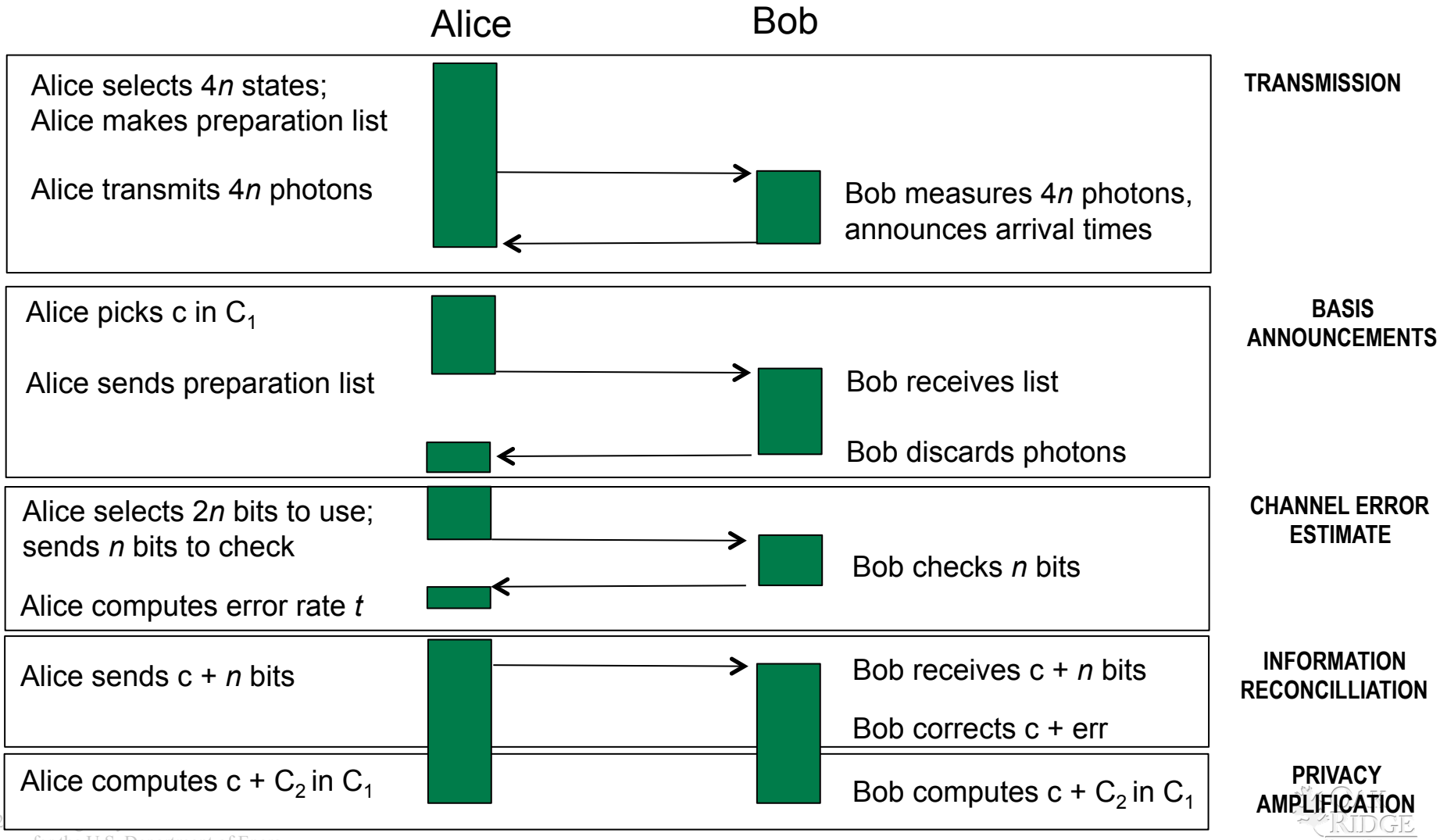


Example: Quantum Key Distribution

- Quantum Communication Protocol:
  - Two separated users, Alice and Bob, securely distribute a one-time pad
  - Consists of 5 distinct phases
    - Transmission
    - Basis Announcements
    - Channel Error Estimate
    - Information Reconciliation
    - Privacy Amplification
  - Many different variants
    - Interaction/communication
    - Processing power
    - Error corrections codes

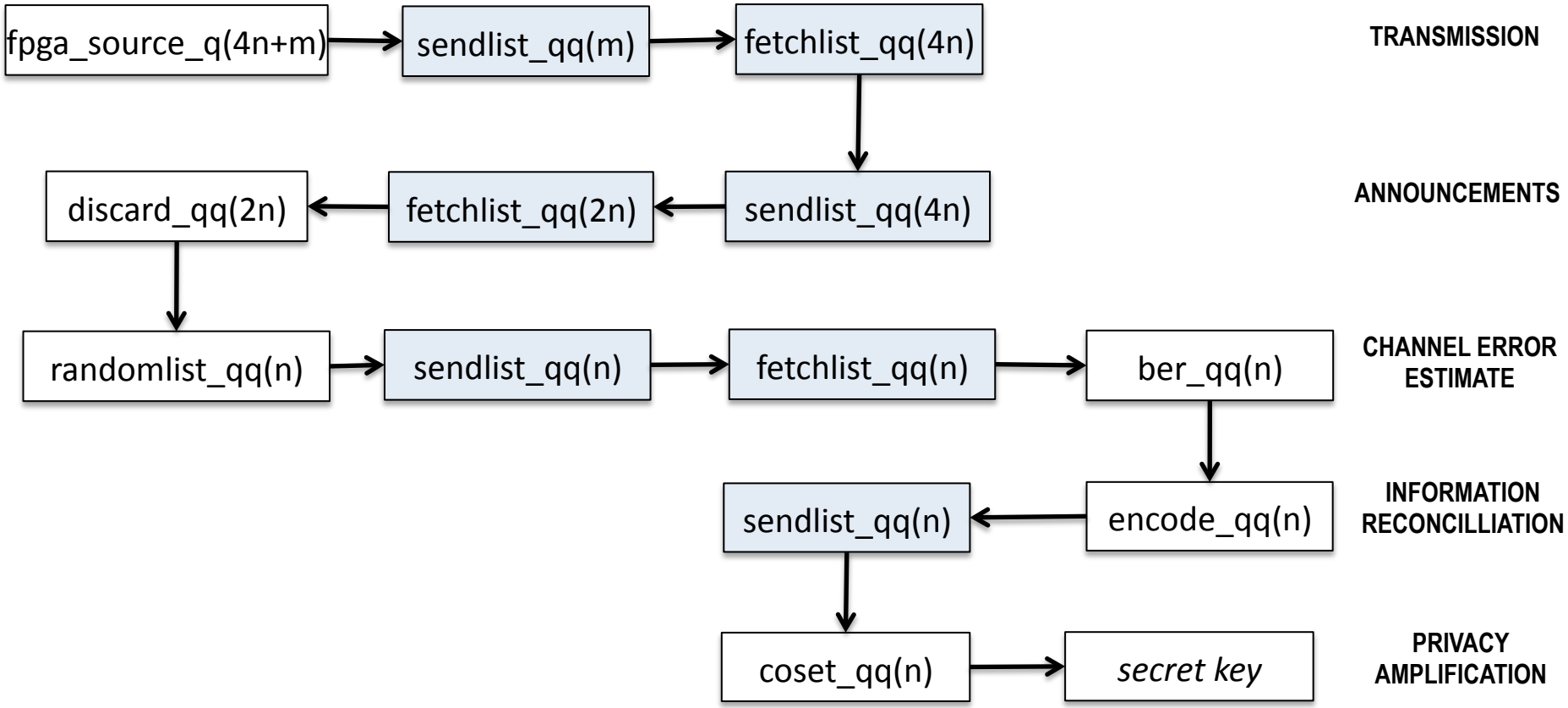
Example: Quantum Key Distribution

- BB84 point-to-point quantum communication (Bennett and Brassard, 1984)



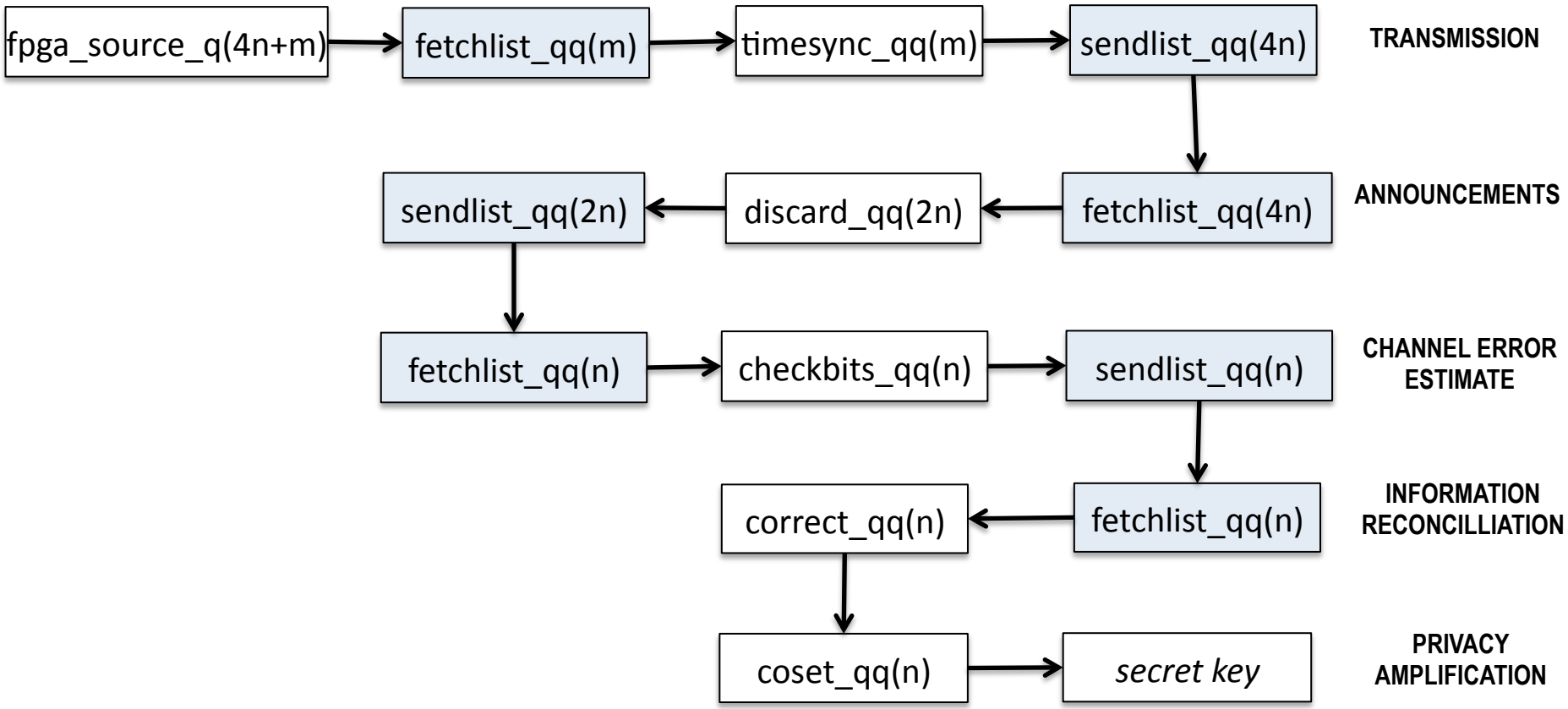
QKD QITKAT Flow Graph

- BB84 Server Side (Alice)



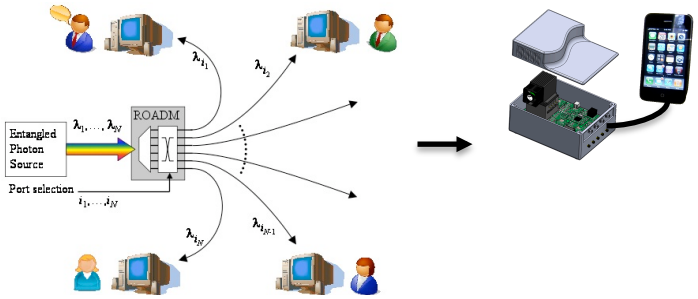
QKD QITKAT Flow Graph

- BB84 Client Side (Bob)



GNU Radio for Quantum Optical Communication

- Summary: Developed QITKAT and DEED's for demonstrating software-defined quantum communication protocols
  - DEED: Single-photon detector integrated with microcontroller
  - QITKAT: GNU Radio-based toolkit for prototyping quantum protocols
  - Quantum Optical Seals
  - Quantum Key Distribution



- The Road Ahead:
  - Demonstrations with DEED's
  - Expansion of QITKAT to other protocols
    - Less interactive QKD protocols

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