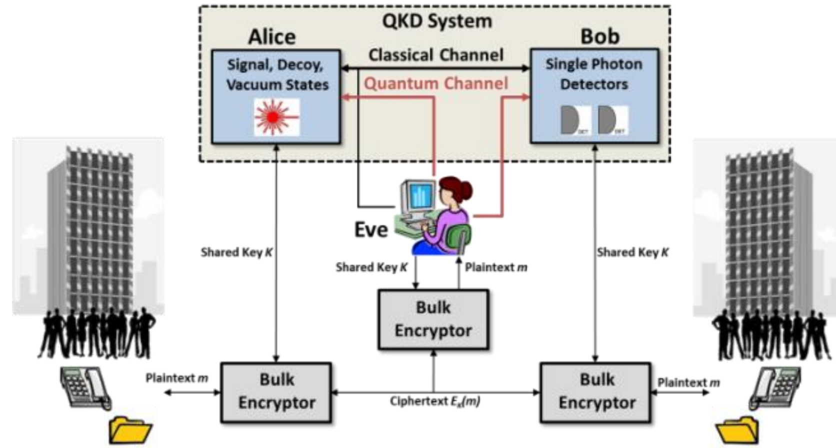
Modeling Quantum Optical Components, Pulses & Fiber Channels Using OMNeT++



Quantum Key Distribution (QKD) System

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Overview

- Motivation: Quantum Key Distribution (QKD)
- Framework Packages & Organization
- Optical Pulses
- Optical Components
- Fiber Channels
- Testing
- Simulation Studies
- Publications

QKD System Operation / Protocol

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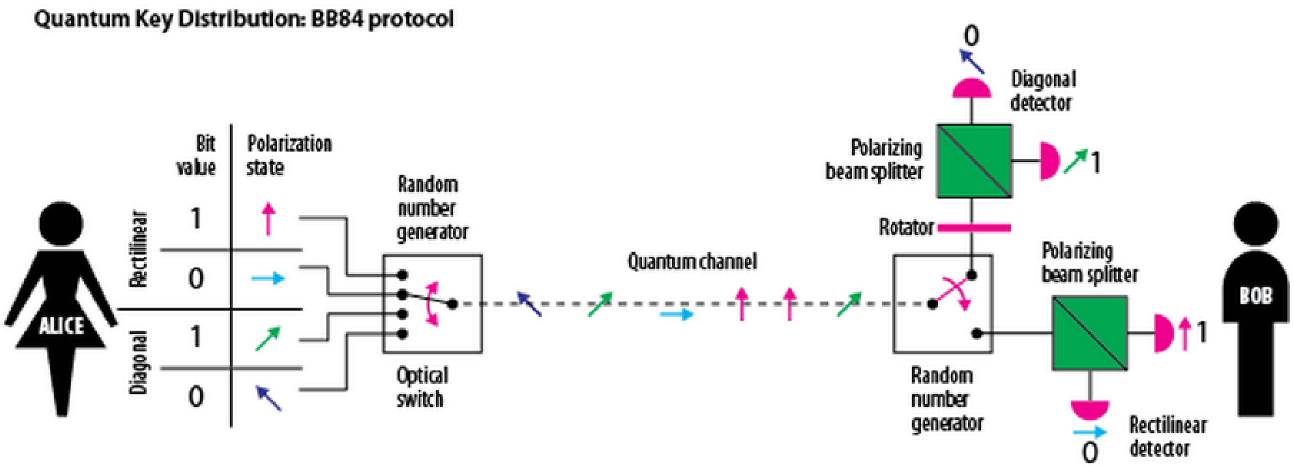

Quantum transmission & detection	ALICE sends photons	↖	↗	→	↑	↑	↗	↖	↑
	ALICE's random bits	0	1	0	1	1	1	0	1
	BOB's detection events	↑	↗	↖	↑	↗	↗	↖	↖
	BOB's detected bit values	1	1	0	1	1	1	0	0
Public discussion (i.e., sifting)	BOB tells ALICE the basis choices he made	Rect	Diag	Diag	Rect	Diag	Diag	Diag	Diag
	ALICE tells BOB which bits to keep		✔		✔		✔	✔	
	ALICE and BOB's shared sifted key	–	1	–	1	–	1	0	–

- Innovative technology which **exploits the laws of quantum mechanics** to generate and distribute unconditionally secure cryptographic keys
- Unique in its ability to **detect the presence of an eavesdropper** attempting to subvert the distribution of key material
- Protocol **assumes certain idealities** with regard to pulse generation and detection

System Architecture

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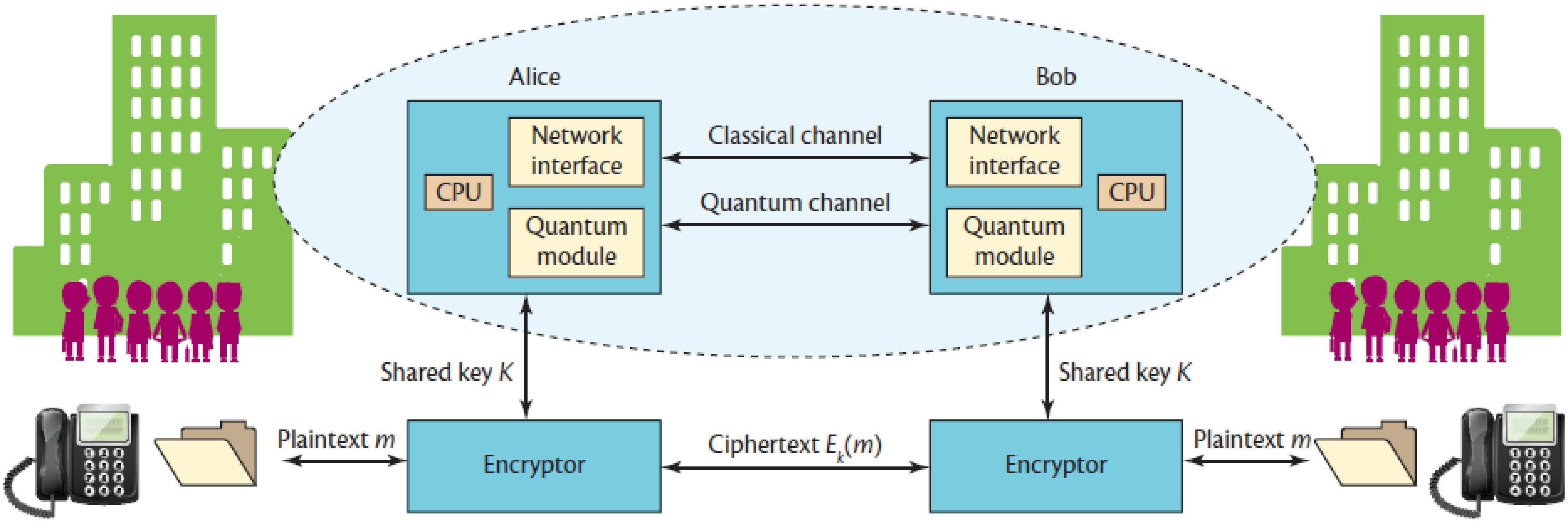
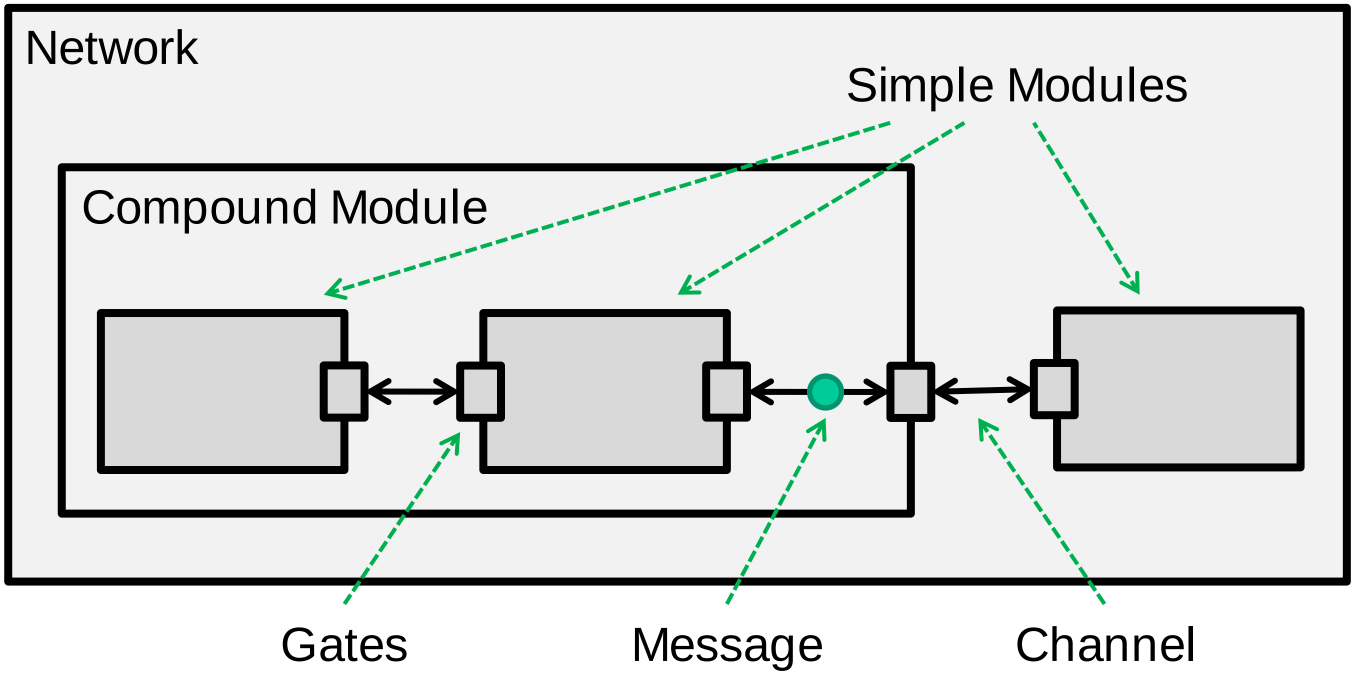


- Motivation: simulate various system designs/architectures to understand the effects of ‘non-idealities’ on security and system performance
- Need to model: optical components (laser, beamsplitters, fiber channels, etc.), optical pulses, detectors
- System architecture easy to describe as a hierarchy of modules/components
- Created a framework to model these types of components (i.e., ‘qkdX’ framework)

OMNeT++ Modeling Concepts



- Simple modules define behavior
- Compound modules are used to assemble a hierarchy
  - A network defines the system of interest (no gates)
- Gates define interface points – data (messages) flows through channels

qkdX Modeling Concepts

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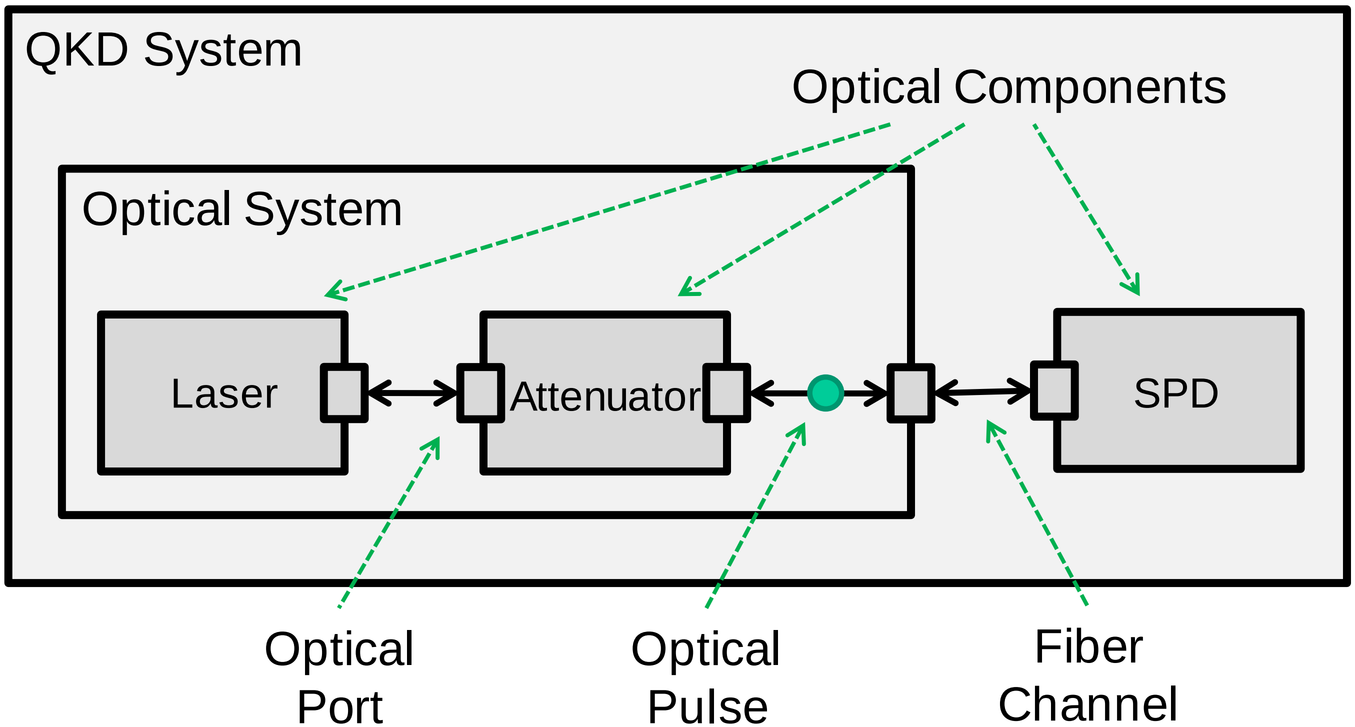

qkdX Classical Pulse Generator

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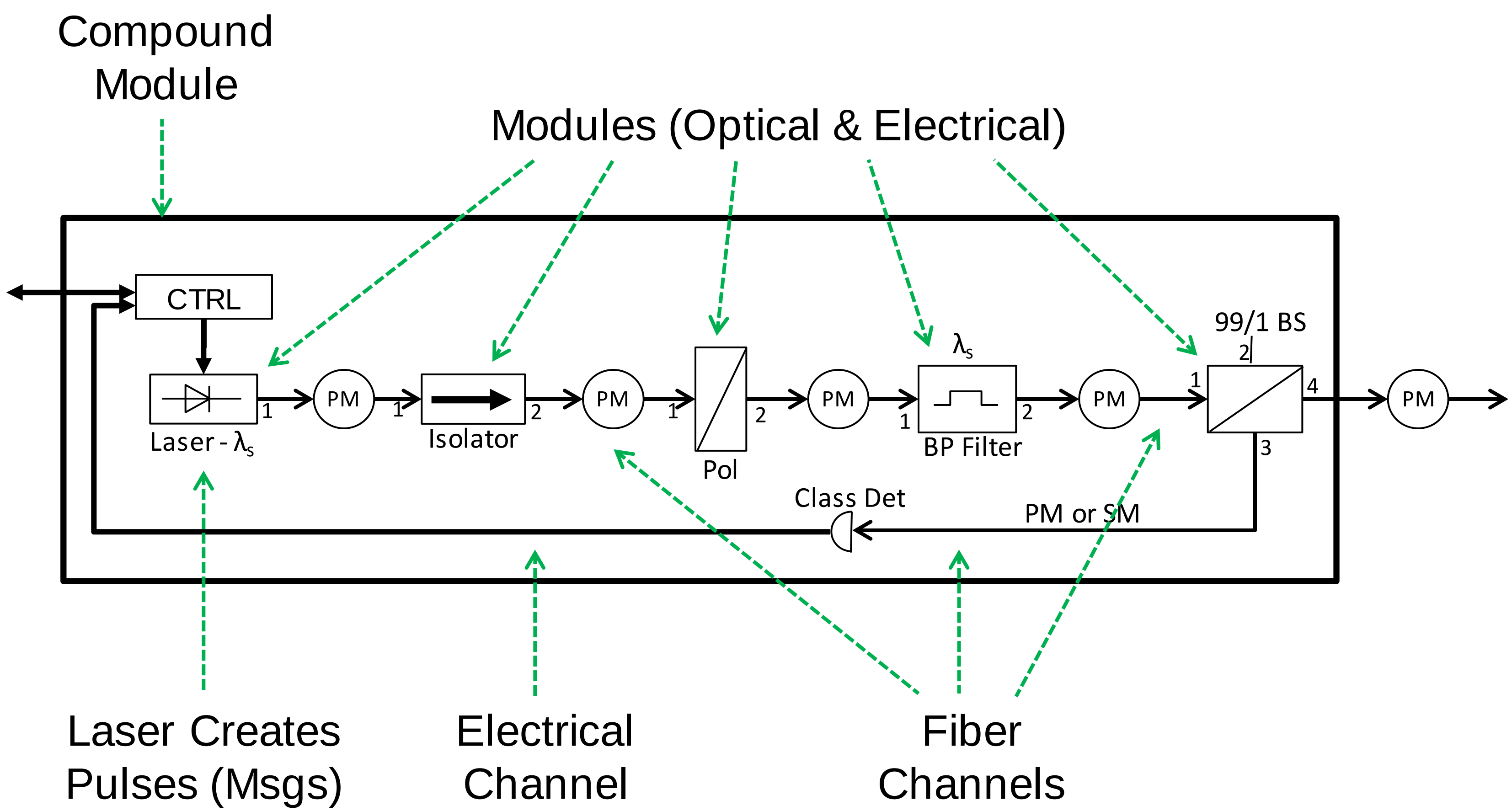
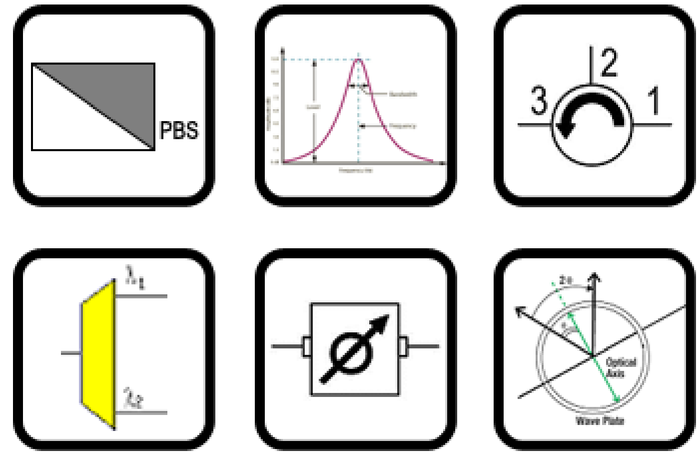


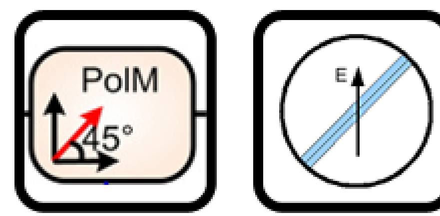
Modeled components must account for mathematics, state, data flow and timing

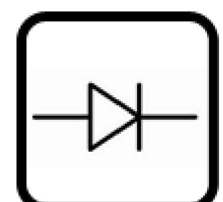
qkdX Components

Each component has multiple attributes:

- Type
- Active or Passive
- Number connections
- Type of connections
  - Input / Output / Bidirectional
  - Optical, Electrical, or Environmental
- Temporal behavior (OMNeT++)
- Functional behavior (C++)
- Component aging
- Failure modes (degraded/damaged)
- Parameterization depends upon abstraction







Package Relationships

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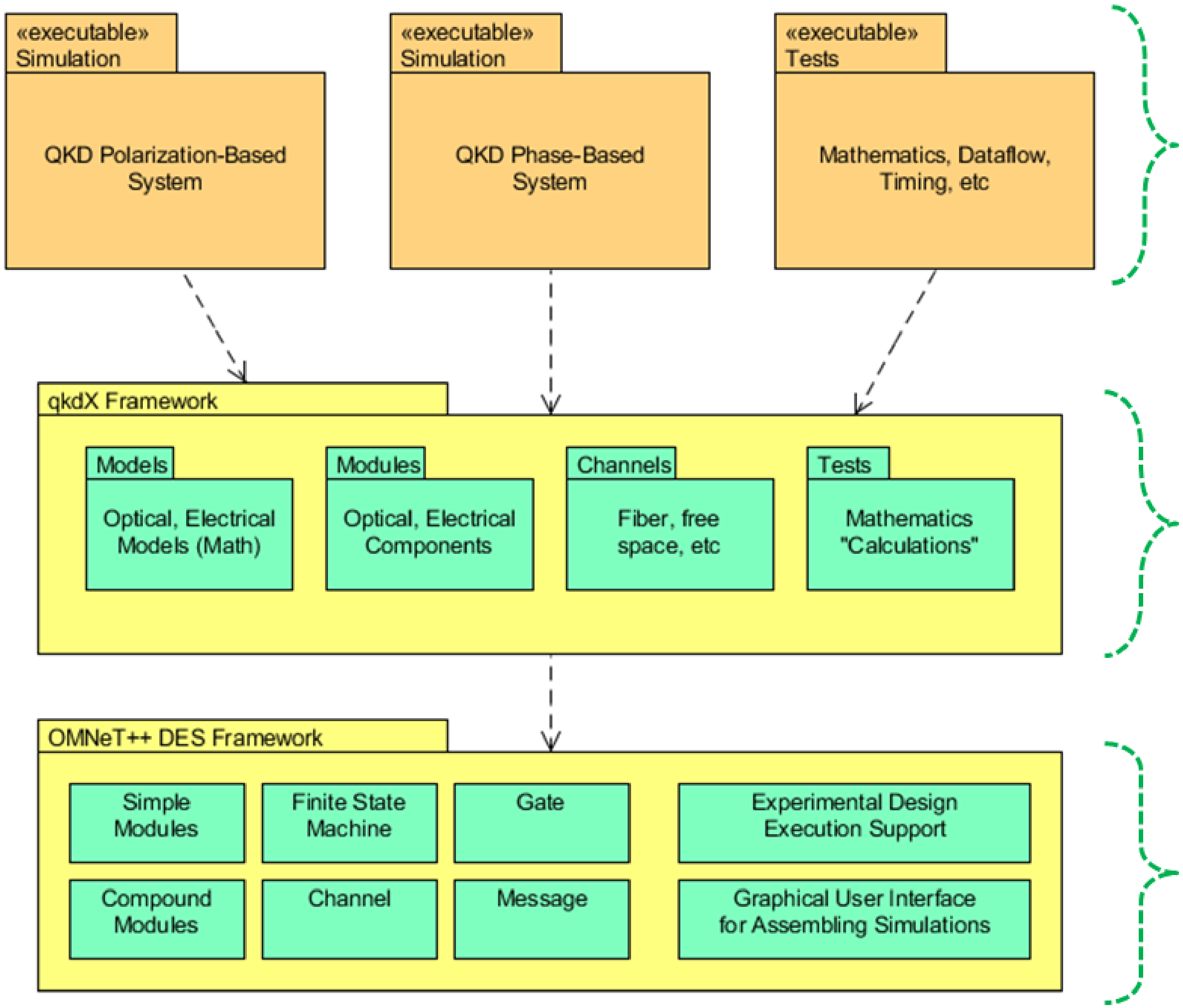
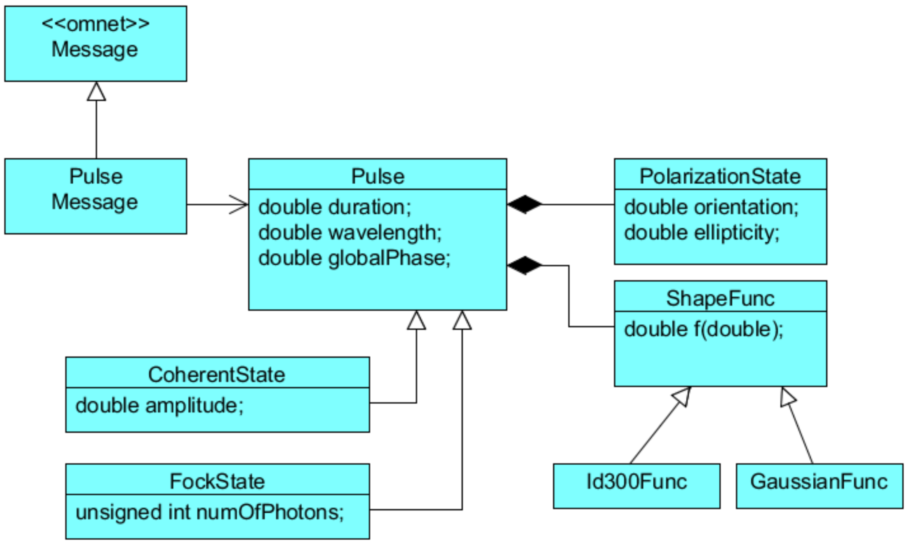


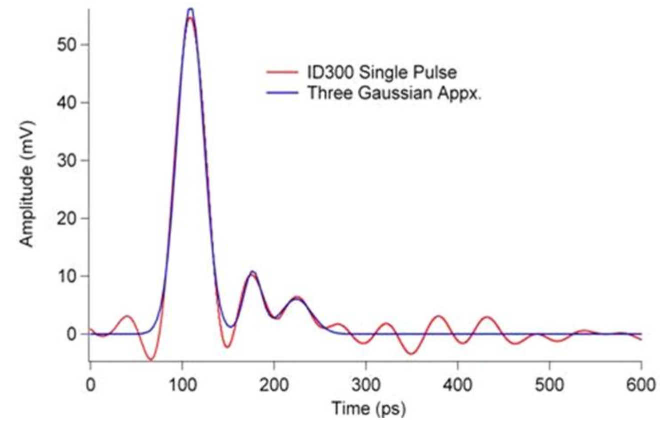
Simulation Products
Unique "applications" or system architectures

qkdX Framework
Defines system models and components common to many different architectures. Defines system abstractions to support different levels of fidelity/detail.

DES Framework (C++)
Provides fundamental infrastructure to build and interconnect system components

Optical Pulse Representation





Example Pulse Representation

- Pulses encoded as messages
- Custom pulse message class created to manage pointer to actual pulse object
  - A variety of pulse objects have been created
  - The shape of pulses are described by functor-like objects

Optical Components

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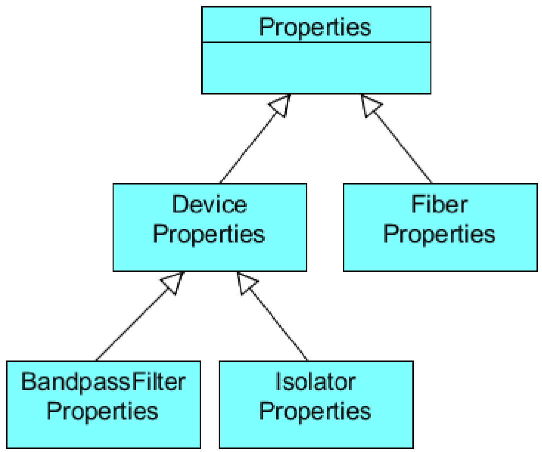
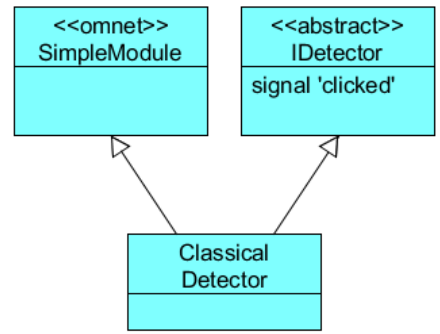


Properties



Interfaces

- Optical components are structured as simple modules
  - Need to account for mathematics (pulse transformations), component state (e.g., damaged), dataflow (physical path pulse traverses and reflections), and timing (propagation delay)
- Much of the code structured so that simple modules facilitate data flow and timing
  - State of components represented by different types (i.e., properties)
- Interfaces (mostly abstract classes) are defined to represent types (and support a public API)
  - Simple modules are viewed as a structuring concept (i.e., not as a 'type')

Fiber Channel

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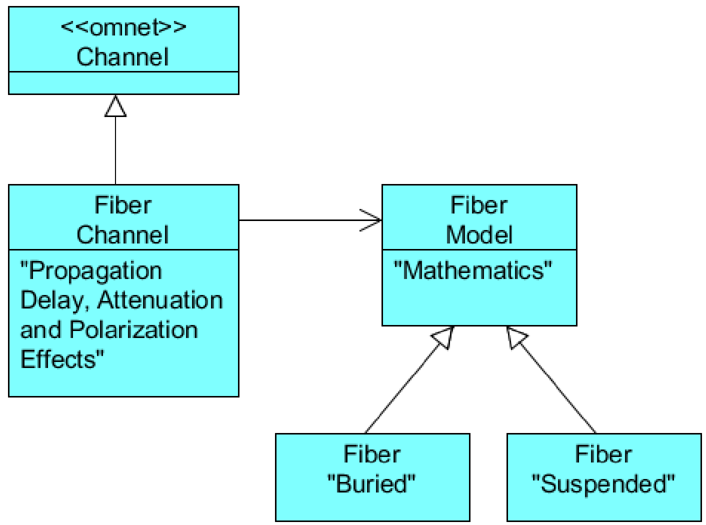
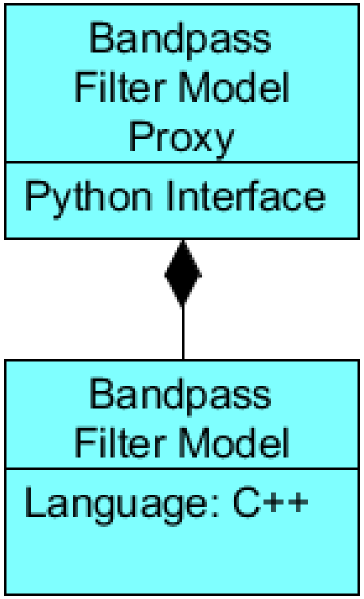


- Fiber channels are implemented as a custom Channel
  - They add 'behavior' to the flow of pulses between components (e.g., attenuation, delay, polarization drift effects, etc.)
  - They include optional 'smarts' to delete pulses below a certain energy level (prevent infinite reflections between components)

Testing



- Mathematics (pulse transformations)
- Component state (e.g., damaged)
- Dataflow (physical path pulse traverses)
- Timing (propagation delay)

- The mathematical calculations/transformations associated with component models does not require reside with simple modules
  - They are simple math functions that can be compiled separately into a library and called from Python
    - SWIG tool was used to generate proxy information
  - Python made it easier to 'script' extensive test cases to ensure this aspect of code is implemented correctly

Example Simulation Studies

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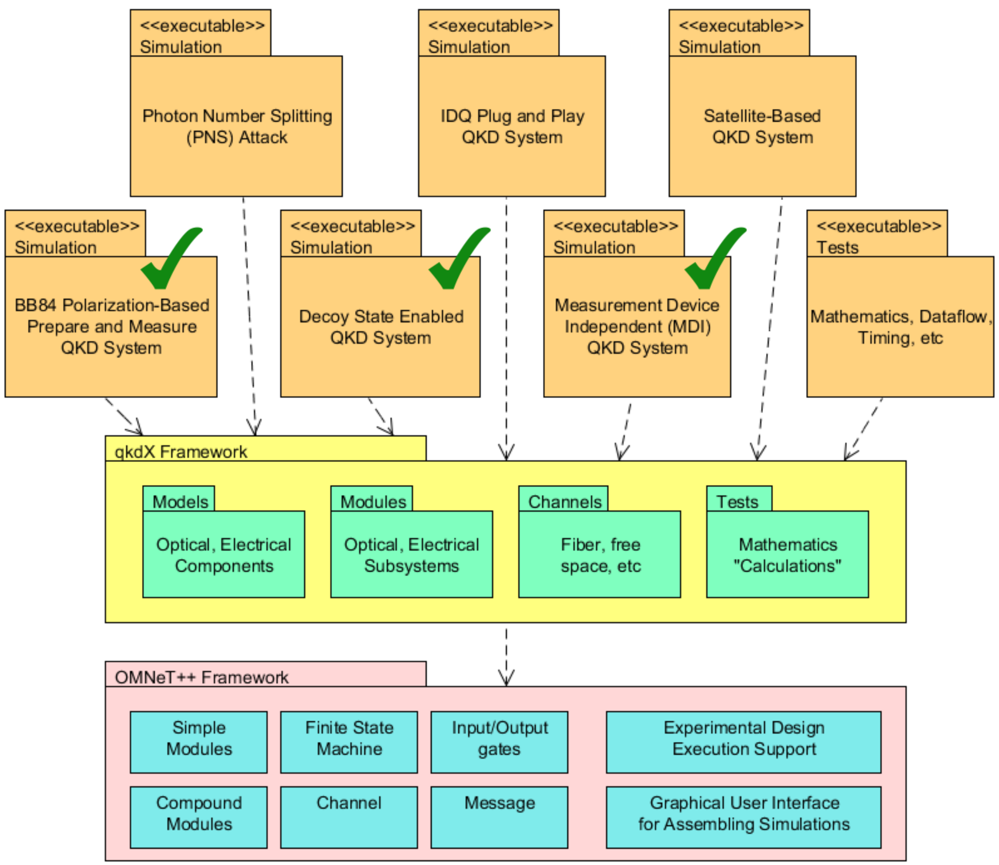

The variety and diversity of products have grown to support a number of Master and PhD thesis students resulting in a number of publications (provided at the end)

Examples:

- Development of a BB84 reference architecture
- Decoy state enabled system designs
- Measurement device independent systems

BB84 Reference Architecture

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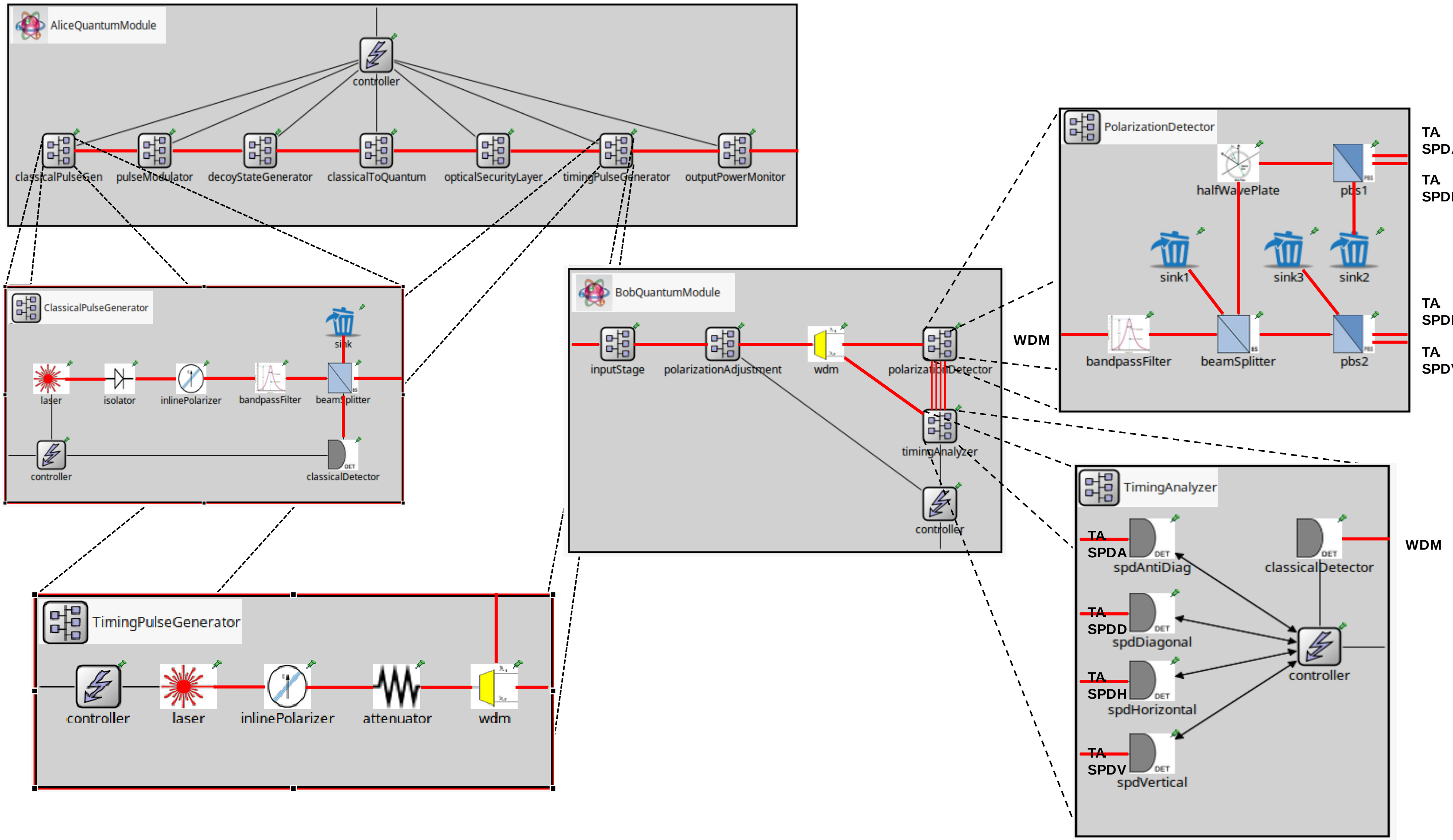
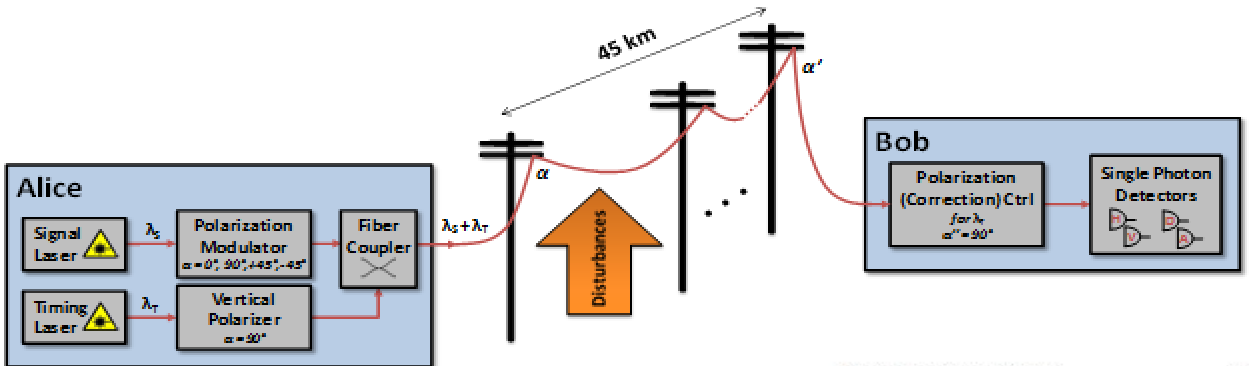
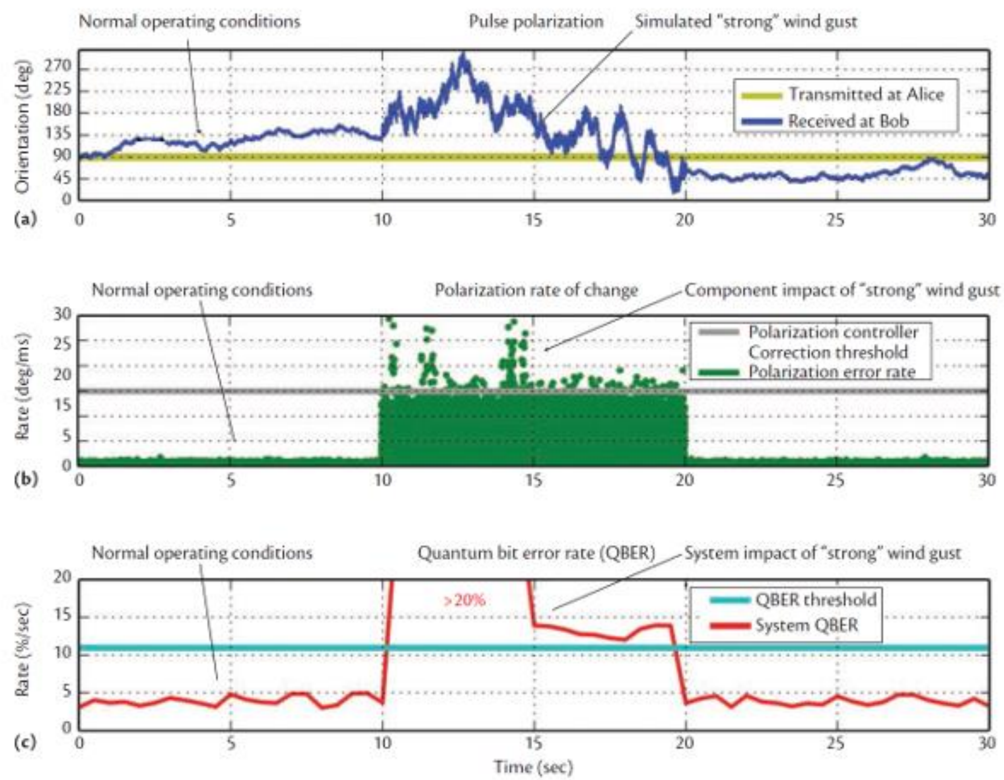
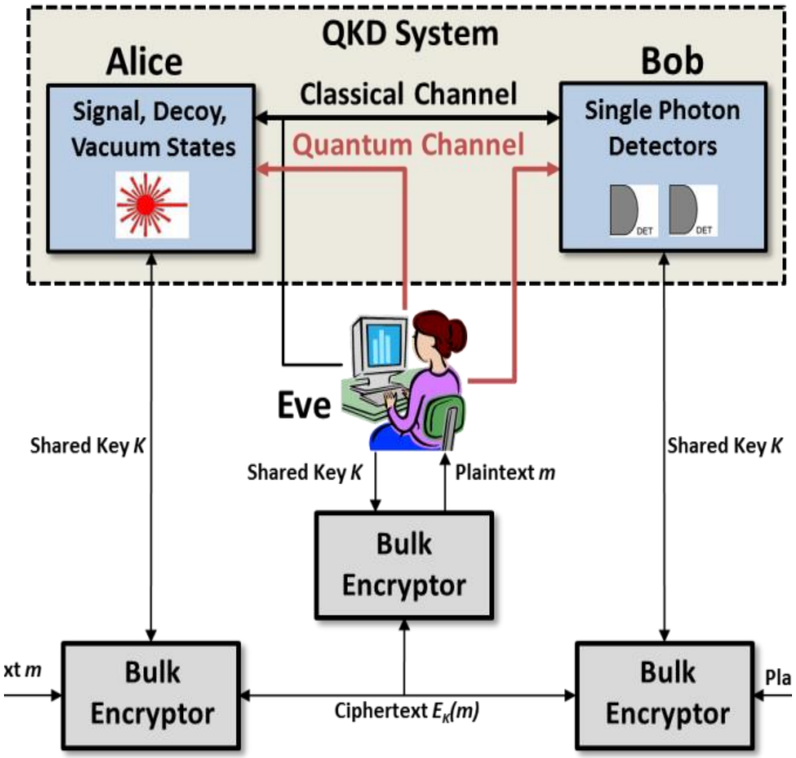


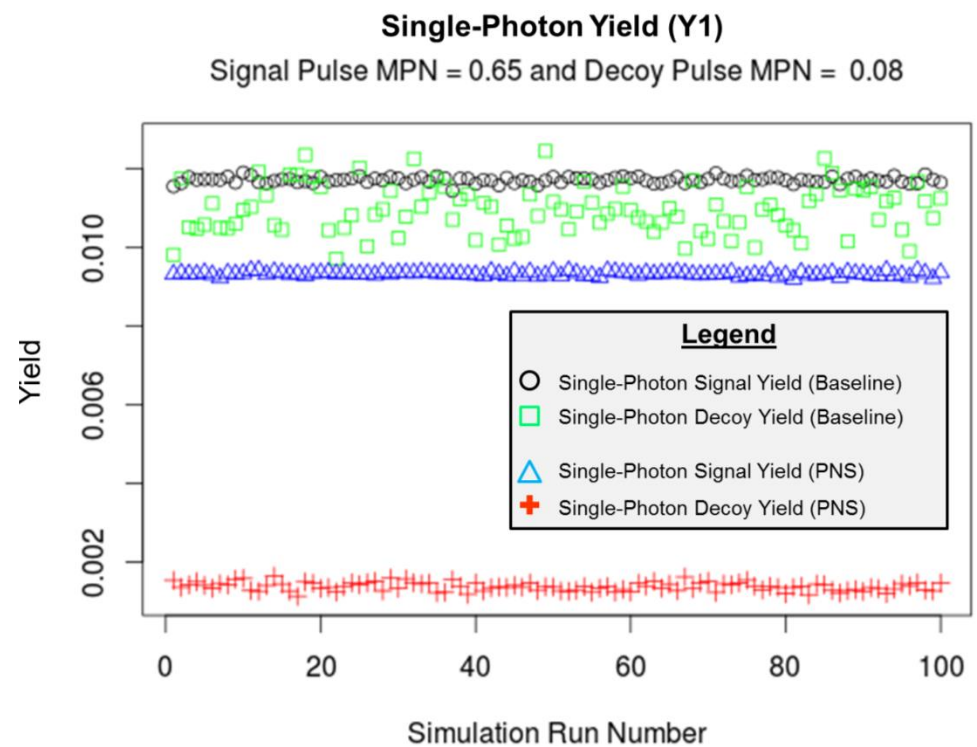
Polarization Drift





Decoy State Enabled QKD





Measurement Device Independent QKD

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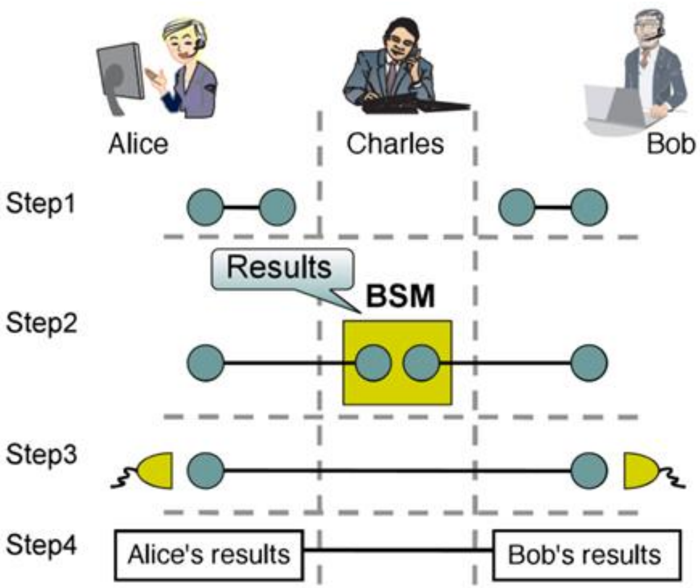
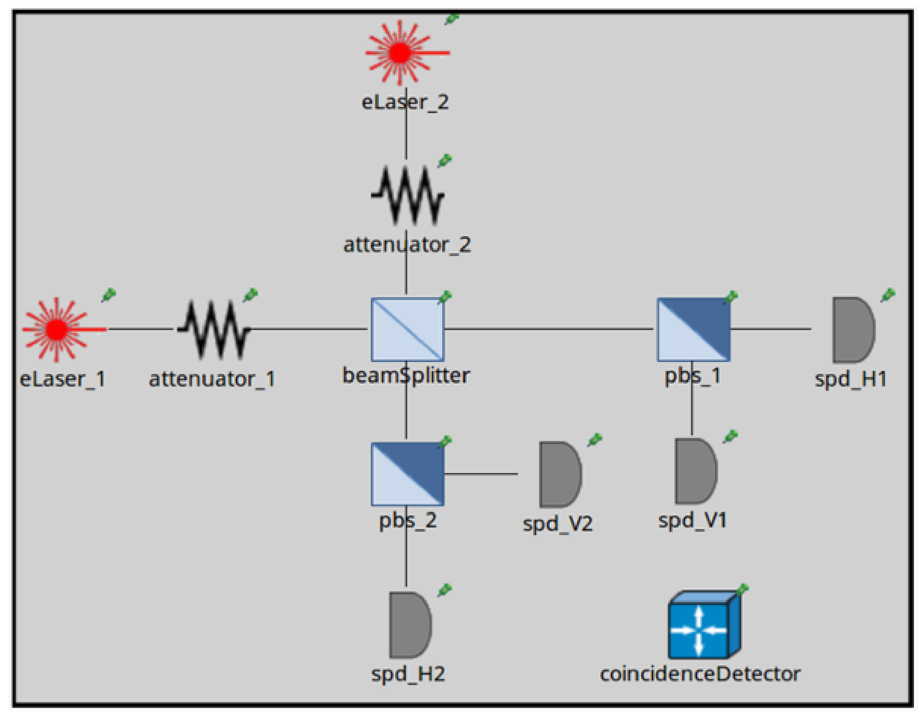


F. Xu, M. Curty, B. Qi, and H.-K. Lo, "Measurement-device-independent quantum cryptography," IEEE Journal of Selected Topics in Quantum Electronics, 2014.



Publications

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- **Archival Journals**
- Mailloux, L.O., Hodson, D.D., Grimaila, M.R., Colombi, J.M., McLaughlin, C.V., and Baumgartner, G.B., "Test and Evaluation of Complex Cybersecurity Systems: A Case Study in Using Modeling and Simulation to More Efficiently Understand, Test, and Evaluate the Security of Quantum Key Distribution Systems," *ITEA Journal*. Submitted June, 2015.
- Mailloux, L.O., Engle, R.D., Grimaila, M.R., Hodson, D.D., Colombi, J.M., and McLaughlin, C.V., "Modeling Decoy State Enabled Quantum Key Distribution Systems," The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, Accepted for Publication April, 2015.
- Mailloux, L.O., Grimaila, M.R., Colombi, J.M., Hodson, D.D., McLaughlin, C., and Baumgartner, G., "Quantum Key Distribution: Evaluation of the Decoy State Protocol," *IEEE Communications Magazine*, Submitted March, 2015.
- Engle, R.D., Grimaila, M.R., Mailloux, L.O., Hodson, D.D., McLaughlin, C., and Baumgartner, G., "Developing a Decoy State Enabled Quantum Key Distribution System Model," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, Submitted February, 2015.
- Mailloux, L.O., Grimaila, M.R., Hodson, D.D., Baumgartner, G., and McLaughlin, C., "Performance Evaluations of Quantum Key Distribution System Architectures," IEEE Security and Privacy, January/February 2015, pp. 30-40. DOI: 10.1109/MSP.2015.11
- Mailloux, L.O., Morris, J.D., Grimaila, M.R., Hodson, D.D., Jacques, D.R., Colombi, J.M., McLaughlin, C.V., and Holes, J.A. "A Modeling Framework for Studying Quantum Key Distribution System Implementation Non-Idealities," *IEEE Access*, January, 2015. DOI: 10.1109/ACCESS.2015.2399101
- Sorensen, N.T., Grimaila, M.R., "Discrete Event Simulation of the Quantum Channel within a Quantum Key Distribution System," The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, February, 2015. DOI: 10.1177/1548512915569743
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- Morris, J.D., Hodson, D.D., Grimaila, M.R., Jacques, D.R., and Baumgartner, G., "Towards the Modeling and Simulation of Quantum Key Distribution Systems," *International Journal of Emerging Technology and Advanced Engineering*, Vol. 4, No. 2, February 2014, pp. 11-22.
- Grimaila, M.R., Morris, J., Hodson, D., "Quantum Key Distribution: A Revolutionary Security Technology," *The Information System Security Association (ISSA) Journal*, 10(6), June 2012, pp. 20-27.
- **Theses/Dissertations**
- Mailloux, L.O. (Scheduled August 2015) A performance and security analysis of practical decoy state enabled quantum key distribution systems (PhD Dissertation, Air Force Institute of Technology).
- Cernera, R.C. (Summer 2015) A System-Level Throughput Model for Quantum Key Distribution (Master's thesis, Air Force Institute of Technology).
- Engle, R.D. (2015) *Modeling, simulation, and analysis of a decoy state enabled quantum key distribution system.* (Master's thesis, Air Force Institute of Technology). Available from Defense Technical Information Center. (ADA615556).
- Morris, J.D. (2014) Conceptual modeling of a quantum key distribution simulation framework using the discrete event system specification (PhD Dissertation, Air Force Institute of Technology). Available from Defense Technical Information Center. (ADA609513)
- Harper, C.A. (2012) *Security standards and best practice considerations for quantum key distribution (qkd)* (Master's thesis, Air Force Institute of Technology). Available from Defense Technical Information Center. (ADA558003)
- Johnson, J.S. (2012) *An analysis of error reconciliation protocols for use in quantum key distribution* (Master's thesis, Air Force Institute of Technology). Available from Defense Technical Information Center. (ADA557404)
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Questions?

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