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2 Physical Layer Security

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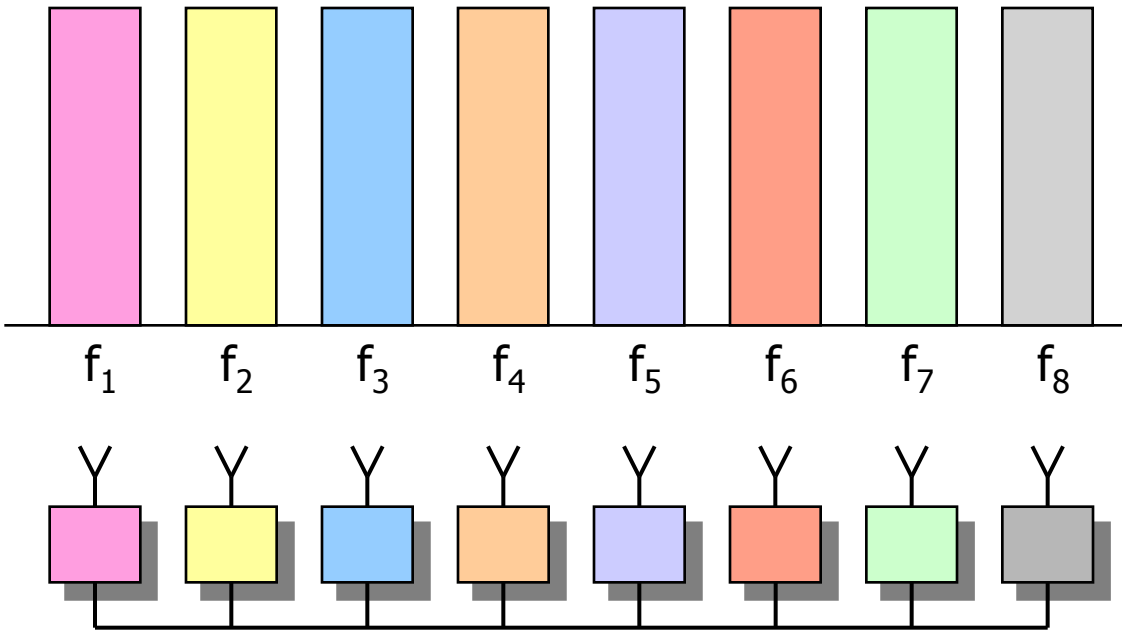
Security Protocols for the OSI Stack

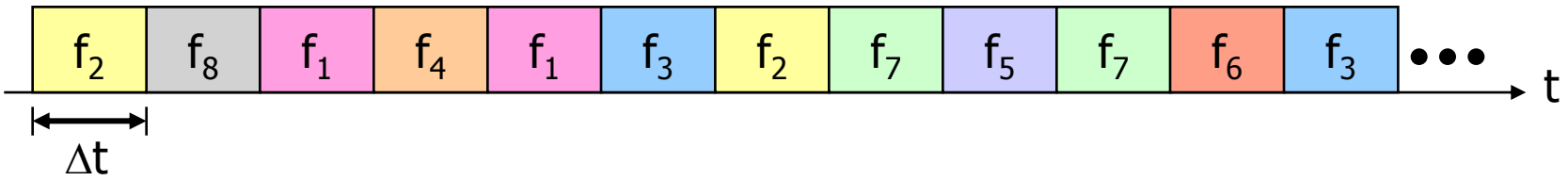
Communication layers	Security protocols
Application layer	Platform Security, Web Application Security, VoIP Security, SW Security
Transport layer	TLS
Network layer	IPsec
Data Link layer	[PPTP, L2TP], IEEE 802.1X, IEEE 802.1AE, IEEE 802.11i (WPA2)
Physical layer	Quantum Cryptography

Layer 1 Security – Frequency Hopping



Frequency band divided into n hopping channels

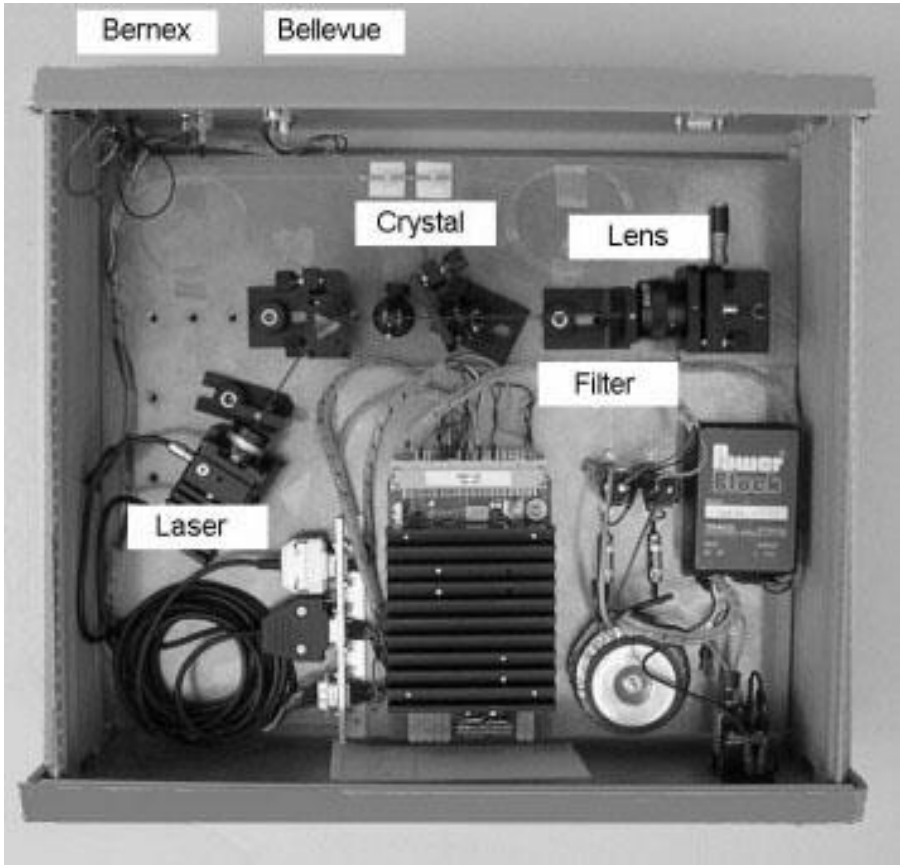
Counter measures: e.g. n parallel receivers

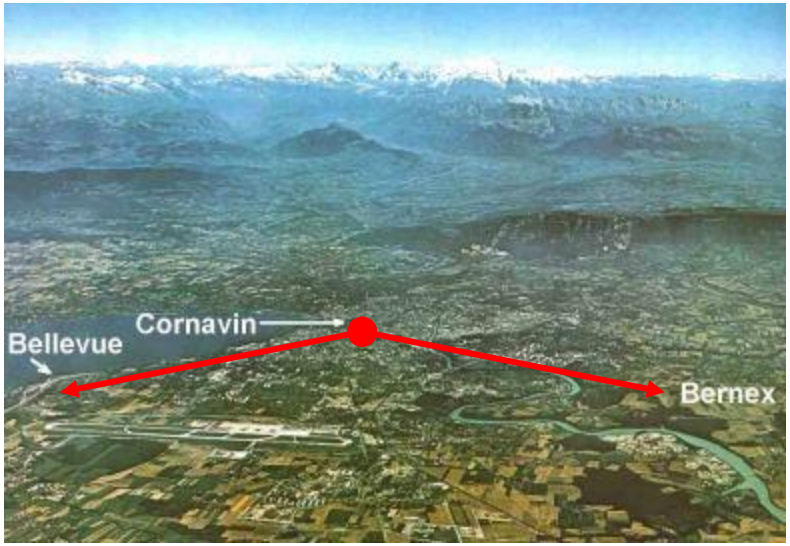


Standardized (public) or secret (military) hopping sequence

2.1 Quantum Cryptography

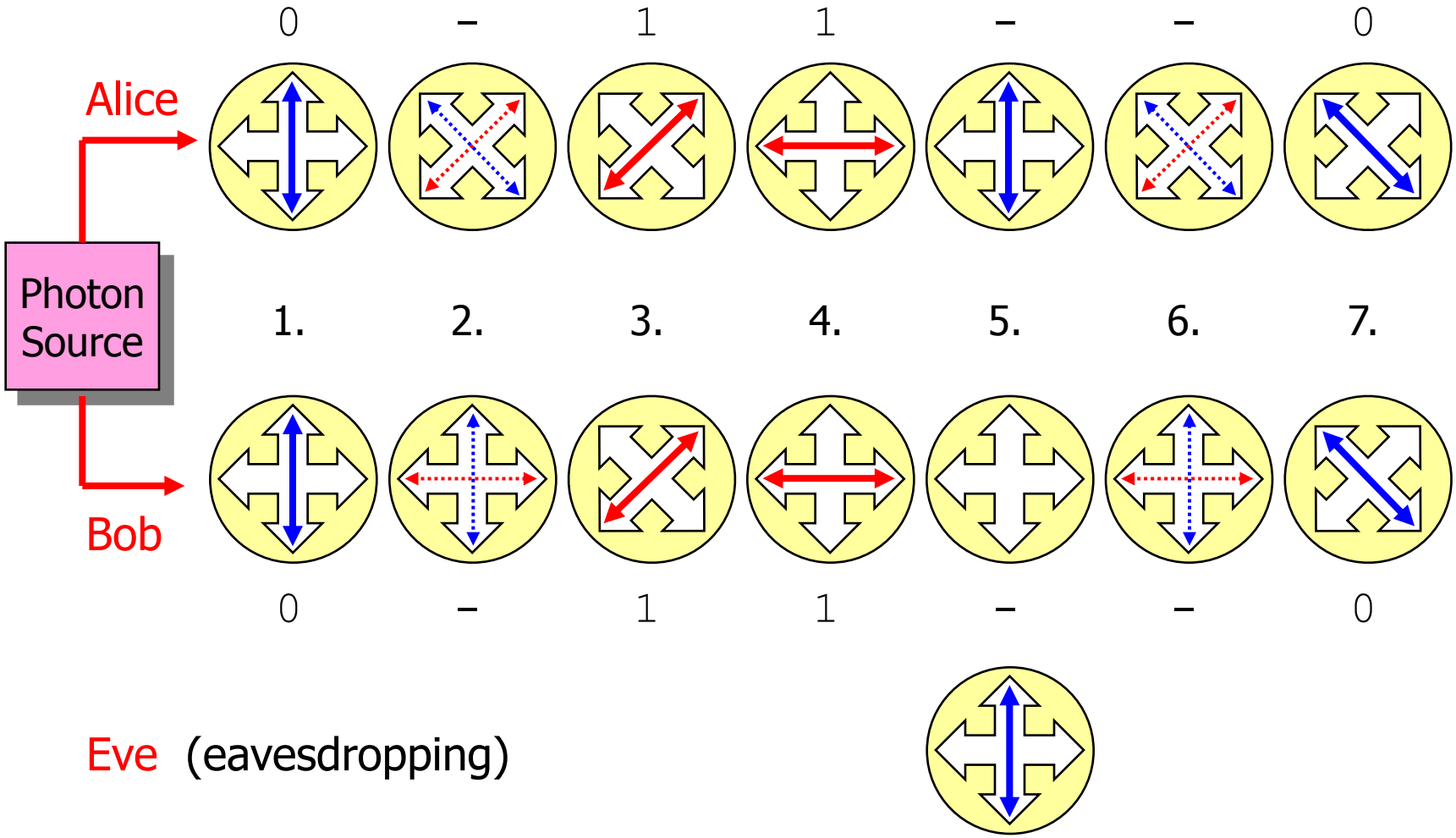
Quantum Cryptography using Entangled Photons





- Nicolas Gisin et al. University of Geneva
- Compact source emitting entangled photon pairs
- Quantum correlation over more than 10 km
- Founding of ID Quantique

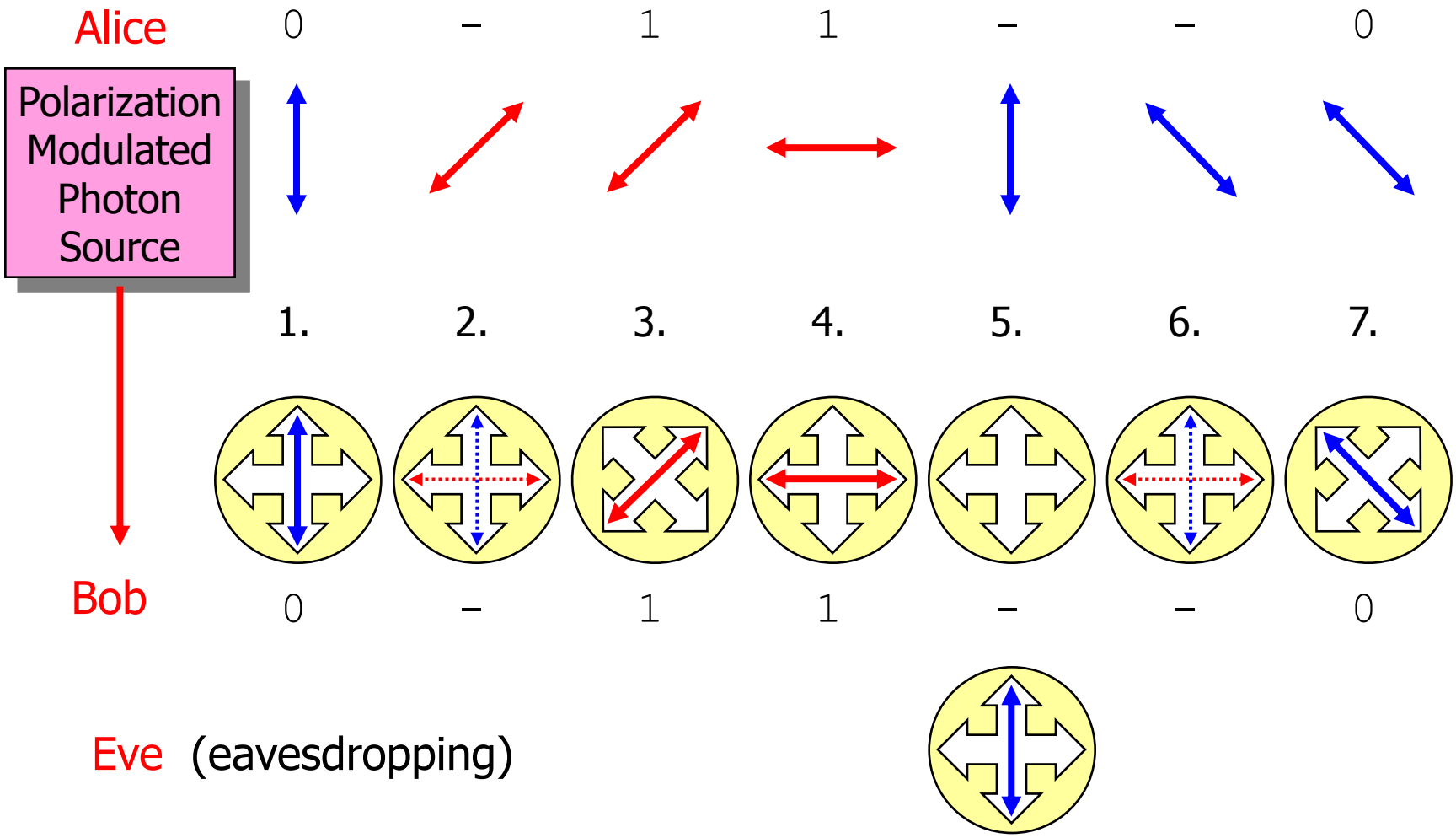
Quantum Key Distribution using Entangled Photons



Eve (eavesdropping)

E91 protocol: Arthur Ekert, 1991

Quantum Key Distribution using the BB84 Protocol



BB84 protocol: Charles Bennett & Gilles Brassard, 1984

Decoy States against Multi-Photon Splitting Attacks

- Single photon lasers are nearly impossible to build.
- The natural Poisson distribution of practical laser sources causes multi-photon pulses to occur which can be split by Eve.
- In order to compensate for the stolen photons, Eve might inject additional photons.
- As a counter measure Alice randomly inserts a certain percentage of decoy states transmitted at a different power level.
- Later Alice reveals to Bob which pulses contained decoy states.
- If Eve was eavesdropping, the yield and bit error rate statistics for the signal and decoy states are modified which can be detected by Alice and Bob.
- The use of decoy states extends the rate of secure key exchange to over 140 km.

Photon Yield versus Power Level

- Poisson distribution of the number of photons in a pulse, measured over 1000 pulses:

	Signal states	Decoy states
Power Level	0.80 photons/pulse	0.12 photons/pulse
0 photons/pulse	449 pulses	887 pulses
1 photon /pulse	360 pulses	106 pulses
2 photons/pulse	144 pulses	7 pulses
3 photons/pulse	38 pulses	0 pulses
4 photons/pulse	8 pulses	0 pulses
5 photons/pulse	1 pulse	0 pulses
Yield	551 of 1000 pulses	113 of 1000 pulses

Photon Yield versus Transmission Distance

- Attenuation in a monomode fiber with λ =1550nm: 0.2 dB/km
  - 50 km: 10dB ⇨ 1 out 10 photons survive
  - 100 km: 20dB ⇨ 1 out of 100 photons survive
  - 150 km: 30dB ⇨ 1 out of 1000 photons survive

Photon Yield in 50 km (10 dB Attenuation)

- Received pulses containing at least one photon, measured over 1000 pulses:

	Signal states	Decoy states
Power Level	0.80 photons/pulse	0.12 photons/pulse
0 photons/pulse	0 pulses	0 pulses
1 photon /pulse	36 pulses	10 pulses
2 photons/pulse	28 pulses	2 pulses
3 photons/pulse	10 pulses	0 pulses
4 photons/pulse	3 pulses	0 pulses
5 photons/pulse	0 pulses	0 pulses
Yield	77 of 1000 pulses	12 of 1000 pulses

Layer 2 Encryption with Quantum Key Distribution

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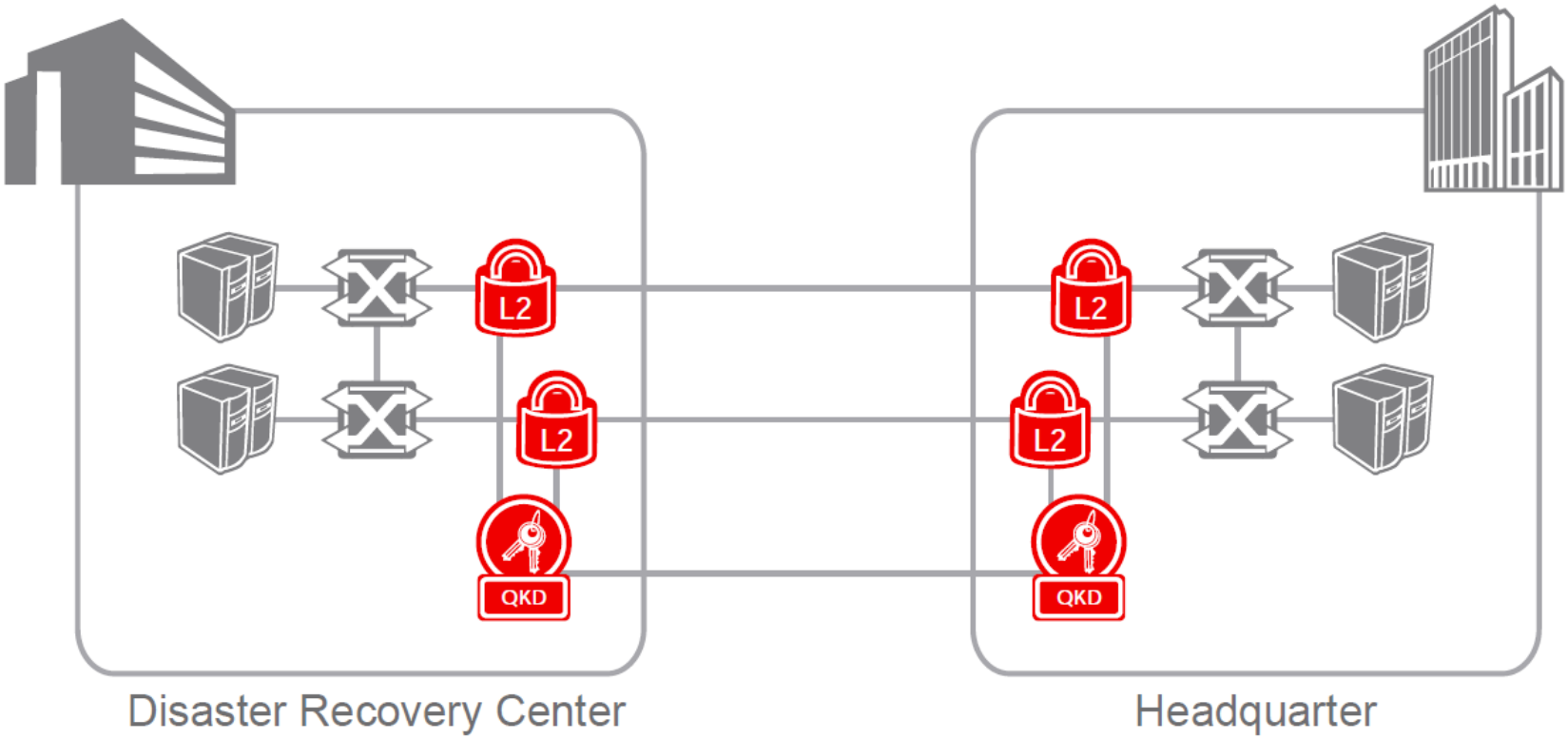
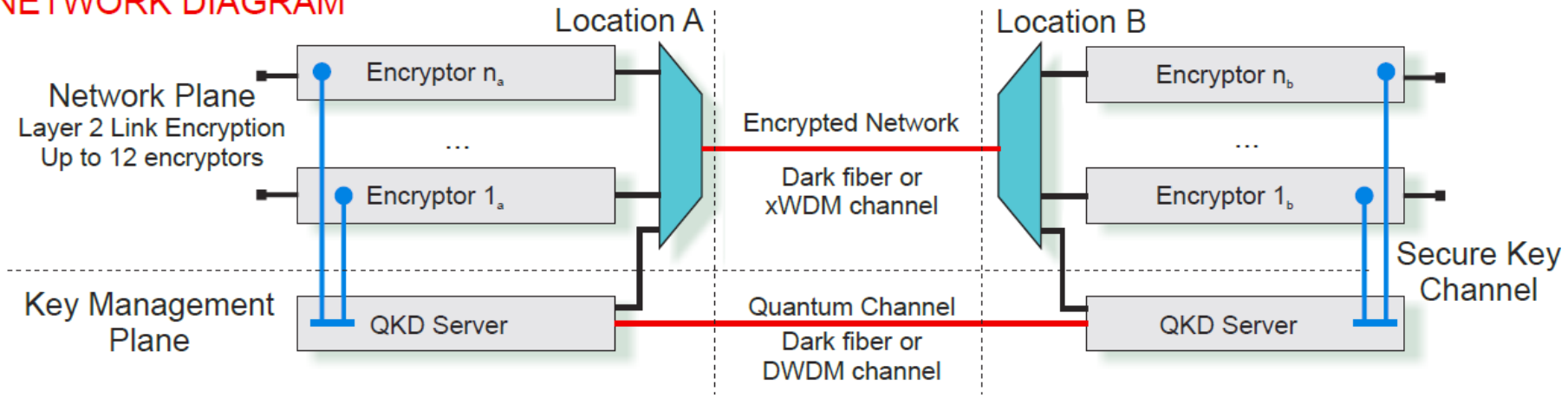


- 10 Gbit/s Ethernet Encryption with AES-256 in Counter Mode
- QKD: RR84 and SARG protocols, up to 50 km (100 km on request)
- Key Management: 1 key/minute up to 12 encryptors

Cerberis QKD Server and Centauris Encryptors

NETWORK DIAGRAM



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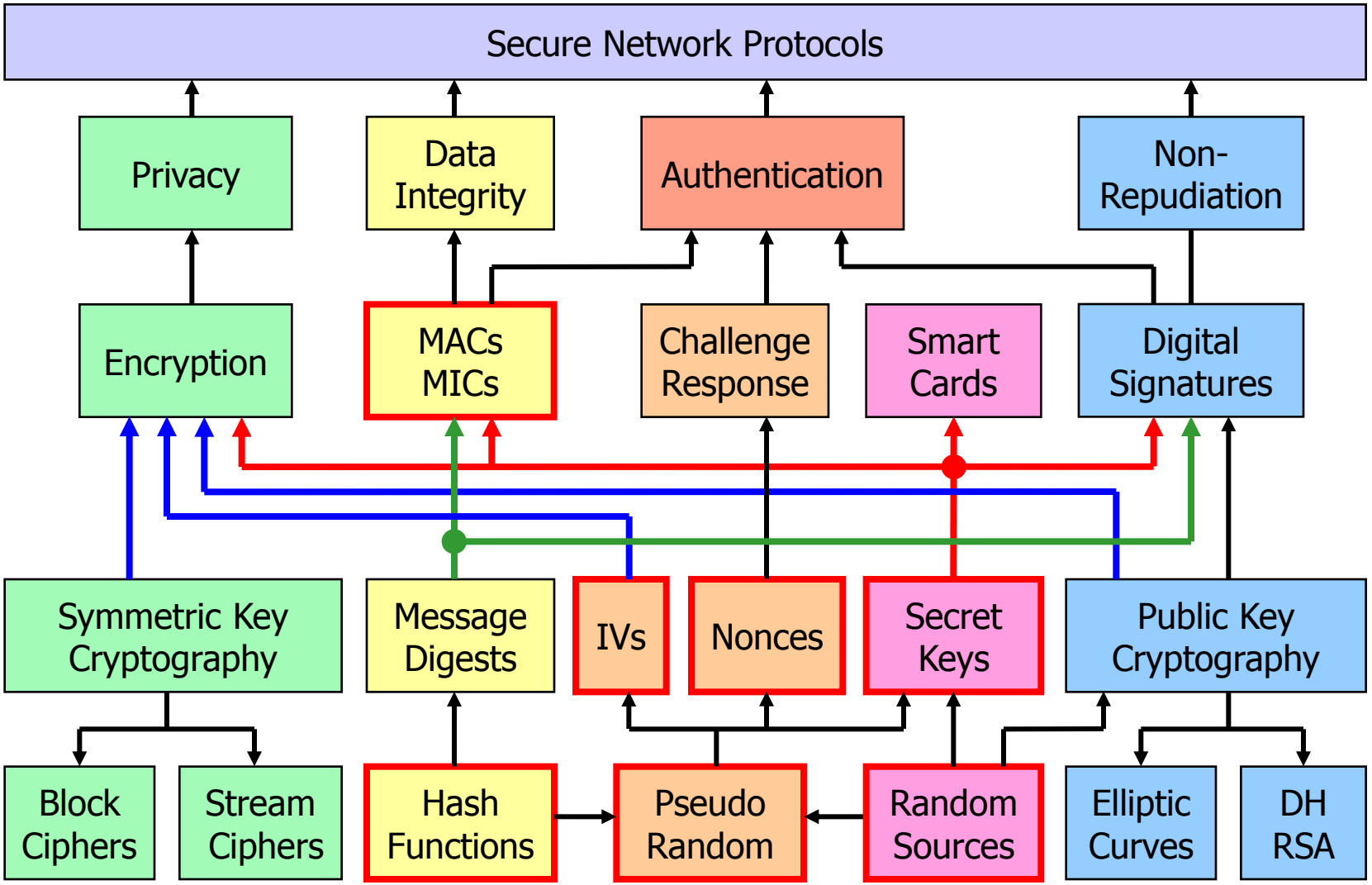
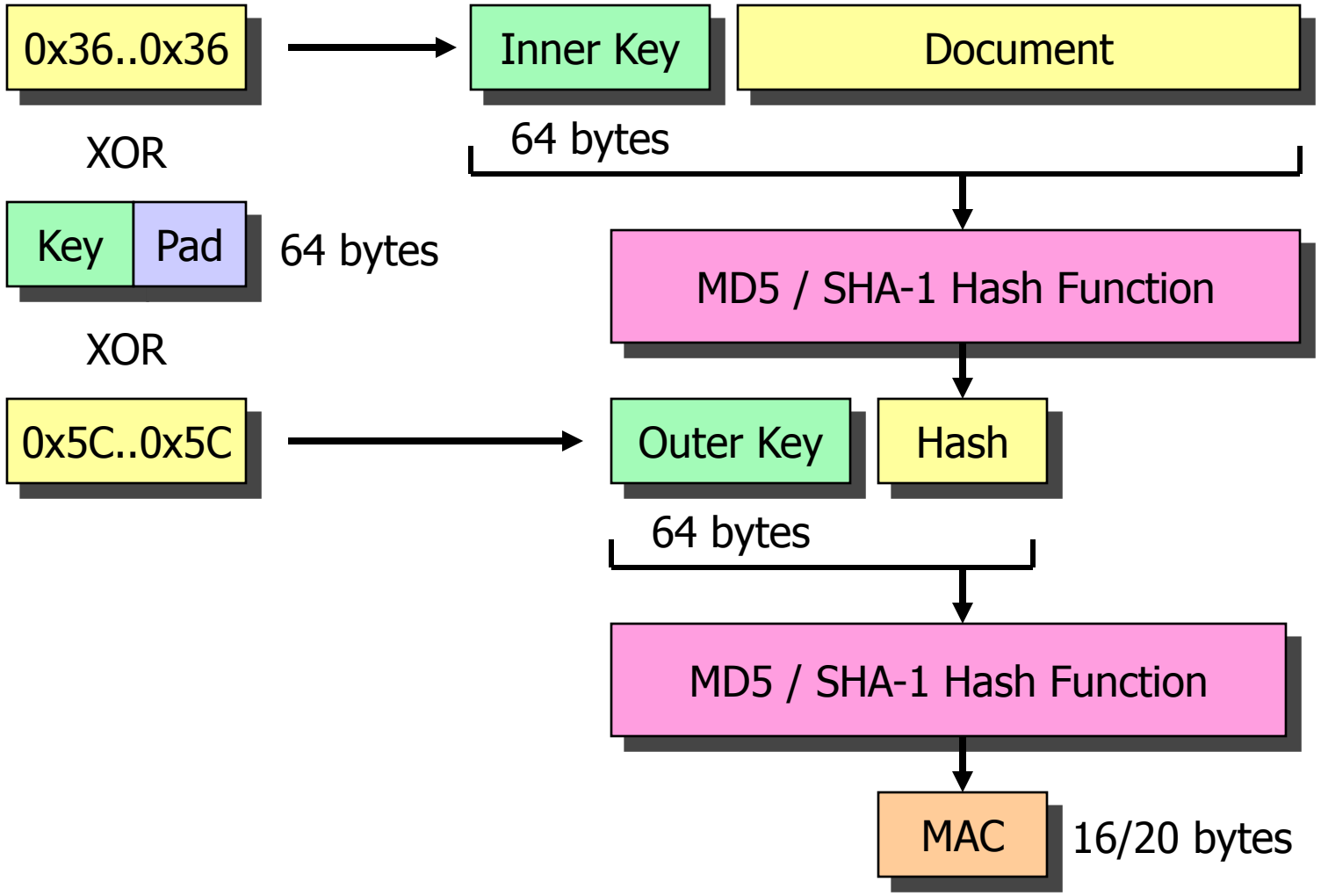
2.2 Key Material and Random Numbers

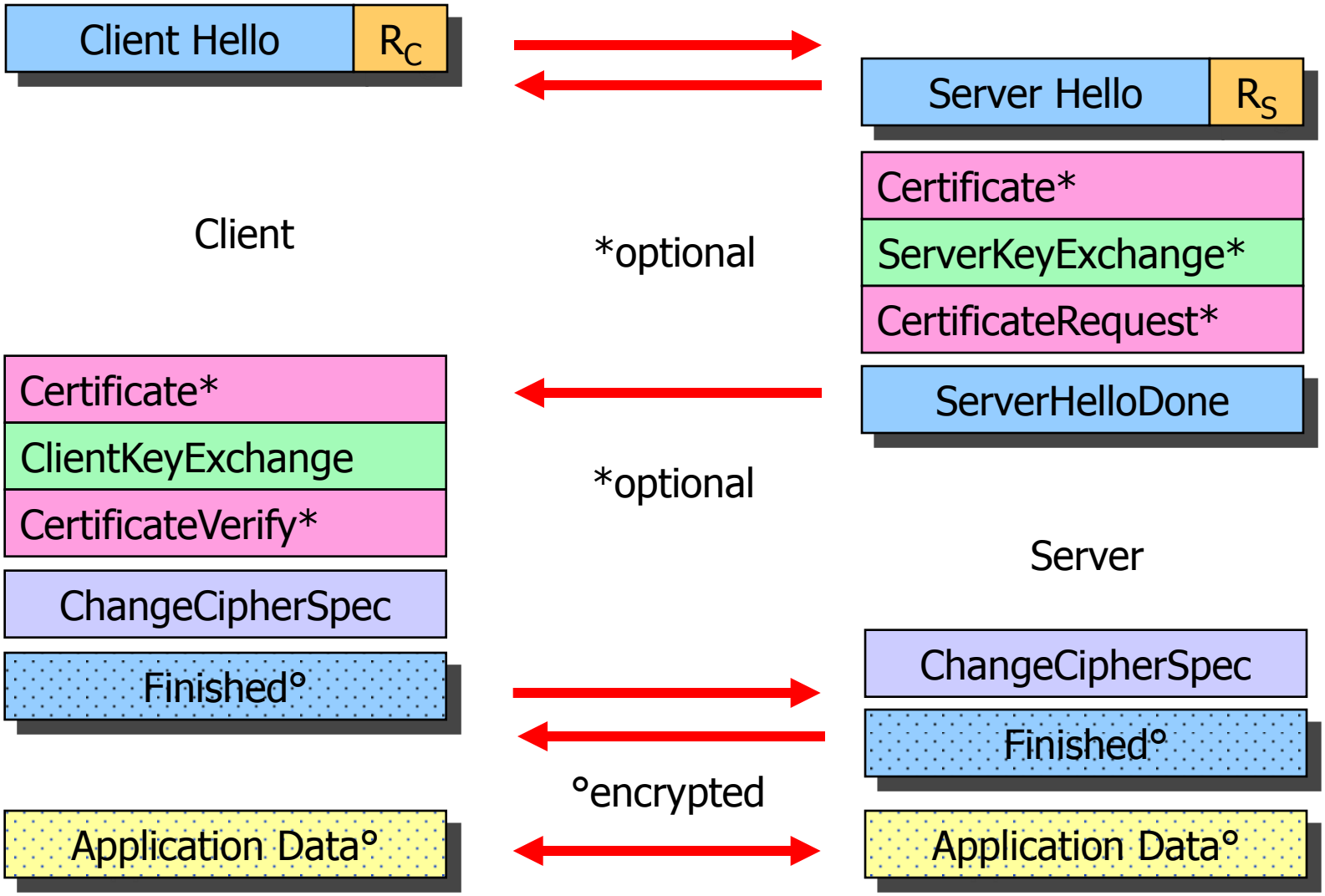
Cryptographical Building Blocks



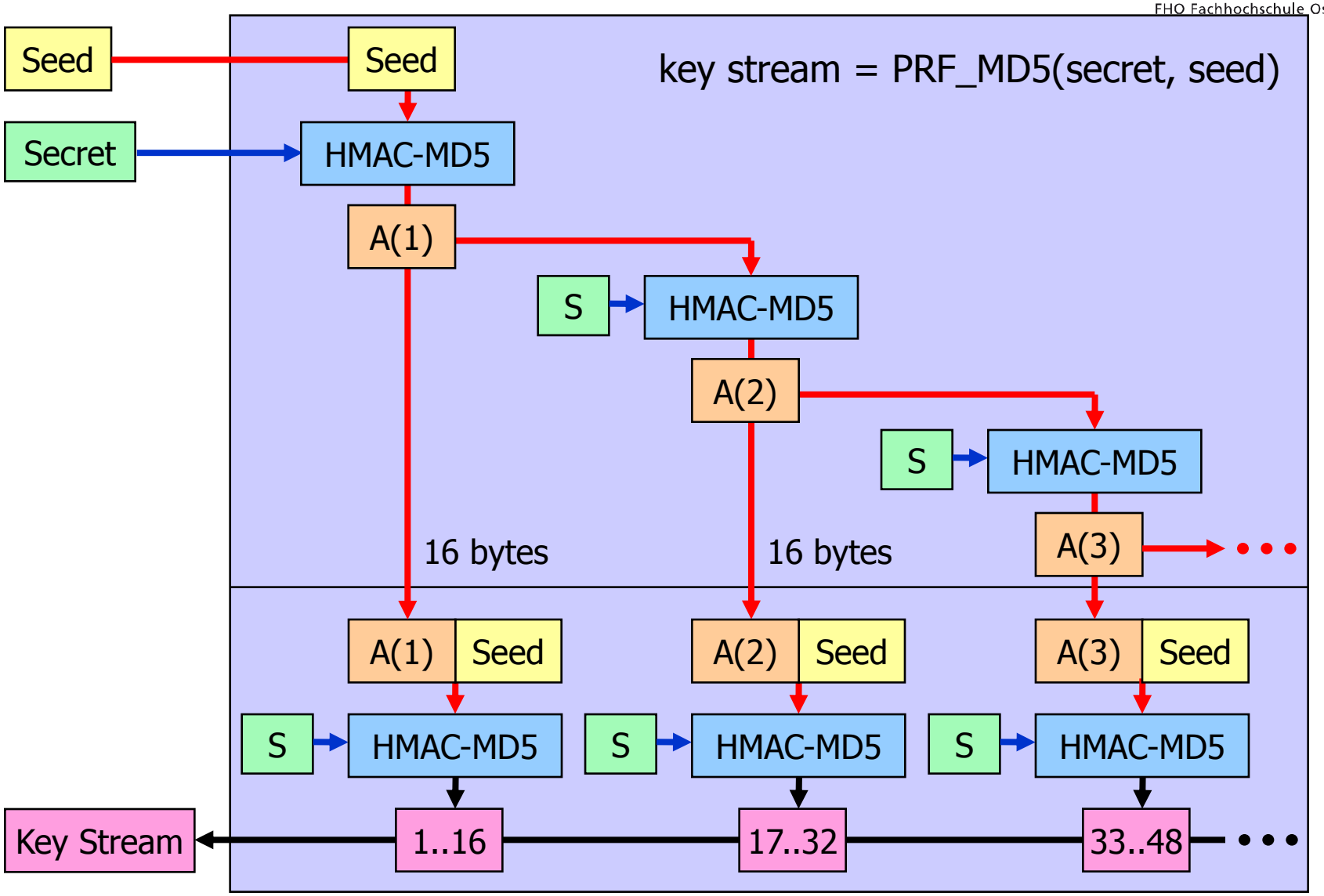
HMAC Function (RFC 2104)



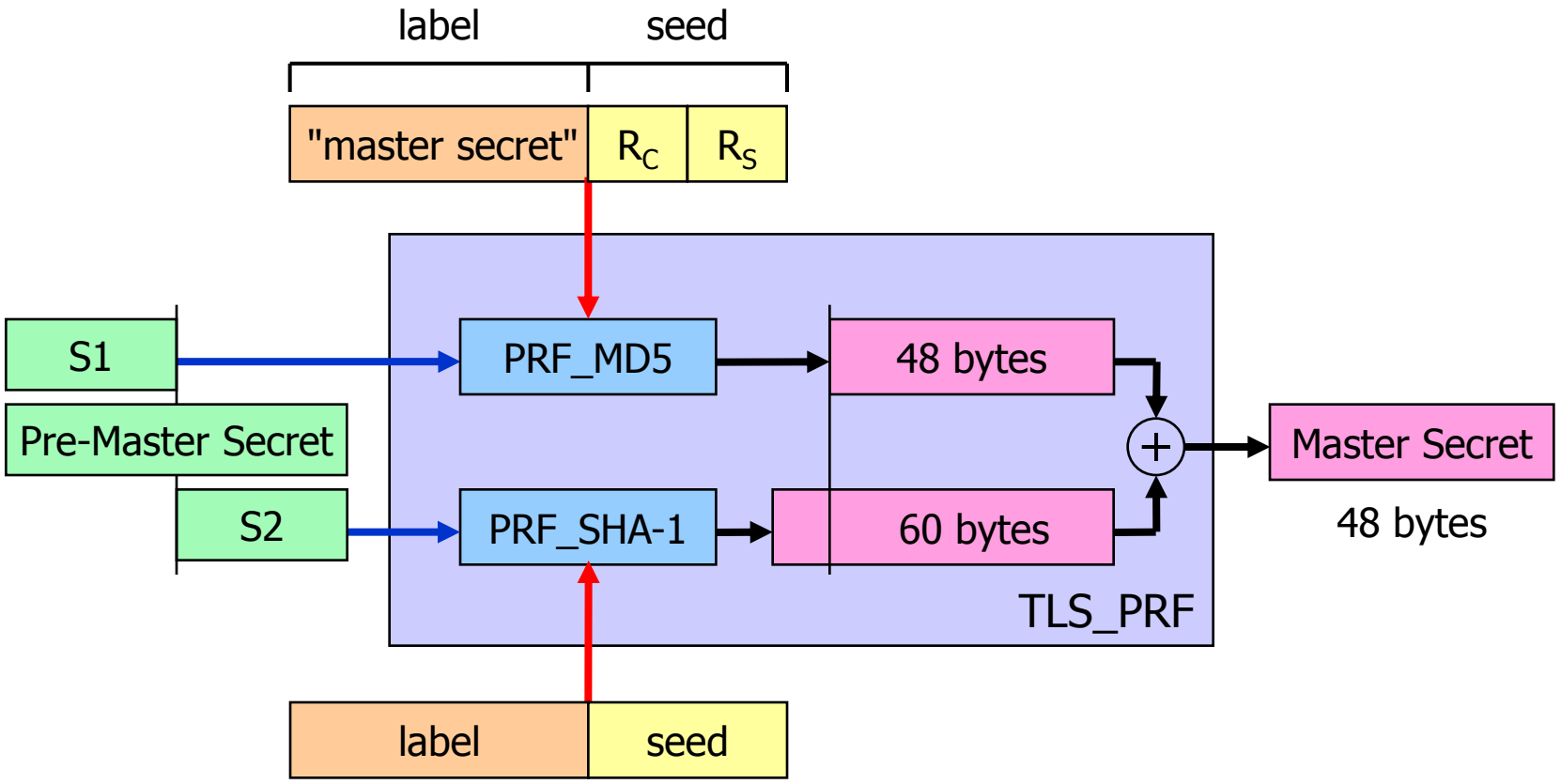
TLS Handshake Protocol



Pseudo Random Function (PRF)

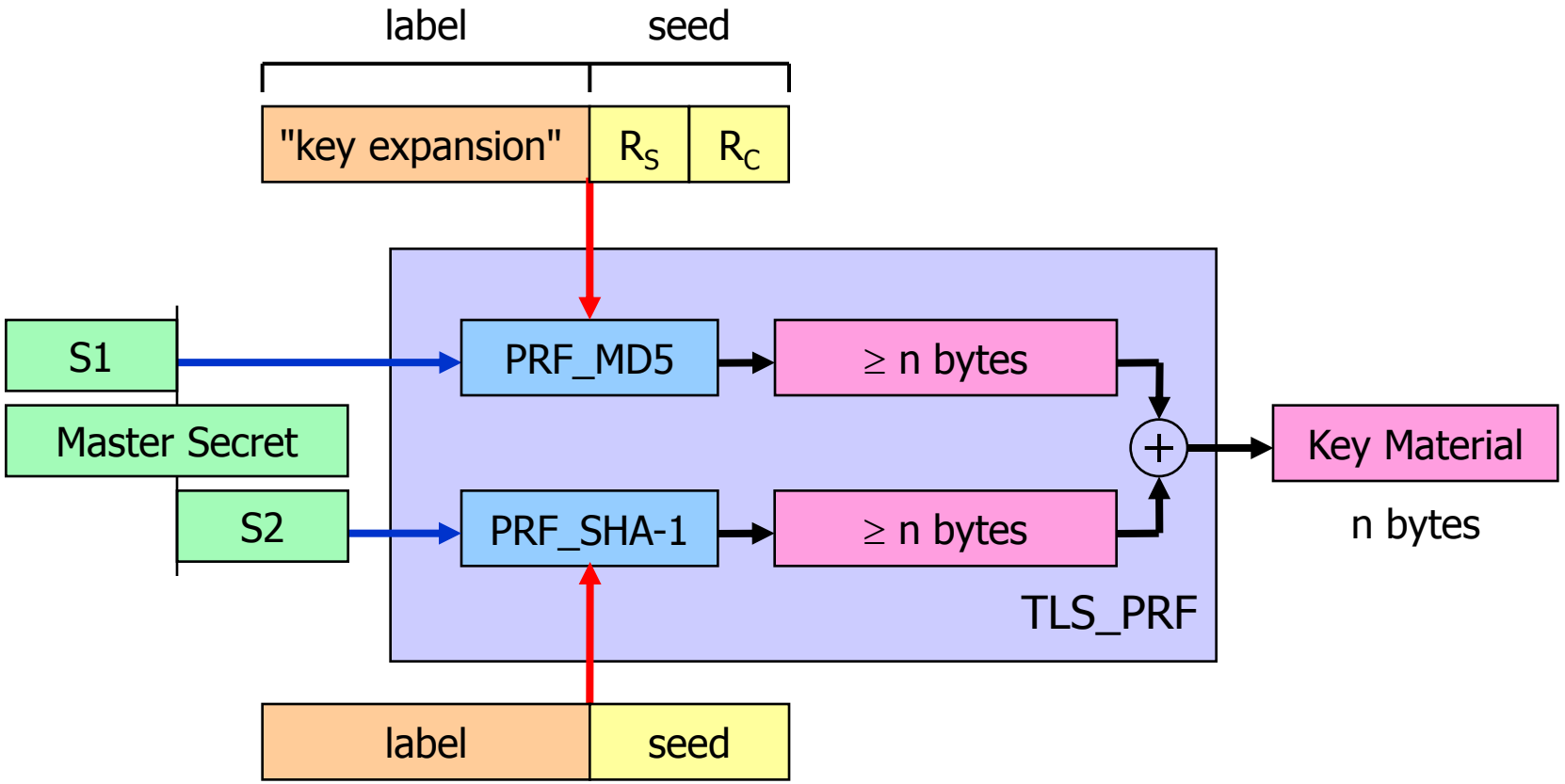


Computing the TLS 1.1 Master Secret



key stream = TLS_PRF(secret, label, seed)

Generating TLS 1.1 Key Material



key stream = TLS_PRF(secret, label, seed)

Generating True Random Numbers (RFC 1750)

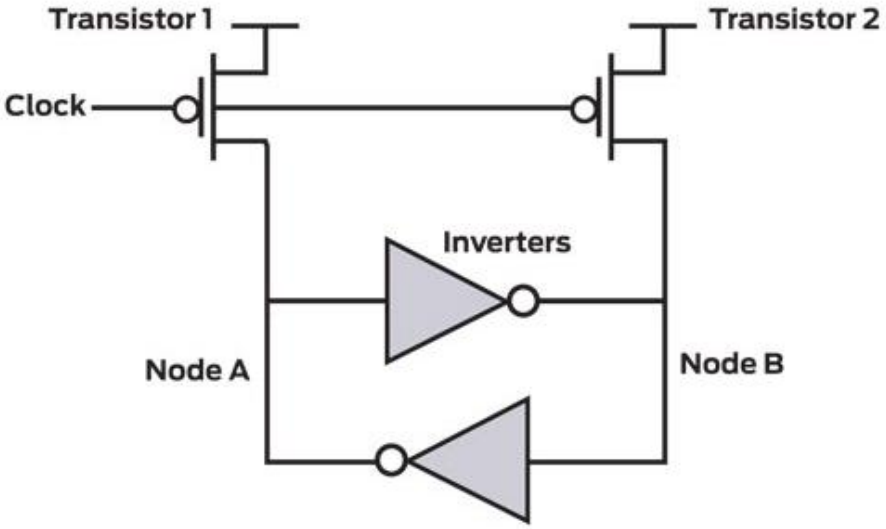
- The security of modern cryptographic protocols relies heavily on the availability of true random key material and nonces.
- On standard computer platforms it is not a trivial task to collect true random material in sufficient quantities:
  - Key Stroke Timing
  - Mouse Movements
  - Sampled Sound Card Input Noise
  - Air Turbulence in Disk Drives
  - RAID Disk Array Controllers
  - Network Packet Arrival Times
  - Computer Clocks
- Best Strategy: Combining various random sources with a strong mixing function (e.g. MD5 or SHA-1 hash) into an entropy pool (e.g. Unix /dev/random) protects against single device failures.

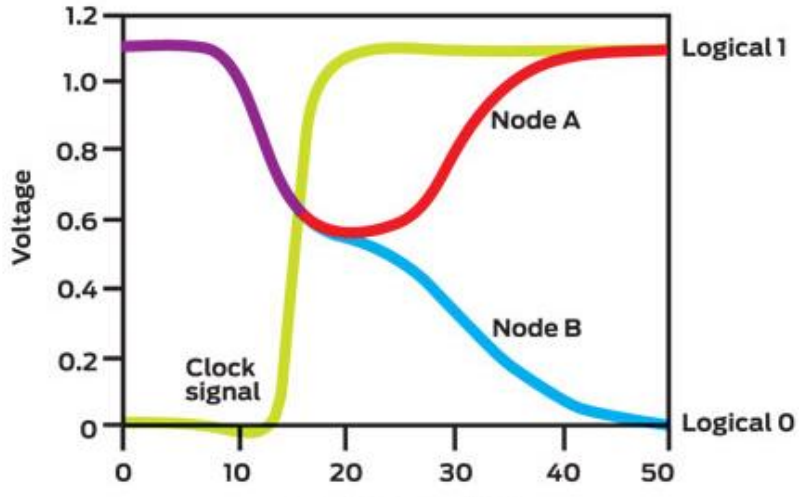
Hardware-based True Random Generators

- Quantum Sources or Radioactive Decay Sources
  - Reliable, high entropy sources, but often bulky and expensive.
- Thermal Noise Sources
  - Noisy diodes or resistors are cheap and compact but level detection usually introduces considerable skew that must be corrected.
- Free Running or Metastable Oscillators
  - The frequency variation of a free running oscillator is a good entropy source if designed and measured properly. Used e.g in smart card crypto co-processors.
  - The Intel Ivy Bridge processor family implements an on-chip metastable digital oscillator.
- Lava Lamps
  - Periodic digital snapshots of a lava lamp exhibit a lot of randomness.

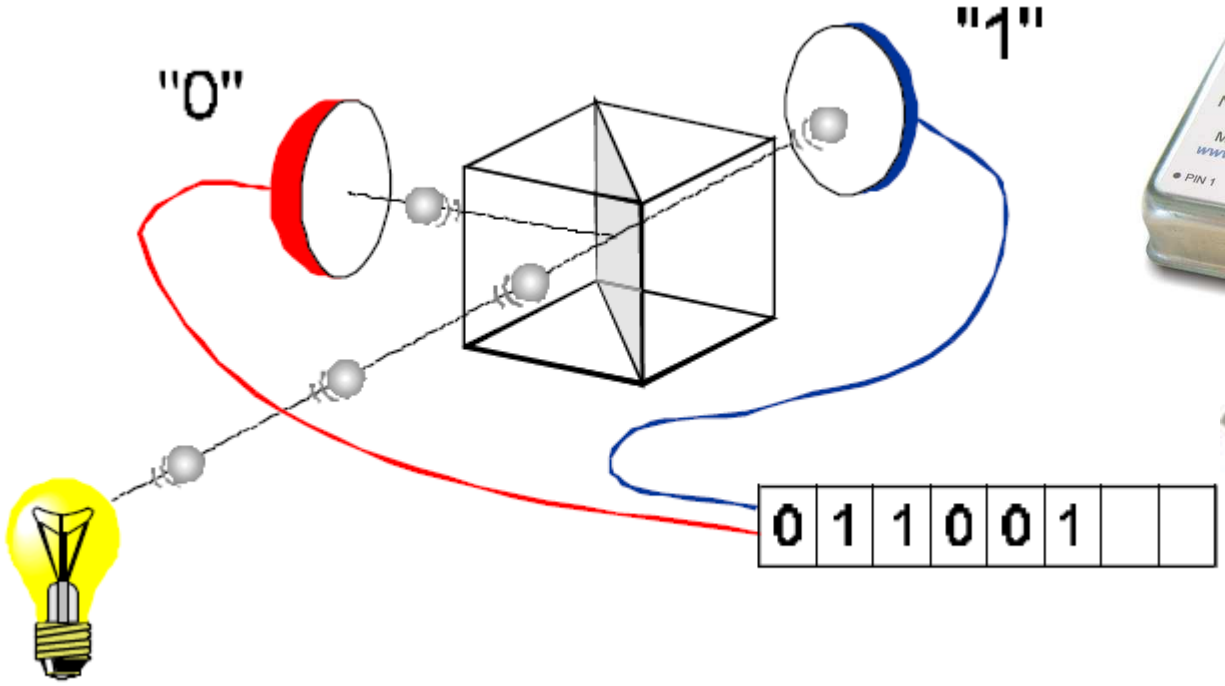
The Intel RDRAND Instruction

- Available with Intel Ivy Bridge Processors (XEON & Core i7)
  - The RDRAND instruction reads a 16, 32 or 64 bit random value
  - Throughput 500+ MB/s random data with 8 concurrent threads
  - The random number generator is compliant with NIST SP800-90, FIPS 140-2, and ANSI X9.82





Quantum Random Number Generator
www.idquantique.com



- Detection of single photons via a semi-transparent mirror
- High throughput: 4 – 16 Mbit/s
- Low cost (990…2230 EUR)

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Skew Corrections and Tests for Randomness

- Simple Skew Correction (John von Neumann)
  - p(1) = 0.5+e, p(0) = 0.5-e, -0.5 < e < 0.5
  - Example with e = 0.20, i.e. p(1) = 0.7, p(0) = 0.3

```
11011111101011011000100111100111011111101101111111110101
 - 0 - - 1 1 - 0 1 - 1 0 - 1 0 - 0 - - 1 - 0 - - - - 0 0
```

- Strong Mixing using Hash functions
  - Hashing improves statistical properties but does not increase entropy.
- Statistical Tests for Randomness
  - A number of statistical tests are defined in FIPS PUB 140-2 "*Security Requirements for Cryptographic Modules*" : Monobit Test, Poker Test, Runs Test, etc.
- Entropy Measurements
  - The entropy of a random or pseudo-random binary sequence can be measured using Ueli Maurer's *"Universal Statistical Test for Random Bit Generators"*