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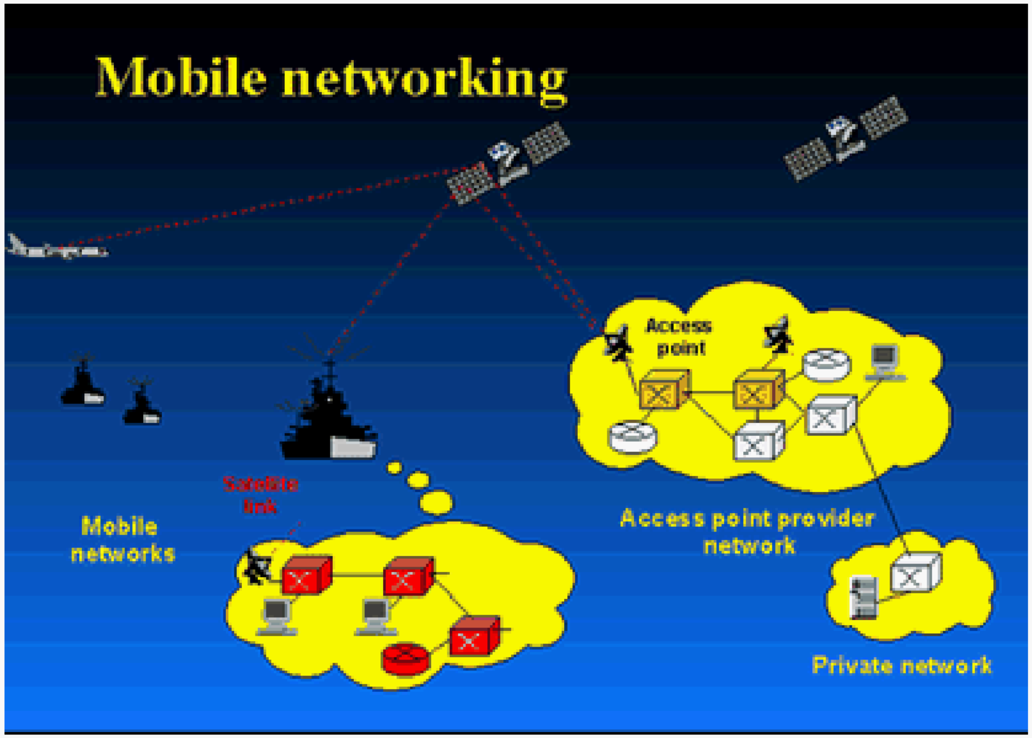
Optical Wireless Communications using Ultra-short Pulsed Lasers and Pulse Shaping



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CICTR WEB LINK: http://cictr.ee.psu.edu

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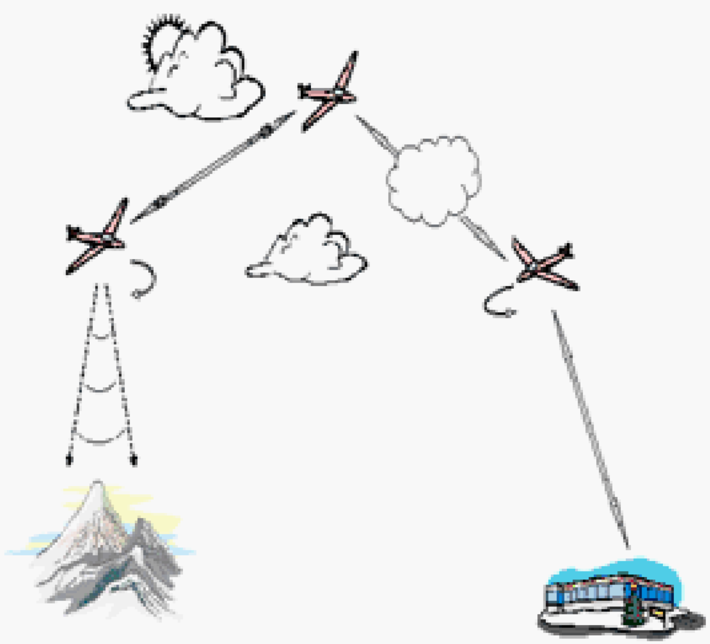
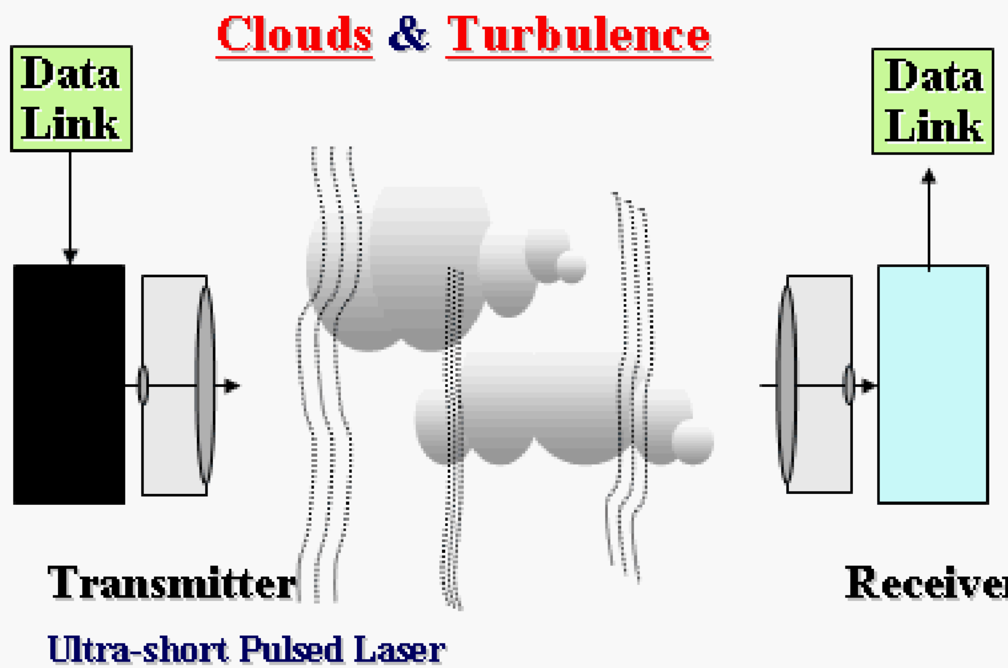
Objectives

Assess the potential of Ultra-Short Pulsed technologies to increase FSO communications availability via analysis and limited laboratory experiments.





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Challenges in Through-Cloud FSO Communications

- Signal Attenuation
- Temporal Dispersion, ISI
- Spatial Dispersion
- Angular Dispersion

→ BER Availability worsens →

Link margin needed

Coding, Modulation, Equalization

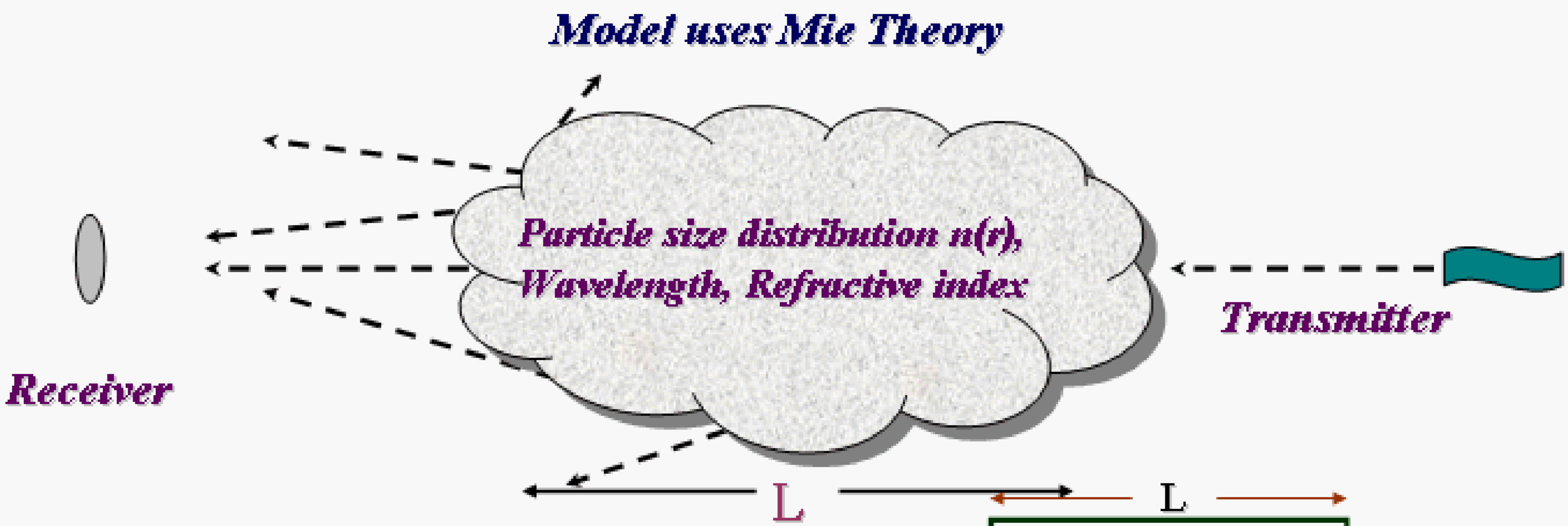
Find proper Aperture size

Adaptive Field-of-View

1. Maritime fog will attenuate 1.5 micron light at the rate of about 80 - 100 dB/km, cumulus cloud will attenuate 1.5 micron light at the rate of about 100 - 130 dB/km, and continental fog will attenuate 1.5 micron light at the rate of about 130 – 200 dB/km. Any attempt to communicate through clouds/fog will require a link margin exceptionally higher than common clear-air margins. System designers must anticipate this.

2. Even one nanosecond of pulse broadening due to Temporal Dispersion wipes out many communication symbols propagating OC-48. So, even if the broadening is weak (~nanoseconds) we will still need mitigation methods (assuming there is enough link margin).

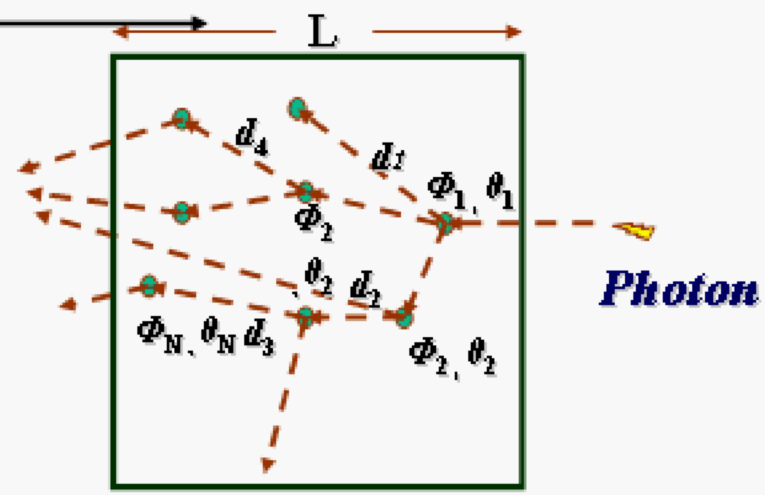
Clouds Multi-Scattering Modeling



- Through Cloud Channel is characterized by:

  Optical Thickness; $\tau = L / d_{AVG}$

- Φ defines the rotation angle of the scattering plane about the incident plane and θ is the angle between the incident ray and the scattered ray.



Dispersive Clouds (Variable Band Filter)

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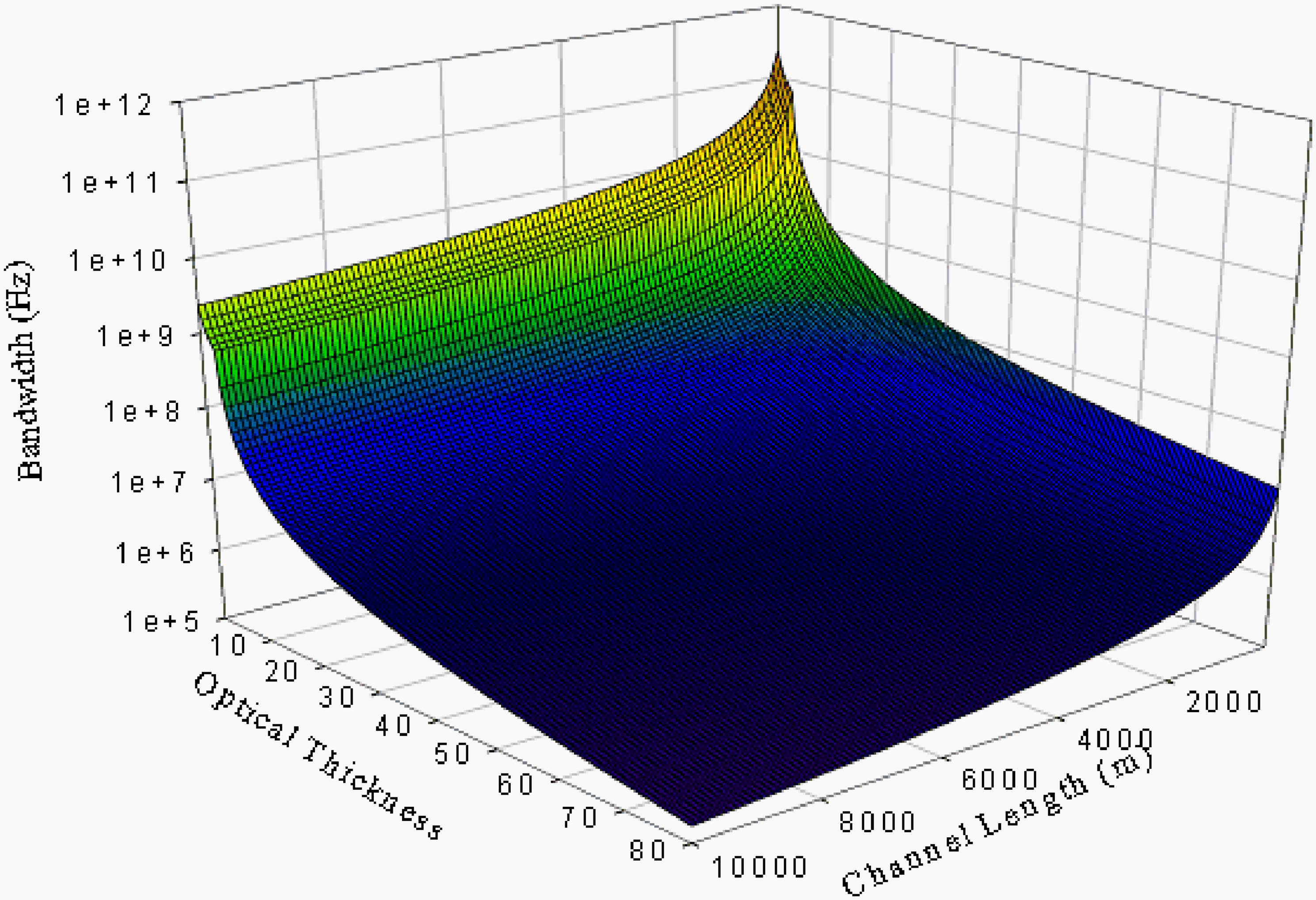
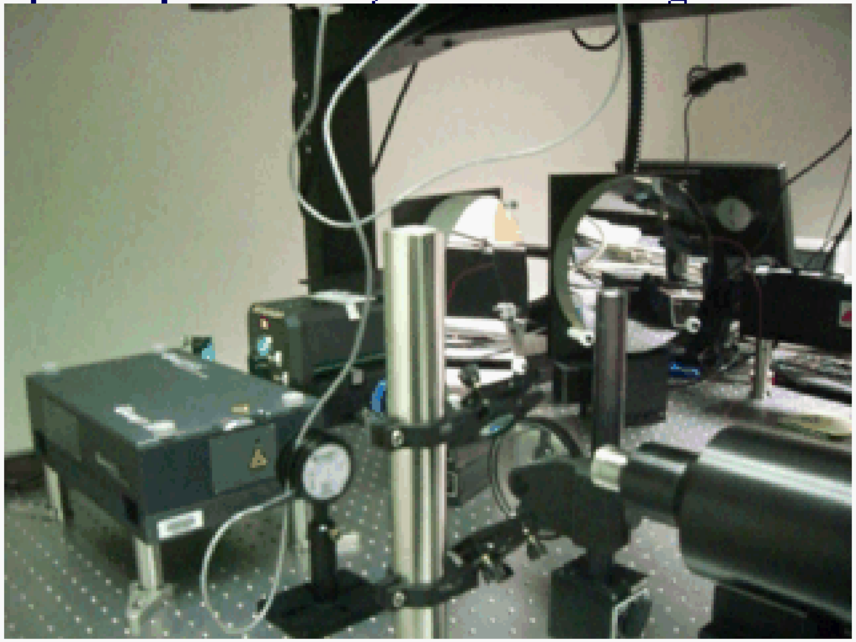
ORCLE

Clouds Bandwidth Estimation



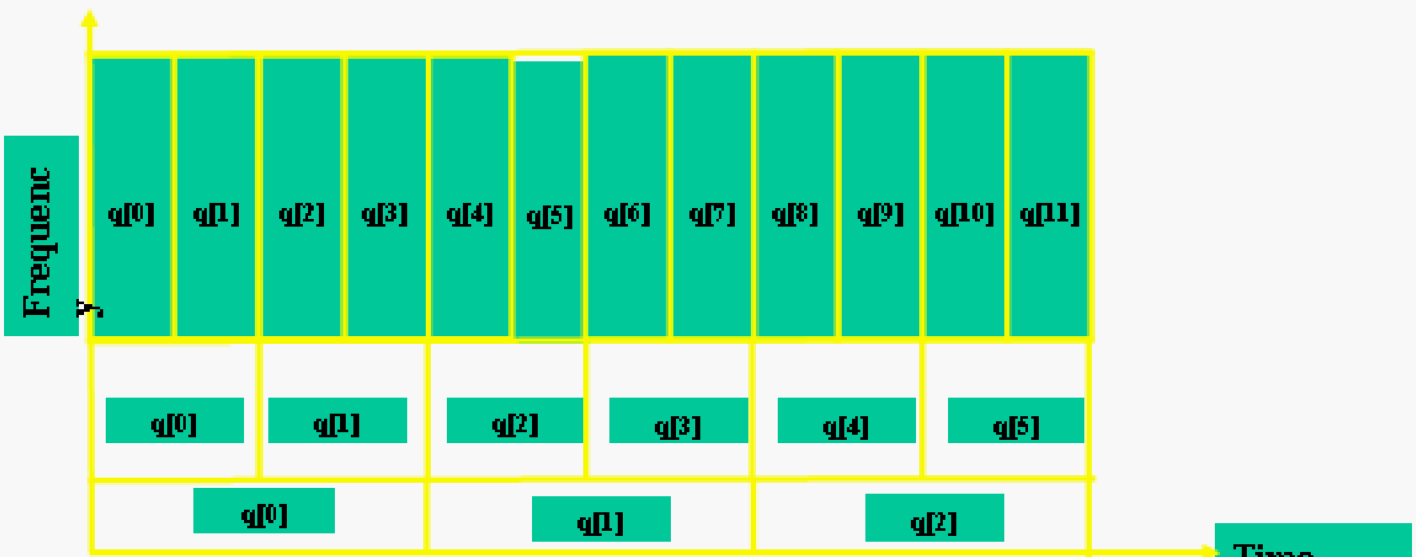
Ultra-short Pulse Laser Technology

- Ultra-fast switching times and ultra-high transmit powers enable communication capabilities that far exceed anything available today.
- Ultra-short pulses shaped through signal processing can help penetration through clouds.
- Our current mode-lock laser uses a pump at 5 watts CW power. Produces 60 fs pulses at a repetition rate of 3 Giga pulses per second (Gpps). Each pulse carries about 0.3 nJ of energy, that means a peak power of 5000 watts per pulse corresponding to an average power of ~ 1 Watt. With EDFA gain, 50 watts average transmit power is possible.
- A 100 fs pulse at 100 mJ per pulse would produce a peak power of 1 Terawatt per pulse; at 3 Giga pulses per second, this is 300 Mega Watts of average power.



Wavelet Fractal Modulation on Ultra-short Laser Pulses

- Increased FSO link availability using wavelet fractal modulation on ultra-short laser pulses
- Transmission spectral efficiency is kept over a broad range of rate-bandwidth ratios using a fixed transmitter configuration.
- Redundant copies of the transmitted data are provided across the time-frequency plane.
- A form of multi-rate communication diversity.



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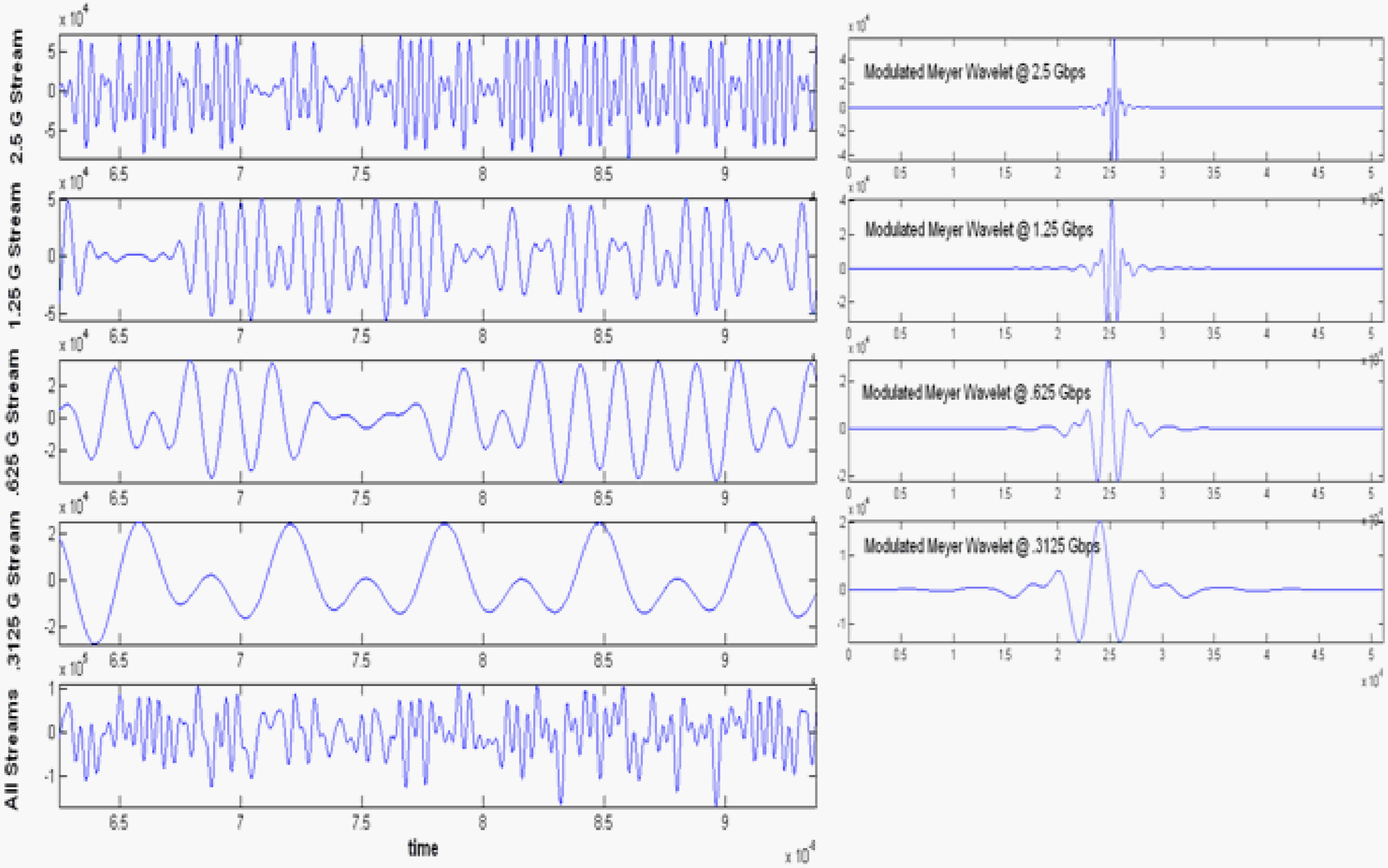
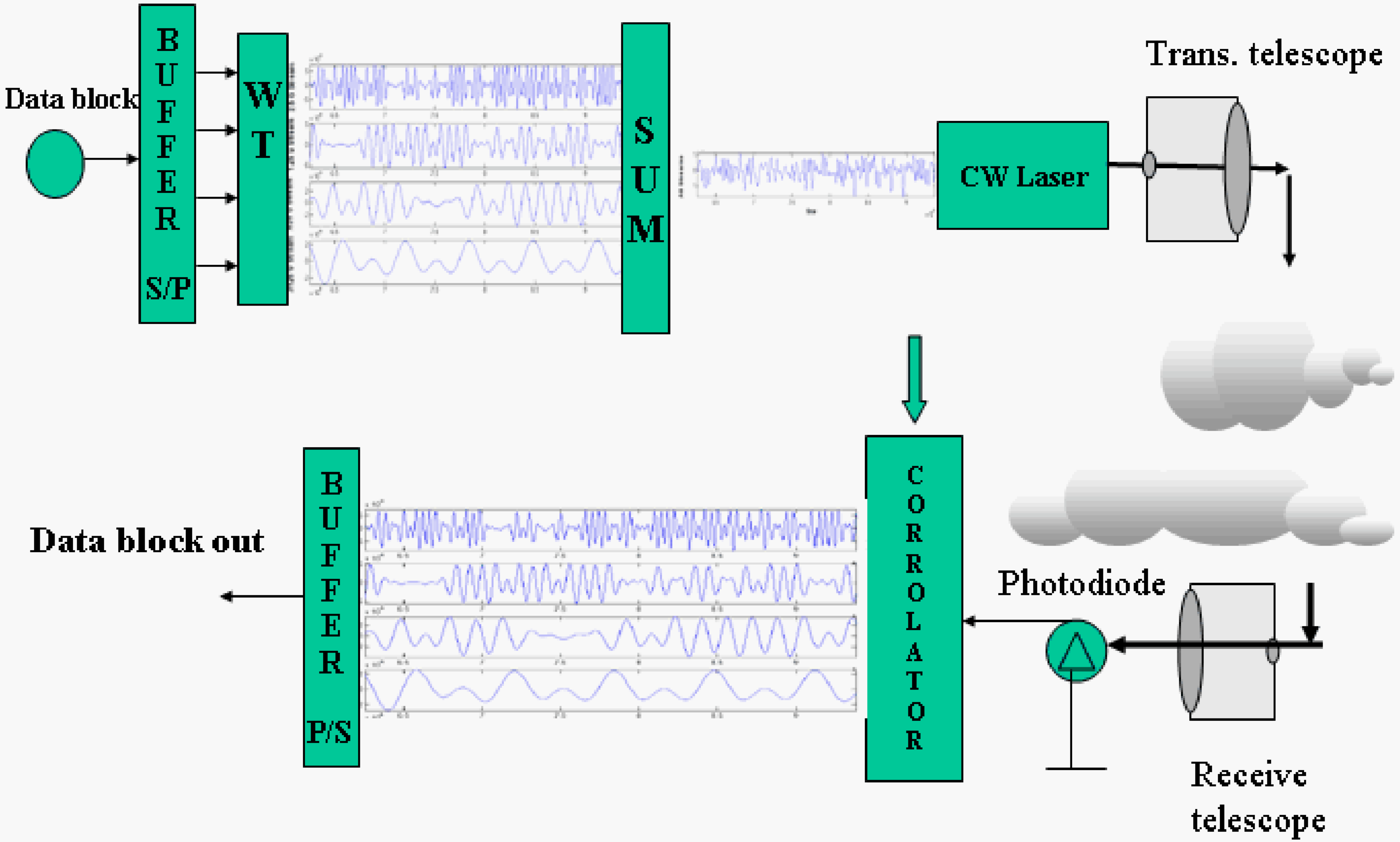
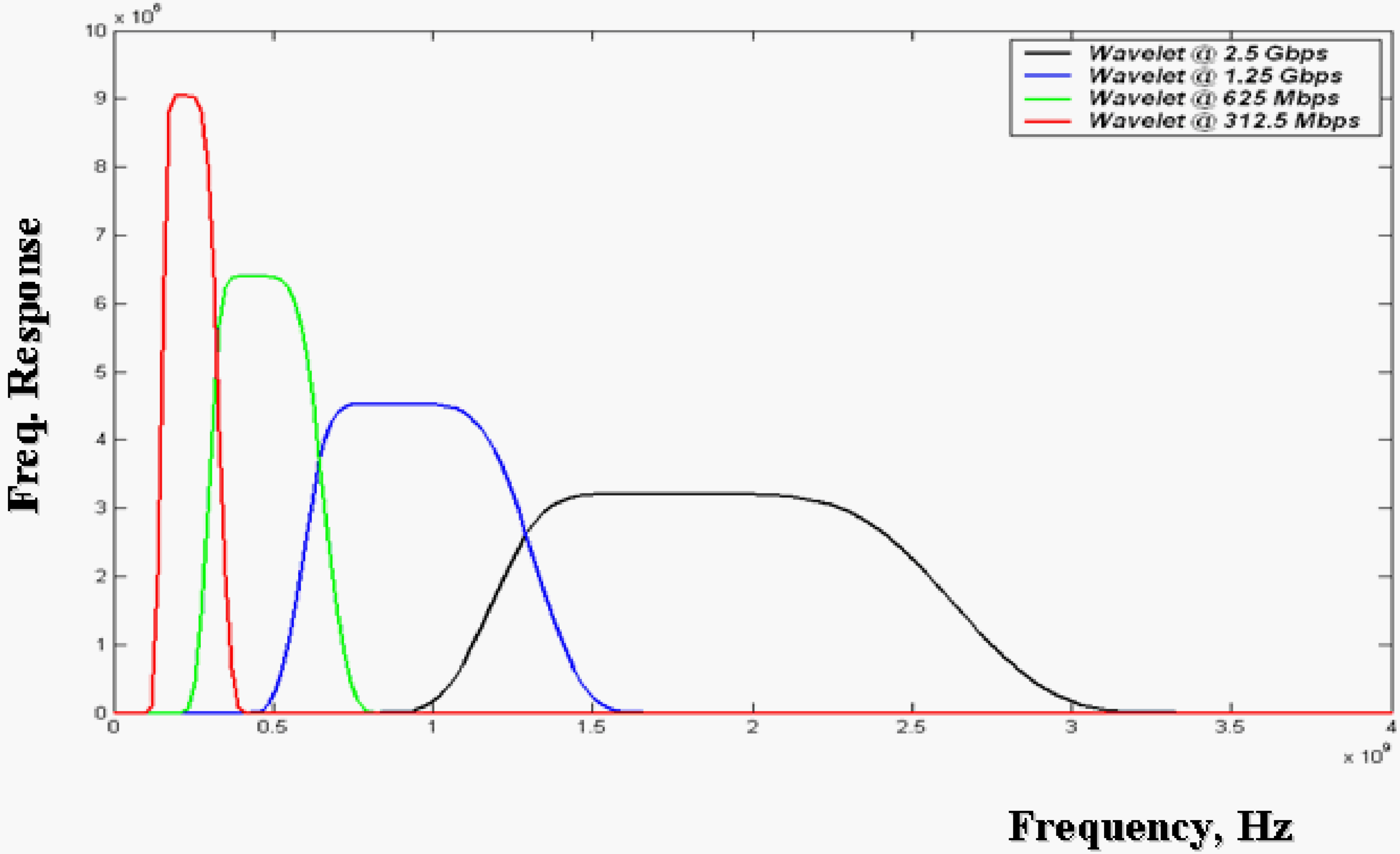
Modulated Meyer's Wavelets



Functional Diagram

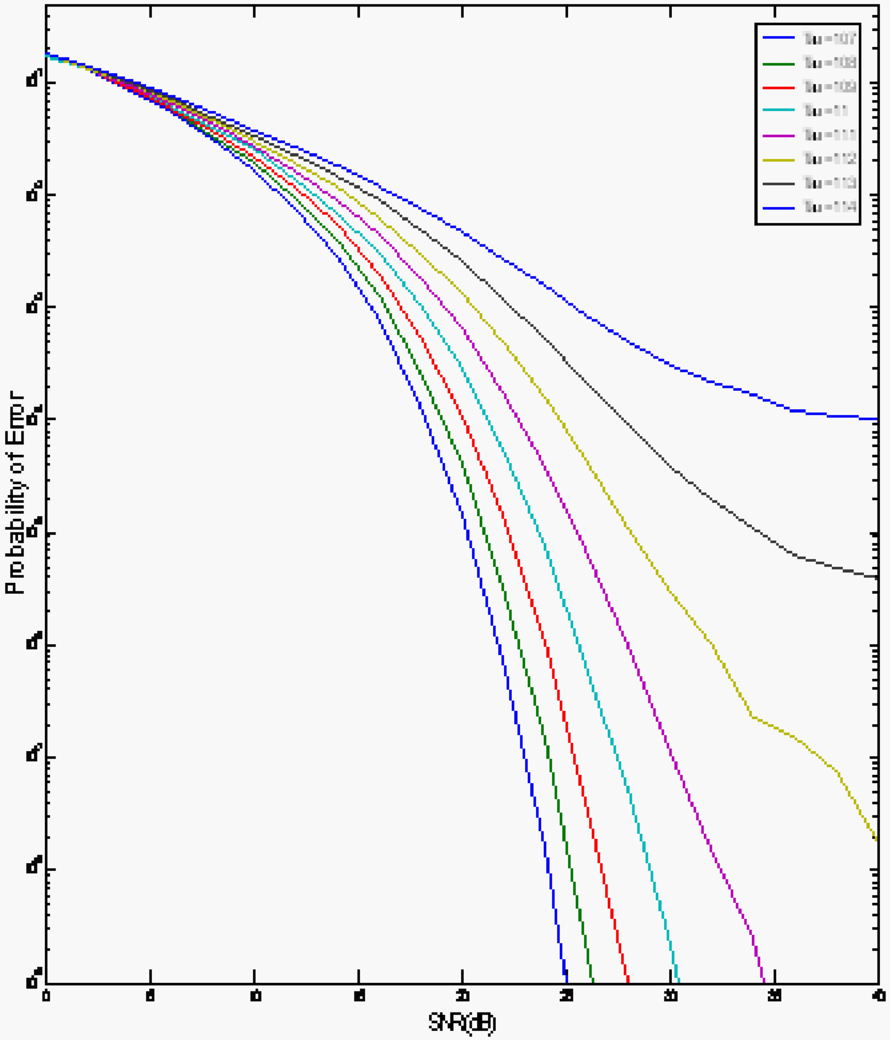


Meyer's Wavelets

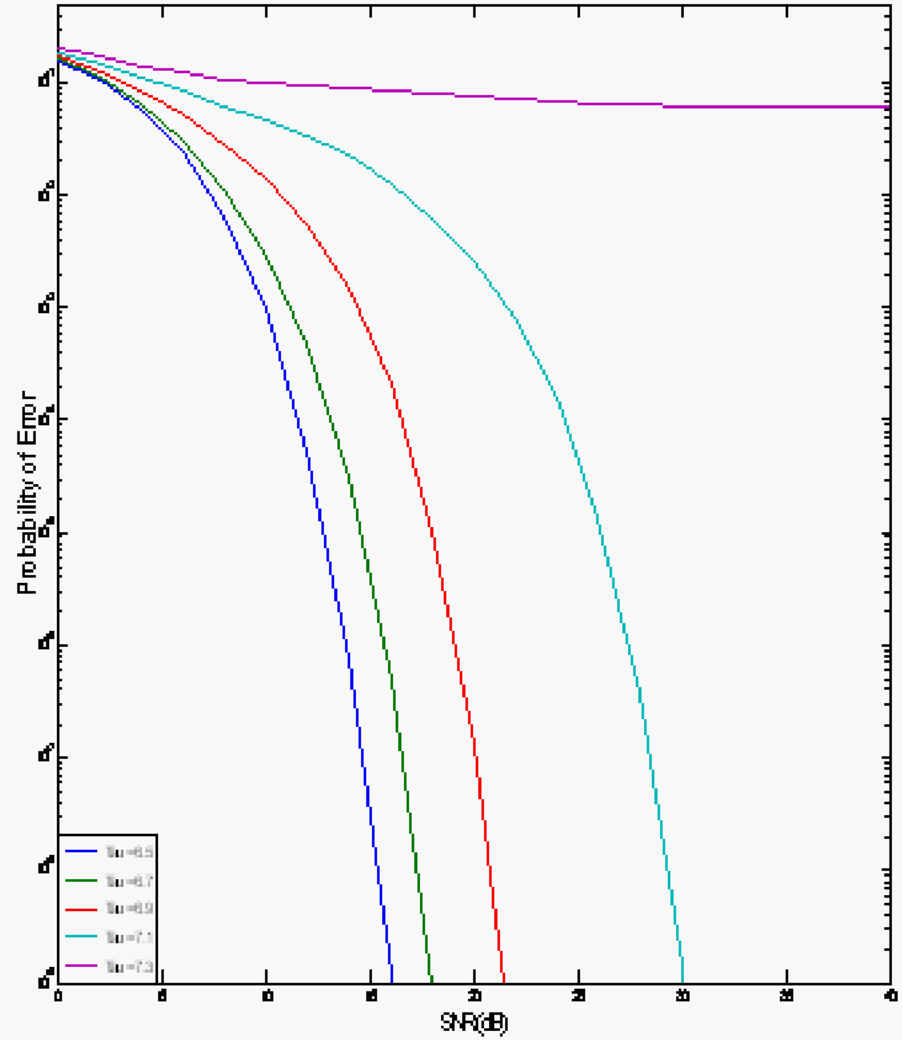


2.5 Gbps Streams

Wavelet



SRRC



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Summary of Results: W/O Coding/Equalization

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Transmission Bit Rate (Gbps)	Wavelet (max τ)	SRRC (max τ)	Conventional (max τ)
10 Gbps	7.6	3.6	2.0
5 Gbps	8.9	6.5	4.2
2.5 Gbps	11.1	7.1	6.6
1.25 Gbps	14.3	8.1	7.3

Maximum optical thicknesses that 4 bit streams with shaped ultra-short pulses can travel through cloud and all achieve a target BER.

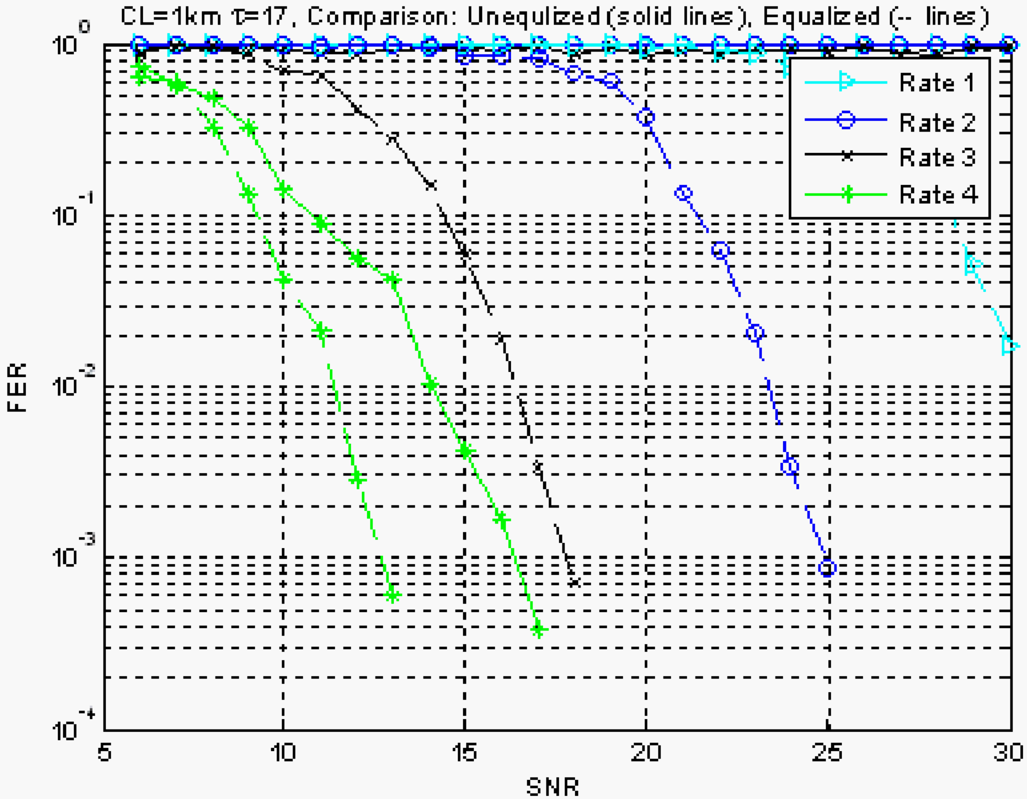
Target BER = 10^{-9}

Cloud Type	K_{scat} (km^{-1})	K_{ext} (km^{-1})
Cumulus	131.825	133.37
Stratus	56.8025	57.2575
Stratus-Stratocumulus	37.45	37.6950
Stratocumulus	44.8275	45.2235
Altostratus	95.024	95.7320
Nimbostratus	80.26	81.0760
Thin Cirrus	0.086585	0.0882
Cirrus	0.811425	1.0164

Scattering coefficient, K_{scat} in kilometer-inverse, for various clouds.

Results with Equalization

- **Observation:**
  - Rate-1 (5.333 Gbps) , rate-2 (2.666 Gbps), rate-3 (1.333Gbps) and rate-4 (0.65Gbps) show an FER=1.0 without equalization.
  - Equalization makes a substantial difference in the system performance, especially at higher transmission rates.

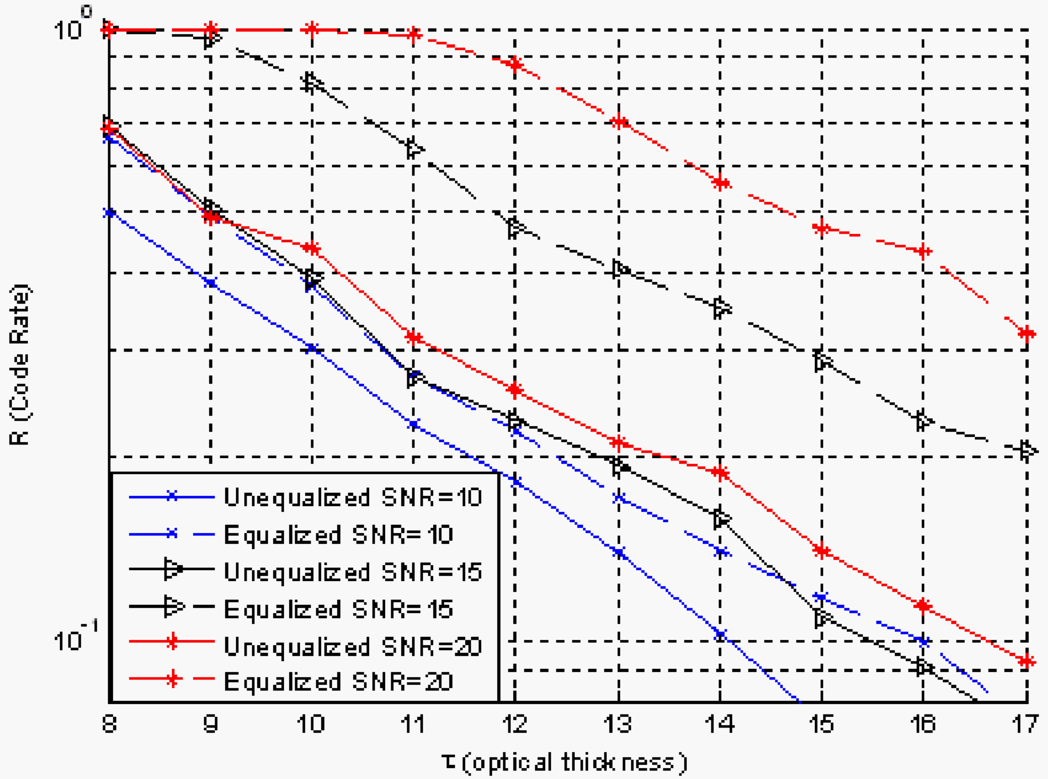


Frame Error Rate versus SNR

Results with Coding/ Equalization

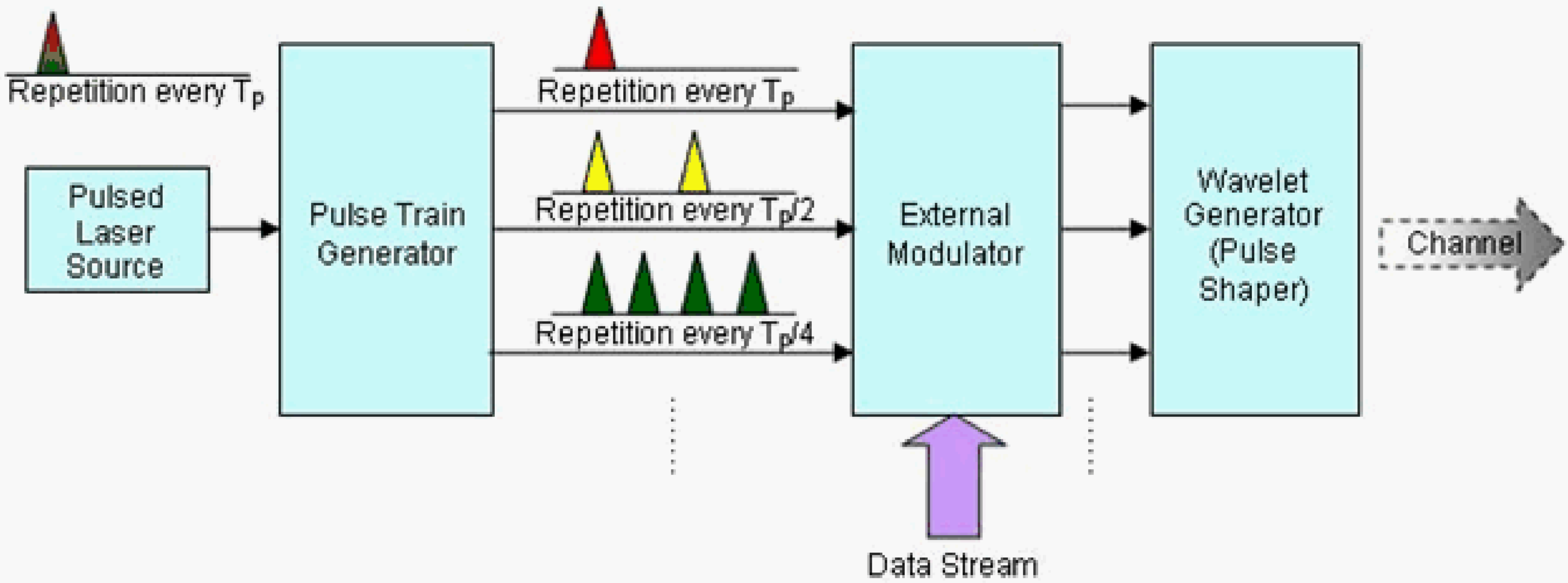
Fountain Coding

- **Observations:**
  - Shows the redundancy needed to achieve an FER=10^{-6} for different SNR values of 10, 15 and 20.
  - Amount of improvement (different between un-equalized and equalized systems) is more pronounced at high SNR values.

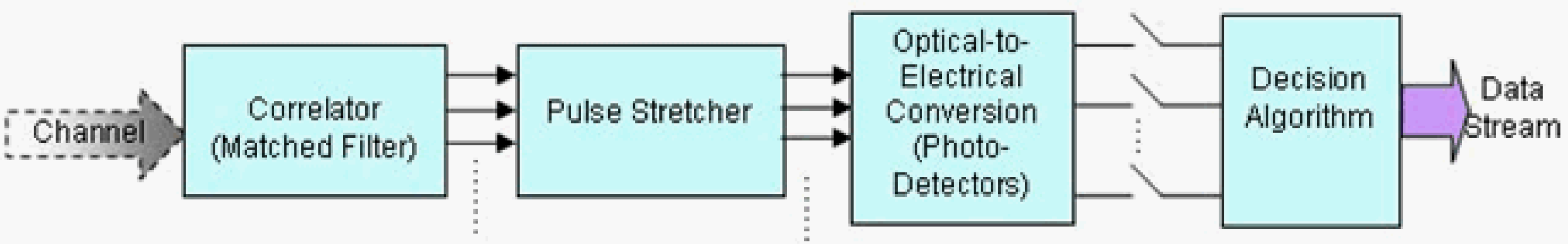


Code Rate versus Optical Thickness Values for a FER=10-6

Ultra-Short Pulse FSO Fractal Transmission Link

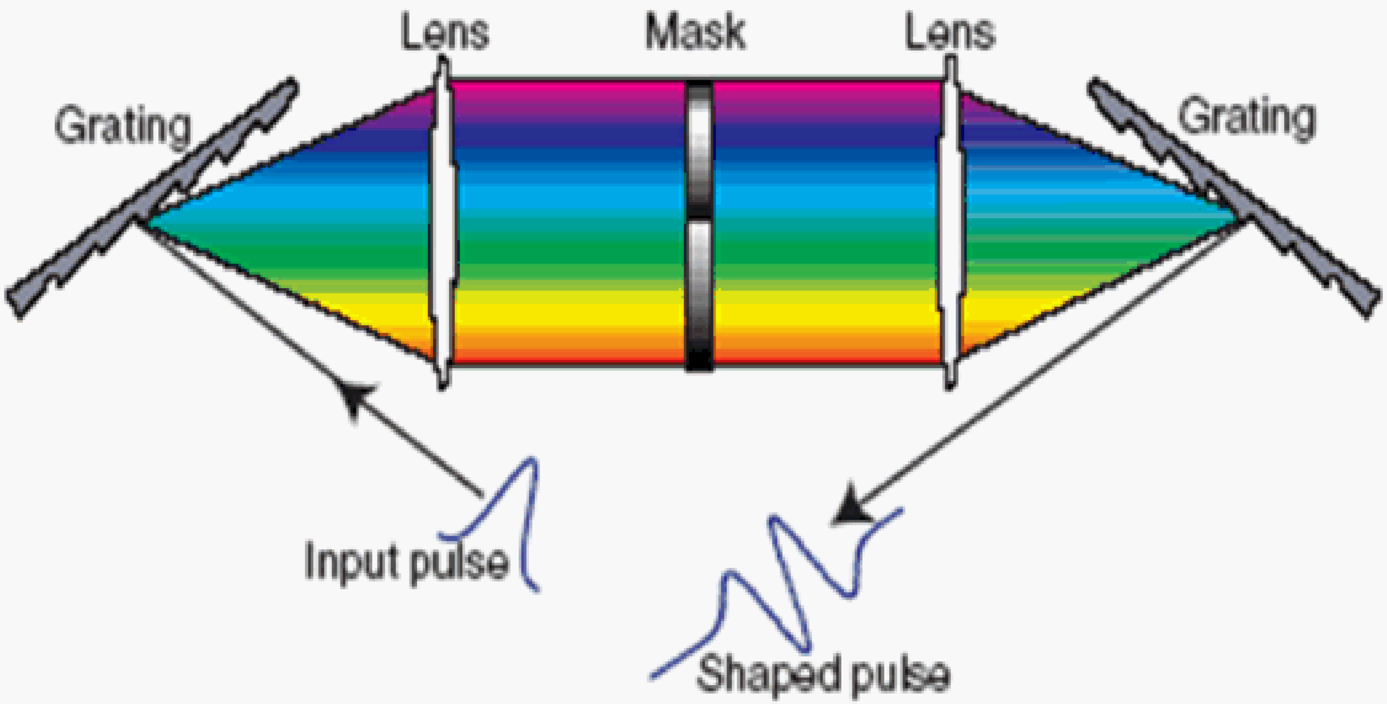


(a) Transmitter



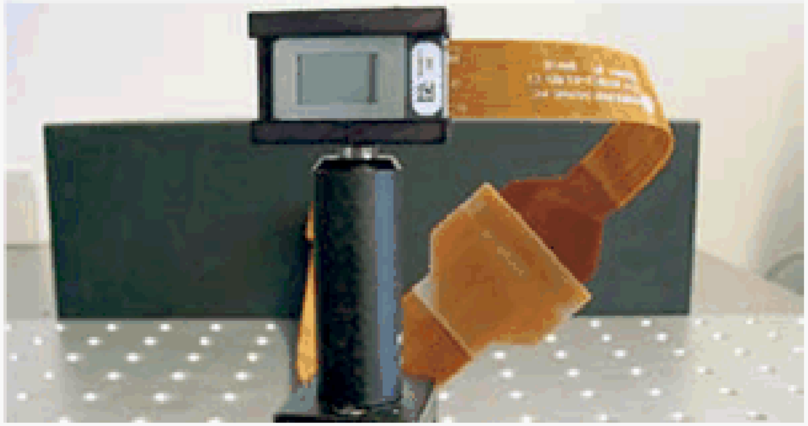
(b) Receiver

Spectral Encoding Wavelet Generator



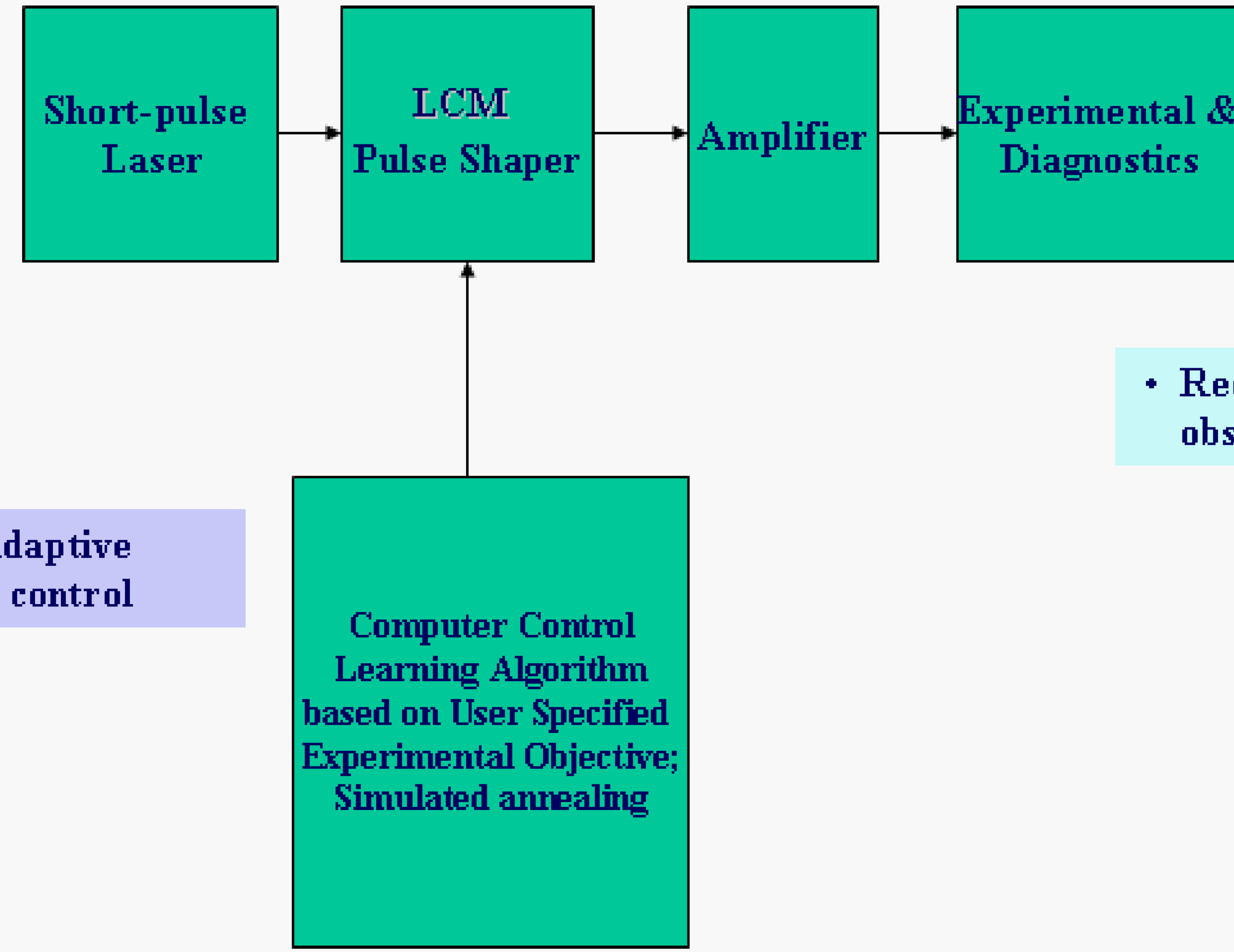
We need sufficient spatial resolution to fit multiple rate photolithographic gratings on the same mask.

Liquid Crystal Spatial Light Modulators Specs.



- 1280 x 768 Pixels
- 60 Hz Frame Rate
- 12 µm Pixel Pitch
- Independent gray-level spectral amplitude or phase control
- 16,0 x 9,86 mm Active Area
- 4000 : 1 Contrast ratio

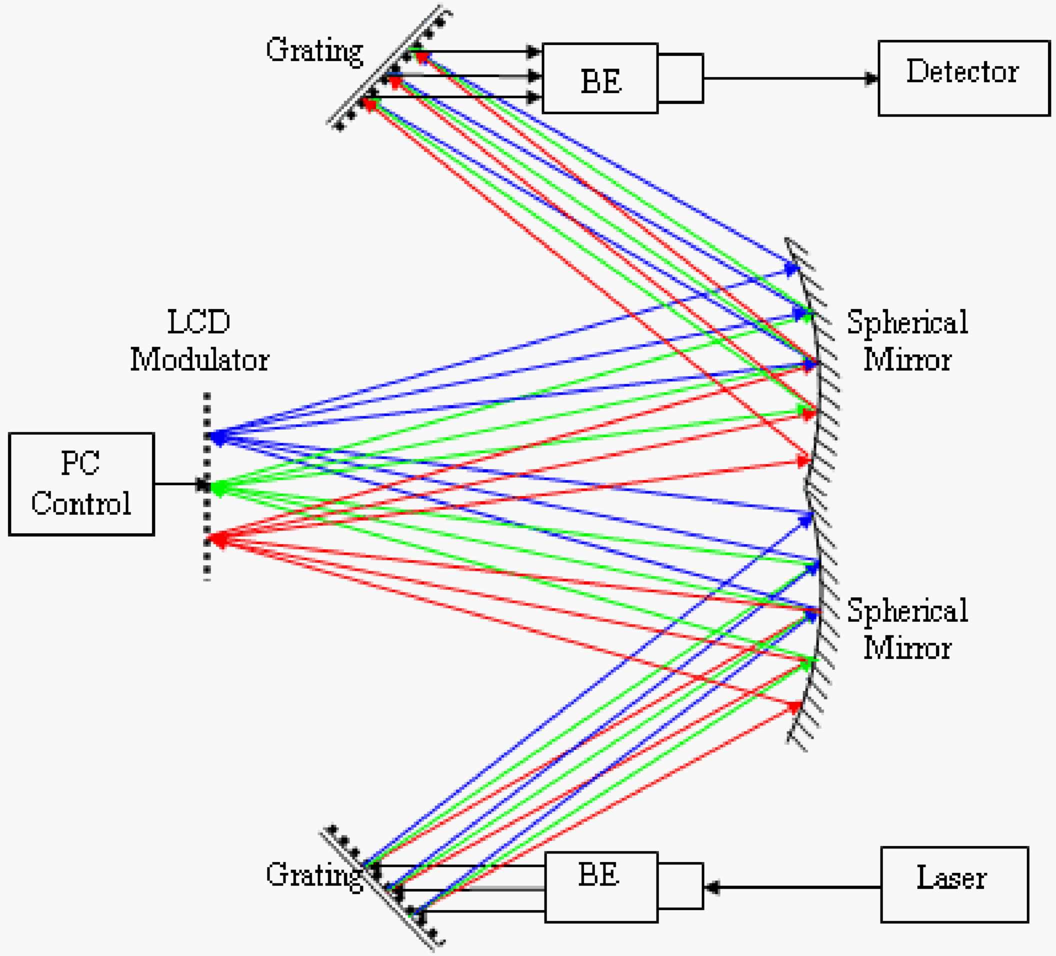
Control Strategies for Femto-second Pulse Shaping



- Requires specification of an observable to be optimized

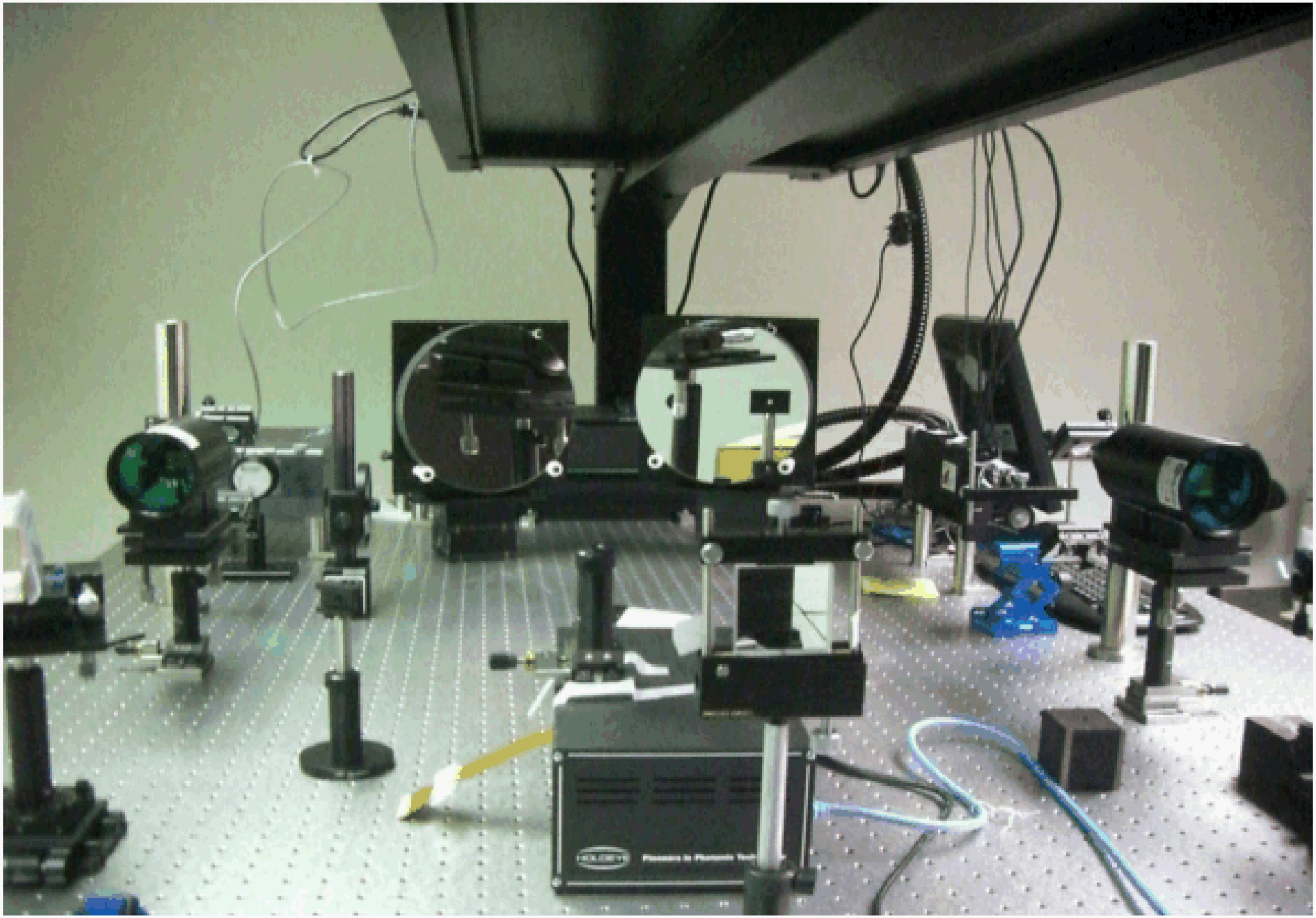
Adaptive control

Experimental Set-up

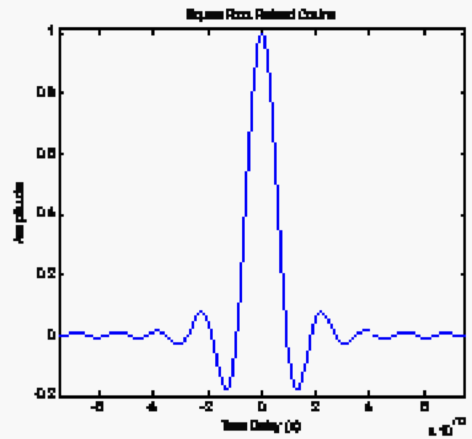


Pulse Shaping Apparatus
BE – Laser Beam Expander

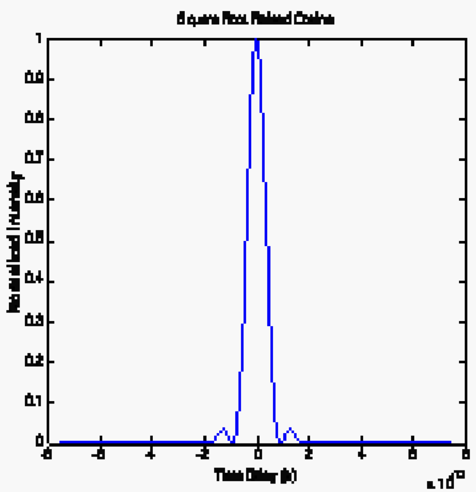
Experimental Set-up at CICTR Labs. Penn-State University



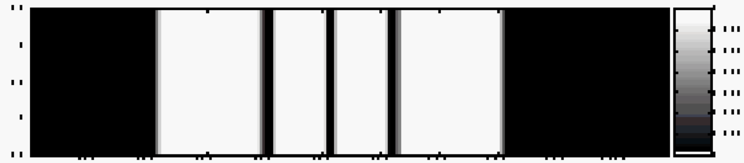
Experimental Set-up



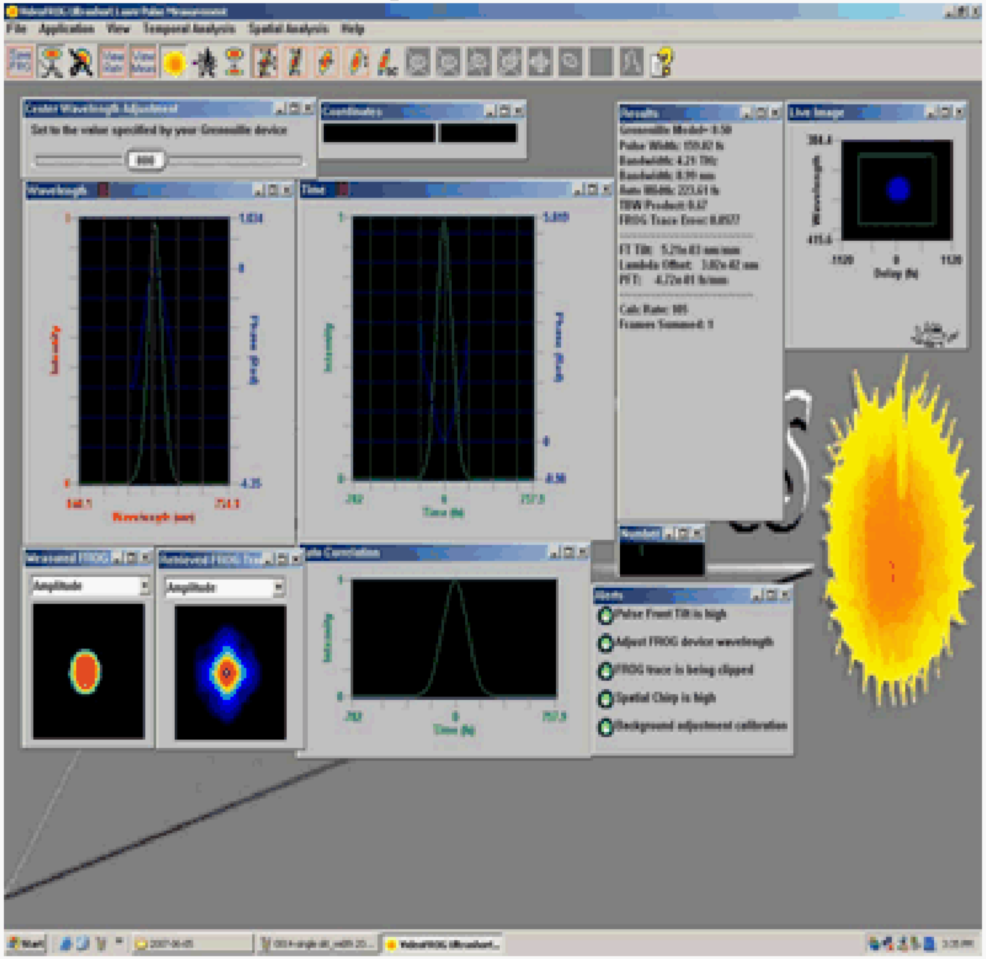
Amplitude of target Square Root Raise Cosine Pulse *(Meyer Scaling Function)*



Intensity of target Square Root Raised Cosine (SRRC) Pulse

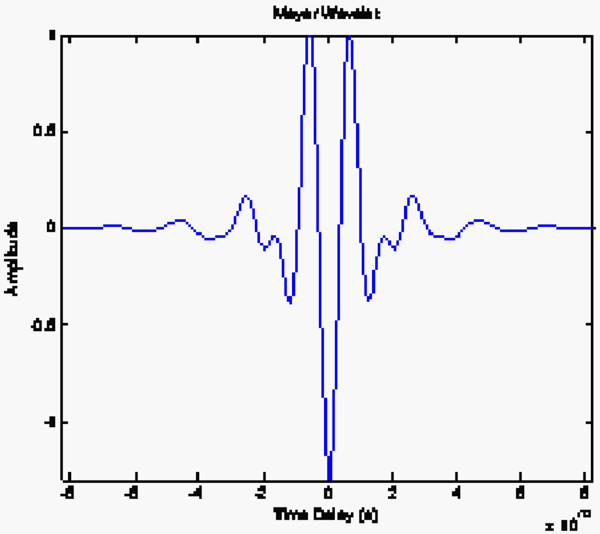


Amplitude Mask – SRRC

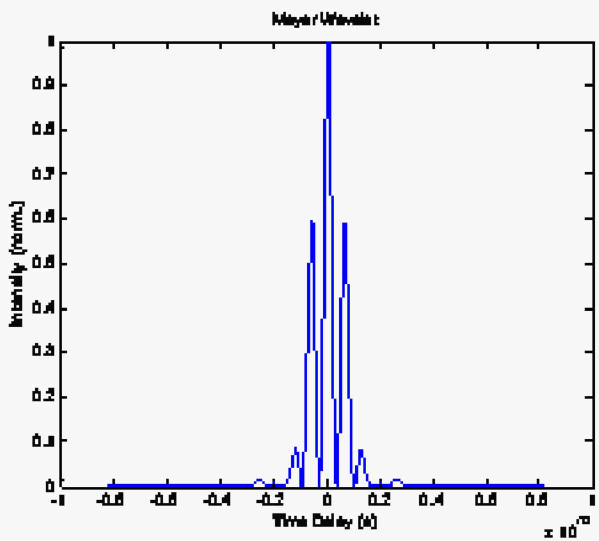


Auto-correlation Intensity of target Square Root Raised Cosine (SRRC) Pulse with 224 femto-second duration at a rate of 3 Giga pulses per second

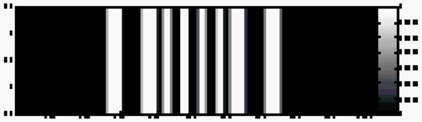
Meyer Wavelet



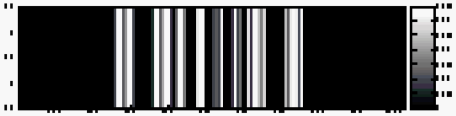
Amplitude of target Meyer Wavelet Pulse



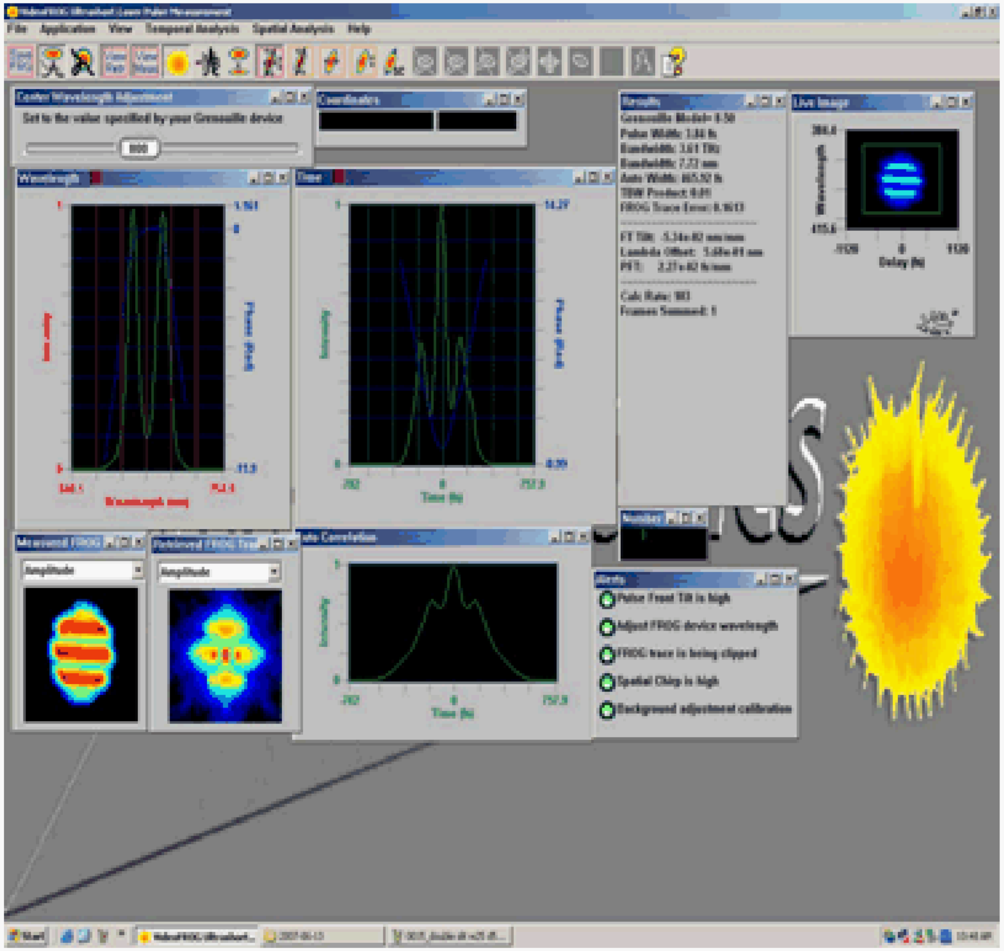
Intensity of target Meyer Wavelet Pulse



Amplitude Mask - Wavelets



Phase Mask - Wavelets



Auto-correlation Intensity of target Square Root Raised Cosine (SRRC) Pulse with 466 femto-second duration at a rate of 3 Giga pulses per second

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Program Plan, SOW and Milestones

Base Efforts SoW		Period 1	Period 2	Period 3
Task-1	Communications Performance Assessment			
Task-2	Development of Wavelet Communication Concept			
Task-3	Laser Pulsed Wavelet Encoded Transceiver Computer Simulations			
Task-4	Design of photo-lithographic Wavelet Encoder			
Task-5	Design of photo-lithographic Wavelet Decoder			

Option Efforts SoW		Period 4	Period 5
Task-1	Overall Design of Laser Pulsed Wavelet Transceiver		
Task-2	Fabrication and Testing of Photo-lithographic Wavelet Encoder / Decoder		

Summary

- **Goal:**

  Increased FSO link availability via feed-forward "opportunistic" transmission.

- **Methodology:**

  Multi-rate communication via "Fractal Modulation" using wavelets, and using ultra-short pulsed lasers.

- **Outcome:**

  Overall systems design and evaluation, with improved performance.