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HUT Communications Laboratory

S-72.3340 Optical Networks Course

Lecture 8: Test, Measurement and Simulation

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Lecture Outline

- Part I: Test and Measurement
  - Performance characterization of digital fiber-optic links
  - Test and measurement cycle

- Part II: Simulation
  - Analytical modelling
  - Link and network simulation tools

Part I: Test and Measurement

1. Introduction

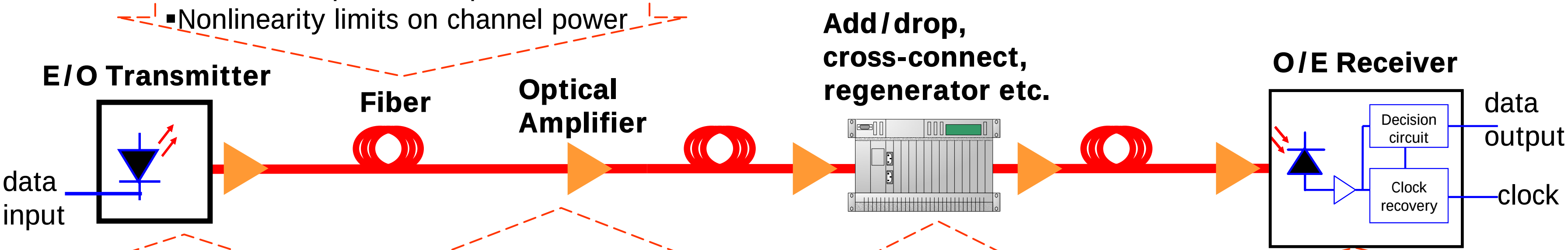
- Optical communcation systems continuously evolving
  - Keep up with capacity demand
  - Extend reach of links
  - Reduce CAPEX and OPEX
- Optical system testing and measurement have become more complex with the evolution
  - Test and measurement requirements were modest for initial systems
  - Current systems more intolerant to impairments $\Rightarrow$ demand more rigorous testing

1. Introduction

- Significant developments in fiber-optic systems influencing test and measurement
  - Multiwavelength operation (WDM transmission)
    - Before: single channel operation around 850 nm or 1300 nm
    - Now: CWDM or DWDM channels in 1260 nm-1625 nm range
  - Increased line rates
    - Before: a few tens of Mbit/s
    - Now: rates up to 40 Gbit/s
  - Deployment of optical amplifiers
    - Before: short links spanning a few km
    - Now: links up to a few thousand km

2. Characterization of Digital Links

- Attenuation, return loss, length
- Splices, connectors, bends, breaks
- CD/PMD, dispersion maps
- Nonlinearity limits on channel power



- Wavelength, λ count
- Main mode power
- Side-mode suppression ratio, mode offset etc.
- Linewidth, chirp, extinction ratio, RIN etc.
- Jitter

- Input/output power
- Gain per channel
- Polarization dependent gain
- Noise figure
- Gain flatness, slope
- PMD

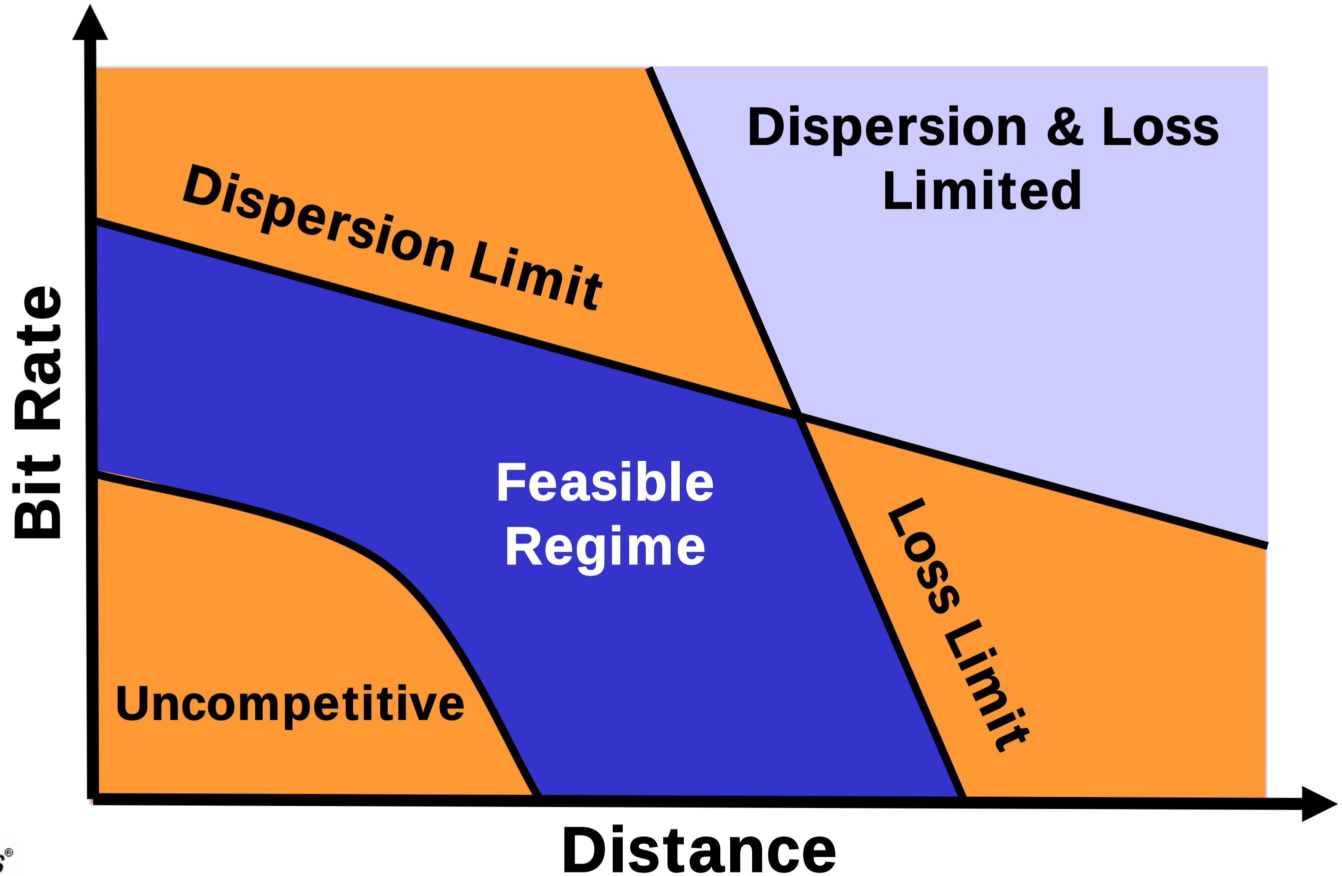
- Insertion loss (multi-channel), PDL
- Power equalization
- Crosstalk
- Spectral response
- Jitter
- PMD

- Receiver sensitivity
- Overload
- Jitter tolerance
- BER vs Power, BER vs OSNR

- **Optical power budget (link loss budget) calculation and allocation of system power margins**
- **Dispersion budget measurement and optimum dispersion compensation**
- **Link jitter budget projections**
- **Performance levels (BER, OSNR, Q-factor etc.) for different bit rates and distances**

2. Characterization of Digital Links

- Impairments limit bit rate (information transfer efficiency) and distance (range)



2. Characterization of Digital Links

- Link characterization important for operator
  - Have precise knowledge of their network limitations
  - How and where to localize faults or performance limitation points

- Essential fiber link test and measurement routines
  - Link loss testing
  - Link dispersion testing

2.1 Loss Testing

- Optical loss testing
  - Individual power meter and light source units or integrated optical loss test set (OLTS)
  - Double-ended measurement requiring two technicians
  - Single OLTS could used for component insertion loss (IL) measurement

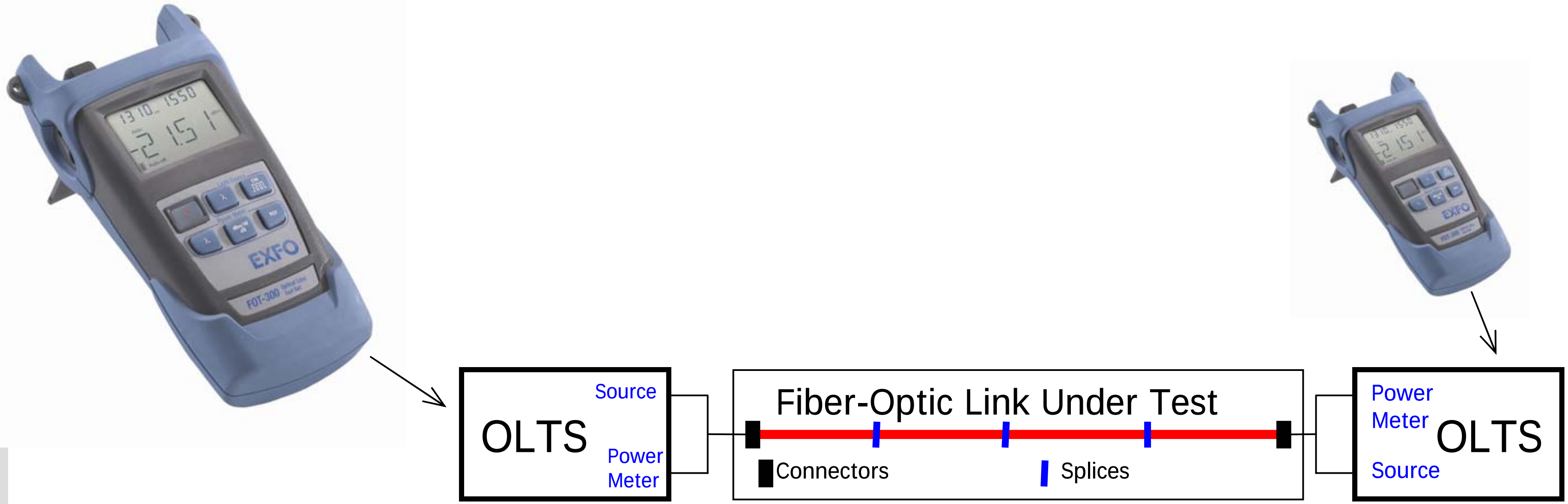


Figure: Link loss measurement using OLTS

2.1 Loss Testing

- Optical time domain reflectometer (OTDR)
  - Take snapshot of fiber span using backscattering and reflections
  - Single-ended measurement by one technician
  - Useful for troubleshooting/fault location

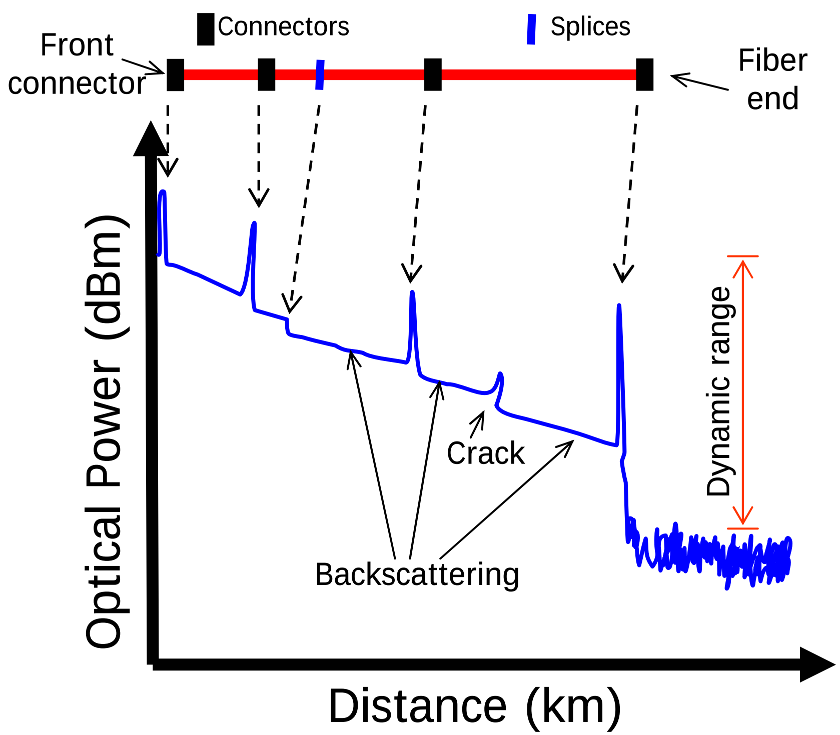


Figure: Example OTDR plots

Figure: Example connector types

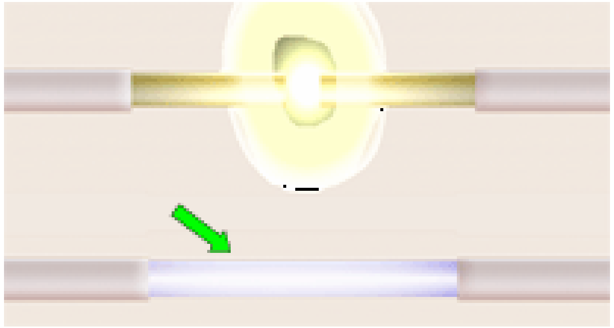


Figure: Example fusion splice

2.1 Loss Testing

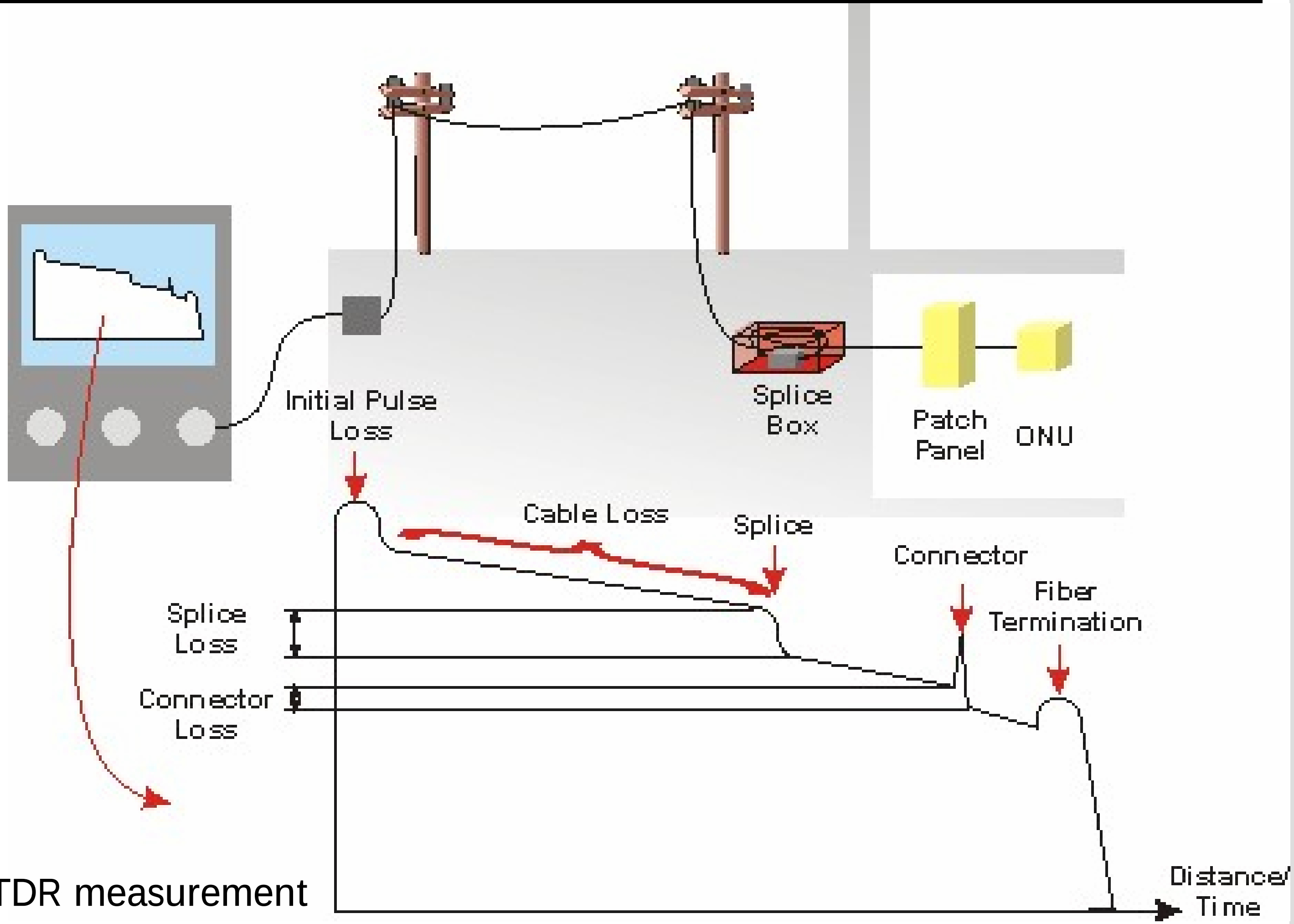


Figure: Example OTDR measurement for a fiber link to customers' optical termination unit (ONU)

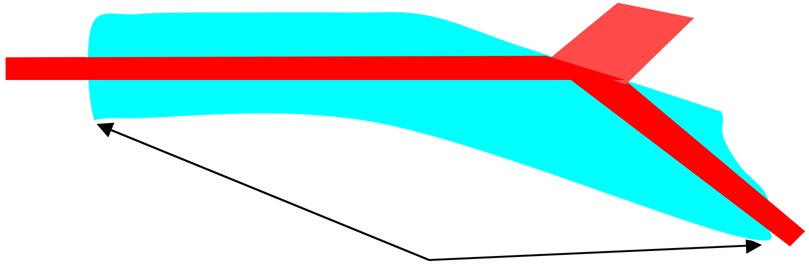
Source: "Introduction to Optical Communications," by L. Hart, Althos Publishing

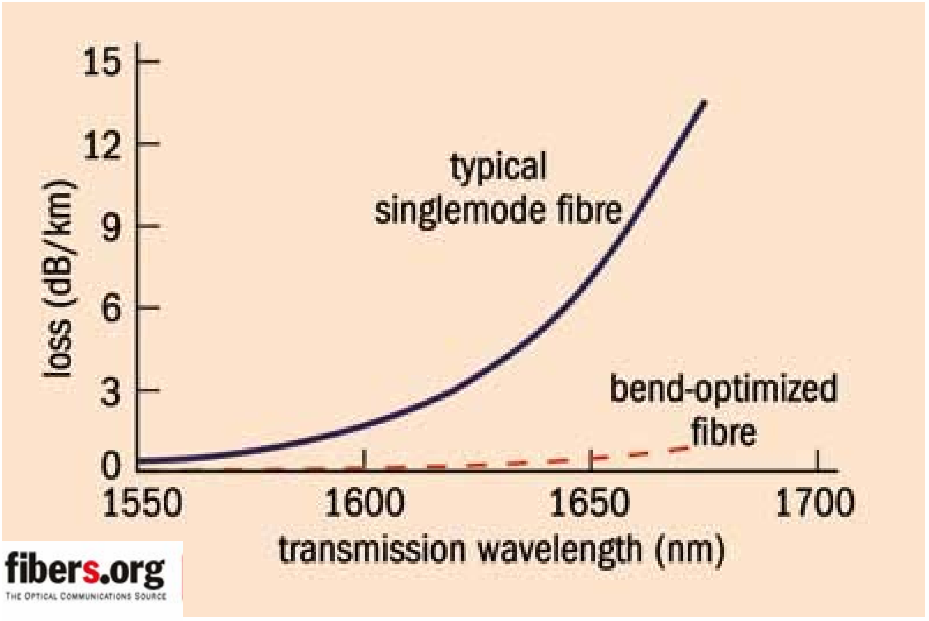
2.1 Loss Testing

- OLTS advantages over OTDR
  - More accurate
  - Larger dynamic range ⇒ longer measurable link length
  - Easily test through EDFAs with isolators
  - Shorter testing time
    - Advantageous since for improved accuracy link needs to be measured from both ends and results averaged
    - Example: Single OTDR and OLTS loss measurements take about 3min and 30s respectively. Therefore, for a 120 fiber cable, OTDR measurements at both ends take at least 11hr longer.

2.1 Loss Testing

- Bending loss
  - Fiber bends increase power leakage from core to cladding
    - Typically at splitting points, intra-office distribution frames etc.
  - Restrictions on minimum bending radius
  - More significant beyond 1600 nm
    - Some CWDM and L-band DWDM channels in that region
    - Rigorous loss testing at wavelengths beyond 1600 nm required





2.2 Dispersion Testing

- Dispersion testing necessary to ascertain fiber link limitations
  - Chromatic dispersion (CD)
  - Polarization mode dispersion (PMD)
- Need for dispersion testing
  - Dispersion of fibers need to be checked for compatibility with high rates
  - Transmitter linewidth must be carefully analyzed and controlled
  - Bandwidth response of various packaged optical modules needs to be optimized

2.2 Dispersion Testing

- Checking how dispersion parameters in field deviate from manufacturers specifications
- Environmental conditions (temperature, pressure, vibrations etc.) varies fiber's refractive index
  - Change location of zero chromatic dispersion wavelength
    - Typical variations for standard singlemode fibers
      - 0.025 nm/°C
      - 1.75 nm/%strain
      - -0.007 nm/MPa
  - More residue dispersion after dispersion compensation
  - Stress also changes fiber symmetry $\Rightarrow$ increased PMD

2.2 Dispersion Testing

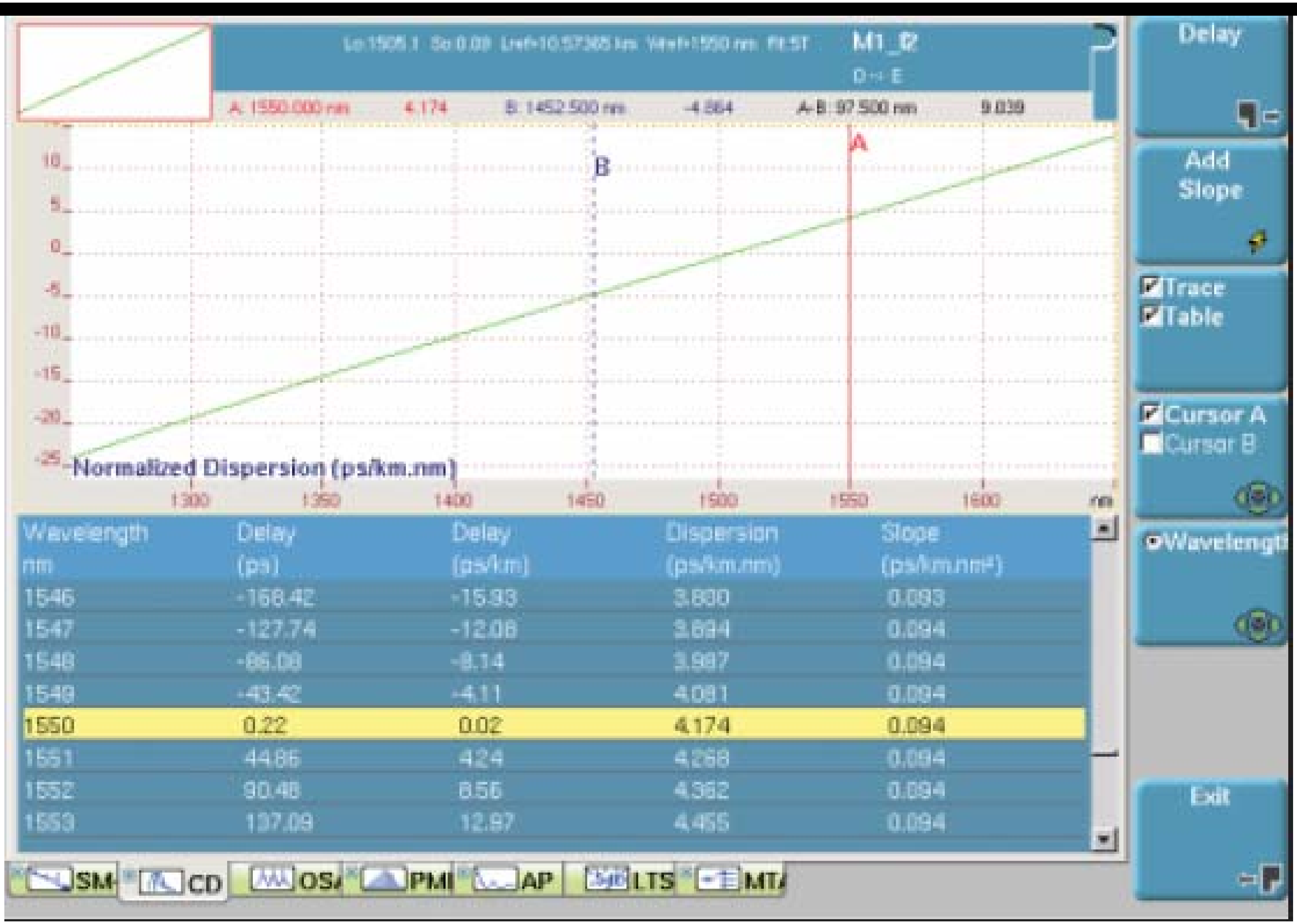


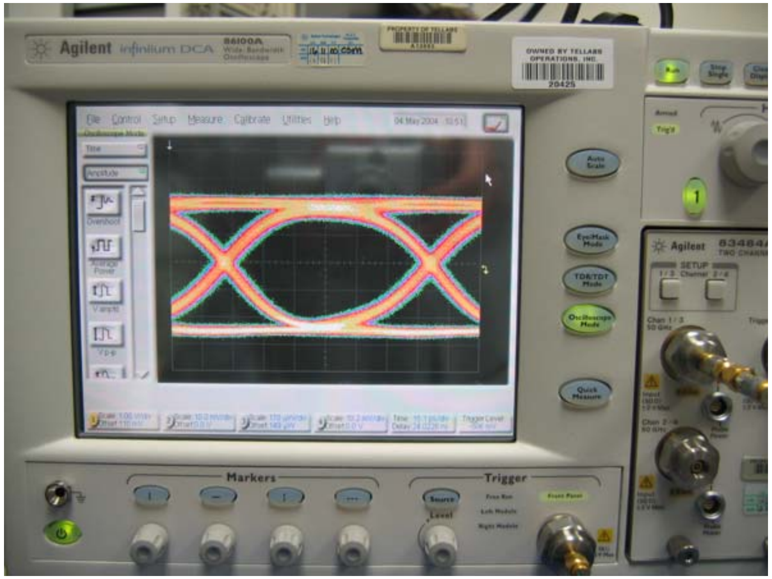
Figure: Example GUI screenshot of MTS-8000 CD tester

3. Performance Testing

- Measure parameters that represent end-to-end link performance
  - Eye opening penalty
  - Bit-error-rate (BER)
  - Q-factor
  - Optical SNR (OSNR)

3.1 Eye Diagram Analysis

- Eye diagram
  - Produced by an oscilloscope
  - Useful for troubleshooting various link problems



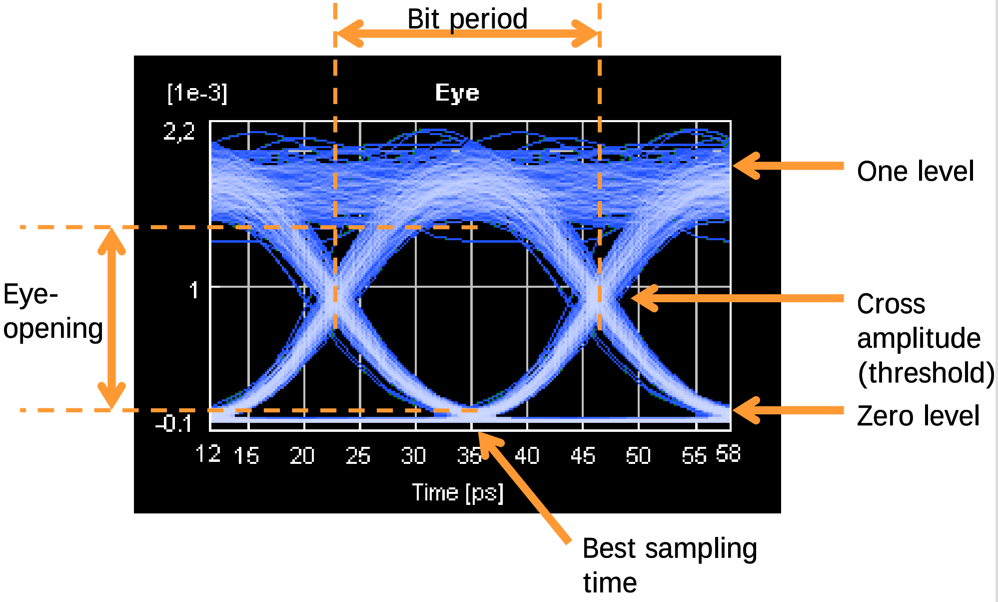
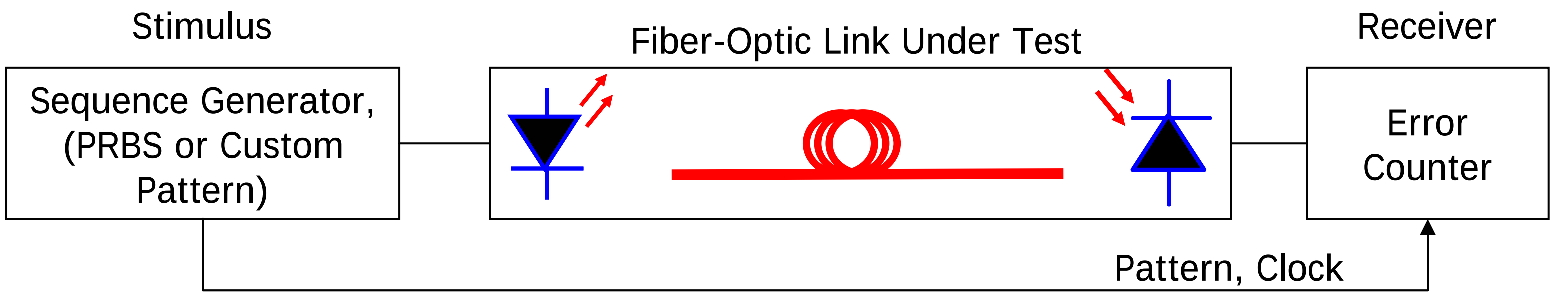


Figure: Fundamental eye (43 Gb/s NRZ) parameters.

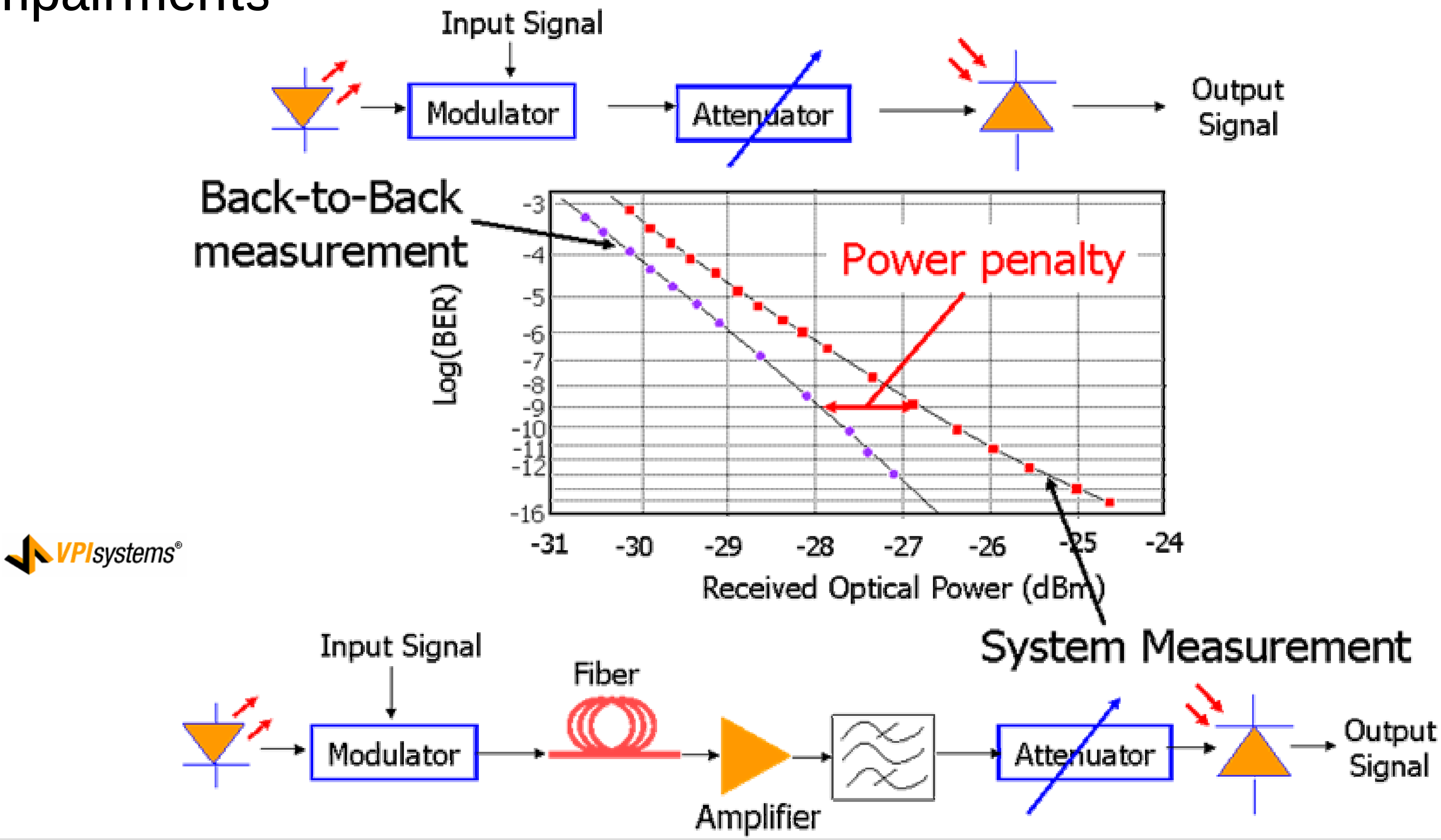
3.2 BER Testing

- Use error counter or detector to compare signal at link's input and output to obtain BER
- Error counter needs to be familiar with the test bit pattern
  - Pseudo-random binary sequence (PRBS) as 2^N-1 patterns with all N-bit combinations, except all '0' bits
    - e.g. ITU-T O.151 recommends N=31 for 2.5 to 40 Gb/s rates
  - Custom pattern
    - e.g. for SDH the N=23 PRBS test sequences (ITU-T O.181) applied to payload bytes of an STM-N frame



3.2 BER Testing

- BER testing also used to evaluate power penalty due to an impairments



3.2 BER Testing

- How many errors do you need to count to get reliable BER measurement?

- Example: 100 counted errors needed to estimate BER with 95% confidence level for a 2.5 Gbit/s link
  - Total 10^{11} bits (errored + unerrored) counted (40 s at 2.5 Gbit/s rate) for 10^{-9} BER estimation
  - Total 10^{15} bits counted (11 hours) for 10^{-12} BER estimation!!!

3.3 Block Errors

- In-service (real-time) performance monitor might measure "errored blocks" instead of calculating BER
  - Blocks in which one or more bits are in error
  - Block is consecutive data bits monitored by an error detection code
  - Example: SDH networks use bit interleaved parity (BIP) for in-service error monitoring
  - Used to evaluate block error rate (BLER)
  - Alternative error parameters employed (ITU-T G.826, G.828) e.g. errored second ratio

$$\text{Errored Second Ratio} = \frac{\text{One second periods with one or more errored blocks}}{\text{Total seconds in measuring interval}}$$

3.3 Block Errors

- Multiple bit errors in one block
  - Still considered as a single errored block
  - Places upper bound on detectable errors (maximum equivalent BER)

$$\text{Maximum Equivalent BER} = \frac{\text{Maximum number of errored blocks per second}}{\text{Total number of bits per second}}$$

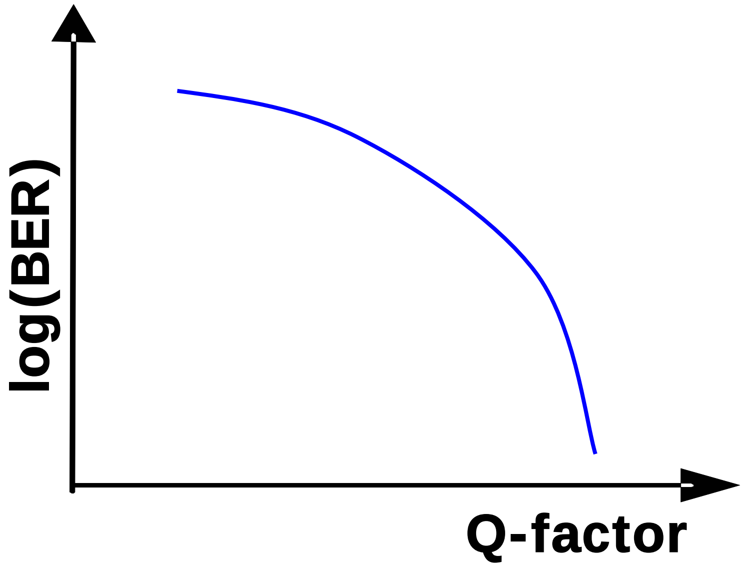
STM rate	Bits per Block	Maximum Equivalent BER
STM-1	19440	$5{,}14 \times 10^{-5}$
STM-4	77760	$1{,}28 \times 10^{-5}$
STM-16	311040	$3{,}21 \times 10^{-6}$
STM-64	1244160	$8{,}04 \times 10^{-7}$

Figure (b): Maximum equivalent BER at different STM rates for BIP-8 error monitoring.

3.4 Q-factor

- Measurement of Q-factor based on method of shifting decision threshold levels (ITU-T O.201)
  - Measure BER at different threshold settings
  - Convert measured BER to Q-factor

$$BER \cong \frac{\exp\left(-Q^2/2\right)}{Q\sqrt{2\pi}}$$



3.4 Q-factor

- Fast measurements by only taking decision threshold levels corresponding to BERs of 10^{-4} to 10^{-8}

BER	10^{-4}	10^{-8}	10^{-14}	10^{-15}
2.5 Gb/s	0.004 ms	0.04 s	11 hr	6 days
10 Gb/s	0.001 ms	0.01 s	3 hr	8 hr

Table: Time to record certain BERs at different bit rates.

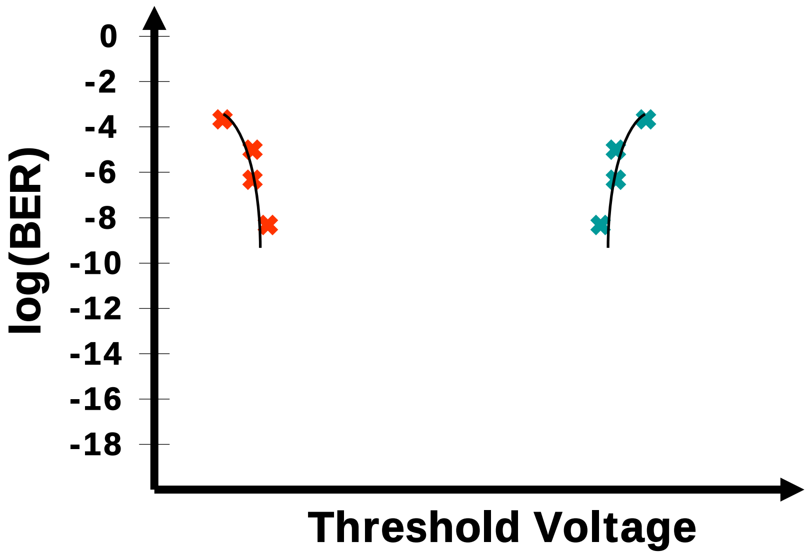


Figure: BER measurement and extrapolation

3.4 Q-factor

- Convert BER versus threshold results into Q-factor versus threshold plot
- Curve fitting to reach an intersection point ⇒ optimum threshold and Q-factor point
- Minimum BER obtained from optimum Q-factor

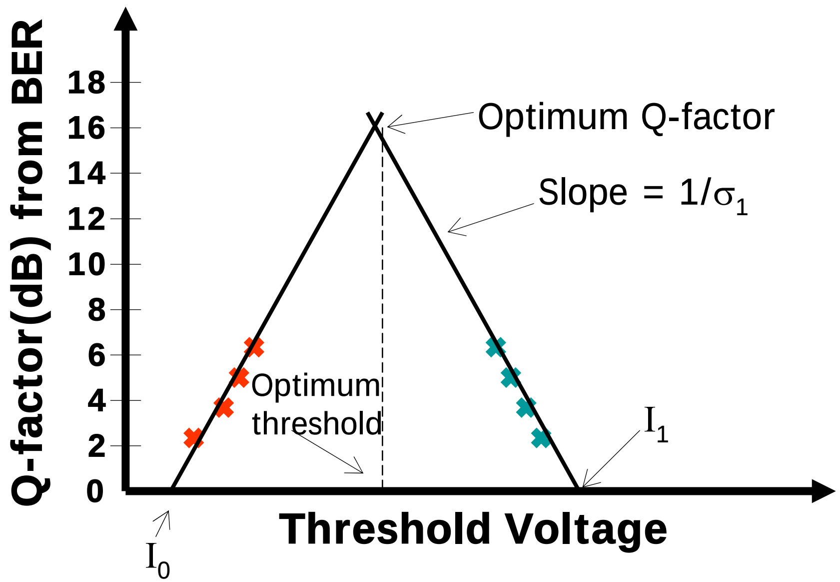


Figure: BER measurement and extrapolation

3.4 Q-factor

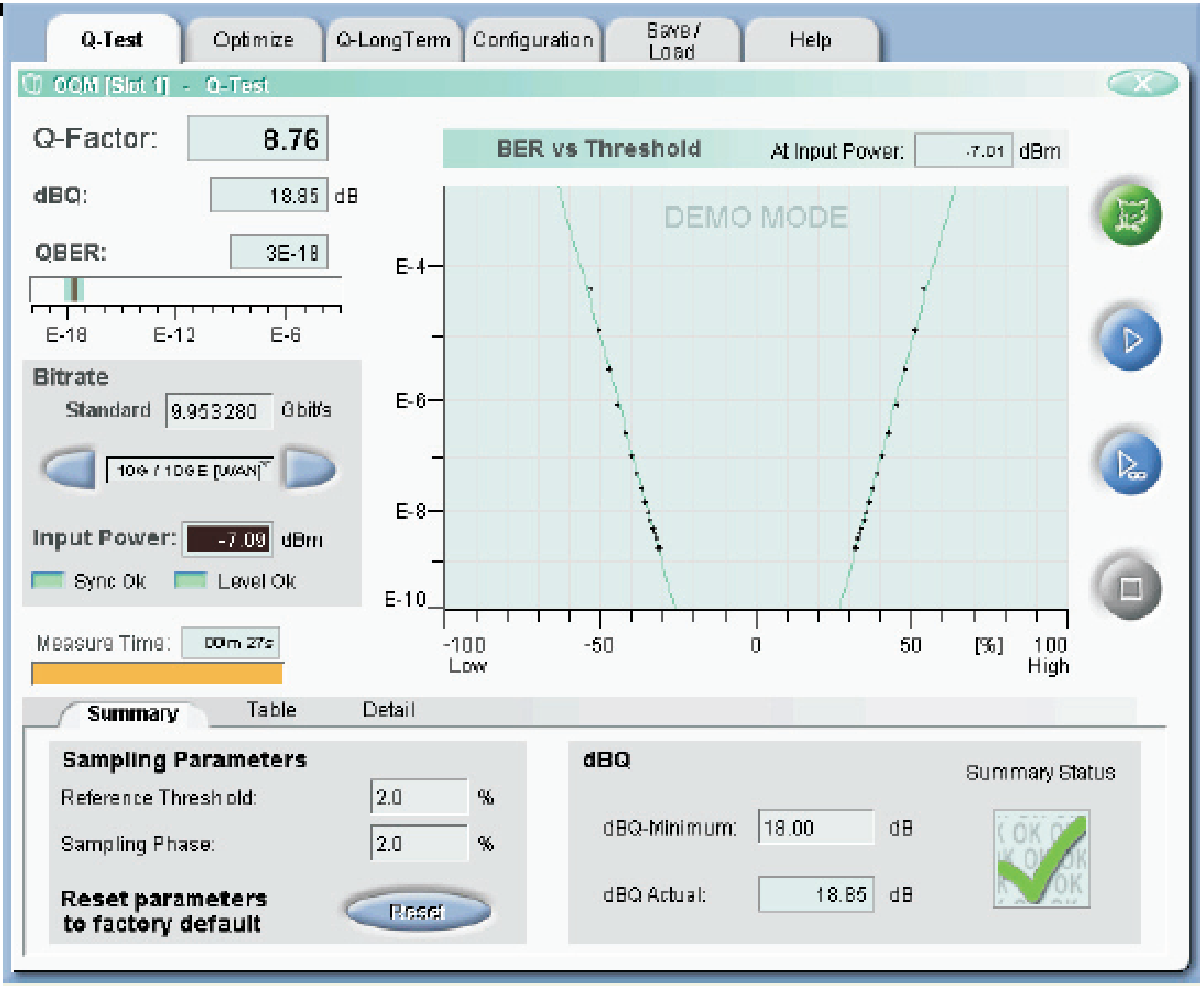


Figure: Screenshot MTS-8000 Q-factor meter

3.5 Optical Signal to Noise Ratio

- Links with optical amplifiers ⇒ ASE beat noise is dominant
- Optical signal to noise ratio (OSNR) a useful performance parameter
  - ASE accumulation along amplifier chain lowers the OSNR
  - OSNR listed as an interface parameter in various standards
    - ITU-T G.692 (amplified WDM systems) and G.959.1 (OTN physical layer)

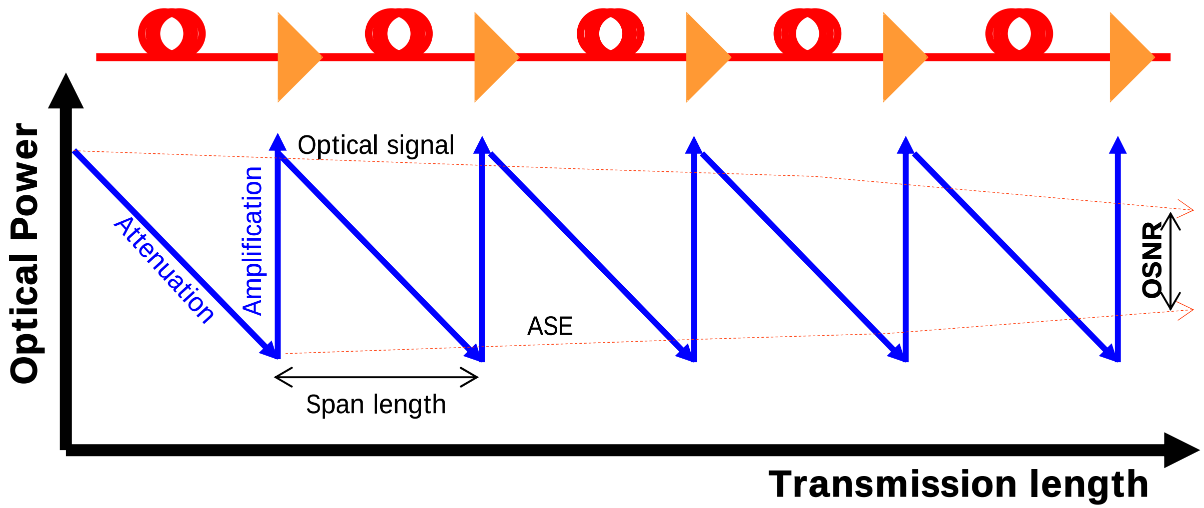
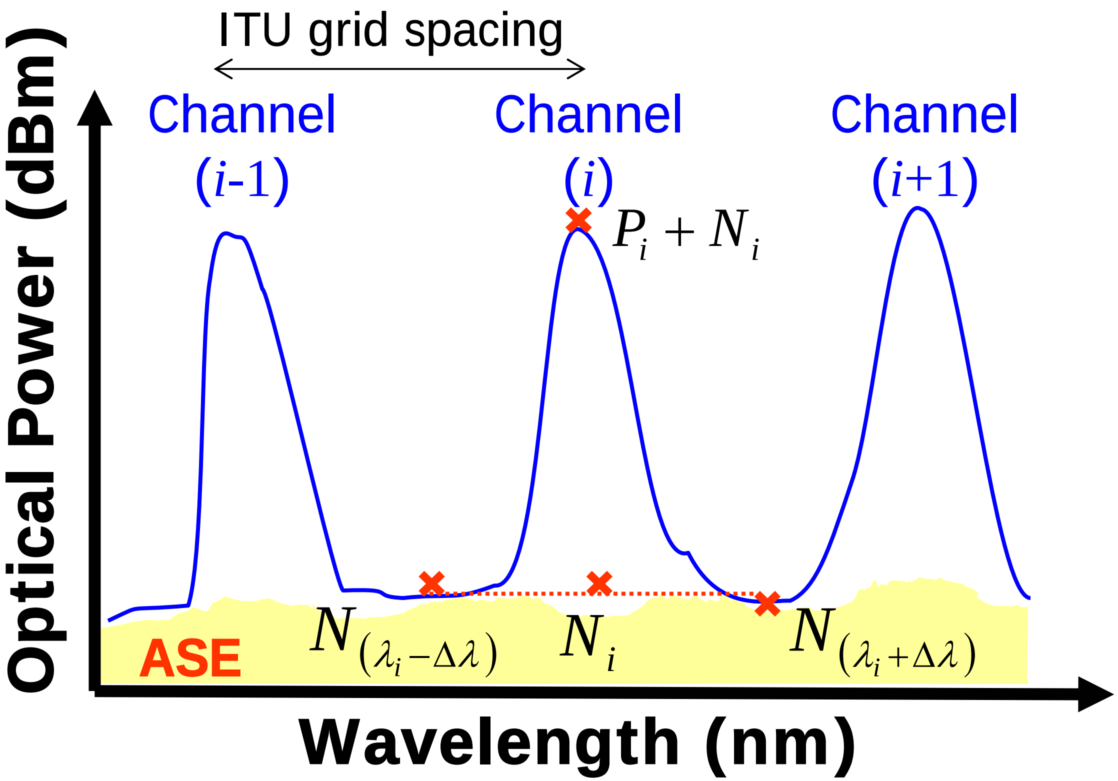


Figure : ASE accumulation and OSNR reduction in an amplified transmission system

3.5 Optical Signal to Noise Ratio

- OSNR measured using optical spectrum analyzer (OSA)
  - Method outlined in IEC 61280-2-9
  - ASE Noise power hidden by signal so obtained by interpolation



$$N_i = \frac{N_{(\lambda_i-\Delta\lambda)} + N_{(\lambda_i+\Delta\lambda)}}{2}$$

Figure: ASE noise evaluation from signal spectrum

3.5 Optical Signal to Noise Ratio

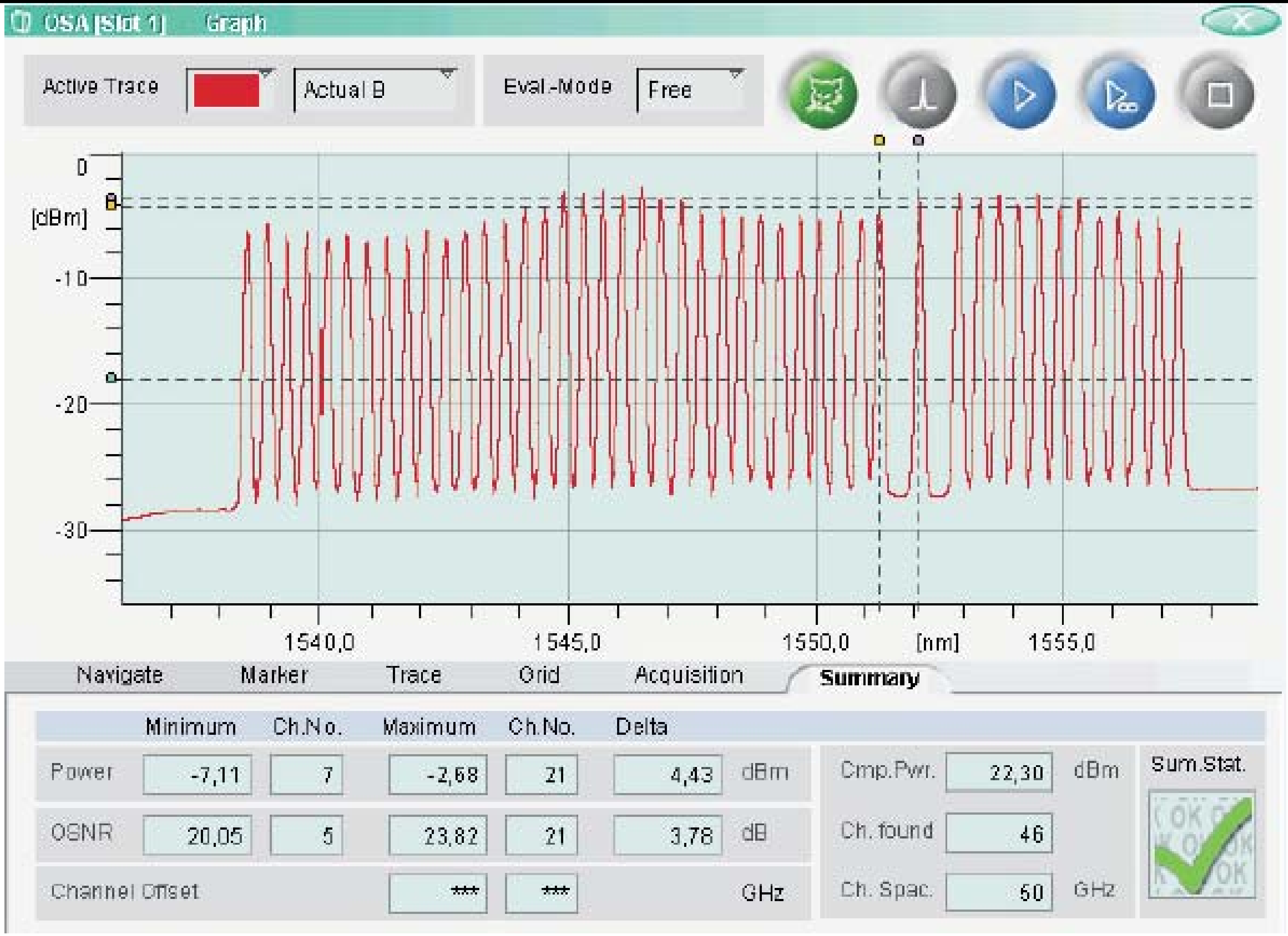
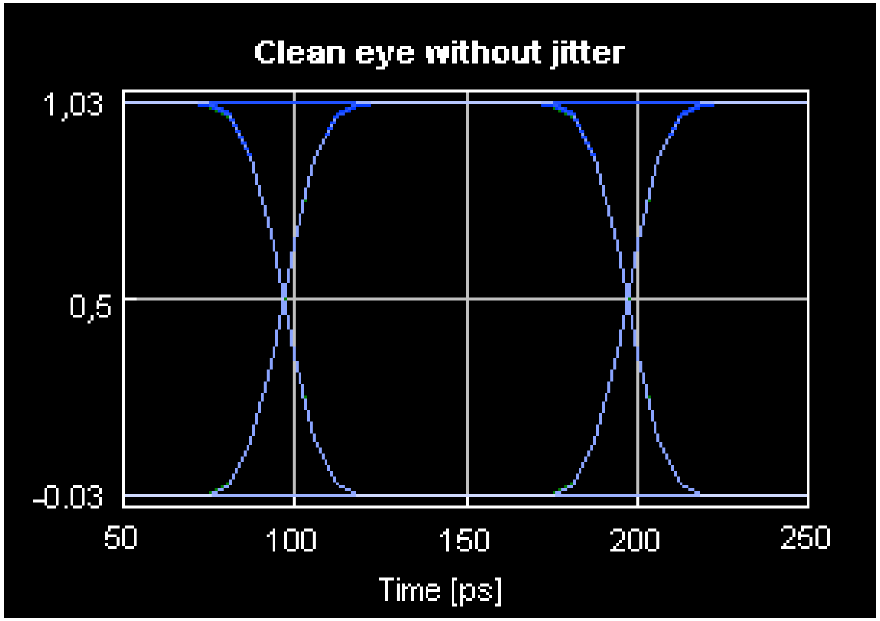


Figure: Example GUI screenshot of MTS-8000 tester OSA

3.6 Jitter Performance Measures

- Jitter leads to horizontal eye closing
  - Successive bit periods might have slightly different durations
  - Sampling not at maximum eye opening due to clock mis-timing ⇨ worse BER



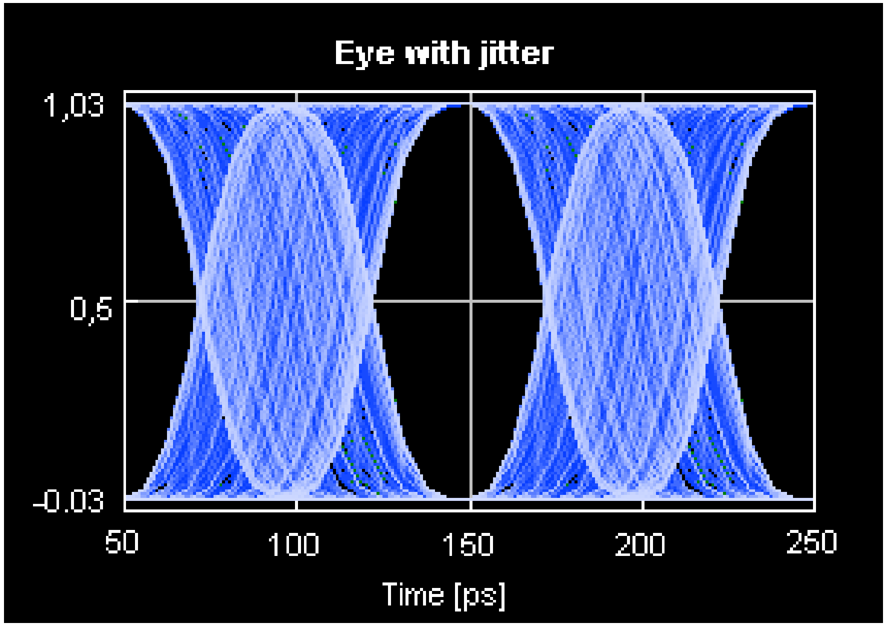


Figure: A 10 Gb/s NRZ signal without jitter [left] and with jitter [right].

3.6 Jitter Performance Measures

- Using dedicated jitter test and analysis tools
  - ITU-T compliant (e.g. O.172 rec. for SDH test equipment)
  - Inbuilt pattern and jitter sources, clock recovery
  - Inbuilt custom peak-to-peak and RMS jitter detectors
  - Real-time accumulation and display of jitter statistics
  - etc.

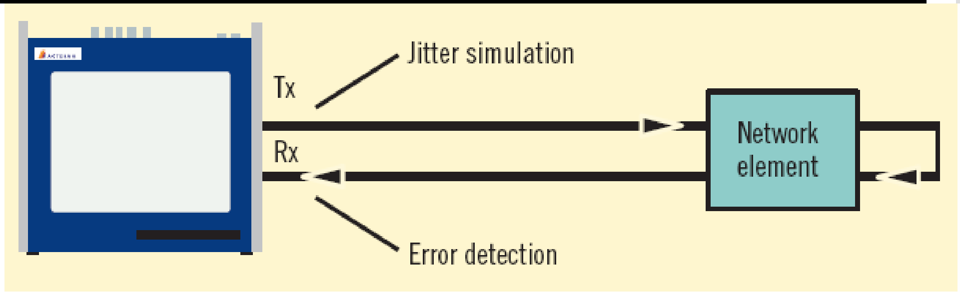


Figure (a): Jitter tolerance measurement

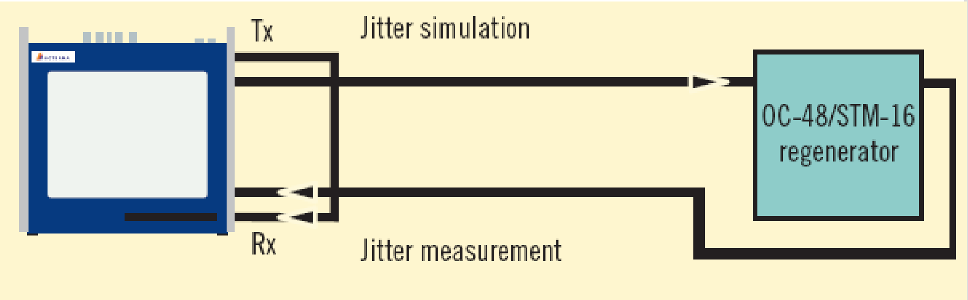


Figure (b): Jitter transfer measurement

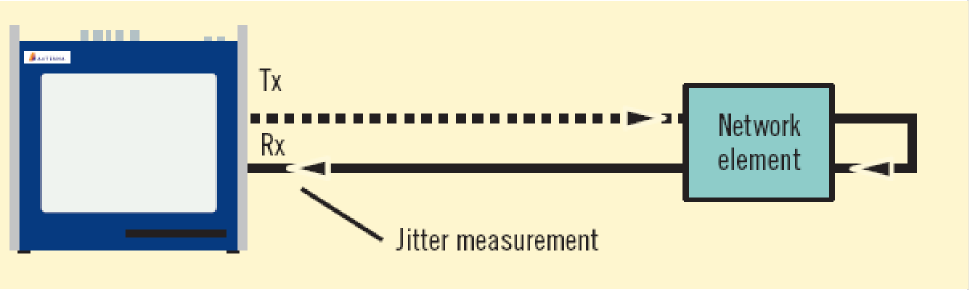


Figure (c): Jitter output measurement

Source: ACTERNA

3.7 Protocol Testing

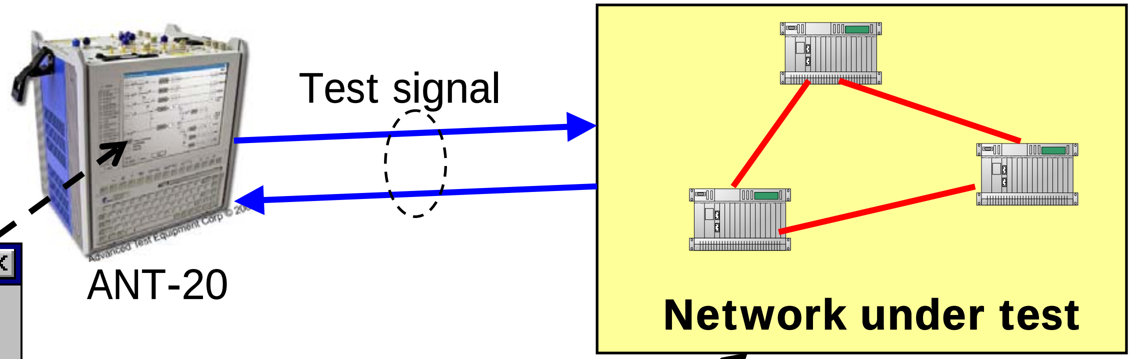
- Networks made of a variety of software and hardware components
- Expected to perform based on particular standards or protocols
- Testing needed to ensure conformance

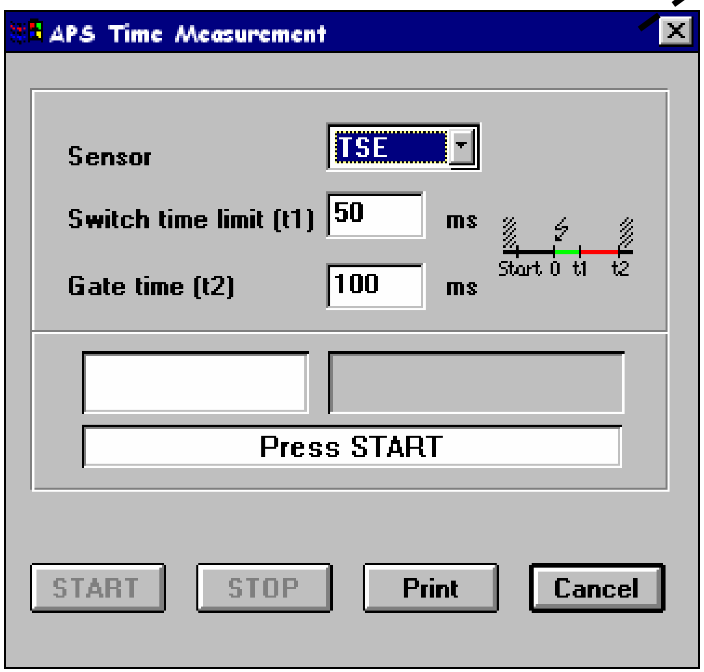
3.7 Protocol Testing

- Example: Acterna ANT-20 Advanced Network Tester
- Testing various SDH functions
  - Test for correct path switching and configuration
  - Editing and analyzing section and path overhead
  - Alarms and responses
  - Synchronization tests
  - Jitter tests
  - Pointer simulation and analysis
  - BER performance tests
  - Testing mapping of PDH and ATM traffic to SDH frames
  - ...and many more

3.7 Protocol Testing

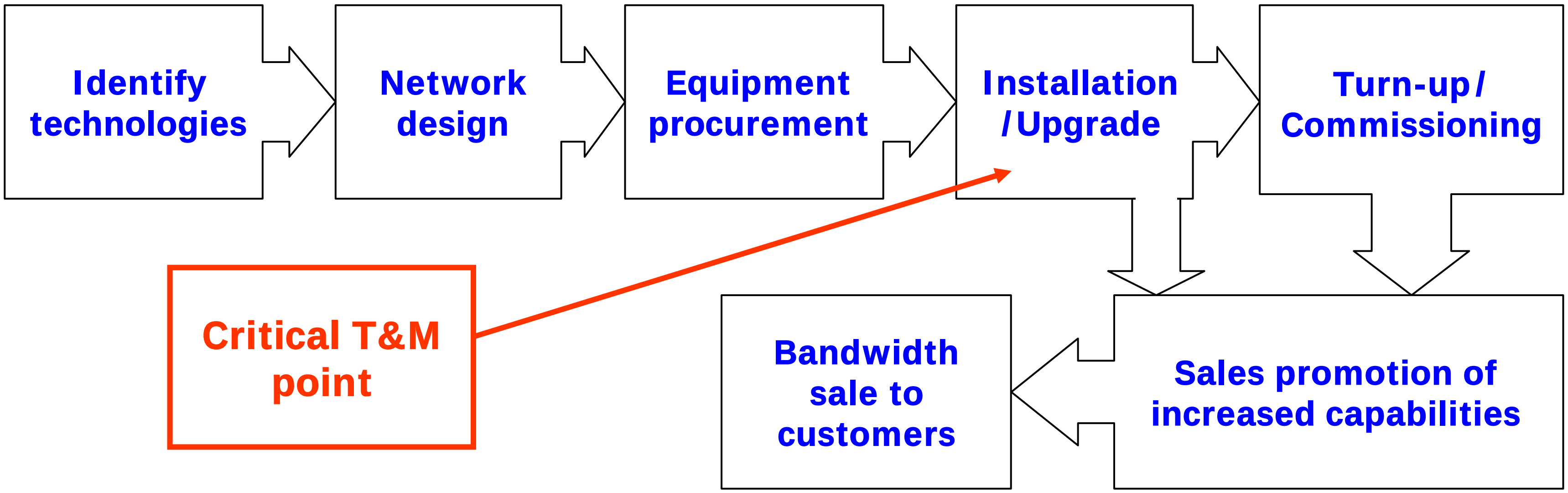
- As an example one possible test is to ensure that switching time for network recovery is within 50 ms SDH limit





4. Test and Measurement Cycle

- T&M duration should be compatible with service provider’s commitments
  - Project postponements or turn-up delays
  - Reduce delays in service provision
  - Avoid unacceptably long repair times

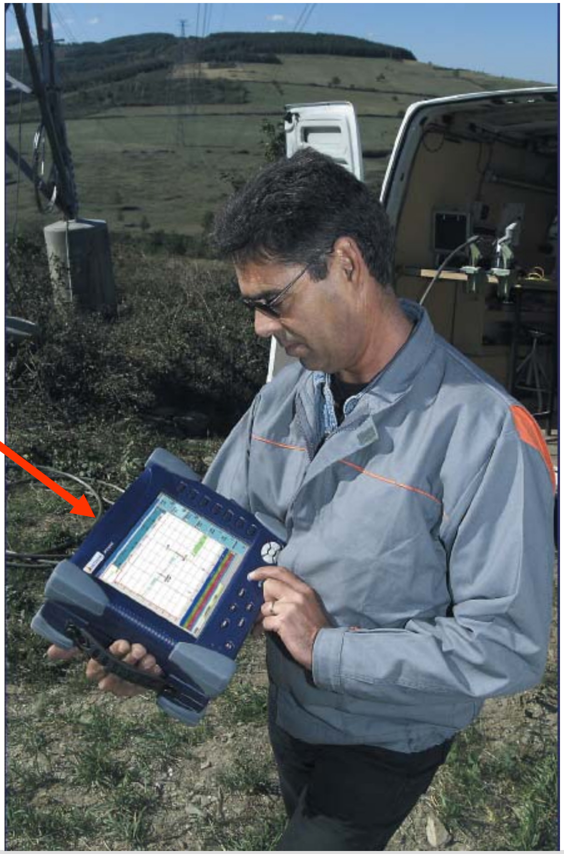


4. Test and Measurement Cycle

- Links span long distances $\Rightarrow$ few to thousands km
- T&M equipment should be easily available on a wider scale in many test locations
  - Portable/lightweight
  - Cost-effective and durable
  - Integrated/multifunctional test sets
  - Reduced learning curve and user-friendly e.g. GUI
- Capability of repeated link T&M is important
  - For ongoing network maintenance
  - For network upgrade operations

4. Test and Measurement Cycle

- Example: Acterna MTS-8000 Tester



Fiber characterization
- OTDR/Power meter
- CD/PMD Testing
- Connection checklist tester

CWDM/DWDM Testing
- OSA (OSNR, LED/laser/EDFA test)
- Q-factor meter

Digital Test Modules
- SDH (up to STM-64)
- PDH
- Ethernet (up to 10GbE)

Talk set (communication & file transfer)

Software tools (result post-processing, report generation)

Source: ACTERNA

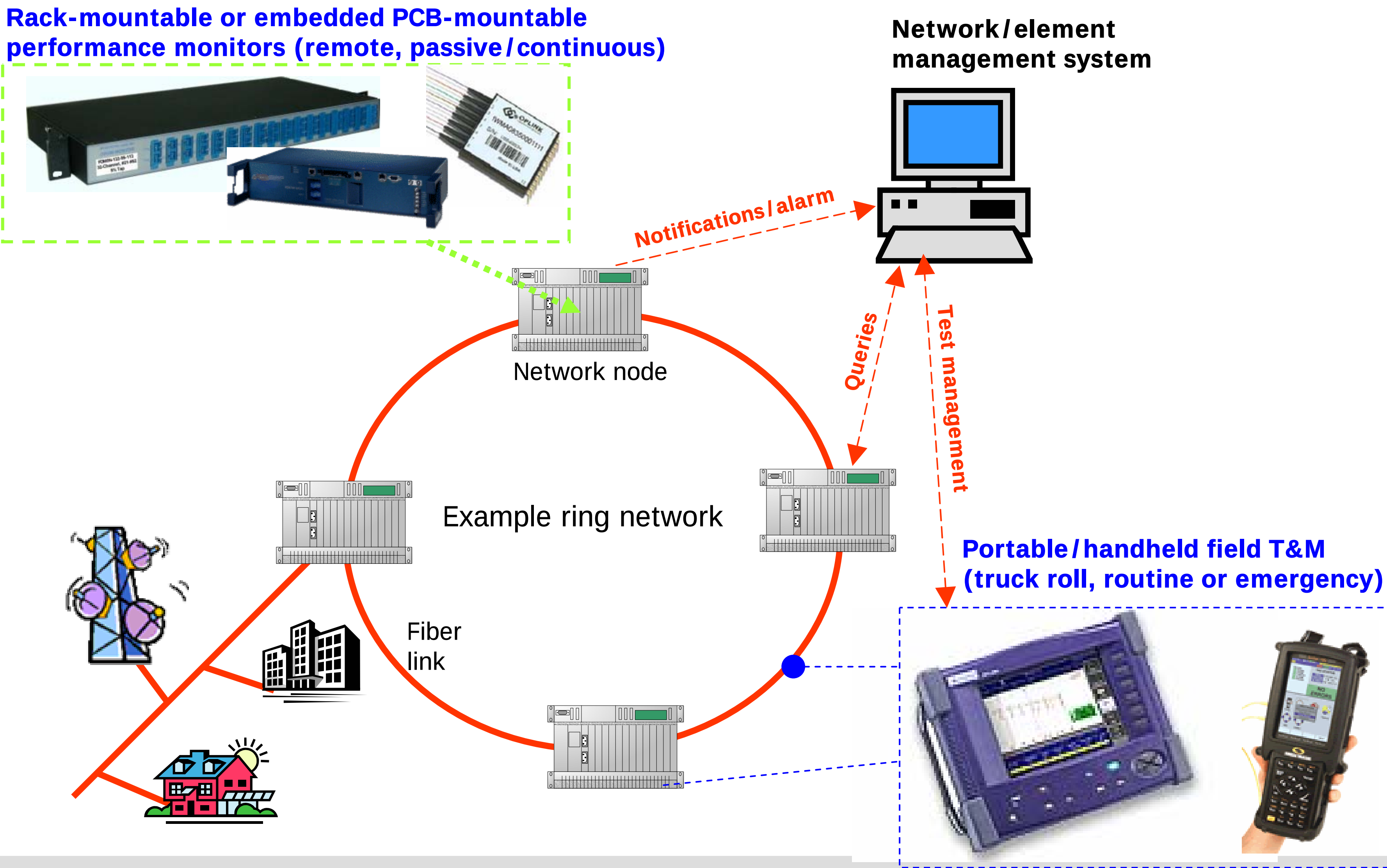
4.1 Link T&M Before Commercial Launch

- Spot manufacturing problems
- Spot shipping problems
- Verification of end nodes and intermediate equipment
  - Verify that power levels at interfaces in line with specifications
  - Verify transmitter wavelengths in line with specifications
- Characterization of fiber plant
  - Loss testing
  - Dispersion testing
- Check alarms generated match listed fault conditions

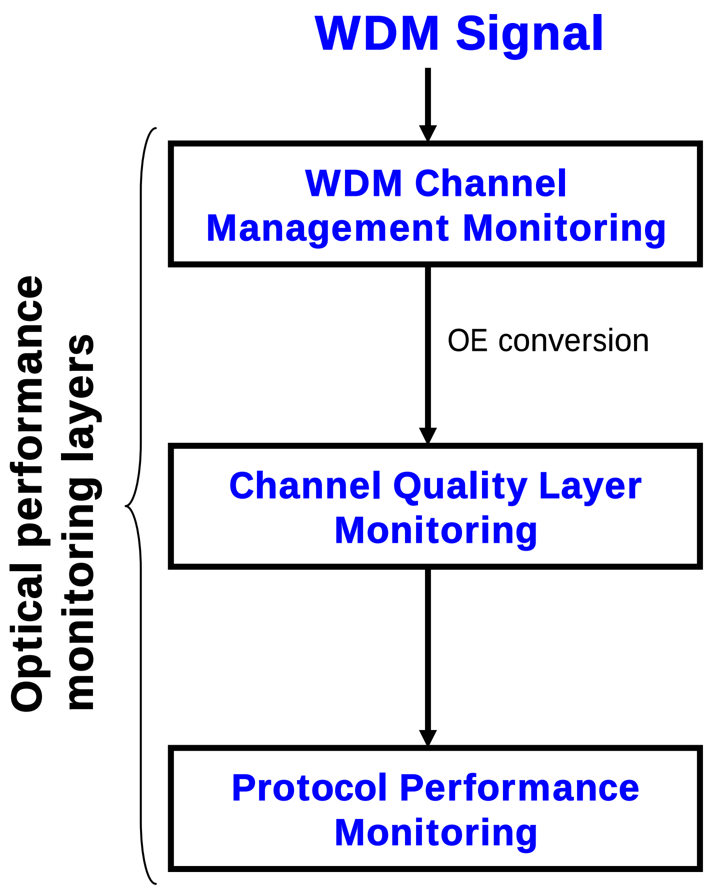
4.2 Link T&M During Operation

- Real-time T&M for remote link monitoring and maintenance operations during normal operation
  - Maintenance and troubleshooting
  - Signal health-assessment
  - Initiate service restoration actions e.g. protection switching
  - Dynamic control of components e.g. EDFA gain control, power equalizers

4.2 Link T&M During Operation



4.2 Link T&M During Operation

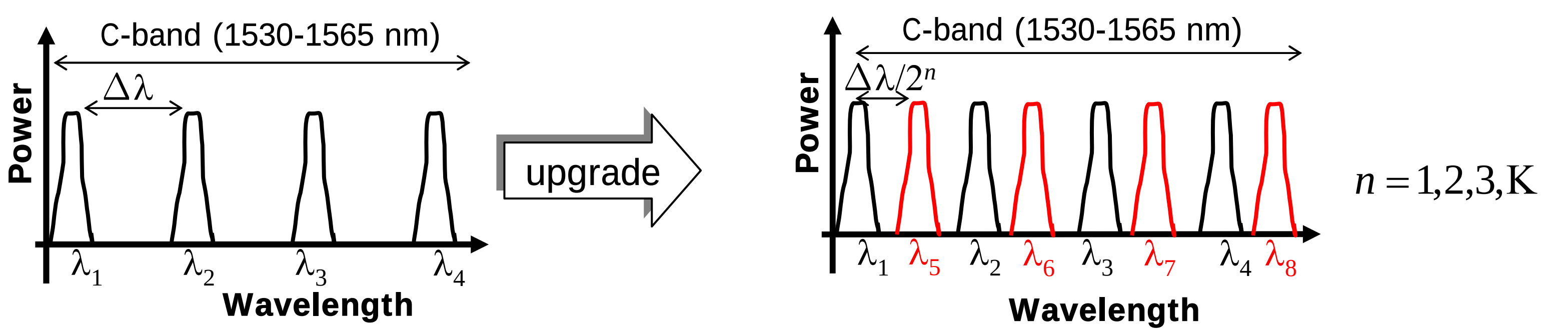


- Determine essential optical domain characteristics of channels
  - Channel power/aggregate power
  - Wavelengths
  - Channel presence
  - OSNR
- Lock onto particular channel and perform more detailed digital (electrical) measurements
  - Q-factor/BER
  - Eye diagram analysis
- Monitoring based on protocol-specific parameters, alarm signals and overhead
  - BLER, FER (e.g. BIP bytes SDH)
  - Dropped packets, frames etc.
  - Delay/latency
  - Frame misalignment, synch loss

Figure: Optical performance monitoring (Source: IEEE Journal of Lightwave Tech., pp. 294, Vol. 22 No.1, Jan. 2004)

4.2 Link T&M for Before Upgrades

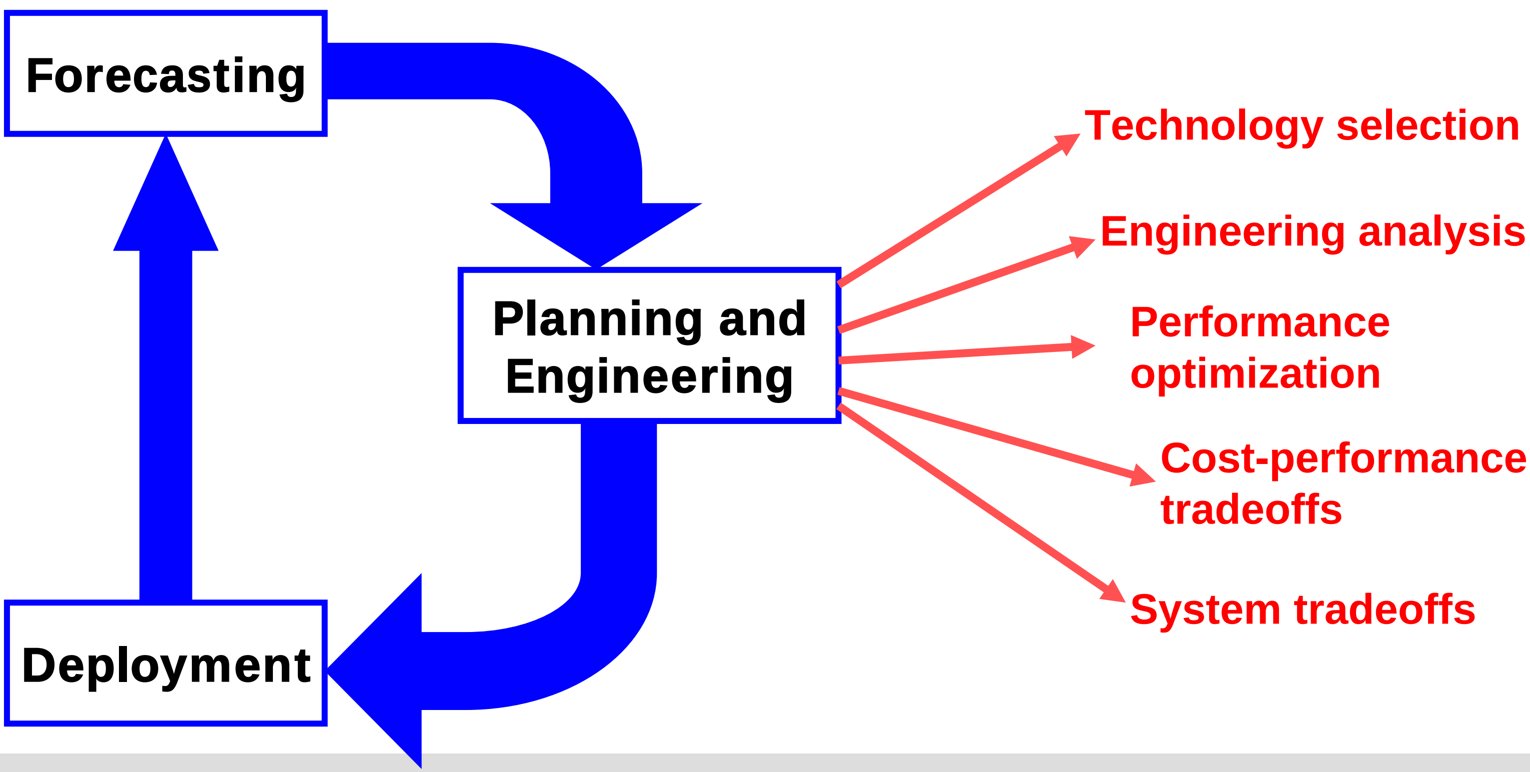
- Various WDM link capacity upgrade scenarios
- Example: Doubling DWDM channel number by halving spacing
  - Fiber characterization ⇒ nonlinearity (four wave mixing, cross-phase modulation)
  - Component characterization ⇒ crosstalk level, spectral response, PDL, wavelength drifts, wavelength misalignments



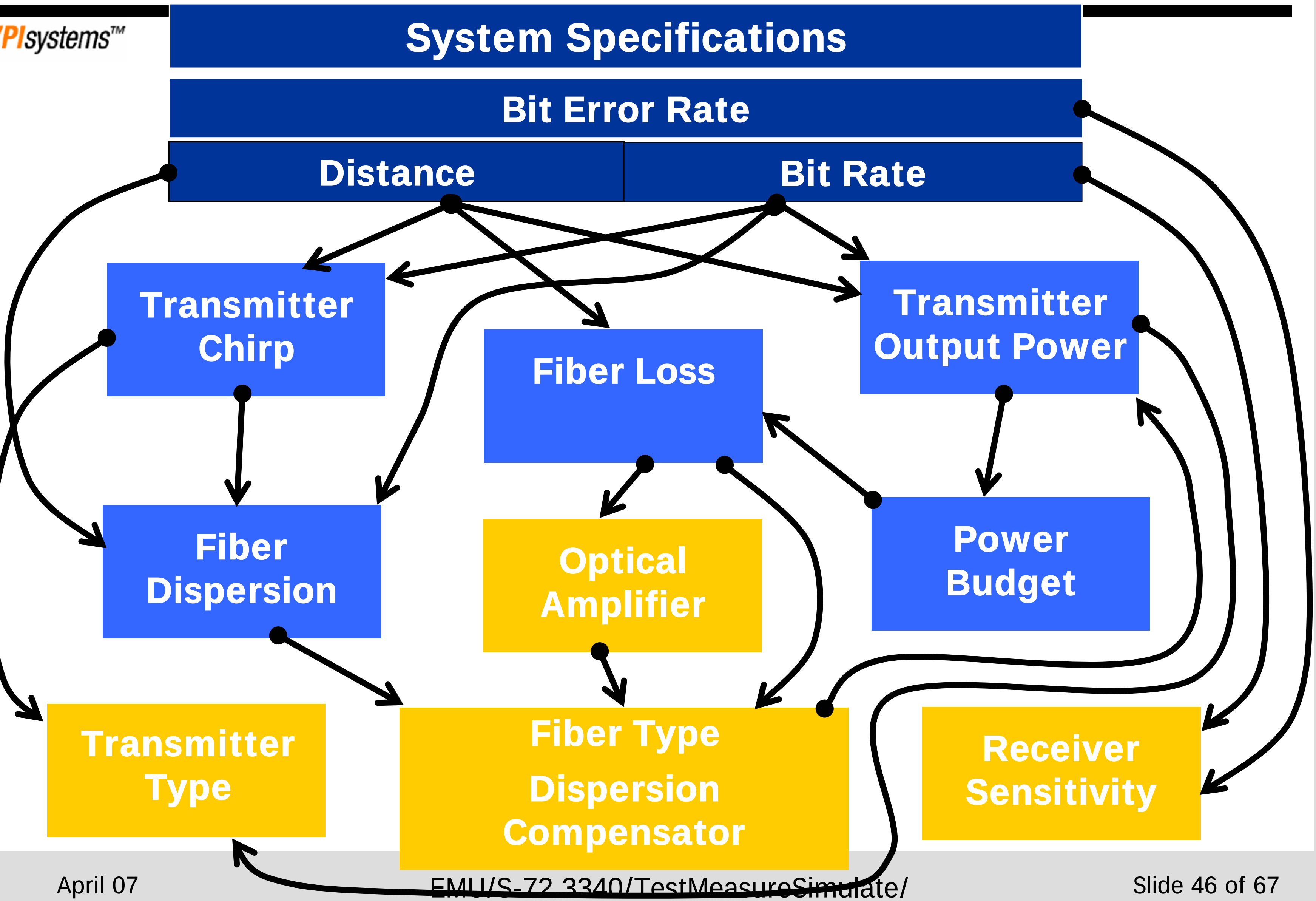
Part II: Simulation

1. Introduction

- ❑ Network demand forecasting, planning, engineering and deployment is a continuous process
  - Various network planning and design tools required

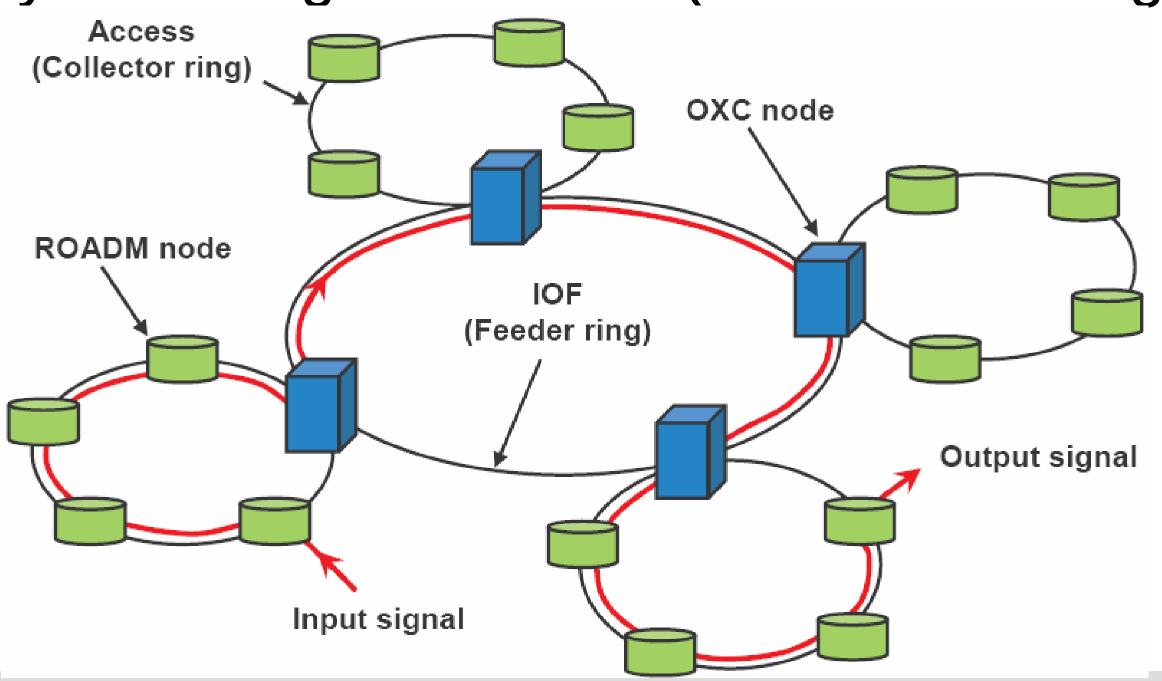


1. Introduction

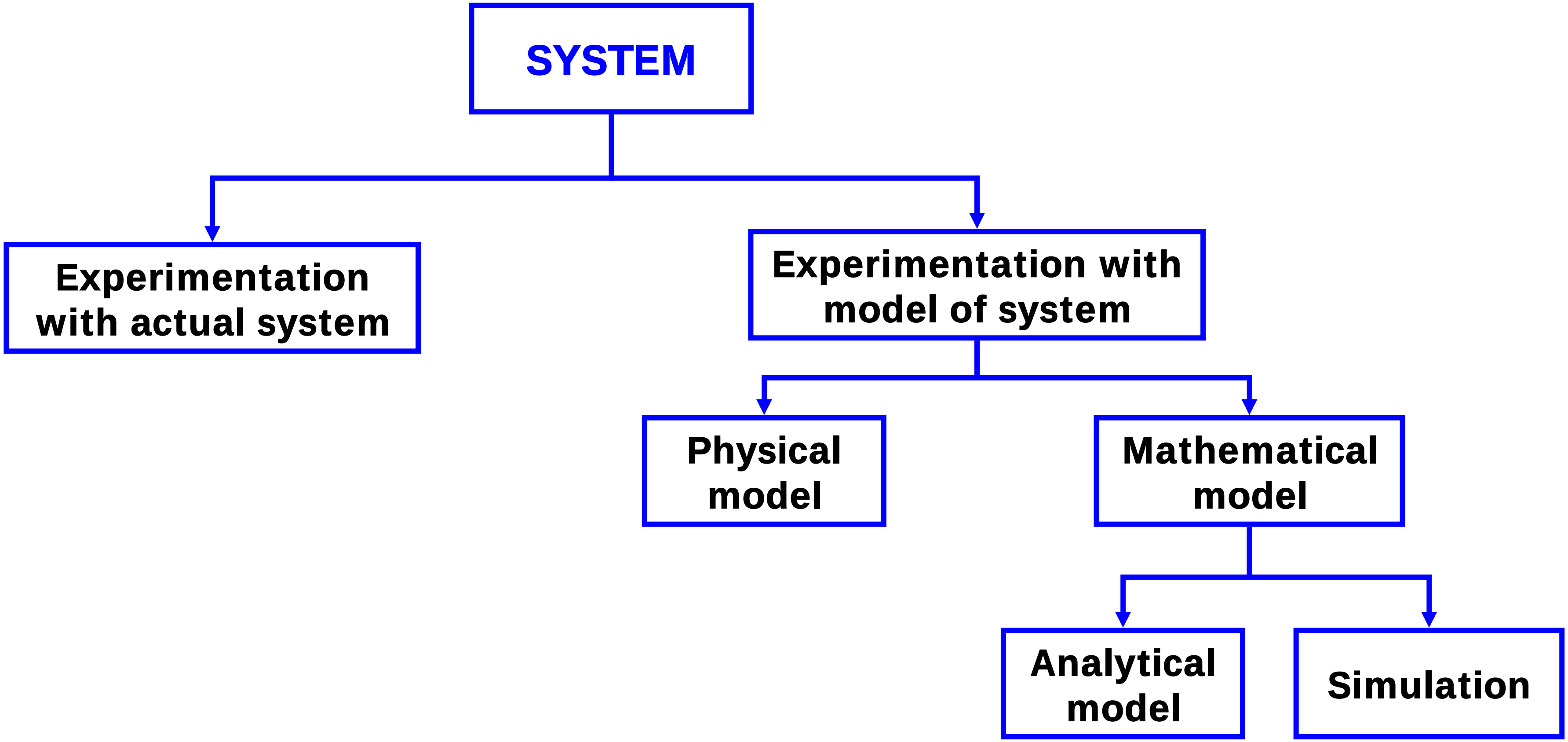


1. Introduction

- Design complexity scales with network size and traffic
  - Longer distances $\Rightarrow$ more amplifiers, switches etc.
  - Faster line rates
  - Many wavelength channels (10s of wavelengths)



2. System Modeling

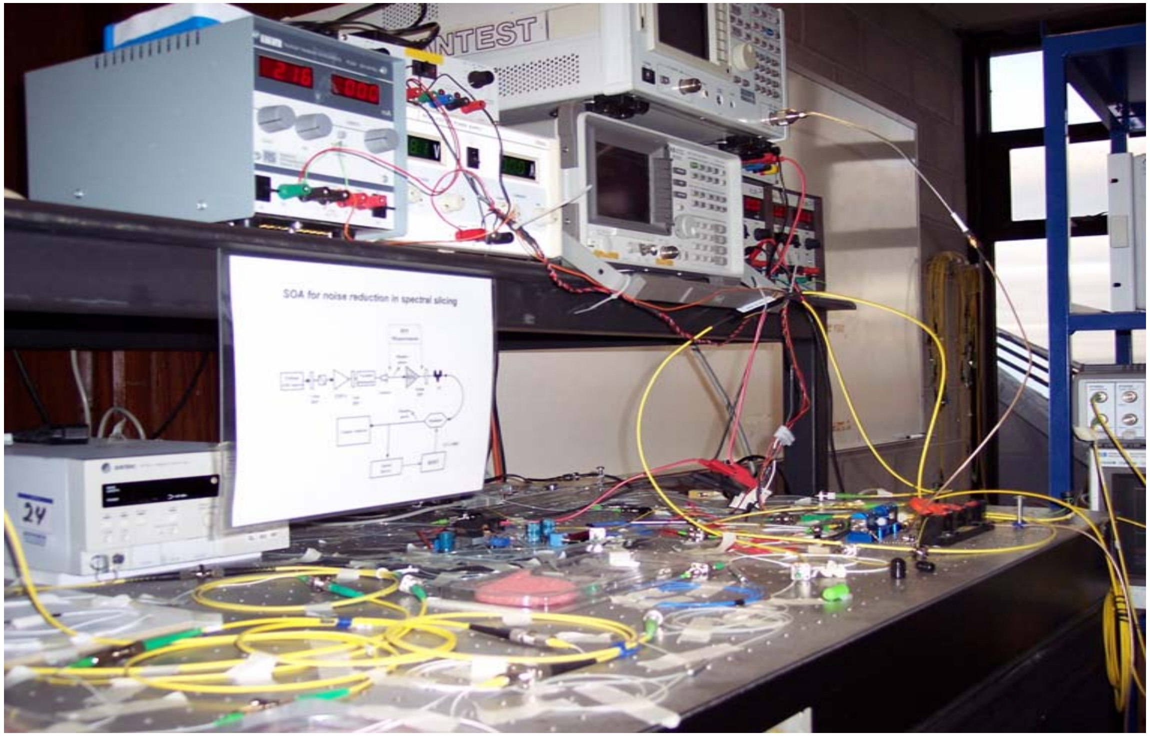


Methodologies for studying system behavior

2. System Modeling

❑ Physical modeling

- Lab experiments, tests and measurements
  - System parts
  - Scaled down version of a system



Example: Spectrum-slicing noise reduction using a semiconductor optical amplifier experiment (Uni. Of Limerick)

2. System Modeling

- Physical modeling disadvantages
  - Requires sufficient and skilled manpower
  - High upfront investment in test and measurement equipment and network devices
    - Limited budget $\Rightarrow$ limited experiments

- Extensive analytical modeling and simulation recommended before physical modeling

3. Analytical Modeling

- Analytical modeling of optical devices and systems
- Mathematical models used to represent optical link devices and impairments
  - Conviniently solved by mathematical packages (Mathcad, Mathematica, Maple, Maxima etc.)
  - Programs in standard languages (Matlab, C/C++, Fortran, Pascal, Java, Python etc.)
- Good accuracy for well developed models

3.1 Example Analytical Modeling

- Propagation of optical pulse over fiber modeled by the nonlinear Schrödinger equation (NLSE)
  - Maxwell's equations in cylindrical coordinates and with boundary conditions of fiber optic cables
  - Equation also applicable in other areas (e.g. water wave theory)
  - Some terms ignored for pulses >10ps (<100 Gbit/s NRZ)
  - NLSE does not have general analytical solution in presence of both dispersion and nonlinearities

Pulse shape or envelope

$$\frac{\partial \underline{A}(z,t)}{\partial z} = -\frac{\alpha}{2}\underline{A}(z,t) + i\frac{\beta_2}{2}\frac{\partial^2 \underline{A}(z,t)}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 \underline{A}(z,t)}{\partial t^3} - i\gamma\left|\underline{A}(z,t)\right|^2 \underline{A}(z,t)$$

Attenuation

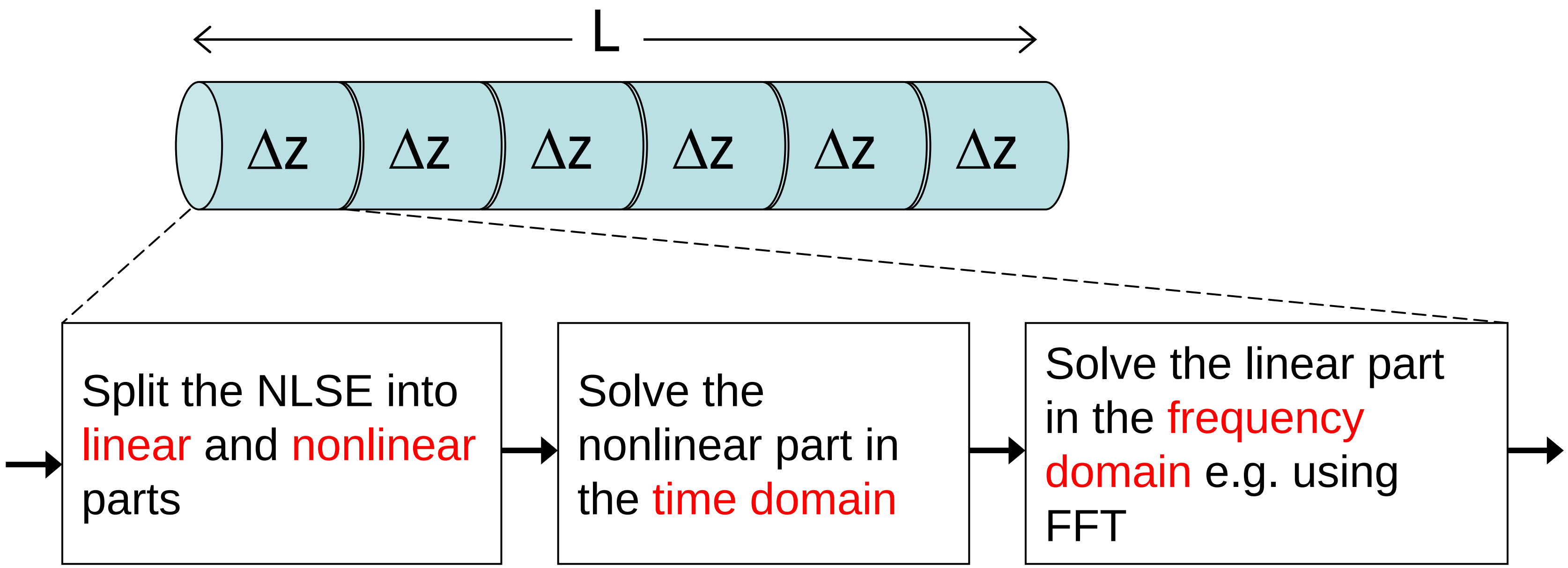
Dispersion

Dispersion slope

Nonlinearities

3.1 Example Analytical Modeling

- Various numerical methods used for solving NLSE
- Split step method most popular
  - Various fiber effects assummed to be independent over length Δz
  - The smaller is Δz the more is accurate is the solution
  - Small steps means (more iterations) longer computation times
  - Optimum step-size selection is crucial



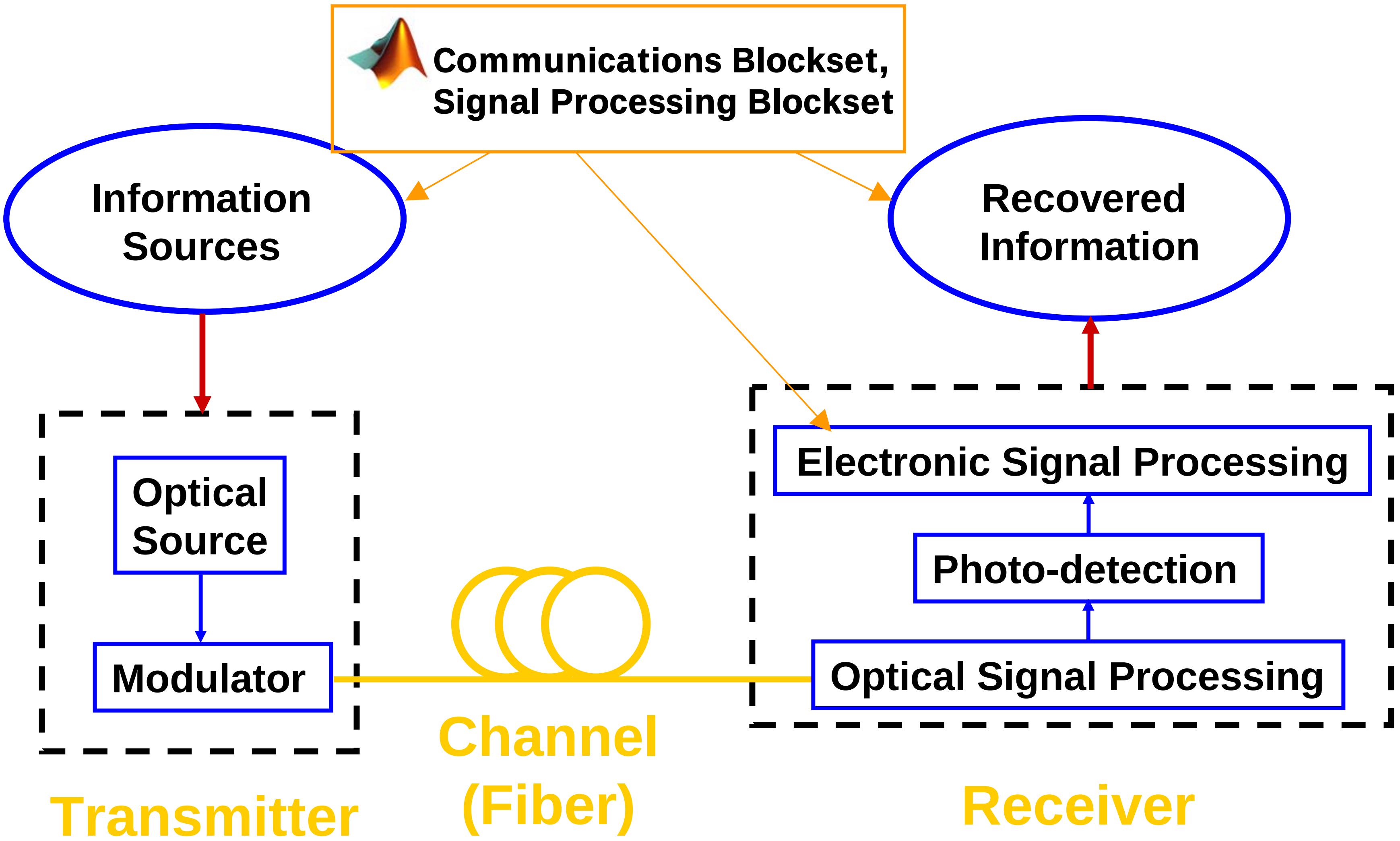
4. Link Simulation Tools

- Simulation of various devices and systems
- Integrated computer-based tools or packages
- For optical link design
  - Simulate or imitate both electrical (e.g. FEC encoders) and optical (lasers, optical amplifiers etc.) components

4.1 Advantages of Simulation

- Advantages of simulation
  - Large library of components ⇒ no need to "reinvent the wheel"
  - Avoid errors from guesswork or back-of-the-envelope computations
  - Time efficient
    - Engineers produce designs quickly (less man hours)
    - Deployment deadlines are met
  - Optimized to run fast on computers unlike own creations
  - Cheaper for analyzing different scenarios than lab experiments
  - Convenient documentation and reporting features
    - For reporting of solutions and sharing results in a design team

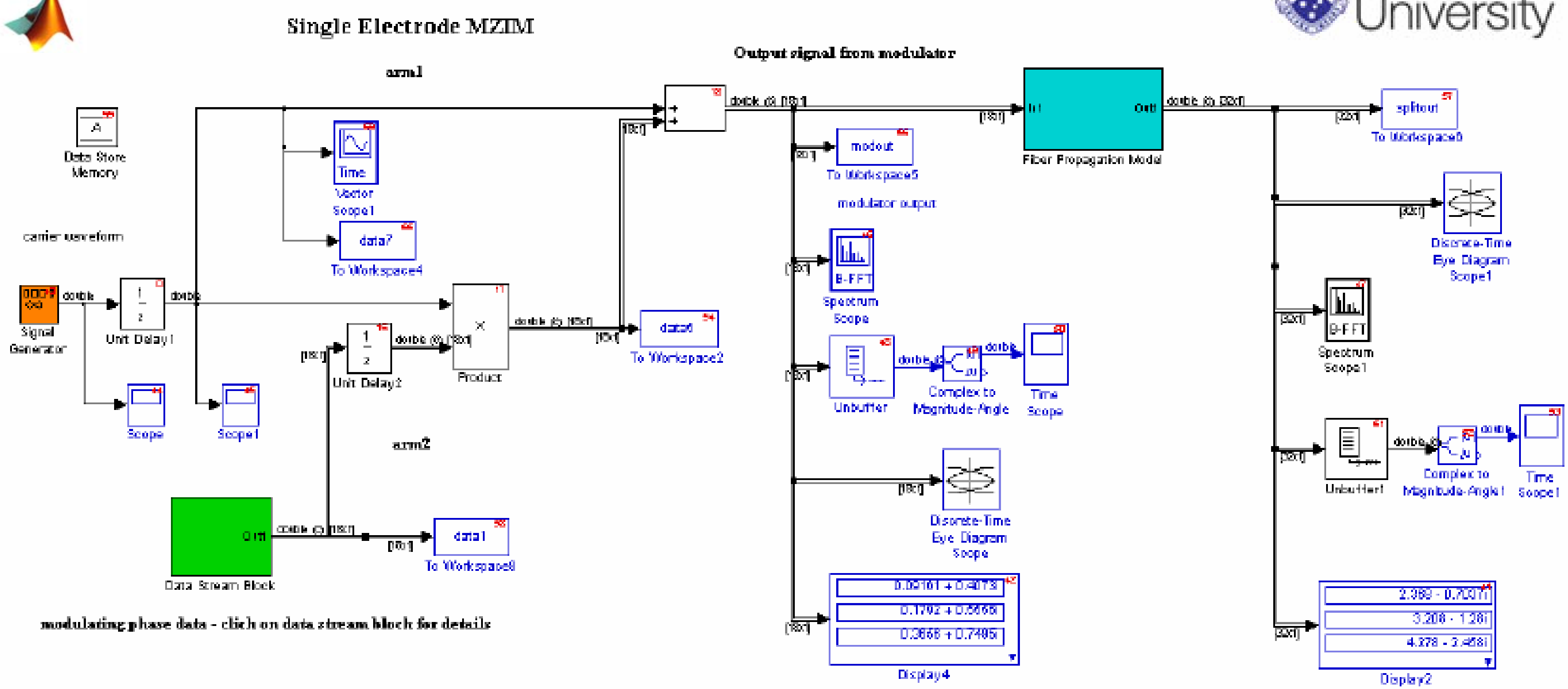
4.2 Simulink



Communications Blockset,
Signal Processing Blockset
Information Sources
Recovered Information
Optical Source
Modulator
Electronic Signal Processing
Photo-detection
Optical Signal Processing
Channel (Fiber)
Transmitter
Receiver

4.2 Simulink

- Custom-made Simulink optical simulators
  - Limited component libraries



4.3 Commercial Simulation Packages

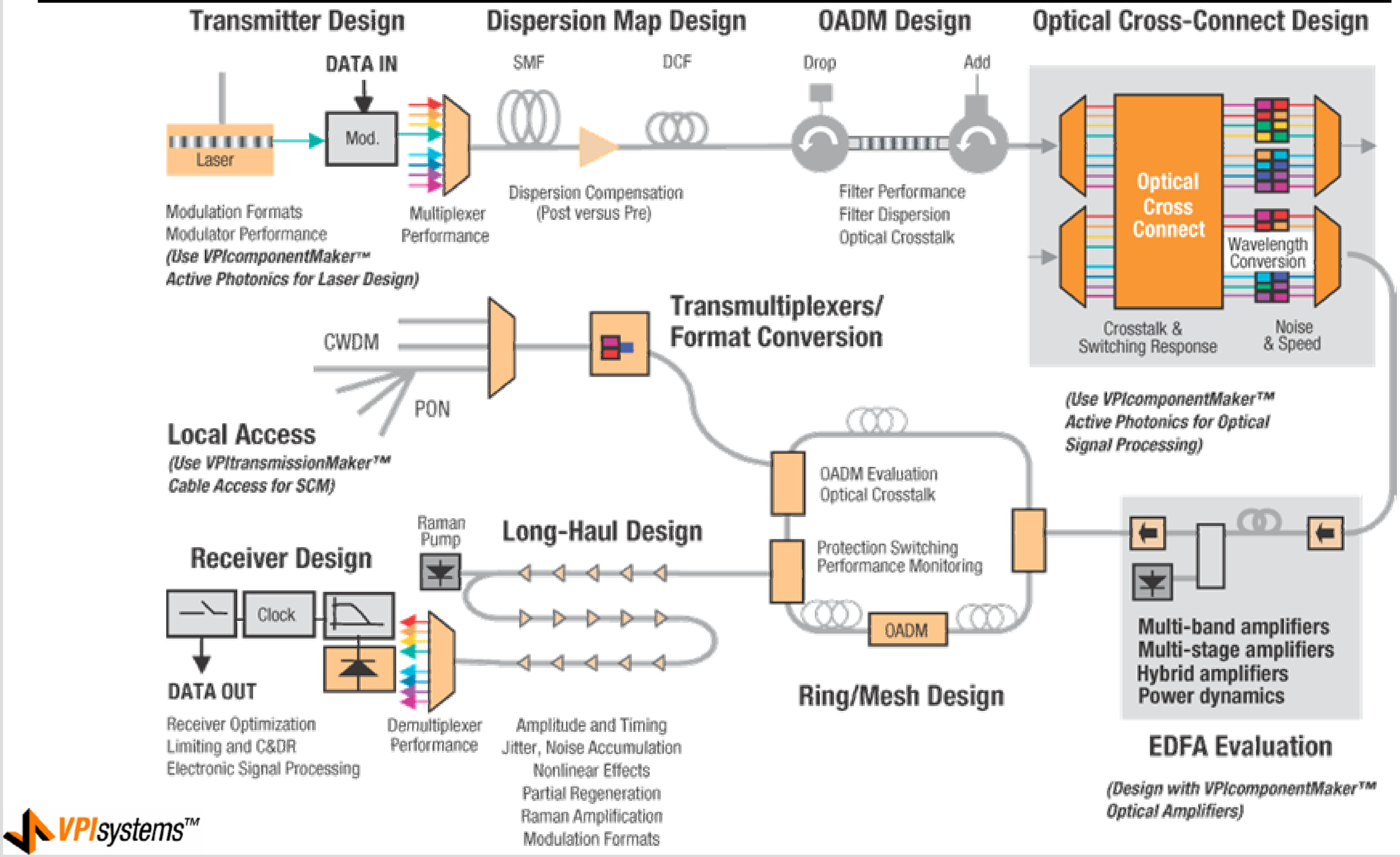
- Optical physical layer design tools in the market

VPIsystems™ → VPItransmissionMaker, VPIcomponentMaker

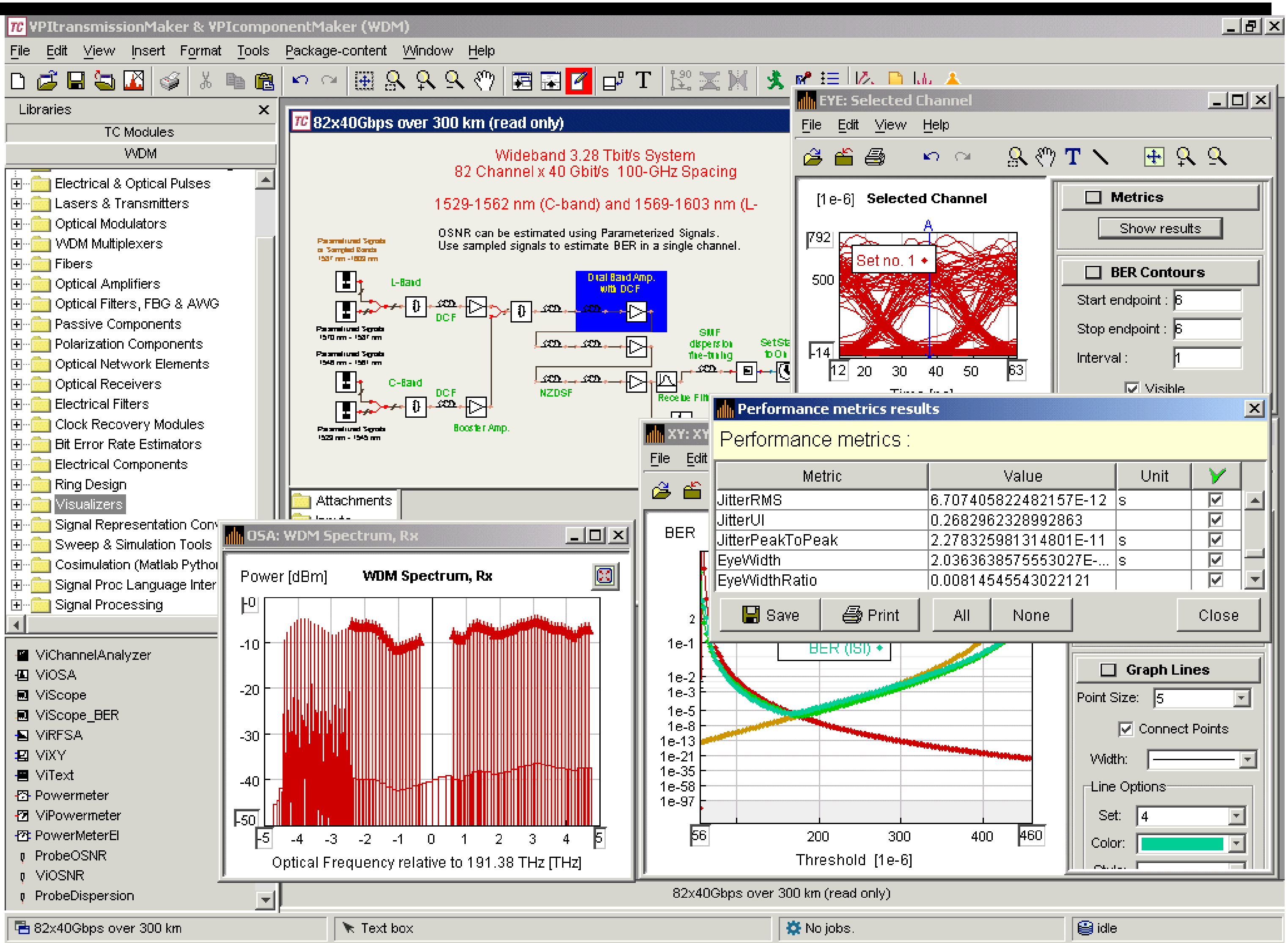
RSOFT Design Group — Full Spectrum Photonic and Network Design Automation → System Simulation OptSim

P.I. SYSTEMTECHNIK → PHOTOSS

4.4 VPItransmissionMaker



4.4 VPItransmissionMaker



VPIsystems™

4.4 VPItransmissionMaker

- VPIplayer is a stripped down version of VPItransmissionMaker
  - Plays simulations (saved as .dds files) that are designed in VPItransmissionMaker simulation environment
  - Produces same results as those obtained when simulations are run VPItransmissionMaker
  - Almost same GUI appearance as VPItransmissionMaker
  - Cannot edit the simulations
  - Unlike VPItransmissionMaker, it is free!
  - View demos at directory X:\Program Files\VPI\VPIplayer 7.0\demos (dynamicDataSheets)
    - X is the drive where you installed the VPIplayer

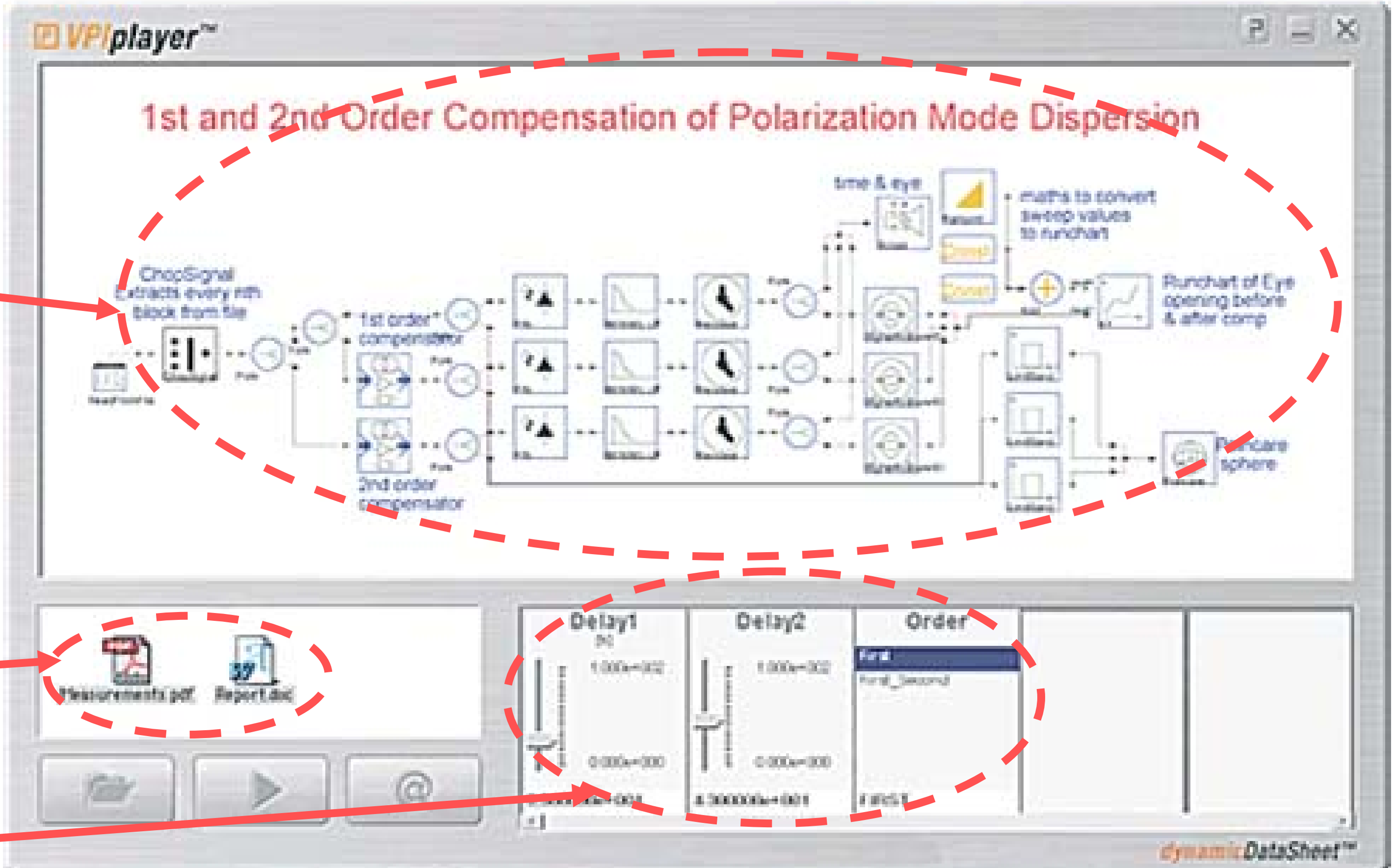
4.4 VPItransmissionMaker

- A few select parameters can be adjusted using sliders to observe different results

System being simulated

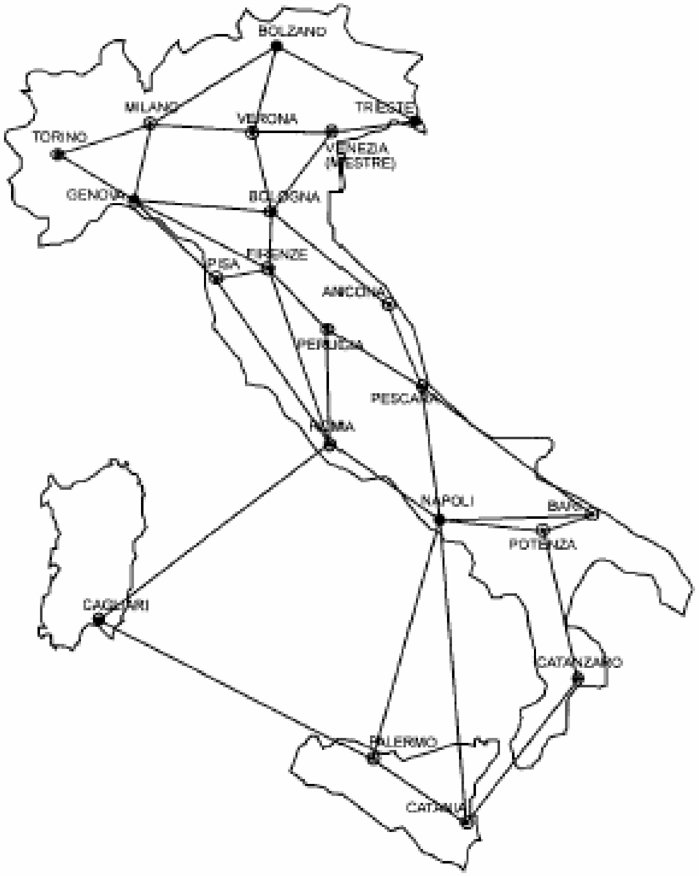
Attached files

Parameter sliders



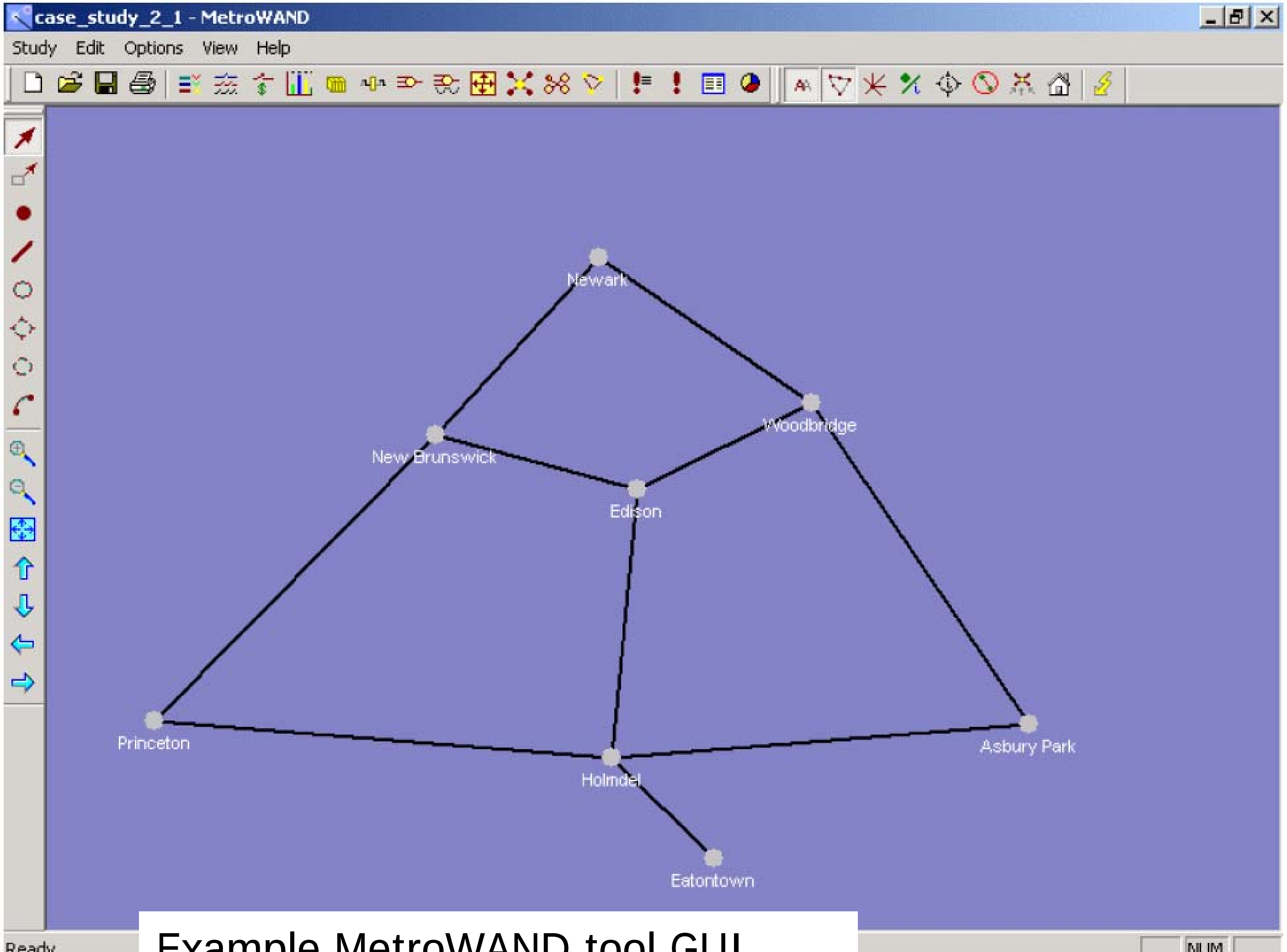
5. Optical Network Design Tools

- What fiber layout to use?
- How many fiber strands required?
- What equipment required at each node site?
- Any intermediate repeaters/regenerators required?
- How is traffic routed between different source and destination nodes?
- Which protection scheme is suited to proposed layout?
- How do we migrate network from ring to mesh topology?
- Cost implications of different designs?



*Ref: R. Sabella et al, Journal of lightwave Technology, Vol. 16, No. 11, Nov. 1998

5.1 Commercial Design Tools: Example 1



Example MetroWAND tool GUI

RSOFT Design Group
Full Spectrum Photonic and Network Design Automation

5.1 Commercial Design Tools: Example 1

- ❑ Reporting generated by MetroWAND tool

sol_summary - Report

File Edit Reports

Sonet Ring Type	No.Sys	No.ADMs	No.Regens	Total Cost
4-Fiber Bi	3	11	0	1,320,000
2-Fiber Bi	0	0	0	0
2-Fiber Uni	1	3	3	261,000
Totals	4	14	3	1,581,000

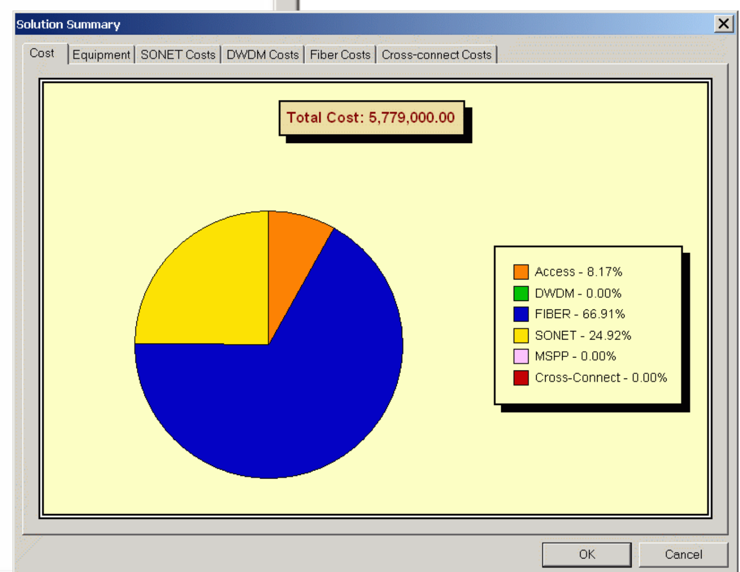
Sonet Term.Type	No.Sys	No. TMs	No.Regens	Total Cost
	2	4	0	240,000
Totals	2	4	0	240,000

No Planned Rings were input

No Potential Rings were input

Access Device Counts and Cost Follow

Device Name	No. Devices	Device Cost
OC3access	0	0
OC12access	16	112,000
1 GbEaccess	4	40,000
OC192access	9	108,000
OC48access	9	90,000
Totals	38	350,000



6. Conclusions

- Part I
  - Test and measurement crucial for increasingly complex optical networks
  - More channels, faster line rates means more impairments need to be measured and monitored in the field
- Part II
  - Role of analytical modeling
  - Link simulation tools
  - Network design tools

Thank You!

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