



ΠΑΝΕΠΙΣΤΗΜΙΟ  
ΠΑΤΡΩΝ  
UNIVERSITY OF PATRAS

ΑΝΟΙΚΤΑ ακαδημαϊκά  
μαθήματα ΠΠ

# Μελέτη Περιπτώσεων στη Λήψη Αποφάσεων



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# Optical Networking

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# Outline

- Optical Communications
- WDM technologies
  - Point to Point WDM
  - Wavelength Routed WDM
- RWA and IA-RWA
- Spectrum-flexible networks

- 
- **Optical Communications**
  - WDM technologies
    - Point to Point WDM
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  - Spectrum-flexible networks

# ΟΠΤΙΚΕΣ ΕΠΙΚΟΙΝΩΝΙΕΣ

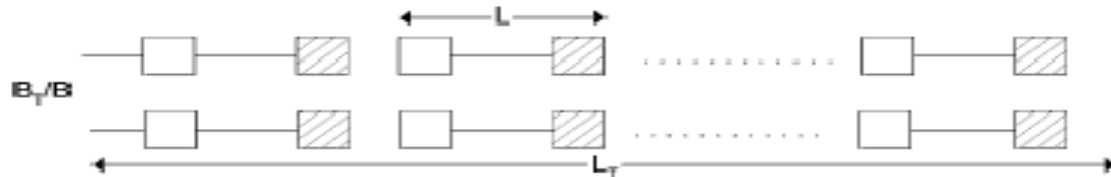


Η τεχνολογία περιγράφεται από το ρυθμό μετάδοσης  $B$  (bps) και την απόσταση  $L$  (km) για δεδομένο BER.

Σήμα των  $B$  bps ανακτάται στα  $L$  km με BER των  $10^{-9}$ .

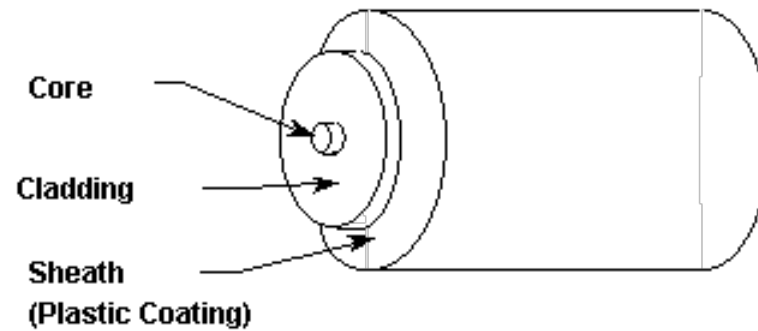
Έστω ότι κάποιος θέλει να μεταδώσει  $B_T$  bps σε  $L_T$  km.

Τότε χρειάζονται  $N_R = \frac{B_T \times L_T}{B \times L}$  επαναληπτές και σύνδεσμοι.

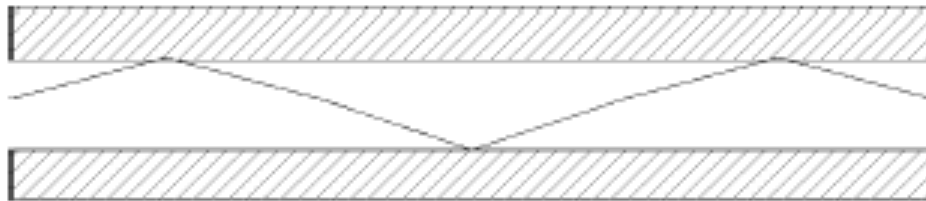


Οικονομικά, ο σημαντικός αριθμός είναι το γινόμενο  $B \times L$  (bps x km).

# Fiber link



Energy is confined to the core of the fiber by giving the core a slightly higher refractive index. The sheath protects the core and keeps moisture out.



$$P(l_1 + l_2) = a(l_1 + l_2)P_T = a(l_2)P(l_1) = a(l_1)a(l_2)P_T$$

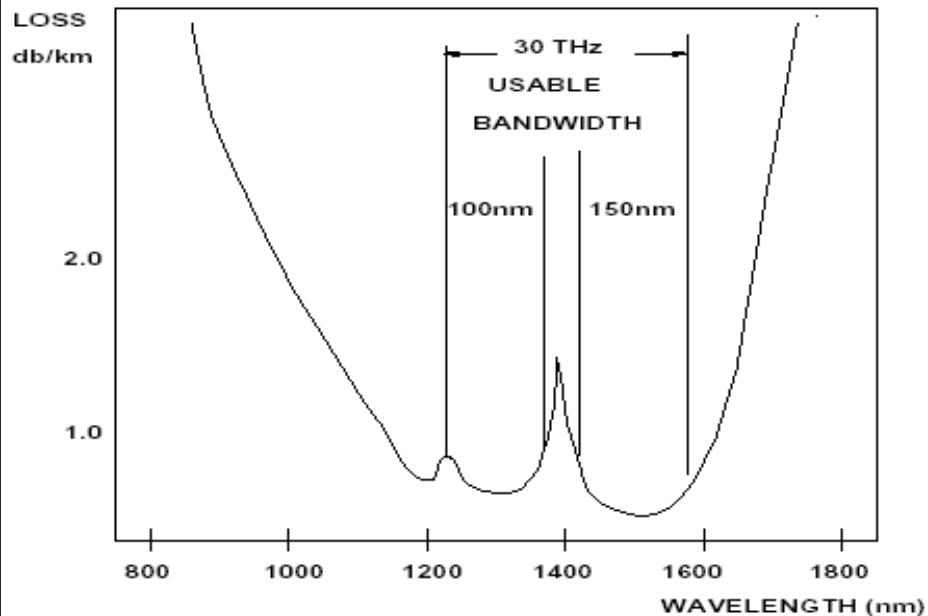
$$\Rightarrow a(l_1 + l_2) = a(l_1)a(l_2) \Rightarrow a(l) = 10^{-\frac{Al}{10}}$$



$A$  (dB/km) = σταθερά εξασθένησης της ίνας (εξαρτάται από το μήκος κύματος  $\lambda$  και την ποιότητα της ίνας)



# Fiber Attenuation



**Low attenuation:**

**0.2 Db/km compared to 30 dB/km for  
coaxial cable**

**Huge bandwidth: 2<sup>nd</sup> window usable spectrum=15THz.**

**More than 30 Tbps can be used**

**Phone call 64Kbps → 460 million calls !!**

# Example

- $L$  = απόσταση πομπού/δέκτη
- $P_T$  = εκπεμπόμενη ισχύς = 1mW
- $P_R = 10^{-4.5}$  mW = απαιτούμενη δεχόμενη ισχύς στα  $B=1$ Gbps για BER=  $10^{-9}$
- $A = 0.2$  dB/Km = σταθερά εξασθένησης

μέγιστο μήκος:

$$P_R = 10^{\frac{-AL}{10}} P_T$$

$$\Rightarrow L = \frac{10}{A} \log_{10} \frac{P_T}{P_R} = 225 \text{ Km}$$

$$\boxed{B \times L = 225 \text{ Gbps} \times \text{Km}} \text{ για οπτική ίνα}$$

σύγ

$$\left. \begin{array}{l} B = 100 \text{ Mbps}, A = 30 \frac{\text{dB}}{\text{Km}} \\ P_T = 1 \text{ W}, P_R = 10^{-7.5} \text{ mW} \end{array} \right\} \Rightarrow L = 3.5 \text{ Km} \Rightarrow B \times L = 0.35 \text{ Gbps} \times \text{Km}$$

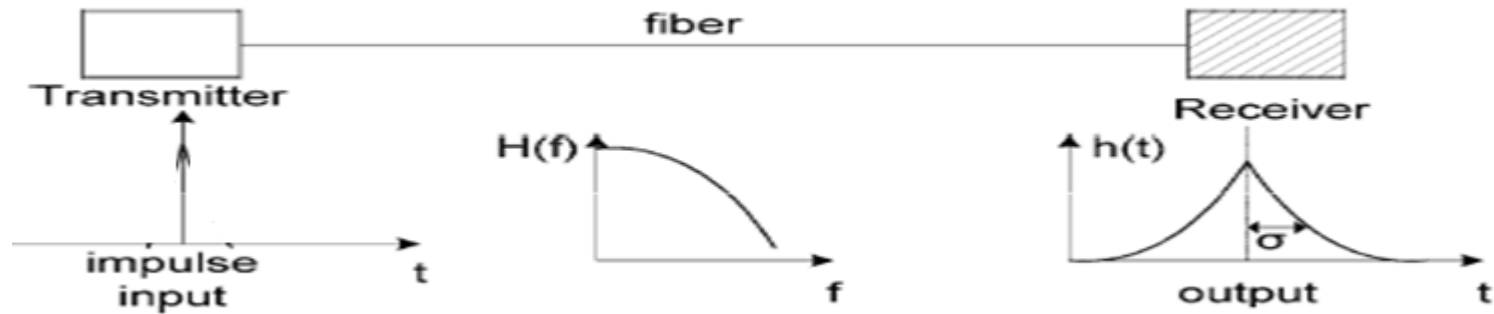
για ομοαξονικό καλώδιο

σημείωση 2:  $P_R = \bar{N} \cdot B \cdot h \frac{c}{\lambda}$ ,  $\lambda = 1.3 \mu\text{m}$

σημείωση 1: το  $L$  αυξάνεται γραμμικά με  $N$  Για BER= $10^{-9}$  και InGaAs PIN δέκτη

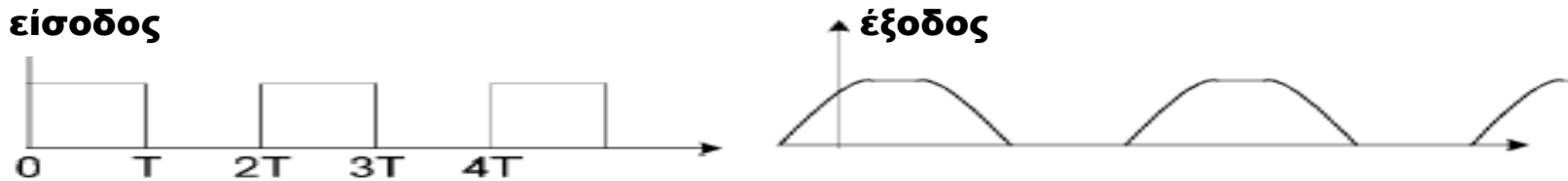
σημείωση 2:  $N = 1000 - 2000 \frac{\text{photons}}{\text{bit}}$

# Dispersion



Διαπλάτυνση  $\sigma = \alpha L$  (το  $\alpha$  εξαρτάται απ' την ίνα)

Έστω ότι η είσοδος είναι 101010 με ρυθμό bit  $B=1/T$ .



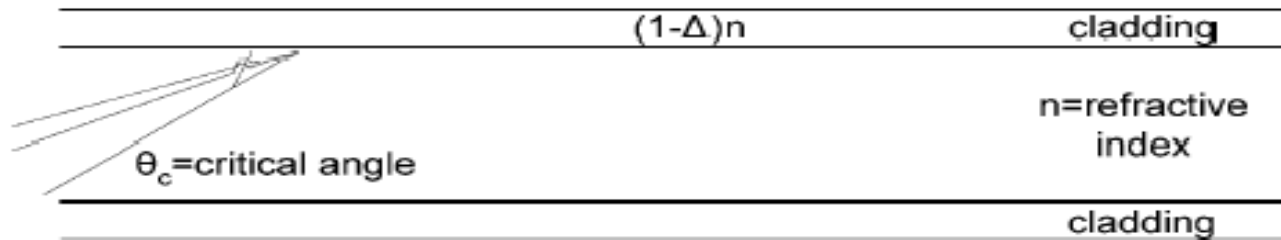
Για να μην οδηγήσει η διαπλάτυνση σε σφάλματα,

απαιτείται, πχ,  $\frac{\sigma}{T} < \frac{1}{4} \Rightarrow \sigma B < \frac{1}{4} \Rightarrow B \cdot L < \frac{1}{4\alpha}$

άνω φράγμα στο γινόμενο  $B \times L$  λόγω της διαπλάτυνσης.

Το όριο διαπλάτυνσης μαζί με το όριο εξασθένησης καθορίζει το μέγιστο χρησιμοποιήσιμο μήκος μιας ίνας για δεδομένο  $B$ .

# Τροπική Διασπορά (modal dispersion)



$$\cos \theta_c = 1 - \Delta \Rightarrow \theta_c \approx \sqrt{2\Delta}$$

Διαφορετικές γωνίες διάδοσης καλούνται τρόποι διάδοσης.

Διαφορετικοί τρόποι διάδοσης ταξιδεύουν διαφορετικές αποστάσεις για να περάσουν τα  $L$  km της ίνας.

Η απόσταση που ταξιδεύεται από τον τρόπο διάδοσης γωνίας  $\theta$  ισούται με  $L / \cos \theta$ , ο χρόνος είναι

$$\frac{Ln}{\cos \theta \cdot c}$$

Η διαφορά χρόνου ανάμεσα στην ταχύτερη και την αργότερη συνιστώσα, που δίνει και το άνω φράγμα του γινομένου  $B \times L$ , όπως αυτό τίθεται από το τροπικό σκόρπισμα, ισούται με

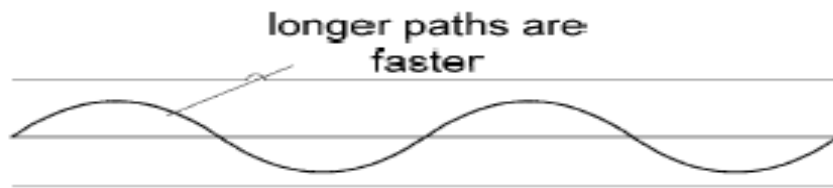
$$\frac{Ln}{c} \left( \frac{1}{\cos \theta} - 1 \right) \approx \frac{Ln\Delta}{c} < \frac{T}{2} = \frac{1}{2B} \Rightarrow BL < \frac{c}{2n\Delta}$$

# Τροπική Διασπορά (II)

- Το όριο τροπικής διασποράς δίνει

$$B \times L < \frac{c}{2n\Delta} = \frac{3 \times 10^8}{2 \times 1.46 \times 0.01} = 10 \text{ Mbps} \times \text{Km}$$

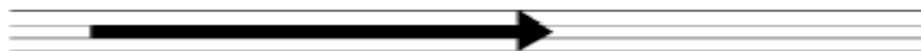
- Δραματική



$$B \times L < \frac{2c}{n\Delta^2} = 4 \text{ Gbps} \times \text{Km}$$

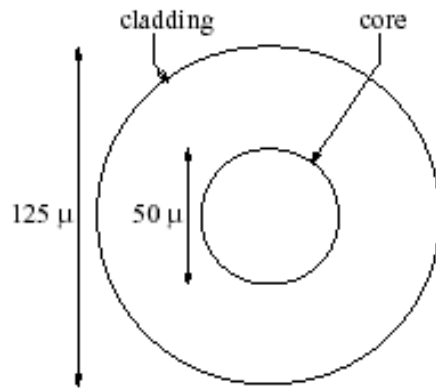
μπορεί να επιτευχθεί

- Σε μονοτροπικές ίνες η τροπική διασπορά απουσιάζει, αφού η διάμετρος του πυρήνα είναι περίπου

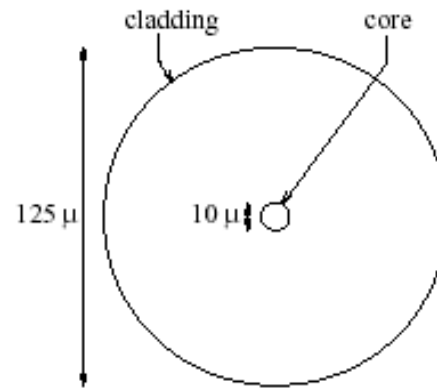
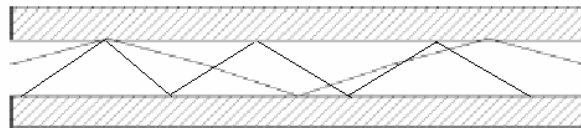


$$B \times L < 250 \text{ Gbps} \times \text{Km}$$

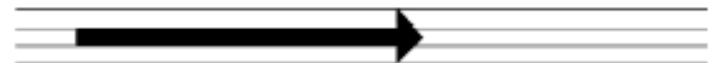
# Multimode and Single-Mode Optical Fibers



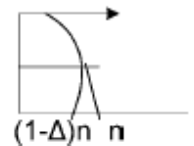
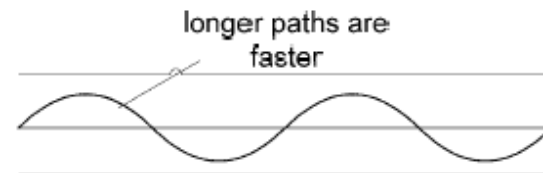
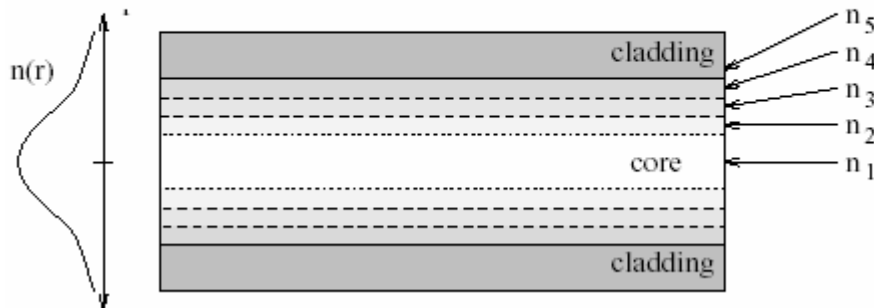
(a) Multimode Optical Fiber



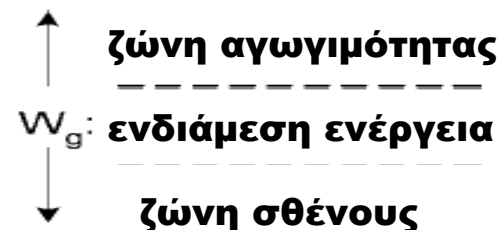
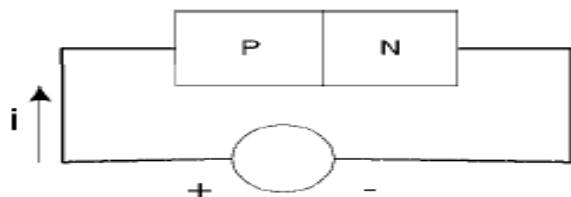
(b) Single-Mode Optical Fiber



## Graded-Index Fiber



# Sources (e.g. LEDs)



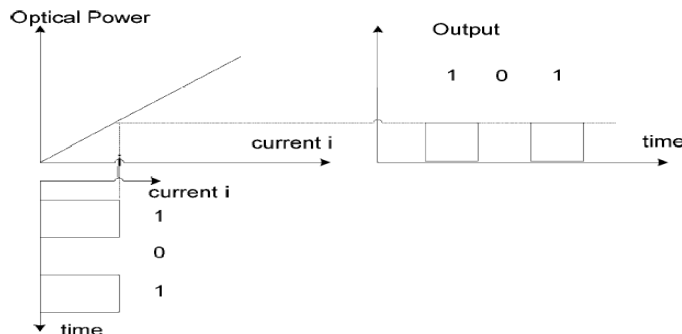
Μηχανισμός φωτός: ανασυνδυασμός των ηλεκτρονίων στη ζώνη αγωγιμότητας με οπές στη ζώνη σθένους : η περίσσεια ενέργεια εκπέμπεται ως φωτόνιο.

Οπτική ισχύς ( $mW$ ):  $P = niW_g$ ,  $n = \frac{\# \text{ photons}}{\# \text{ injected electrons}}$

$$E = \frac{hc}{\lambda}$$

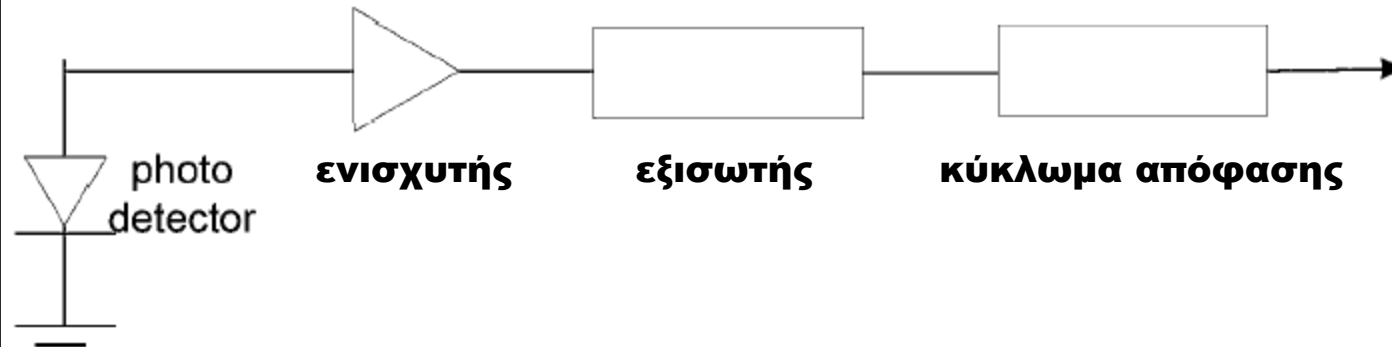
Τυπική ισχύς =  $1mW$ , Φασματικό εύρος  $\approx 100nm$

Το φως που εκπέμπεται είναι ασυνεπές (incoherent) δηλαδή περιέχει διαφορετικές συχνότητες/φάσεις.

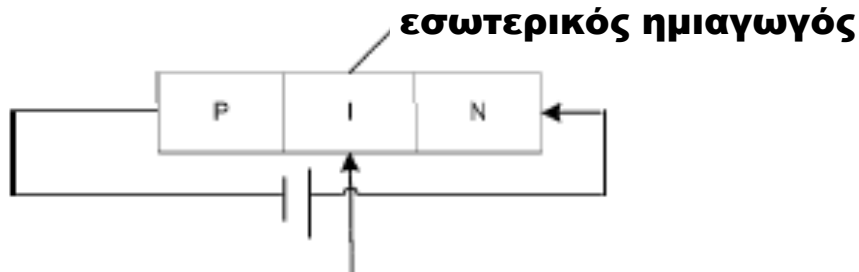


## Ανιχνευτές

Ένας ανιχνευτής πρέπει να καθορίσει αν σταλθηκε '0' ή '1'.



Ο ανιχνευτής φωτονίων (photo detector) συνήθως είναι μια PIN δίοδος.



**Το φωτόνιο διεγείρει ένα ζεύγος οπή-ηλεκτρόνιο αν η ενέργειά του είναι μεγαλύτερη από  $W_g$ .**

**Το ηλεκτρόνιο ρέει στο ηλεκτρικό κύκλωμα.**

**Το υλικό της PIN διόδου είναι ίδιο με αυτό των LED και LD.**

**Το ρεύμα είναι ανάλογο με τον αριθμό των φωτονίων που αφίκνυνται.**

**Η ευαισθησία μειώνεται μέσω του 'shot' θορύβου.**

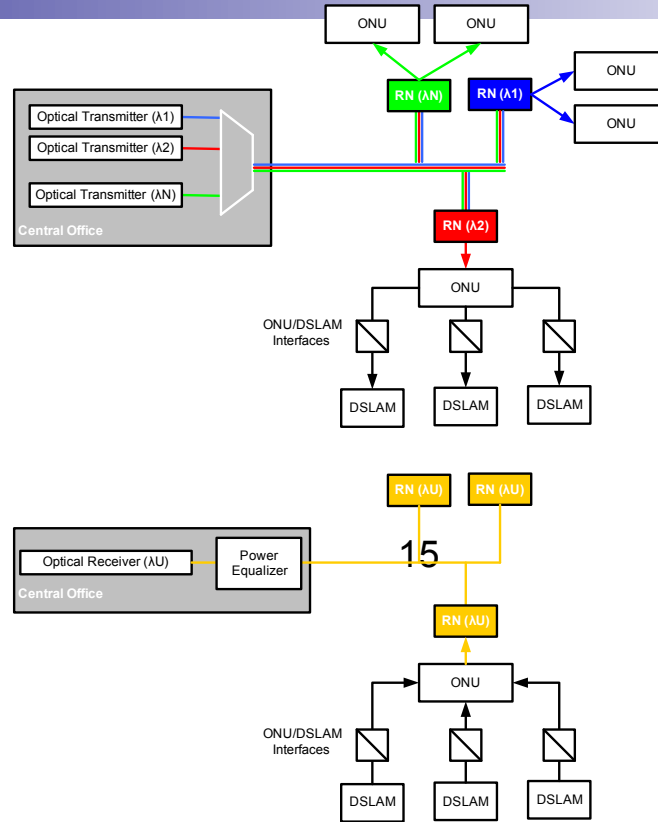




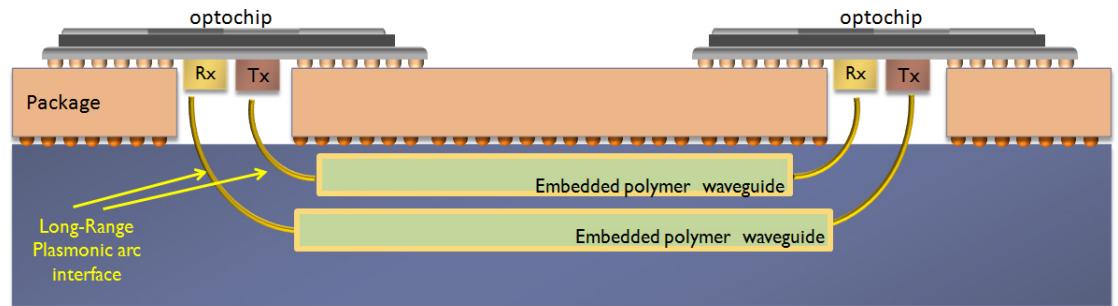
# Why Optical Communications?

- Huge bandwidth (more than 30 Tbps)
- Low signal attenuation (as low as 0.2 dB/km)
- Low signal distortion
- Low power consumption → Low power requirement
- Low material usage → Small space requirement
- Low Cost

# FTT-X

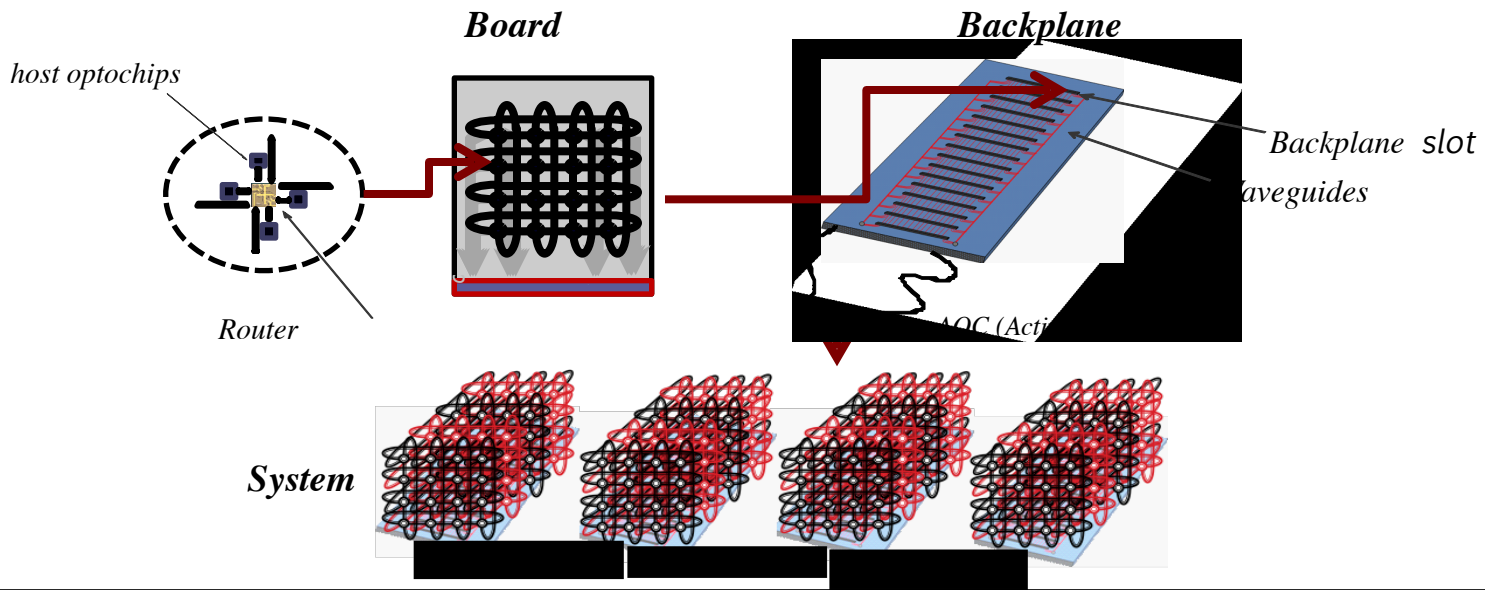
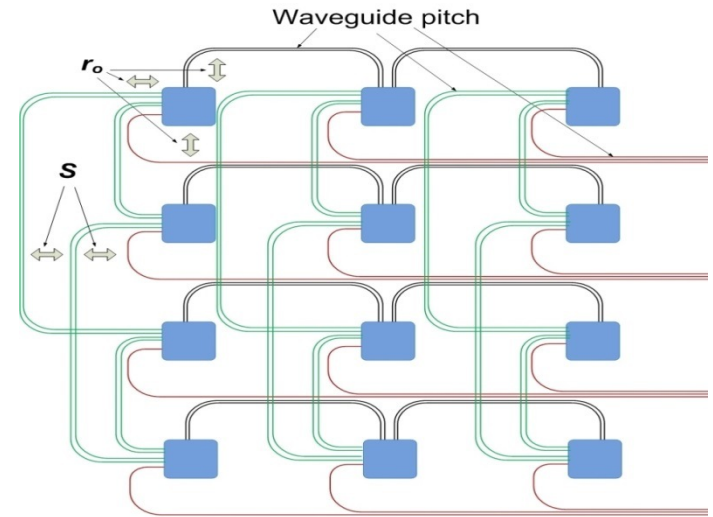
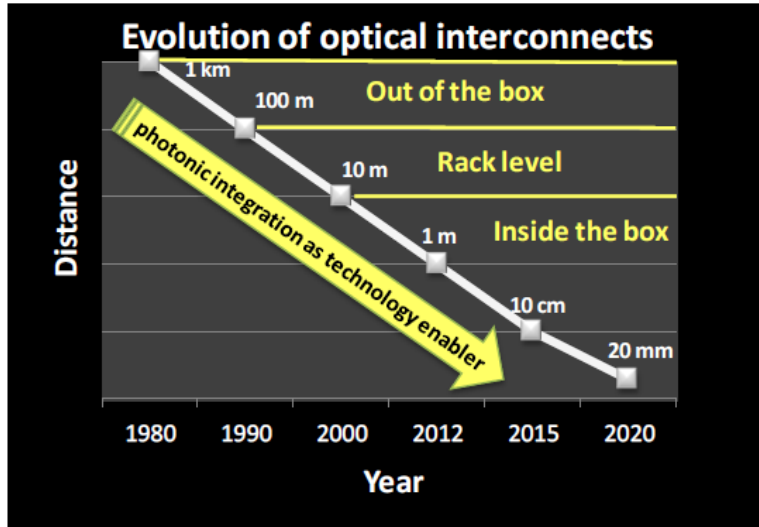


Οπτικά πλέον  
και on chip



Need: Appropriate multiplexing techniques and network architecture

# Optical interconnects



# Optical Multiplexing Techniques

Wavelength or Frequency = Wavelength Division Multiplexing (WDM)

Time slots = Time Division Multiplexing (TDM)

Wave shape or spread spectrum = Code Division Multiplexing (CDM)

- Optical TDM



- Each end-user should be able to synchronize to within one time slot
- Optical TDM bit rate = aggregate rate over all TDM channels

- Optical CDM: optical SCM chip rate may be much higher than each user's data rate

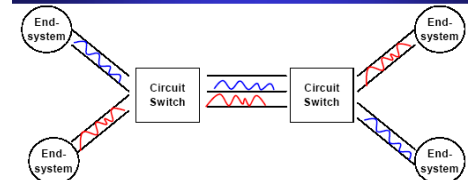
- WDM: current favorite



- Ανεξαρτήτως διαμορφωμένα κανάλια.

- Κάθε κανάλι λειτουργεί στη μέγιστη ηλεκτρονική ταχύτητα (1-10-40 Gb/s).

Frequency Division Multiplexing (FDM)

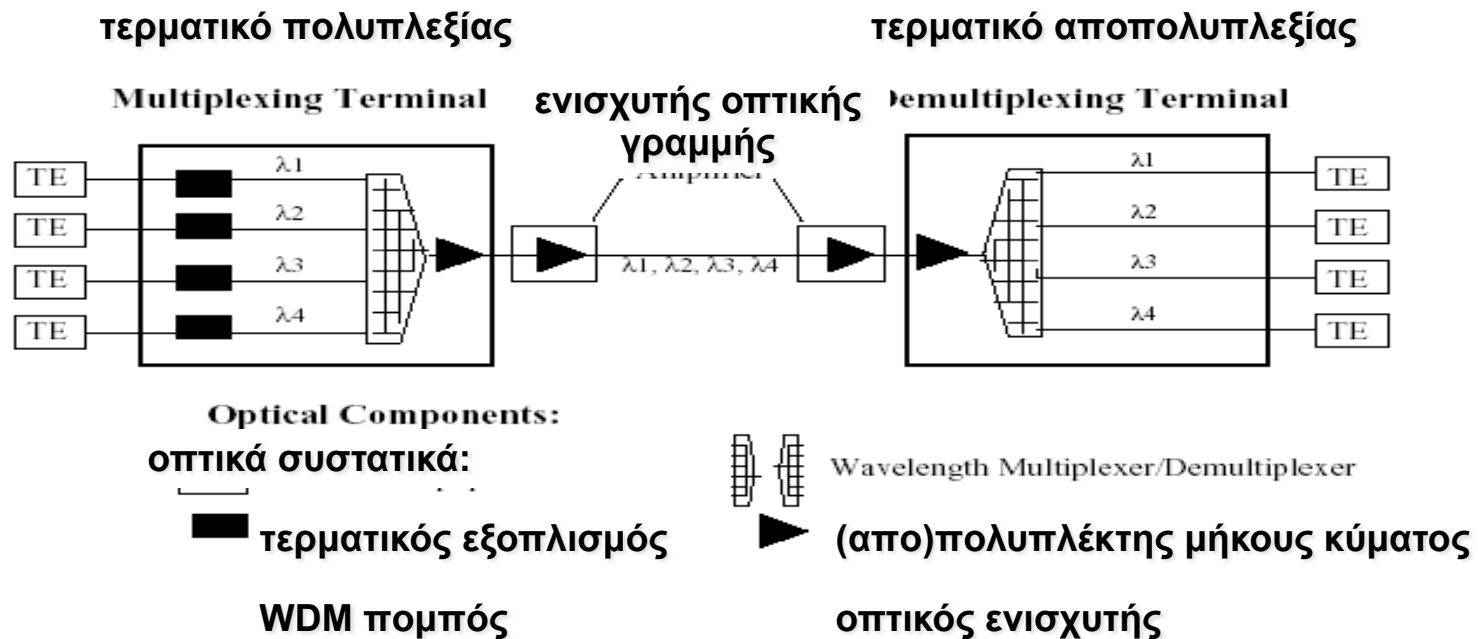


**Παράδειγμα :** αναβάθμιση της χωρητικότητας μετάδοσης ενός σημείο-προς-σημείο συνδέσμου μετάδοσης από OC-48 (2.5 Gbps) σε OC-192 (10 Gbps) μέσω τριών δυνατών λύσεων ('OC' = 'οπτικό κανάλι', 'OC- $n$ ' = ρυθμός δεδομένων  $n \times 51.84$  Mbps περίπου):

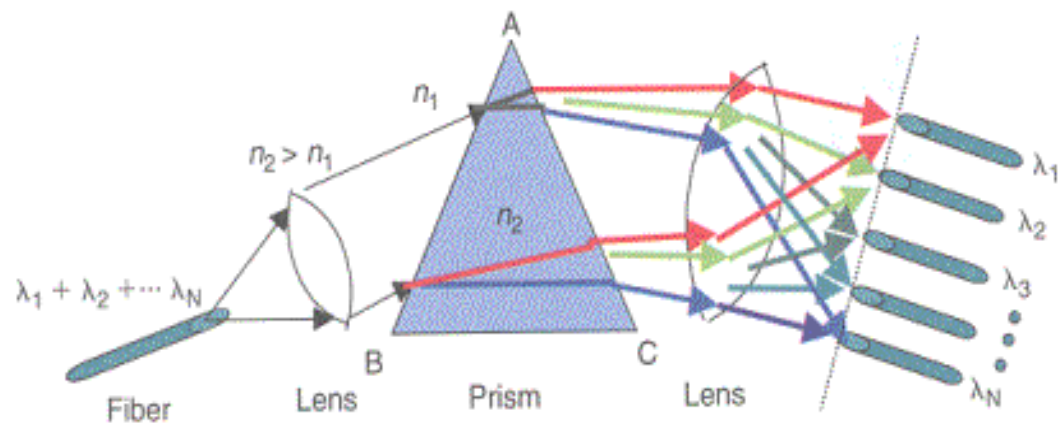
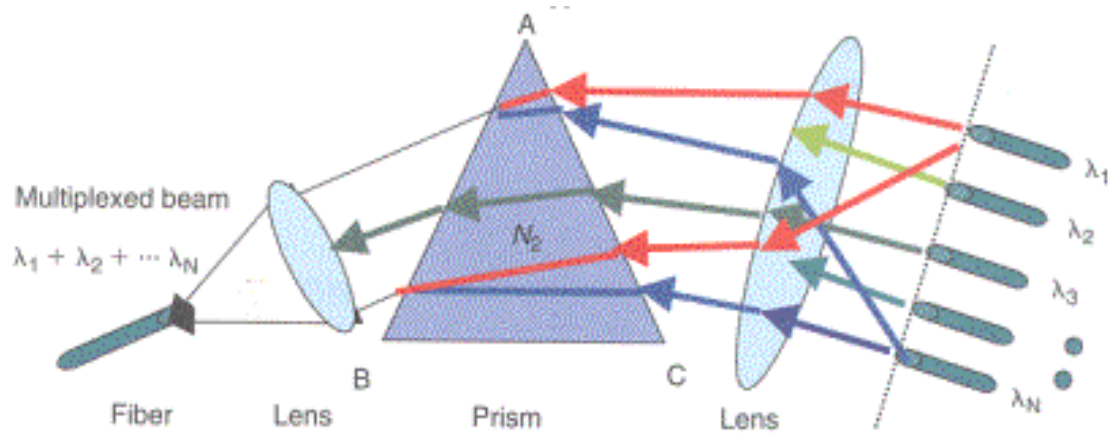
1. Λύση 'πολλαπλών ινών' – εγκατάσταση επιπρόσθετων ινών και τερματικού εξοπλισμού
2. Λύση WDM 4 καναλιών (δες σχήμα)
3. Λύση 'υψηλότερης ηλεκτρονικής ταχύτητας' – OC-192

## Σημείο-προς-σημείο WDM σύστημα εκπομπής 4 καναλιών

Four-Channel Point-To-Point WDM Transmission System

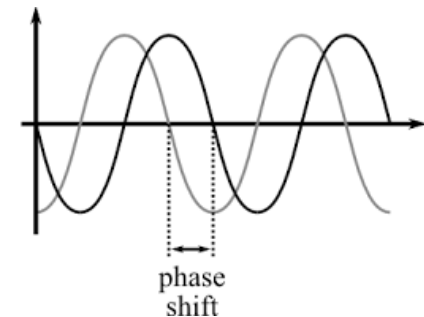
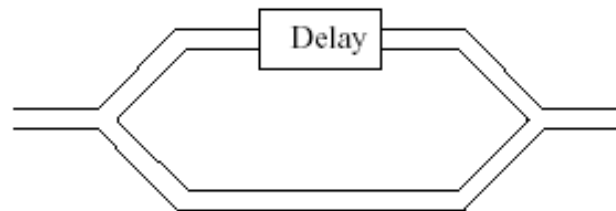


# Optical Multiplexer/Demultiplexer

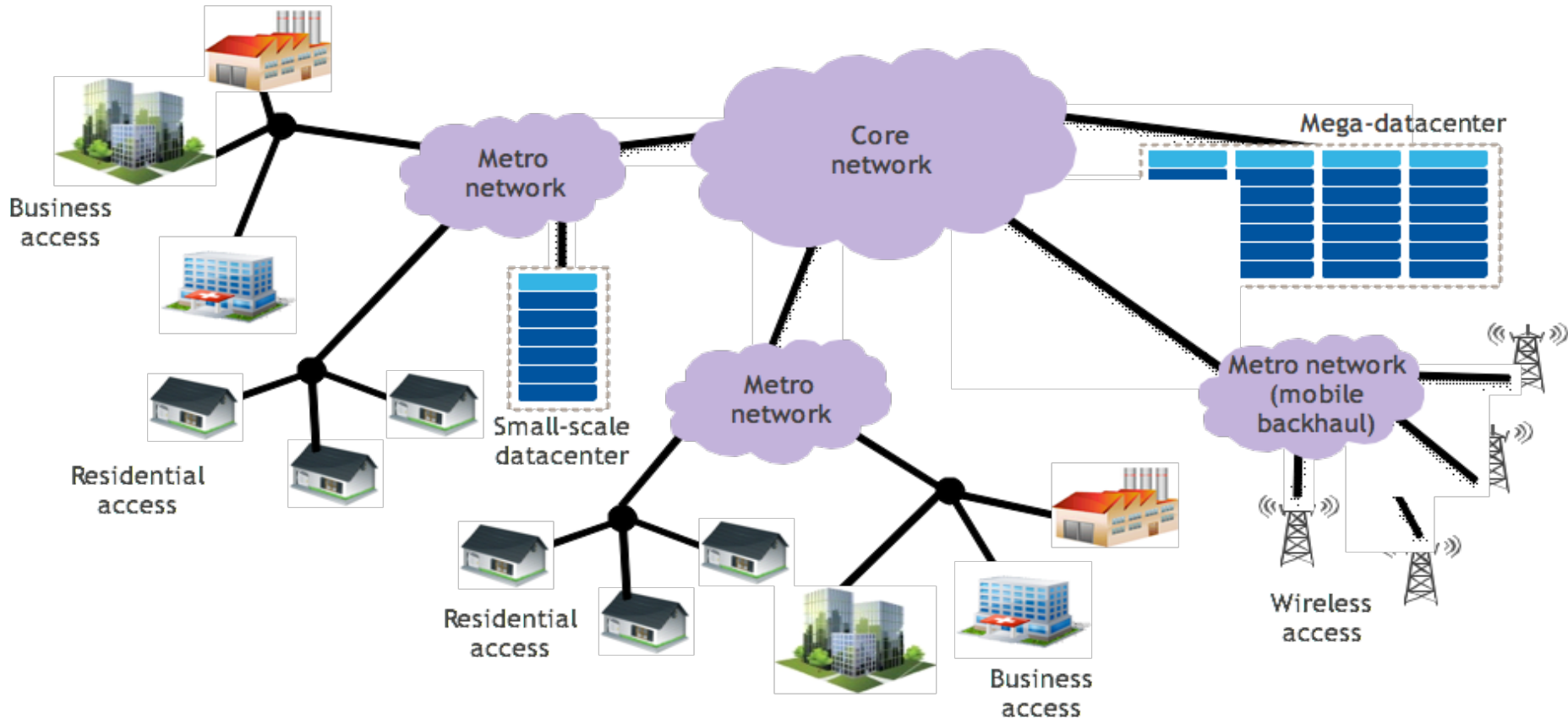


## Συντονίσια φίλτρα

-αλυσίδα **Mach-Zehnder (MZ)**: διαχωρίζει το εισερχόμενο κύμα σε δύο φορείς και ανασυνδυάζει τα σήματα των εξόδων (δες σχήμα). Ένα ρυθμίσιμο στοιχείο καθυστέρησης (delay) ελέγχει το μήκος του οπτικού μονοπατιού σε έναν απ'τους φορείς κύματος, προκαλώντας μια διαφορά φάσης ανάμεσα στα δύο σήματα όταν ανασυνδυάζονται. Τα μήκη κύματος με διαφορά φάσης 180 μοίρες φιλτράρονται και απομακρύνονται. Κατασκευάζοντας μια αλυσίδα από τέτοια στοιχεία ένα μοναδικό επιθυμητό οπτικό μήκος κύματος μπορεί να επιλεγεί.



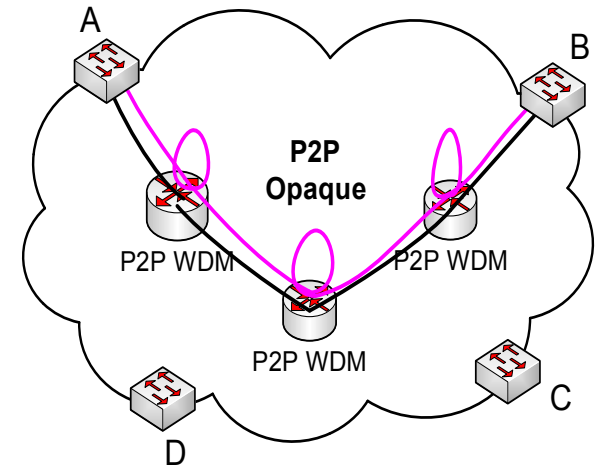
# Today's optical network



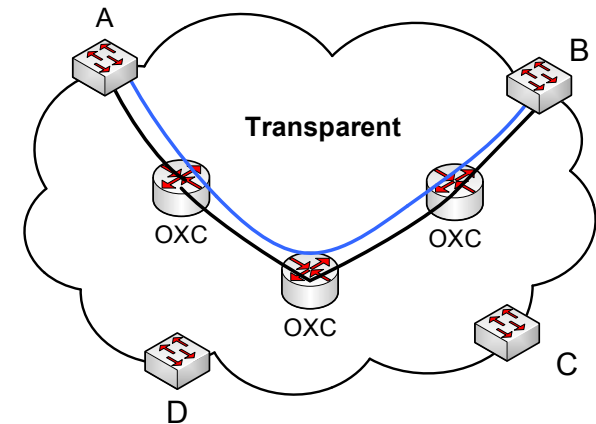


# Point-to-Point vs Wavelength Routed

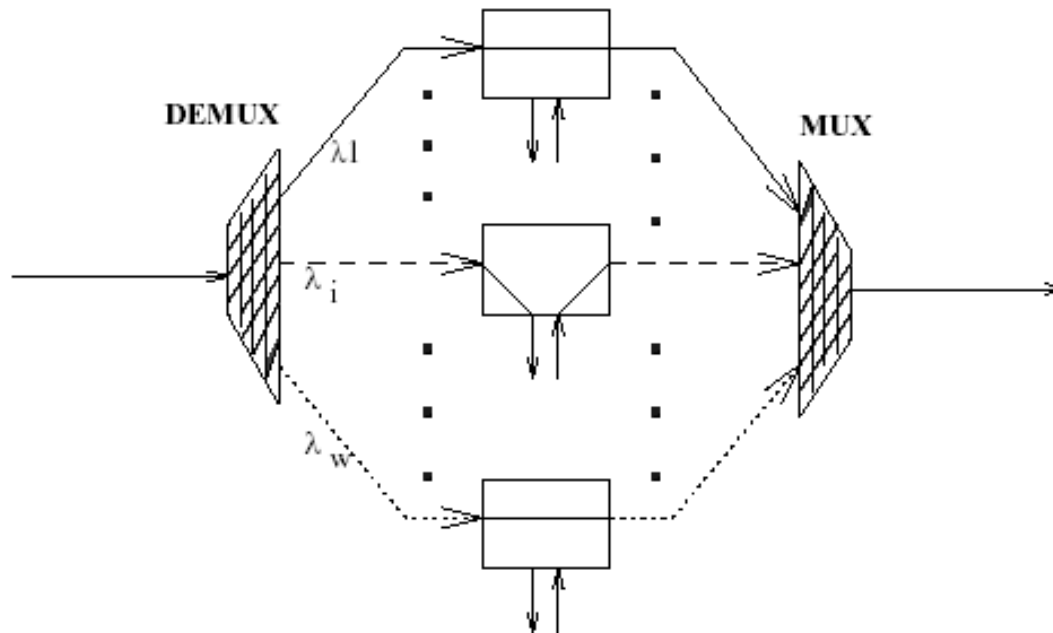
- Point-to-Point WDM  
Electrical Packet Switching
  - Packet processing overhead
  - Efficient bandwidth utilization
  - Poor scalability, Good flexibility
  - High energy consumption



- Wavelength Routed  
Circuit switching (end-to-end)
  - No packet processing
  - Inefficient bandwidth utilization
  - Good scalability, Mediocre flexibility
  - Low energy consumption

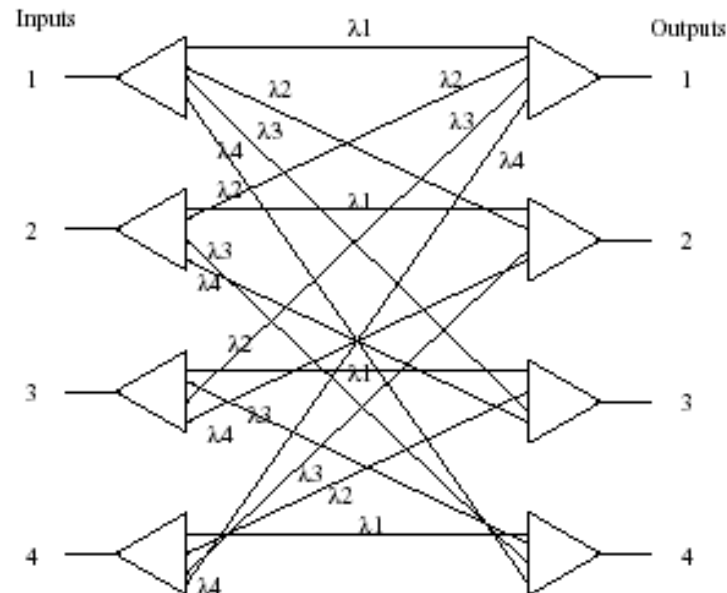


## Εξέλιξη του WDM δικτύου: 2. Add/Drop πολυπλέκτης μήκους κύματος (WADM)



ROADMs: Reconfigurable Optical Add Drop Multiplexers

## WDM Network Evolution: 3b. Crossconnect – Passive Router

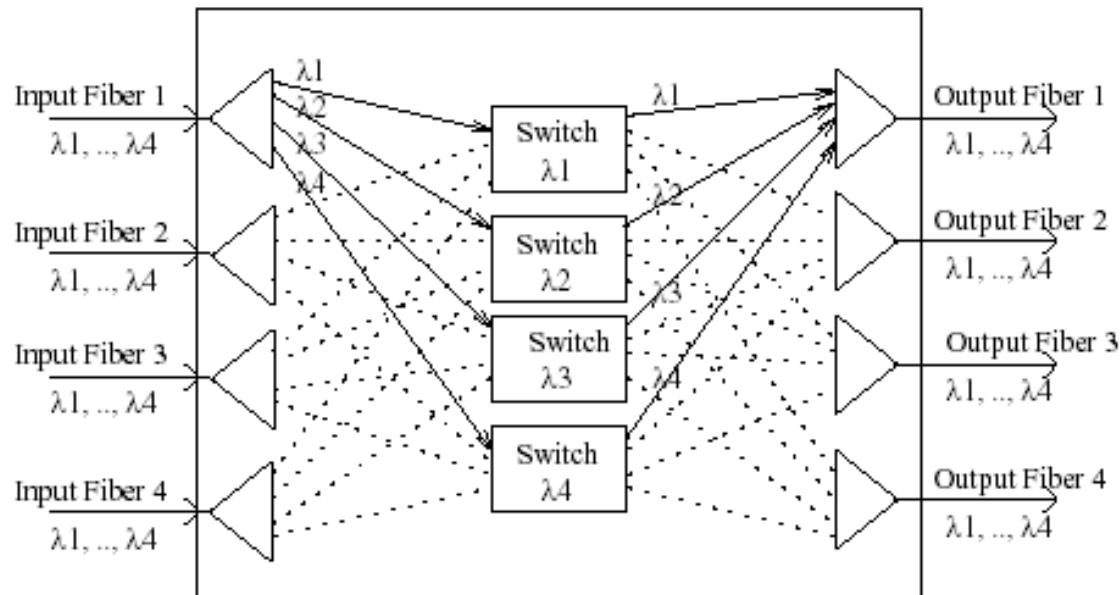


- ένας  $N \times N$  δρομολογητής μπορεί να δρομολογήσει  $N^2$  ταυτόχρονες συνδέσεις
- πίνακας σταθερών δρομολογήσεων (όχι εκπομπή)

**Ο κανόνας είναι, ότι η συχνότητα  $\lambda_j$  στη θύρα εισόδου  $i$  εξέρχεται απ'τη θύρα εξόδου  $(i+j-1) \bmod N$ .**

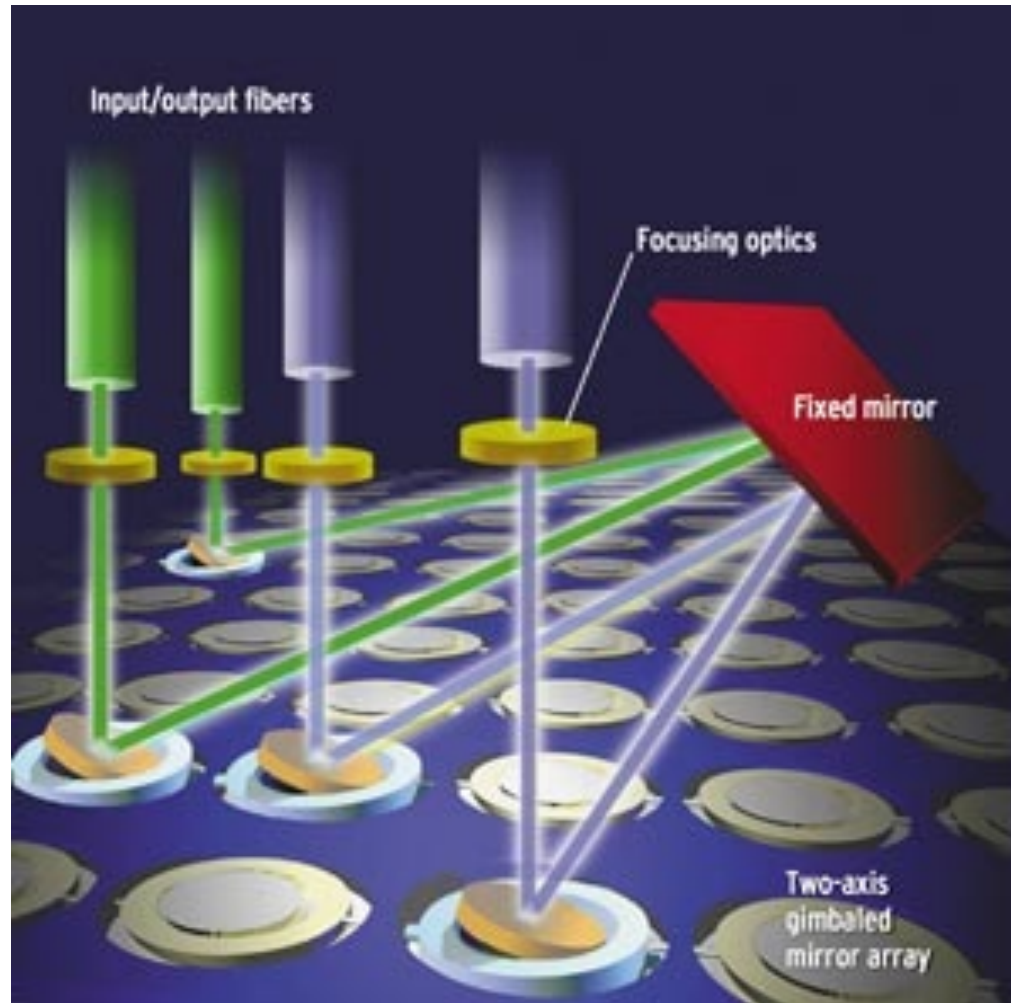
**Υπάρχει πλήρης επαναχρησιμοποίηση συχνοτήτων. Λείπει όμως η ευελιξία (πχ δεν μπορεί να γίνει μεταγωγή του  $\lambda_1$  απ'τη είσοδο 1 στην έξοδο 3).**

## Εξέλιξη του WDM δικτύου: 3c. Crossconnect – Ενεργός Μεταγωγέας

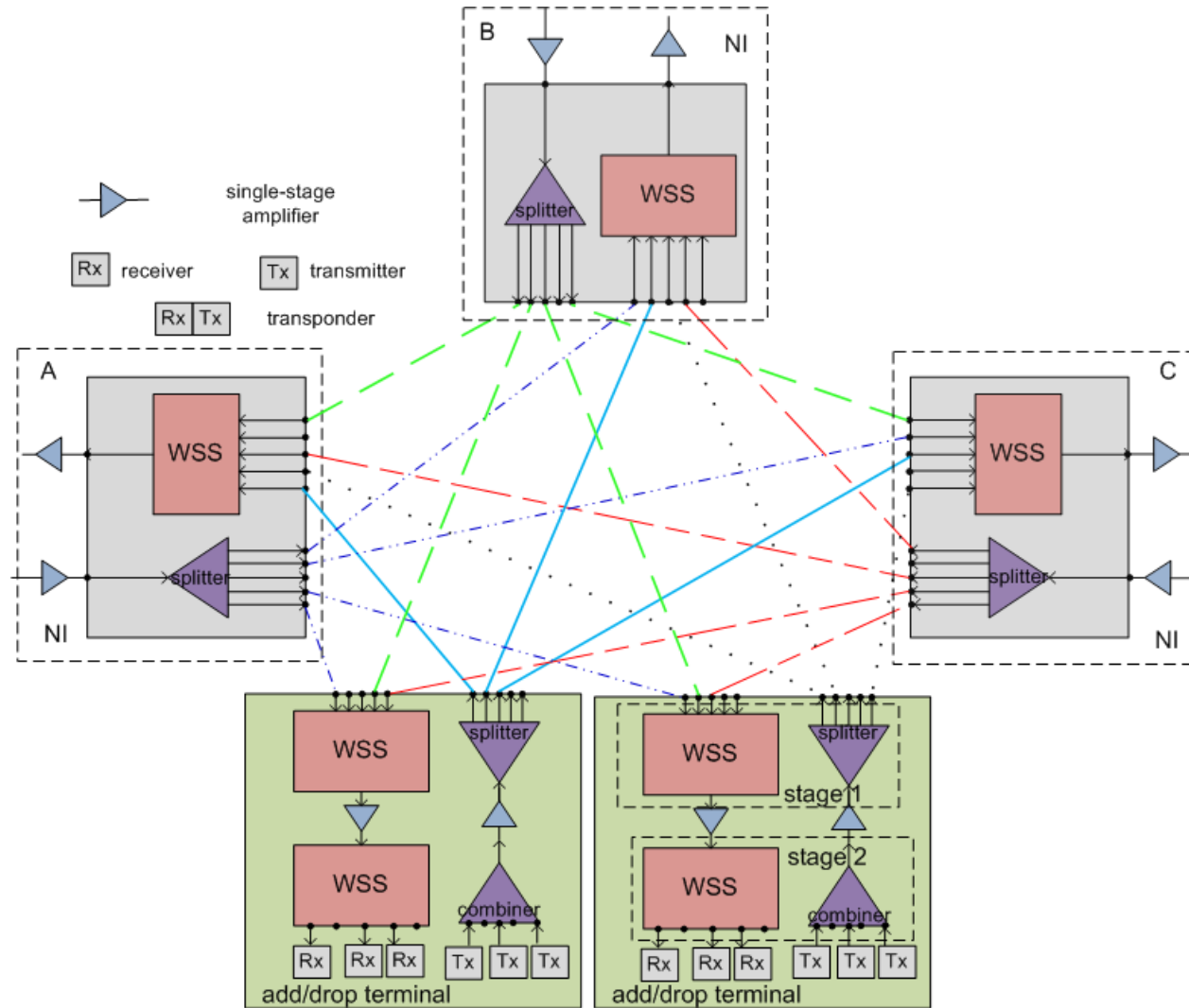


- ένας  $N \times N$  ενεργός μεταγωγέας μπορεί να δρομολογήσει  $N^2$  ταυτόχρονες συνδέσεις (σαν τον παθητικό δρομολογητή)
- αλλά ο πίνακας δρομολογήσεων είναι επαναδιαμορφώσιμος

# MEMS switches



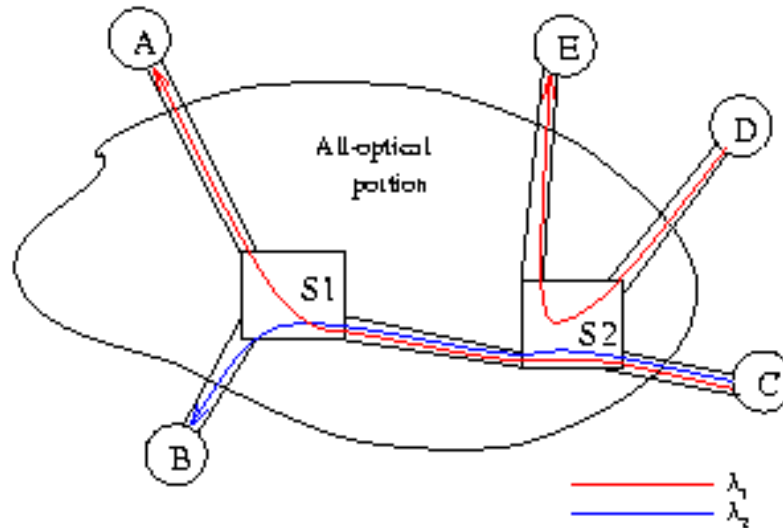
# OXC



- Switch model

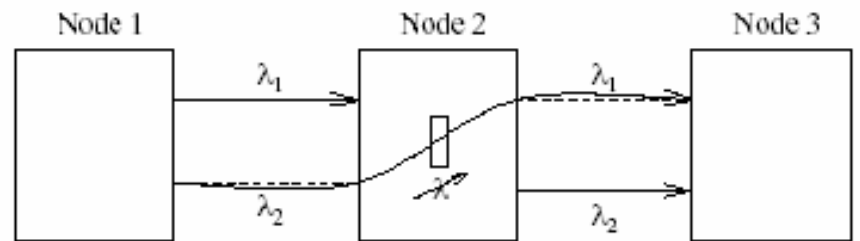
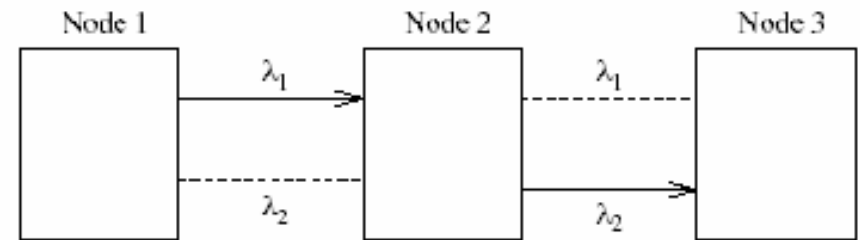
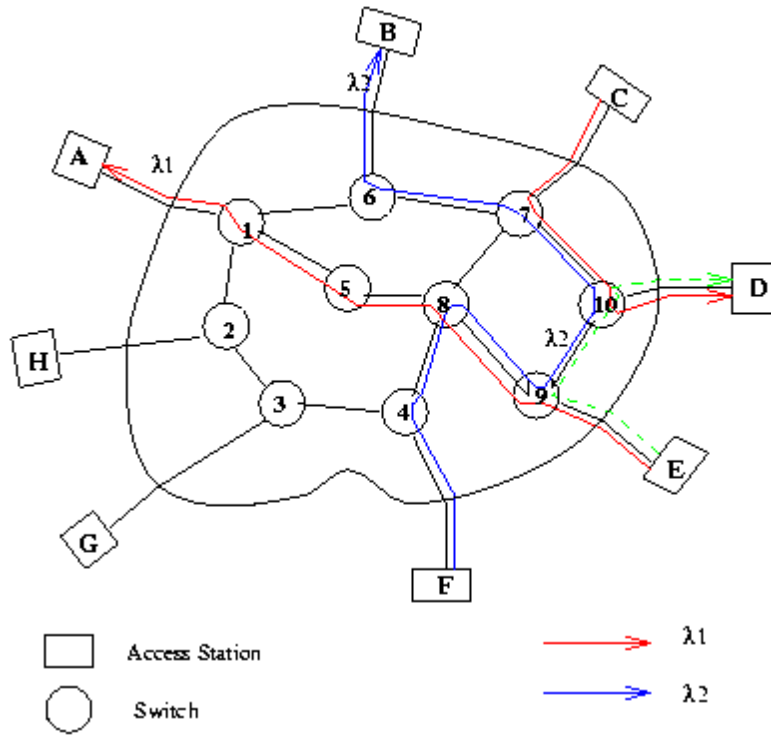
Based on WSS

## Δίκτυα δρομολόγησης μηκών κύματος



- οι μεταγωγείς δρομολόγησης μηκών κύματος συνδέονται με ίνες δύο κατευθύνσεων
- δρομολόγηση μηκών κύματος
- επαναχρησιμοποίηση μηκών κύματος
- πλήθος μηκών κύματος  $\ll$  πλήθος σταθμών
- αλγόριθμοι δρομολόγησης και ανάθεσης μηκών κύματος

## Wavelength Continuity Constraint

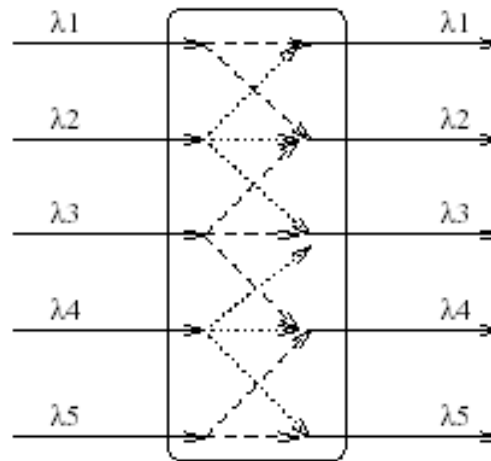




## Αραιή μετατροπή μηκών κύματος

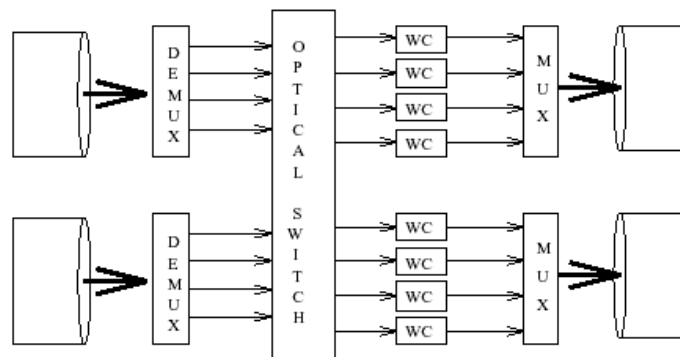
- αραιή κομβική μετατροπή: δίνει μόνο σε ένα περιορισμένο αριθμό κόμβων πλήρεις δυνατότητες μετατροπής
- αραιή μετατροπή εξόδων μεταγωγέων: χρησιμοποιεί μεταγωγείς που μοιράζονται ένα περιορισμένο πλήθος μετατροπέων μηκών κύματος
- αραιή (ή περιορισμένη) μετατροπή εύρους: δίνει μόνο ένα περιορισμένο εύρος στους μεταγωγείς που αναπτύσσονται, εξαιτίας περιορισμένου κόστους και ισχύος

### Αραιή μετατροπή εύρους

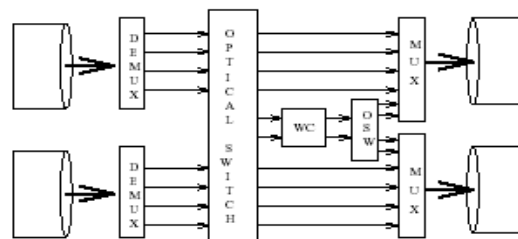


εύρος μετατροπής = 1

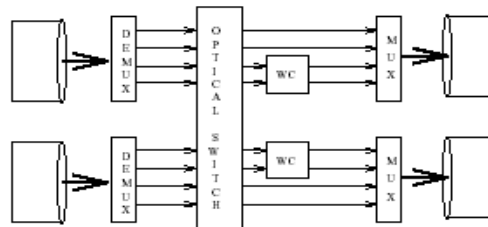
## A Switch with Dedicated Converters for each Wavelength



## Switches Which Allow Sharing of Converters



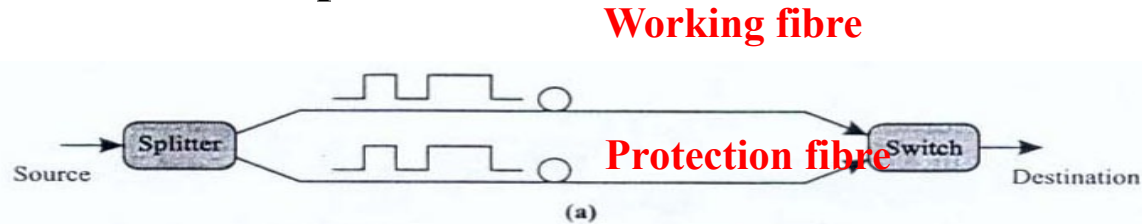
(a) Share-per-node wavelength-convertible switch architecture



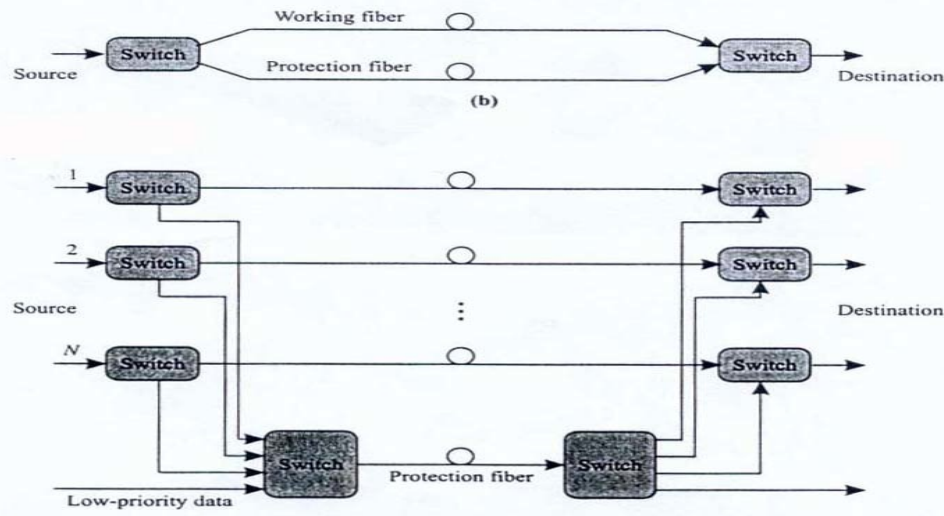
(b) Share-per-link wavelength-convertible switch architecture

# Protection Mechanisms


- The 1+1 protection. No protocol is needed



- The 1:1 and 1:N protection. Signaling protocol is needed

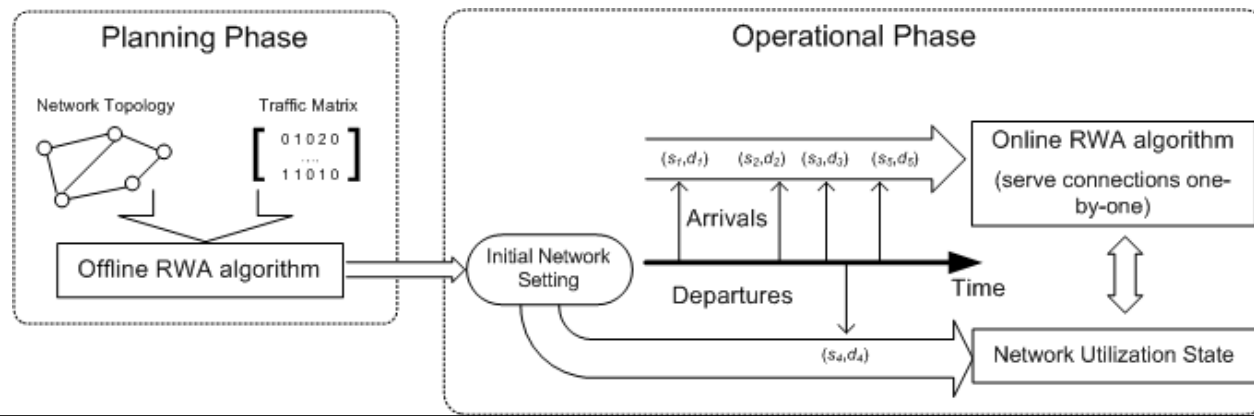


- 1+1 is faster than 1:1 but in the latter case the spare fibre could be used for low priority traffic (extra Tx, Rx)

- 
- Optical Communications
  - WDM
  - Point to Point WDM
  - Wavelength Routed WDM
  - **RWA and IA-RWA**
  - Spectrum-flexible networks

# RWA: Routing and Wavelength Assignment

- Definition
  - Given: network topology, end-to-end connection requests
  - Problem: Determine routes and wavelengths for the requests
- Offline RWA (network planning phase)
  - The entire set of requests are given in advance (traffic matrix).
- Online RWA (network operation phase)
  - Requests arrive randomly over time and are served one-by-one
- **Objective: Minimizing the Overall Blocking Probability**



# Πρόβλημα δρομολόγησης και ανάθεσης μηκών κύματος

Ελαχιστοποίησε :  $F_{max}$  (1)

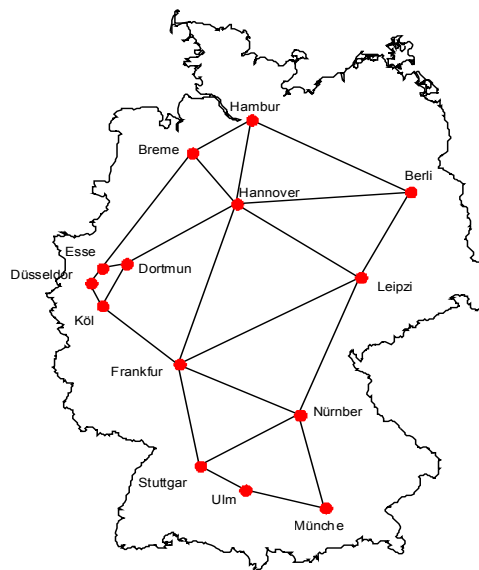
έτσι ώστε  $F_{max} \geq \sum_{s,d,u} F_{ij}^{sdu} \quad \forall ij$  (2)

$$\sum_i F_{ij}^{sdu} - \sum_k F_{jk}^{sdu} = \begin{cases} -\lambda_{sdu} & \text{if } s = j \\ \lambda_{sdu} & \text{if } d = j \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

$$\sum_u \lambda_{sdu} = \Lambda_{sd} \quad (4)$$

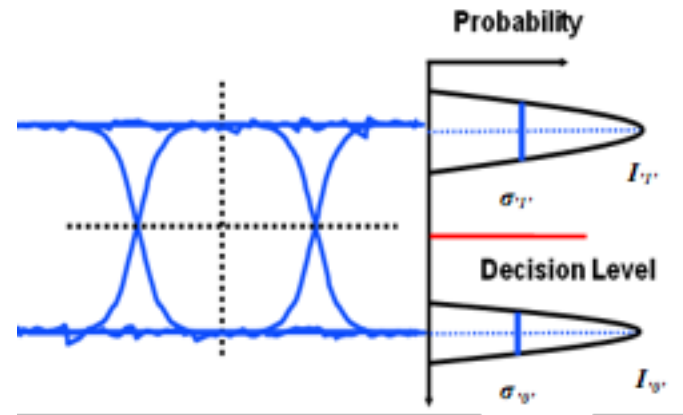
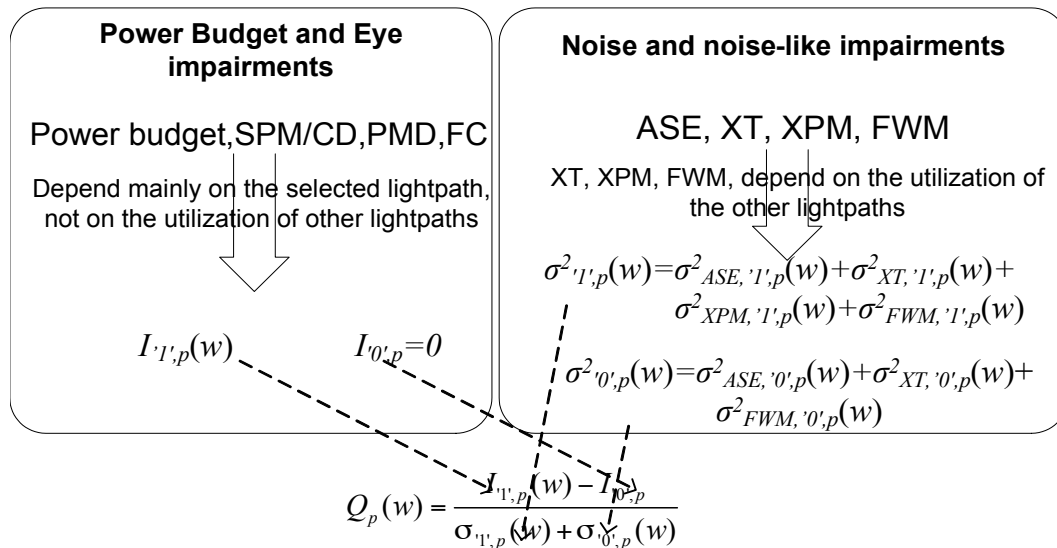
$$F_{ij}^{sdu} = 0, 1 \quad (5)$$

$$\sum_{s,d} F_{ij}^{sdu} \leq 1 \quad (6)$$



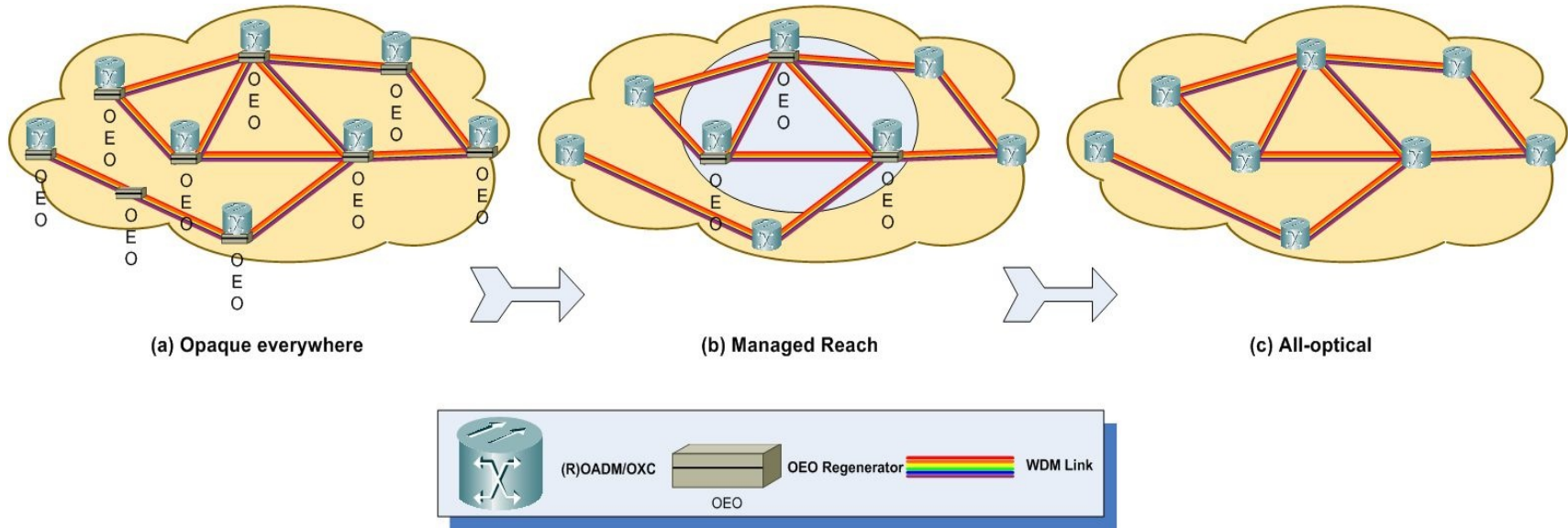
$$\Lambda = \begin{bmatrix} 0 & 1 & 2 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 2 & 0 \\ 2 & 1 & 0 & 1 & 0 & 1 \\ 0 & 2 & 1 & 1 & 1 & 0 \end{bmatrix}$$

# Physical layer evaluation: Q-factor



- Use the Q factor to estimate the feasibility of a lightpath
- The Q factor is related to the BER
- Analytical formulas can be used to calculate the Q factor

# Transparent wavelength routed networks



- All-optical transparent networks: advantages in capacity, cost and energy
- The transmission quality is affected by physical layer impairments (PLIs)
- Physical layer blocking: the signal detection at the receiver may be infeasible
- ☑ Impairment aware (IA)-RWA algorithms
- ☑ Regenerator placement algorithms



# Worst Case and Actual Interference

## Worst case interference algo:

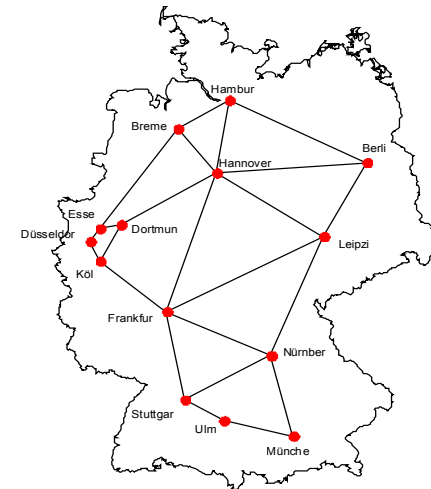
- Consider PLIs that do not depend on interference (1<sup>st</sup> class PLIs)
- Assume all wavelengths active (2<sup>nd</sup> class PLIs)
- Prune candidate lightpaths that do not have acceptable QoT

## Actual interference: cross layer optimization algo:

- Consider PLIs that do not depend on interference (1<sup>st</sup> class PLIs)
- Prune candidate lightpaths that do not have acceptable QoT
- Formulate the interference among lightpaths into the RWA

Illustrative example: DTnet topology - single connection request between all (s,d) pairs

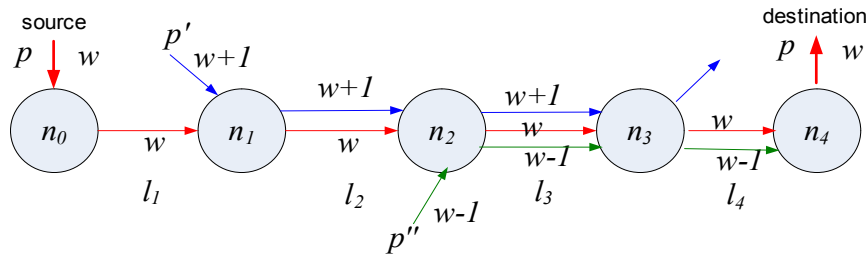
	(a)	(b)	(c)
	Initial population ( <i>k</i> -shortest length paths)	Population after discarding paths due to impairments of class 1	Population after discarding paths due to impairments of class 1 and class 2 — assuming worst case interference
<i>k</i> = 1	182	182	182
<i>k</i> = 2	364	359	333
<i>k</i> = 3	546	528	427
<i>k</i> = 4	728	653	479
<i>k</i> = 5	910	751	506
<i>k</i> = 6	1092	817	513



The reduction in the solution space can deteriorate wavelength performance

# Indirect (Parametric) IA-RWA algo

Number of active adjacent channels  
(Affected PLIs: Intra-XT, XPM and FWM)



(Soft) constrain the number of adjacent channel interfering sources on lightpath  $(p, w)$

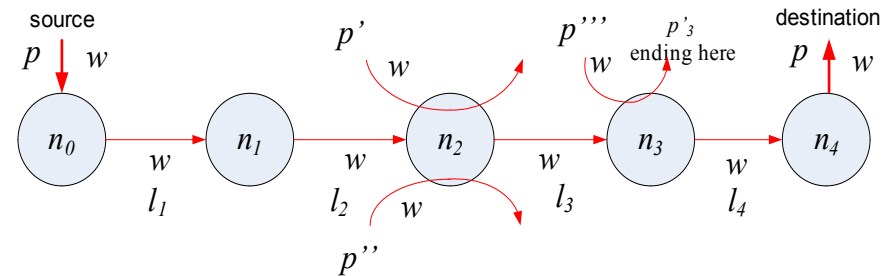
$$\sum_{(p,w) \in \mathcal{L}} \left( \sum_{(p',w-1) \in \mathcal{L}} (x_{p',w-1} + x_{p',w+1}) \right) + B \cdot x_{pw} - S_p' \leq N_{adj-acceptable} + B$$

$B$  is a large constant used to activate/deactivate the constraint

Similarly we constrain the second-adjacent channel interfering sources

Curry the surplus variables in the minimization objective

Number of intra-channel XT sources



(Soft) constrain the number of intra-XT interfering sources on lightpath  $(p, w)$

$$\sum_{(p,w) \in \mathcal{L}} \left( \sum_{(p',w) \in \mathcal{L}} x_{p',w} \right) + B \cdot x_{pw} - S_p''' \leq N_{XT-acceptable} + B$$

$B$  is a large constant used to activate/deactivate the constraint

Similarly we constrain the second-adjacent channel interfering sources

# Direct (Sigma Bound) IA-RWA algo

- For each candidate lightpath  $(p, w)$  inserted in the RWA formulation, we calculate an upper bound on the interference noise variance it can tolerate, after accounting for the impairments that do not depend on the utilization of the other lightpaths (account for 1<sup>st</sup> Class PLIs).

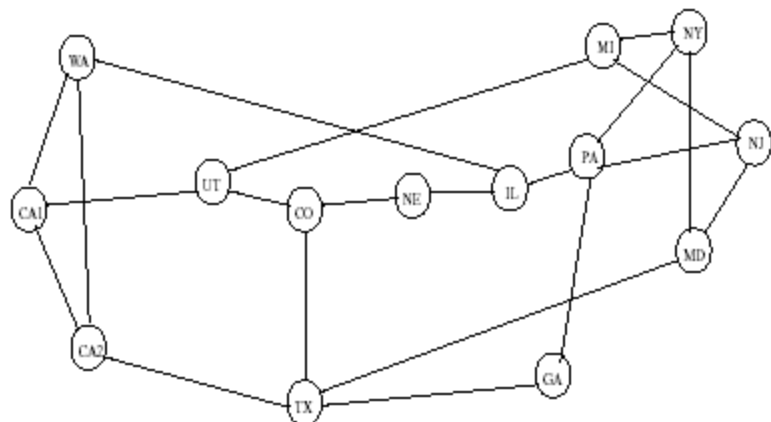
$$\sigma_{XT, '1'}^2(p, w) + \sigma_{XPM, '1'}^2(p, w) \leq \sigma_{\max}^2(p, w)$$

- Then using noise-variance related parameters per link we can constrain the interference (due to 2<sup>nd</sup> Class PLIs) accumulated on lightpath  $(p, w)$

$$\sum_{\{l \in p | n \text{ end of } l\}} \left( \overbrace{S_{XT, n}^2 \cdot \left( \sum_{\{p' | n \in p'\}} x_{p', w} \right)}^{\text{intra-XT}} + \overbrace{S_{XPM, l}^2 \cdot \left( \sum_{\{p' | l \in p'\}} x_{p', w-1} + x_{p', w+1} \right)}^{\text{XPM from adjacent channels}} + \overbrace{S_{2-XPM, l}^2 \cdot \left( \sum_{\{p' | l \in p'\}} x_{p', w-2} + x_{p', w+2} \right)}^{\text{XPM from second adjacent channels}} \right) + B \cdot x_{pw} - S_p \leq \sigma_{\max}^2(p, w) + B$$

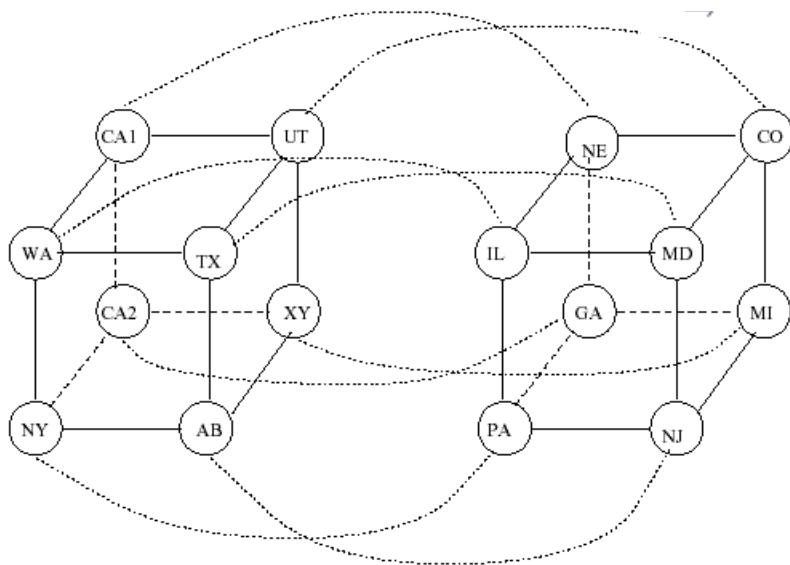
- If the selected lightpaths satisfy these constraints they have, by definition, acceptable quality of transmission

# Μονοπάτια φως και δρομολόγηση μηκών κύματος

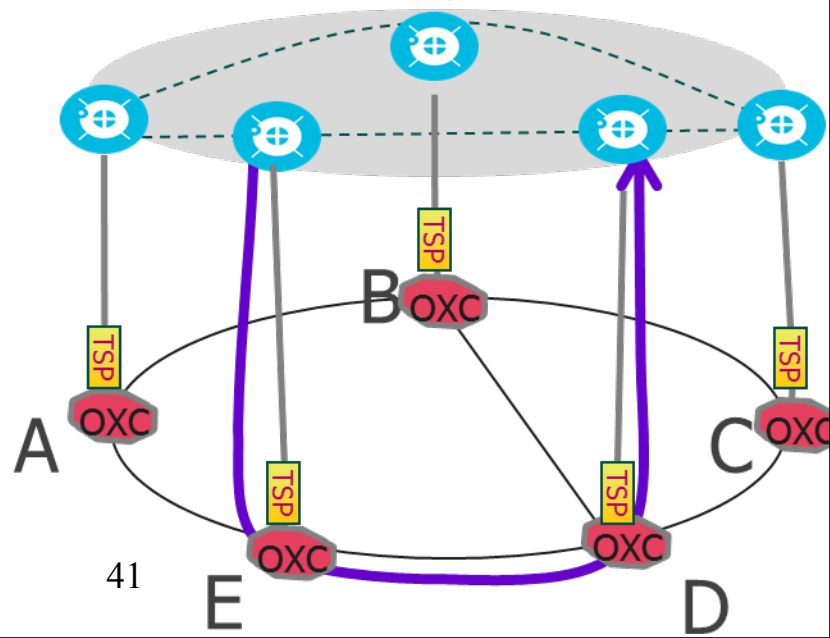


**Εικονική τοπολογία**

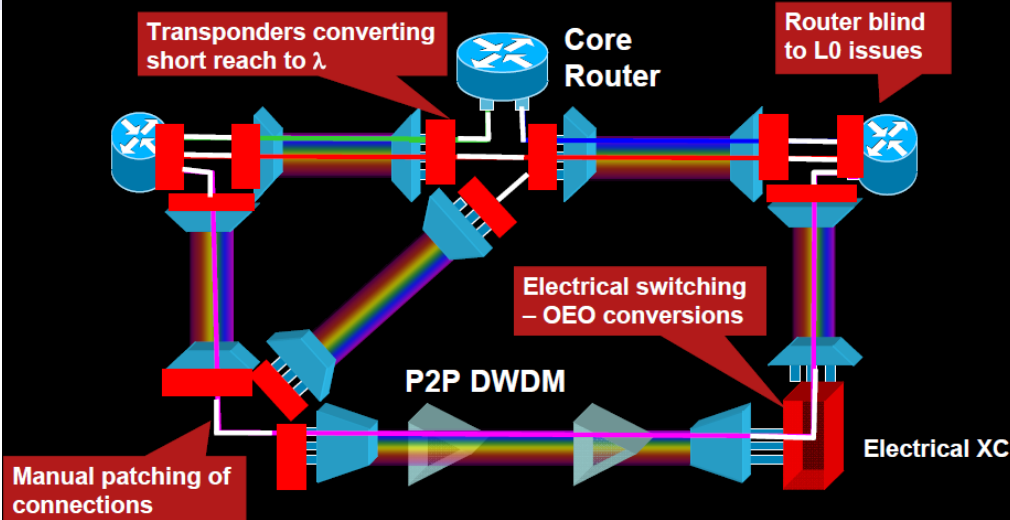
- μονοπάτι φως
- εικονική τοπολογία
- περιορισμός συνέχειας μηκών κύματος
- μετατροπή μηκών κύματος
- δρομολόγηση πακέτων
  
- φραγμένο μήκος μονοπατιών φως



Core routers or OTN switches



# Typical IP Network + Optical Network



**CRS-1**

**12000**

**7600**

**IP Layer**

---

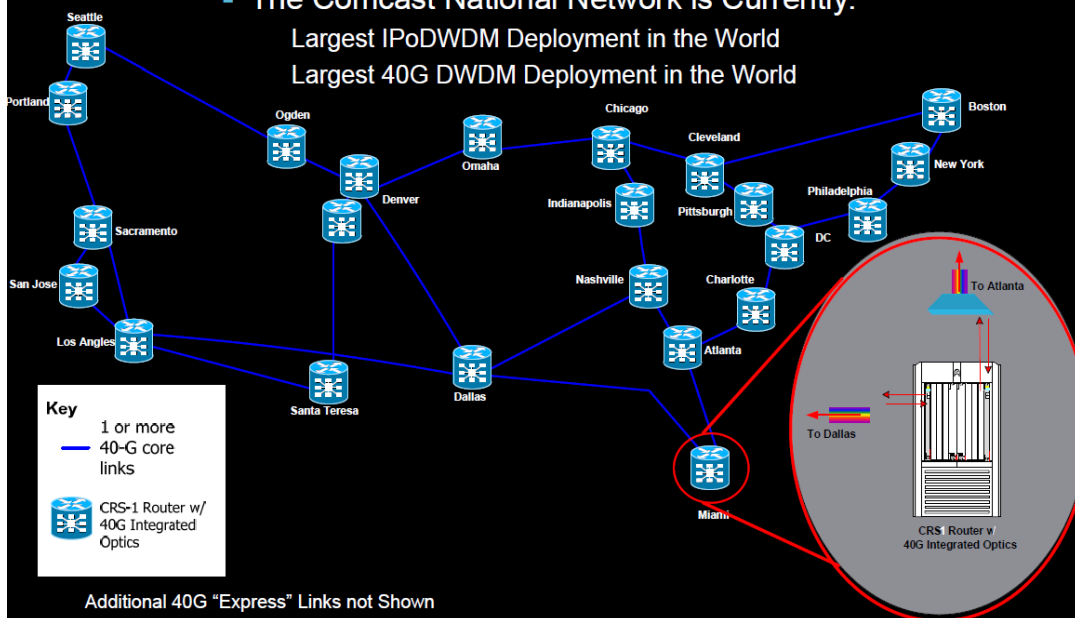
**DWDM Layer**

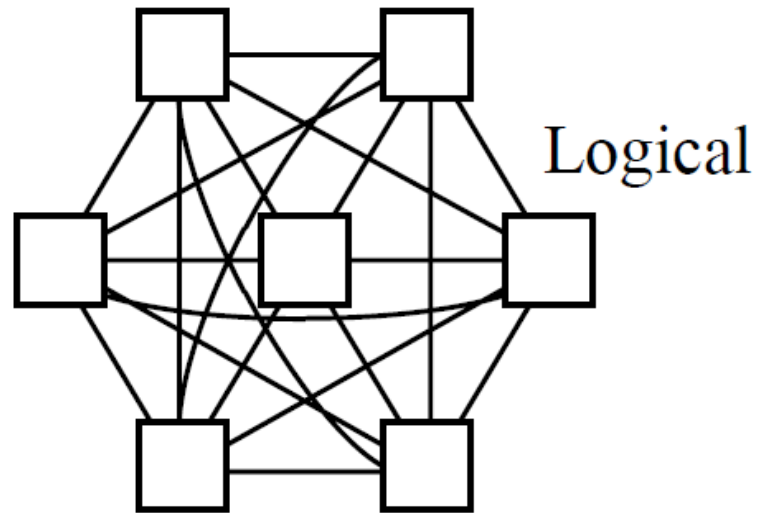
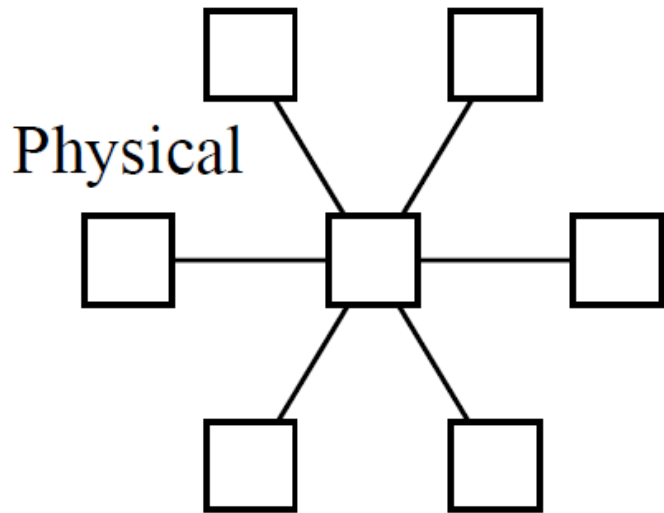
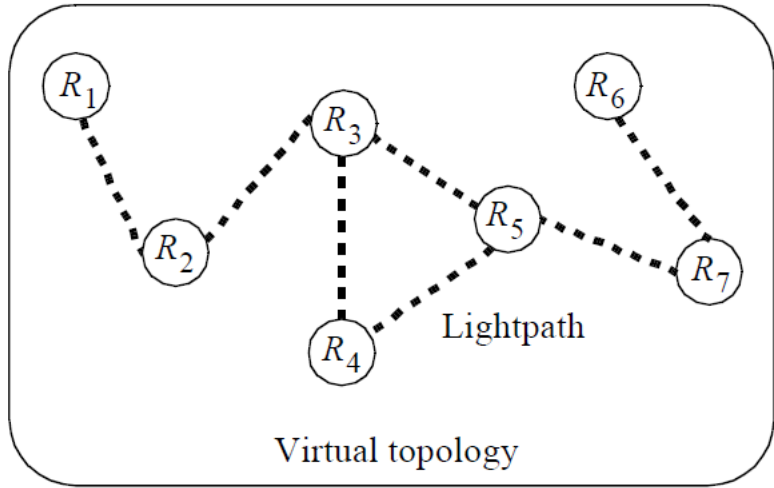
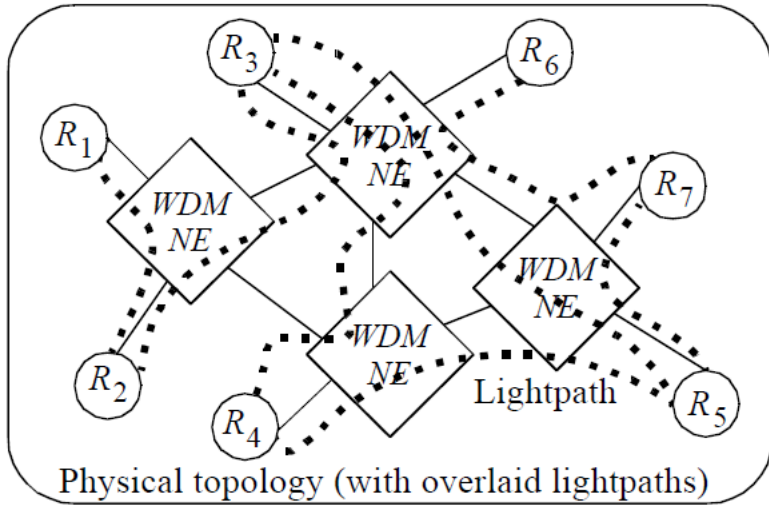
**ONS 15454 MSTP ROADM & WXC**

## Network Architecture

### First 40G IPoDWDM Network in the World

- The Comcast National Network is Currently:  
Largest IPoDWDM Deployment in the World  
Largest 40G DWDM Deployment in the World

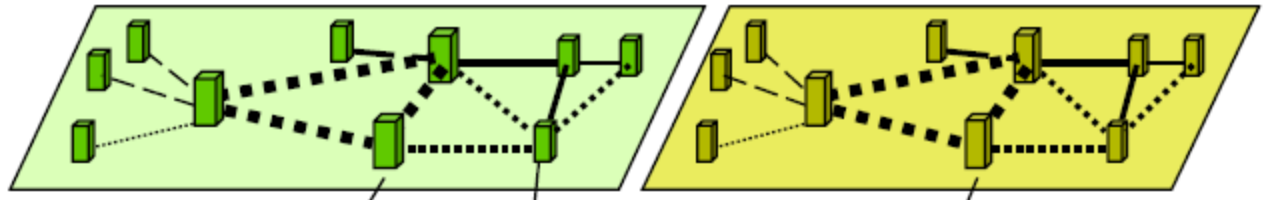




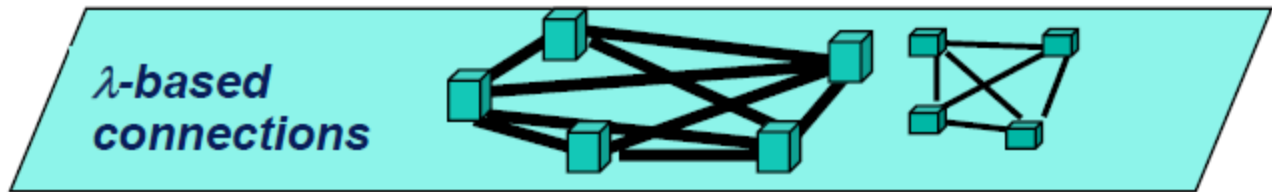
# Προσέγγιση λύσης στο σχεδιασμό της εικονικής τοπολογίας WDM WAN

1. επιλογή της 'βέλτιστης' εικονικής τοπολογίας
  - βελτιστοποίηση βασισμένη στη μεγιστοποίηση της ρυθμαπόδοσης, στην ελαχιστοποίηση της καθυστέρησης, στη μεγιστοποίηση της κυκλοφορίας ενός hop, κλπ
2. δρομολόγηση των μονοπατιών φωτός επί της φυσικής τοπολογίας
  - δρομολόγηση εναλλακτικού μονοπατιού, έκφραση ροής με πολλές πηγές και προορισμούς (multicommodity flow), τυχαιοποιημένη στρογγύλευση
3. ανάθεση μηκών κύματος: χρωματισμός των μονοπατιών φωτός για να αποφευχθούν οι συγκρούσεις των μηκών κύματος
  - αλγόριθμοι χρωματισμού γράφων, μοντέλα γράφων με επίπεδα
4. (βέλτιστη) δρομολόγηση των πακέτων επί της εικονικής τοπολογίας
  - δρομολόγηση συντομότερου μονοπατιού, αλγόριθμος εκτροπής ροής, κλπ
5. επαναληπτικά: έλεγξε για σύγκλιση και πήγαινε πίσω στο βήμα 1, αν είναι απαραίτητο

IP layer



Optical layer



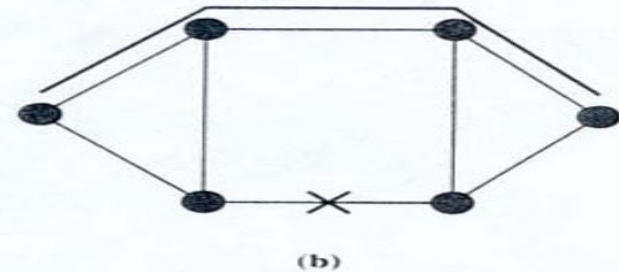
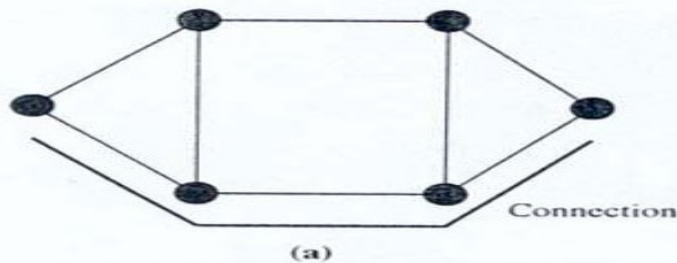
Fiber/ duct layer





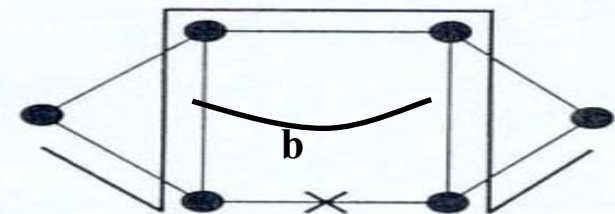
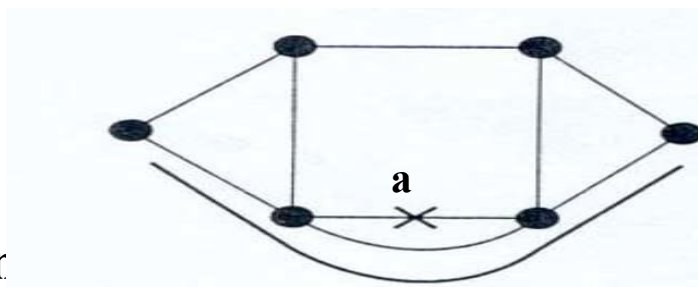
# What should be protected?

## Path protection



Note that rerouting is handled by source-destination nodes.

## Link protection:



In (b) each channel may take a different route.

# Single and Multi-objective optimization

- Most problems are formulated as single-objective optimization problems  
e.g. minimize #transponders, **or** # wavelengths, **or** energy consumption, etc.
- What if we want to optimize more than one metric  
e.g. minimize both the #transponders **and** #wavelengths
  - No single solution simultaneously accomplishes the two
  - Non-dominated or Pareto front: the set of solutions that cannot be improved in one objective without deteriorating their performance in at least one of the rest

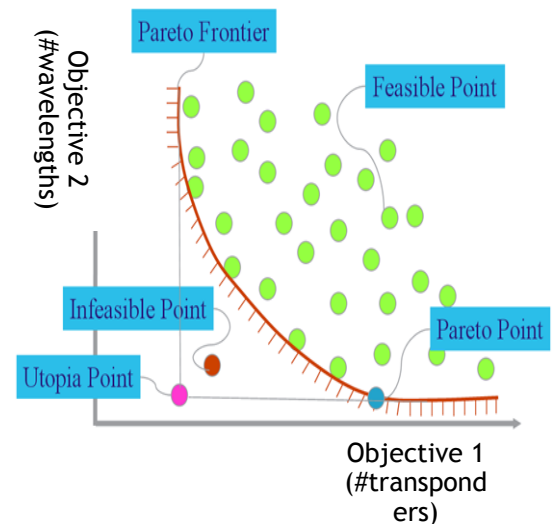
## ▶ Use single objective methods

*Scalarizing*: use a single-objective defined as a weighted combination of the multi-objectives

$$\text{minimize: } (w \cdot \# \text{transponders}) + [(1 - w) \cdot \# \text{wavelengths}]$$

weighing coefficient  $w$  controls the dependence on each metric

## OFC 2013 ▶ Use multi-objective methods

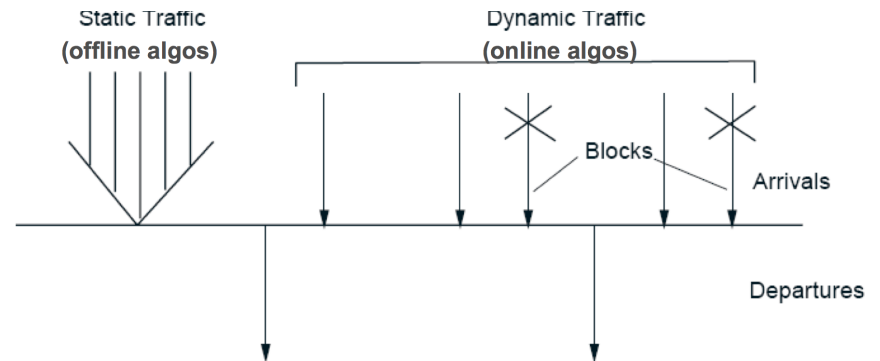


# Dynamic IA-RWA Algorithm

- Input:

New connection request

Current network state



- Objective: serve the connections and minimize blocking over (infinite) time
- We use a multcost algorithm with 2 phases
  1. Calculate the set of non-dominated paths from the given source to the given destination
  2. Choose the lightpath that minimizes the objective function

# Calculating the Set of Non-Dominated Paths

- Cost vector of link  $l$ :  $V_l = (d_l, \overline{G}_l, \overline{\sigma^2_{1,l}}, \overline{\sigma^2_{0,l}}, \overline{W}_l)$

Vector  $\overline{W}_l$  maps the utilization of wavelengths

- The cost vector of path  $p$  can be calculated based on the cost vectors of links  $l=1,2,\dots,m$ , that comprise it

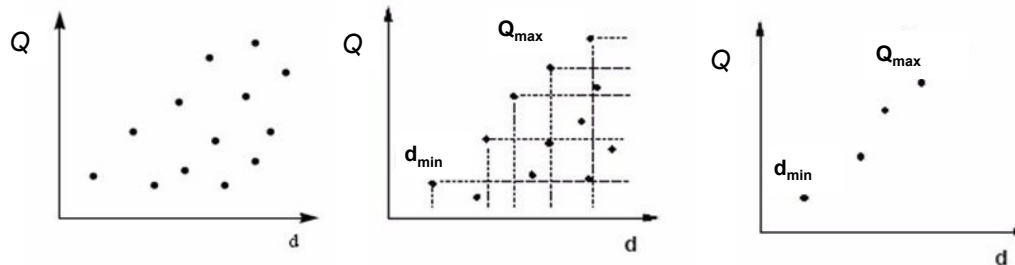
$$V_p = (d_l, \overline{G}_l, \overline{\sigma^2_{1,l}}, \overline{\sigma^2_{0,l}}, \overline{W}_l, * p) = \left( \sum_{l=1}^m d_l, \sum_{l=1}^m \overline{G}_l, \sum_{l=1}^m \left( \overline{\sigma^2_{1,l}} \cdot \prod_{i=l+1}^m 10^{2 \cdot \overline{G}_i / 10} \right), \sum_{l=1}^m \left( \overline{\sigma^2_{0,l}} \cdot \prod_{i=l+1}^m 10^{2 \cdot \overline{G}_i / 10} \right), \& \overline{W}_l, (1, \dots, m) \right)$$

- The cost parameters of a path can be combined so as to calculate the Q factors of the available lightpaths over that path
- Prune the solution space
  - For each  $p$ , we check the Q factor of available lightpaths and we make unavailable those that do not have acceptable performance
  - Σταματάμε να επεκτείνουμε μονοπάτια αν δεν έχουν τουλάχιστον ένα διαθέσιμο μήκος κύματος

# Calculating the Set of Non-Dominated Paths

Domination relationship between two paths

$p_1$  dominates  $p_2$  ( $p_1 > p_2$ ) iff  $d_{p_1} \leq d_{p_2}$  and  $\overline{W}_{p_1} \geq \overline{W}_{p_2}$  and  $\overline{Q}_{p_1} \geq \overline{Q}_{p_2}$



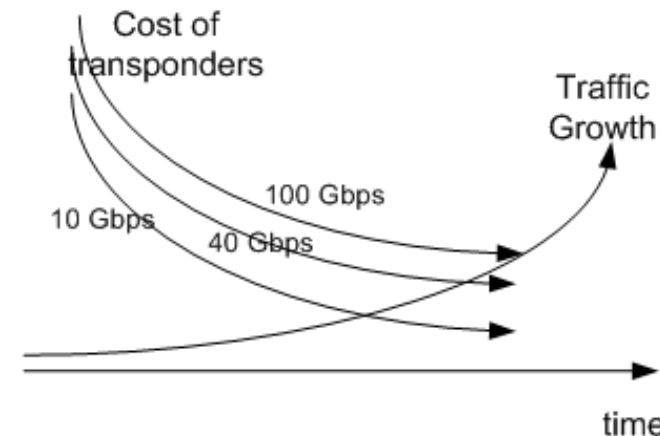
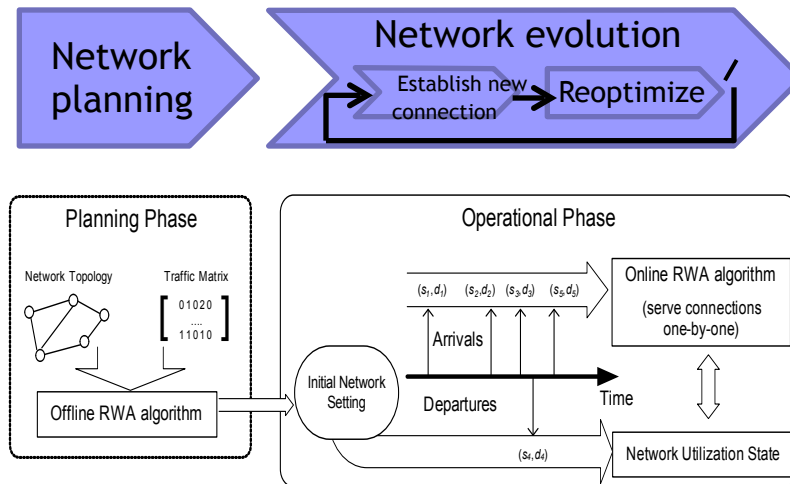
- Using the above definitions we use a multicost algorithm, which is a generalization of Dijkstra algorithm, to compute the set of non-dominated paths  $P_{n-d}$  from the given source to the given destination
- By definition, the paths that are included in  $P_{n-d}$  have
  - At least one available wavelength
  - The available wavelength have acceptable transmission performance (Q factor)

# WDM network evolution

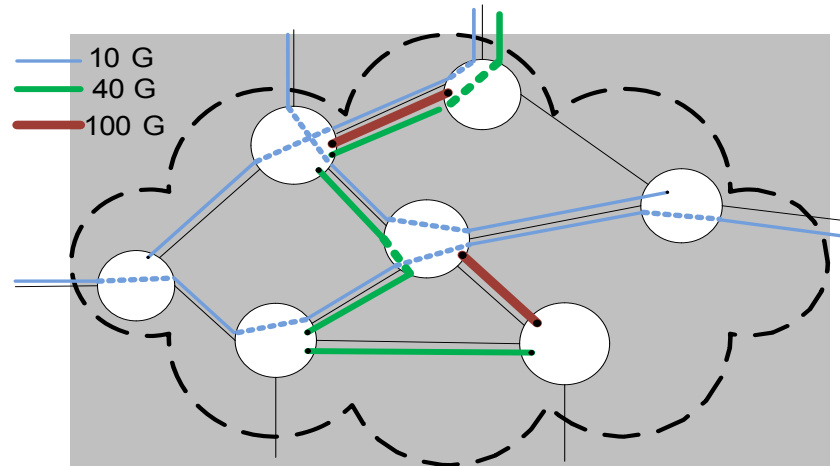
- As the network evolves, established connections are teared-down and new are established
- Operational phase
  - Establish new connection one-by-one (or a small set)
  - Penalize re-routing of established lightpaths

minimize  $f(x_{pw}) + \gamma \cdot \sum_p \sum_w |x_{pw} - \bar{x}_{pw}|$ ,  $\bar{x}_{pw}$  previous solution,  $f(x_{pw})$  optimization objective

- Re-plan (re-optimize) the network
  - Periodically or On-demand

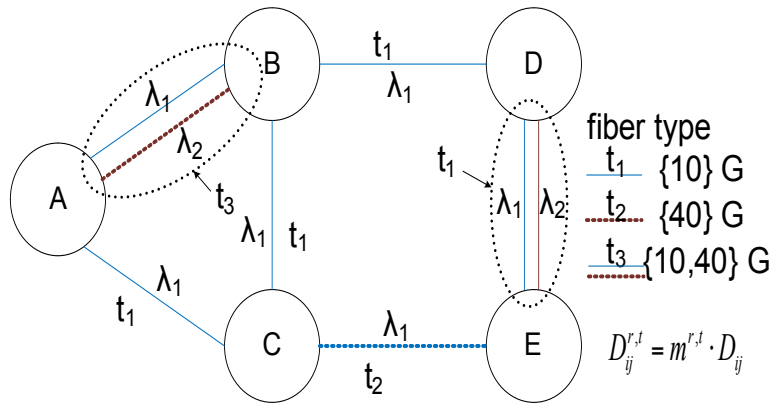


# Mixed Line Rates WDM Networks



- Several Line Rates (10/40/100)Gbps
- Exploit the MLR heterogeneity to reduce the cost of the network
  - Long-distance low-bit-rate connections could be served with inexpensive low-rate and long-reach (e.g. 10 Gbps) transponders
  - High bit-rate connections could be served with more expensive higher-rate transponders. Typically, higher rate transponders have shorter reach
- Interference among lightpaths of different rates
- ☑ Mixed Line Rates RWA algorithms

# Transmission Reach & Effective Length



- Length of link  $l$ :  $D_l$
- Maximum transmission reach at  $r$ :  $D^r$
- Effective length of fiber  $t$  for a transmission of rate  $r$

$$D_l^{r,t} = m^{r,t} \cdot D_l$$

- Effective length of the path  $p$  at rate  $r$

$$D_p^r = D_{l_1}^{r,t_1} + D_{l_2}^{r,t_2} + \dots + D_{l_n}^{r,t_n}$$

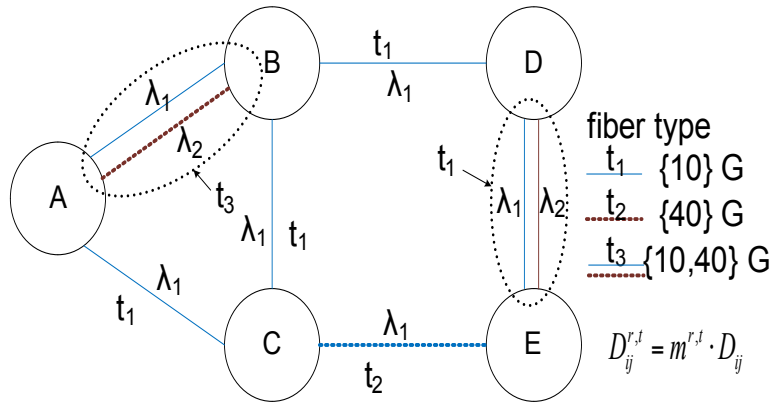
- Satisfy:

$$D_p^r < D^r$$

- Rates:  $r = \{10, 40, 100\}$  Gbps
- Fiber types:  $t = \{\{10\}, \{40\}, \{100\}, \{10, 40\}, \{10, 100\}, \{40, 100\}, \{10, 40, 100\}\}$
- Interference* between different modulation format/rates
- $m^{r,t} \geq 1$ : the increase of the length of the link for a connection of rate  $r$ , due to *interference* effects generated by the other modulation formats/rates concurrently transmitted over the fiber  $t$
- $m^{r,t \equiv \{r\}} = 1$ : a fiber ( $t \equiv \{r\}$ ) is used only by connections of a certain rate  $r$  (its effective length is equal to its real length)



# Transmission Reach & Effective Length



- Length of link  $l$ :  $D_l$
- Maximum transmission reach at  $r$ :  $D^r$
- Effective length of fiber  $t$  for a transmission of rate  $r$

$$D_l^{r,t} = m^{r,t} \cdot D_l$$

- Effective length of the path  $p$  at rate  $r$

$$D_p^r = D_{l_1}^{r,t_1} + D_{l_2}^{r,t_2} + \dots + D_{l_n}^{r,t_n}$$

- Satisfy:  $D_p^r < D^r$

- AC and CB are  $t=\{10\}$
- AB is  $t=\{10,40\}$
- Effective length of the path  $p_{ACB}$  at rate 10

$$D_{ACB}^{10} = m^{10,\{10\}} \cdot D_{AC} + m^{10,\{10\}} \cdot D_{CB}$$

- Effective length of the path  $p_{ABD}$  at rate 10

$$D_{ABD}^{10} = m^{10,\{10,40\}} \cdot D_{AB} + m^{10,\{10\}} \cdot D_{BD}$$

- $m^{10,\{10\}} = 1$
- $m^{10,\{10,40\}} \geq 1$

# ILP Formulation

- Incoming traffic constraints

For all  $(s,d)$ ,  $\sum_{p \in P_{sd}} \sum_w r \cdot x_{pw}^r \geq \Lambda_{sd}$  (1)

- Single wavelength assignment constraints

For all  $l$ , for all  $w$ ,  $\sum_{p:l \in p} \sum_r x_{pw}^r < 1$  (2)

- Link-rate utilization constraints

For all  $l$ , for all  $p:l \in p$ , for all  $w$ , for all  $r$ ,  $x_{pw}^r \leq u_l^r$  (3)

- Fiber type constraints

For all  $l$ ,  $\sum_t f_l^t = 1$  (4)

For all  $r$ , for all  $t: r \neq t$ , and for all  $l$ ,  $f_l^t \leq 1 - u_l^r$ . (5)

For the case of an MLR system with  $r=\{10,40,100\}$ Gbps, we have the following set of constraints

For all  $l$ ,  $f_l^{t=\{40\}} \leq 1 - u_l^{r=10}$ ,  $f_l^{t=\{100\}} \leq 1 - u_l^{r=10}$ ,  
 $f_l^{t=\{40,100\}} \leq 1 - u_l^{r=10}$ ,

$f_l^{t=\{10\}} \leq 1 - u_l^{r=40}$ ,  $f_l^{t=\{100\}} \leq 1 - u_l^{r=40}$ ,  
 $f_l^{t=\{10,100\}} \leq 1 - u_l^{r=40}$ ,

$f_l^{t=\{10\}} \leq 1 - u_l^{r=100}$ ,  $f_l^{t=\{40\}} \leq 1 - u_l^{r=100}$ ,  
 $f_l^{t=\{10,40\}} \leq 1 - u_l^{r=100}$ .

utilization of different rates of a link

- Effective length constraints

For all  $p$ , for all  $r$ ,  $\sum_{l \in p} \sum_t D_l^{r,t} \cdot f_l^t \leq D^r + B \cdot y_p^r$ , (6)

where  $B$  is a large constant (e.g. greater than the length of the longer length path in the network).

type of fiber used on link

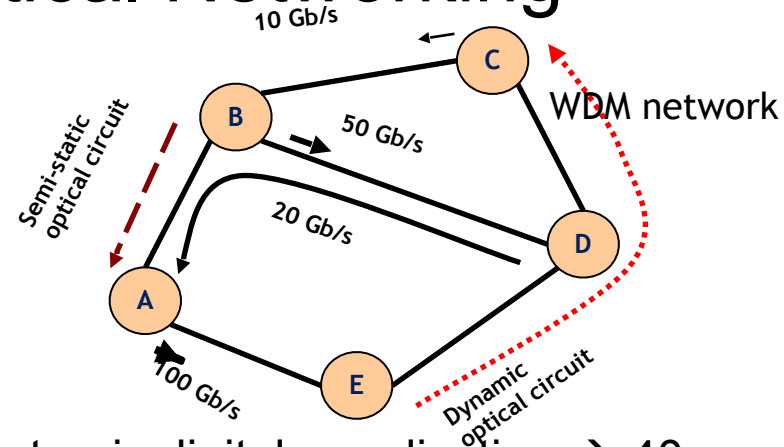
For all  $p$ , for all  $r$ , for all  $w$ ,  $x_{pw}^r \leq 1 - y_p^r$ . (7)

Prohibit the utilization of lightpaths over paths that cannot be used for a transmission at a certain rate

Enable/disable the use of a certain path for a certain rate based on the effective lengths of the links that it comprise it

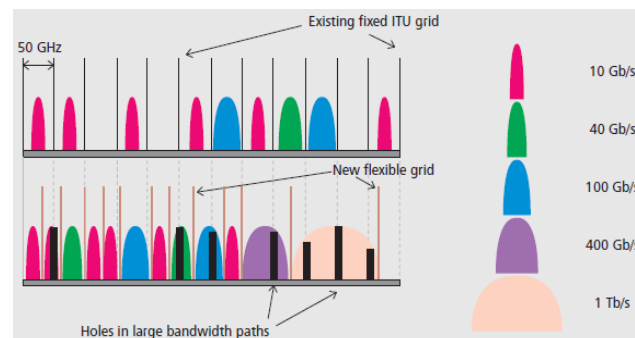
# Requirements for Flexible Optical Networking

- Continuous growth of consumers IP traffic
- Emerging high-rate applications, sometimes bursty (video on demand, HDTV, cloud and grid applications, DC interconnection)
- WDM: advanced modulation formats and electronic digital equalization → 40 and 100 Gbps channel bandwidths
- ☒ WDM has *rigid* and *coarse granularity*. A problem that becomes even more severe at higher channel rates
- ☑ Requirements: *cost* and *energy scalable*, *flexible*, and with *fine granularity* network



## ☑ Flexgrid optical networks

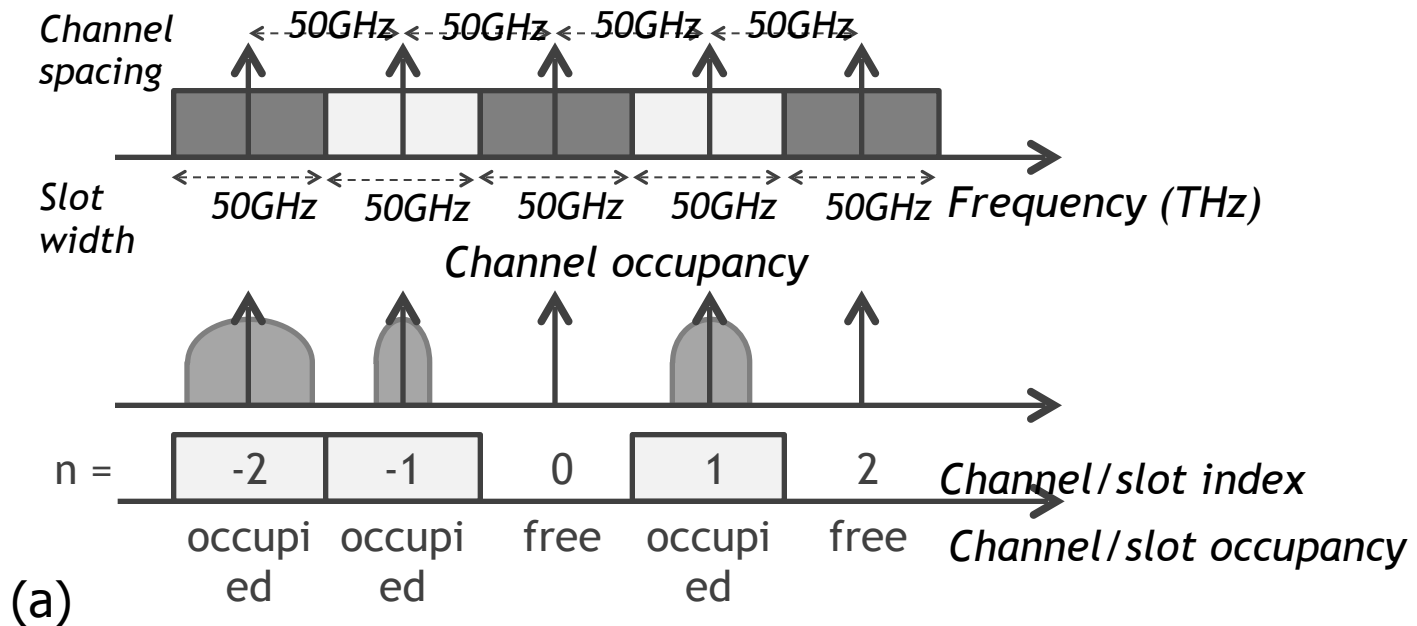
- 6.25 or 12.5 GHz slots



# Fixed vs. flexgrid

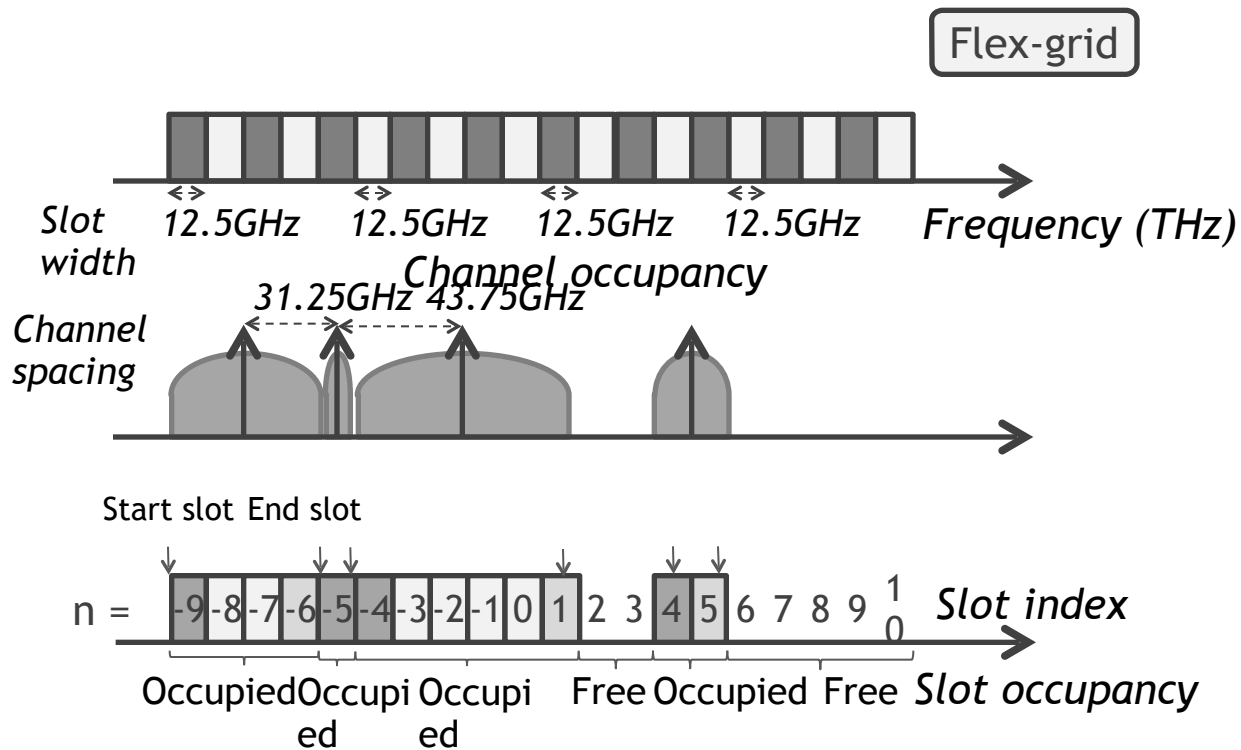
- Fixed 50GHz grid

Fixed 50GHz grid 



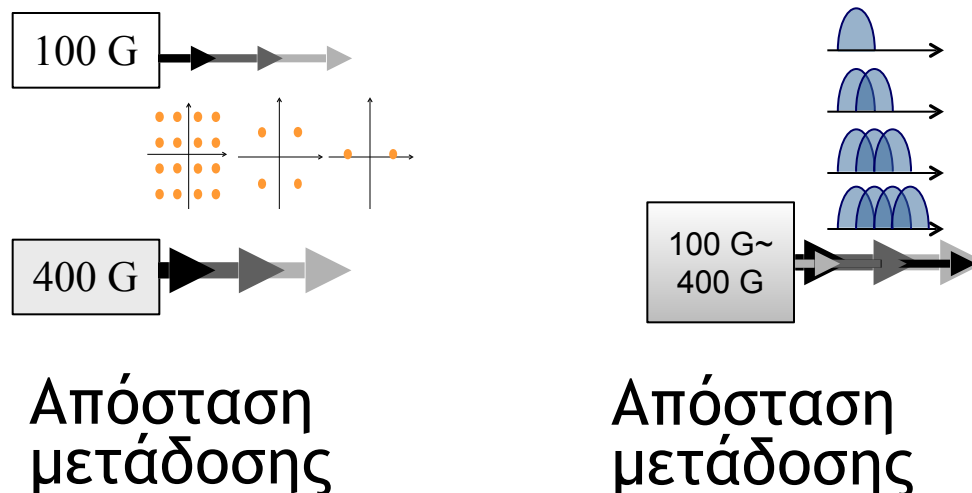
# Fixed vs. flexgrid

- Flexgrid



# Transponder

- Σύμφωνη ανίχνευση και DSP
  - Με τη βελτιστοποίηση των παρακάτω παραμέτρων παρέχεται ο απαιτούμενος ρυθμός μετάδοσης και η επιθυμητή απόσταση μετάδοσης ελαχιστοποιώντας το χρησιμοποιούμενο φάσμα
    - $(\text{Symbol rate}) \times (\text{Number of modulation levels}) \times (\text{Number of sub-carriers})$
- Μεταβλητή απόσταση μετάδοσης (reach)
  - Αλλαγή του αριθμού των bits ανά σύμβολο με DAC μετατροπείς και IQ-διαμορφωτές
- Μεταβλητός ρυθμός.
  - Μεταβλητός αριθμός OFDM υποφερουσών



# Spectrum flexible optical network

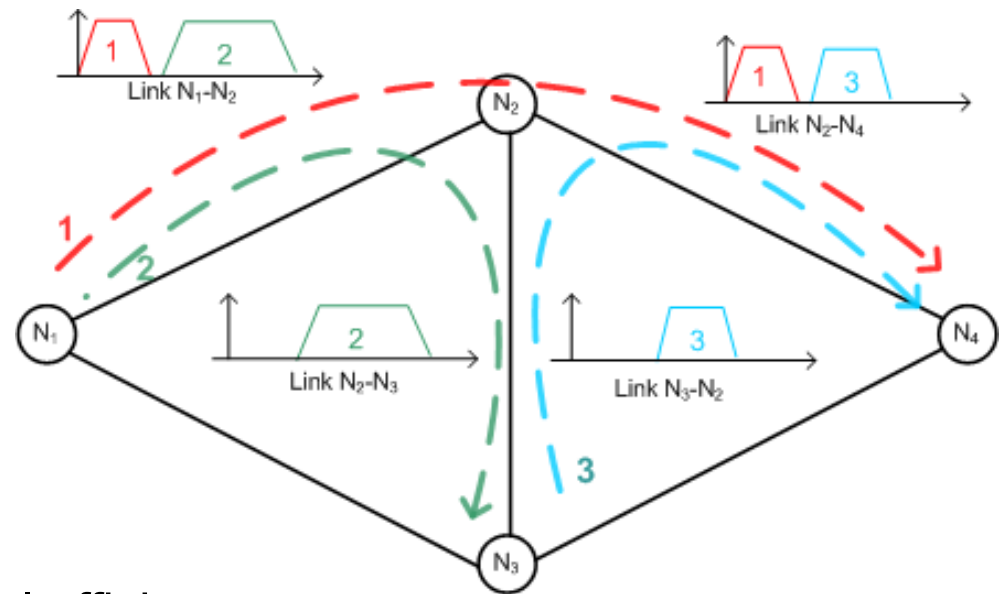
*Spectrum variable (non-constant) connections*

- Spectrum flexible OXCs
- Spectrum flexible transponders

Gains:

- ▶ Spectrum savings, higher spectral efficiency
- ▶ Dynamic spectrum sharing : statistical multiplexing gains similar to those observed in time sharing systems (e.g. OBS, OPS nets)

Traditional RWA algos are not directly applicable in OFDM networks

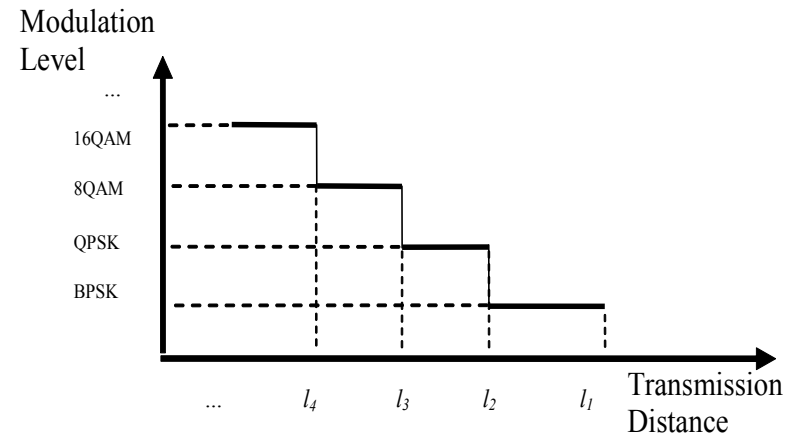
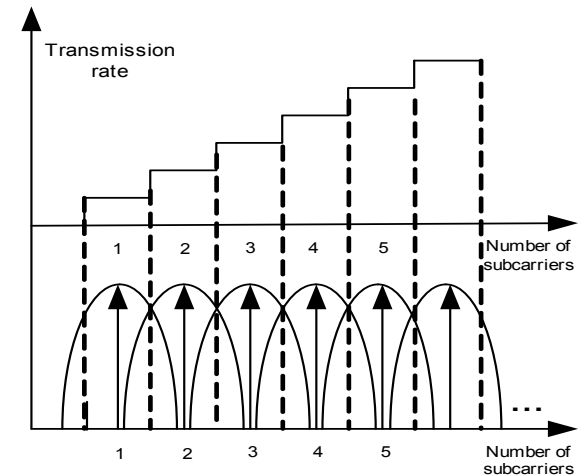


# Optical OFDM Transmission

## Bandwidth-variable OFDM transponders

### 2 degrees of flexibility

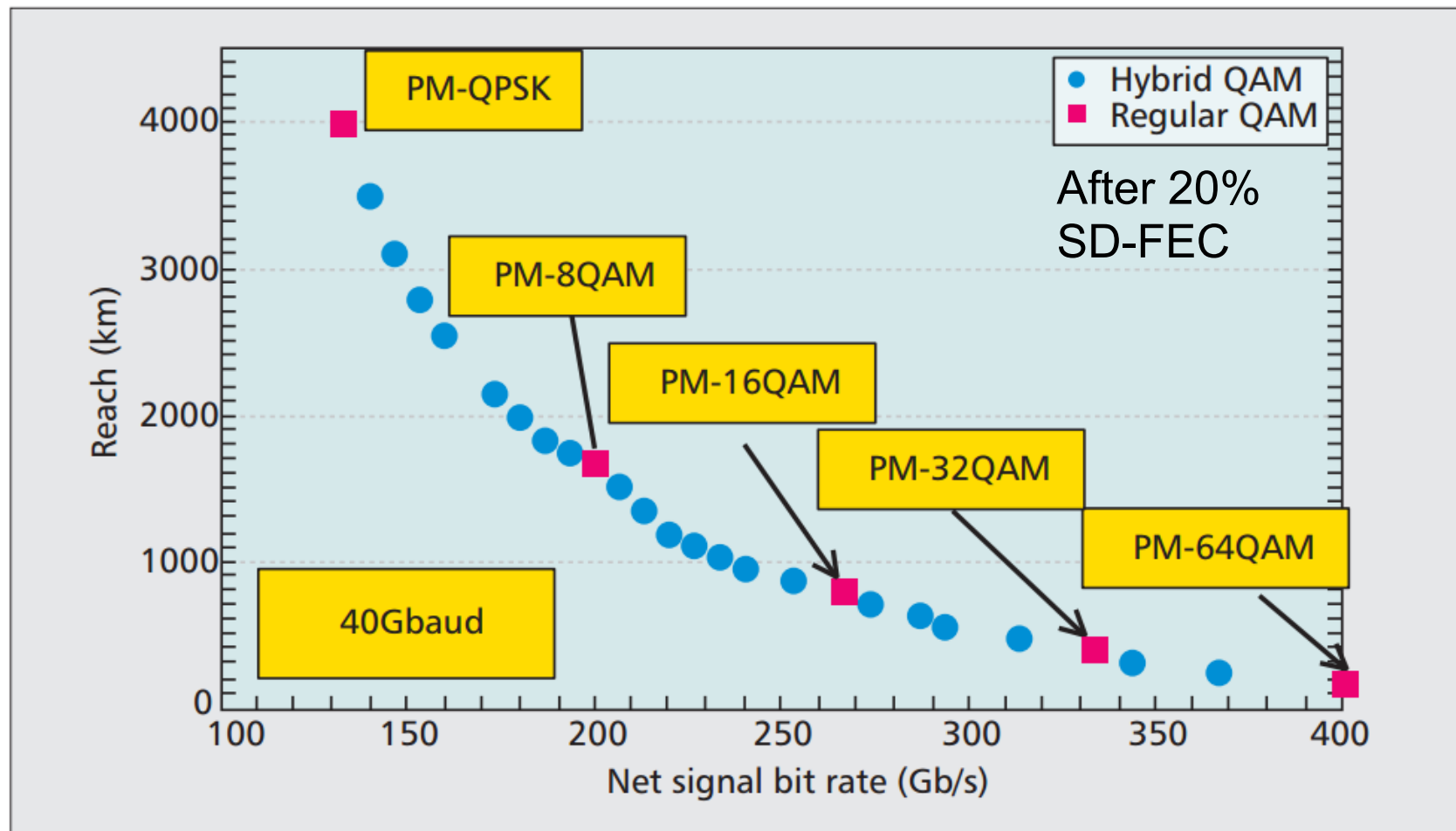
- *Frequency domain*: elastic allocation of spectrum, in terms of subcarriers
- *Modulation format*: control the modulation format of the subcarriers through DSP: single bit per symbol binary phase-shift keying (BPSK), QPSK (2 bits per symbol), 8QAM (3 bits per symbol), etc.



M. Jinno, et. al., "Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network" IEEE Commun. Mag., 2010.



# Spectral density: Reach vs. capacity



Note: typical commercial reach at 100 Gb/s (PDM-QPSK, 12% FEC) is 2500 km. Zhou et al., IEEE Comm. Mag., 2013.

# ILP formulation

## Inputs:

$\Lambda$	Traffic matrix that includes the requested demands, where $\Lambda_{s,d}$ corresponds to the demand $(s,d)$
$P_{s,d}$	Set of alternative paths for demand $(s,d)$
$Q_{s,d}$	Set of non-dominated path-tuple pairs for demand $(s,d)$ assuming a translucent network setting
$C_{p,t}$	Cost of transponders required to serve demand $(s,d)$ using path $p \in P_{s,d}$ and tuple $t \in T$ , that is, using path-tuple pair $(p,t)$
$W_{p,t}$	Number of connections required to serve demand $(s,d)$ using path $p \in P_{s,d}$ and tuple $t \in T$ , that is, using path-tuple pair $(p,t)$
$b_{p,t,i}$	Number of spectrum slots required for data transmission without guardband for flexgrid lightpath $(p,t,i)$ [lightpath $i \in \{1,2,\dots,W_{p,t}\}$ of path-tuple pair $(p,t)$ ]. In particular, if $W_{p,t}=1$ then $b_{p,t,i}=b_i$ , and if $W_{p,t}>1$ then $b_{p,t,i}=b_i$ for $i \in \{1,2,\dots,W_{p,t}-1\}$ and $b_{p,t,i}=b_{i+1}$ for $i=W_{p,t}$ .
$g_{p,t,i}$	Number of guardband spectrum slots required for the data transmission for flexgrid lightpath $(p,t,i)$ . In particular, if $W_{p,t}=1$ then $g_{p,t,i}=g_i$ , and if $W_{p,t}>1$ then $g_{p,t,i}=g_i$ for $i \in \{1,2,\dots,W_{p,t}-1\}$ and $g_{p,t,i}=g_{i+1}$ for $i=W_{p,t}$ .
$F_{total}$	Upper bound on the number of spectrum slots required for serving all connections set to $F_{total} = \sum_{(s,d) \in Q_{sd}} \max_{(p,t) \in Q_{sd}} (S_{p,t})$
$W$	Objective weighting coefficient, taking values between 0 and 1. Setting $w=0$ (or $w=1$ ) minimizes solely the cost of transponders used (or the total spectrum used, respectively).

## Variables:

$x_{p,t}$	Boolean variable, equal to 1 if path-tuple pair $(p,t) \in Q_{s,d}$ is used to serve demand $(s,d)$ and equal to 0 otherwise.
$f_{p,m,t,i}$	Integer variable that denotes the starting spectrum slot for flexgrid transparent lightpath $(p,m,t,i)$ [lightpath over sub-path $m \in R_{p,t}$ of translucent connection $i \in \{1,2,\dots,W_{p,t}\}$ of path-tuple pair $(p,t)$ ]. If path-tuple pair $(p,t)$ is not utilized to serve $(s,d)$ then variable $f_{p,m,t,i}$ is free and does not play a role in the solution. Note that $f_{p,m,t,i} < F_{total}$ .
$\delta_{p,m,t,i,p',m',t',i'}$	Boolean variable that equals 0 if the starting frequency $f_{p,m,t,i}$ for flexgrid transparent lightpath $(p,m,t,i)$ is smaller than the starting frequency $f_{p',m',t',i'}$ for flexgrid lightpath $(p',m',t',i')$ , i.e., $f_{p,m,t,i} < f_{p',m',t',i'}$ . Variable $\delta_{p,m,t,i,p',m',t',i'}$ is defined only if sub-paths $m \in R_{p,t}$ and $m' \in R_{p',t'}$ share a common link.
$S$	Highest spectrum slot used.
$C$	Cost of utilized transponders.

$$\text{minimize } w \cdot S + (1-w) \cdot C$$

### Cost function definition:

For all  $(s,d)$  pairs, all  $(p,t) \in Q_{s,d}$ , all  $i \in \{1,2,\dots,W_{p,t}\}$ , and all  $m \in R_{p,t}$ ,

$$S \geq f_{p,m,t,i} + b_{p,t,i}.$$

$$C = \sum_{sd} \sum_{(p,t) \in Q_{sd}} C_{p,t} \cdot x_{p,t}.$$

### Path-tuple pair selection:

For all  $(s,d)$  pairs,  $\sum_{(p,t) \in Q_{sd}} x_{p,t} = 1$ .

### Starting frequencies ordering constraints:

For all  $(s,d)$  pairs, all  $(p,t) \in Q_{s,d}$ , all  $m \in R_{p,t}$ , all  $i \in \{1,2,\dots,W_{p,t}\}$ , all  $(s',d')$ , all  $(p',t') \in Q_{s',d'}$ , all  $m' \in R_{p',t'}$  where  $m$  and  $m'$  share at least one common link, and all  $i' \in \{1,2,\dots,W_{p',t'}\}$ ,

$$\delta_{p,m,t,i,p',m',t',i'} + \delta_{p',m',t',i',p,m,t,i} = 1,$$

$$f_{p',m',t',i'} - f_{p,m,t,i} \leq F_{total} \cdot \delta_{p,m,t,i,p',m',t',i'},$$

$$f_{p,m,t,i} - f_{p',m',t',i'} \leq F_{total} \cdot \delta_{p',m',t',i',p,m,t,i}.$$

### Non-overlapping spectrum constraints:

For all  $(s,d)$  pairs, all  $(p,t) \in Q_{s,d}$ , all  $m \in R_{p,t}$ , all  $i \in \{1,2,\dots,W_{p,t}\}$ , all  $(s',d')$ , all  $(p',t') \in Q_{s',d'}$ , all  $m' \in R_{p',t'}$  where  $m$  and  $m'$  share at least one common link, and all  $i' \in \{1,2,\dots,W_{p',t'}\}$

$$f_{p,m,t,i} - (b_{p,t,i} + \max(g_{p,t,i}, g_{p',t',i'})) - f_{p',m',t',i'} \leq$$

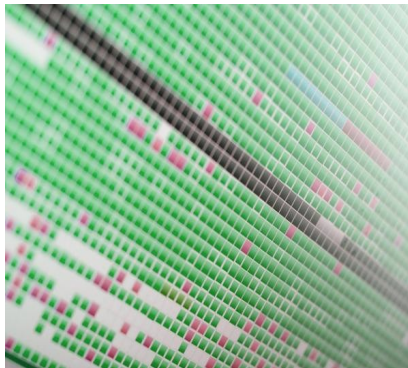
$$(F_{total} + \max(g_{p,t,i}, g_{p',t',i'})) (1 - \delta_{p,m,t,i,p',m',t',i'} + 2 - x_{p,t} - x_{p',t'})$$

$$f_{p',m',t',i'} - (b_{p',t',i'} + \max(g_{p,t,i}, g_{p',t',i'})) - f_{p,m,t,i} \leq$$

$$(F_{total} + \max(g_{p,t,i}, g_{p',t',i'})) (1 - \delta_{p',m',t',i',p,m,t,i} + 2 - x_{p',t'} - x_{p,t})$$

# Flexgrid network evolution

- Flexgrid: finer granularity and more flexibility (when compared to WDM that have wavelength-level granularity, non-tunable transmissions)
- Flexgrid network evolution differs from WDM
  - Traffic variation can be accommodated at different levels
    - new connection requests
    - traffic variation of established connections, served by tuning the TxRx
  - Re-optimization: spectrum fragmentation (more severe in flexgrid)

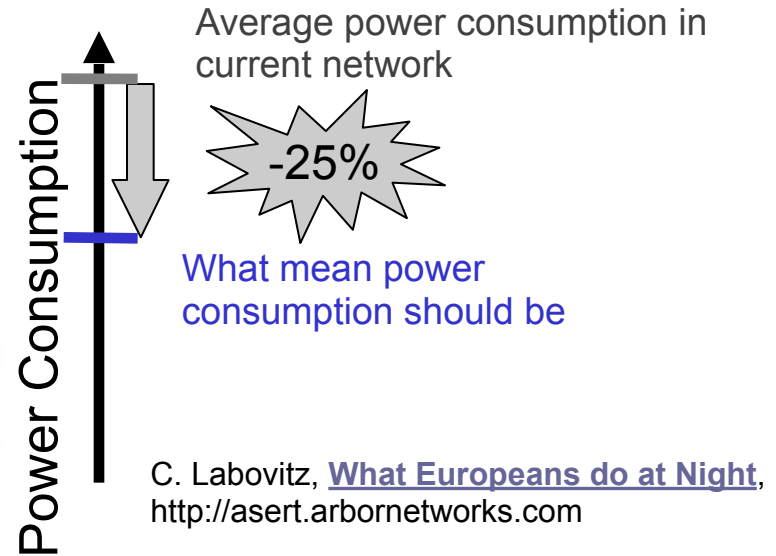
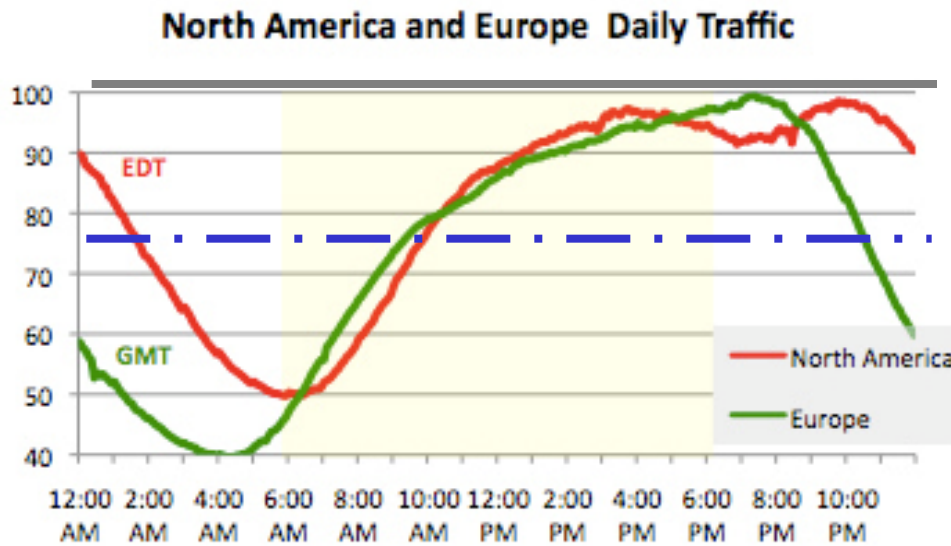


Hard disc  
defragmentation

# Benefit: Energy

Nowadays, 7-8% of the world energy consumption is due to ICT

- Internet represents ~25% of this amount



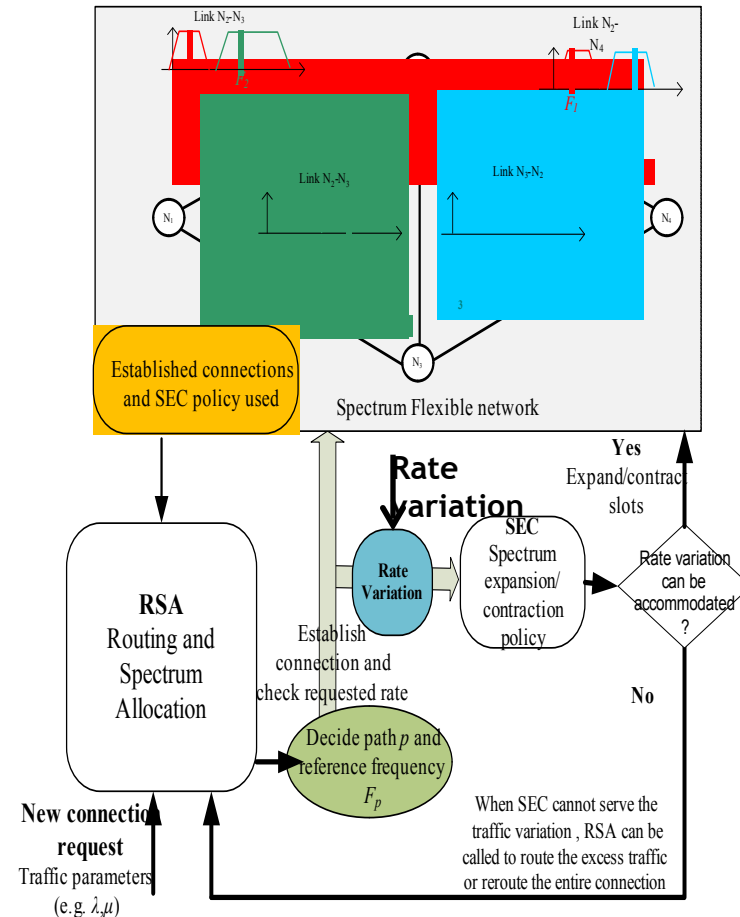
Today, the network is designed and works all the time for the **peak** requested traffic.

If the power consumption of optical transport was **proportional** to the requested capacity, **in average** core networks would consume **25% less** than current networks.

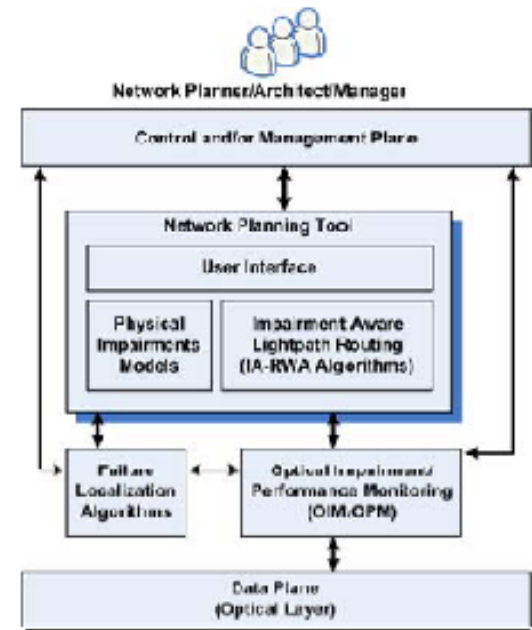
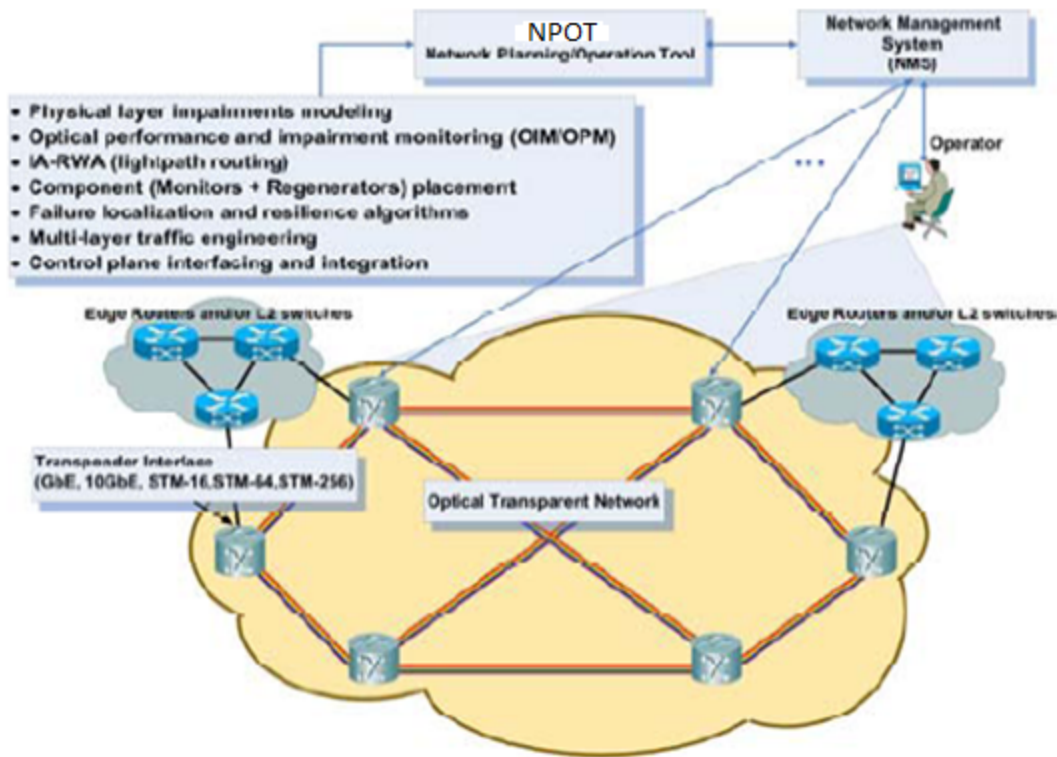
# Flexgrid network evolution

Traffic variations can be accommodated at different levels

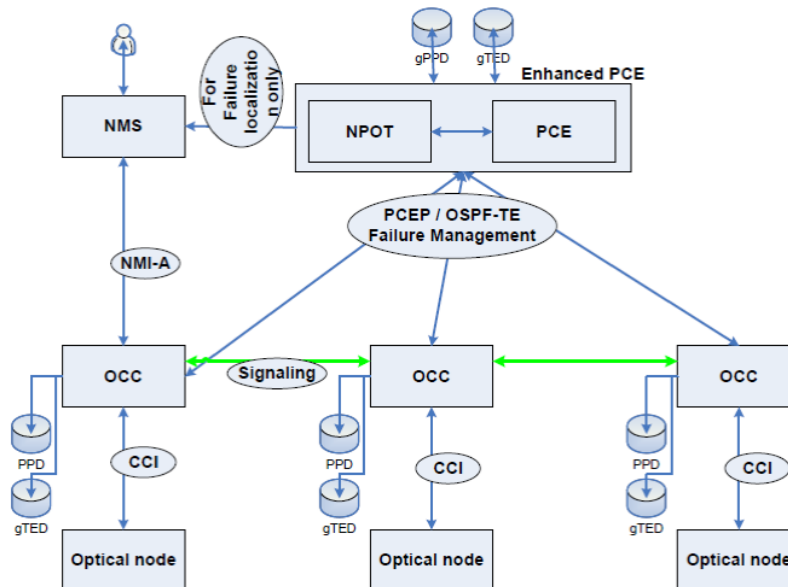
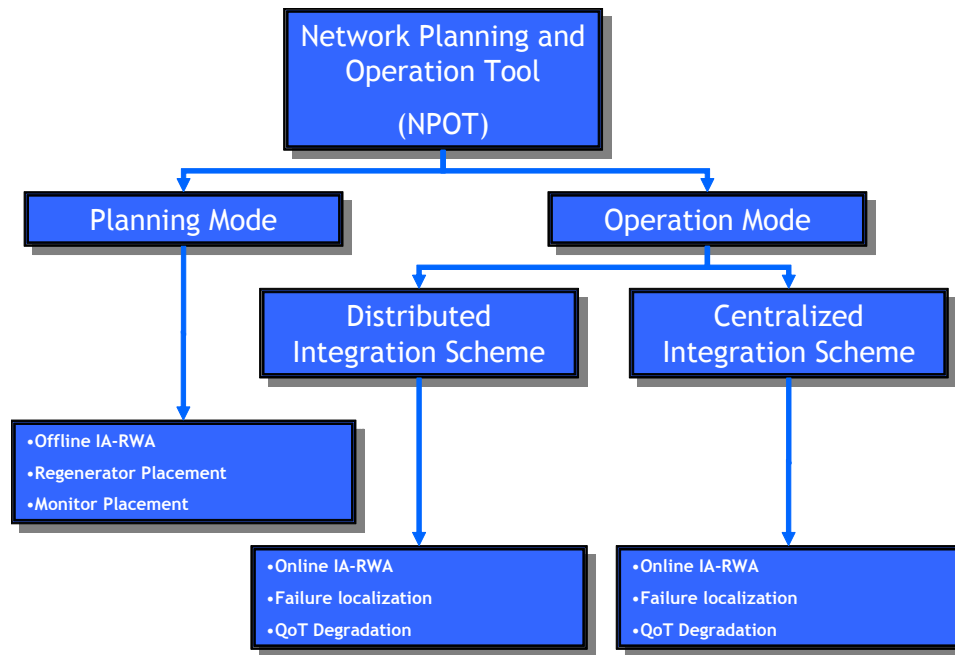
- ▶ **1<sup>st</sup> level:** New connection request
  - ▶ RSA also serves the request (assign path and reference frequency)
- ▶ **2<sup>nd</sup> level:** traffic variation of existing connection
  - ▶ Spectrum Expansion/Contraction (SEC)
  - ▶ If the SEC fails (cannot find free additional slots) → trigger RSA to setup an additional connection or reroute the existing



# The “whole” picture

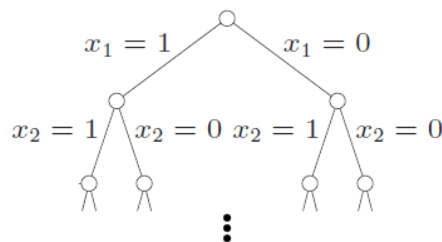
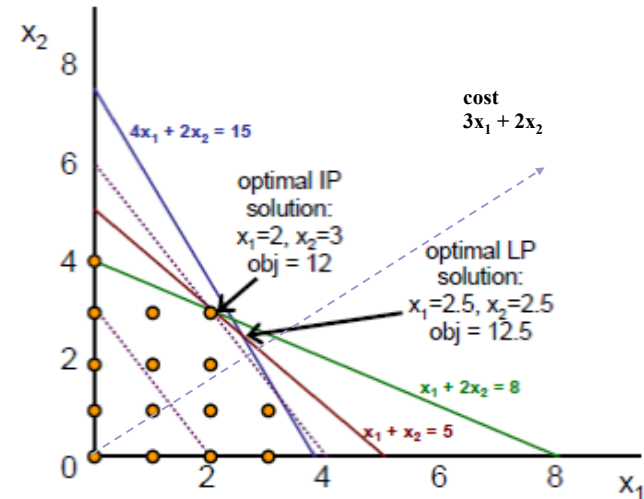


# Control

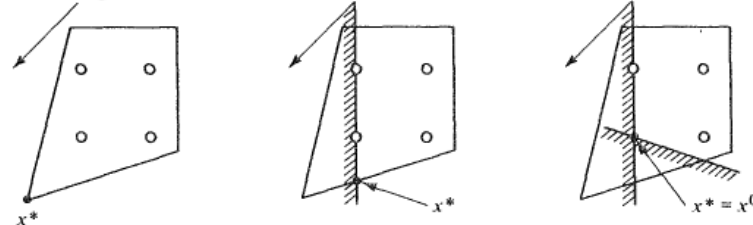


# Integer Linear Programming (ILP)

- Integer variables  $\mathbf{x}$ 
  - minimize  $c^T \cdot \mathbf{x}$
  - subject to  $A \cdot \mathbf{x} \leq b, \mathbf{x} = (x_1, \dots, x_n) \in \mathbb{Z}^n$
- The general ILP problem is NP-complete
- Algorithms
  - Solve small-medium size ILP problems
  - Branch-and-bound
  - Cutting plane
- Mixed Integer Linear Programming (MILP): integer and float variables



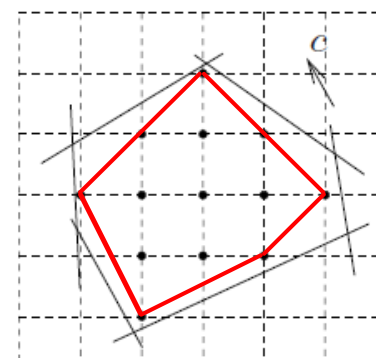
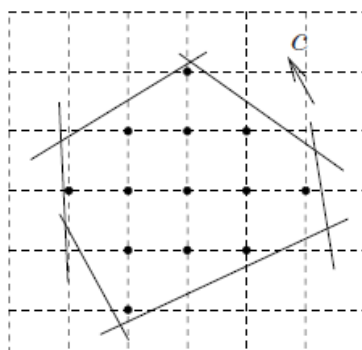
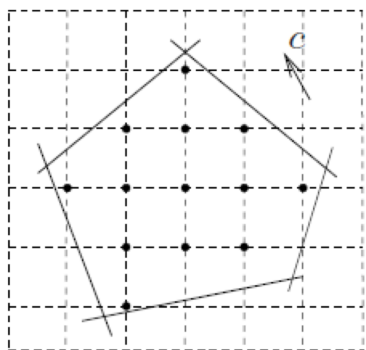
Decreasing cost





# Convex Hull

- The same set of integer solutions can be described by different sets of constraints (the same set of integer solutions can be included in different-shaped  $n$ -dimensional polyhedrons)
- The *convex hull* is the minimum convex set that includes all the integer solutions of the problem
- Given the convex hull we can use a LP algorithm to obtain the optimal ILP solution in polynomial time
- The transformation of a general  $n$ -dimension polyhedron to the corresponding convex hull is difficult (process used in cutting plane techniques)
- *Good ILP formulation*: the feasible region defined by the linear constraints is close (tight) to the corresponding convex hull
  - A large number of vertices consist of integer variables. This increases the probability of obtaining an integer solution when solving the corresponding LP-relaxation of the initial ILP problem



# LP Formulation and Flow Cost Function

## Parameters:

- $s, d \in V$ : network nodes
- $w \in C$ : an available wavelength
- $l \in E$ : a network link
- $p \in P_{sd}$ : a candidate path

## Constant:

- $\Lambda_{sd}$ : the number of requested connections from node  $s$  to  $d$

## Variables:

- $x_{pw}$ : an indicator variable, equal to 1 if path  $p$  occupies wavelength  $w$ , else 0
- $F_l$ : the flow cost function value of link  $l$

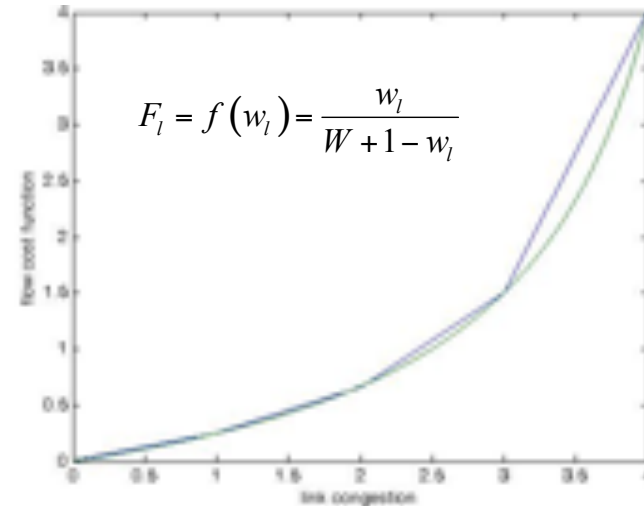
## RWA LP FORMULATION

$$\text{minimize : } \sum_l F_l$$

subject to the following constraints:

- Distinct wavelength assignment constraints,
 
$$\sum_{\{p|l \in p\}} x_{pw} \leq 1, \text{ for all } l \in E, \text{ for all } w \in C$$
- Incoming traffic constraints,
 
$$\sum_{p \in P_{sd}} \sum_w x_{pw} = \Lambda_{sd}, \text{ for all } (s, d) \text{ pairs}$$
- Flow cost function constraints,
 
$$F_l \geq f(w_l) = f\left(\sum_{\{p|l \in p\}} \sum_w x_{pw}\right)$$
- The integrality constraint is relaxed to
 
$$0 \leq x_{pw} \leq 1.$$

## Flow Cost Function

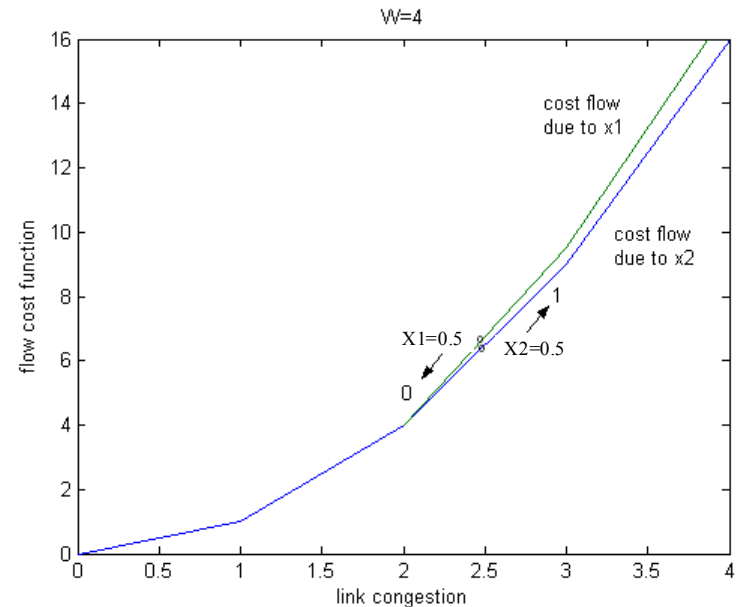


- Increasing and Convex (to imply a greater amount of 'undesirability' when a link becomes congested)
- Approximated by a piecewise linear function
- Integer break points (makes Simplex yield integer optimal solutions with high probability)

We obtain integer solutions in 98% of the problem instances!

# Random perturbation

- In the general multicommodity problem, a flow that is served by more than one paths has equal sum of first derivatives over the links of those paths
- In our problem a request that is served by more than one lightpaths has equal sums of first derivatives over the links of these paths
- To avoid such cases, we multiply the slopes of each variable on each link with a random number that is close to 1
- In this way, the cases that two variables have equal derivatives over the links that comprise a path are reduced, and thus we obtain more integer solutions



# Handling non-integer solutions

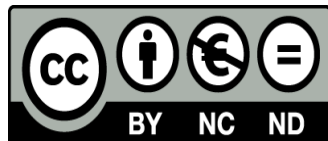
- Make Simplex yield integer optimal solutions
  - Piecewise linear cost functions
  - Random perturbation technique
- Still the solution may be non-integer
- Iterative fixings
  - Fix the integer variables of the solutions and solve the remaining (reduced) LP problem
  - The objective cost does not change → if we get to an integer solution it is optimal
  - When fixing does not further increase the integrality, we proceed to the rounding process
- Iterative rounding
  - Round a single variable, the one closest to 1, and continue solving the reduced LP problem
  - Rounding helps us move to a higher objective and search for an integer solution there
  - If the objective changes we are not sure anymore that we will find an optimal solution

# Meta-heuristics

- Iteratively try to improve a candidate solution with regards to a given metric
- Do not guarantee to find an optimal, as opposed to exact methods (like ILP)
- A meta-heuristic typically defines:
  - The representation or encoding of a solution
  - The cost function
  - Iterative procedure
- Meta-heuristic types
  - Local search: iteratively make small changes to a single solution
  - Constructive: construct solutions from their constituting parts
  - Population-based: iteratively combine solutions into new ones

However, these classes are not mutually exclusive and many algos combine them
- Popular meta-heuristics: Genetic/evolutionary algorithms, ant colony optimization, simulated annealing

# Τέλος Ενότητας



# Σημείωμα Ιστορικού Εκδόσεων Έργου

Το παρόν έργο αποτελεί την έκδοση 1.0.

# Σημείωμα Αναφοράς

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Διαθέσιμο από τη δικτυακή διεύθυνση:

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