The Capacity Crunch:
Avoidance, Adaptation and Reform

Helio Waldman

Outline

- The Impending Crunch
- Avoidance
  - Elastic Optical Networks (EON)
    - Multiclass traffic
    - Distance adaptiveness
  - Next Infrastructure: Space Division Multiplexing (SDM) Networks
- Adaptation for EON's
  - Fairness versus Efficiency
  - Squeezed Protection
- Reform
  - Energy Bottleneck
- Conclusions

Introduction and Motivation

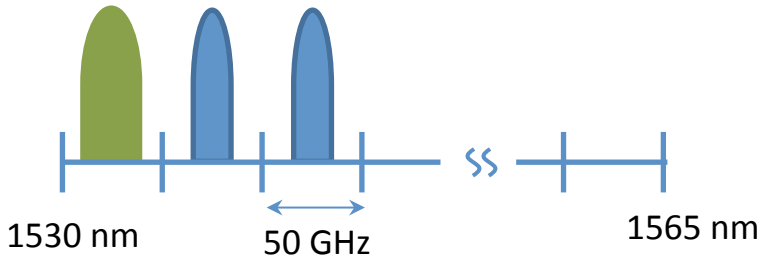
- Y2K: overprovision of capacity (spectral occupation < 1%)
  - Internet traffic becomes dominant
  - Internet traffic growth: 50-100%/year = x165-1000/decade

- As the capacity of installed fibers approaches saturation under the WDM paradigm, there is a need to improve the spectral efficiency (bps/Hz) of the spectrum usage

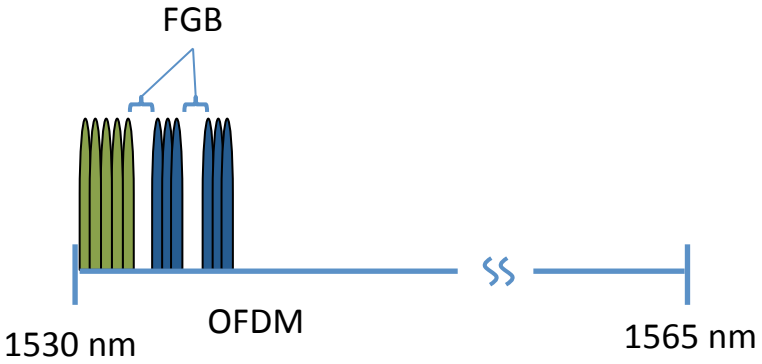
- Elastic Optical Networks (EON's) respond to this need, but are likely to be the last bandwidth mining technology on the current physical plant.

A Brief View about
Elastic Optical Network

- A Highly efficient spectrum allocation scheme:
  - Client requests only the spectral resources that he/she needs
  - Distance-adaptive modulation schemes provide as many bps/Hz as possible to enhance spectral efficiency while preserving noise immunity



Conventional WDM network

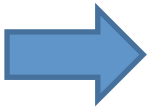


Elastic Optical Network (EON)

Flexible/Tight Resource Assignment

- Lightpath bandwidth is flexible and can provide both a finer and coarser granularity when compared to that of current WDM optical path networks

Routing and Wavelength Assignment (RWA)



Routing and Spectrum Assignment (RSA)

- Our research is currently focused on the RSA problem.

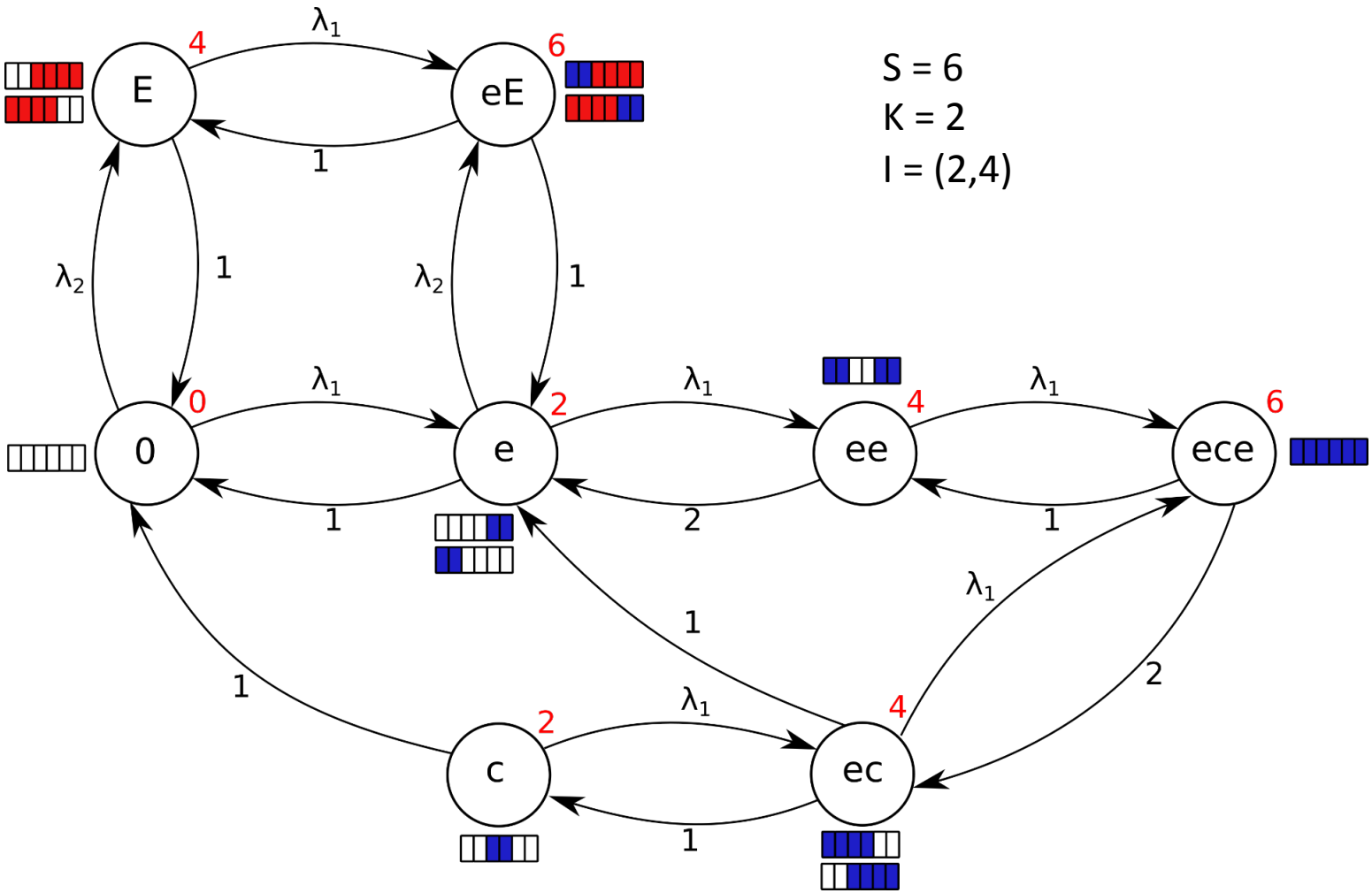
Multiclass Traffic over EON's

- Spectrum is assigned in integer number of **contiguous** frequency slots (OFDM, NFDM)
- One frequency slot = 12.5 GHz
- EDFA gain bandwidth = 4 THz = 320 slots
- Main service typical requirements:
  - 4 slots for 100 Gbps
  - 9 slots for 400 Gbps
  - 23 slots for 1 Tbps
- Distance Adaptive: (bitrate,distance)----> #slots

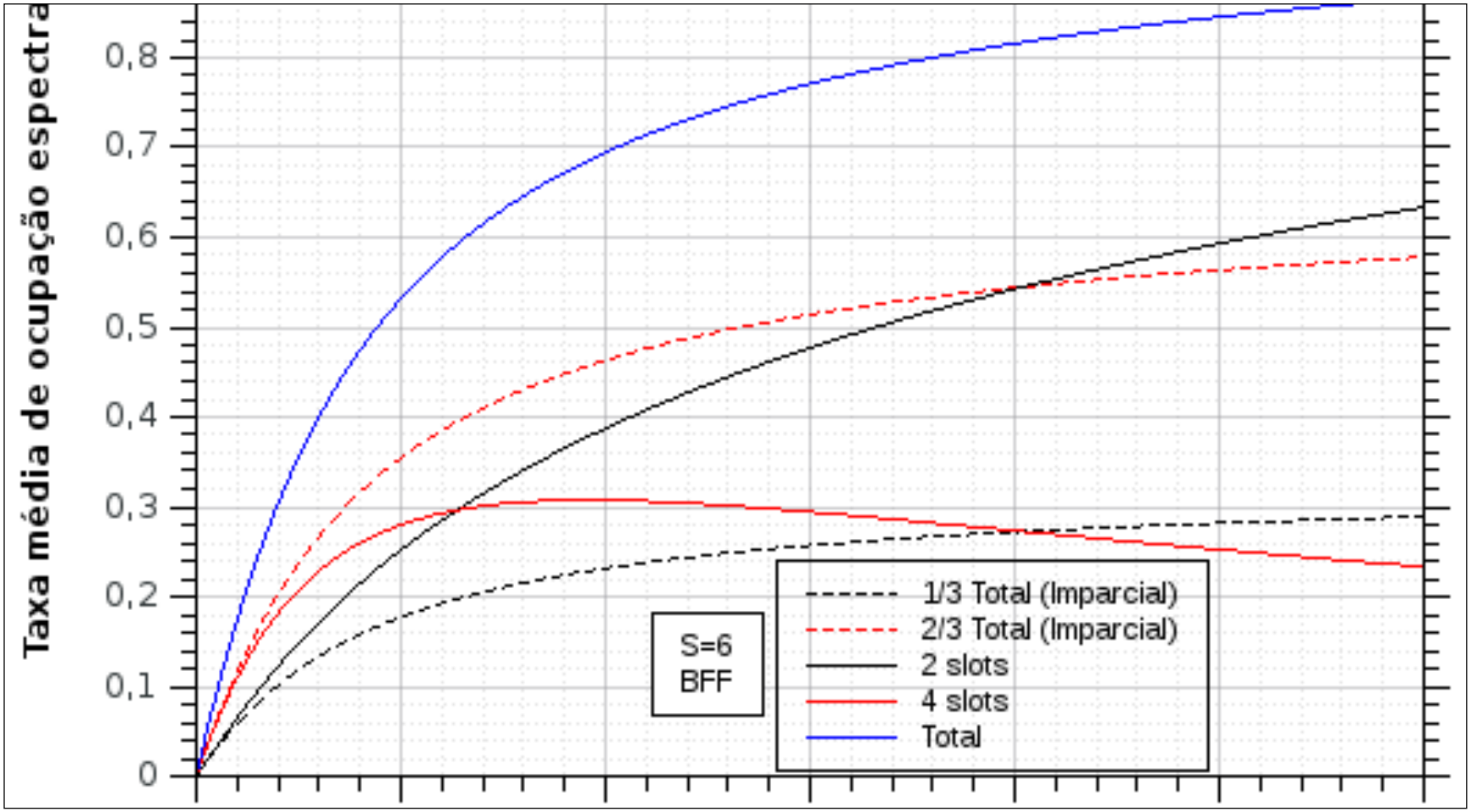
Fragmentation Losses

Single Link (vertical)		Multi-link (horizontal)	
WDM	EON	WDM	EON
No Fragmentation Losses	Vertical Fragmentation Losses	Wavelength Continuity Constraint	Spectrum Continuity (Contiguity) Constraint

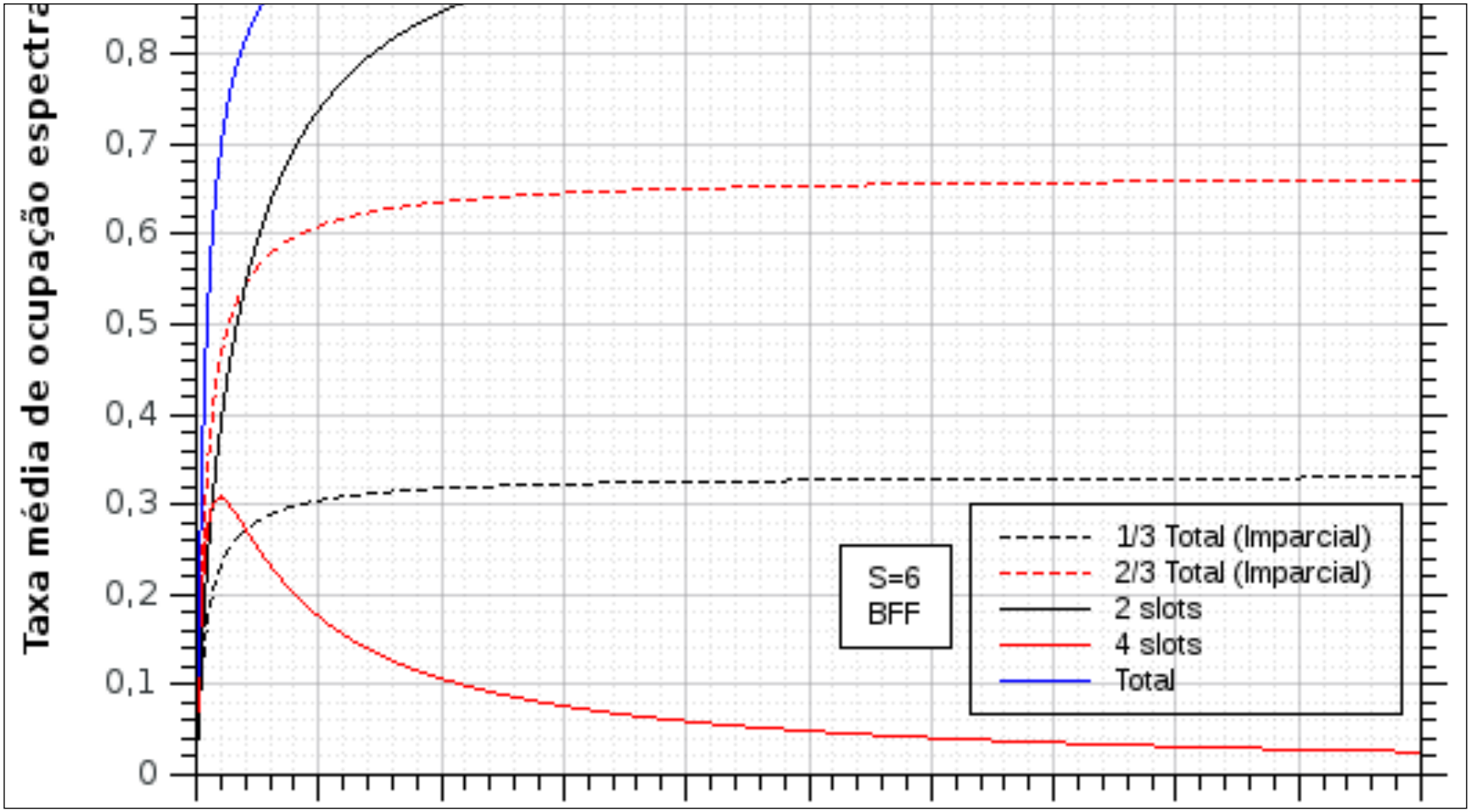
BFF algorithm on a single link



Unfairness among classes



Even worse under congestion

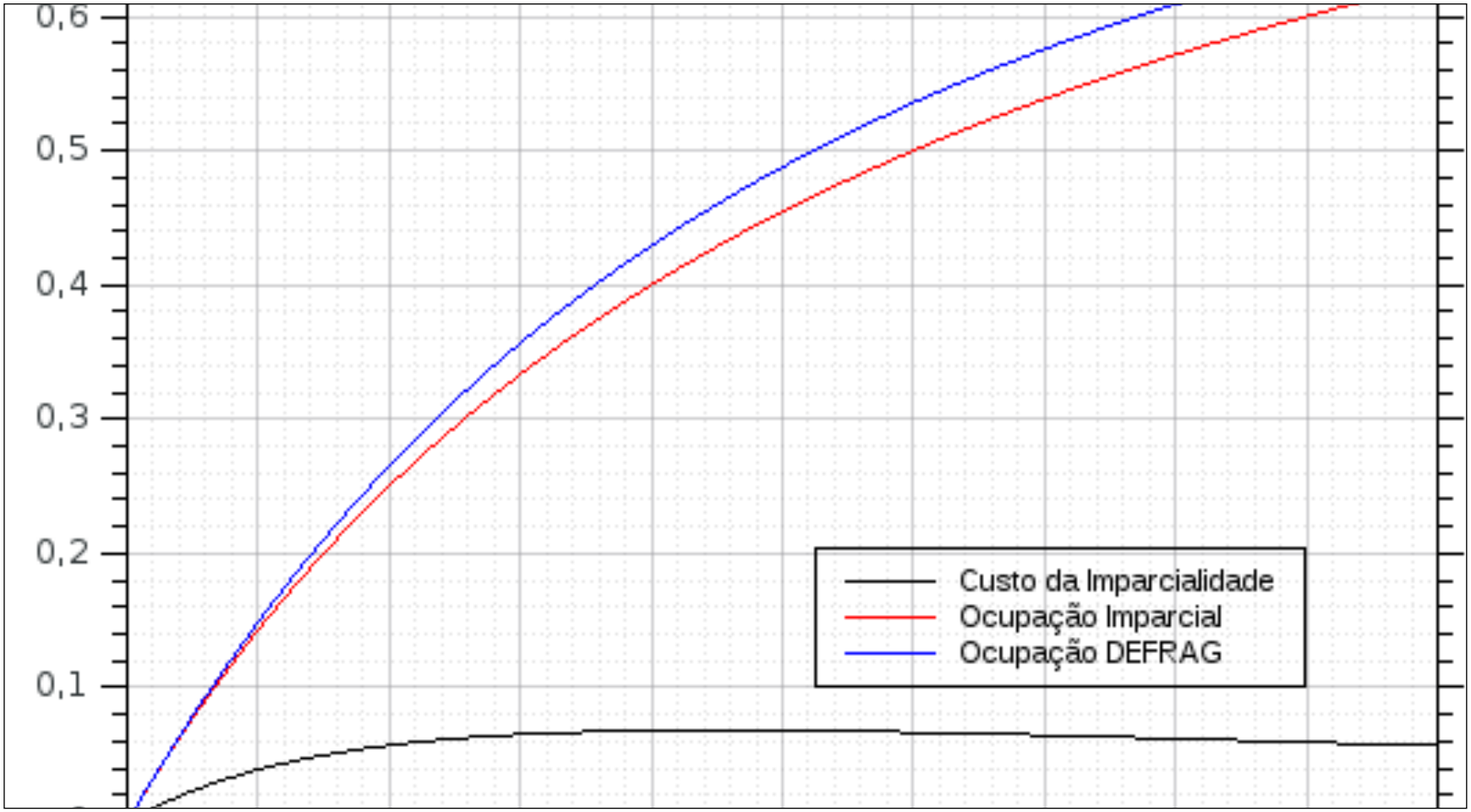


Fair Algorithms

- Spectrum Partitioning
  - Produces perfect fairness only for some traffic profiles, if the algorithm is aware
  - Performance degrades with the number of classes
- Pseudo-partitioning
  - Requires “clustering” if more than two classes.
- Trunk Reservation
  - It is a modifier of any algorithm
  - Produces perfect fairness for any traffic profile.

Defrag versus fair partitioning:

the cost of fairness



Squeezed Protection

- Elastic networking generates an opportunity to split the connection into two or more disjoint paths, thus reducing or eliminating the need for additional protection capacity, at the cost of reduced surviving capacity and enhanced guardband overhead.
- This may be an evolutionary step towards elastic service to an **elastic traffic** in the future.

Next Infrastructure

- When EON's have exhausted the capacity of current single-mode fibers, a new generation of multimode fibers must be deployed to accommodate the ever expanding Internet.
- Few-mode fibers (FMF)
- Multi-core Fibers (MCF)
- Space-Division Multiplexing (SDM)
  - Signal-processing intensive.

Energy Bottleneck

- This will be the ultimate crunch in the physical layer.
- Best effort services may face the risk of preemption in a competitive environment
- It may impact the business and regulatory model of the Internet.
- Current network neutrality debate may be an early symptom of this impending crunch.

Conclusion

- Dealing with impending capacity crunches in the coming decades is bound to demand innovative solutions in technology, business and regulation.