Future Research Ideas on Flexible Network Architectures

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Outline

- Multiband optical line systems
- Spectrally–spatially flexible optical networks
- Spectrum trading in virtual optical networks

Multiband Optical Line Systems: Motivation

Shannon–Hartley theorem: *In an additive white Gaussian noise (AWGN) limited channel, information capacity is linearly proportional to channel bandwidth but logarithmically proportional to signal-to-noise ratio (SNR).*

- $C = B\, log_2(1 + S/N)$
- C = Channel capacity
- B = Bandwidth
- S/N = Signal to noise ratio

Increase capacity by increasing fiber spectrum in fiber than increasing SNR using advanced modulation formats.

Multiband Optical Line Systems

C-band: 1530 nm to 1565 nm
(Conventional) Lowest fiber loss

L-band: 1565 nm to 1625 nm

(Long Band) Low attenuation

Erbium-doped fiber amplifier operating in L-band is widely available.

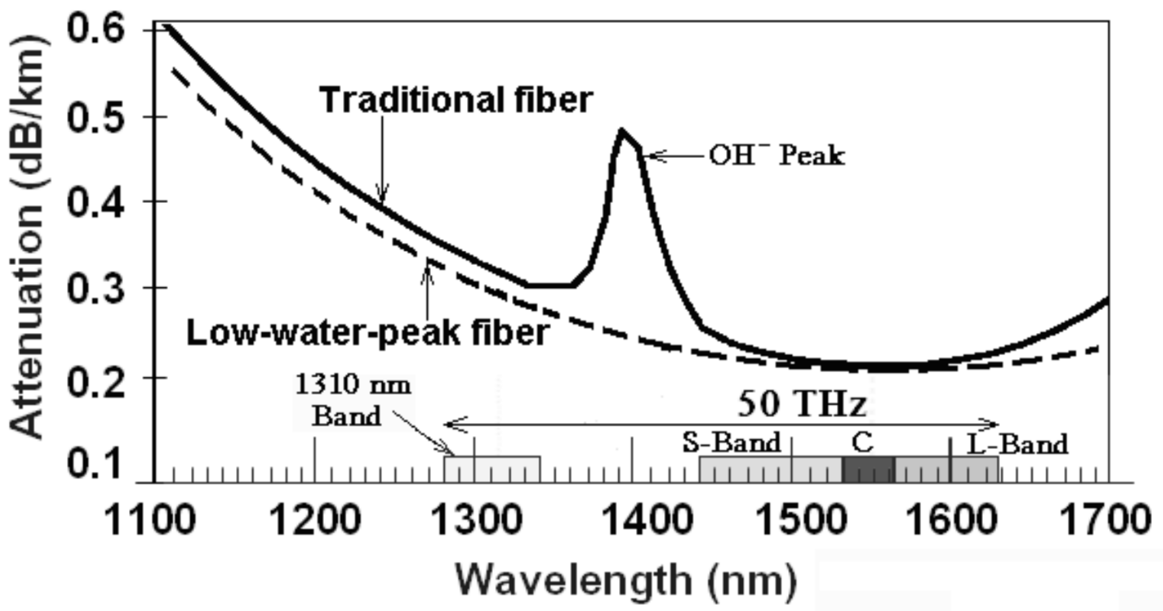


Image courtesy: B. Mukherjee, "Optical WDM networks," *Springer Science & Business Media*, 2006.

Challenges of Using Multiband Transmission

- Attenuation is higher than C band
- Quality-of-transmission estimator (QoT-E)
    1. Amplified spontaneous emission (ASE) noise
    2. Nonlinear impairments caused by nonlinear Kerr effect

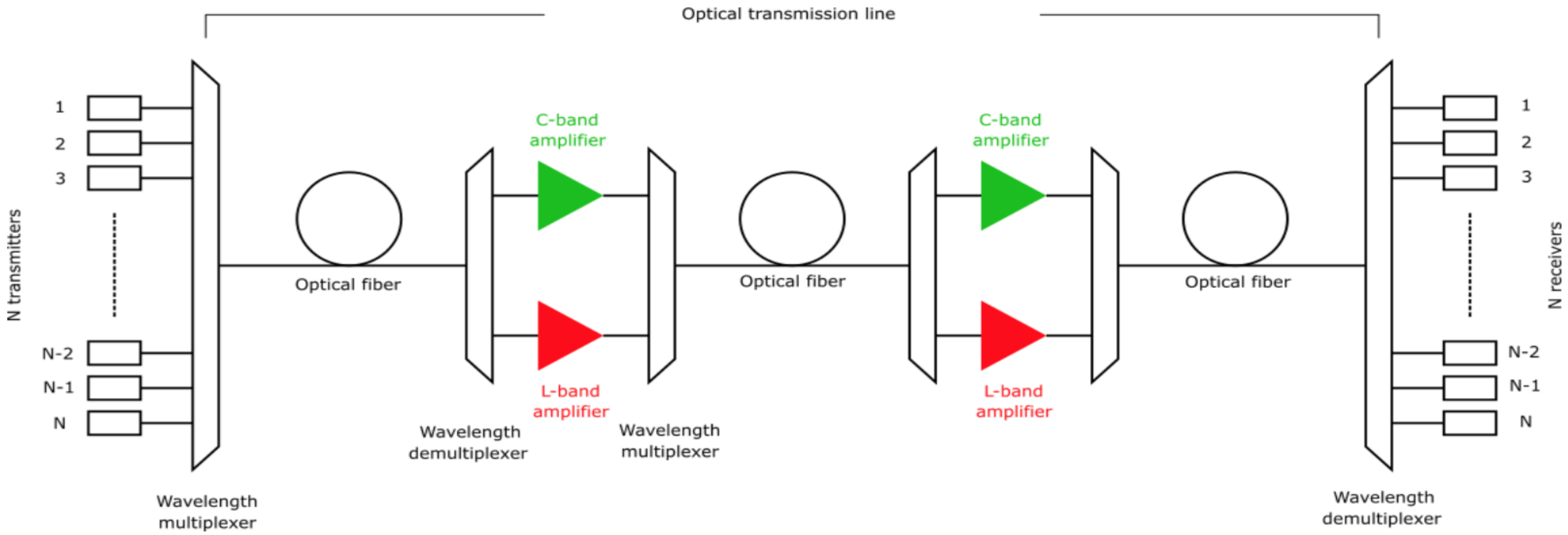
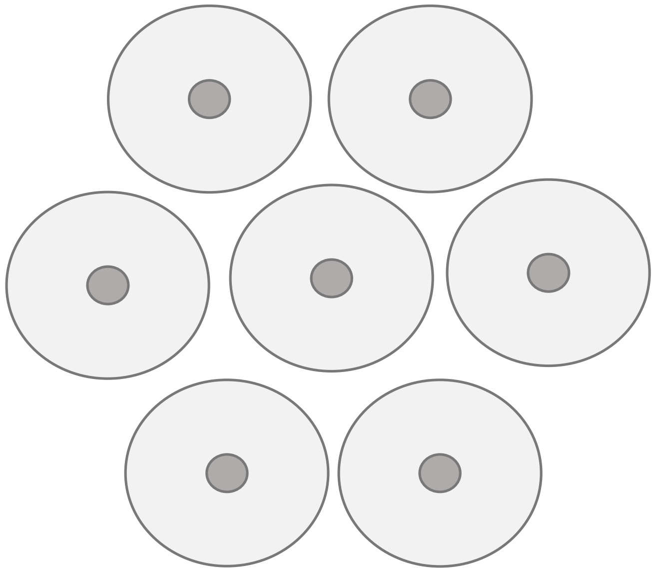
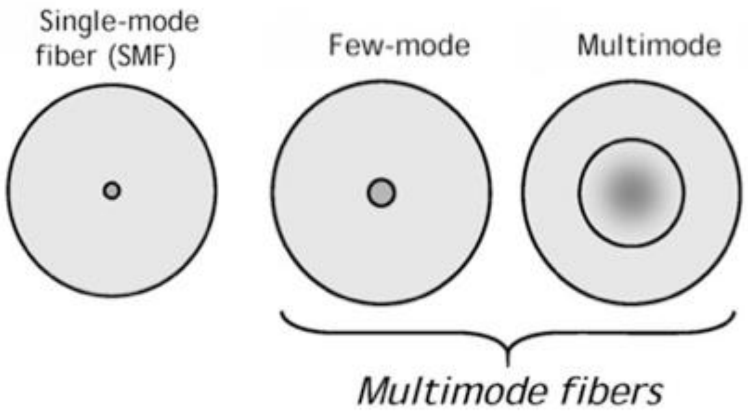


Image courtesy: https://www.fiberlabs.com/glossary/long-wavelength-band/

Spectrally–Spatially Flexible Optical Networks

- Multiple fibers per link
- Multimode fibers
- Multicore fiber

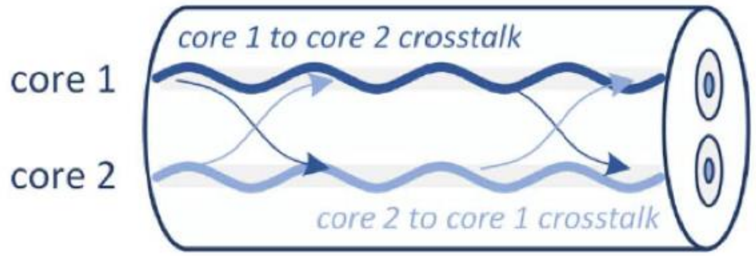


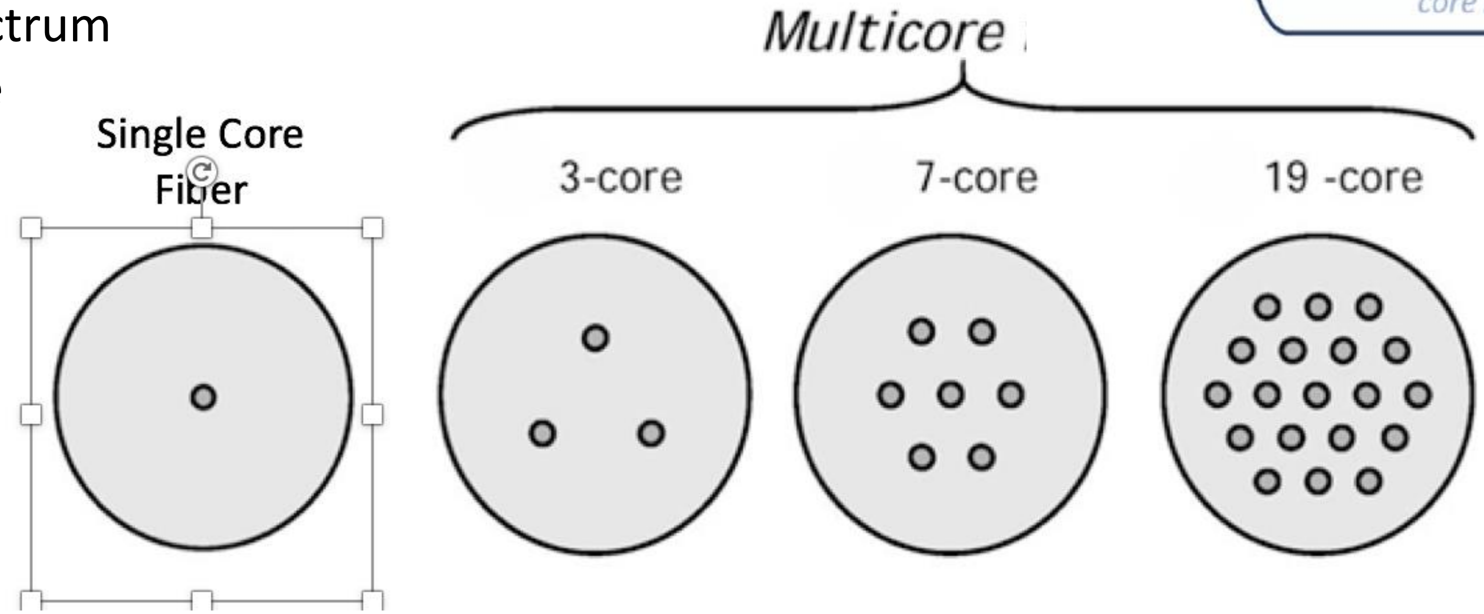


Spectrally–Spatially Flexible Optical Networks

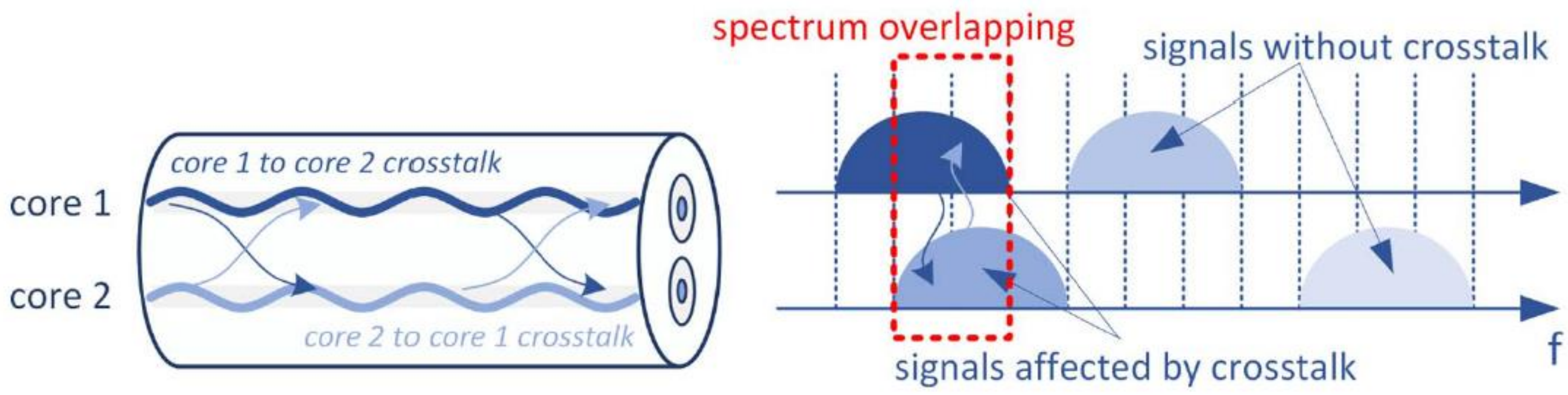
Spectrally-Spatially Flexible Optical Networks (SSFON)

1. Routing
2. Spectrum
3. Core





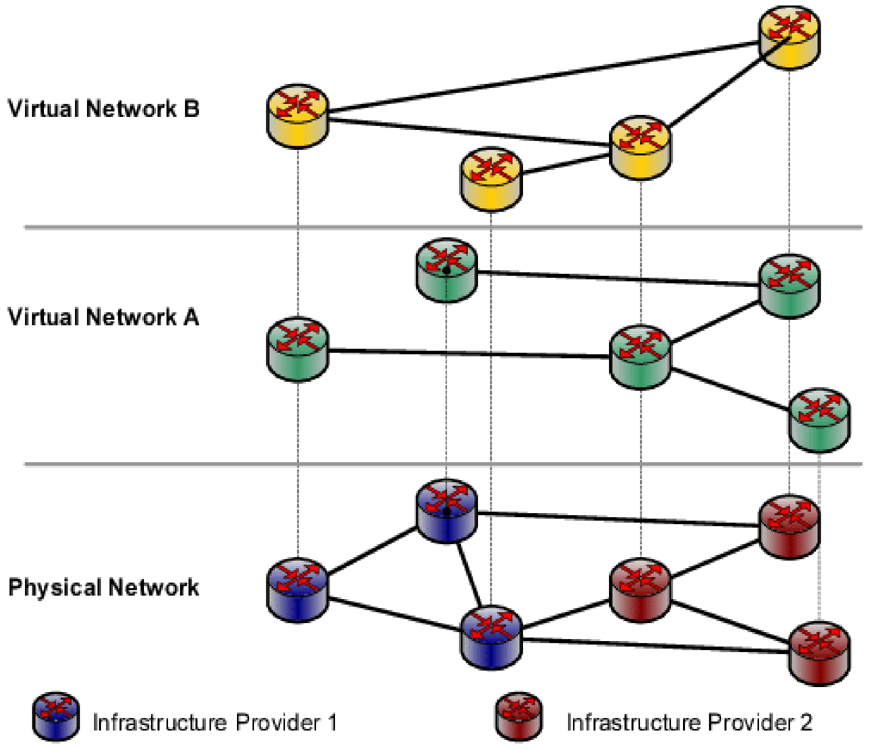
Spectrally–Spatially Flexible Optical Networks



M. Klinkowski and G. Zalewski, “Dynamic Crosstalk-Aware Lightpath Provisioning in Spectrally–Spatially Flexible Optical Networks,” *Journal of Optical Communications and Networking*, vol. 11, no. 5, pp. 213–225, May 2019.

Spectrum Trading: Motivation

- Network virtualization splits capacity of a physical network into multiple independent virtual optical networks (VONs).
- It is embedded with fixed capacity within its contract period.
- Real-time capacity requirements fluctuates.
- Large idle capacity and capacity shortage is observed on virtual links.
- Spectrum trading (ST).
- Capacity is traded based on current capacity needs and returned if situation reverses.



Spectrum Utilization Improved!

S. Ding, X. Fu, B. Jiang, S. K. Bose, and G. Shen, "Spectrum Trading between Virtual Optical Networks Embedded in an Elastic Optical Network," in *Proc. Optical Fiber Communication Conference*, Mar. 2019.

Spectrum Trading between VONs

ST scheme

- Divides lifecycle of VON into time slots.
- Idle capacity (frequency slot (FSs)) trade idle FSs with virtual links that are short of capacity.
- Virtual links share common physical link (s) to be able to trade.
- Positive credit.
- Negative credit.

Example of Spectrum Trading

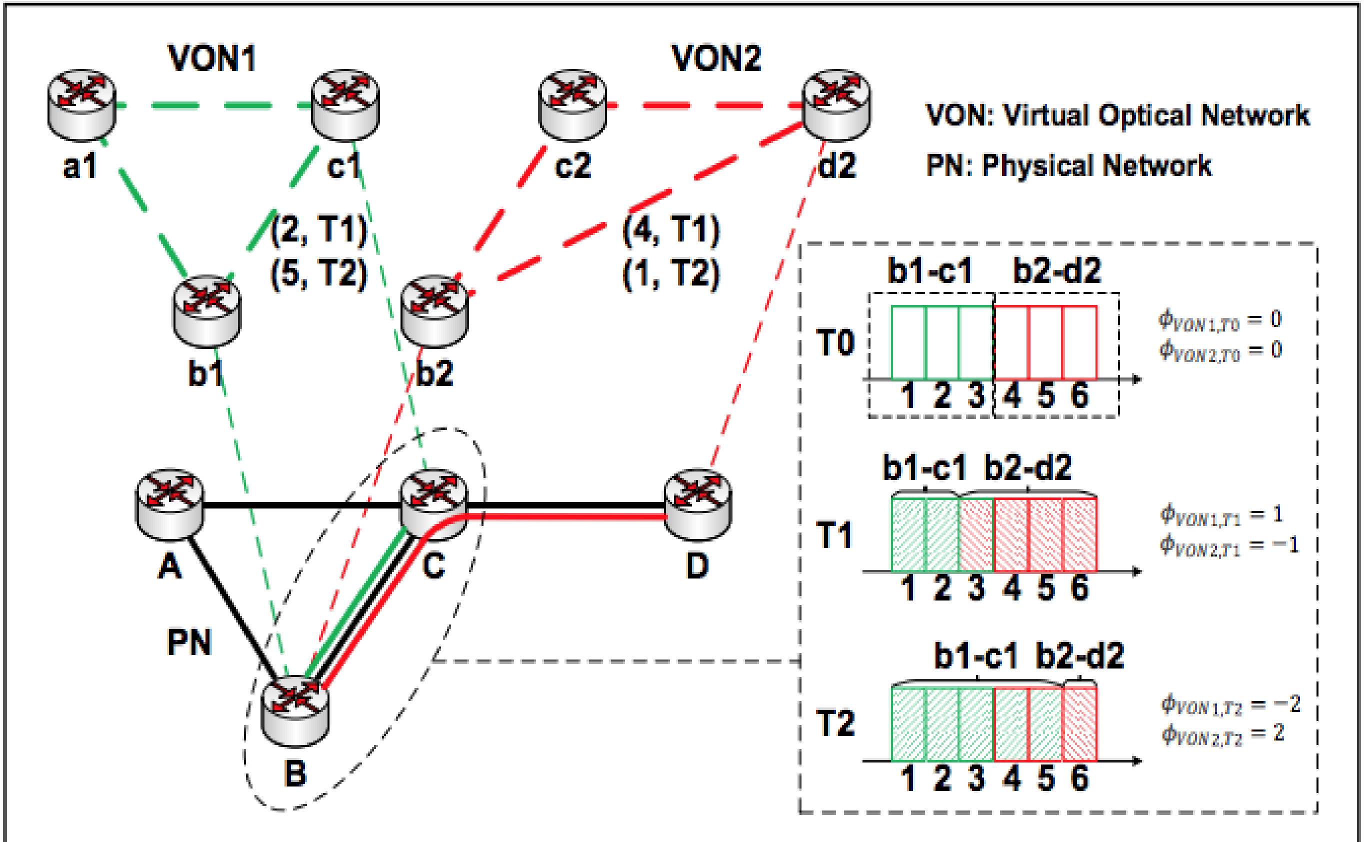


Fig. 1. An example of spectrum trading.

Common shared link is B-C.

At T0, b1-c1 and b2-d2 are assigned to 3 FSs.

At T1, b1-c1 needs 2 FSs & b2-d2 needs 4 FSs.

25% traffic block in b2-d2.

At T2, b1-c1 needs 5 FSs & b2-d2 needs 1 FS.

40% traffic block in b1-c1.

Fairness in Trading

- Cumulative credit parameter is calculated for each VON.
- If cumulative credit parameter < threshold (in time T), stop VON from borrowing any resources.
- This threshold is pre-decided.
- This avoids a selfish client situation which only uses other's resources, without sharing its own.

$$\gamma_{v,T} = \sum_{i=1...T} \phi_{v,i},$$

$$\gamma_{v,T} < \mu$$

Integer Linear Programming Constraints

Objective function: Maximize the amount of traffic demand that can be supported by the VONs in different time slots.

Input:

Physical topology

Set of VONs

Each VON has predefined topology

$C(v, s, d, x, y)$: each virtual links of VONs are assigned to set of FSs

$R(v, s, d, t, Ft)$: bandwidth demand on each virtual link of a VON at different time slots

v = index of VON

s, d = Source, destination

x = Starting of FS index

y = Ending of FS index

t = index of time-slot

F_t = No of FSs required for traffic allocation in t

Integer Linear Programming Constraints

Constraints:

(1) A virtual link uses its own FSs to carry its own traffic demand at the first place.

(2) A virtual link cannot use an FS if it is not owned by any VON.

(3) Number of FSs that a virtual link borrows should not exceed its need.

(4) Spectrum assigned for two virtual links should not overlap if their mapped physical routes share common link (s).

(5) A VON cannot borrow any FS from other VONs in subsequent time slots if its cumulative credit is negative and smaller than threshold μ mentioned earlier.

Heuristic algorithm

Heuristic algorithm for Spectrum Trading
Step 1: Use the capacity assigned to each virtual link of a VON to carry its traffic demand; **Step 2:** Sort all the virtual links in a descending order based on the amounts of traffic demands that cannot be accommodated using their own capacities; the ordered list is denoted as *L*; **Step 3:** Get the first virtual link *l* from *L*; if the cumulative credit of its corresponding VON is not smaller than a preset negative threshold , go to Step 4; otherwise, go to Step 5; **Step 4:** Borrow unused capacity on other virtual links to accommodate the unserved traffic demand of virtual link *l* at the best effort through spectrum trading; update the cumulative credits for all the related VONs in the trading process; **Step 5:** If not all the links in *L* have been considered, then get the next virtual link *l* from *L*, go back to Step 4; otherwise, go to Step 6; **Step 6:** Stop the traffic demand provisioning process and output the results.

Illustrative Results

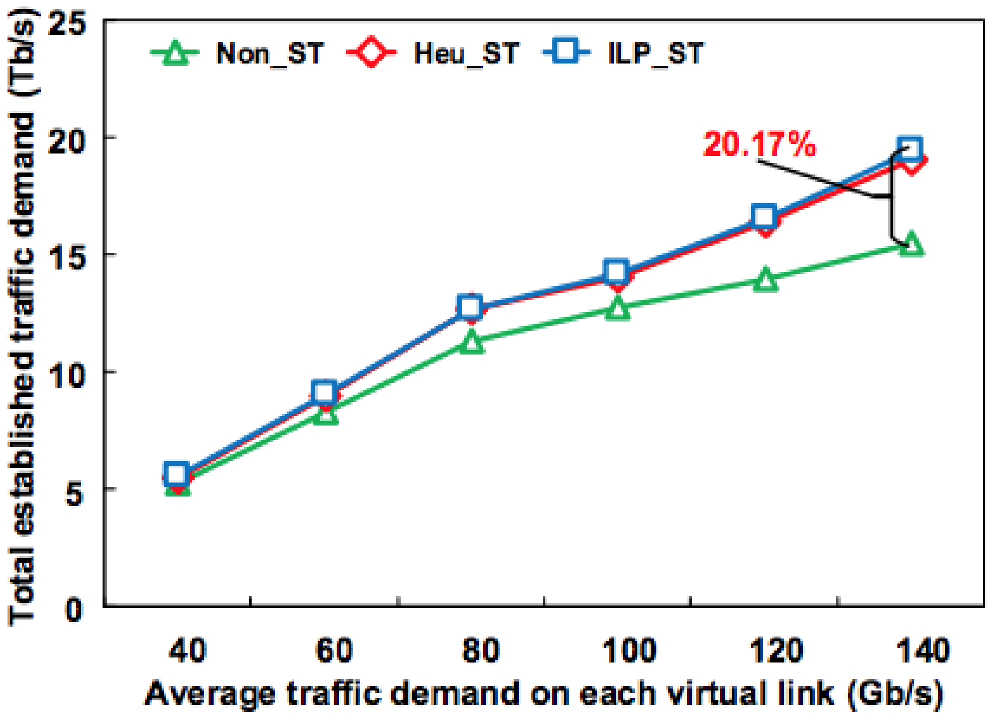


Fig. 3. Results of the n6s8 network.

Non_ST: Without ST
Heu_ST: Heuristic of ST
ILP_ST: ILP of ST

- Larger average traffic demand corresponds to larger fluctuation of actual traffic demand. So ST gets opportunity to improve capacity utilization by trading spectrum between VONs.
- Heuristic is very close to ILP.

Compares amount of overall traffic demand that is actually carried by VONs under different average traffic demands in n6s8 network,

Illustrative Results

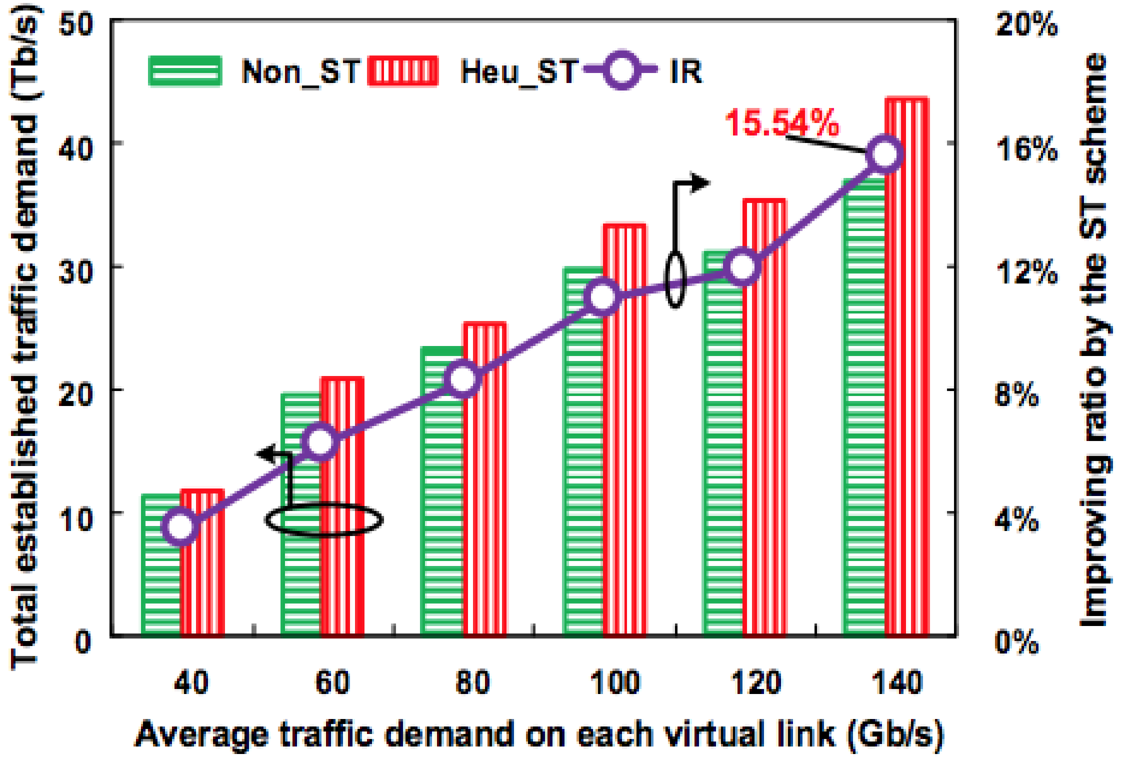


Fig. 4. Results of the NSFNET network.

Non_ST: without ST
Heu_ST: Heuristic of ST
IR: Improvement ratio

Curve of “IR” shows the improvement ratio by ST scheme over without ST. ST scheme performs better with an increasing average traffic demand, by more than 15%.

Illustrative Results

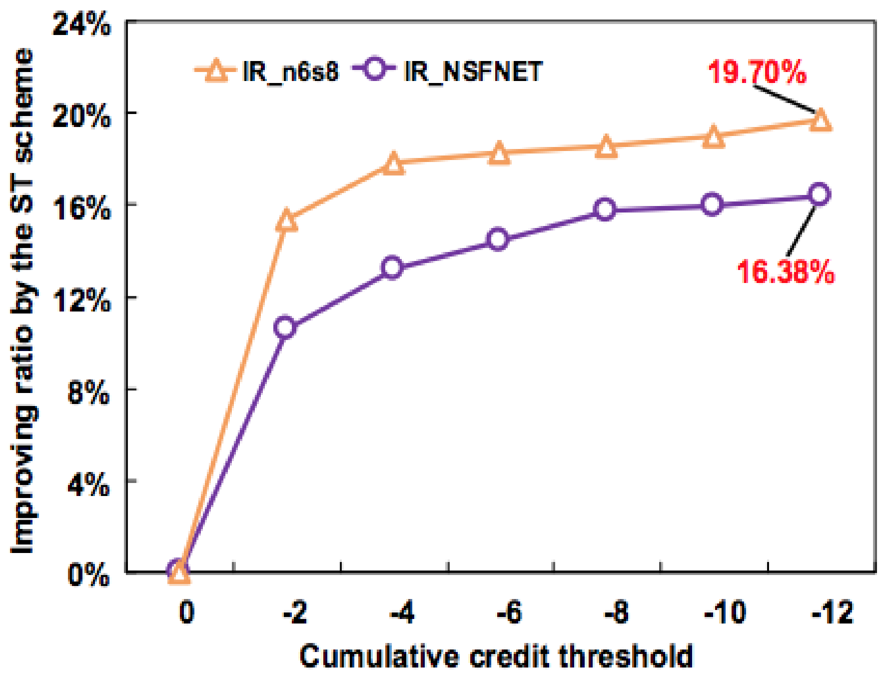


Fig. 5. Impact of cumulative credit threshold (X=140 Gb/s)

With increase of threshold, improvement ratio increases for both networks. However, this improvement saturates for a large cumulative credit threshold, implying that a small credit threshold may be sufficient to give good performance and prevent selfishness.

Observations

- Proposed scheme that allows VONs to trade their spectrum resources according to their actual traffic demands in different time slots.
- Although this study uses the term ‘trading’. The trading is not immediate.
- No explanation of how to choose cumulative credit threshold.
- What happens in case traded capacity does not match with requirements.