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A New Transport Network Architecture with Joint Time and Wavelength Multiplexing

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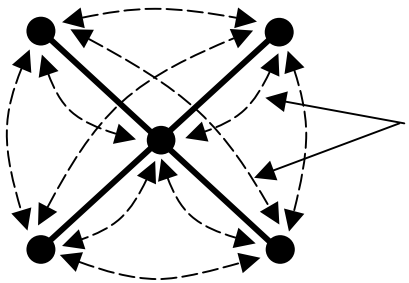
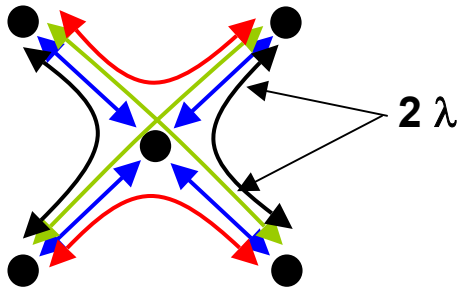
Why?

- Per unit cost of fully utilized wavelengths (λs) is low
- Applications require a very small fraction of λ capacity
- Effective use of λs currently requires electronic grooming -- unpacking and repacking of λs at most nodes
- We propose a cost-effective optical transport architecture that exploits the emerging technologies in optical transport to combine *datagram* and *circuit-switched* technologies
- The proposed architecture, TWIN,
  - Uses transport resource efficiently
  - Pushes intelligence to the (electronic) edge
  - Exploits inexpensive computational power
  - Is cost-effective, scalable, protocol agnostic
  - Has SONET-like restoration times
  - Achieves security at same level as today's circuit-switched network

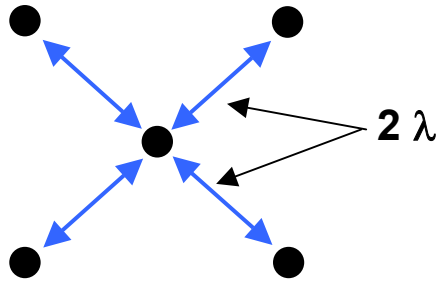
Example: OEO, OOO & TWIN

- Simple example: demands are 1/4 of λ between all node pairs in a 5 node network



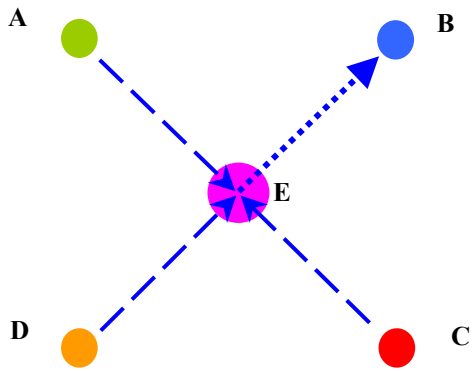


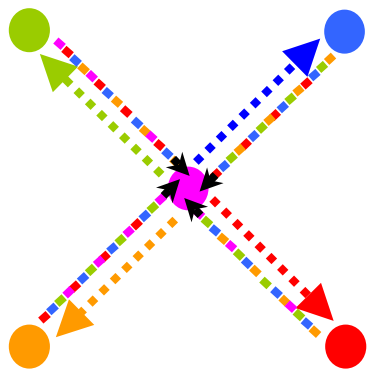
20 wavelengths and 20 lasers



8 wavelengths and 5 lasers

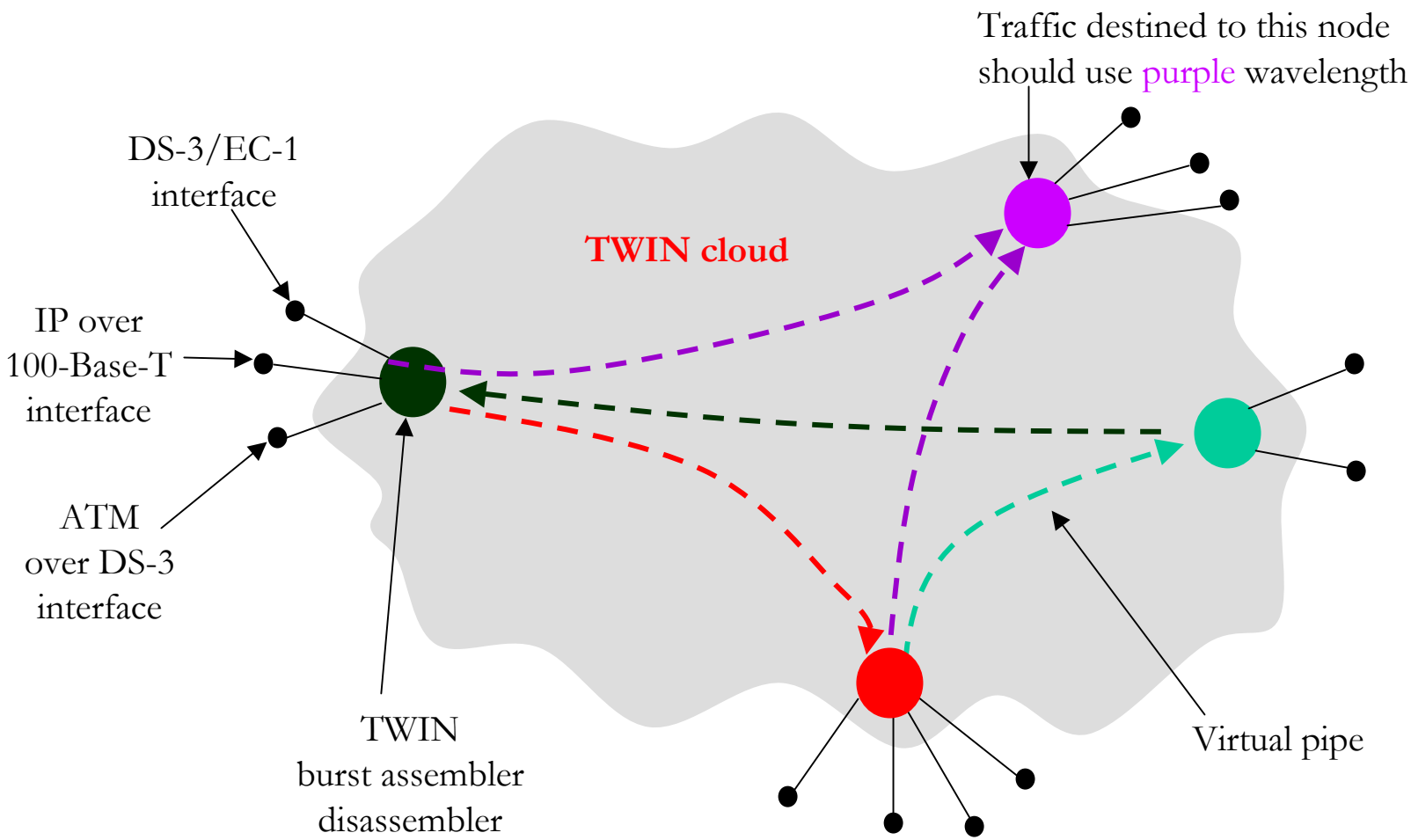
- TWIN requires construction of 5 optical "wavelength trees", with the blue tree shown below on left





8 "equivalent" wavelengths and 5 *tunable* lasers

TWIN: The Network as a Switch



Comparison of Different Architectures

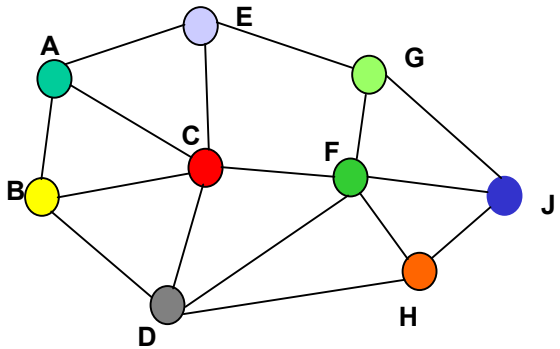
Optical network architecture	*Bandwidth efficiency*	*Core switching speed requirement*	*Optical buffering in the core*	*Data processing in the core*	*Response to dynamic traffic*
Optical Circuit Switching	Low	Low	No	No	Slow
Optical Burst Switching	High	High	Possibly	Yes	Fast
TWIN	High	Low	No	No	Fast

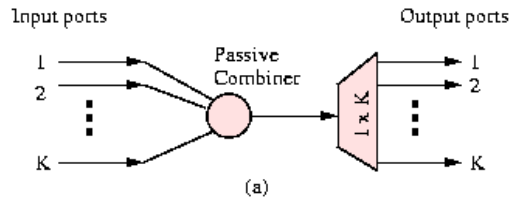
TWIN

- Architecture
- Routing
- Framing & encapsulation
- Scheduling
- Protection
- Resource discovery
- Signaling

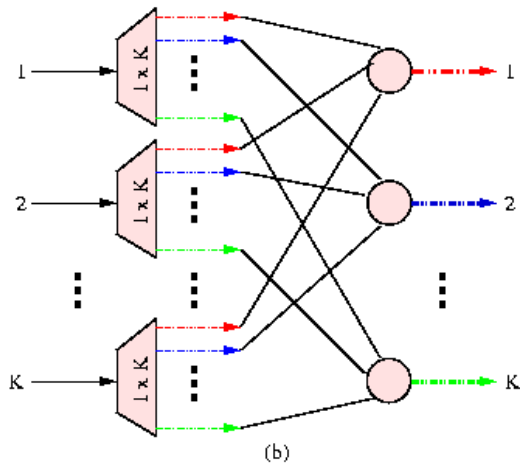
Routing (Self-Routing) in TWIN

- Destination nodes have pre-assigned (set of) colors

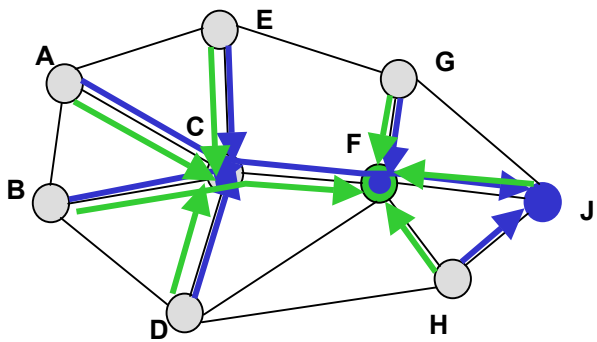




- Pre-configured WSSs with merging ensure correct routing at intermediate nodes

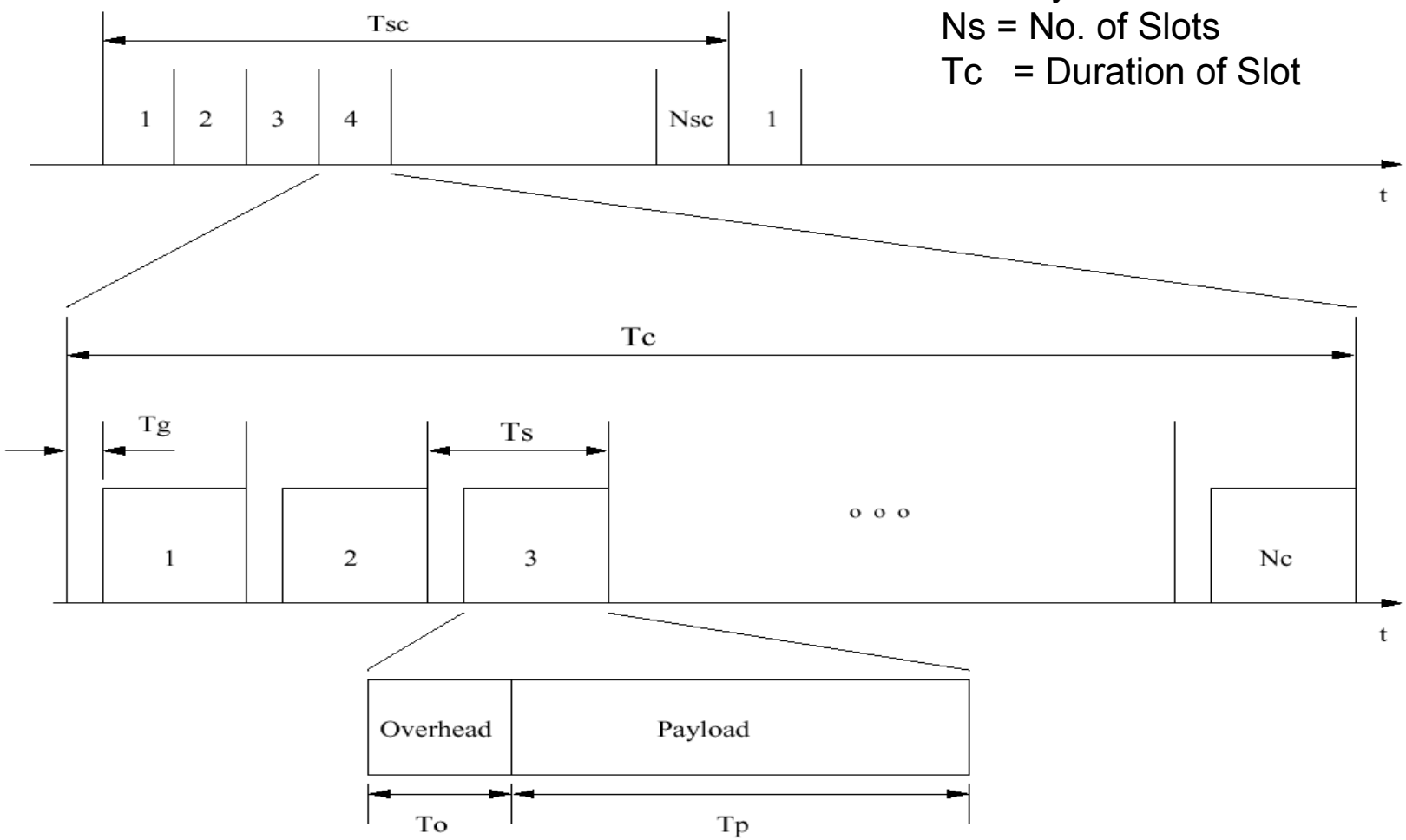


- Routing is source-based and is passive on destination trees



Framing and Encapsulation

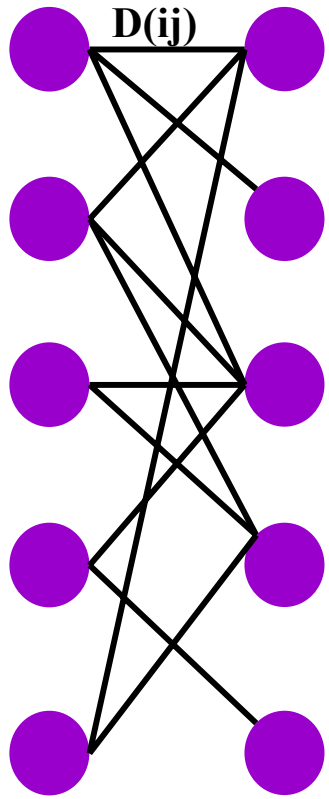
Ts = Cycle Time
Ns = No. of Slots
Tc = Duration of Slot



Scheduling -- Zero Propagation Delays

Problem is matching in a bipartide graph:

- Each edge (i,j) is assigned demand D(ij)
- Edges with common input or output conflict
- A matching is a set of edges with no input or output conflict
- Select *minimal* set of matchings to cover demands
- Well-studied crossbar switch scheduling problem
    - Birkhoff-von Neumann decomposition
    - Chang, Chen, Huang (offline)
    - McKeown (online)



Optimal Schedule

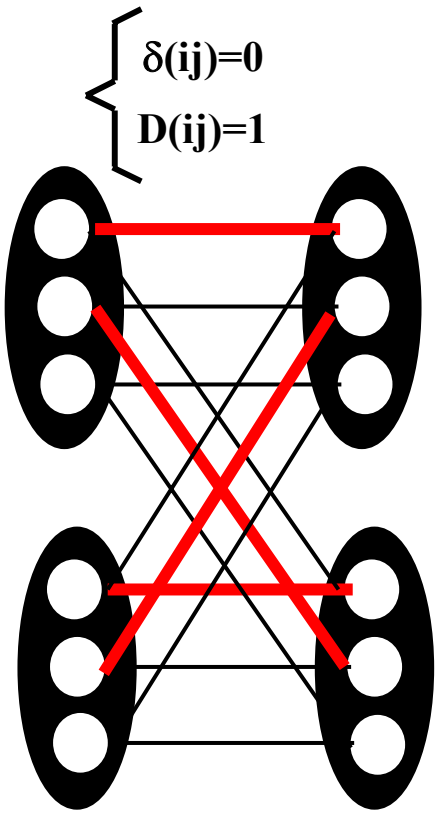
- Minimal schedule length =

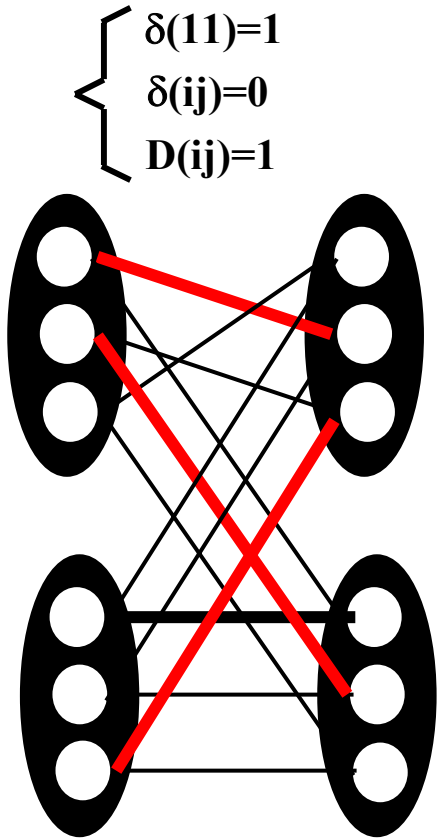
$$T^* = \max\left\{ \max_j \sum_i D(i,j), \max_i \sum_j D(i,j) \right\}$$

- Edge coloring of bipartite graphs achieves this
- TWIN scheduling is harder due to substantial propagation delays

Matching with Propagation Delays

- Schedules without (left) and with (right) delays





Centralized Scheduler

- Schedule for synchronous traffic via *iterative maximum independent set approximation* ***TWIN Iterative Scheduler (TIS)***

Let $D = [d_{ij}]$.

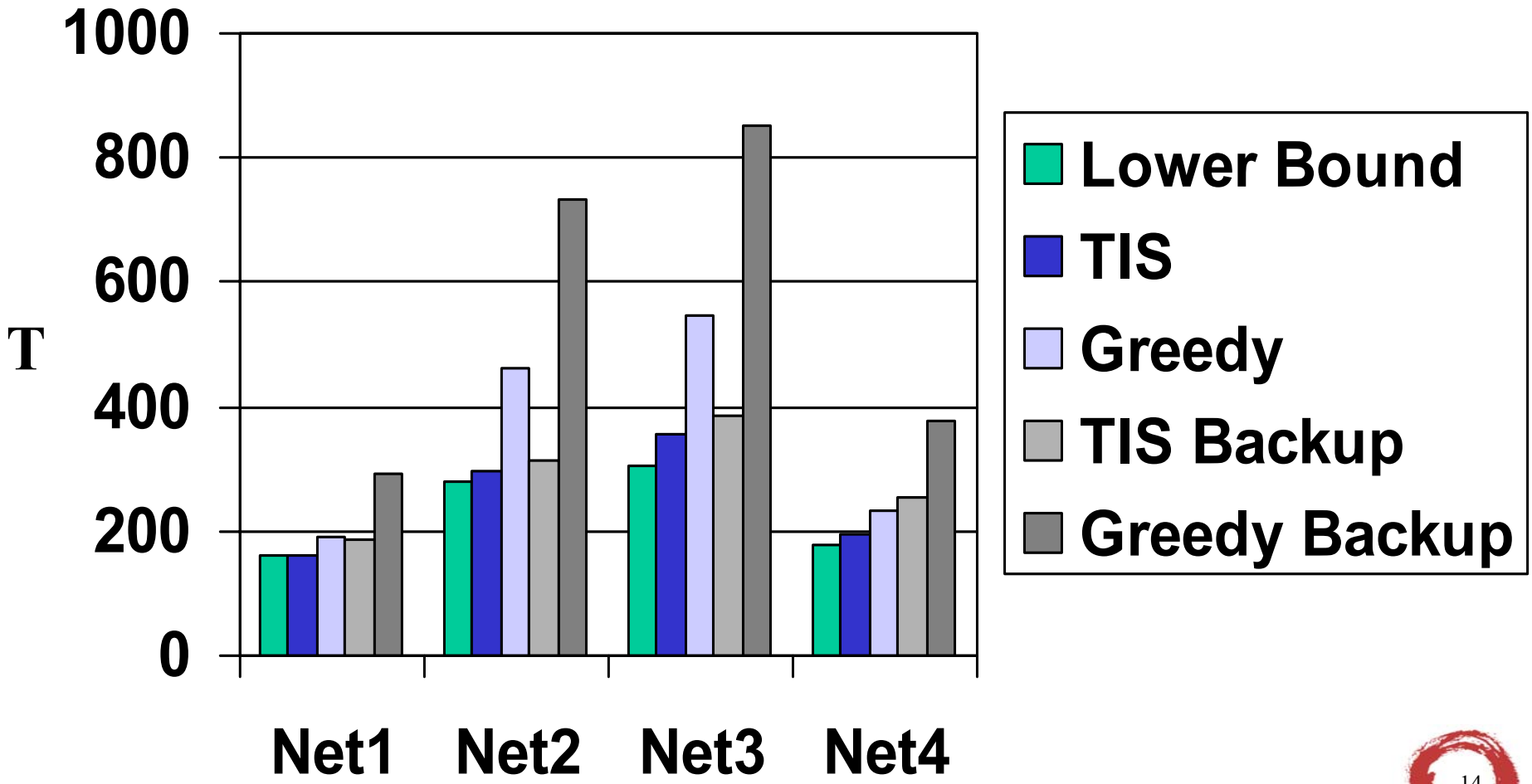
1. Set $S_{ij}(t) \leftarrow 0, k = 0, \cdots, B-1$
2. Set $\hat{D} \leftarrow D$
3. Let $(i^*, j^*, t^*) = \text{argmax}_{i,j,t} \frac{f_{ij}(t)\hat{d}_{ij}}{\sum_{i',j',t' \in \Gamma_{ij}(t)} f_{i'j'}(t')\hat{d}_{i'j'}}$
4. Set $S_{i^*j^*}(t^*) \leftarrow 1, \hat{d}_{i^*j^*} \leftarrow \hat{d}_{i^*j^*} - 1$
5. Repeat (3) until either $f_{ij}(t) = 0$ for all (i, j, t) or $\hat{d} = 0$,

where $\Gamma_{ij}(t) = \{i', j, t; \forall i'\} \cup \{i, j', t' : (t - \delta_{ij}) \text{mod}\, B = (t' - \delta_{ij'}) \text{mod}\, B; \forall j'\}$, and $\{i, j, t\}$ denotes a burst from i is scheduled for j in slot t.

Sample Networks

Network	A	B	C	D
Number of nodes	10	11	6	10
Distances (km)	150-2000	50-600	1-20	100-2000
Demand pattern	close to uniform	non-uniform	highly non-uniform	uniform

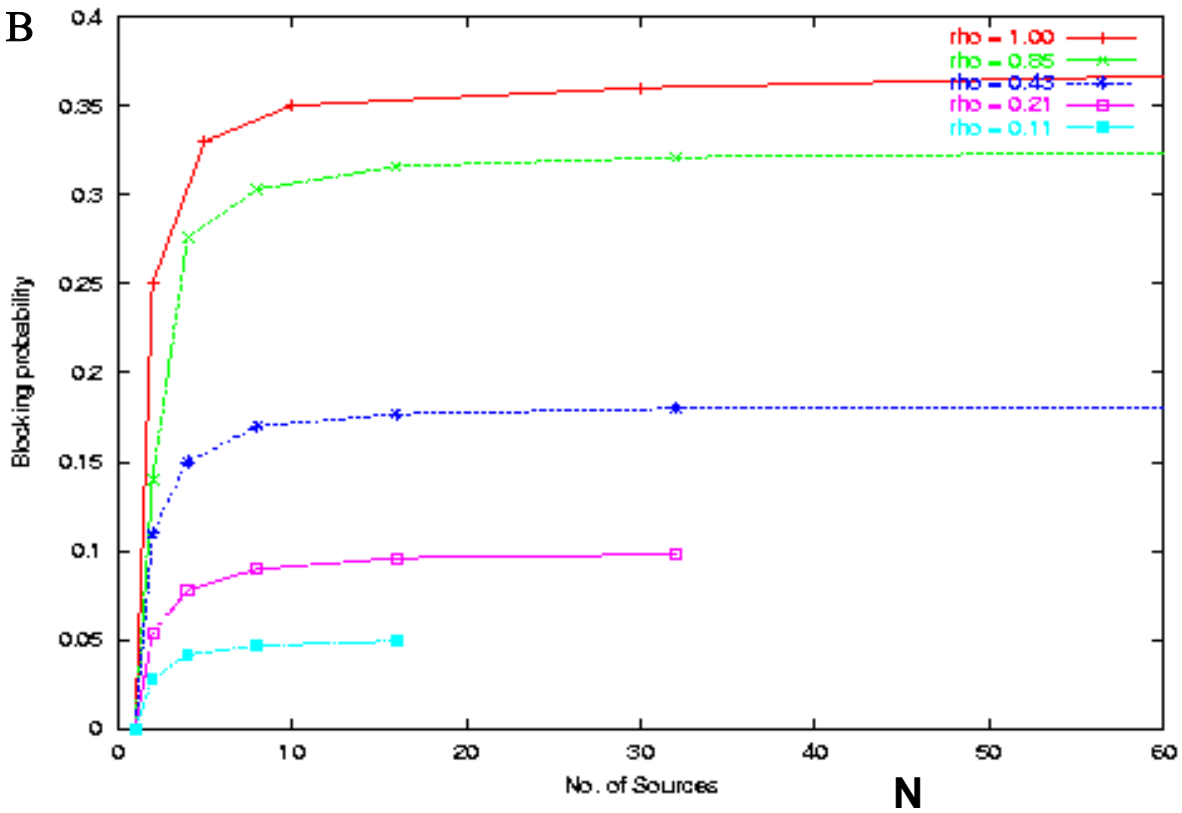
TIS Scheduling Results



Distributed TWIN Scheduling

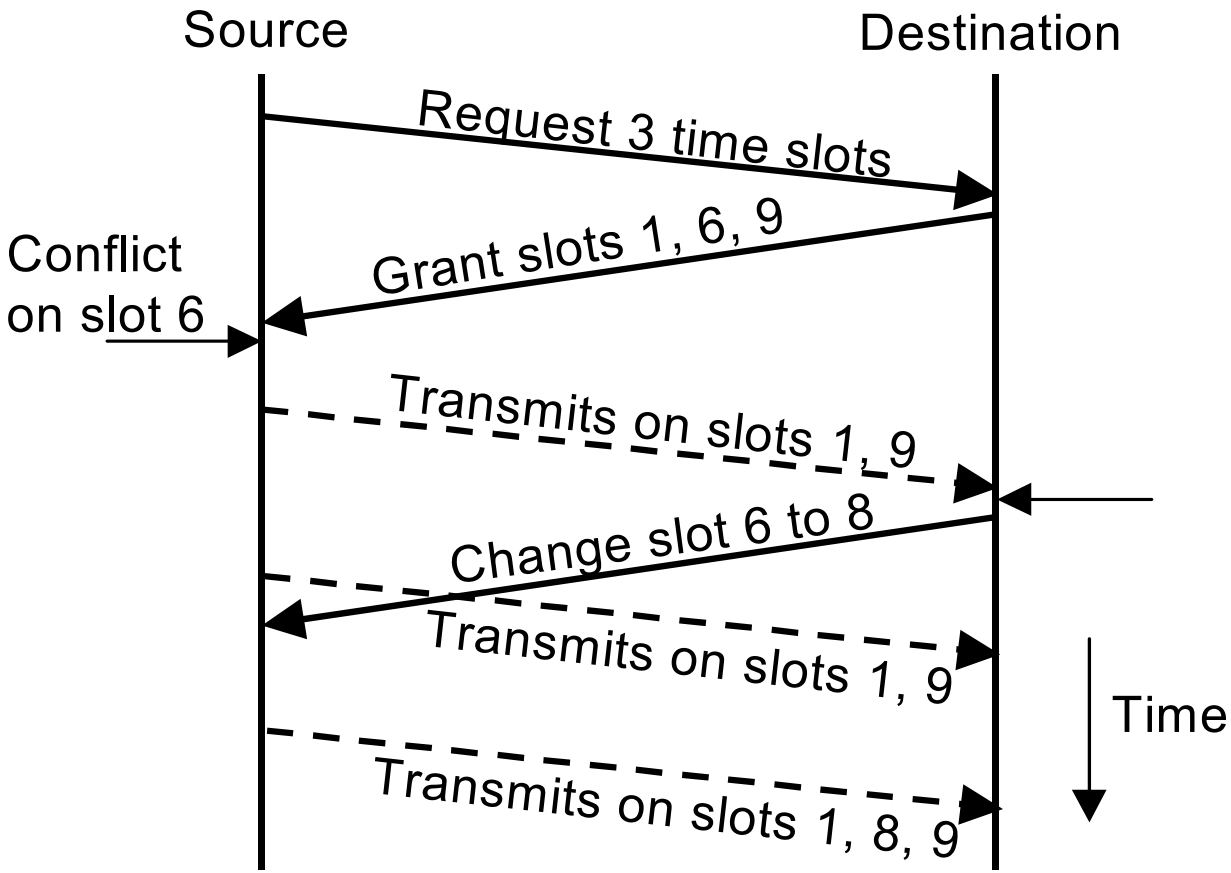
- Slotted ALOHA like Random Access Scheduler – Each node sends a batch of size d in an uncoordinated fashion

When Nd = 150 (or ρ =1.0), observe that blocking probability is about B=35% as N becomes large. This also corresponds to the case when a source is completely uncoordinated. Note that the blocking probability drops to about B=5% when Nd = 16 (ρ = 0.11).



TWIN Distributed Scheduling (TWS)

- A more intelligent distributed protocol – Destinations assign time slots based on requests to prevent collisions



Comparison Between TIS and TWS

- Comparison between TWIN centralized and distributed schedulers

Network	A	B	C	D
Lower bound B_0^*	160	279	306	180
TIIS	160	295	356	195
DS-AT	175	378	387	210
DS-ATDT	161	297	317	185