Resource allocation algorithms for QoS delivery in wireless networks

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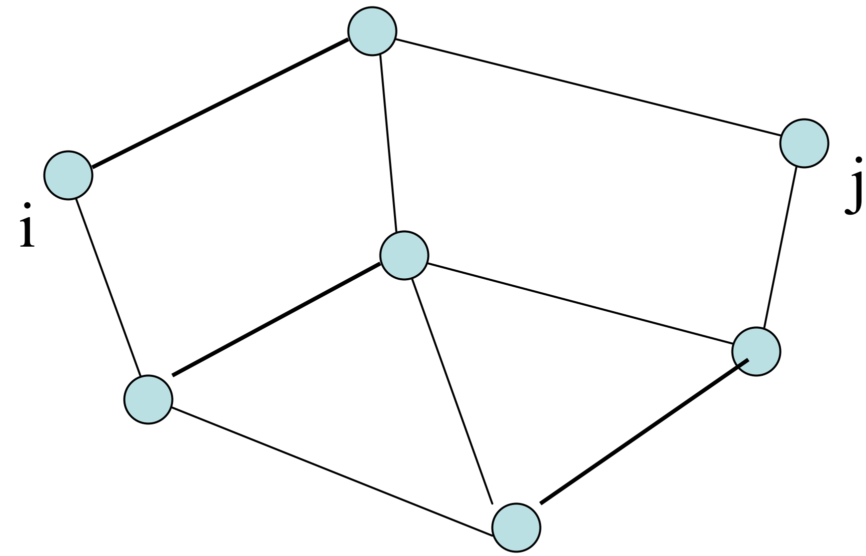
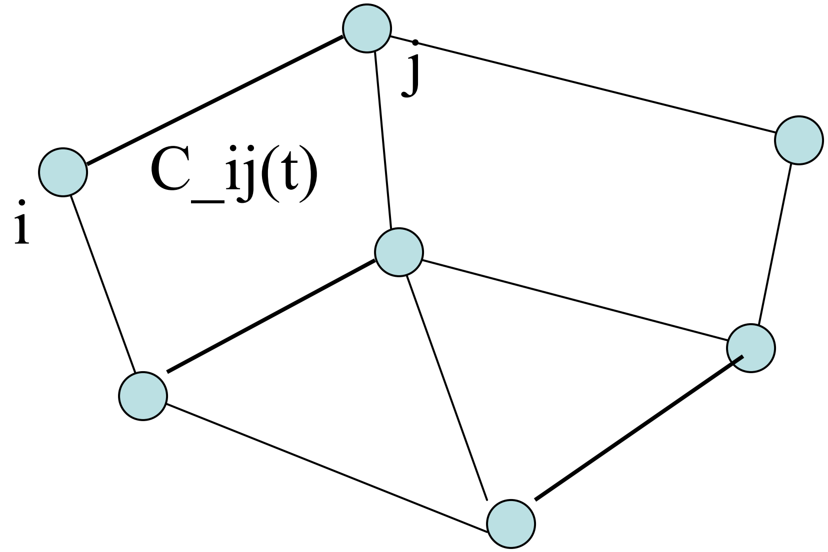
Wireless adhoc network model



- Collection of wireless nodes moving over a terrain
- Traffic may be generated at any node i with destination any other node j (or many), not necessarily within one hop from i
- Nodes control transmission power, access decision (transmit, don't transmit, which code (in CDMA) etc.), other physical layer parameters represented collectively by vector I(t)
- The environment changes as well due to mobility of the nodes and the environment itself; "topology" S(t)



- $C_{ij}(t)=C_{ij}(S(t),I(t))$: rate of bit pipe from i to j at t
- C(t) communication topology at time t determined partly by environment S(t) (uncontrollable), physical and access layer decisions I(t) (controllable)
- Multiple traffic classes 1,..,N, distinguished based on our objective.
- Network layer decision R(t): which traffic class through (i,j), or how to split $C_{ij}(t)$ to the different traffic classes

•Interested on traffic flow in the above model and associated performance objectives: throughput, delay, rate guarantees, etc

•Initial focus on **multihop information forwarding**: S(t), I(t) assumed constant, control R(t) for throughput optimality

•**Joint routing and access control** R(t), I(t), in the presence of variable topology S(t). Extension of the throughput optimality

•Dealing with complex optimization problems through **randomized** scheduling

•**Rate guarantees and fairness** when topology (S(t)) is fixed through access control and forwarding

•**Optimizing a linear objective function** in a single hop network with time varying topology

Information exchange and traffic forwarding modes

Unicasting

Each node i has traffic potentially for each other node j of rate a_{ij}.

Traffic matrix $A=\{a_{ij}\}$

Session oriented forwarding: *virtual circuits*

Datagram forwarding

Multicasting

Multicasting groups consisting of source node s and group of destinations $d_1,..d_N$

Information in a group may be forwarded through one *multicast tree* or split (load balanced) among several trees

Special case: *Broadcasting*

Traffic models and throughput definitions

- Traffic enters the system according to some arrival processes
- Throughput equals the arrival rates if the network is stable
- Stability means bounded queue lengths

$$\sup_{\{t>0\}} E[X_{ij}(t)] < \infty$$

- The arrival process are assumed to be i.i.d
- Most of the results hold for arrival processes being general Markov modulated processes with rates equal to the i.i.d rates

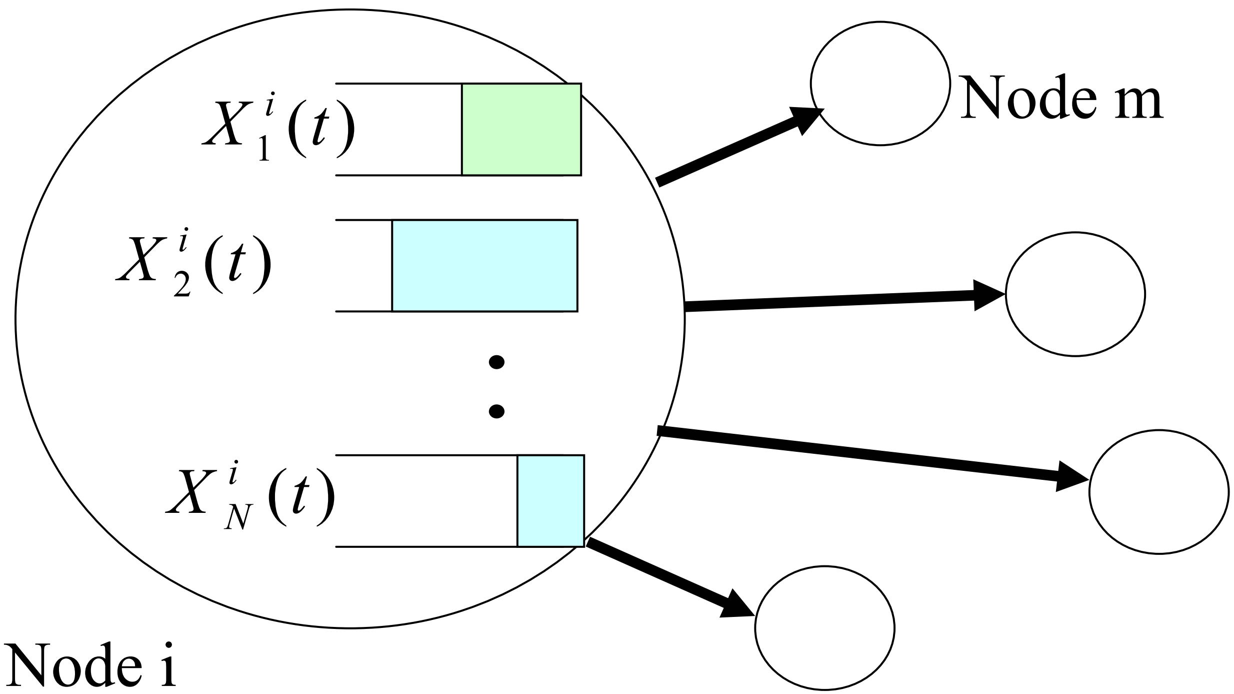
Same for fluid deterministic arrivals of bounded burstiness

Datagram traffic forwarding

A packet in transit is characterized by its destination alone
At each node packets of N traffic classes, one for each destination

One packet may be forwarded through each link

$R_{ij}(t)$: class of packet through link (i,j) at t, or 0 if no transmission



Necessary condition for feasibility

Traffic matrix A: arbitrary nonuniform

a_{ij} rate from node i to j

f_{im}^{j} long term average rate of class j traffic from node i to m

Flow conservation at each node i for each traffic class m

$$\sum_{k=1}^{N} f_{ki}^{m} + a_{im} = \sum_{j=1}^{N} f_{ij}^{m}$$

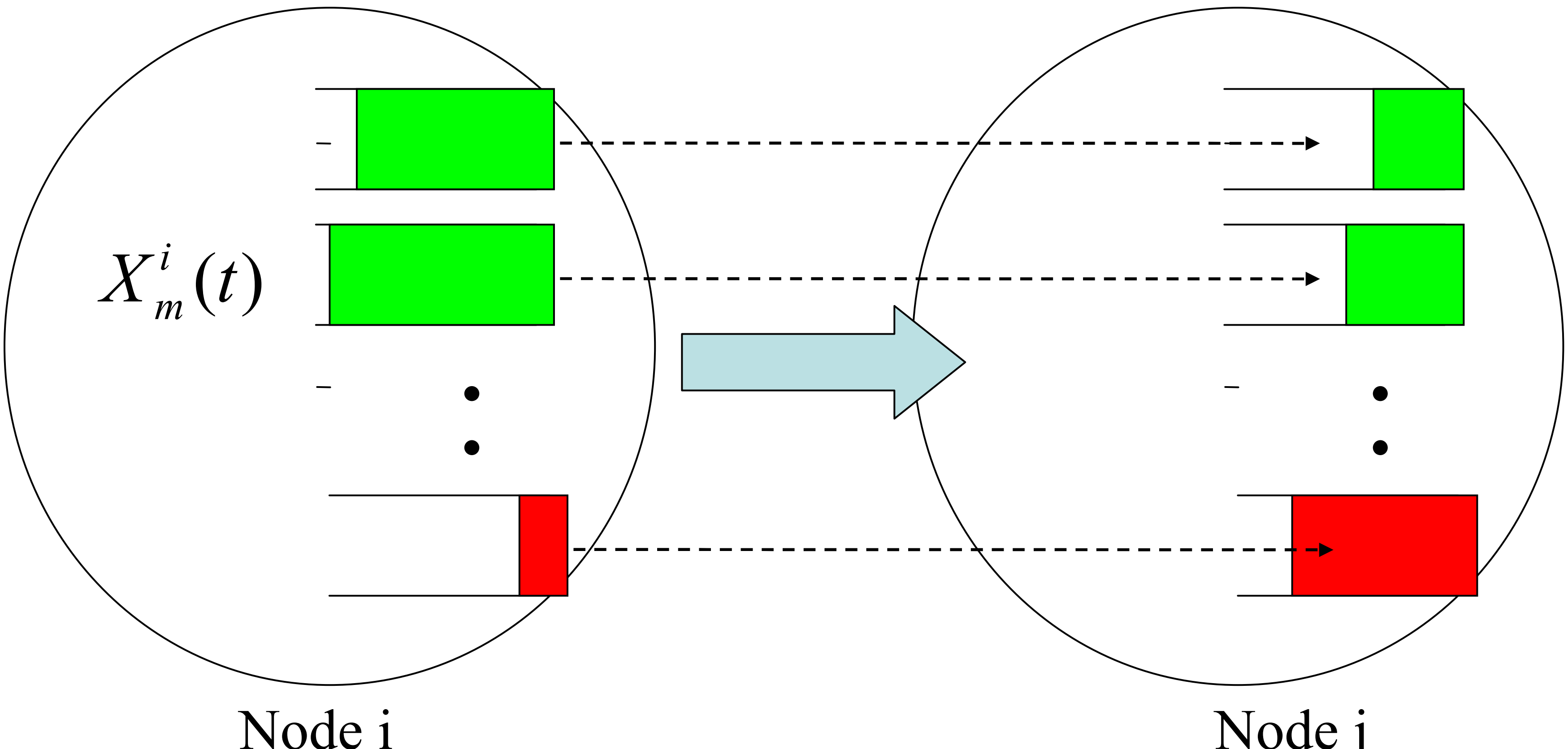
(if not then class m backlog of node i will grow to infinity)

Link capacity condition

$$\sum_{m=1}^{N} f_{ij}^{m} < C_{ij}$$

Back pressure flow control

If $X_m^i(t) - X_m^j(t)$ is negative then class m is no eligible for transmission from i to j

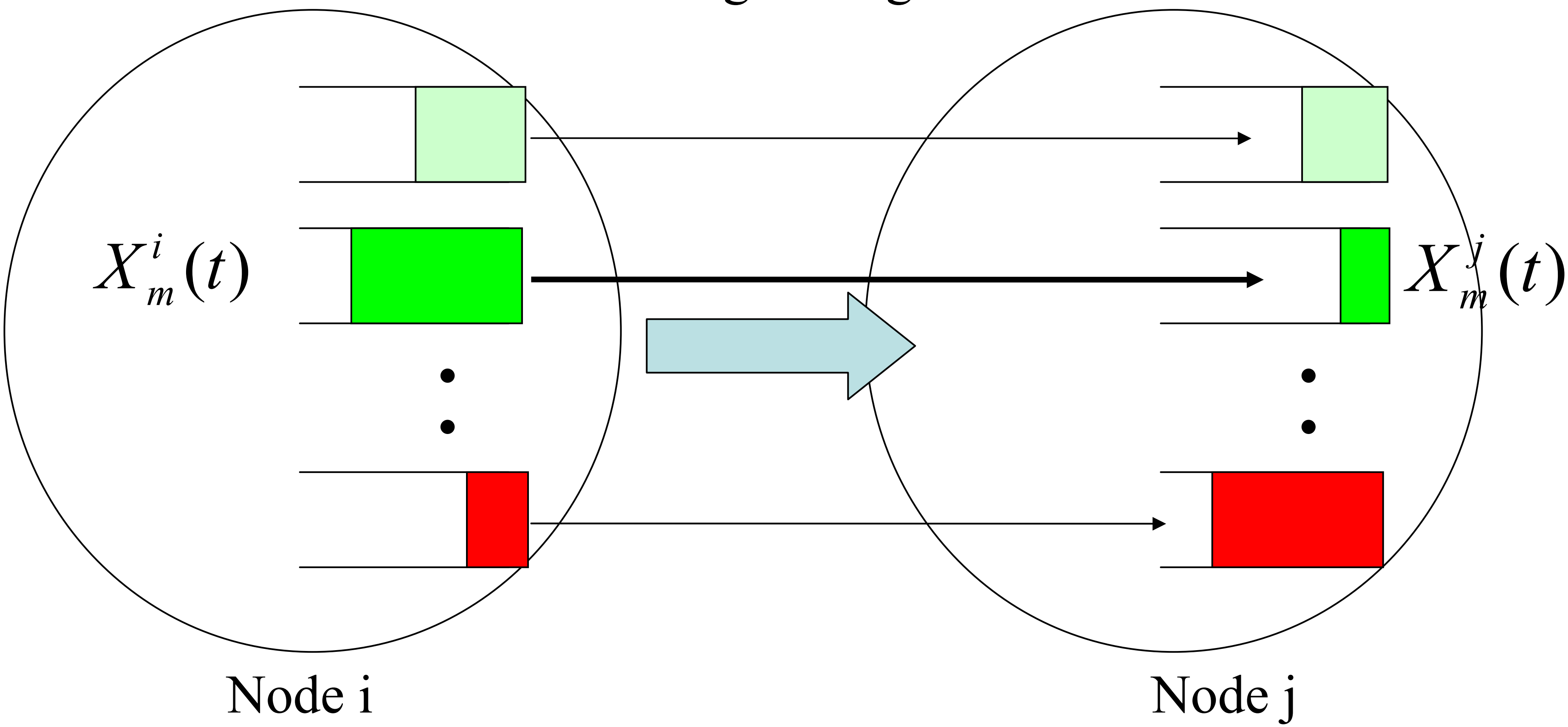


Class priority scheduling

Transmit a packet of class m for which

$$X_m^i(t) - X_m^j(t)$$

is maximum among all eligible classes

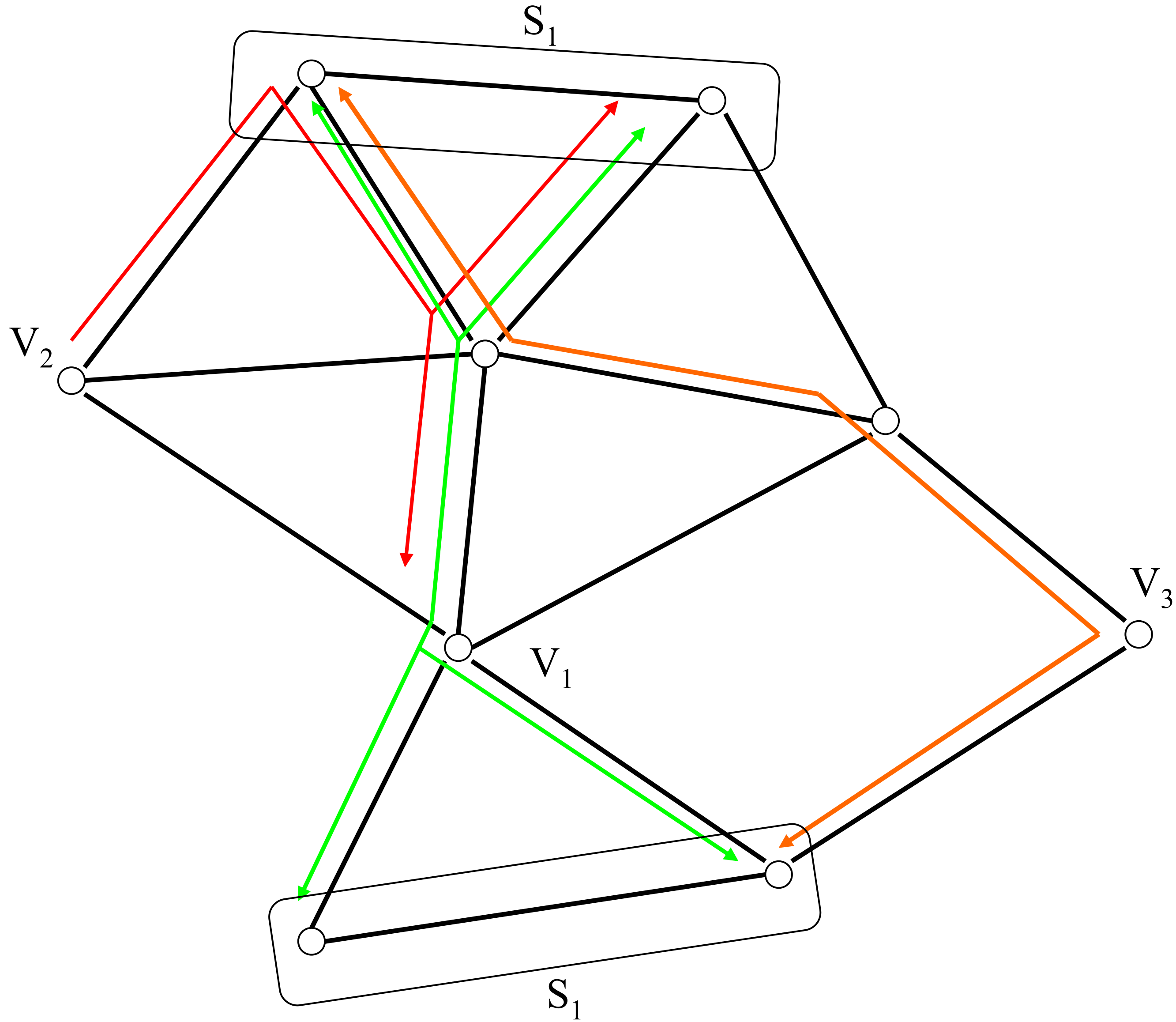


The combination of backpressure flow control with class priority scheduling achieves maximum traffic forwarding throughput in the datagram network

(Tassiulas, Ephremides Autom Contr Trans 92,
Tassiulas AC Trans 95)

Multicasting

- Consider N multicast sessions (v_1,S_1), (v_2,S_2),…,(v_N,S_N)
  v_{n} : Information Source
  S_{n} : Group of intended destinations for information source v_{n}
- τ_n : Collection of directed trees rooted at v_n with leaves ending in the set on nodes S_n that may carry session n traffic
- τ_n may include
  - All multicast trees routed at v_n with leaves terminating in S_n
  - Some pre-selected multicast trees.
- a_{n} : traffic rate of session n, split among the trees of τ_n



One multicast tree per session is depicted, there are three sessions

Necessary and sufficient throughput feasibility condition

A collection of traffic rates a_n, $n = 1,2,\ldots,N$ is feasible if there exist a traffic splitting a_n^m, $m = 1,2,\ldots,M_n$ for each session n,

$$a_n = \sum_{m=1}^{M_n} a_n^m T_n^m$$

such that the capacity condition is satisfied

$$\sum_{n=1}^{N} \sum_{m=1}^{M_n} (a_n^m T_n^m) \le C$$

$$C = (C_e : e \in E)$$

$$C_e : \text{Capacity of link } e$$

T_n^m : The m^{th} multicast tree that may carry session n traffic represente d by a binary indicator vector $T_n^m = (t_e : e \in E)$

Verifying feasibility NP-hard, Steiner tree packing problem

Backpressure and per link priority scheduling

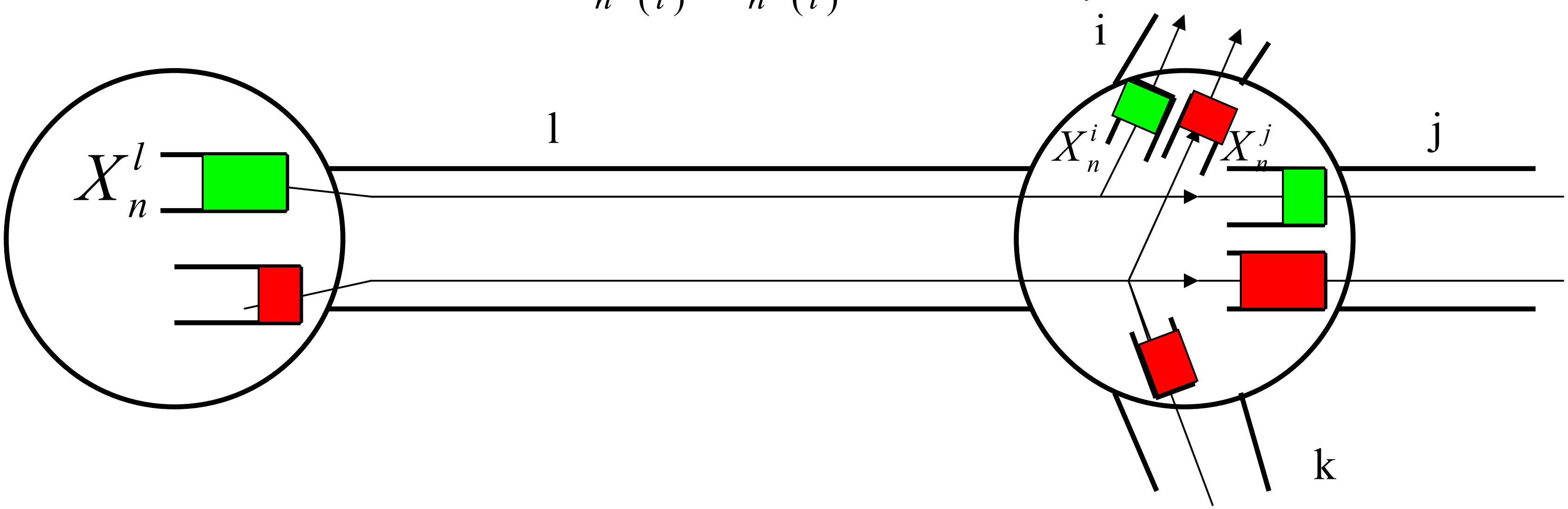
- $X_n^l(t)$: Backlog of tree n traffic in front of link l

$$W_n^l(t) = X_n^l(t) - \max_{\text{k is a descendent of l}} X_n^k(t)$$

- $W_n^l(t)$:Weight (backlog gradient) of tree n at link l
- $b_n^l W_n^l(t)$: Priority index of tree n trough link l.

$$n^l(t) = \arg\max_n b_n^l W_n^l(t)$$

$$if \;\; b^l_{n^l(t)} W^l_{n^l(t)}(t) < -T_l \;\; then \;\; idle$$



Traffic splitting among trees at the source: Load balancing

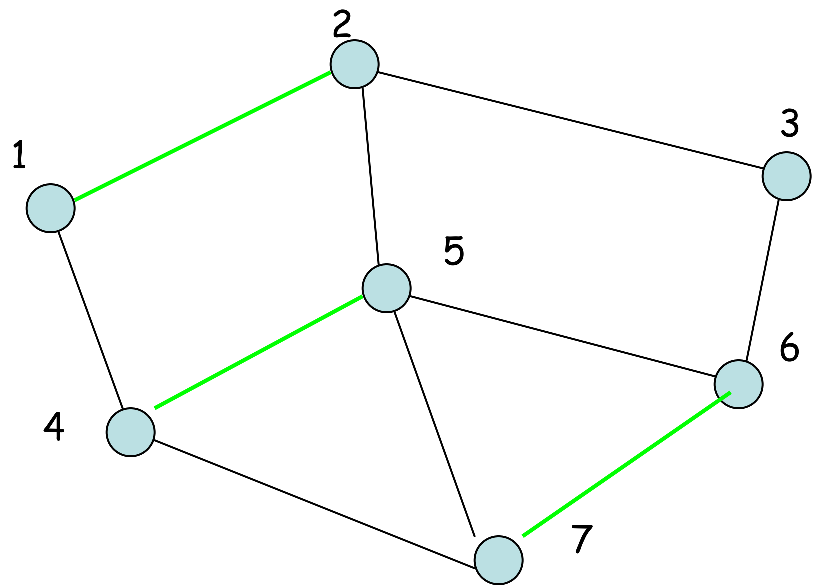
Rule1: at the source node the traffic is assigned to the multicast tree with minimum local backlog

Rule 2: at the source node the traffic is assigned to the multicast tree with minimum weight, where the weight of a tree is the sum of the weights of its links and the weight of a link is the maximum traffic backlog through the link.

The combination of the link scheduling prioritization scheme with either of the load balancing rules for traffic assignment achieve maximum throughput

(Sarkar Tassiulas IT Trans 02)

Sharing the locally common channel in different neighborhoods of a multihop ad-hoc network: **Access Control**



- Simultaneous transmissions of several links may result in conflicts
- Transmission conflict conditions depend on: signaling (spread spectrum, narrowband,..), number of wireless transceivers per node, directivity of transmissions,..

- Access Control vector I(t) represents the selection of various access and physical layer parameters at t

- Access Control policy designates I(t), t=1,2,… I(t) in *A* where *A* the collection of all possible access control vectors

In a **slotted synchronized system** I(t) explicitly selected by a controller. In a **random access** scheme the I(t) is the result of the random access mechanism

Rate vector for some fixed state S(t)=s and access policy I(t)

$$C = \lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T} C(s, I(t)), \quad I(t) \in A$$

Capacity region C(s) includes all rate vectors realized by any access policy

C(s) the convex hall of {C(s,I): I in *A*}

(Tassiulas Ephremides AC Trans 92)

Interesting special case

The topology process is binary, i.e. S(t) is a graph process indicating at each time slot t which nodes are within direct communication range

Access control selects links transmitting at each slot under the constraint that no two links may not share the same node

Set of feasible access controls A is the set of all matching of graph S(t)

Dynamic Access Control to maximize throughput

- Fixed topology state S(t)=s
- Focus on access: single hop traffic demands, packets are generated at the origin node of a link, exit at destination
- Traffic generation rates associated with links, traffic rate vector feasible if it belongs to capacity region C(s)
- **Max weight access control** policy selects I(t) to maximize

$$X(t)*C(s,I(t))$$

X(t) vector of packet backlog for each link

maxweight guarantees stability if arrival rate vector in C(s)

(Tassiulas Ephremides Autom. Cont. Trans 92)

Feasible rate region time varying case

$$\mathbf{C} = E\ [\mathbf{C}(s)]$$

With respect to the stationary distribution of topology process S(t) i.e.

$$\mathbf{C}=\{C: C=E[C(s)], C(s)\varepsilon\ \mathbf{C}(s), i=1,\ldots,N\}$$

Max weight access control policy selects I(t) to maximize

X(t)*C(s(t),I(t))

max- througput as well for the time varying case

(Tassiulas IT Trans 97)

Capacity region for end-to-end traffic

Traffic matrix A: arbitrary nonuniform

a_{ij} rate from node i to j

f_{im}^{j} long term average rate of class j traffic from node i to m

Flow conservation at each node i for each traffic class m

$$\sum_{k=1}^{N} f_{ki}^{m} + a_{im} = \sum_{j=1}^{N} f_{ij}^{m}$$

There exists an access control policy π to select I(t) such

$$\sum_{m=1}^{N} f_{ij}^{m} < E^{\pi}[C_{ij}(t)]$$

Access control jointly with traffic forwarding

Select I(t) to maximize the following objective

$$\sum_{i,j=1}^{N} w_{ij} C_{ij}(S(t), I(t))$$

where

$$w_{ij} = \max_{m=1..N} \left\{ X_m^i(t) - X_m^j(t) \right\}$$

The joint scheme above achieves max end-to-end throughput

(Tassiulas, Ephremides AC Trans 92, Tassiulas IT Trans 97)

Dealing with complex optimization problems

Crucial step: select I(t) to maximize

$$\sum_{i,j=1}^{N} w_{ij} C_{ij}(S(t), I(t))$$

Use instead **randomized** low complexity scheduling

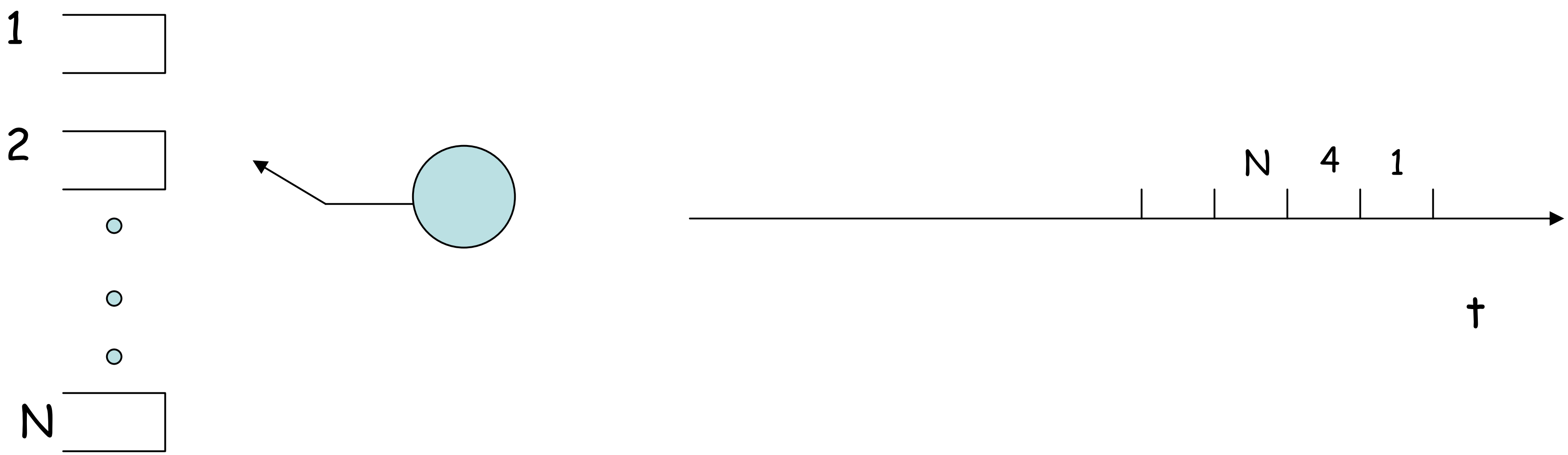
Select I randomly, let I(t) be equal to I or I(t-1) depending on which gives larger value to the objective function

Randomized scheme maximum throughput for a wide class low complexity randomization mechanisms

(Tassiulas, Infocom 98)

QoS provisioning beyond throughput: rate guarantees and fairness

Link schedulers for QoS provisioning: RR,FQ,GPS, PGPS, etc..



Network level fair session rate allocation

End-to-end fair rate allocation through fair queueing at the link level and hop-by-hop flow control

Challenges in wireless

- Neighboring links cannot be scheduled independently due to local interdependencies in transmission.
- When a link is scheduled it is as if it receives service from both its end nodes.
- Each node is viewed as an independent server that allocates service to the links emenating from him.
- A link can be served only if its two end nodes are synchronized to provide their service at the same time.
- Challenge: Scheduling at a node should be done in coordination with its neighbors.

QoS provisioning objective

Operate the network with a scheduling policy that provides a feasible rate vector that satisfies certain minimum rate requirements and maximum rate constraints and furthermore it is maxmin fair

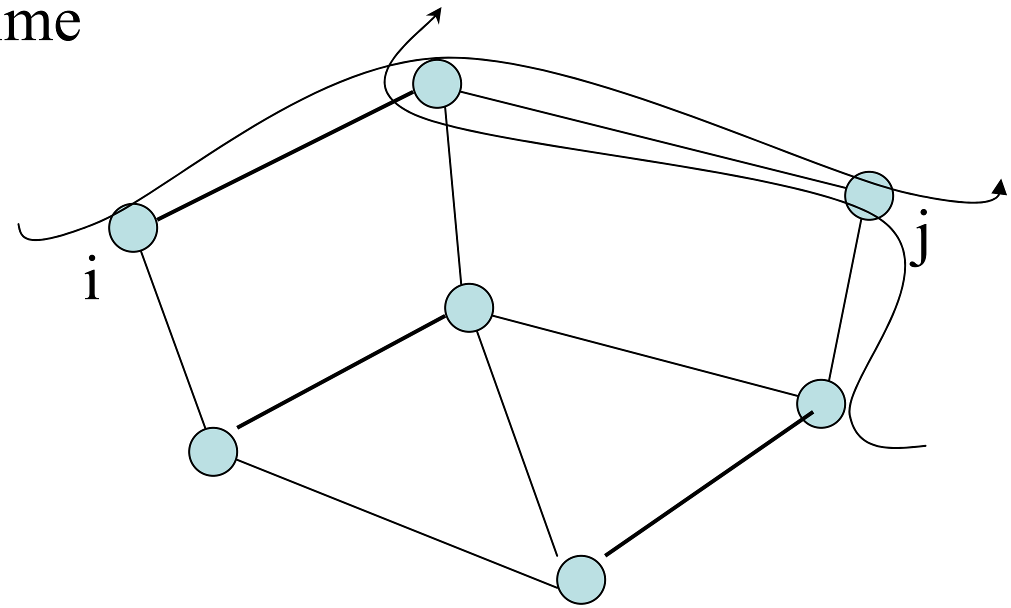
Maxmin Fairness

A rate vector is *maxmin fair* if subject to feasibility, one **can not increase** the rate of a flow, **without decreasing** the rate of another flow having **equal or lesser** rate

Dynamic scheduling for maxmin fairness in multihop ad-hoc (Sarkar, Tassiulas infocom02, cdc03, JSAC05(to appear))

Set-up for max min fair control

- The topology is fixed
- The controller only selects the matching of links to transmit at each time



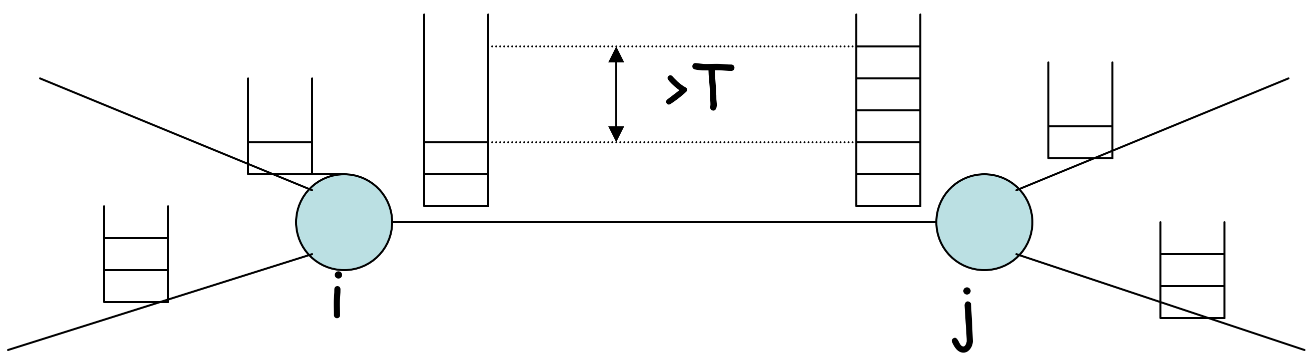
•Traffic is session oriented, i.e. route is specified
•Initially assume single hop sessions, single session per link, generalize to multihop later
•Initially assume bipartite connectivity graph, generalize later

Scheduling for rate guarantees in wireless

- Each node allocates service tokens to the links emenating from him in a "round-robin-like" fashion.
- Each link maintains two service token buckets, one for each end node, where it stores the tokens received by the corresponding end node.
- The "service credit" of the link equals to the minimum of the two service token buckets.
- The collection of non-conflicting links with maximum service credit is selected for service at each slot.
- Whenever a link is served one token is deducted from each one of its token buckets.

Service token allocation: *saturated system*

- Assume that each link has an infinite packet supply
- A link (i,j) is eligible to receive a service token at slot t from node i if the size of the token bucket i of the link does not exceed the size of the token bucket j of the link by more than T service tokens.
- Each node i allocates the service tokens in a round-robin fashion, considering at each slot only the elligible links at that slot



Link elligibility is node dependent, i.e. a link may be elligible for service by one of its nodes (i) and ineligible by the other (j)

Maxmin-fairness in saturated system

$R(t)$ the vector of tokens allocated to each link in $[0,t)$

There is a threshold T such that

$$R(t)/t \rightarrow Ro \quad \text{as } t \rightarrow \infty$$

where Ro is maxmin vector in the region of achievable rate vectors

The token buffer lengths are bounded

System with arrivals

The packets in link (i,j) are generated according to an arrival process with rate aij.

The service token allocation is done as in the saturated system with the difference that if a link packet buffer is empty then the link is ineligible for service.

Link scheduling relies on service credits and not on queue lengths

The service rate vector of the links converges to the maxmin feasible service rate vector. Furthermore the links for which the arrival rate equals the service rate the packet length process is stable.

Multihop flows

Modify token scheduling algorithm such that intermediate nodes consider both upstream and downstream one-hop neighbors when do token allocation.

Control packet release at the source with a similar token mechanism

Apply maxweight scheduling with session prioritization at all links

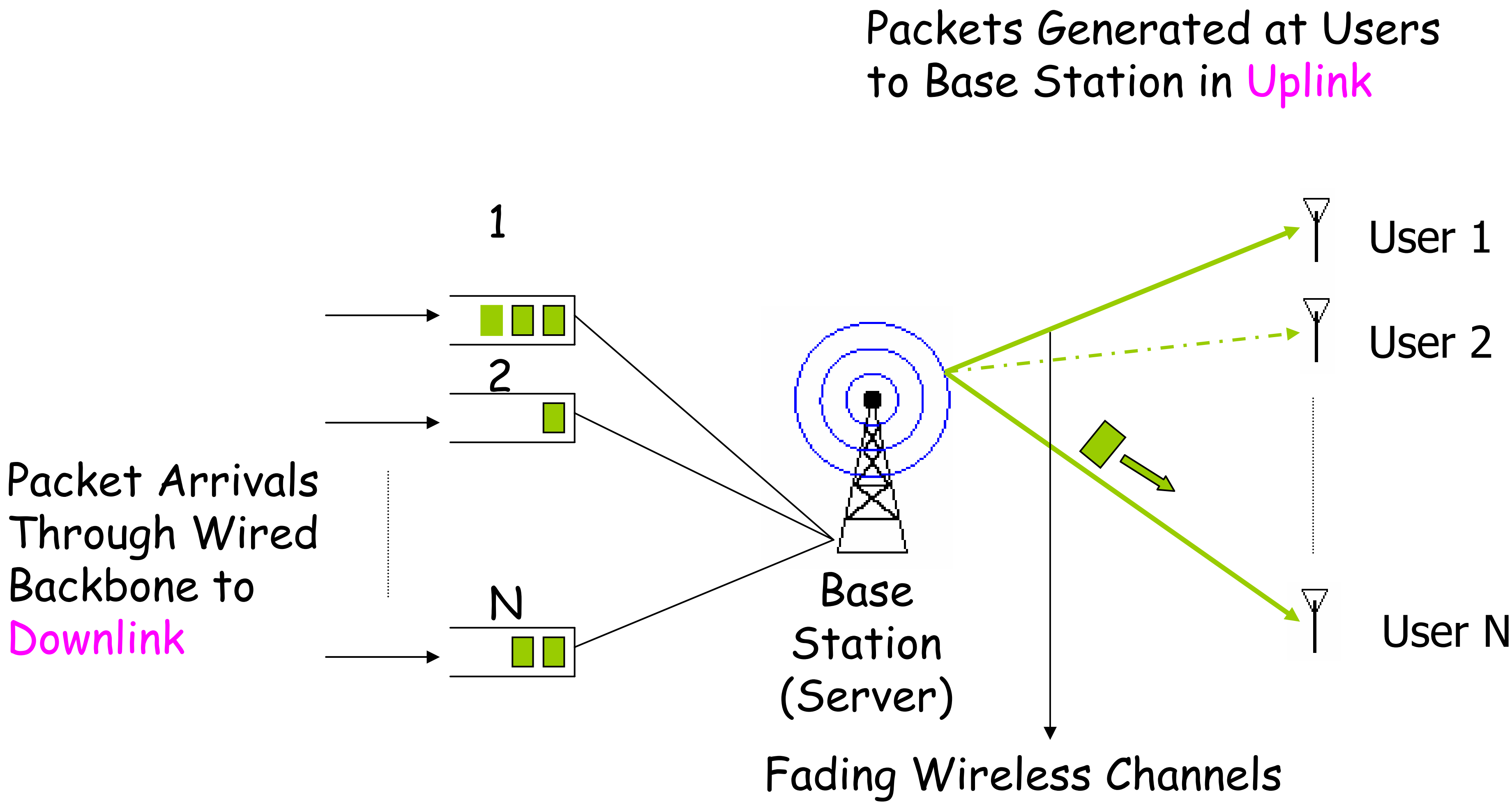
Achieve maxmin fairness end-to-end

(Sarkar,Tassiulas cdc 03)

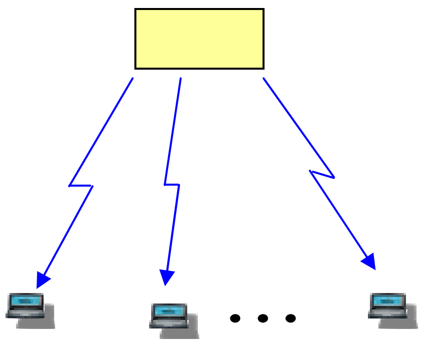
Other Issues

- Other topologies and wireless constraints: extensions possible with multiple credit buckets per link, one for each constraint that affects the link.
- Minimal control information exchange and only between one hop away neighbors
- Distributed versus centralized: in the current algorithm the maximum matching computation is the only centralized part.

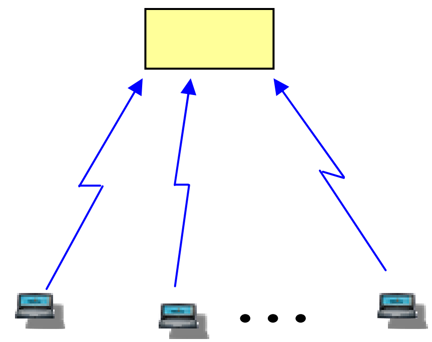
Dealing with time-varying topology: Single-hop linear optimization objective



Information Theoretic Models



Broadcast channel



Multi-access channel

- Capacity studied by many the last 30 years

Information theoretic models miss temporal dimension of data traffic (all information available a-priori to the disposal of the encoders)

Recent information theoretic results for fading multiaccess channel

Capacity characterization for fading channels with full channel information available to the encoder (Tse, Hanly 99)

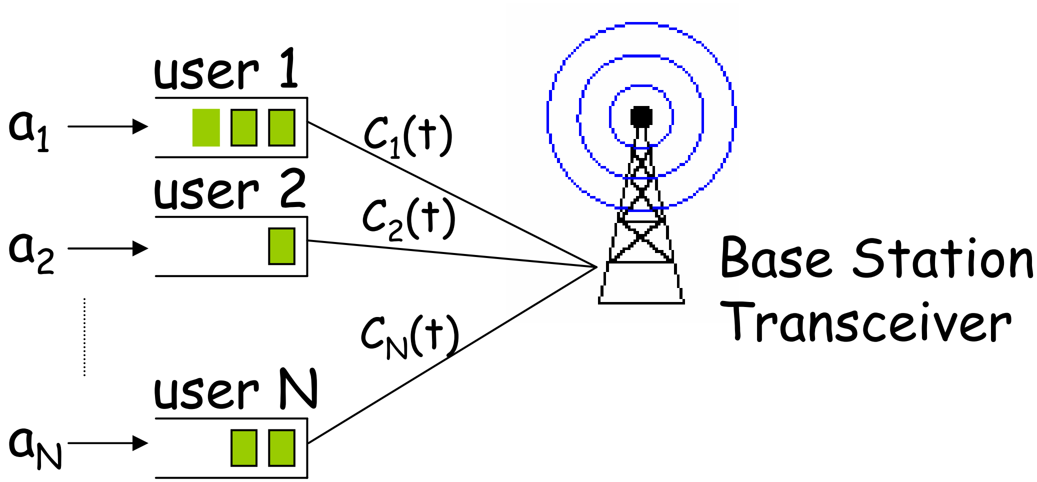
Symmetric fading, limitation on the average power transmission (Knopp, Humblet 95)

Capacity achieved by "Multiuser water filling" :

When all channel states are sufficiently unfavorable no one transmits

Otherwise only the user with best channel transmits

A (gross) model of a fading multi access system with teletraffic



- Fading state of channel n

$$C_n(t) = \begin{cases} 1 & \text{Channel available} \\ 0 & \text{Channel unavailable} \end{cases}$$

- a_n: user n traffic generation rate
- Throughput capacity region

C = { (a_1, …, a_N) for which stable operation feasible for some appropriate access control policy}

Independent Bernoulli fading processes

$P[C_n(t) = 1] = P_n$

Capacity region characterization

$$\sum_{n \in S} a_n \leq 1 - \prod_{n \in S} (1 - P_n) \quad \forall S \in \{1,\ldots, N\}$$

Maximum throughput access policy

“Among the users with good channel enable the one with largest backlog”

Adaptive, no need for channel statistics

(Tassiulas Ephremides IT Trans 93)

Refined model of a fading multi access system with teletraffic

Multi access channel state $S(t)$
(arbitrary Hidden Markov process)

Access allocation decision $G(t)$
(may include e.g. user encoding order in successive decoding

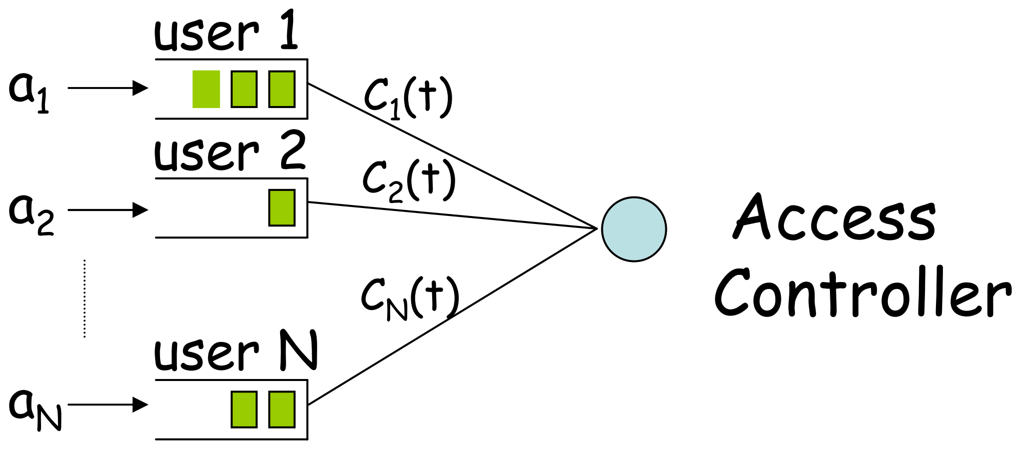
Rate function $(C1(t), \ldots, CN(t)) = C(S(t), I(t))$

Throughput region:
Convex combination of polytopes like those in "gross" model

Maximum throughput policy
Select $I(t)$ to maximize $\Sigma X(t)^{*}\, C(S(t), G(t))$

(Tassiulas IT Trans 97)

Access control to maximize a linear objective function



R_n: long term average throughput rate of user n

Linear Quantitative Quality of Service Objective

$$\sum_{n=1}^{N} w_n R_n$$

Decreasing weights reflect decreasing user priorities from 1 to N

Find Access Control to maximize

$$\sum_{n=1}^{N} w_n R_n$$

Why linear objective ?

Crucial step for achieving more general objectives like sums of convex functions that approximate fair allocation (maximum or proportional)

Optimal Policy in two extreme cases

Case A

- $(a_1, a_2, \ldots, a_N)$ belongs to feasible throughput region
- The LCQ policy achieves $R_n = a_n$, all n, therefore optimal

Case B

- $(a_1, a_2, \ldots, a_N)$ too big, all users operate in saturated (backlogged) mode
- Strict priority does the job
- Among the users with available channel ($C_n(t) = 1$) activate the one with largest weight
- Backlog independent

Optimal policy in general case

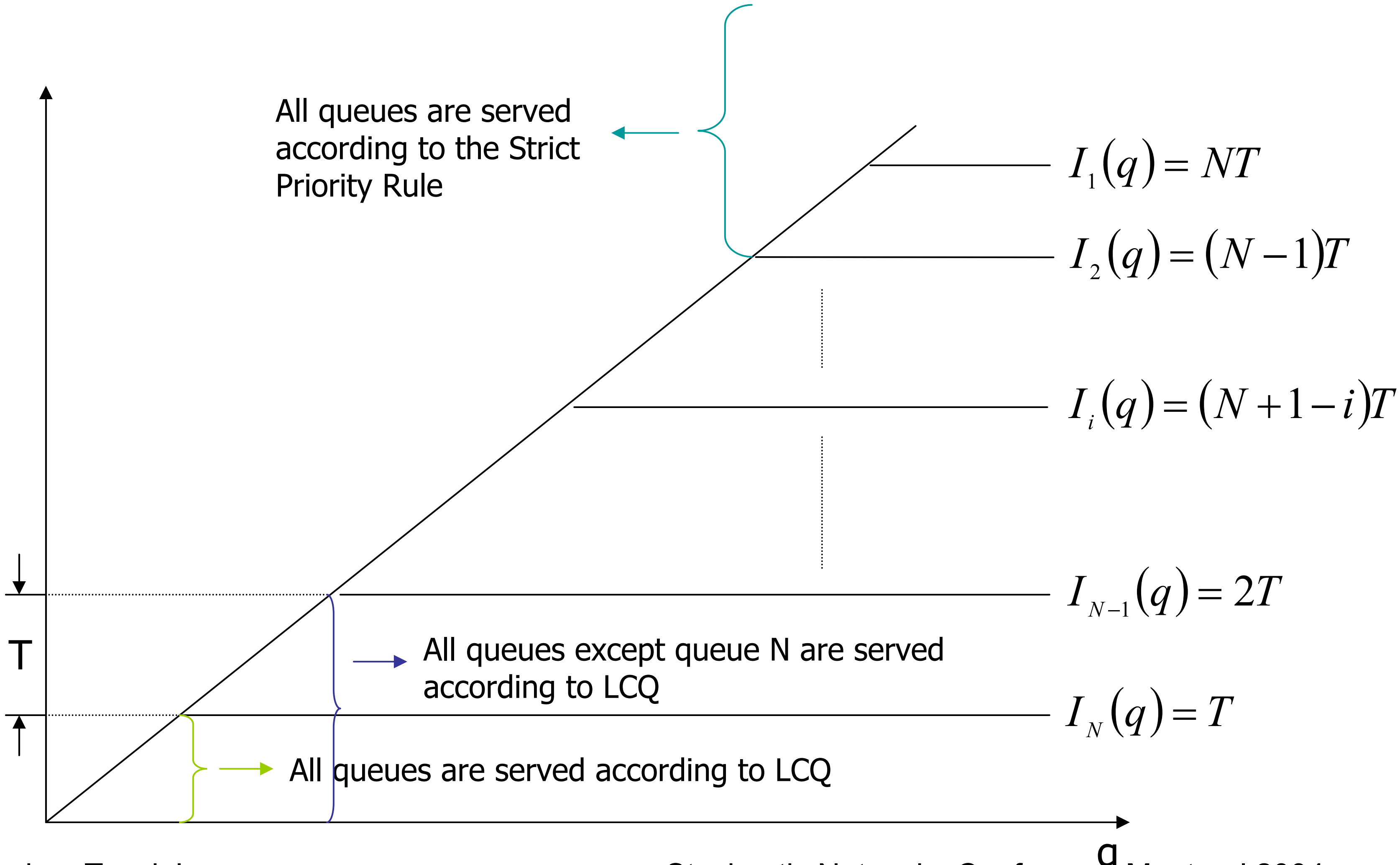
Index In(t) = I(bn(t)) associated with user n where bn(t) backlog of user n and

$$I(b) = \begin{cases} b, & \text{if } b \le (N+1-i)T \\ (N+1-i)T, & \text{if } b > (N+1-i)T \end{cases}$$

Among the users with available channel select at each slot the one with largest index

(Tsimbonis, Georgiadis, Tassiulas infocom03, IT Trans 05 to appear)

Operating Diagram



Traffic Model

- Let $A_i(s,t)$ be the number of packets that arrive at queue i during the time interval $[s,t]$
- Burstiness Constraints: $A_i(s,t)$ is $(\sigma_i^U, \sigma_i^L, \alpha_i)$-constrained, i.e.,

$$\alpha_i(t-s) - \sigma_i^L \leq A_i(s,t) \leq \alpha_i(t-s) + \sigma_i^U$$

Note: α_i is the long-term arrival rate to queue i

Channel Availability Model

- The wireless channel state varies with time between "on" and "off" states for the various users
- Let $C_Q(s,t)$ denote the number of slots in the time interval $[s,t]$ such that at least one of the channels in Q is "on"
- Burstiness Constraints: $C_Q(s,t)$ is $(\theta_Q^U, \theta_Q^L, F(Q))$-constrained, i.e.,

$$F(Q)(t-s) - \theta_Q^L \le C_Q(s,t) \le F(Q)(t-s) + \theta_Q^U$$

Note: $F(Q)$ is the long-term fraction of time that at least one of the channels in Q is "on"

Example

Channel 1	on	off	off	on
Channel 2	off	off	on	on

0 1 2 3 4

$$C_{\{1,2\}}(0,4) = 3$$

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