MEASUREMENT-BASED HYBRID FLUID-FLOW MODELS FOR FAST MULTI-SCALE SIMULATION

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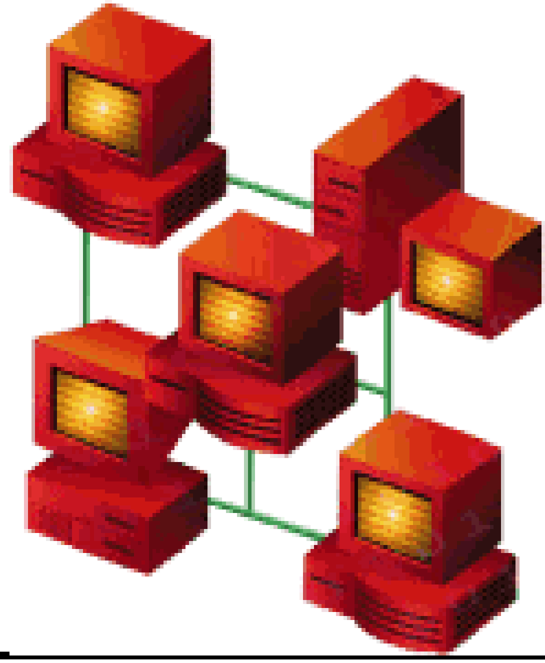


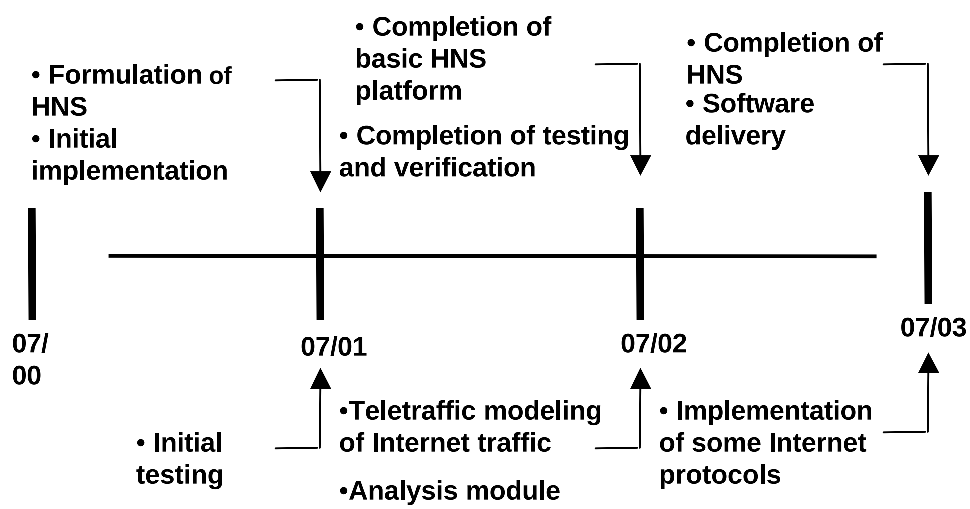
New Ideas

- ***Novel measurement-based traffic modeling methodology based on general time-Series processes (e.g., Auto-regressive Modular)***

- ***New hybrid discrete-continuous flow (HDFC) paradigm to combine discrete and continues flows resulting in fast simulation and considerable modeling flexibility***

Impact

- **Accurate traffic modeling driven by measurement-based models**
- **Multi-scale simulation paradigm from packet transport to protocol-based messages**
- **Identification of generic scalable network topologies**



MOTIVATION

- **Emerging high-speed packet-based telecommunications networks carry enormous traffic loads**
  - **compressed video**
  - **file transfer**

- **Network modeling and analysis technologies are urgently needed (*witness Internet congestion*)**
  - **network control (admission and congestion)**
  - **network provisioning and planning**

PROJECT GOALS

- **PROBLEM: Emerging high-speed packet-based telecommunications networks are hard to analyze**
  - **current analytical models cannot capture teletraffic burstiness and are overly optimistic**
  - **simulation of complex networks is either infeasible, or takes forever to complete**

- **SOLUTION GOALS: Develop a new modeling and simulation paradigm**
  - **hybrid simulation paradigm that combines traditional discrete flows with continuous ones**
  - **multi-scale simulation paradigm from packet transport to protocol-based messages**
  - **accurate teletraffic modeling driven by measurement-based teletraffic models**

TECHNICAL CHALLENGES

- **How to achieve a high expressive power of simulation models by capturing multiple scales?**
  - **transaction level (discrete and continuous flows)**
  - **message level (subject to prescribed protocols)**

- **How to speed up simulation runs?**
  - **large and complex network models give rise to enormous numbers of packet-based events**
  - **traditional simulation would require prohibitive computational resources to process**

- **How to achieve a high accuracy of predicted performance measures?**
  - **burstiness modeling**
  - **measurement-based teletraffic modeling**

NEW IDEAS

- **New Hybrid Discrete-Continuous Flow (HDCF) paradigm combines discrete and continuous flows**
  - **fast simulation takes advantage of fluid transport**
  - **flexible modeling allows modeler to assign type of flows (traditional discrete jobs or fluid-flow streams)**

- **Traffic model**
  - **new accurate measurement-based teletraffic modeling methods via ARM (AutoRegressive Modular processes), e.g., TES, QTES**

BENEFITS TO DOD

- **Ability to model and simulate complex networks**
  - **accurate simulation models whose computational complexity using traditional models is currently infeasible or prohibitive**
  - **flexible paradigm allows users to control trade-off between computational complexity and model fidelity**

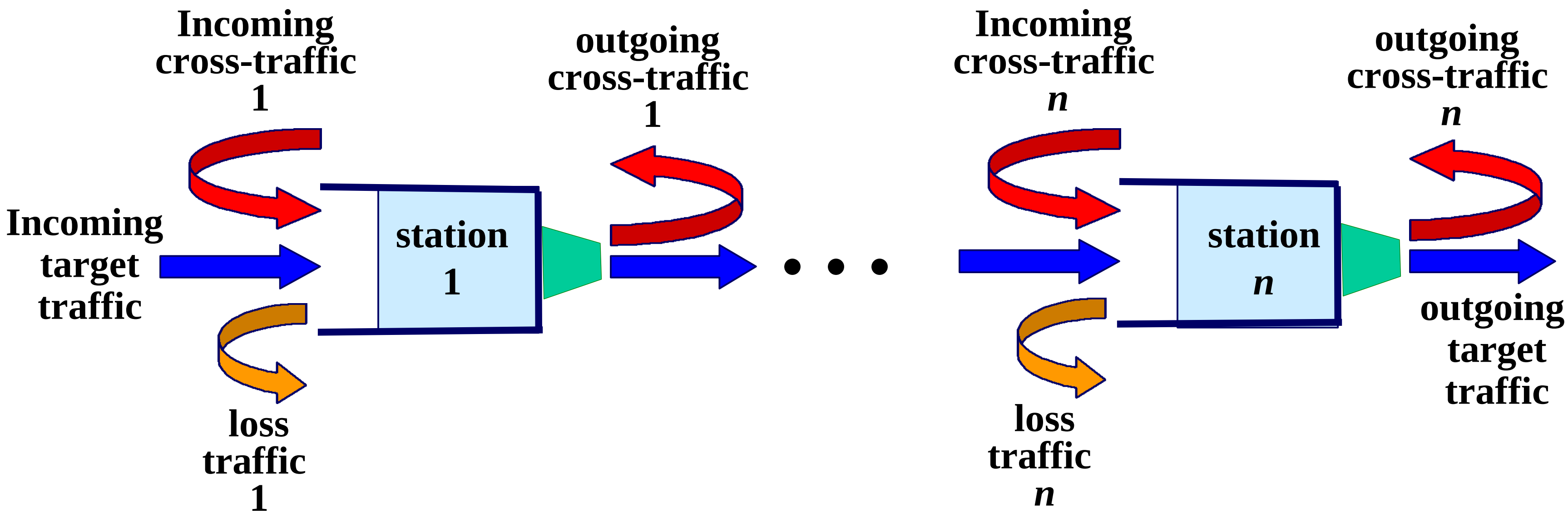
- **Integration with network applications**
  - **modeling of Next Generation Internet at multiple levels of detail**
  - **network design and capacity planning**
  - **network control (buffer management, service allocation)**

FLUID-FLOW MODEL SOLUTION

- ***Problem*: traditional discrete-event simulation at packet level is often *infeasible***
  - **time complexity (too many packets to process)**
  - **space complexity (too many packets to store)**

- ***Proposed Solution*: *fluid-flow models***
  - **transactions (customers, packets) become fluid**
  - **random discrete arrivals become random arrival rates**
  - **random discrete services become random service rates**
  - **random routing becomes rate thinning and merging**
  - **sample paths governed by differential equations**
  - **complex networks are modeled as TT/CT (Target-Traffic /Cross-Traffic) networks**

THE GENERIC TT/CT NETWORK MODEL

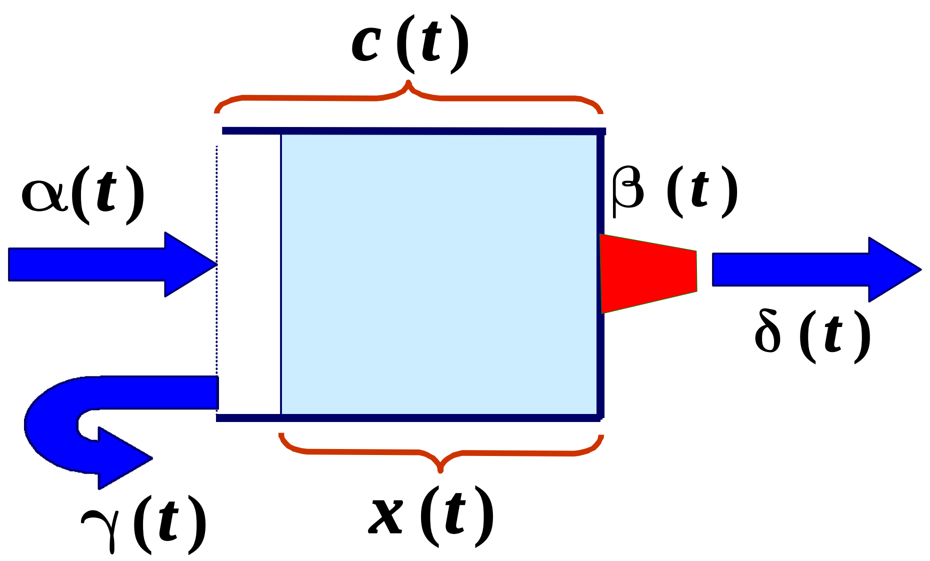


- **The generic TT/CT (Target-Traffic / Cross-Traffic) network model is a useful class of networks**
  - **simple HDCF network with tandem topology**
  - **reduced complexity renders simulation scalable in path size *n***
  - **accurate measurement- based teletraffic modeling and generation methods (e.g., QTES) already developed under a previous DARPA/ITO project**

FLUID-FLOW MODELING IMPLICATIONS

- **Fluid-flow simulation implications**
  - **events correspond to rate changes, which occur far less frequently than packet arrivals, service and routing**
  - **rate changes affect all downstream flows in a fluid-flow network, so fluid-flow events are more expensive than packet–flow events**
  - **overall, a fluid-flow simulation usually runs much faster than its packet–flow counterpart**

BASIC CONTINUOUS-FLOW MODEL (CFM)



Defining Processes

$\alpha(t)$ = inflow rate at time t

$\beta(t)$ = service rate at time t

$c(t)$ = capacity rate at time t

Derived Processes

$x(t)$ = workload at time t

$\gamma(t)$ = loss rate at time t

$\delta(t)$ = outflow rate at time t

DEFINING PROCESSES ASSUMPTIONS

- **The time horizon is an interval $[0,T)$**
- **The inflow rate process $\{\alpha(t)\}_{t=0}^{T}$ satisfies**
  - **with probability 1, the sample paths $\alpha(\cdot)$ are piecewise continuous and continuously differentiable in their continuity intervals**
- **The service rate process $\{\beta(t)\}_{t=0}^{T}$ satisfies**
  - **with probability 1, the sample paths $\beta(\cdot)$ are piecewise continuous and continuously differentiable in their continuity intervals**
- **The buffer capacity rate process $\{c(t)\}_{t=0}^{T}$ satisfies**
  - **with probability 1, the sample paths $c(\cdot)$ are piecewise continuous and continuously differentiable in their continuity intervals**

CFM AND DISCRETE-EVENT SIMULATION

- **Suppose that with probability 1, all defining processes of the basic CFM satisfy**
  - **all defining sample paths are piecewise constant**
  - **the number of jumps in finite time intervals is finite**
- **Then**
  - **the CFM is a DEDS (Discrete-Event Dynamic System)**
  - **the CFM can be simulated by a discrete-event simulation**
  - **the superposition of all jump time points of all defining processes over any finite interval can be written (with probability 1) as a strictly increasing finite sequence**

$$\{[t_i, t_{i+1})\}_{i=0}^{N}$$

  - **in particular, for any initial interval,**

$$t_0 = 0, \quad t_{N+1} = T$$

WORKFLOW PROCESS

- The workload process $\{x(t)\}_{t=0}^{T}$ is governed by

$$\frac{d}{dt}x(t) = \begin{cases} 0, & \text{if } x(t)=0 \text{ and } \alpha(t) \le \beta(t) \\ c(t), & \text{if } x(t)=c(t) \text{ and } \alpha(t) - \beta(t) \ge c(t) \\ \alpha(t) - \beta(t), & \text{otherwise} \end{cases}$$

- Let all defining sample paths be piecewise constant, with finite number of jumps in finite time intervals
  - then the workload process is piecewise linear, and its values at event times can be computed recursively by

$$x_{i+1} = \min\{\max\{x(t_i) + [\alpha(t_i) - \beta(t_i)][t_{i+1} - t_i], 0\}, c(t_{i+1})\}$$

for a given initial value $x(0) = x_0$

OUTFLOW RATE PROCESS

- **The outflow rate process $\{\delta(t)\}_{t=0}^{T}$ is defined by**

$$\delta(t) = \begin{cases} \alpha(t), & \text{if } x(t) = 0 \\ \beta(t), & \text{if } x(t) > 0 \end{cases}$$

  - **if the defining sample paths are piecewise constant, then the loss rate process is piecewise constant, and can be computed from the workload process**

- **The average outflow (throughput) over $[0,T)$ is**

$$\bar{\delta}(T) = \frac{1}{T}\int_0^T \delta(t)\,dt$$

LOSS RATE PROCESSES

- **The loss rate process $\{\gamma(t)\}_{t=0}^{T}$ is defined by**

$$\gamma(t) = \begin{cases} \alpha(t) - \beta(t) - c(t), & \text{if } x(t) = c(t) \text{ and } \\ & \alpha(t) \geq \beta(t) + c(t) \\ 0, & \text{otherwise} \end{cases}$$

  - **if the defining sample paths are piecewise constant, then the loss rate process is piecewise constant, and can be computed from the workload process**

LOSS VOLUME PROCESSES

- The loss volume $L(t_1,t_2)$ over $[t_1,t_2)$ is defined by

$$L(t_1,t_2) = \int_{t_1}^{t_2} \gamma(t)\,dt$$

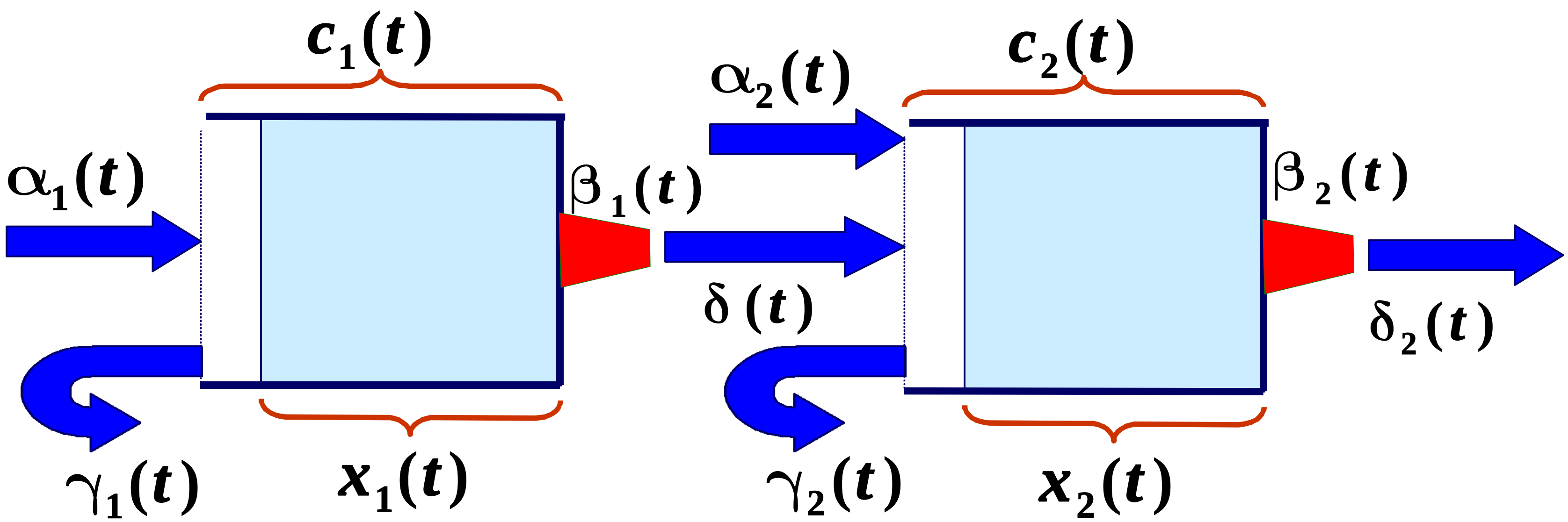
- Let all defining sample paths be piecewise constant, with finite number of jumps in finite time intervals
  - then the partial loss volumes over $[t_1,t_2)$ are given by

$$L(t_i,t_{i+1}) = \begin{cases} [\alpha(t_i)-\beta(t_i)][t_{i+1}-t_i]+x(t_i)-c(t_{i+1}), & \text{if } x(t_i)=c(t_{i+1}) \\ 0, & \text{otherwise} \end{cases}$$

- The loss fraction over $[t_1,t_2)$ is defined by

$$L_f(t_1,t_2) = \int_{t_1}^{t_2} \gamma(t)\,dt \Big/ \int_{t_1}^{t_2} \alpha(t)\,dt$$

CFM NETWORKS



Defining Processes

$\alpha_i(t)$ = inflow rate at node i

$\beta_i(t)$ = service rate at node i

$c_i(t)$ = capacity rate at node i

Derived Processes

$x_i(t)$ = workload at node i

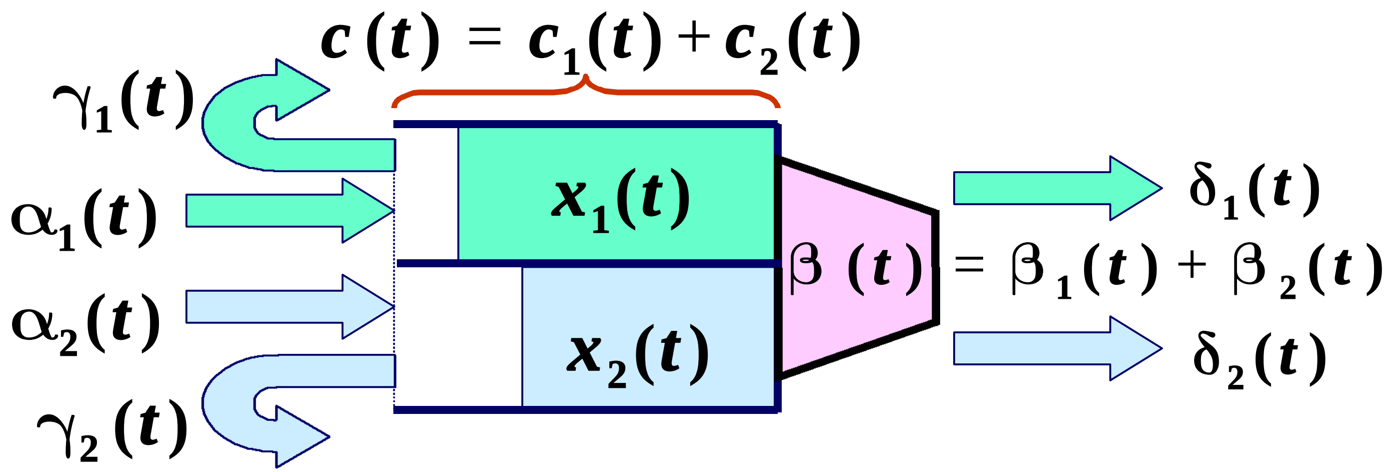
$\gamma_i(t)$ = loss rate at node i

$\delta_i(t)$ = outflow rate at node i

CFM NETWORKS (Cont.)

- A *CFM network* is a set of *interacting* basic CFM nodes
  - shared buffer
  - shared server
- Basic CFM nodes may be interconnected
  - flows have an itinerary of multiple nodes
  - flows may split and merge
- For piecewise constant defining processes
  - CFM network is a DEDS, with all derived processes being piecewise constant
  - CFM network is amenable to discrete-event simulation

MULTIPLE-FLOW CFM's



Defining Processes

$\alpha_i(t) = i$ - *th* inflow rate

$\beta_i(t) = i$ - *th* service rate

$\beta(t)$ = total service rate

$c_i(t) = i$ - *th* capacity rate

$c(t)$ = total buffer capacity

Derived Processes

$x_i(t) = i$ - *th* workload

$\gamma_i(t) = i$ - *th* loss rate

$\delta_i(t) = i$ - *th* outflow rate

INTERACTING EQUAL-PRIORITY FLOWS

- **Basic equal-priority CFM_1 and CFM_2**
- **Defining processes**
  - inflow rates are $\alpha_i(t),\ i=1,2$
  - service rates are $\beta_i(t),\ i=1,2,$ subject to a shared total service rate $\beta(t) = \beta_1(t) + \beta_2(t)$
  - buffer capacities are $c_i(t),\ i=1,2,$ subject to a shared total buffer capacity $c(t) = c_1(t) + c_2(t)$
- **Derived processes**
  - workloads $x_i(t),\ i=1,2,$ computed separately
  - loss rates $\gamma_i(t),\ i=1,2,$ computed separately
  - outflow rates $\delta_i(t),\ i=1,2,$ computed separately

INTERACTING PREEMPTIVE-PRIORITY FLOWS

- Basic CFM_1 of higher priority than basic CFM_2
- Defining processes
  - inflow rates are $\alpha_i(t),\ i = 1, 2$
  - service rates are $\beta_i(t),\ i = 1, 2,$ subject to a shared total service rate $\beta(t) = \beta_1(t) + \beta_2(t)$ such that

$$\beta_1(t) = \begin{cases} \beta(t), & \text{if } x_1(t) > 0 \\ \alpha_1(t), & \text{if } x_1(t) = 0 \end{cases} \qquad \beta_2(t) = \beta(t) - \beta_1(t)$$

  - buffer capacities are $c_i(t),\ i = 1, 2,$ subject to a shared total buffer capacity $c(t) = c_1(t) + c_2(t)$ such that

$$c_1(t) = \begin{cases} c(t), & \text{if } x_1(t) > 0 \\ 0, & \text{if } x_1(t) = 0 \end{cases} \qquad c_2(t) = c(t) - c_1(t)$$

- Derived processes are computed separately

NETWORK SERVICE RATE ALLOCATION

- **CFM simulation requires a service rate allocation algorithm, invoked on state changes**
- **Input**
  - **network nodes** $\{1, \ldots, n\}$
  - **current inflow rate at each node** $\{\alpha_j : j = 1, \ldots, n\}$
  - **current workload at each node** $\{x_j : j = 1, \ldots, n\}$
  - **network total service rate** β **to be allocated to nodes**
- **Output**
  - **service rates at each node** $\beta_j, j = 1, \ldots, n,$ **such that**

$$\sum_{j=1}^{n} \beta_j = \beta$$

SERVICE RATE ALLOCATION ALGORITHM

- **Initialize**

  set N ¬ {1, ¼ , n}

  set Z ¬ {j Î N : x_j = 0 **and** α_j < β/n}

  set b ¬ β

- **Main loop**

  while (Z ¹ Æ)

  set β_j ¬ α_j **for all** j Î Z

  set b ¬ b - å $_{j \,\text{Î}\, Z}\, \alpha_j$

  set N ¬ N - Z

  set Z ¬ {j Î N : x_j = 0 **and** α_j < $\beta/|N|$}

- **Finalize**

  if (N ¹ Æ)

  set β_j ¬ $b/|N|$ **for all** j Î N

FLUID VS. PACKET TRANSPORT

- **Main simulation events in packet-based transport**
  - **arrivals, service completions, packet loss**
- **Main simulation events in CFM**
  - **changes in arrival rate, service rate and capacity rate**

- **Comparison of Computational Complexity**
  - **packet-based transport has enormous number of events, each being local**
  - **CFM transport has far fewer events in single-node models**
  - **events in CFM transport are global (rate re-computation)**
  - **in feed-forward CFM networks, rate re-computation is fast, but events grow quadratically via the *ripple effect***
  - **in general CFM networks, rate re-computation is hard, and events can grow explosively via the *echo effect***

PROPOSED CFM RESEARCH

- **CFM telecommunications applications**
  - **network design, planning and provisioning**
  - **network resource allocation**

- **CFM software tools**
  - **object-oriented CFM simulator architecture and software**