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

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MEASUREMENT-BASED HYBRID MODELS FOR FAST MULTI-SCALE SIMULATION

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 continuous 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

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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
• 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)
• **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 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:
- $\alpha(t) = \text{inflow rate at time } t$
- $\beta(t) = \text{service rate at time } t$
- $c(t) = \text{capacity rate at time } t$

Derived Processes:
- $x(t) = \text{workload at time } t$
- $\gamma(t) = \text{loss rate at time } t$
- $\delta(t) = \text{outflow rate at time } t$
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 \(\alpha(\mathbb{X})\) 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 \(\beta(\mathbb{X})\) 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 \(c(\mathbb{X})\) are piecewise continuous and continuously differentiable in their continuity intervals.
• 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

\[
\frac{dx(t)}{dt} = \begin{cases} 
0, & \text{if } x(t) = 0 \text{ and } \alpha(t) \leq \beta(t) \\
c(t), & \text{if } x(t) = c(t) \text{ and } \alpha(t) - \beta(t) \geq 3c(t) \\
\alpha(t) - \beta(t), & \text{otherwise}
\end{cases}
\]

• 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 \( x(0) = x_0 \)
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

\[
\bar{\delta}(T) = \frac{1}{T} \int_{0}^{T} \delta(t) \, dt
\]
The loss rate process \( \{ \gamma(t) \}_{t=0}^{T} \) is defined by

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

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

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

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

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

\[ c(t) = c_1(t) + c_2(t) \]

\[ \gamma_1(t) \]
\[ \alpha_1(t) \]
\[ \alpha_2(t) \]
\[ \gamma_2(t) \]
\[ \beta(t) = \beta_1(t) + \beta_2(t) \]
\[ \delta_1(t) \]
\[ \delta_2(t) \]

**Defining Processes**

\[ \alpha_i(t) = i - \text{th inflow rate} \]
\[ \beta_i(t) = i - \text{th service rate} \]
\[ \beta(t) = \text{total service rate} \]
\[ c_i(t) = i - \text{th capacity rate} \]
\[ c(t) = \text{total buffer capacity} \]

**Derived Processes**

\[ x_i(t) = i - \text{th workload} \]
\[ \gamma_i(t) = i - \text{th loss rate} \]
\[ \delta_i(t) = i - \text{th outflow rate} \]
INTERACTING EQUAL-PRIORITY FLOWS

• Basic equal-priority CFM₁ and CFM₂

• 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 CFM₁ of higher priority than basic CFM₂
- 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
    \[
    \beta_1(t) = \begin{cases} 
    \beta(t), & \text{if } x_1(t) > 0 \\
    \alpha_1(t), & \text{if } x_1(t) = 0
    \end{cases}
    \]
    \[
    \beta_2(t) = \beta(t) - \beta_1(t)
    \]
  - 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
    \[
    c_1(t) = \begin{cases} 
    c(t), & \text{if } x_1(t) > 0 \\
    0, & \text{if } x_1(t) = 0
    \end{cases}
    \]
    \[
    c_2(t) = c(t) - c_1(t)
    \]
- Derived processes are computed separately
NETWORK SERVICE RATE ALLOCATION

• CFM simulation requires a service rate allocation algorithm, invoked on state changes

• Input
  • network nodes \( \{1, \frac{1}{4}, n\} \)
  • 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 \( \beta \) 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 \( N \leftarrow \{1^{1/4}, n\} \)
  
  set \( Z \leftarrow \{j \in N : x_j = 0 \text{ and } \alpha_j < \beta/n\} \)
  
  set \( b \leftarrow \beta \)

• Main loop

  while \( (Z \neq \emptyset) \)
  
  set \( \beta_j \leftarrow \alpha_j \) for all \( j \in Z \)
  
  set \( b \leftarrow b - \hat{\alpha}_j z \alpha_j \)
  
  set \( N \leftarrow N - Z \)
  
  set \( Z \leftarrow \{j \in N : x_j = 0 \text{ and } \alpha_j < \beta/|N|\} \)

• Finalize

  if \( (N \neq \emptyset) \)
  
  set \( \beta_j \leftarrow b/|N| \) for all \( j \in N \)
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