Modelling network performance with a spatial stochastic process algebra

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17 June 2010
Introduction

- model network performance
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- introduce spatial concepts to a stochastic process algebra
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- analysis using continuous time Markov chains (CTMCs)
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▶ introduce spatial concepts to a stochastic process algebra
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▶ demonstrate through an example
▶ other approaches to network modelling
  ▶ using the same spatial stochastic process algebra
  ▶ using a process algebra with stochastic, continuous and discrete aspects
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- demonstrate through an example
- other approaches to network modelling
  - using the same spatial stochastic process algebra
  - using a process algebra with stochastic, continuous and discrete aspects
- conclusions and further work
Motivation

- PEPA [Hillston 1996]

▶ compact syntax, rules of behaviour

\[
P(\alpha, r) \rightarrow P'\]

▶ transitions labelled with \((\alpha, r) \in A \times R^+\)

▶ interpret as continuous time Markov chain or ODEs

▶ various analyses to understand performance

▶ add a general notion of location

- location names, cities

- points in \(n\)-dimensional space
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P + Q \xrightarrow{(\alpha,r)} P' \\
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Spatial stochastic process algebra

- locations, $\mathcal{L}$ and collections of locations, $\mathcal{P}_\mathcal{L}$
Spatial stochastic process algebra

- locations, $\mathcal{L}$ and collections of locations, $\mathcal{P}_\mathcal{L}$
- structure over $\mathcal{P}_\mathcal{L}$, weighted graph $G = (\mathcal{L}, E, w)$
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- $L \in \mathcal{P}_\mathcal{L}$, $\alpha \in \mathcal{A}$, $M \subseteq \mathcal{A}$, $r > 0$
- sequential components
  
  $$S ::= (\alpha@L, r).S \mid S + S \mid C_s@L$$
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Spatial stochastic process algebra

- locations, $L$ and collections of locations, $P_L$
- structure over $P_L$, weighted graph $G = (L, E, w)$
  - undirected hypergraph or directed graph
  - $E \subseteq P_L$ and $w : E \rightarrow \mathbb{R}$
  - weights modify rates on actions between locations
- $L \in P_L \quad \alpha \in A \quad M \subseteq A \quad r > 0$
- sequential components
  \[ S ::= (\alpha @ L, r).S \mid S + S \mid C_s @ L \]
- locations defined at sequential level only
Spatial stochastic process algebra

- locations, \( \mathcal{L} \) and collections of locations, \( \mathcal{P}_\mathcal{L} \)
- structure over \( \mathcal{P}_\mathcal{L} \), weighted graph \( G = (\mathcal{L}, E, w) \)
  - undirected hypergraph or directed graph
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- \( L \in \mathcal{P}_\mathcal{L} \), \( \alpha \in \mathcal{A} \), \( M \subseteq \mathcal{A} \), \( r > 0 \)
- sequential components
  \[
  S ::= (\alpha @ L, r).S \mid S + S \mid C_s @ L
  \]
- locations defined at sequential level only
- model components
  \[
  P ::= P \boxtimes \!_M P \mid P / M \mid C
  \]
Parameterised operational semantics

- define abstract process algebra parameterised by three functions
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- transitions labelled with $\mathcal{A} \times \mathcal{P}_L \times \mathbb{R}^+$
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- Prefix

$$L' = \text{apref}((\alpha @ L, r).S)$$
Parameterised operational semantics

- define abstract process algebra parameterised by three functions
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- Prefix

$$\frac{L' = \text{apref}((\alpha \otimes L, r).S)}{(\alpha \otimes L, r).S \xrightarrow{(\alpha \otimes L', r)} S}$$

- Cooperation

$$\frac{P_1 \xrightarrow{(\alpha \otimes L_1, r_1)} P'_1}{P_1 \bowtie_M P_2 \xrightarrow{(\alpha \otimes L, R)} P'_1 \bowtie_M P'_2} \quad \frac{P_2 \xrightarrow{(\alpha \otimes L_2, r_2)} P'_2}{\alpha \in M}$$

$$L = \text{async}(P_1, P_2, L_1, L_2) \quad R = \text{rsync}(P_1, P_2, L_1, L_2, r_1, r_2)$$
Parameterised operational semantics

- define abstract process algebra parameterised by three functions
- transitions labelled with $\mathcal{A} \times \mathcal{P}_{\mathcal{L}} \times \mathbb{R}^+$
- Prefix

\[
(\alpha \otimes L, r).S \xrightarrow{(\alpha \otimes L', r)} S
\]

- Cooperation

\[
\begin{align*}
P_1 & \xrightarrow{(\alpha \otimes L_1, r_1)} P'_1 \\
P_2 & \xrightarrow{(\alpha \otimes L_2, r_2)} P'_2 \\
\otimes_{\mathcal{M}} P_1 & \xrightarrow{(\alpha \otimes L, R)} \otimes_{\mathcal{M}} P_2
\end{align*}
\]

\[
L = \text{async}(P_1, P_2, L_1, L_2) \quad R = \text{rsync}(P_1, P_2, L_1, L_2, r_1, r_2)
\]

- other rules defined in the obvious manner
Parameterised operational semantics

- define abstract process algebra parameterised by three functions
- transitions labelled with $A \times P_L \times \mathbb{R}^+$
- Prefix

$$\frac{(\alpha \otimes L, r).S}{(\alpha \otimes L', r)} \xrightarrow{\alpha \otimes L', r} S$$

$$L' = \text{apref}((\alpha \otimes L, r).S)$$

- Cooperation

$$\frac{P_1}{P_1} \xrightarrow{(\alpha \otimes L_1, r_1)} P'_1 \quad \frac{P_2}{P_2} \xrightarrow{(\alpha \otimes L_2, r_2)} P'_2$$

$$\frac{P_1 \boxdot \downarrow \boxdot M P_2}{P_1 \boxdot \downarrow \boxdot M P_2} \xrightarrow{(\alpha \otimes L, R)} P'_1 \boxdot \downarrow \boxdot M P'_2$$

$$L = \text{async}(P_1, P_2, L_1, L_2) \quad R = \text{rsync}(P_1, P_2, L_1, L_2, r_1, r_2)$$

- other rules defined in the obvious manner
- instantiate functions to obtain concrete process algebra
Concrete process algebra for modelling networks

- networking performance
Concrete process algebra for modelling networks

- networking performance
- scenario
Concrete process algebra for modelling networks

- networking performance
- scenario
  - arbitrary topology
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  - single packet traversal through network
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- choose functions to create process algebra
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  - each sequential component must have single fixed location
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  - processes can be collocated
- want to model different topologies and traffic
- choose functions to create process algebra
  - each sequential component must have single fixed location
  - communication must be pairwise and directional
- let $\mathcal{P}_\mathcal{L} = \mathcal{L} \cup (\mathcal{L} \times \mathcal{L})$, singletons and ordered pairs
Functions for concrete process algebra

- functions
Functions for concrete process algebra

- \( \text{apref}(S) = \begin{cases} \ell & \text{if } ploc(S) = \{\ell\} \\ \bot & \text{otherwise} \end{cases} \)
Functions for concrete process algebra

- functions

\[
apref(S) = \begin{cases} 
  \ell & \text{if } ploc(S) = \{\ell\} \\
  \bot & \text{otherwise}
\end{cases}
\]

\[
async(P_1, P_2, L_1, L_2) = \begin{cases} 
  (\ell_1, \ell_2) & \text{if } L_1 = \{\ell_1\}, L_2 = \{\ell_2\}, (\ell_1, \ell_2) \in E \\
  \bot & \text{otherwise}
\end{cases}
\]
Functions for concrete process algebra

- functions

\[ \text{apref}(S) = \begin{cases} \ell & \text{if } \text{ploc}(S) = \{\ell\} \\ \bot & \text{otherwise} \end{cases} \]

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\[ \text{rsync}(P_1, P_2, L_1, L_2, r_1, r_2) = \begin{cases} \frac{r_1}{r_\alpha(P_1)} \cdot \frac{r_2}{r_\alpha(P_2)} \cdot \min(r_\alpha(P_1), r_\alpha(P_2)) \cdot w((\ell_1, \ell_2)) & \text{if } L_1 = \{\ell_1\}, L_2 = \{\ell_2\}, (\ell_1, \ell_2) \in E \\ \bot & \text{otherwise} \end{cases} \]
Example network

Sender

A

P1

B

P2

C

P3

D

P4

E

P5

F

P6

Receiver

Example network

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PEPA model

\[
\begin{align*}
\text{Sender}@A & \overset{\text{def}}{=} (\text{prepare}, \rho).\text{Sending}@A \\
\text{Sending}@A & \overset{\text{def}}{=} \sum_{i=1}^{6} (c_{Si}, r_{s}).(\text{ack}, r_{ack}).\text{Sender}@A \\
\text{Receiver}@F & \overset{\text{def}}{=} \sum_{i=1}^{6} (c_{iR}, r_{6}).\text{Receiving}@F \\
\text{Receiving}@F & \overset{\text{def}}{=} (\text{consume}, \gamma).(\text{ack}, r_{ack}).\text{Receiver}@F
\end{align*}
\]

\[
\begin{align*}
P_i@l_i & \overset{\text{def}}{=} (c_{Si}, \top).Q_i@l_i + \sum_{j=1,j\neq i}^{6} (c_{ji}, r).Q_i@l_i \\
Q_i@l_i & \overset{\text{def}}{=} (c_{iR}, \top).P_i@l_i + \sum_{j=1,j\neq i}^{6} (c_{ij}, r).P_i@l_i
\end{align*}
\]

\[
\text{Network} \overset{\text{def}}{=} (\text{Sender}@A \Join (P1@B \Join (P2@C \Join (P3@C \Join (P4@D \Join (P5@E \Join (P6@F \Join \text{Receiver}@F)))))})
\]
Graphs

rates: \( r = r_R = r_S = 10 \)
Graphs

rates: \( r = r_R = r_S = 10 \)

the weighted graph \( G \) describes the topology

\[
\begin{array}{cccccc}
  & A & B & C & D & E & F \\
A & 1 & 1 & & & & \\
B & & 1 & 1 & & & \\
C & 1 & 1 & 1 & & & \\
D & 1 & & 1 & 1 & & \\
E & & 1 & 1 & 1 & & \\
F & 1 & & 1 & 1 & 1 & \\
\end{array}
\]
Graphs

- $G_1$ represents heavy traffic between $C$ and $E$

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>1</td>
<td></td>
<td></td>
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<tr>
<td>B</td>
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<td>D</td>
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<td>E</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
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</tr>
</tbody>
</table>
Graphs

- $G_2$ represents no connectivity between $C$ and $E$

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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</thead>
<tbody>
<tr>
<td>A</td>
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<td>1</td>
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<tr>
<td>C</td>
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<tr>
<td>D</td>
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<tr>
<td>F</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
Graphs

- $G_3$ represents high connectivity between colocated processes

\[
\begin{array}{ccccccc}
 & A & B & C & D & E & F \\
A & 1 & 1 & & & & \\
B & & & 1 & 1 & & \\
C & & & 1 & 10 & 1 & \\
D & & & 1 & & 1 & 1 \\
E & & & 1 & 1 & 1 & 1 \\
F & & 1 & 1 & 1 & & 10 \\
\end{array}
\]
Analysis

- cumulative density function of passage time

Comparison of different network models

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Evaluation

- uniform description for each node in the network
Evaluation

- uniform description for each node in the network
- network topology captured by graph
Evaluation

- uniform description for each node in the network
- network topology captured by graph
- graph modifications capture network variations
Evaluation

- uniform description for each node in the network
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- existing analysis framework
Evaluation

- uniform description for each node in the network
- network topology captured by graph
- graph modifications capture network variations
- existing analysis framework
- abstract process algebra is flexible
Different concrete process algebras

- multiple packets
Different concrete process algebras

- multiple packets
  - each located node in network is one or more buffers
Different concrete process algebras

- multiple packets
  - each located node in network is one or more buffers
  - similar approach
Different concrete process algebras

- multiple packets
  - each located node in network is one or more buffers
  - similar approach
  - throughput, loss rates
Different concrete process algebras

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- wireless sensor networks
Different concrete process algebras

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  - actual physical location
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- wireless sensor networks
  - actual physical location
  - weights capture performance characteristics over distance
Different concrete process algebras

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- scope for many other scenarios
Different concrete process algebras

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Different concrete process algebras

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- scope for many other scenarios
  - different types of networks
  - virus transmission in vineyards
And now for something slightly different

- Stochastic HYPE, joint with Jane Hillston and Luca Bortolussi
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- process algebra to model discrete, stochastic and continuous behaviour
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- process algebra to model discrete, stochastic and continuous behaviour
- semantic model
  - piecewise deterministic Markov processes
  - transition-driven stochastic hybrid automata

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  - periods of connectivity modelled stochastically
  - full buffers modelled discretely
  - determine storage required at nodes
Conclusion and further work

- conclusion
Conclusion and further work

- conclusion
  - stochastic process algebra with location

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Conclusion and further work

- conclusion
  - stochastic process algebra with location
  - designed to be flexible
Conclusion and further work

- conclusion
  - stochastic process algebra with location
  - designed to be flexible
  - useful for modelling network performance

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- further research
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- further research
  - explore how it can be applied in modelling networks
Conclusion and further work

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- conclusion
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  - designed to be flexible
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- further research
  - explore how it can be applied in modelling networks
  - explore how it can be applied elsewhere
  - comparison with other location-based formalism
Conclusion and further work

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Thank you

This research was funded by the EPSRC SIGNAL Project.
More comments

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  - then apply to concrete process algebra