A Signal Processing Approach to the Analysis of Chemical Networking Protocols

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Chemically Inspired Communication System

Communication Model

Chemical Model

Congestion Avoidance CNP  (T.Meyer, to be published)

Dynamics
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Concept of Chemical Networking Protocols (CNPs)

Equilibrium
Robustness
Self-Healing
Self-Optimization
Self-Protection

Goal

Chemical Metaphor

Molecules ↔ Packets
Chemical vessel ↔ Communication network nodes
Chemical reactions ↔ Communication links
Chemical virtual machines ↔ Computers with standard CPU

Chemical model implementation: Fraglets simulator.
User Information

*User information* is encoded inside packets.

A certain type of molecules (*species*) contain the same string of symbols.

*e.g.* [node2 HELLO WORLD]

System State Information

*System state information* is encoded in the *packet rate* itself.

- Concentration of a chemical species ≡ Number of molecules of that species.
- Reactions happen according to the «Law of mass action»:
  
  \[
  \text{Reaction Rate} \propto \text{Species concentration}
  \]

- Randomize queue entries
- Schedule the service
  - Forwarding as fast as possible
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CNP Properties

Dynamics Forecast

- Communication protocol implementations \(\rightarrow\) Abstract chemical models
- Chemical model dynamics are analyzable
- Dynamics analysis \(\rightarrow\) Chemical model optimization

Protocol implementation optimization
The Chemical Master Equation (CME)

The chemical model as

\[ \text{a continuous time discrete space Markov jump process} \]

(System state equals species concentration)

Dynamics of the system probability distribution governed by the CME

Features:

- Exact analysis of the \textit{stochastic} dynamical behavior of a model
- Very high computational complexity
- Solution not always possible
Standard Analysis of Network Dynamics (2/2)

The Differential Rate Equations Approximation (DREs)

Deterministic approximation of the exact stochastic behavior.

Features:

- Decrease of the computational complexity (still high)
- High concentration systems required
- Dependence on initial condition
Chemical networks as systems of blocks and interconnections. Concentration seen as a continuos-time continuos-value signal.

- Transfer function description
  - Generality of results
- Based on Differential Rate Equations (DREs) approximation
  - Low computational complexity
  - Deterministic approximation
  - Dependence on initial condition
The Disperser CNP

Disperser Features:
Species ≡ Vessels ≡ Nodes
Impulse input ≡ Injexion of molecules
Distributed average computation
Molecules equally distributed over the network

Connections Typology

Parallel of N-Node

Series of N-Node

Loop Network

Elementary Reactions

I Output

N Output
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Simulink Schematic

Node 1

Node 2

Node 3

Node 4
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Analysis Results (1/2)

Frequency Transforms

The Disperser CNP

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Analysis Results (2/2)

Impulse Responses

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State Variable Representation

\[
\begin{align*}
\dot{x}(t) &= A \cdot x(t) + B \cdot u(t) \\
y(t) &= C \cdot x(t) + D \cdot u(t)
\end{align*}
\]

- \(A\) State matrix
- \(B\) Input matrix
- \(C\) Output matrix
- \(D\) Direct transmission matrix

Analyzed systems must be **Linear Time Invariant (LTI)**
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System Control Theory (2/2)

Frequency Transform

Frequency characterization of species concentration

\[ C(s) = \frac{O}{(I \cdot s - A)^{-1} B + D} \]

Dynamical behavior of the network

\[ Y(s) = \frac{1}{s} \cdot C(s) \Leftrightarrow y(t) \]

Analyzed systems must be Linear Time Invariant (LTI)
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A Non-Linear CNP

Non-Linear Chemical Model

- Traffic Generation of Tx.1
- Tx.1 Output Rate
- Tx.2 Output Rate
- Channel Limitation
- Actual Network Output Rate
- Selective Feedbacks

DREs with Non-Linearities

- Species
- Molecules
- Reactions
  - Chemical Homeostasis
  - Species Dilution Flow
- Reaction Coefficients

\[
\begin{align*}
\dot{w} &= k_1 + 0 - k_3 \cdot w \cdot l + 0 \\
\dot{i} &= 0 + k_2 \cdot w - \frac{k_2 \cdot w}{k_2 \cdot w + v_{in}} + 0 - k_4 \cdot l
\end{align*}
\]
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Metabolic Control Analysis to Non-Linear CNPs

Non-Linear Chemical Model

DREs with Non-Linearities

Concept: System linearization around a fixed point (steady states)

\[
\dot{s}(t) = N \cdot v(s(t), p(t)) \quad \rightarrow \quad \dot{x}(t) = N \cdot \frac{\partial v}{\partial s} \cdot x(t) + N \cdot \frac{\partial v}{\partial p} \cdot u(t)
\]

State Variable Representation

\[
A = N \cdot \left. \frac{\partial v}{\partial s} \right|_{(s^{st}, p^{st})} \quad B = N \cdot \left. \frac{\partial v}{\partial p} \right|_{(s^{st}, p^{st})} \quad O = I \quad D = 0
\]
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Analysis Results (1/2)

Frequency Transform $W^{(n)}(s)$

Diagram showing signal processing components and their interactions.

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Step Response

Analysis Results (2/2)

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Telecommunications Engineering
Transmission and Communication Systems

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Step Response

$V_{out}$

$V_{in}$

$V_{out}$

$V_{out}$

$k_3=1, k_4=1$

$k_3=1, k_4=10$

$k_3=1, k_4=50$

$k_3=0.01, k_4=10$

$k_3=1, k_4=10$

Amplitude

Time (sec)
Discussion

Protocol behavior was not easily predictable.

- Now, all linear chemical networks are analyzable, with similar procedures to those shown.
- Non-linear networks are linearizable (MCA), with the side effect of a high computational complexity.
- Even links with delay have been analyzed (not shown).

Bi-stable systems.
- Fixed point near the saddle point.
- Stochasticity of CNPs briefly introduced.

Limits & Future
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Thank You

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