On Noise-Induced Adaptive Network Control in Ad Hoc Networks Based on Biological Models

(アドホックネットワークにおける生物モデルにもとづいた
ゆらぎを活用する適応型ネットワーク制御)

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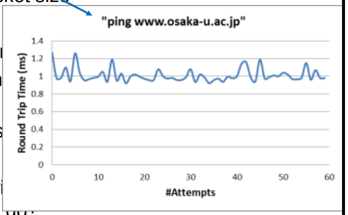
Outline of Thesis

- Introduction — Chapter 1
  - Noise, biological systems, and communications networks
  - Bio-inspired models
- Resilient mobile ad hoc routing — Chapter 2
  - Bio-inspired attractor selection model
- Concurrent multipath traffic distribution — Chapter 3
  - Bio-inspired attractor perturbation model
- Design considerations for future applications of noise-based models — Chapter 4
- Conclusion — Chapter 5

Fluctuations (Noise) in Networks

- Many fluctuating variables in communications networks
  - Random bit errors, measurement errors, signal level
  - Propagation time, retransmission rate, collision rate
  - Routing delay, packet size
  - Throughput, RTT,
- Conventional questio
  - How to eliminate n
- However, fluctuations
- <u>New question</u>:
  - How do we deal wi
    biological systems do?



Biological Systems and Noise

- Biological systems
  - can be regarded as dynamic systems
  - are adaptive to fluctuating environments
  - integrate noise internally as a part of their mechanisms

- Questions:
  - Do we really need to eliminate noise in artificial systems?
    → explore an alternative approach in this study
  - What are the features in biological systems that can be used in communications networks?

From Biological Systems to Network Control

Biological Systems	Ideal Network Control
Adaptable and survivable in various environments using noise	Adaptability to various conditions, including emerging problems
Self-organized and distributed control using local information and noise	Simple configuration (or self-organized)
Revertible to stable states after received external influences by noise	Ability to recover from errors and failures (or robustness)

Features of biological systems can be useful to communications network control

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Existing Techniques

Ideal Network Control	Limitations
Adaptability to various conditions, including emerging problems	Parameters fine-tuning required for adapting, i.e., human intervention needed
Simple configuration (or self-organized)	Many parameters to be configured for each deployment attempt
Ability to recover from errors and failures (or robustness)	Robust only within the scope of predefined rules and preconfigured parameters

Contribution of This Study

Problem:

A lack of adaptability towards emerging problems
of existing network control

due to

dependence on limited predefined rules
and
fine-tuned parameters

Contribution:

Propose noise-based network control to solve
the adaptability problem using biological models

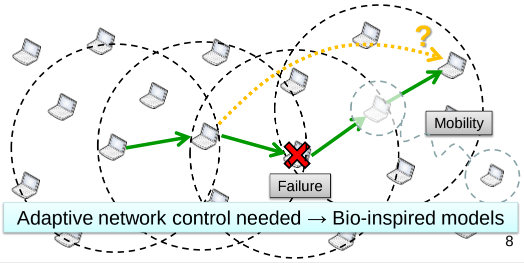
Our Focus: Mobile Ad Hoc Networks

- Limited transmission range
- Continuous topology changes

⇨ Adaptive routing protocol

- Limited bandwidth
- Limited battery lifetime

⇨ Bandwidth improvement and load balancing technique



Adaptive network control needed → Bio-inspired models

Bio-Inspired Models

Attractor Selection [33]

- Derived from a synthetic bistable gene switch in *E. coli* in which mutually inhibitory operons govern the expression of two genes
- Noise is used for randomly selecting operons
- Proposal: mobile ad hoc routing protocol

Attractor Perturbation [54]

- Derived from fluctuation and response relationship in an evolutionary molecular experiment
- Noise or fluctuation is used to determine the response of the applied amount of controlling force
- Proposal: concurrent multipath traffic distribution

Noise is used to increase adaptability in these models

[33] A. Kashiwagi, I. Urabe, K. Kaneko, and T. Yomo. "Adaptive response of a gene network to environmental changes by fitness-induced attractor selection." PLoS ONE, 1(1):e49(1{10), Dec. 2006.
[54] K. Sato et al., "On the Relation between Fluctuation and Response in Biological Systems," in Proceedings of the National Academy of Sciences, volume 100, pages 14086{14090, 2003.

CHAPTER 2: RESILIENT MOBILE AD HOC ROUTING WITH ATTRACTOR SELECTION

[5] N. Asvarujanon, K. Leibnitz, N. Wakamiya, and M. Murata. Extension and evaluation of biologically-inspired routing protocol for MANETs. In Technical Report of IEICE (NS2009-52), July 2009.

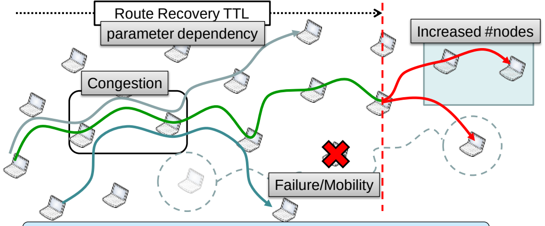
[6] N. Asvarujanon, K. Leibnitz, N. Wakamiya, and M. Murata. Evaluation of robustness and adaptability of a biologically-inspired MANET routing protocol. In Technical Report of IEICE (NS2009-52), Jan. 2010.

[7] N. Asvarujanon, K. Leibnitz, N. Wakamiya, and M. Murata. Robust and adaptive mobile ad hoc routing with attractor selection. In Proceedings of the 4th International workshop on Adaptive and DependAble Mobile Ubiquitous Systems (ADAMUS), Berlin, Germany, July 2010.

[10] N. Asvarujanon, K. Leibnitz, N. Wakamiya, and M. Murata. Resilient mobile ad hoc routing with attractor selection for dense and heavy traffic scenarios. To appear in Special Issue of International Journal on Autonomous and Adaptive Communications Systems (IJAACS) on Self-* Systems, 2013.

MANET Routing Desirable Features

- Adaptability to overcome parameter fine-tuning needs
- Resilience to topology changes (e.g. failure/mobility)
- Scalability to increased number of node (also density)
- Survivability to increased traffic load (congestion)



Adaptive routing protocol with **Attractor Selection**

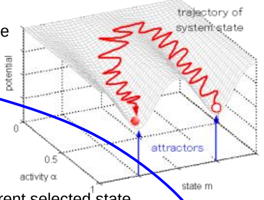
Attractor Selection Mechanism

- Biologically-inspired mechanism
  - ➢ Adopted from the mechanism of gene expression in cell biology
  - ➢ Robust and adaptive against the external influences and noise
  - ➢ **Feedback driven**
- Model

$$\frac{d\vec{m}}{dt} = f(\vec{m}) \times \alpha + \vec{\eta}$$

- Key controlling factors
  - ➢ Activity α: goodness of the current selected state
  - ➢ Noise η: randomness for discovering a better state

[33] A. Kashiwagi, I. Urabe, K. Kaneko, and T. Yomo. "Adaptive response of a gene network to environmental changes by fitness-induced attractor selection." PLoS ONE, 1(1):e49(1{10), Dec. 2006.

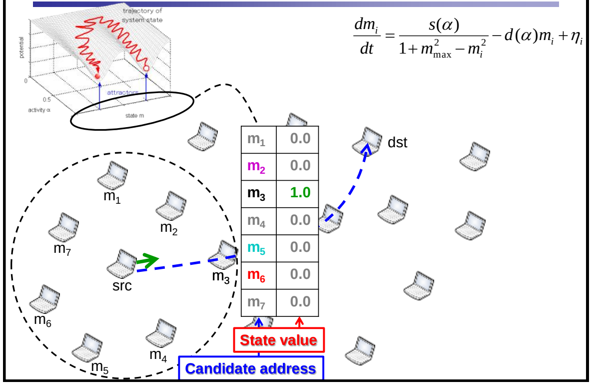


Applied to next hop selection process

$$\text{Activity } \alpha = \frac{\text{minimum known hop count}}{\text{current path's hop count}}$$

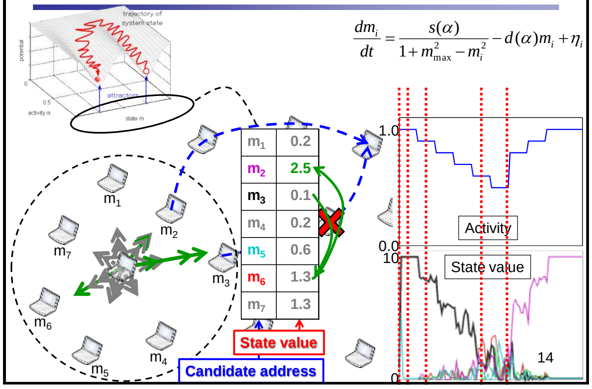
Example: Routing Setup

$$\frac{dm_i}{dt} = \frac{s(\alpha)}{1+m_{\max}^2 - m_i^2} - d(\alpha)m_i + \eta_i$$



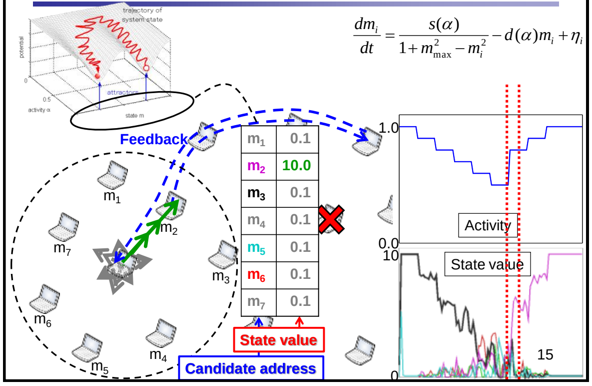
Example: Noise Based Recovery

$$\frac{dm_i}{dt} = \frac{s(\alpha)}{1+m_{\max}^2 - m_i^2} - d(\alpha)m_i + \eta_i$$



Example: Feedback Update

$$\frac{dm_i}{dt} = \frac{s(\alpha)}{1+m_{\max}^2 - m_i^2} - d(\alpha)m_i + \eta_i$$

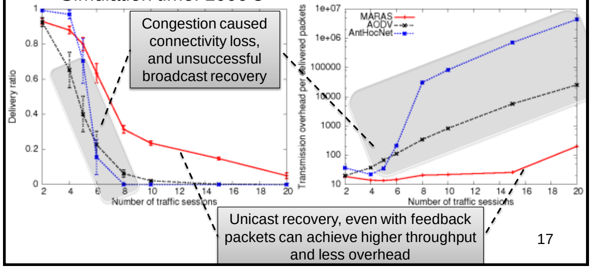


Evaluation

- Our proposal: MARAS
- Comparison targets: AODV, AntHocNet (ACO-inspired)
- Simulator: QualNet (commercial)
- Metrics
  - Delivery count/ratio
  - Transmission count (overhead)
- Scenarios
  - Against failures
  - Against number of nodes (node density)
  - Against traffic load (congestion)
  - Against mobility and number of nodes
  - Against mobility, number of nodes, and traffic load

Evaluation against Traffic Load

- Fixed: 256 nodes, simulation area of 1500x1500 m^2
- 802.11b Data rate 2 Mbps, transmission range ~510m
- Traffic rate 8 Kbps per session, 2 to 20 sessions
- Simulation time: 1000 s



Congestion caused connectivity loss, and unsuccessful broadcast recovery

Unicast recovery, even with feedback packets can achieve higher throughput and less overhead

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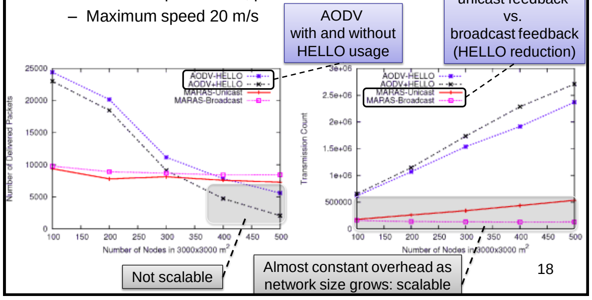
Evaluation against Mobility and #Nodes

- Simulation area 3000x3000 m^2
- Random waypoint mobility: highly mobile scenario
  - Minimum speed 1 m/s, pause-time 0 s
  - Maximum speed 20 m/s

AODV with and without HELLO usage

unicast feedback vs. broadcast feedback (HELLO reduction)



Not scalable

Almost constant overhead as network size grows: scalable

Chapter 2: Summary

- We proposed a bio-inspired MANET routing protocol
  - Next hop selection is based on attractor selection model
  - Noise-driven route maintenance controlled by attractor selection and feedback information-based activity

Merits:

- Adaptive to various scenarios without parameter modification, in contrast to other protocols that perform well in one but worse in the others
- Resilient to topology changes seen in the mobility scenario
- Scalable as the delivery performance and the amount overhead is maintained regardless of the number of nodes
- Survivable in extreme condition as high traffic load and high node density

CHAPTER 3: CONCURRENT MULTIPATH TRAFFIC DISTRIBUTION WITH ATTRACTOR PERTURBATION

[8] N. Asvarujanon, K. Leibnitz, N. Wakamiya, and M. Murata. Noise-assisted traffic distribution over multi-path ad hoc routing. In Proceedings of 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL), Barcelona, Spain, Oct. 2011.

[9] N. Asvarujanon, K. Leibnitz, N. Wakamiya, and M. Murata. Noise-assisted concurrent multipath traffic distribution in ad hoc networks. Conditionally accepted for IEICE Transactions on Communications (Special Section on Progress in Information Network Science), Nov. 2013.

[*] Narun Asvarujanon, Kenji Leibnitz, Naoki Wakamiya, and Masayuki Murata, An Attractor Perturbation-Based Traffic Distribution Method and Its Practical Experiments. To appear in Proceedings of the 2013 International Symposium on Nonlinear Theory and its Applications (NOLTA), (Santa Fe, USA), September 2013.

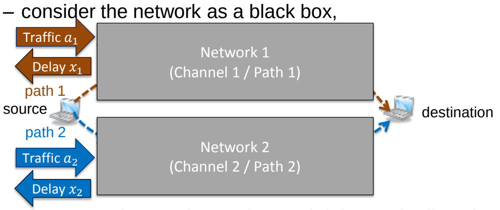
Motivation

- Multi-path approach has been used to increase robustness and available bandwidth

- However, existing traffic distribution approaches require **active** resource estimation, e.g., available bandwidth, number of flows, etc. to perform load balancing
  - resulting in high complexity and overhead

Research Overview

- Instead of tracking the complex resource information of each path to distribute traffic, we aim to
  - consider the network as a black box,



  - observe **only passive** end-to-end delay and adjust the traffic rate based on delay statistics
- Ability to estimate the effect of traffic rate change is required
  - Attractor perturbation concept is used

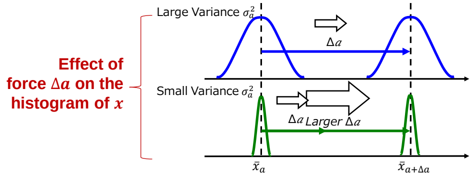
Attractor Perturbation (AP)

From an observation in cell biology [54] :

Given an *observable variable* x, which could be influenced by *parameter* a, when applying Δa (called *force*) to the system, the average of x is perturbed as follows:

$$\underbrace{\bar{x}_{a+\Delta a} - \bar{x}_a}_{\text{perturbation of average}} = \overset{\text{coefficient}}{b}\ \underbrace{\Delta a}_{\text{controllable force}}\ \overbrace{\sigma_a^2}^{\text{observed variance/noise}}$$

The above equation shows that the larger the **variance** is, the larger **perturbation of average** can be observed



[54] K. Sato et al., “On the Relation between Fluctuation and Response in Biological Systems," Proc. Nat'l. Academy Sci. USA, vol. 100, Nov. 2003, pp. 14086–90.

Attractor Perturbation in Networks

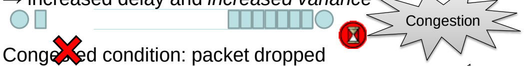
$$\bar{x}_{a+\Delta a} - \bar{x}_a = b\ \Delta a\ \sigma_a^2$$

x is the observed per-packet end-to-end delay

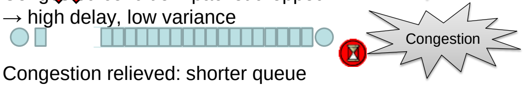
a is the traffic rate (amount of traffic on the path)

- No congestion: low delay and low variance

- Congestion started: Increased queuing time
→ increased delay and *increased variance*



- Congested condition: packet dropped
→ high delay, low variance



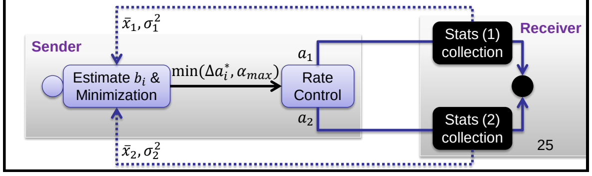
- Congestion relieved: shorter queue
→ decreased delay, *increased variance*

Implementation

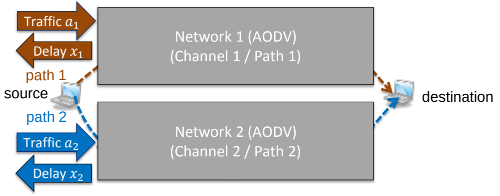
Minimization problem:

- Total delay $=\sum_{\text{all path } i}$(amount of traffic × delay)$=\sum_i a_i \bar{x}_i$
- Average delay of path i after traffic rate change
  $$\bar{x}'_i = \bar{x}_i + b_i \Delta a_i \sigma_i^2$$
- Total delay after traffic rate change $=\sum_i (a_i + \Delta a_i)\bar{x}'_i$
- Minimize $\sum_i (a_i + \Delta a_i)\bar{x}'_i$ s.t. $\sum_i \Delta a_i = 0$

Δa_i^* are solvable using Lagrangian



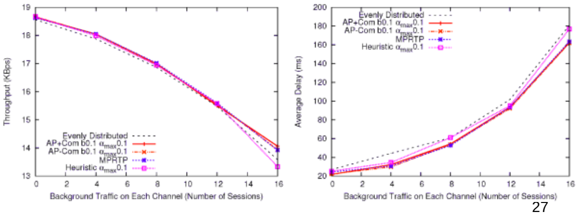
Evaluation Settings



- Two ad hoc networks on two non-interfering channels
- AODV is used as a routing protocol on both channels
- 100 nodes, area 1500x1500 m^2, simulation length 1000 s
- Random waypoint model: min 2 m/s, max 10 m/s, pause 30 s
- Main traffic: CBR 1000 bytes/packet, 20 packets/s
- Background traffic: 1 packet/s, 0-16 sessions

Evaluation Results

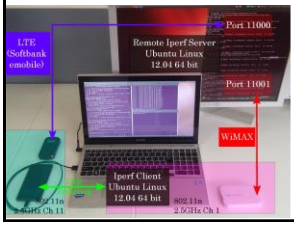
- Comparison: Multipath RTP (*MPRTP*) estimating throughput using delivered bytes, loss rate, and delay, shifting traffic to path with smaller average delay (*heuristic*), and *evenly distributed* on both paths
- AP can achieve approximately the same average end-to-end delay as MPRTP using only delay statistics without sacrificing throughput
- AP achieve lower average delay than two other approaches

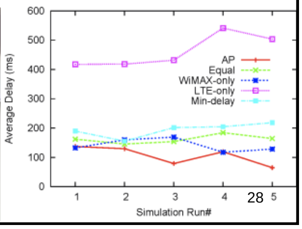


Note: Conclusion is made based on results with Confidence Interval (CI) of 97.5%

AP in Multi-homing Traffic Distribution

- Implementation using actual Linux device
- Send 7000 Kbps traffic (using Iperf UDP) over UQ WiMAX and Softbank emobile LTE
  - Sampling interval 5 s, Traffic session 100 s, 5 runs
  - Using only end-to-end delay average and variance





Chapter 3: Summary

- A concurrent multipath traffic distribution protocol based on attractor perturbation model
  - observed variable x = end-to-end delay
  - control variable a = traffic rate
- Objective: minimize total average end-to-end delay using only delay statistics between end nodes
- Results:
  - lower average delay than using both paths evenly
  - lower average delay than heuristic method that relies only on average delay (does not use variance)
  - same average delay as multipath RTP which uses full information of delivered bytes, loss rate, and delay
  - all without sacrificing throughput

Conclusion

- Alternative: utilizing noise instead of eliminating it
  - increased robustness against inaccurate information
  - increased adaptability to external influences including unknown conditions (emerging problems)
- Attractor selection based routing protocol
  - adaptive to various scenarios without reconfiguration
  - scalable due to random walk (noise) unicast recovery
- Attractor perturbation based traffic distribution method
  - lower average delay without sacrificing throughput using only end-to-end delay statistics
  - simplify system view to black box and influence performance using only end-to-end statistics

Thank you for your attention

Q&A