On Attractor Perturbation through System-inherent Fluctuations and its Response

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Network Traffic is not “Smooth”!

- However, network traffic is not smooth because:
  - Devices and services have different bandwidth requirements (browsing, VoIP, multimedia streaming, ...)
  - Background traffic from other users and external protocols (e.g., BGP routing updates) causes fluctuations in the perceived performance
- Therefore, it is necessary to apply new mechanisms that deviate from conventional teletraffic metrics in designing ambient network architectures
  - Focus is on including robustness and adaptability with traditional QoS measures, such as latency, jitter, etc.
  - We can take inspiration from dynamics found in biological systems

Considered Access Router Scenario

we want to control traffic into access router without affecting global traffic

Local buffer must control packet input flow from local observations only

Global buffer is isolated from the view of local buffer and should remain unmatched

Ambient Networks

- In future networks we will have ubiquitous connectivity:
  - Increased diversity in (wirelessly connected) devices and services
  - Requirement of efficient cooperation and interaction of devices
  - Concept of “ambient networks” makes the device adapt to the situation and user’s preferences

Why Use Robustness as Measure?

- Performance and sustainability of modern networks are becoming more important
- New approach focuses on robustness and adaptability
- Self-organizing networks based on bio-inspired approaches

Attractors and Robustness

- Nonlinear dynamics provides definitions for equilibrium point $x^*$:
  - $x^*$ is attracting if any trajectory starting close to $x^*$ will eventually converge to $x^*$
  - $x^*$ is Lyapunov stable, if all trajectories starting sufficiently close to $x^*$ remain close to it
  - $x^*$ is asymptotically stable, if it is both attracting and Lyapunov stable
- An attractor is an invariant closed set, which attracts all trajectories that start sufficiently near to it (basin of attractor)
Influence of Control on Fluctuations

- Relationship between fluctuation and its response (Sato et al. 2003)
- System has measurable variable \( x \) (protein concentration) and parameter \( \alpha \) (DNA sequence)
- Applying a force \( \alpha \rightarrow \alpha + \Delta \alpha \) to the system results in a linear perturbation of \( \mu \) (mean of \( x \)) proportional to \( \Delta \alpha \) (variance of \( x \) before applying the force):
  \[ \mu_{t+1} - \mu_t = b \Delta \alpha \sigma_x^2 \]

Proposed Control Scheme

- Control of local arrival probabilities \( p_\alpha(t) \), only by measuring time series \( x(t), \ldots, x(t) \) in a sliding window \( W \)
- Calculate variance over measured values as:
  \[ \sigma_x = \text{Var}[x(t), \ldots, x(t)] \]
- Update local probability \( p_\alpha(t) \) as follows:
  - Direction of adaptation \( \delta(t) = \text{sign}(\eta/2 - x(t)) \)
  - Strength of adaptation \( \eta(t) = p(t) \) utilizes linear relationship of variance
- “Force” is adapted as \( p_\alpha(t+1) = p_\alpha(t) + \delta(t) \sigma_x^2 \)

Attractors vs. Distributions?

- Simple dynamic equation with attractor at \( x \) given by
  \[ \frac{dx(t)}{dt} = -p(x(t) - x) + \eta(t) \]
- The term \( p \) is the “softness” of control in the system and \( \eta \) is the constant background noise (Gaussian) with variance \( \sigma^2 \)
- Noise follows a Gaussian distribution with pdf
  \[ p(x) = \frac{1}{\sqrt{2\pi \sigma^2}} \exp \left( -\frac{(x-x_0)^2}{2\sigma^2} \right) \]
- Taking the negative logarithm and deriving over \( x \) results in the energy potential function
  \[ -\log(p(x)) = \frac{(x-x_0)^2}{2\sigma^2} - \log(p(x_0)) \Rightarrow E(x) = -\frac{p(x-x_0)}{\sigma^2} \]

Dynamics of 1-Dimensional System

- Applying same force to system with different internal fluctuations results in different degrees of perturbations!
- So if we know the fluctuations (from measurements), we can directly compute the force necessary for “pushing” the system to a favorable operating region
Conclusion

- Ambient networks are composed of many diverse devices and services → many internal fluctuations
- Application of biologically inspired concept to adaptive network control to improve robustness
- Attractor perturbation permits to compute the force necessary to “push” the system state to a good solution
- Simple example was shown for controlling local buffer at gateway router based on local information only
- Applicability of attractor perturbation to other applications in ambient networks are being studied
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