Self-Organization & AI

BOWW 2025 | Berlin | H. Lehmann | Sep 9th 2025

GROUP **TECHNOLOGY**

Talk Rationale

With numerous internal degrees of freedom, telecommunication systems are capable of self-organization.

This has been known for a long time (cf. control theory approaches).

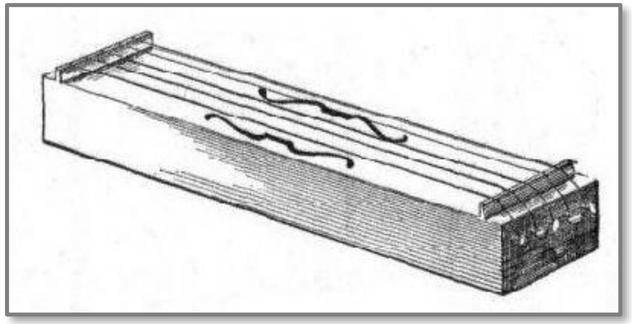
AI network management agents introduce a new quality of feedback loop.

A new type of study is required.

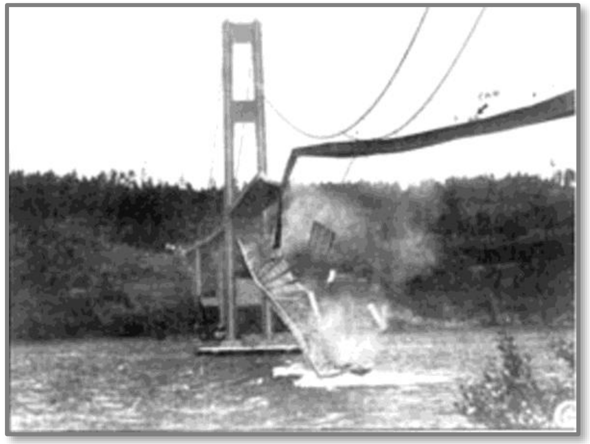
Conclusion:

- necessity of a powerful tool (aka Network Digital Twin) to study
  - qualitatively new feedback loops
  - achievable system optima with AI capability utilization

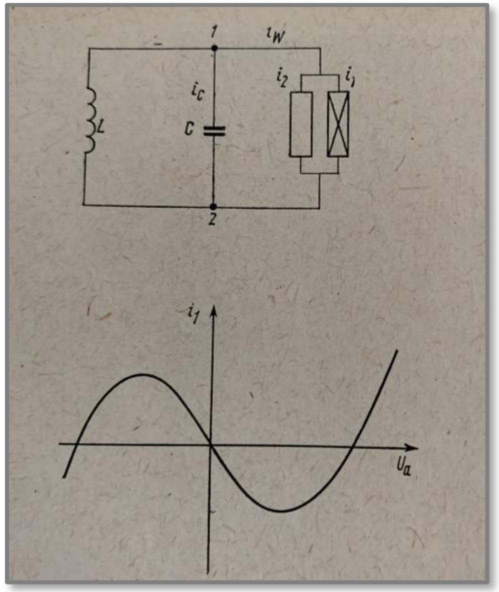
Intro: Why is this important?



Aeolic Harp



Tacoma Bridge Desaster



Resonant Circuit (active element)

Note: SON is something else entirely.

lexikon-musikinstrumente.de, hubpages.com, W. Ebeling, Strukturbildung bei irreversiblen Prozessen, Teubner, 1976

Thermodynamics of the Telecoms System

+ E_{in} (~0.3 TWh/a),
S low

Telecommunication System (wide)

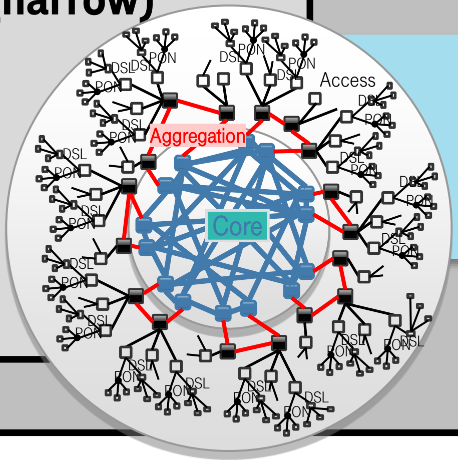
- including UEs
- interactions with network (energy, mobility, traffic **& AI**)

E_{out}, S high

E_{in} (~2.3 TWh/a), **S** low

Telecommunication System (narrow)

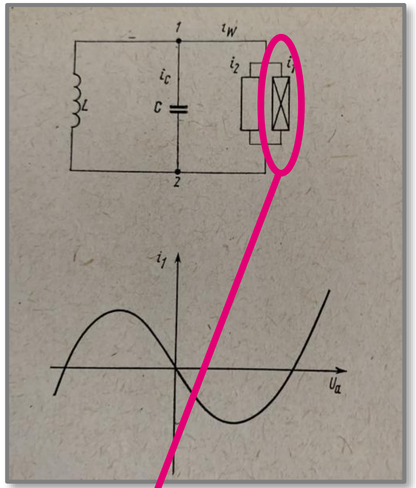
- hierarchical
- network mesh
- highly non-linear coupling



E_{out}, S high

- flow equilibrium, dissipative structure
- eigenfrequencies are independent of external excitation
- nonlinearities and active elements are of the essence

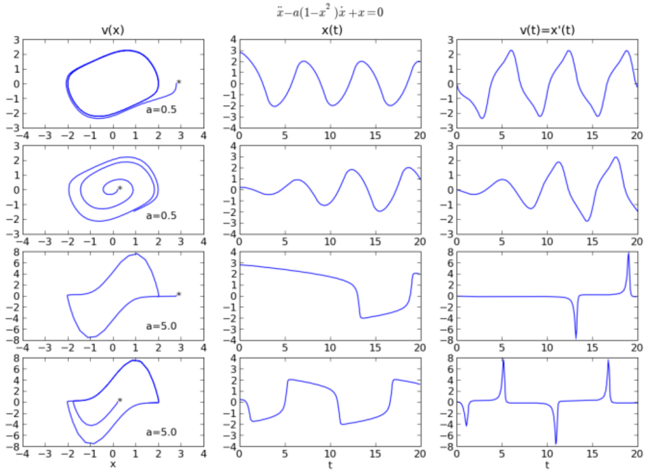
Eigenoscillations in the Network



- van-der-Pol oscillator

$$\ddot{x} - \varepsilon(1 - x^2)\dot{x} + x = 0$$

- treat telco system (narrow) analogously (factor 10^n ...)



- active element
- nonlinear characteristic
- but it's deterministic and local

AI agents work differently – they are not local, they are not deterministic, they are implicit and opaque.

Eigenoscillations in the Network

- Which variables to look at, how to tackle the problem:
  - classical engineering:
    - *i, v* - currents, voltages
personnel of laws of nature (Kirchhoff, Ohm, ...)
deterministic character
carried out all the time in the vendors' labs
  - chemistry, statistical physics, epidemiology:
    - *n* - concentrations, densities, populations
personnel of rate equations (these are empirical)
statistical & aggregate character
typical example: viral spreading (Corona), "patient zero"

Eigenoscillations in the Network

- rate equations for conflict energy ←→ throughput:

$$N = N_e + N_t (+ N_0)$$

$$\frac{d}{dt} N_e = \alpha_e N_t + \beta_e N_e$$

$$\frac{d}{dt} N_t = \alpha_t N_e + \beta_t N_t$$

$$\frac{d^2 N_e}{dt^2} - \beta_e \frac{dN_e}{dt} - \alpha_e(\alpha_t - \beta_t) N_e + C = 0$$

$N_{e/t}$ - number of cells being managed by a dedicated app

$\alpha > 0$ - competition, ~ *time*$^{-1}$

β ? 0 - infection, ~ *time*$^{-1}$

This is a damped linear oscillator.

... forget the damping (β) for a moment →

$$\boldsymbol{N_e \sim \exp[i\alpha t]}$$

Experimental Findings

Colosseum Experiments

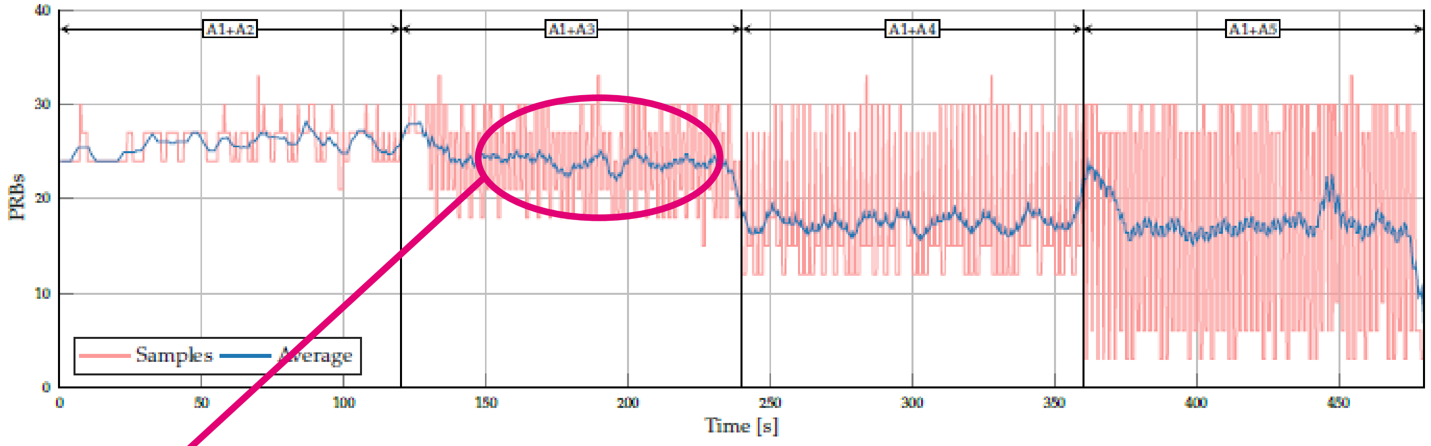
Northeastern University

Basic conflict

- Energy saving versus throughput maximization

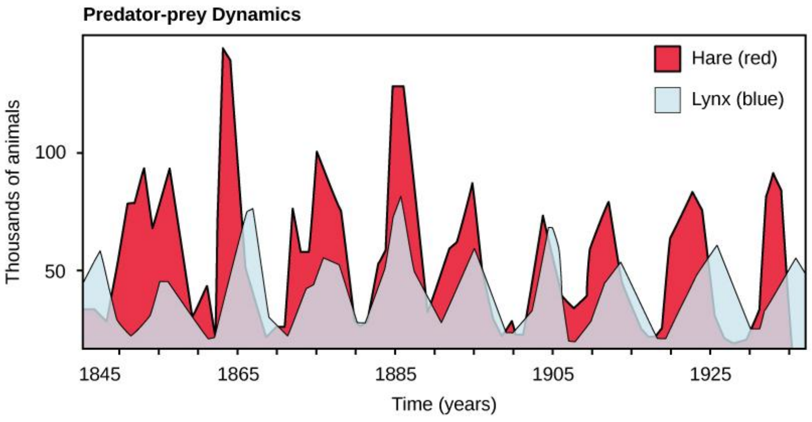
Stability

- PRB allocation with simultaneously running conflicting xApps

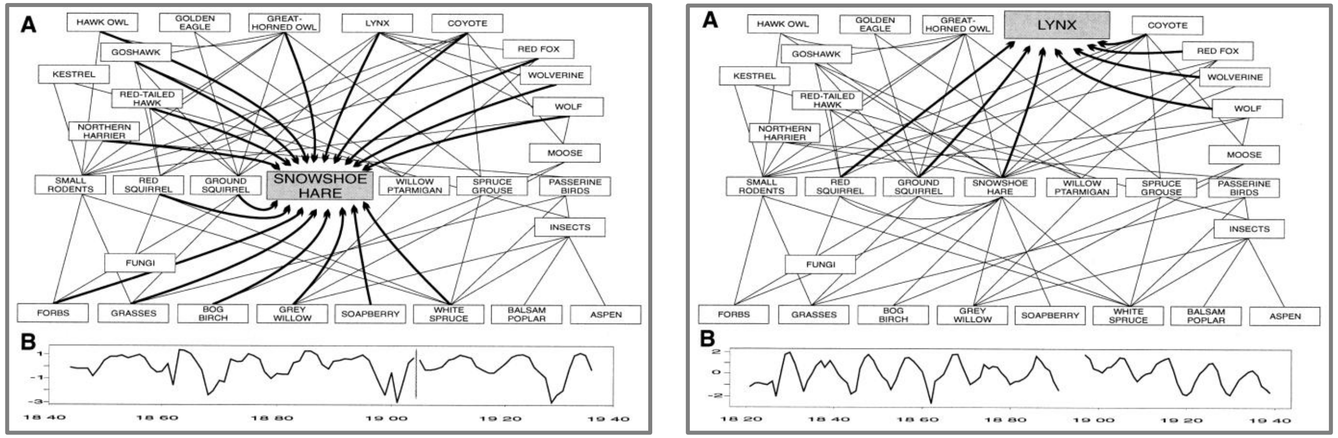


- auto-oscillation with $\alpha \sim 1Hz$
- feedback loop non-local, but restricted to RIC (narrow system)
- average is artifice

Eigenoscillations in Predator-Prey Dynamics



(CNX OpenStax CC BY 4.0, via Wikimedia Commons)



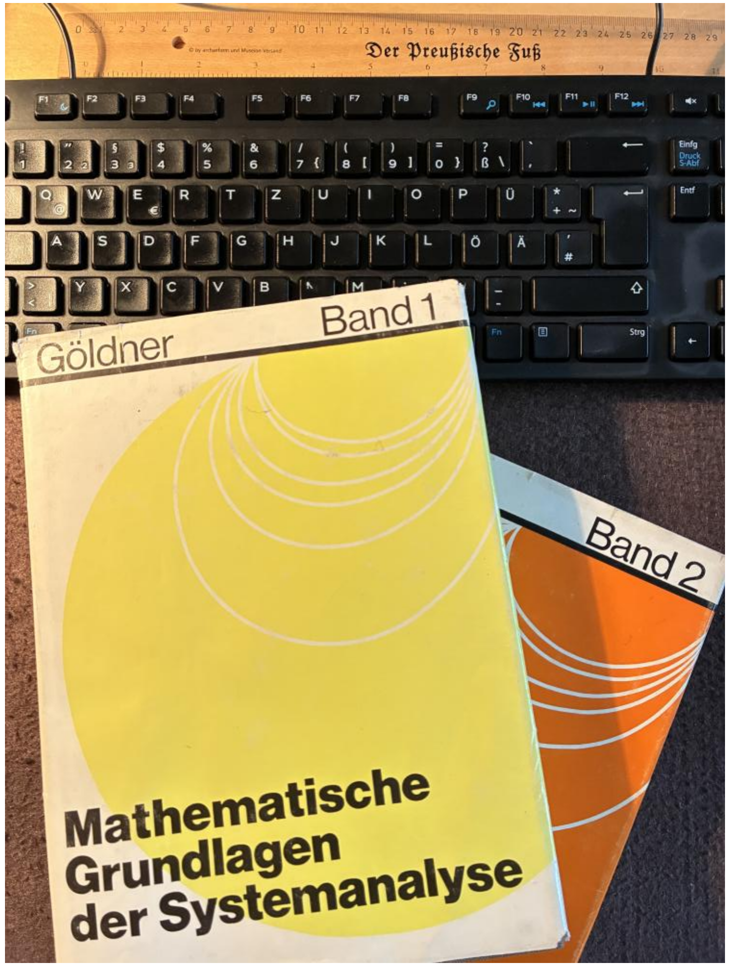
https://doi.org/10.1073/pnas.94.10.5147; *Nils Chr. Stenseth et al.*

- From 1845 to 1935, the Hudson Bay Company logged the number of furs delivered by hunters of the *Snowshoe Hare* and the *Lynx*.
- Soon, it was suspected that the cyclicity is not just stochastics but follows a deterministic pattern. This was, then, formulated in the *Lotka-Volterra* equations.
- On the right: There are not just two animals in the Canadian wild,

  .... as there are not just two xApps in the RIC.

Eigenoscillations in the Network

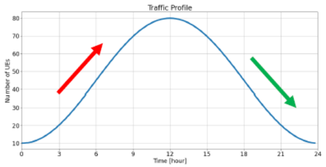
- Known for a long time (in the electrotechnical, deterministic variant),
  folks know how to deal with it:
  - hysteresis times
  - thresholds
  - other remedies
- In the RICs, we would need to install similar stabilization mechanisms.



courtesy of the “Andreas Gladisch Library”

... and now something new: The AI Feedback Loop

Increasing traffic load (**high** load)



Decreasing traffic load (**low** load)

ES-rApp:
- Capacity Cells – **ON**
- TS Policy – **balance load**

O-RU:
- Capacity cells - **ON**

TS-xApp:
- Handover commands:
  - **Distribute users to coverage and capacity cells**

ES-rApp:
- TS Policy – **move all users to the coverage cell**
- Capacity cells – **OFF**

TS-xApp:
- Handover commands:
  - **ALL Users** to **coverage cell**

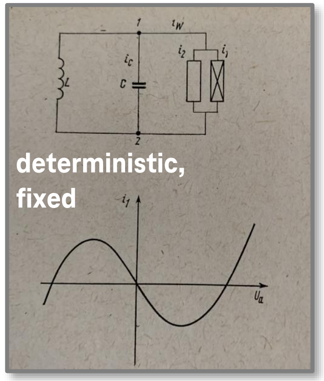
O-RU:
- Capacity cells - **OFF**

Telecommunication System (wide)

- some state vector (UE-derived) $\vec{\boldsymbol{\mu}}(t)$

Telecommunication System (narrow)

- some state vector (telemetry) $\vec{\boldsymbol{\sigma}}(N_i(t))$
- AI agents γ_i



$$\{N_i(t)\} \rightarrow \gamma_i\left[N_i(t-\tau_j), \boldsymbol{\sigma}, \boldsymbol{\mu}\right] \rightarrow \{N_i(t+\Delta t)\}$$

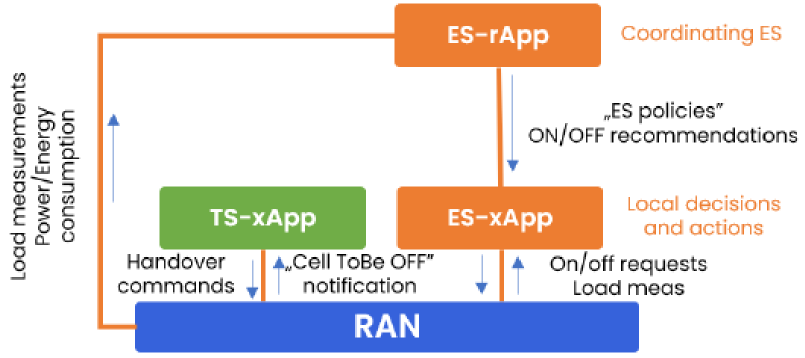
new quality feedback

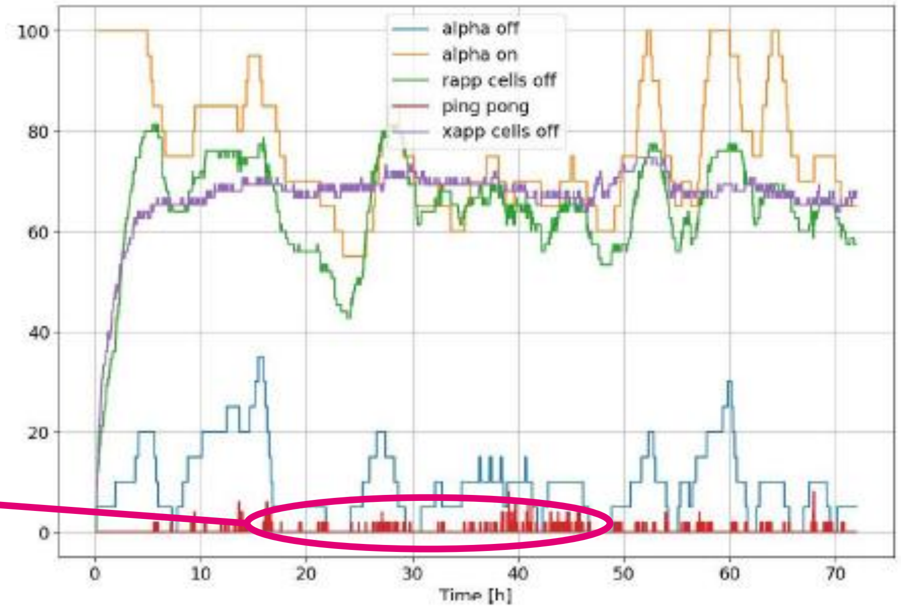
- execution times (cf. RICs, SMO, ...)
- data capture cycle times
- (re-) learning cycles
- hysteresis times
- typical traffic times
- ...

Experimental Findings

Harmonization over Scales:

- Energy saving COOS xApp is always faster than COOS rApp
- rApp and xApp interplay: the xApp provides fast, localized control with significant energy savings, while the rApp enhances dynamic adaptability and stability





- frequencies: ~ dozens of minutes
- feedback loop in wide system

Understanding the AI Feedback Loop

- alternative formulation (response integral):

$$N_i(t) = \int_{-\infty}^{t} dt' \sum_j \chi_{ij}(t - t')\, h(t')$$

$$\tilde{N}_i(\omega) = \sum_j \tilde{\chi}_{ij}(\omega) * \tilde{h}(\omega)\,,$$

with the pre-knowledge of characteristic times τ_j.

$\chi(t) \rightarrow \chi[\{N_i(t)\}]$: the transfer function is a functional of the distributions, it is thought here to incorporate the AI actions.

$h(t)$: traffic

Understanding the AI Feedback Loop

- Try some (very, very much) hand-waving reasoning; start with a damped oscillator in frequency space:

$$\tilde{\chi}_j(\omega) \sim [\omega^2 + (1/\tau_j)^2 + i\beta_{ij}\omega]^{-1}$$

$$\tilde{N}_i(\omega) \sim \sum_j \frac{1}{\omega^2 + i\beta_{ij}\omega + \tau_j^{-2}} h_j$$

BUT:

- These are only the resonances on <u>known</u> frequencies.
- We have no knowledge on nonlinearly generated eigenfrequencies (see above: *van der Pol oscillator*, or the *Hare & Lynx* (~11 years)).
  These, then would be interactive: $\tau_i \rightarrow \tau_{ij}$.
- It would be nice to have some destabilization experiments to study analytical approaches, but for the time being, it's just:
- **Network Digital Twin to the rescue.**

Consequences for Telco Systems Engineering

- The technical system alone is highly complex; it is capable of self-organization (this is not SON).
- AI agents introduce an additional quality to that (novel quality of feedback).
- For a thorough system analysis of this new quality,
  a comprehensive simulation tool (Network Digital Twin) is required.
- Any attempt to install 'self-X' routines (autonomous network elements) requires this systems analysis of the involved AI feedback.
- Operating truly open networks requires an AI guardian with suitable role & rights.

thx