Criticality in Neural Systems

Symposium April 30 & May 1 2012

Natcher Conference Center
NIH, Bethesda, USA

Optimal Channel Efficiency in a Sensory Network

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Preprint: arXiv:1204.0751v1

We show that **the entropy of the distribution of avalanche lifetimes in the Kinouchi-Copelli model always achieves a maximum jointly with the dynamic range**. The newly found optimization occurs for all topologies we tested, **even when the distribution of avalanche lifetimes itself is not a power-law and when the entropy of the size distribution of avalanches is not concomitantly maximized**, strongly suggesting that **dynamical rules allowing a proper temporal matching of the states** of the interacting neurons **is the key for achieving good performance in information processing**.

1. Introduction

- In 2003, Beggs and Plenz observed avalanches in cortical tissues

- Several other groups have reported by now avalanches:

  Ribeiro *et al*, PLoS ONE, Public Library of Science, 2010, v. 5, p. e14129
  Mazzoni *et al*, PLoS ONE, Public Library of Science, 2007, v. 2, p. e439
  Shew *et al*, Journal of Neuroscience, 2009, v. 29, p. 15595
  Shew *et al*, Journal of Neuroscience, 2011, v. 31, p. 55

- **Kinouchi-Copelli model**: optimal dynamic range **at criticality**.

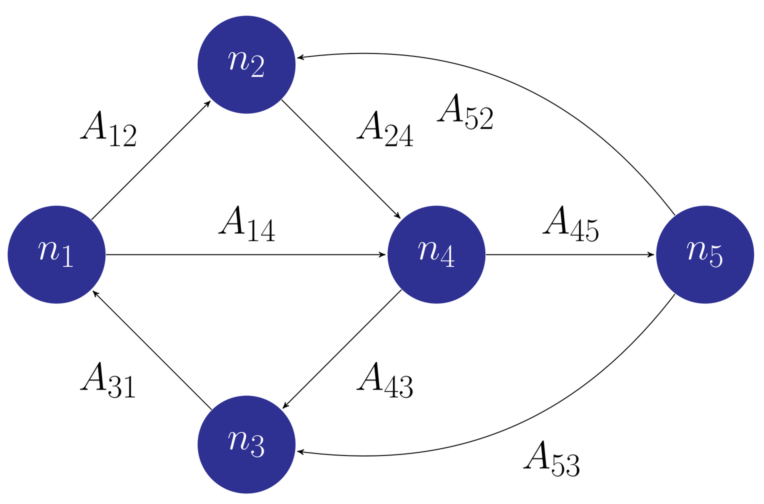
- We have found: optimization of **dynamic range** and entropy of **lifetimes**
- **Channel efficiency** (= entropy of **lifetimes**): efficiency coding info. through firing rate

Channel efficiency always exhibit a ***critical optimization***

2. Kinouchi-Copelli Model

- N nodes connected through adjacency matrix A
- State of j-th node: $X_j(t)$
- $X_j = 0$: quiescent
- $X_j = 1$: excited
- $m > X_j > 1$: refractory

Kinouchi and Copelli, Nat. Phys., 2006



- Dynamics as follows:
- if $1 \le X_j(t) \le m-2$, then $X_j(t+1) = X_j(t)+1$;
- if $X_j(t) = m-1$, then $X_j(t+1) = 0$;
- if $X_j(t) = 0$, then $X_j(t+1) = 1$ with probability
  - η (external stimulus);
  - $A_{jk}, \forall k$, by each of its neighbors.

Instantaneous mean activity:

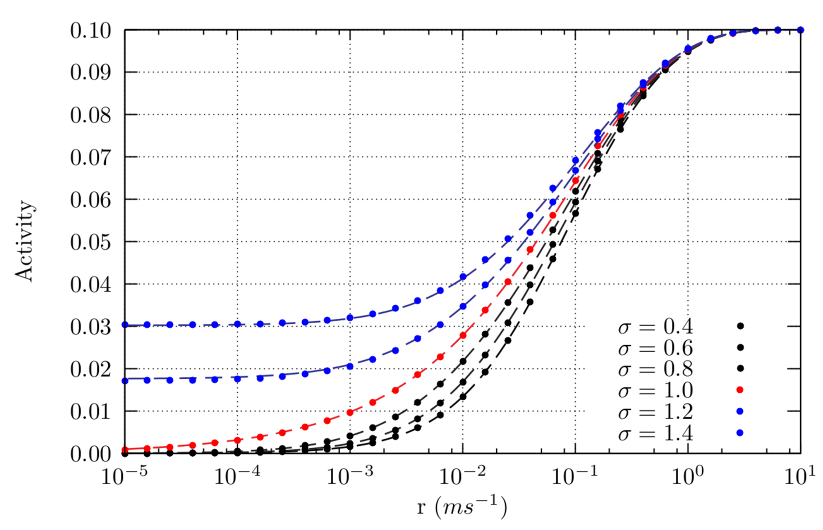
$$\rho(t) = \sum_{j=1}^{N} X_j(t)$$

Mean activity:

$$F_T = \frac{1}{T}\sum_{t=1}^{T}\rho(t)$$

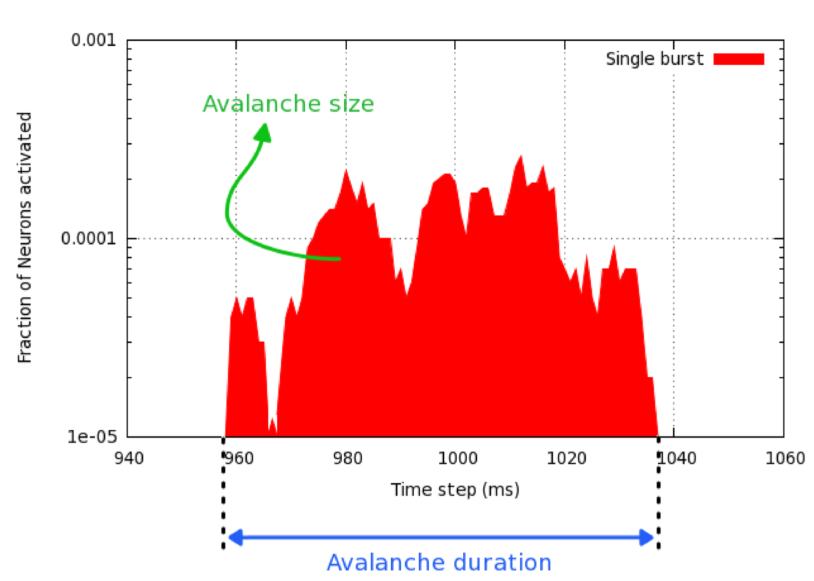
Average branching ratio:

$$\sigma = \sum_{j=1}^{N}\frac{1}{N}\sum_{p=1}^{N} A_{jp}$$



Dynamic range is an **equilibrium** measure.

3. Avalanches



- Activity initiated by a single neuron: **burst**

Avalanches: critical bursts

- We study **distribution** of **size** and **duration** of these **bursts** when varying σ
- **Size**: number of neurons without repetition
- **Time**: number of a single burst time steps

Avalanche size and lifetime are **out of equilibrium** measures.

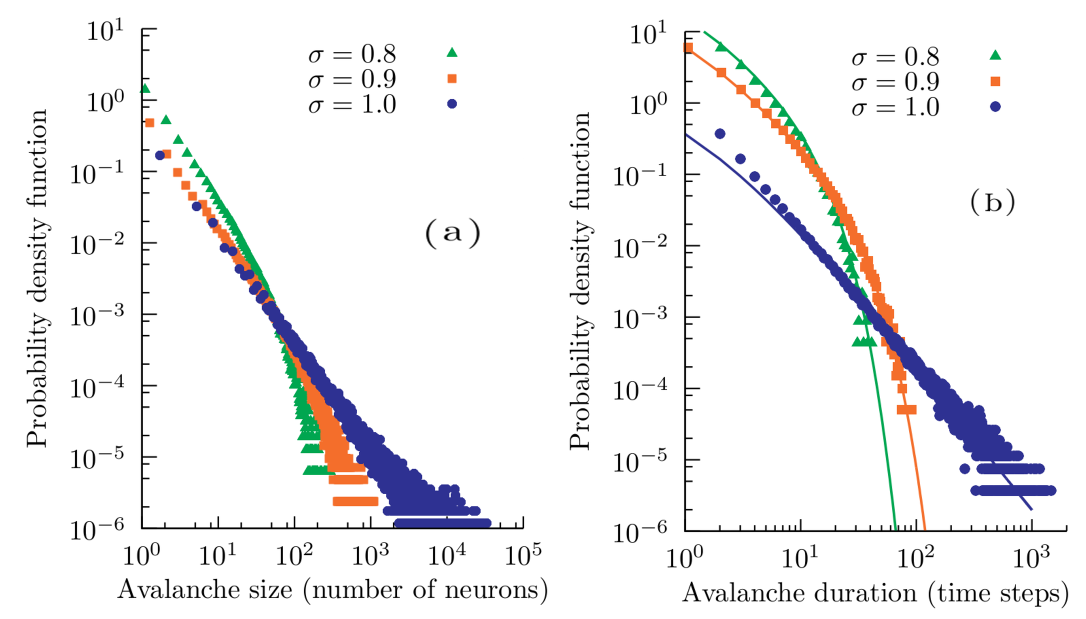
- Simulations run 10^6 bursts with $N = 10^5$, $m = 10$ and $K \in \{2, 5, 10, 15\}$.

4. Random graphs – Erdős-Rényi topology

- Simulations and theory
- **Size exponent: -3/2**
- **Lifetime exponent: -1.9**

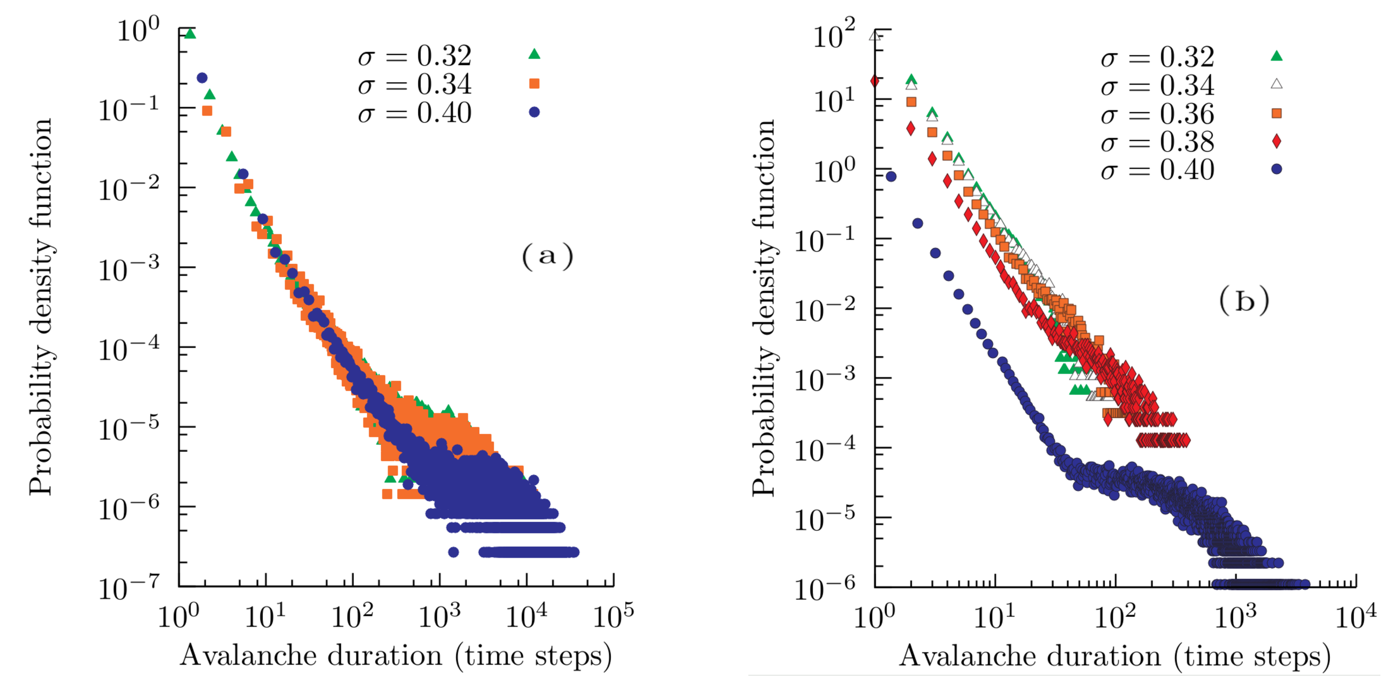
Shew et al, Journal of Neuroscience, 2009, 29, 15595-15600

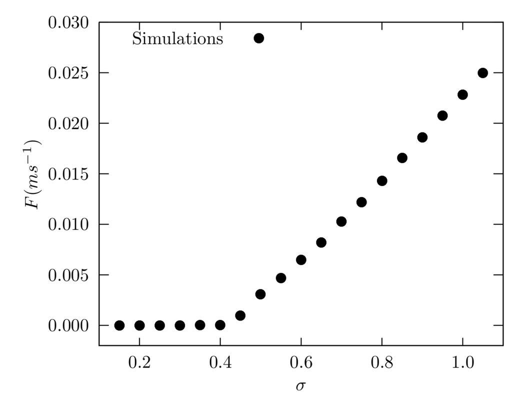
Beggs and Plenz, The Journal of Neuroscience, 2003, 23, 11167-11177



Mosqueiro, Akimushkin and Maia – **DINCON 2011, doi: 10.5540/DINCON.2011.001.1.0064**

5. Scale-free graphs – Barabási-Álbert topology





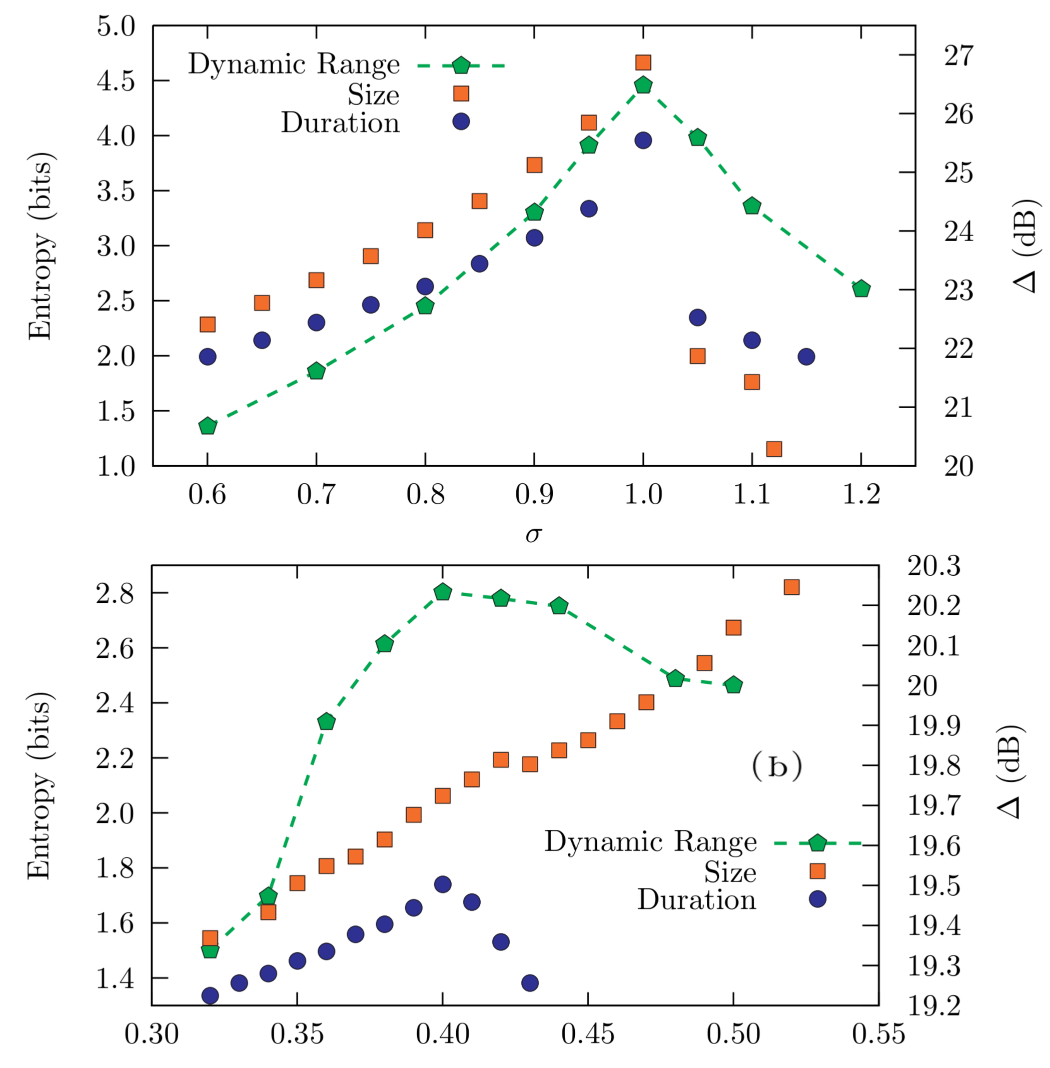
- Lower exponents in power law degree distro.: **also exhibit lack of scale invariance**
- **Branching process** analysis **agree** with this critical σ
- Networks with **several values of** N were tested and no meaningful change was detected in distributions
- Critical point: $\sigma_c = 0.4$

6. Entropy in both topologies

Similar as in Shew et al, Journal of Neuroscience, 2011, 31, 15595

- **Erdős-Rényi results**
- Entropy of both avalanche lifetimes and sizes are optimized at criticality

- **Barabási-Álbert results**
- Entropy of **avalanche** lifetimes is optimized at criticality
- **Dynamic range** and **avalanche lifetimes** are both **not** optimized at $K = 2$



7. Conclusion

Summarizing, we studied the avalanches in Kinouchi-Copelli model in a first attempt to figure out **detailed mechanisms of information transmission in sensory systems**. We discovered that, in a critical point, **the entropy of avalanche lifetime statistics (information efficiency) is always maximized jointly with the dynamic range**, an important measure of information transmission extracted from the tuning curves from psychophysics. Our findings fit in the discussions regarding the **role of criticality in information processing and the relationship of long bursts of activity with the dynamic range**, specially because they suggest critical behavior without pure scaleinvariance.

8. Acknowledgements

The authors would like to thank financial support from CAPES and FAPESP.