Dynamic Modeling
of
the Electric Power Network

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Historical Overview of the Electric Power Industry

1st step: *Industrial Revolution Driven Development*

- End of the 19th century: LOCAL generation, transmission and distribution of Electric Power (ELECTRIC UTILITIES)
- At that time, many businesses (non-utilities) generated their own electricity
- When utilities began to install more efficient generators, the associated increase in convenience and economical service prompted many industrial consumers to shift to the UTILITIES for their electricity needs
- Utilities operated in designated exclusive franchise areas which, in the early years, were usually municipalities

Electric Power Network

Development based on demand in a monopolistic environment

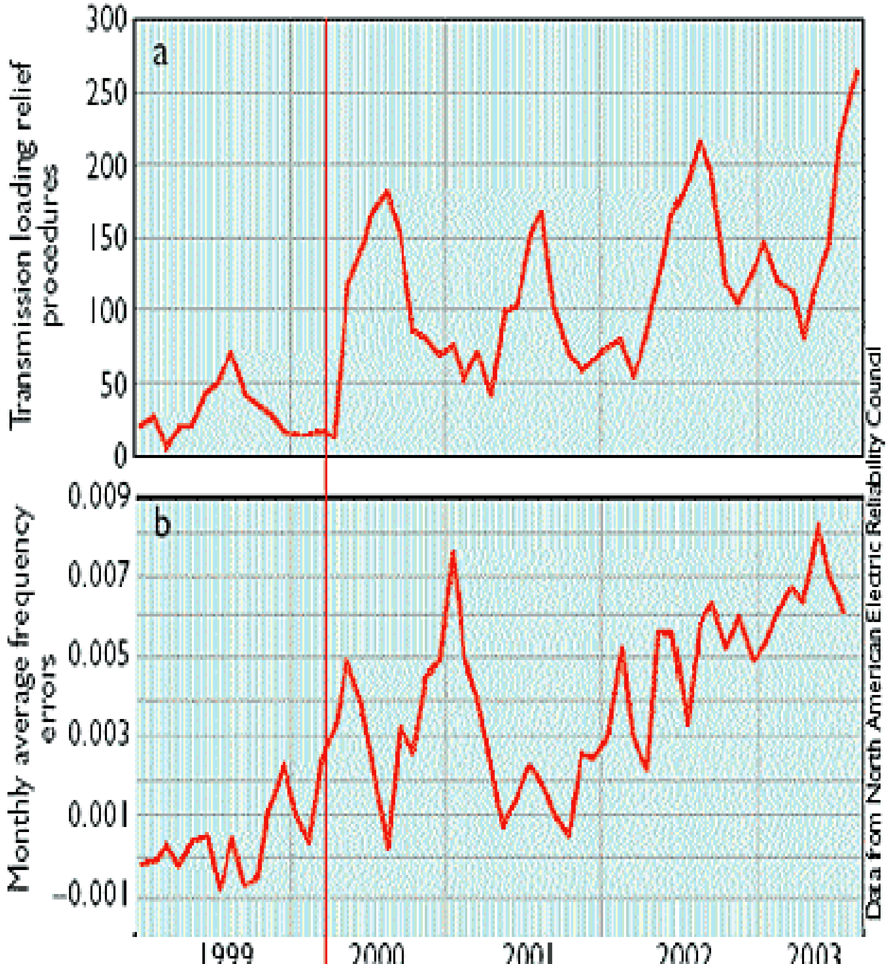
- The growth of utility service territories brought State Regulation of privately owned electric utilities in the early 1900s
- The early structure of the electric utility industry was predicated on the concept that a central source of power supplied by efficient, low-cost utility generation, transmission, and distribution was a natural monopoly [*Sherman Antitrust Act, 1907*]
- In the mid-1930s, the rural areas were still without lights. It was too expensive for the investor-owned utilities that served the cities to stretch their lines into the countryside. The Federal Government encouraged the growth of rural electricity service by subsidizing the formation of rural electric cooperatives [*Rural Electrification Act,1936*]
- For decades, utilities were able to meet the increasing demand for electricity at decreasing prices. The monopolistic environment in which they operated left EPN growth unhindered by the worries that would have been created by competitor, until the 1960s

…reversal in the growth and well-being of the EP industry

- Northeast Blackout of 1965 raised pressing concerns about reliability
- Clean Air Act of 1970 required utilities to reduce polluting emissions
- Oil Embargo of 1973-1974 resulted in increases in fossil-fuel prices
- Economic recession, inflation (in general) caused interest rates to more than triple in 1979
- *Public Utility Regulatory Policies Act of 1978 (PURPA). PURPA became a catalyst for competition in the electricity supply industry, because it allowed nonutility facilities that met certain ownership, operating, and efficiency criteria to enter the wholesale market*
- DEREGULATION PROCESS: FERC’s Order 888 mandated the wheeling of electric power across utility lines in 1996. But that order remained in litigation until March 4, 2000, when the U.S. Supreme Court validated it and it went into force. It states that generating companies now sell their power for the best price they could get, and utilities would buy at the lowest price possible.

Effect of deregulation on EPN Reliability

- Stress indicator: the number of transmission loading relief procedures (TLRs) increased. [*events that include relieving line loads by shifting power to other lines*]
- Equally important, the frequency stability of the grid rapidly deteriorated
- August 14, 2003, a series of seemingly unrelated eventes conspired to produce a massive power black-out, affecting a huge area of the northeasrtern US and Canada



Order 888 goes into effect

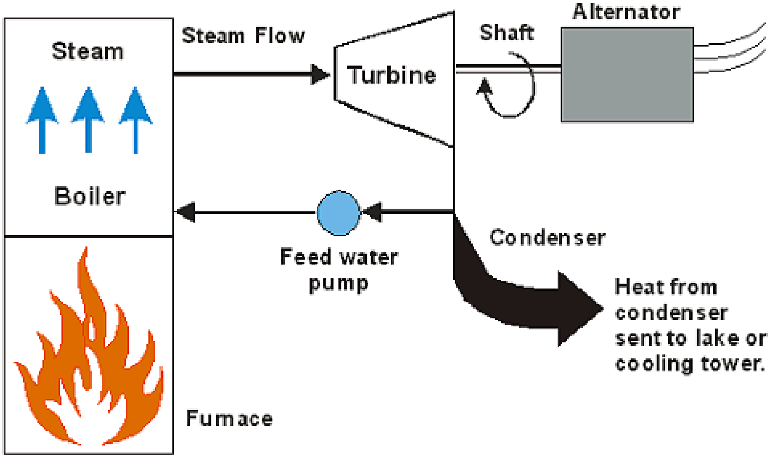
Data from North American Electric Reliability Council

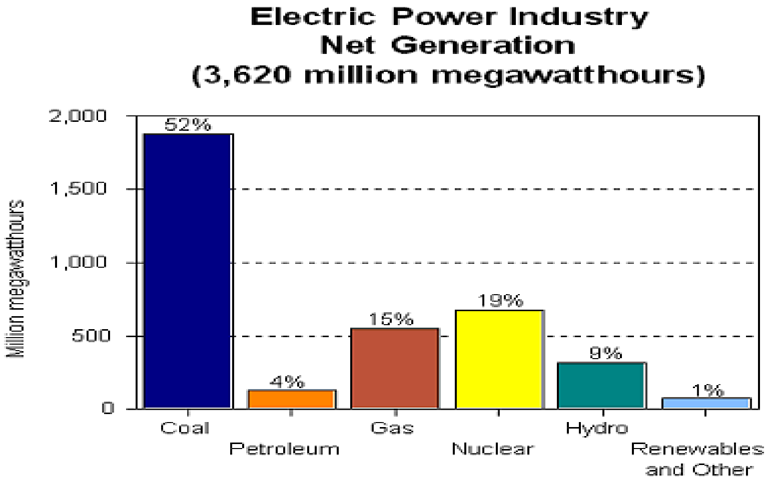
[Mountford, J. D.; Austria, R. R. Power Technologies Inc. Keeping the lights on IEEE Spectrum 1999, 36 (6), 34–39.]

[Tucker, R. J. Facilitating Infrastructure Development: A Critical Role for Electric Restructuring. Presented at the National Energy Modeling System/Annual Energy Outlook Conference, Washington, DC, March 10, 2003]

Electric Power Generation

- *Steam Units*: Steam produced in a boiler turns a turbine to drive an electric generator. Fossil fuels (coal, petroleum and petroleum products, natural gas or other gaseous fuels) and other combustible fuels, such as biomass and waste products, are burned in a boiler to produce the steam. Nuclear plants use nuclear fission as the heat source to make steam
- *Gas Units*: Gas turbines and combustion engines use the hot gas from burning fossil fuels, rather than steam, to turn a turbine that drives the generator.

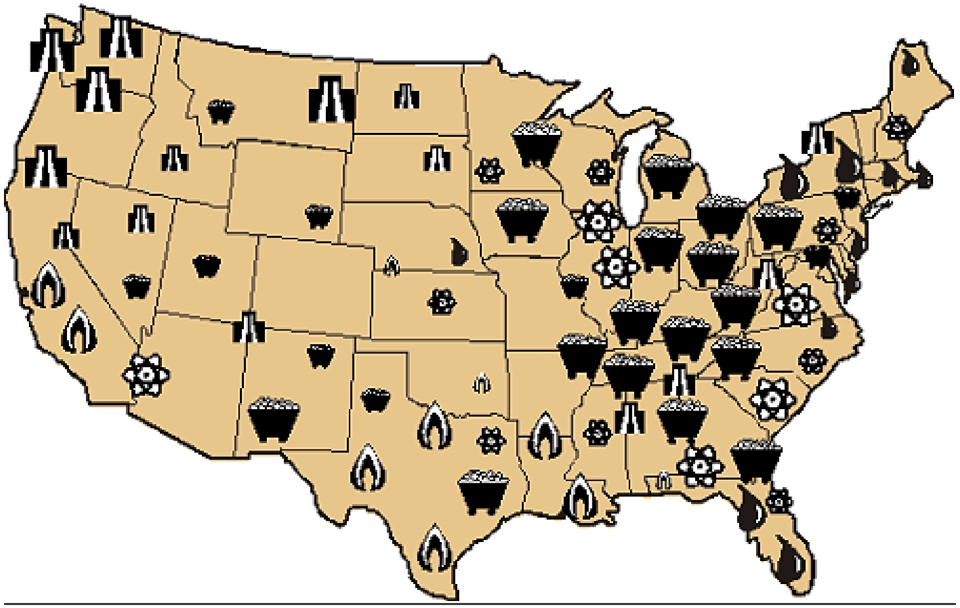




Generation: Form EIA-860B, “Annual Electric Generation Report – Nonutility” and Form EIA-759, “Monthly Power Plant Report.”

Dishomogenities in the EP Generation

- The type of energy source used for generating electricity varies in the United States by region and is usually dictated by the availability of natural resources …
- … either by local legislation e.g. California's tight restrictions on air emissions discourage coal-fired generation.
- The Pacific Northwest generates most of its power at large hydroelectric projects owned by the Federal Government
- Much of the Nation's petroleum-fired generation is concentrated in Florida and New York.
- Ohio, West Virginia, Kentucky, and Tennessee are the largest users of coal for electricity generation in the Nation. Texas, Louisiana, and Oklahoma are rich in natural gas, and make use of it for electricity generation.



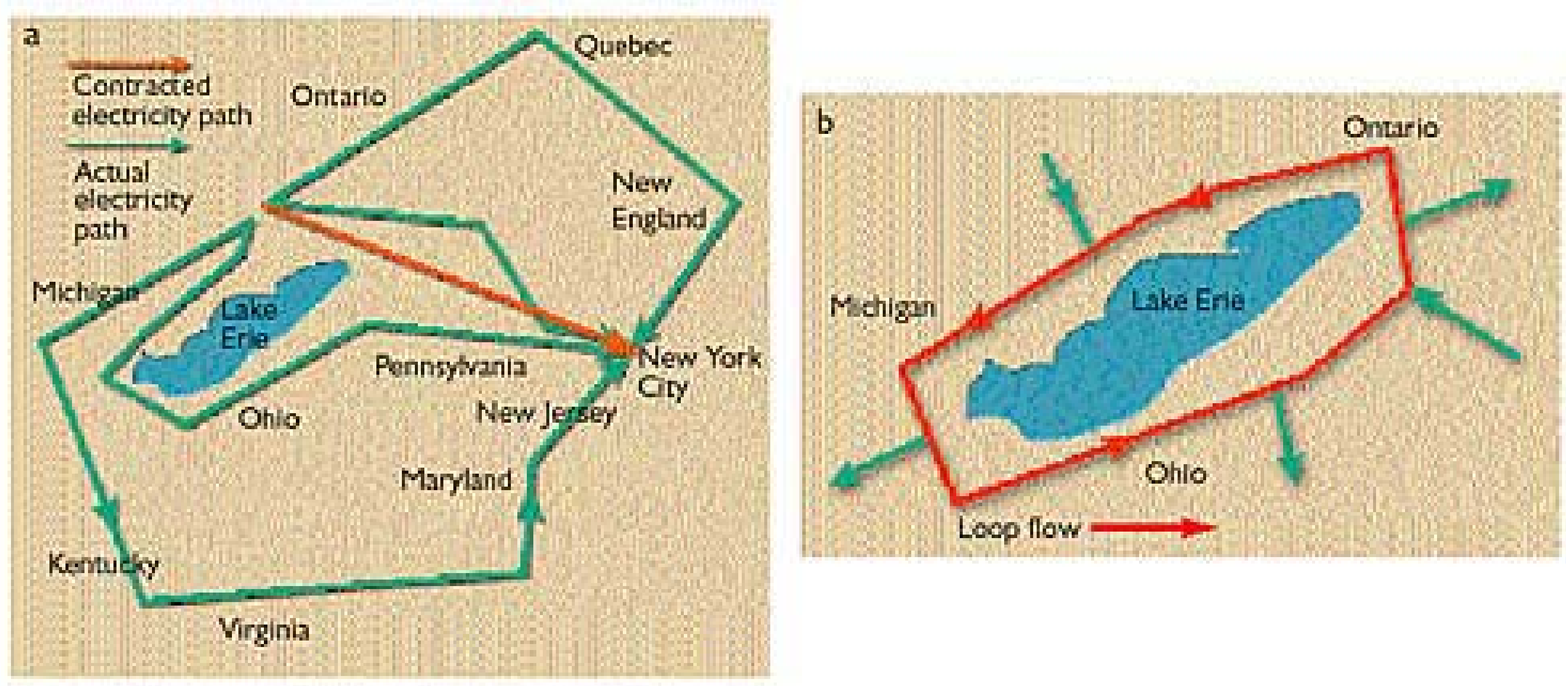
Source: Form EIA-860A, "Annual Electric Generator Report – Utility" and Form EIA-860B, "Annual Electric Generator Report – Nonutility."

What's wrong with the electric grid?

- Prior to deregulation, a single company controlled electricity generation, transmission, and distribution in a given geographical area. Each utility generally maintained sufficient generation capacity to meet its customers' needs, and long-distance energy shipments were usually reserved for emergencies.
- This limited use of long-distance connections aided system reliability, because the physical complexities of power transmission rise rapidly as distance and the complexity of interconnections grow. Power in an electric network does not travel along a set path, as coal does, for example.
- Deregulation made the power-flow experience the complexity of the network

“Topological” effect of deregulation

- When utility A agrees to send electricity to utility B, utility A increases the amount of power generated while utility B decreases production or has an increased demand. The power then flows from the “source” (A) to the “sink” (B) along all the paths that can connect them. This means that changes in generation and transmission at any point in the system will change loads on generators and transmission lines at every other point—often in ways not anticipated or easily controlled



- *EPN is a complex network grown on local needs in a highly etherogeneous generation environment. It’s made up of many components whose interactions are not effectively computable.*

Can we contribute in understanding the

- topological aspects
- Stability (*reliability*)

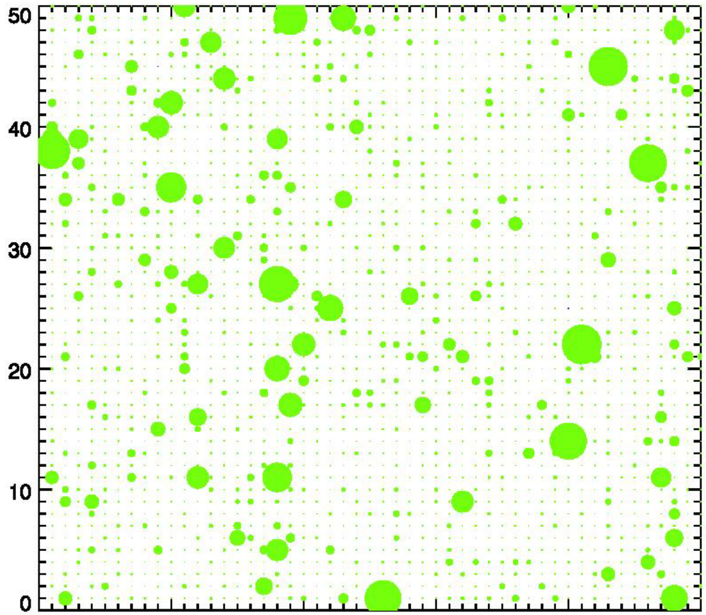
of a network dynamically grown on energy demand/sharing criteria in a heterogeneous environment?

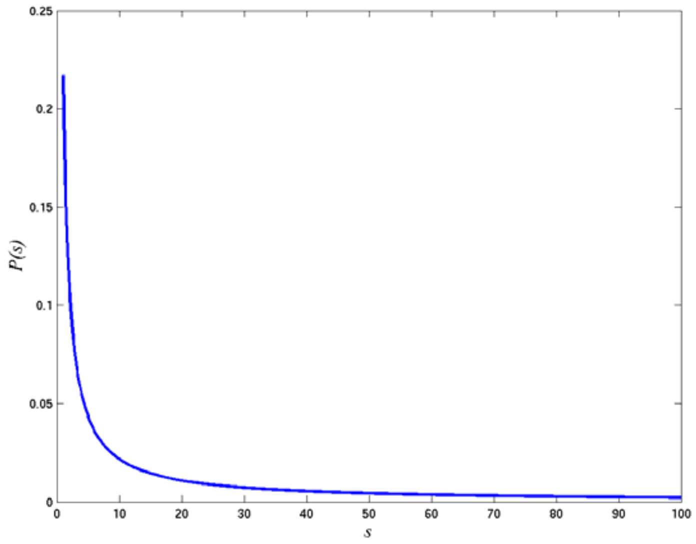
A model for EPN growth and dynamics. 1

- We consider N dynamic elements located in the nodes of a two-dimensional lattice. Each element is characterized by its size s_i drawn from a distribution $P(s)$
- to each element are associated two dynamic variables:

1) The energy consumption (load) $l_i(t)=m_i+\eta_i(t)$ *where* m_i *is a constant value and* $\eta_i(t)$ *represents a fluctuation term;*

2) The available energy $f_i(t)$

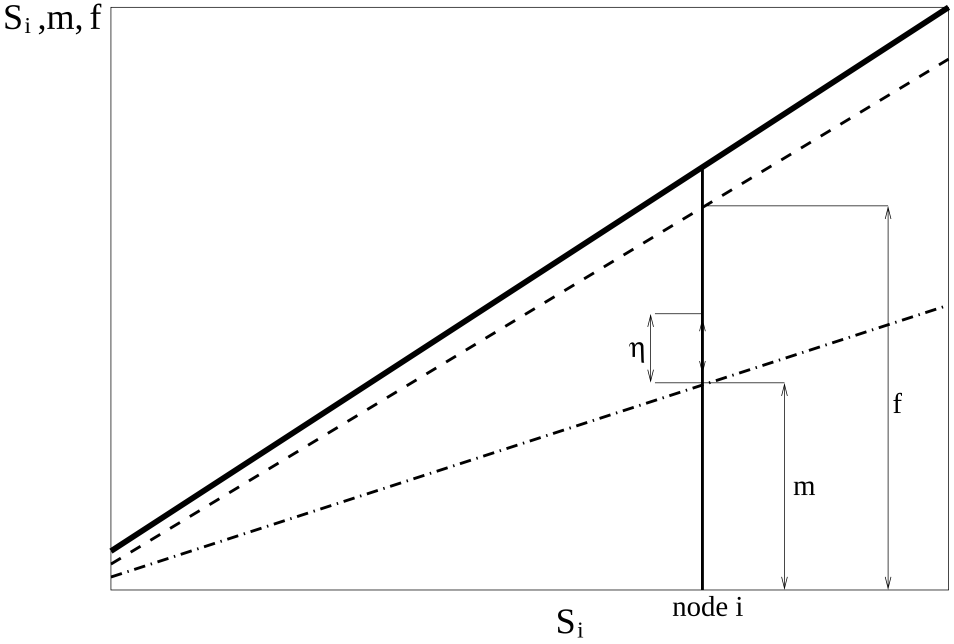




A model for EPN growth and dynamics. 2

- at $t = 0$ the available energy and the constant load at each element are proportional to its size s_i
- $f_i(0) = f_r s_i$
- $m_i = m_r s_i$
- f_r and m_r are constant values and in general $f_r > m_r$

To reduce the number of free parameters : $m_r = 0.5 f_r$



A model for EPN growth and dynamics. 3

failures and energy redistribution

- If, due to fluctuations, the load overcomes the amount of energy made avaliable by the generator at the node i
  - $f_i(t) < l_i(t)$
- A <u>failure</u> occurs, and a link is established between the failing element i and a neighbor. The energy function $f_i(t)$ is updated according to

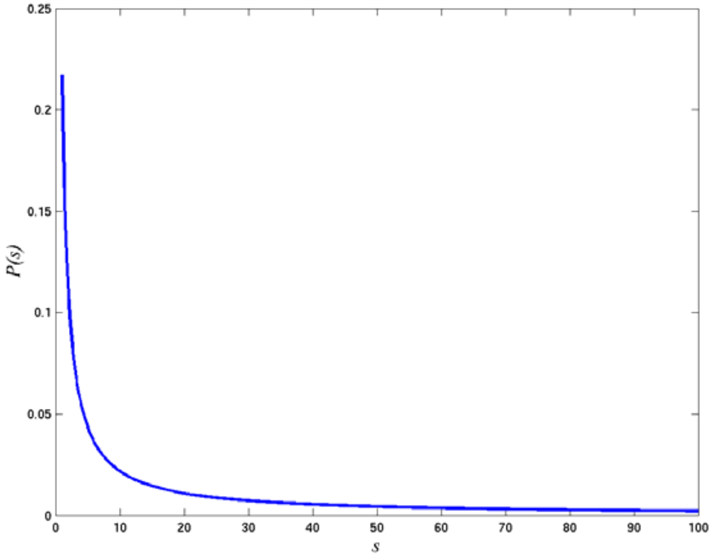
$$f_i^{t+1} = \begin{cases} f_i^t & \text{if } k_i = 0 \\ l_i^t + \sum_{j \in \mathcal{V}(i)} \frac{f_j^t - l_j^t}{k_j} & \text{if } k_i \neq 0 \end{cases}$$

i.e. the available energy $f_i(t) - l_i(t)$ is SHARED among the linked nodes

To be concrete…

size distribution, chaotic fluctuations, energy and load per node

The size distribution is chosen as a Zipf-law = A/s ; $A^{-1} = \ln(s_{max})$

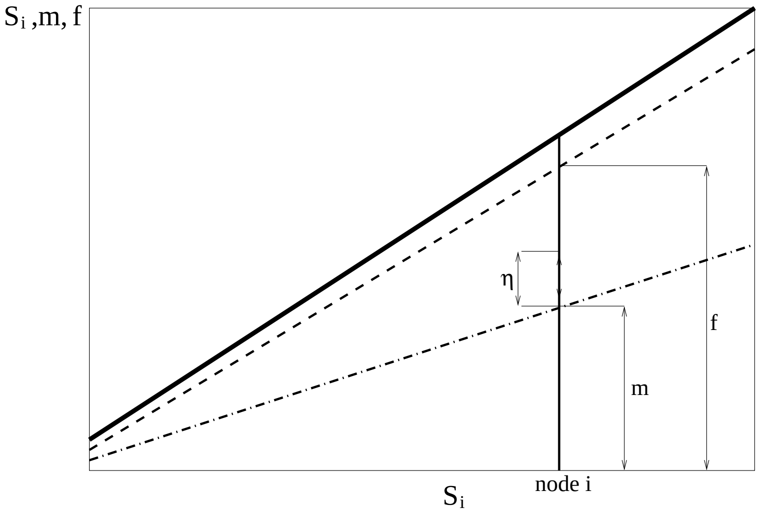


The time evolution of η_i is described by the logistic map in the chaotic regime:

$$\eta_i^{t+1} = 4\eta_i^t(1-\eta_i^t) \ . \qquad (6)$$

$$\varepsilon = \frac{E}{N} = f_r \frac{s_{\max}-1}{\ln s_{\max}} \equiv f_r \Theta(s_{\max})$$

$$\lambda = \frac{L}{N} = m_r \Theta(s_{\max}) + \frac{1}{2} \ .$$



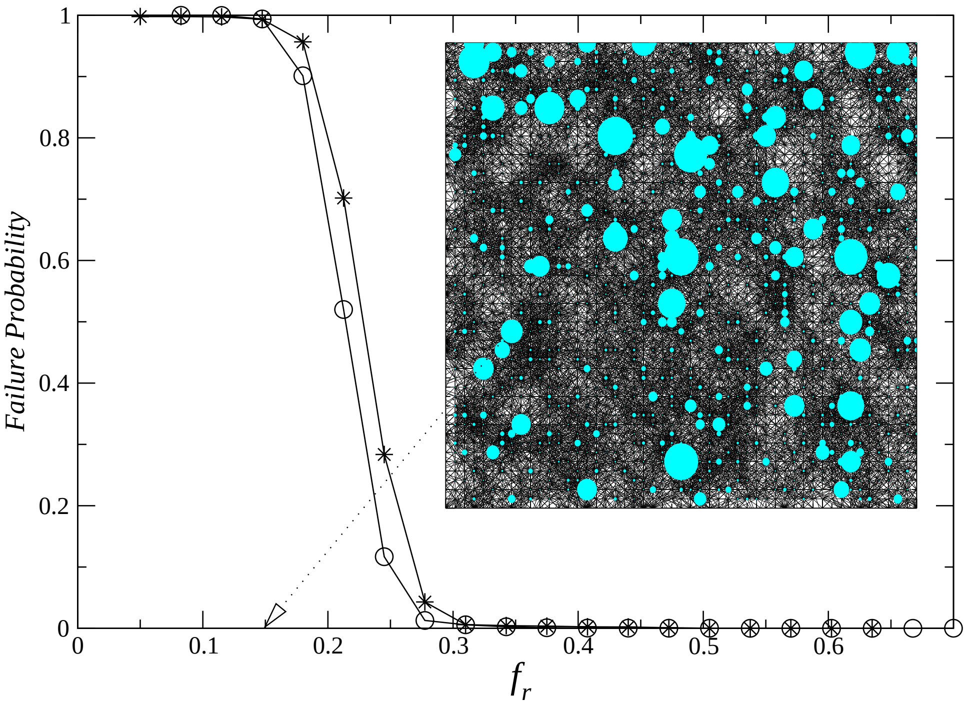
Failure free isolated system Energy

It is worth noting that at any given time the maximum possible total load in the network is $\lambda_{\max} = m_r \Theta(s_{\max}) + 1$. Thus for a system composed by the same nodes following the same dynamics but without the possiblity to form links with other elements, the total energy that guarantees that all the nodes have access to the energy they may need is

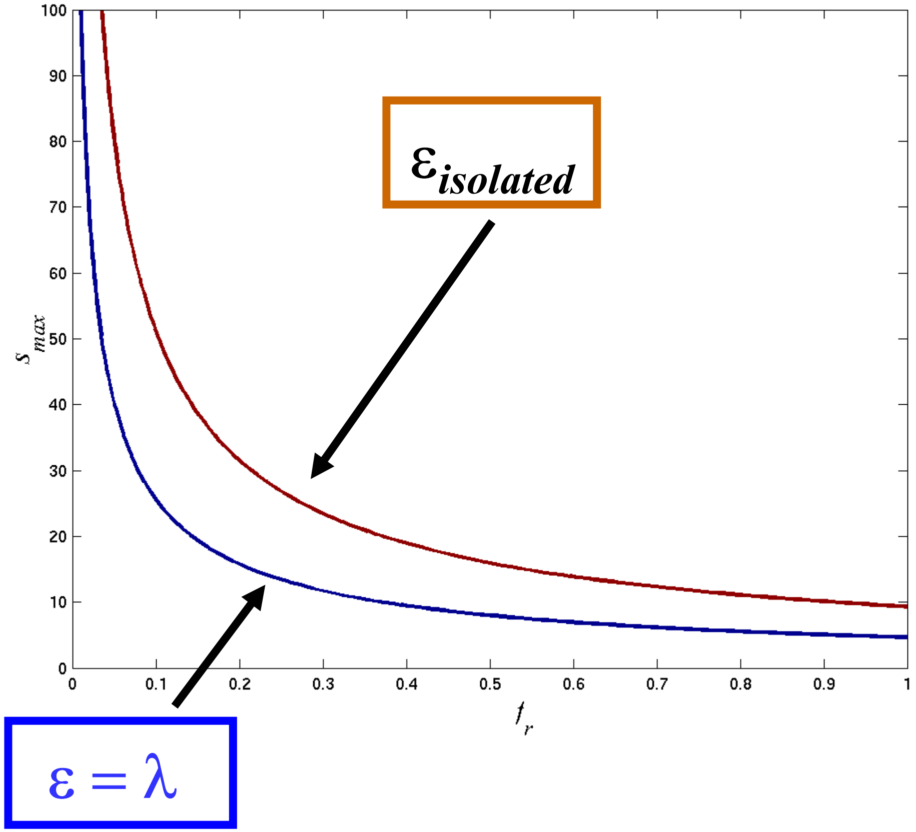
$$\varepsilon_{\text{isolated}} = \lambda_{\max} = m_r \Theta(s_{\max}) + 1 \; . \tag{9}$$

Transition point

$< energy > = < load > : \varepsilon = \lambda$



For low values of f_r the system evolves towards a fully connected network in which the total energy in the system is not able to sustain the needs



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$$\lambda = \frac{L}{N} = m_r \Theta(s_{\max}) + \frac{1}{2} \ .$$

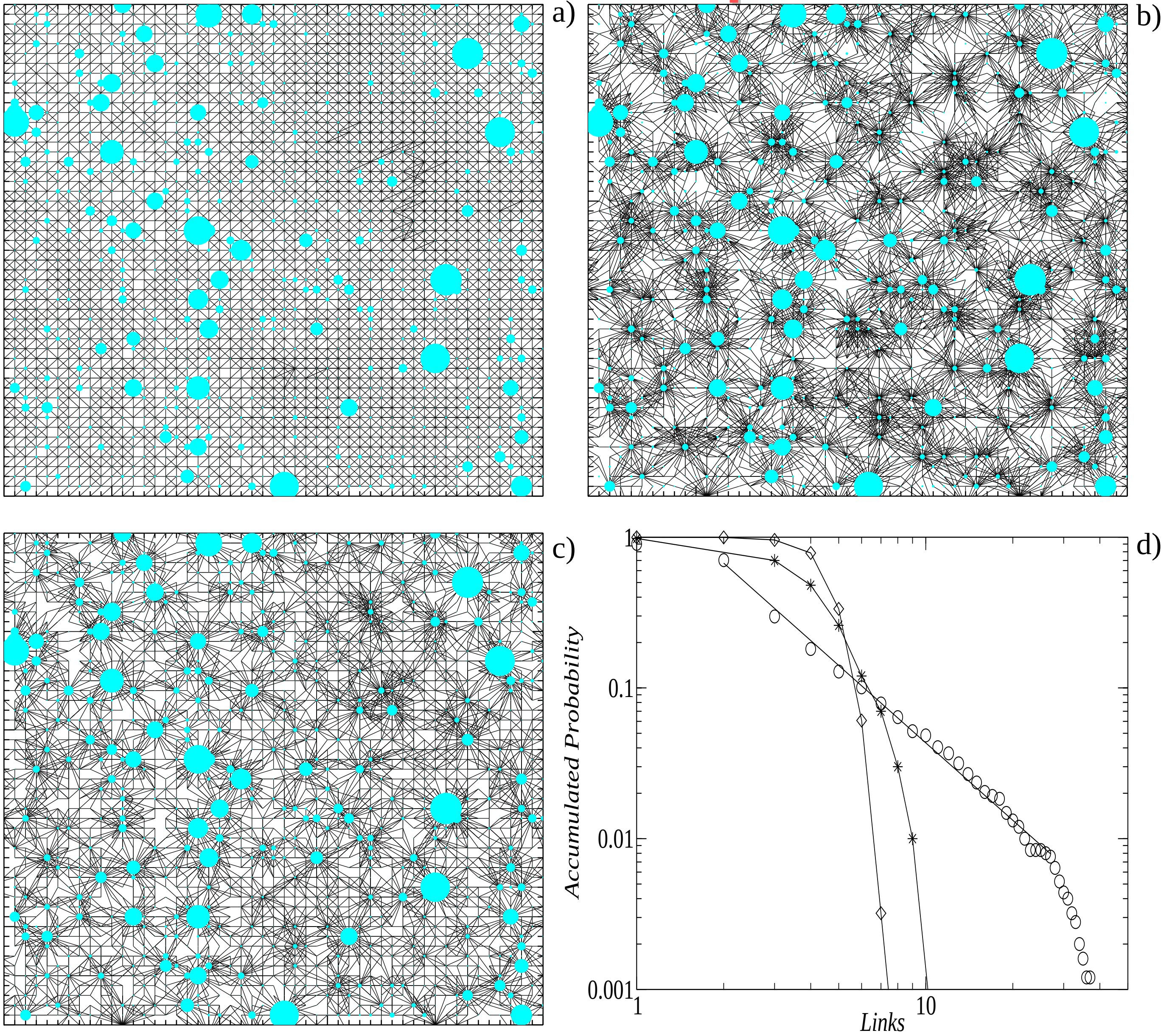
The dynamic network

- If $\varepsilon > \lambda$ a statistically failure-free network, with non-trivial topology is formed, depending both on the wiring strategy and on the available energy
- Following the results of networks with spatial constraints [*Yook, Jeong, Barabàsi, Proc. Natl .Acad. Sci, USA 99,13382 (2002)*],a link between the node i and j is set if is maximized the following function

$$\pi(i,j) = \frac{s_j^{\beta}}{d_{ij}^{\gamma}} \; ,$$

Topologies above the transition point

- **a)** *Gaussian*
  $\beta=0, \gamma=1$;
- **b)** *Power-law*
  $\beta=1, \gamma=0$
- **c)** *Exponential*
  $\beta=1, \gamma=3$
- **d)** *link distribution corresponding to network*
  - a) diamonds,
  - b) circles,
  - c) stars.



Dependence on the available energy

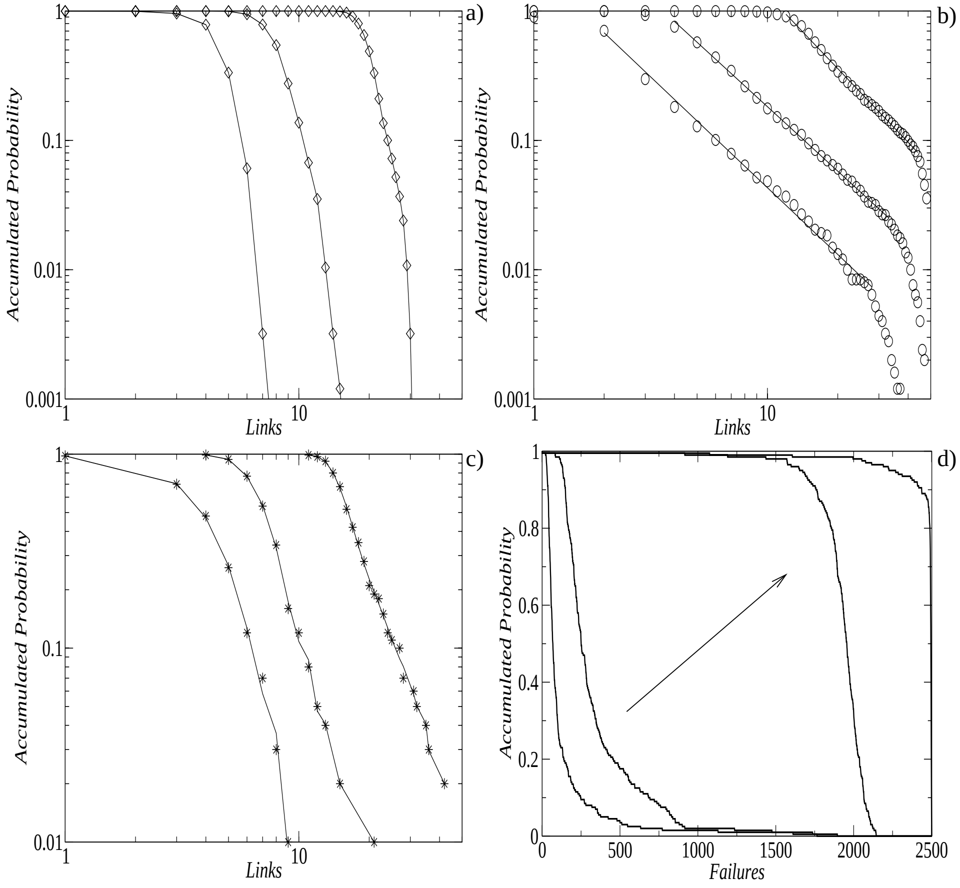
- **LINK DISTRIBUTION for increasing available energy**

a) *Gaussian* β=0, γ=1;

b) *Exponential* β=1, γ=3

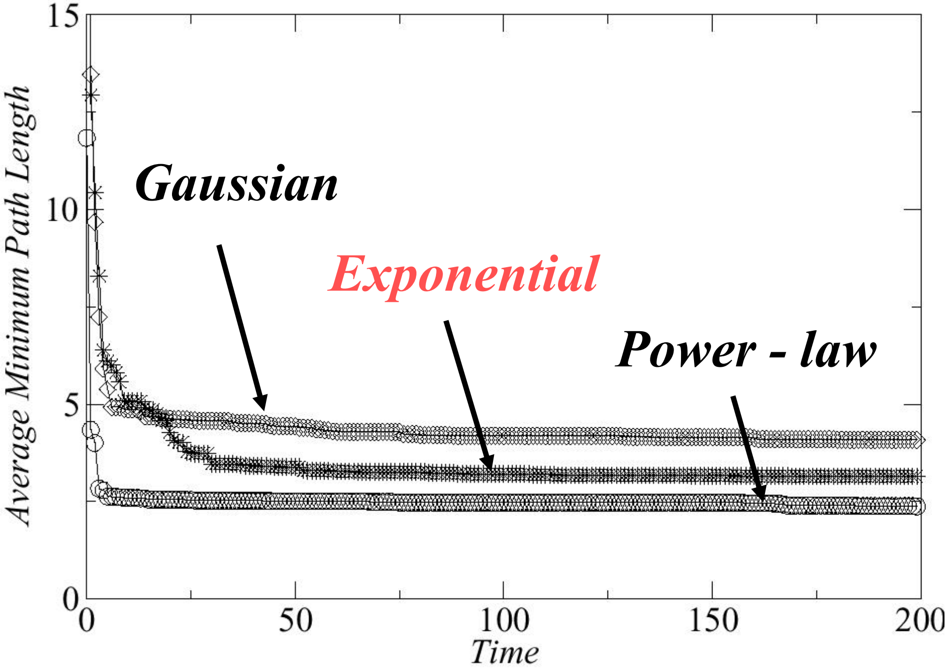
c) *Power-law* β=1, γ=0

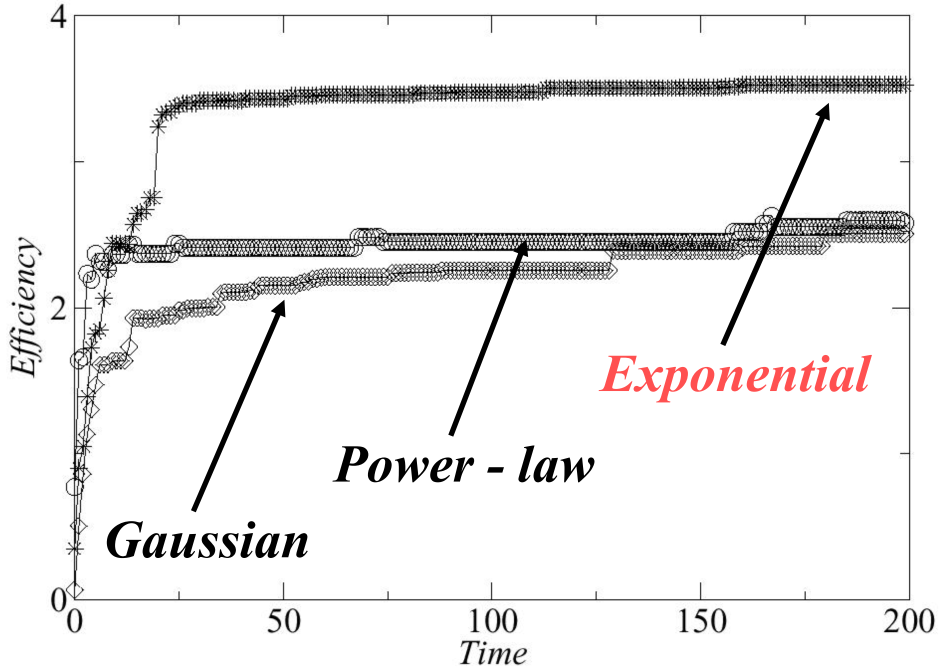
- **d) *FAILURE DISTRIBUTION across the transition point***



Minimum average path length and Weighted Efficiency

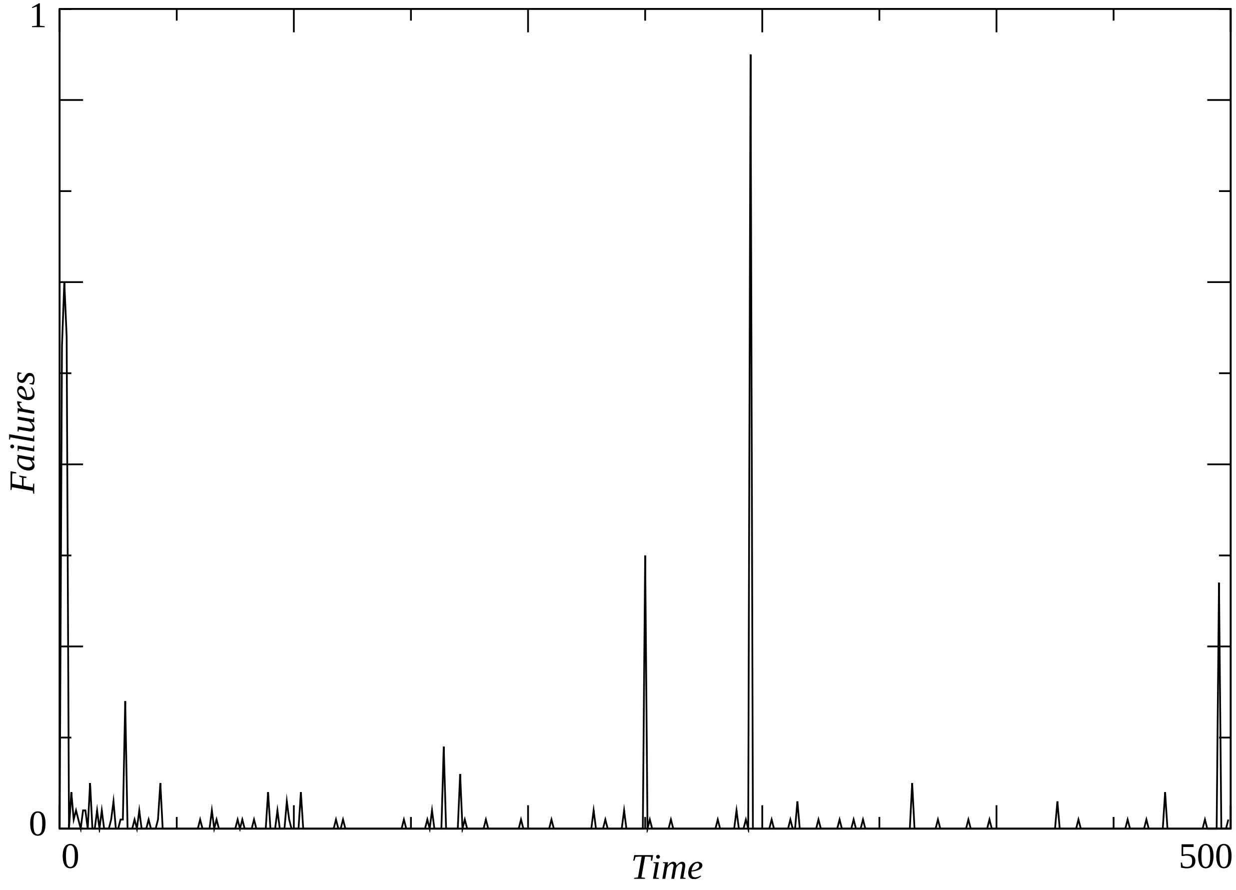
$$\langle \ell \rangle = \frac{1}{N(N-1)} \sum_{i,j} \delta_{ij} \qquad \epsilon = \frac{1}{N(N-1)} \sum_{i,j} \frac{s_j}{\delta_{ij}}$$





Cascade Break-down Events

- A peculiar feature of our model is the presence of isolated events in which a considerable percentage of elements simultaneously fail, even in the stable regime. The frequency of these events increases closer to the transition point .



Conclusions

- In summary we have introduced a dynamic model for the self-organization of a transportation network, based on local demand and energy sharing criteria.

If the total energy is below the average consumption, the system reaches an unstable fully connected network.

If the system has enough energy, the emerging network is statistically failure free and reflects a cooperative behavior in which the resources are globally shared.

- The emerging non--trivial topology is shaped by the wiring strategy and the available total energy.
- Quantitatively, our model selects as the most efficient topology, the one with an exponential link distribution, in agreement with the topology of the real electric power-grid. This is due to the inhomogeneity in the energy generation.

The most efficient network has the shortest average path to biggest energy reservoir

- Our model intrinsically presents self-induced break-down events, which can be thought as representative of real black-outs.