Small-World Power-Law Interconnects for Nanoscale Computing Architectures

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Abstract:

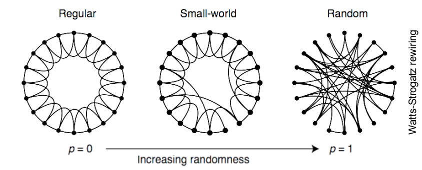
- **Goal**: investigate the properties of an irregular, abstract, yet physically plausible **small-world interconnect fabric for self-assembled nanoscale electronics** that is inspired by modern network-on-chip (NoC) paradigms.
- We vary the framework's key parameters, such as the connectivity, the number of switch blocks, the number of virtual channels, the routing strategy, and the distribution of long- and short-range connections.
- We measure the network's **transport characteristics**, the robustness against failures, and solve toy problems.
- Is computation in **irregular and imperfect assemblies** a promising new computing paradigm for nanoscale electronics?
- **Yes**, great transport characteristics, **robust**, **physically plausible**, and **fabrication friendly**.

Introduction and motivation:

- Today, interconnects are more important than transistors.
- Current ad hoc interconnect technology is not suitable (global signals, delays, scalability) for self-assembled multi-billion-component nanoscale electronics.
- We argue that **radically new approaches** potentially offer better performance for a lower price.
- We need physically plausible and fabrication friendly approaches.
- Nanoscale electronics and novel fabrication technologies bear unique opportunities for **self-assembling multi-billion component systems in a largely random manner**, which would likely lower fabrication costs significantly compared to a definite ad hoc assembly.

Complex networks:

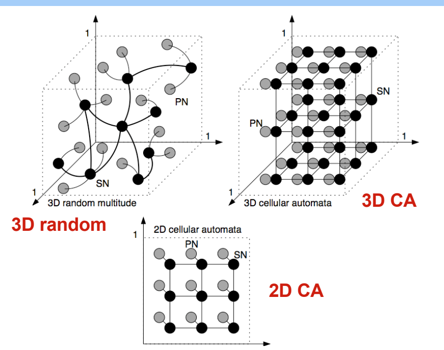
- Small-world networks have a short average path length.
- A **regular topology** is easy to build (local connections), but has poor transport characteristics.
  A **random network** is not physically plausible (uniform connection probability, independent of distance).
- **Small-world** nets with a **power-law distribution of the connection lengths** are physically plausible and have great transport characteristics.



The framework:

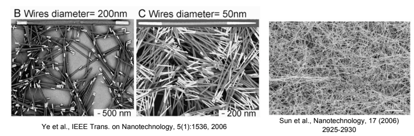
- Compare 2D and 3D regular with random small-world topologies.
- Network-on-chip (NoC) approach:
  - programmable **computing/processing nodes** (PNs)
  - **switch nodes** (SNs), and
  - bi-directional point-to-point interconnects.
- SNs only route packets, PNs can do computation, every PN is connected to the nearest SN.
- SNs can have a rich interconnect fabric among themselves and do **random** or **shortest-path** routing.
- **Random multitude** (RM):
  - PNs and SNs are randomly arranged in space
  - **Power law** ($l^{-\alpha}$) and **Gaussian** connection distribution as a function of the Euclidian distance.
  - **Lots of local, few "global" connections,** depending on the Euclidian distance
  - α = 0: original Watts-Strogatz topology

Comparing different interconnects:



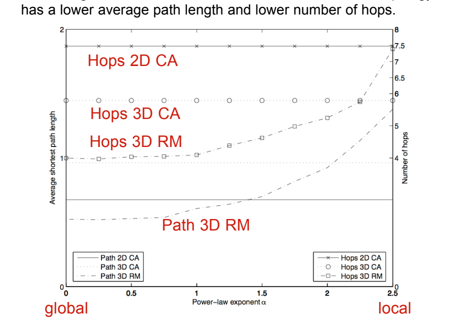
Fabricational issues:

- We imagine a hybrid approach first:
  - Nodes: traditional silicon
  - Interconnections: self-assembled nanowires or nanotubes
- Wires can be easily fabricated (self-assembled) in huge quantities.
- It is easier to establish random and imperfect inter-connections than to come up with a perfect alignment.
- Power-law distributions occur often in Nature (optimal transport under restricted resources).
- Detailed wire-growth models are needed.



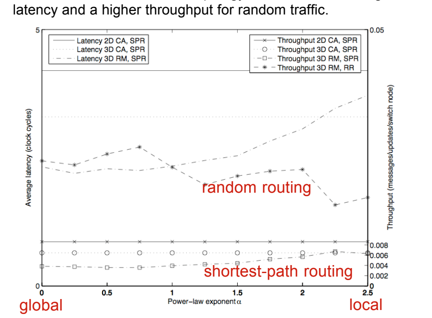
Average path length and number of hops:

- With few global connections, the 3D random small-world topology has a lower average path length and lower number of hops.



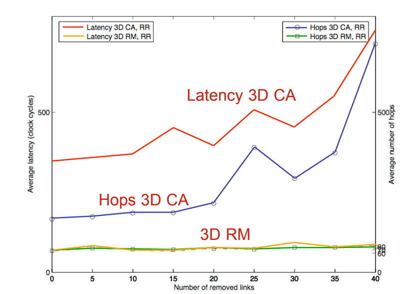
Latency and throughput:

- The 3D random small-world topology offers a lower average latency and a higher throughput for random traffic.



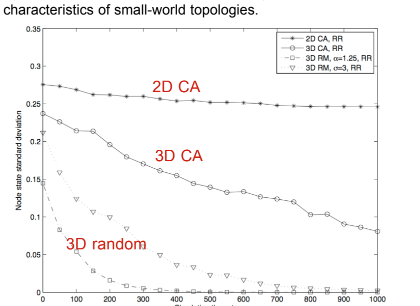
Robustness against link removals:

- The small-world random network is more robust against random link removals than the regular 2D and 3D topologies.



Solving the synchronization and density task:

- Synchronization is faster because of the great network transport characteristics of small-world topologies.



Conclusions and future work:

- Small-world-like interconnects with a power-law distribution of the connections as a function of the Euclidian distance:
  - are physically plausible since long distance connections are costly, and
  - offer great transport characteristics using minimal resources.
- Regular 3D is better than regular 2D, irregular small-world 3D is better than regular 3D.
- Problems can be solved more efficiently because of the great transport characteristics.
- Programmability can be challenging.
- Future work:
  - Simple and localized routing algorithms
  - More realistic traffic models
  - Realistic wire-growth models and address fabricational issues
  - Do arbitrary computations on a random assembly
  - …

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Unclassified LA-UR 06-4954