Interaction Patterns for Resilient Intermittently-Connected Static Sensor Networks

Michel Charpentier, Radim Bartoš, and Ying Li
Department of Computer Science
University of New Hampshire

Motivation

Considering:

- Sensor networks built using energy-constrained nodes
- Scenarios where general purpose networking is not available or desirable:
  - Energy consumption constraints
  - Vastness of the environment
  - Clandestine operations

Approach:

- We propose to forgo the standard networking paradigm in favor of communication that relies on *local, group-based, short-lived interactions* to achieve the desired global behavior of the network

Network model - scheduled meetings

Assumptions:

- Nodes interact in local groups
- Nodes do not attempt to reach specific nodes outside of their group
- The model is applicable to mobile nodes and larger groups
  – this work considers static nodes and pair-wise meetings
- *Partnership graph*: two nodes are connected if they regularly interact (but are not necessarily connected at all times)
- Nodes connected in a partnership need to schedule meetings – points in time (and space, in case of mobile nodes) at which they interact
- For simplicity, we restrict attention to periodic schedules.
- Interaction at a meeting can be elaborate (e.g., calculation of a function based on the aggregated knowledge of the group)

Related work

- Wireless Sensor Networks
  - General networking infrastructure is often assumed
  - Many schemes reduce the energy consumption through scheduling of modes of operation
- Underwater Acoustic Networks
  - Difficulty in maintaining connected network
  - Desirability of local coordination
- Delay/Disruption Tolerant Networks
  - Disconnected mode of operation
  - Encounters among nodes are driven by forces unrelated to the mission
- Asymptotic Capacity of Wireless Networks
  - Random node placement or mobility
  - Exploit opportunistic communication
- Analytical models (population protocols, self-similar algorithms)
  - More rigorous studies of meeting-based computation

Problem definition

Event detection mission:

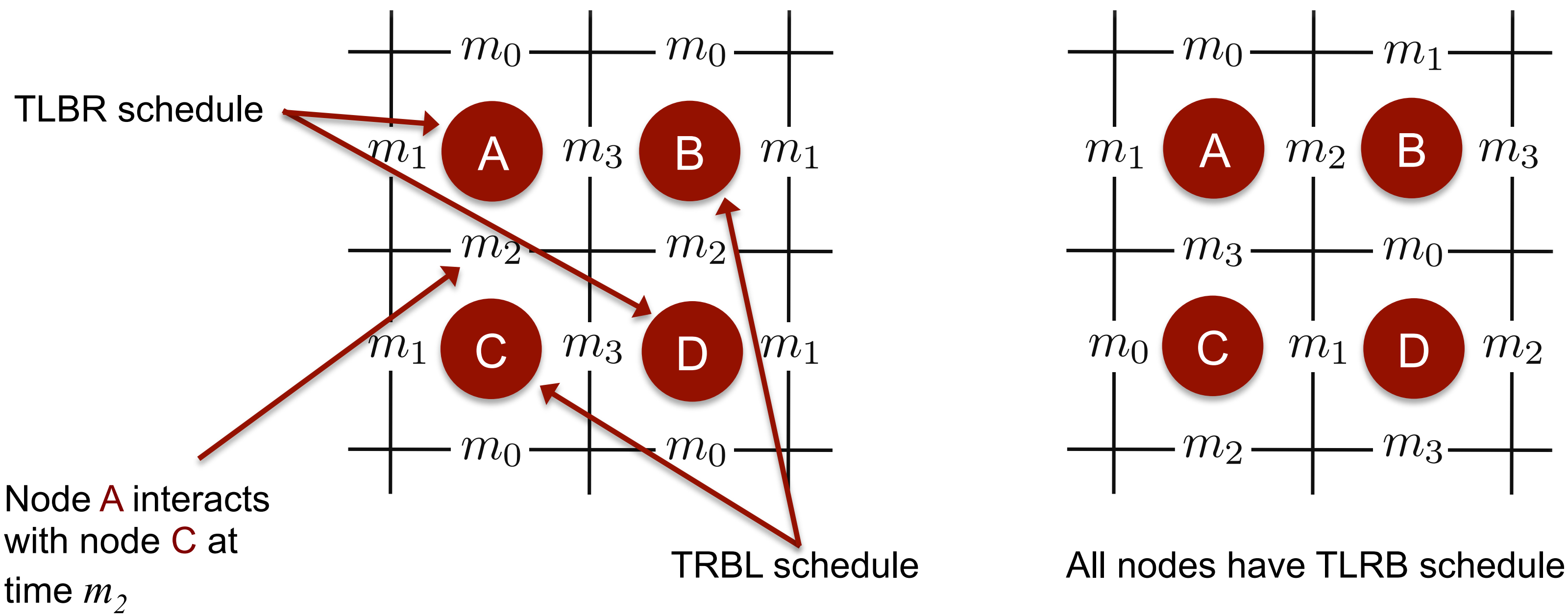
- Topology:
  - Regular grid
  - Agents have four neighbors: *T, B, L*, and *R*

- Agents perform pair-wise interactions according to the network schedule:
  - The schedule is fixed and periodic
  - The interactions (meetings) of a node happen sequentially

- The network includes destination nodes (sinks):
  - One or more destination nodes in the network
  - Detection mission is completed when at least one of the sink nodes is informed about the detected event

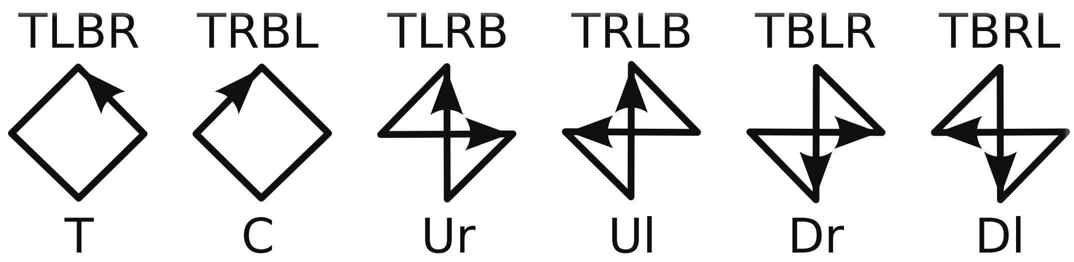
Meeting schedules

- Nodes are synchronized and know the meeting schedule
- Many different schedules:
  – Considering only schedules with 4 meetings per period (nodes talk to each of the neighbors exactly once during a period)
- **Example** - schedules and meeting times ($m_0 < m_1 < m_2 < m_3$):

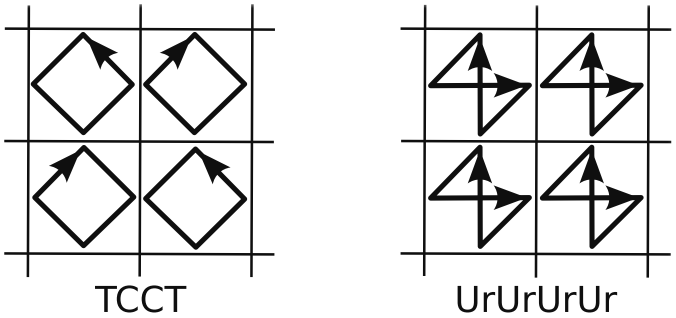


Schedules and tiling

- Six possible permutations of the four interactions:



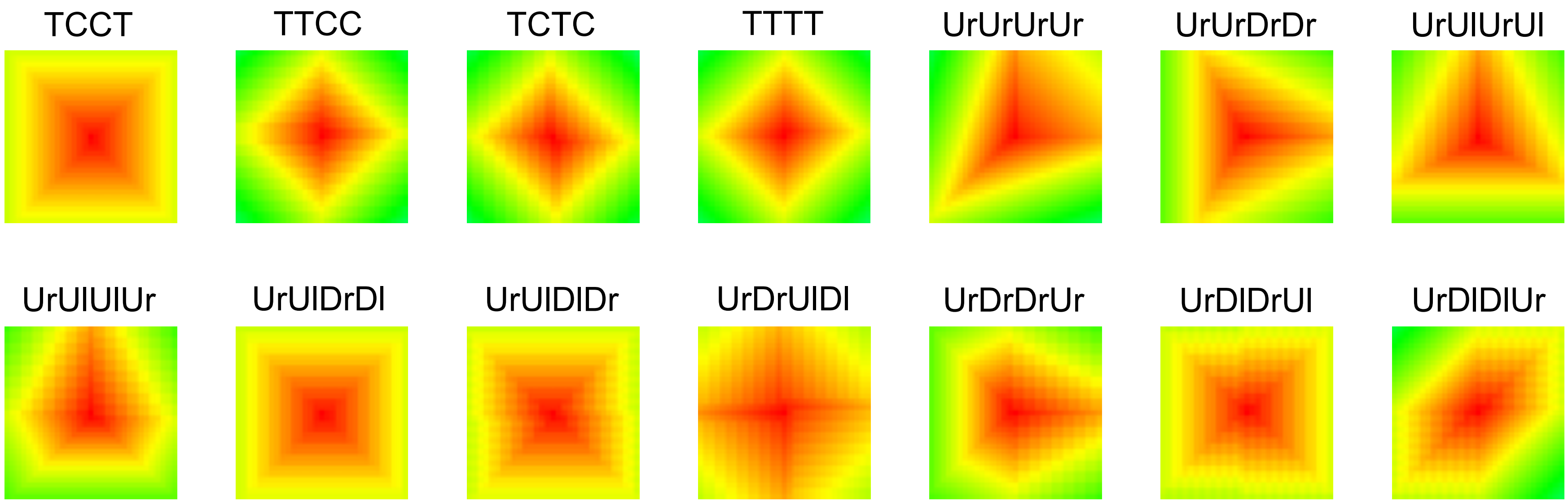
- Tiling of patterns:
  (patterns must form a consistent schedule)



- 14 possible tilings from 2x2 patterns (while not mixing the “circular” and “cross” patterns):
  - TCCT, TTCC, TCTC, TTTT
  - UrUrUrUr, UrUrDrDr, UrUlUrUl, UrUlUlUr, UrUlDrDl, UrUlDlDr, UrDrUlDl, UrDrDrUr, UrDlDrUl, UrDlDlUr

Characteristics and properties

Information propagation from the center of a 31x31 grid:



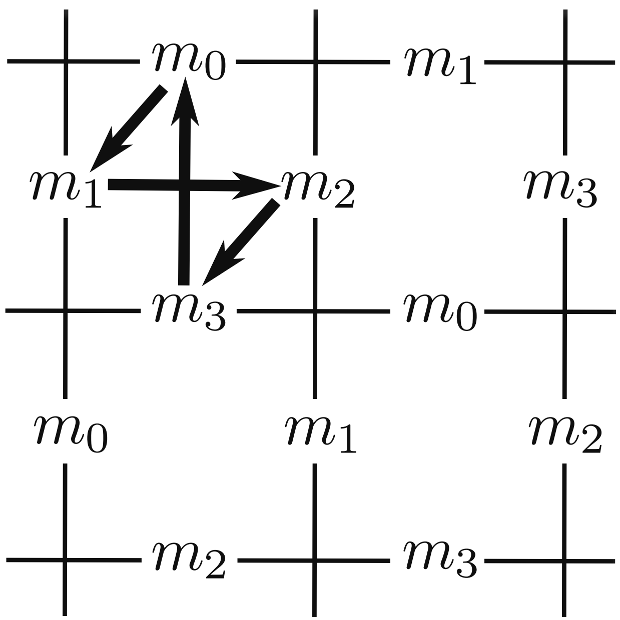
Observations:

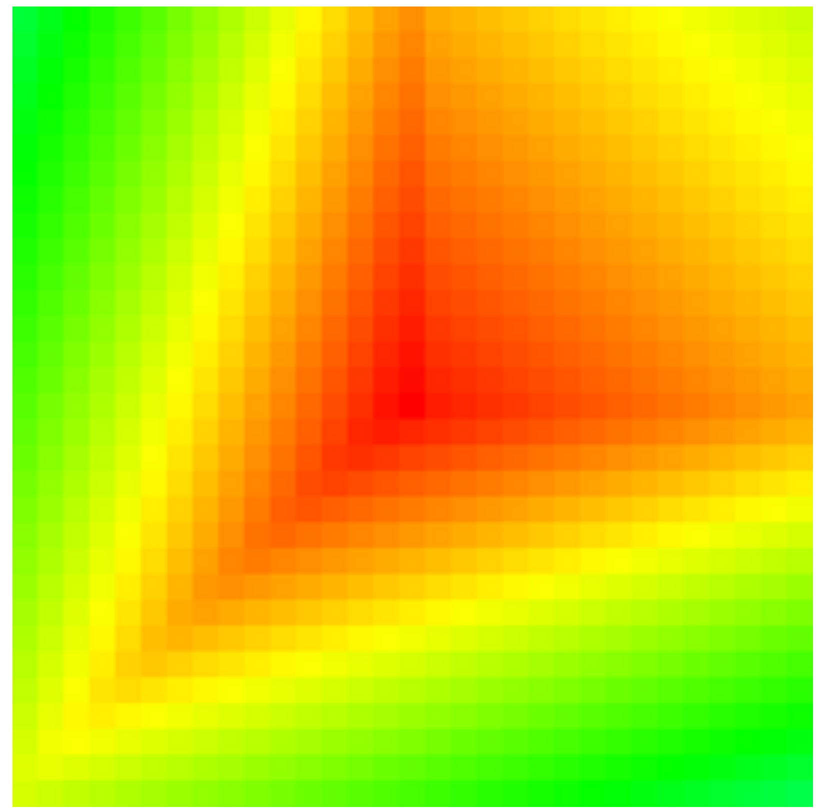
1. Different patterns propagate information at different speeds and in different directions
2. The number of informed nodes grows in time at different rates

Propagation speed and direction

- Different patterns propagate information at different speeds and in different directions.

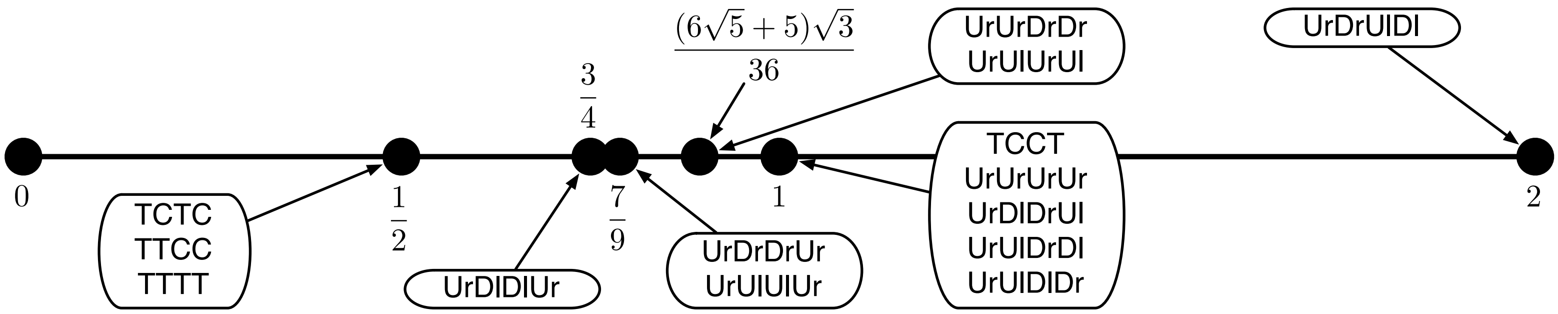
- **Example** - UrUrUrUr pattern:

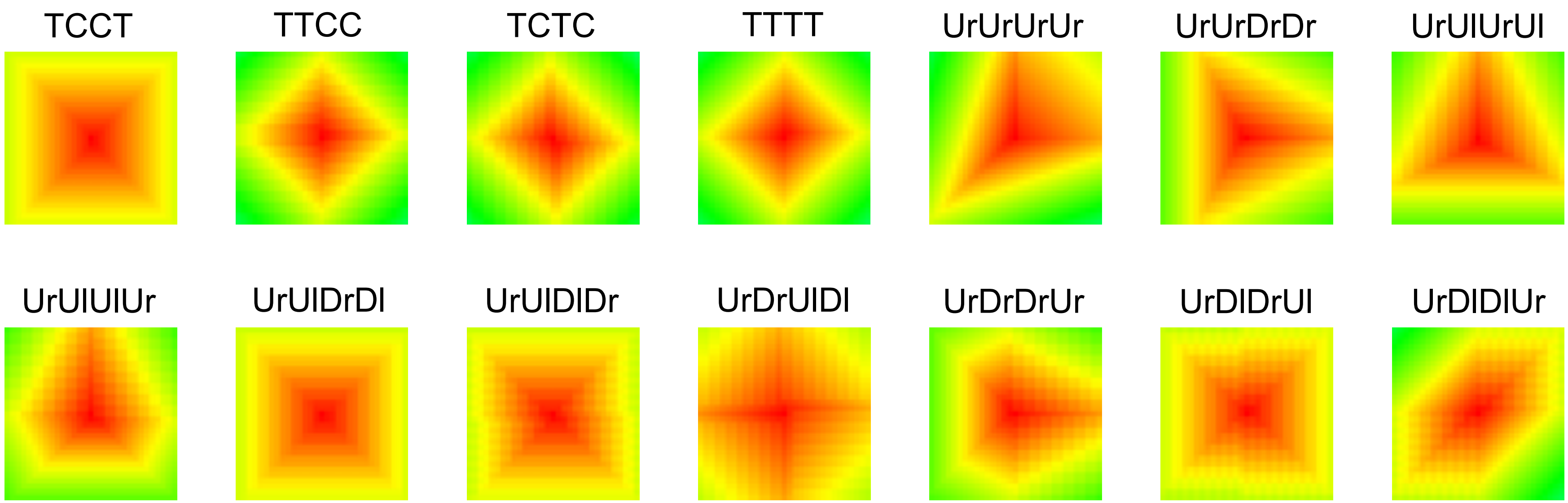




Growth factor

- The number of informed nodes t units of time after the event is in the order of gt^2, where the constant g is referred to as the ***growth factor*** :





Characteristics and properties

- Two **main characteristics** of interaction patterns:
  - Preferred direction of propagation
  - Growth of the number of informed nodes

- Key **implications**:
  - Not all consistent schedules are equivalent
  - The choice of a well-suited pattern depends on the mission

- **Simulation study:** Event detection missions

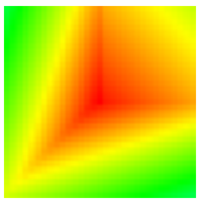
  Destination:
    - Top right corner node
    - Either top corner node
    - Any corner node
    - Any node on the top edge
    - Any node on the top or right edge
    - Any edge node
    - Small number of nodes randomly and uniformly distributed on the grid

Propagation delay

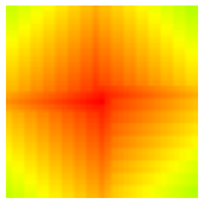
- Destination: **top right corner**

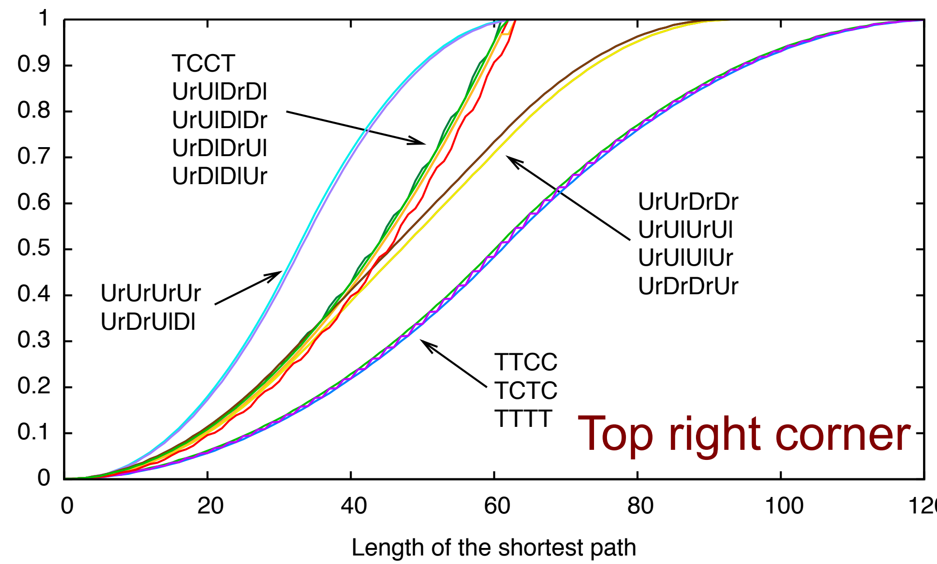
  Fastest patterns:

UrUrUrUr



UrDrUlDl

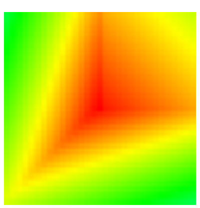




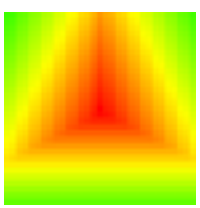
- Destination: **top edge**

  Fastest patterns:

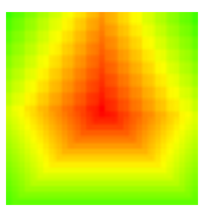
UrUrUrUr



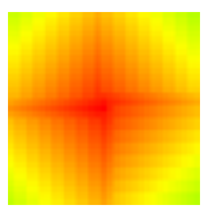
UrUlUlUr

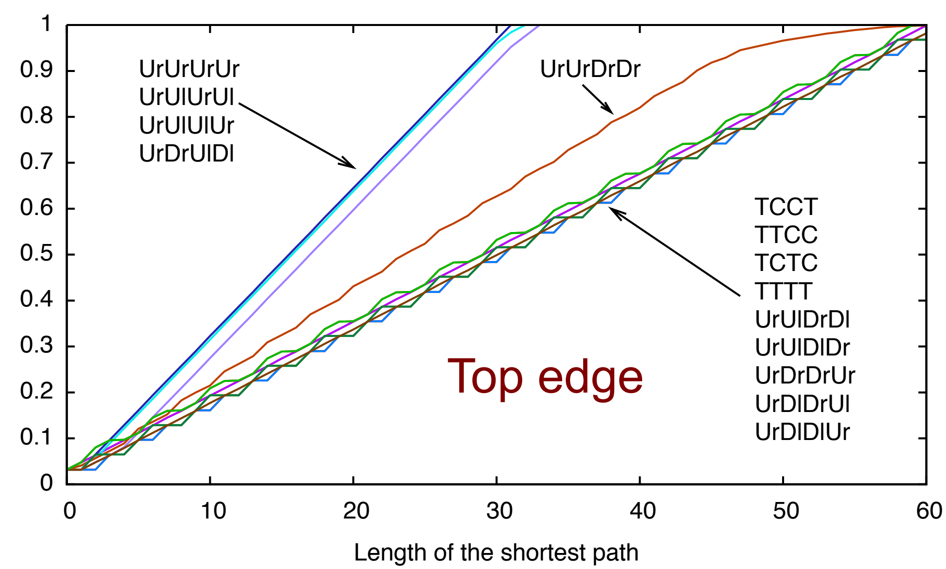


UrUlUlUr



UrDrUlDl

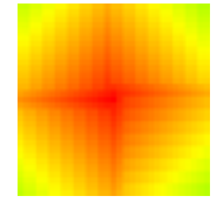




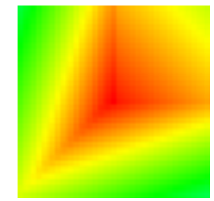
Pattern growth & energy consumption

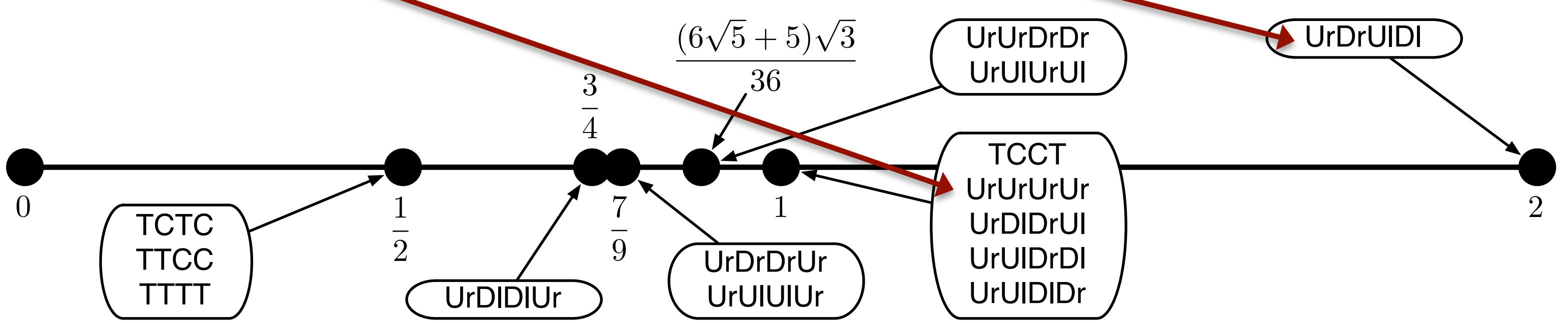
- If the **speed of information propagation** is the only measure, **UrDrUlDl** outperforms all other patterns for many scenarios
- Consider mission with top-right corner as the destination:
  - Both UrDrUlDl and UrUrUrUr have the same propagation speed
  - However, the growth factor of UrDrUlDl is double that of UrUrUrUr

UrDrUlDl



UrUrUrUr

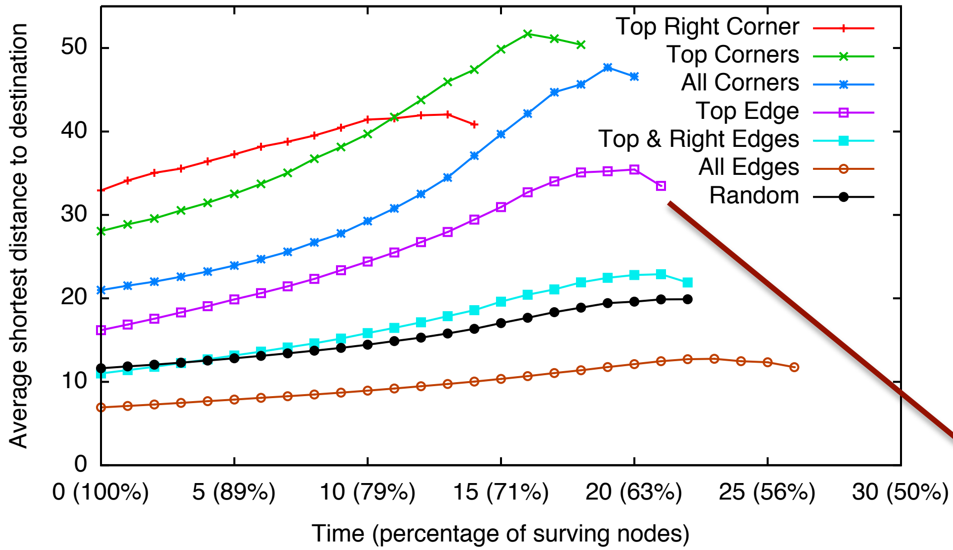




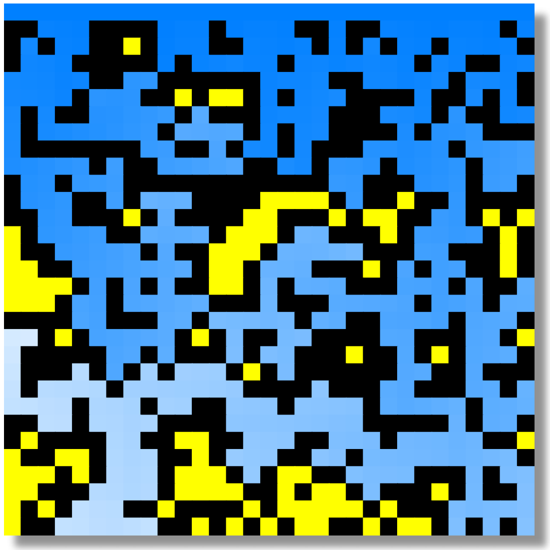
- Assuming that the distance to the destination can be estimated, well selected Time-To-Live can be used to control the propagation of information and hence the overall **energy consumption**

LOCKHEED MARTIN AFCEA IEEE AEROSPACE

Network robustness



Shortest distance to destination



Top edge destination, 42% failed nodes plus 9% unreachable nodes

Example:

- UrUrUrUr pattern
- All 7 destination distributions
- Exponentially distributed **node failures**
- Average shortest distance to destination measured

Conclusions and future work

- Despite commoditization of networking, there are scenarios in which building a general purpose network is not possible or desirable
- We propose to forgo the standard networking abstraction and to explore different ways for system entities to interact
- Simple patterns of pair-wise communications on a regular grid can be used as basic building blocks
- Different patterns can be used to satisfy the goals and constraints of a particular mission
- Our current and future work includes
  - Exploration of other topologies (hexagonal or square with corner meetings)
  - Networks with mobile nodes and mobility aided repair schemes
  - Analytical models of meeting-based computation

Questions?

Acknowledgement: The initial work on this project was sponsored in part by a grant from the U.S. Office of Naval Research