Simulating Large-scale Dynamic Random Graphs in OMNeT++

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OMNeT++ Workshop
March 23, 2012

Reykjavik University

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Introduction and motivation

- *Networked communications systems* are an important research topic.
- *New paradigms* impact our everyday lives in new and sometimes unforeseen ways.
- Can expect distributed systems to grow both in *number* and *scale*.
  - wireless sensors
  - collaborative sensing and sharing
  - the internet of things
  - ...

The case for simulation

- New protocols and distributed applications require careful evaluation.
- Notoriously hard to test.
  - Repeatability
  - Access to testbeds
  - Practical size limitations of testbeds
  - ...
- Simulation is an important tool for analysis

- We can specify a *fine grained model*:
  - Mobility characteristics
  - Full protocol stack
  - Detailed infrastructure
  - ...
- Highly domain specific

The case for random graph based simulation

- We may want to model at a more *abstract* level using some general but realistic system assumptions.
- Handy tool: Random graph models
  - Simulations of networked systems are based on an *underlying network graph*
  - Random graph models may be applied in case of a non-deterministic network.

Approach

- Construct a high-level *approximation* of a networked system by picking an appropriate *generation algorithm* and *parameters*.
  - **Size/scale**
  - **Dynamism**, e.g. mobility – VANETs, MANETs, pedestrian networks.
  - **Comm links**: range, capacity, protocol, loss model.
  - **Means of establishing links**: Graph connectivity, degree distribution.
  - . . .

Random graphs and generation algorithms

Definition

Random graph. A *random graph* is a graph $G = (V, E)$ in which vertices and edges are determined by some random process.

Random graph generators

The *algorithms* used to construct random graphs.

- **Binomial graphs** – Erdös-Rényi.
- **Small world models** – e.g. Watts-Strogats
- **Scale-free models** – e.g. Barabási-Albert

Our objective

Present an approach and a **set of components** *to enable dynamic generation and maintenance of random graphs at* **runtime** *within OMNeT++.*

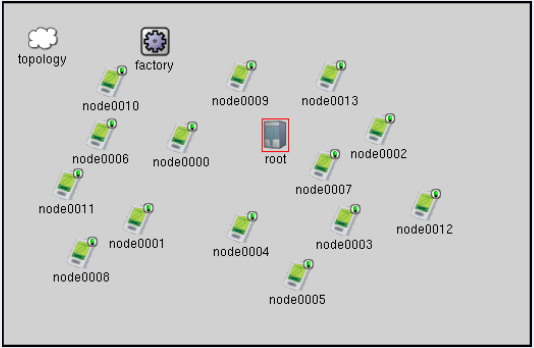
https://github.com/kristjanvj/DRGSimLib

The simulation toolbox

Components

- **Nodes** – a compound node representing simulated objects
- **Node factory** – manages lifetime of nodes
- **Topology** – manages node relations – the *network graph*

Sample scenario



The node factory – Factory

- *Dynamic* instantiation and destruction of nodes
- Operates *independently* of the graph generation

Parameters

`nodeType` The class name of a OMNeT++ compound module – the type of node to be manufactured.

`generateInterval` The node generation interval.

`lifetime` The lifetime of generated nodes.

`minLifetime` The minimum lifetime of generated nodes.

Volatile parameters – can plug in OMNeT++ standard random functions in ini file.

Topology management – `Topology`

- Flexible generation/maintenance of random graphs.
- Architecture:
  - *controller*
  - a plug-in generator instance

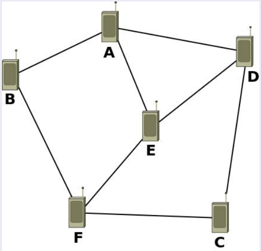
Parameters

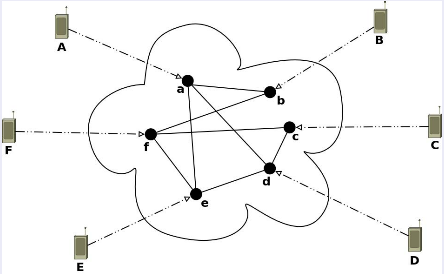
`topologyGenerator` The name of a topology generator class implementing the `IBasicGenerator` interface.

`updateInterval` The interval in seconds between updates of the edge structure of the graph.

`snapshotFile` The name of a file for storing snapshots of the graph topology for off-line analysis.

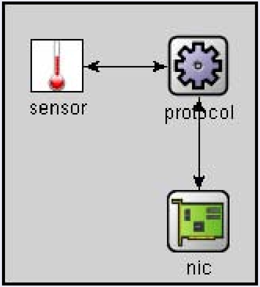
Representing a communications model as a graph





- Communications network represented by a *single data structure*
  - managed by the *controller*
  - via algorithms implemented in the *plug-in generator*
- Direct message passing (with delay) between nodes
  - $\Rightarrow$ *Minimal message object generation*

A sample node



- Node: the simulated object
- **NIC** required

The `TopologyControlNIC`

Parameters

`dataRate` The data rate in Kbps.

`bitErrorRate` A volatile parameter for the bit error rate.

`processingDelay` The processing delay in seconds.

`propagationDelay` The propagation delay in seconds.

- The **per-node** counterpart to the `topologyControl`
- *Registers* the host node with Topology upon instantiation
- *De-registers* upon destruction
- Stores *local neighbourhood view*

Plug-ins for graph generation and management

- The graph generator is a *plug-in* instantiated at start of simulation vial ini file parameter.
- Derived from a *base class*, implementing `IBasicGenerator` interface.
- Users can derive their own random graph generator classes

`IBasicGenerator`

`addNode` Adds a vertex to the graph data structure and creates edges in accordance with the implemented algorithm.

`void removeNode` Removes a vertex from the graph. All incident edges are also removed.

`bool update` Periodic updates of the graph edges to simulate dynamic effects other than node churn.

`void constructInitialTopology` Called after initialization of the topology manager to create edges between nodes instantiated at time zero.

Binomial graph generation

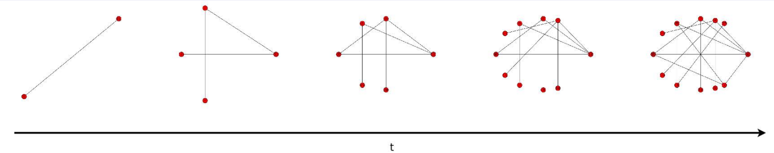
The binomial graph $g_{n,p}$, also known as a Erdös-Rényi graph.

Generation algorithm

Generate n nodes $\in V$. For a node $v \in V$, create an edge $e = (u, v) \in E$ with probability p to each node $u \in V \setminus v$.

$g_{n,p}$ insertion of nodes

{Upon registration of node v}
insert v into V, the vertices collection
if $|V| = 1$ **then**
    return
else if $|V| = 2$ **then**
    createLink(u,v)
else
    select node $u \in V$ uniformly at random.
    createLink(u,v)
    for each $z \in V \setminus u$ **do**
        createLink(v,z) with probability p
    end for
end if

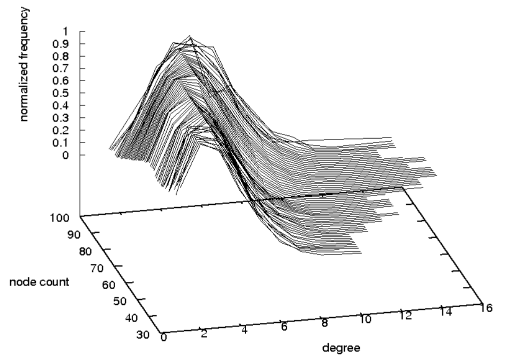


$g_{n,p}$ graph maintenance

{Executed periodically, T_Δ is the time units since last update.}
$p_r \leftarrow T_\Delta \cdot p_C$
$p_a \leftarrow T_\Delta \cdot p_C \cdot |E|/|V|$
for each $e \in E$ **do**
  remove e with probability p_r
end for
for each $v \in V$ **do**
  do with probability p_a: pick a neighbor $u \in V \setminus v$ uniformly at random and add edge (v, u)
end for

A small $g_{n,p}$ graph evolution experiment

Average degree distribution



- Note the characteristic *Poisson* shape of the curves
- Not scale-free

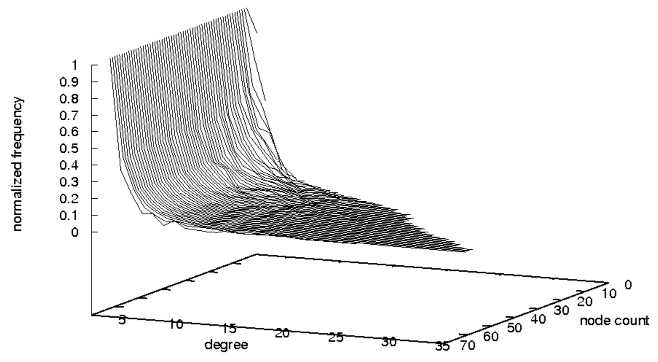
Barabási-Albert (BA) graph generation

Generation algorithm

Generate a new node v in the graph $G = (V, E)$. For the node v, create an edge $e = (u, v)$ with any peer $u \in V \setminus v$ with probability $p(u) = k_u / \sum_{z \in V} k_z$, where k_z is the degree of a node $z \in V$.

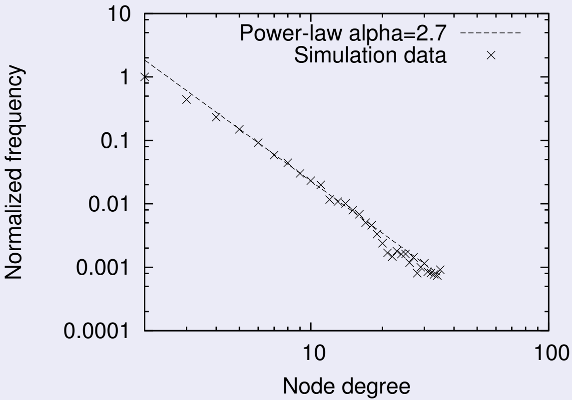
A small BA graph evolution experiment

Average degree distribution



- Distinctive *power-law* shape
- Scale-free?

Power law characteristics of a BA graph



Problematic effects of graph dynamism

- *Dynamism* $\Rightarrow$ graph connectivity not guaranteed
- Fact of life but complicates analysis
- `Topology` *optionally* guarantees connectivity

(i) Cut vertices

(ii) Cut edges

Remedy

1. Search k-neighbourhood recursively to determine connectivity.
2. Connect components which have not been confirmed as connected.

Application example: GAP

- The Generic Aggregation Algorithm – GAP[1].
- Designed for *network monitoring applications*
- Continuous monitoring in *dynamic* networks.
- Distributed construction and maintenance of a spanning-tree overlay – the aggregation overlay.

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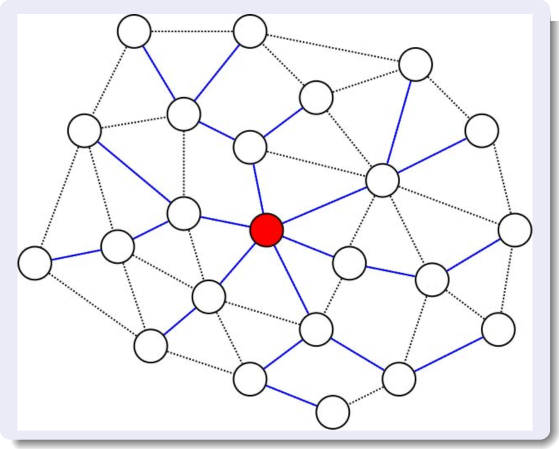
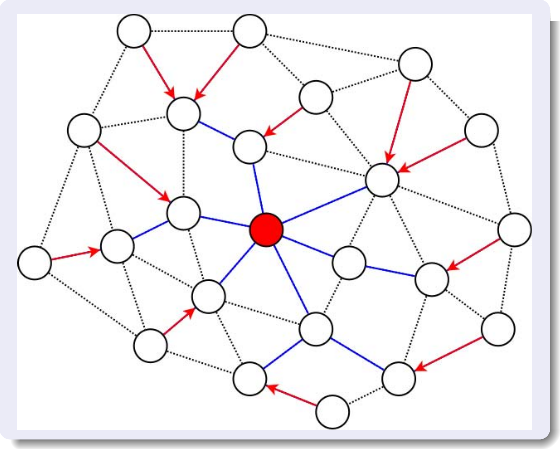
[1] Dam, M. & Stadler, R., *A generic protocol for network state aggregation*. In Proc. Radiovetenskap och Kommunikation (RVK), pp. 14–16, Linköping, Sweden. 2005.

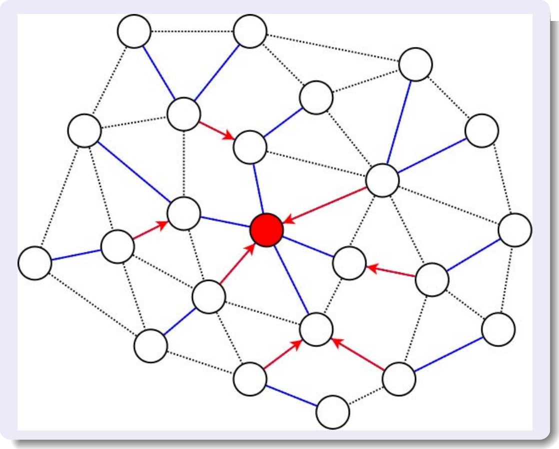
In-network computation



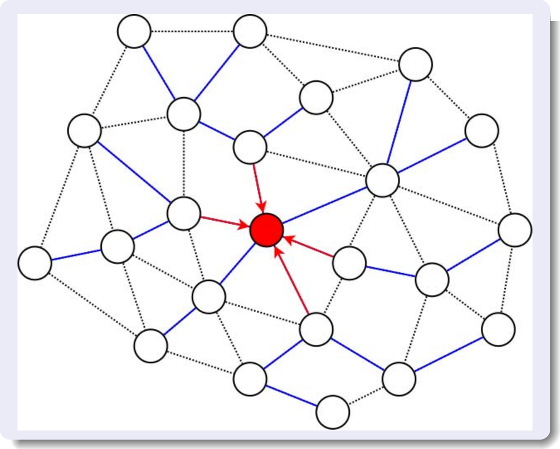
In-network computation



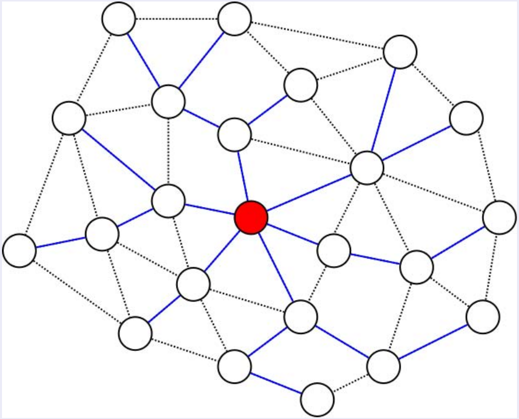
In-network computation



In-network computation



In-network computation



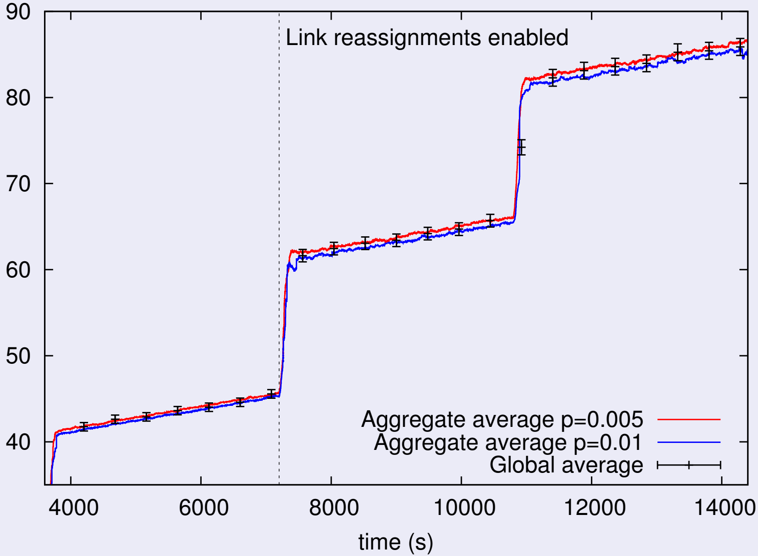
- Each node provides updates on *own* schedule
- Example shows *synchronous operation* for simplicity
- Recipients of updates compute *new* contributions *in-network*

Constant node population

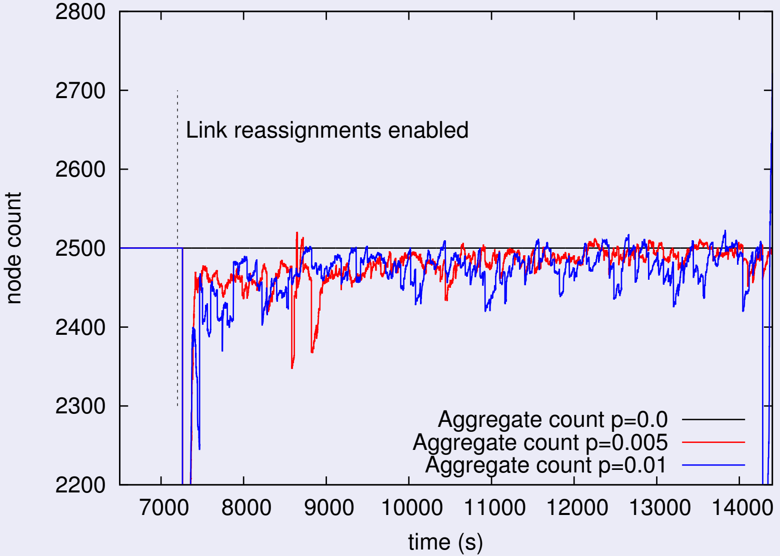
Experimental setup

- BA graph, $m_0 = 5, m = 3$
- 2500 nodes, static population
- Dynamic link reassignments in window $t = [2h, 4h]$.
- Failure detection latency: $1s + \mathcal{N}(0s, 1s)$.

Aggregate – AVERAGE



Aggregate – COUNT

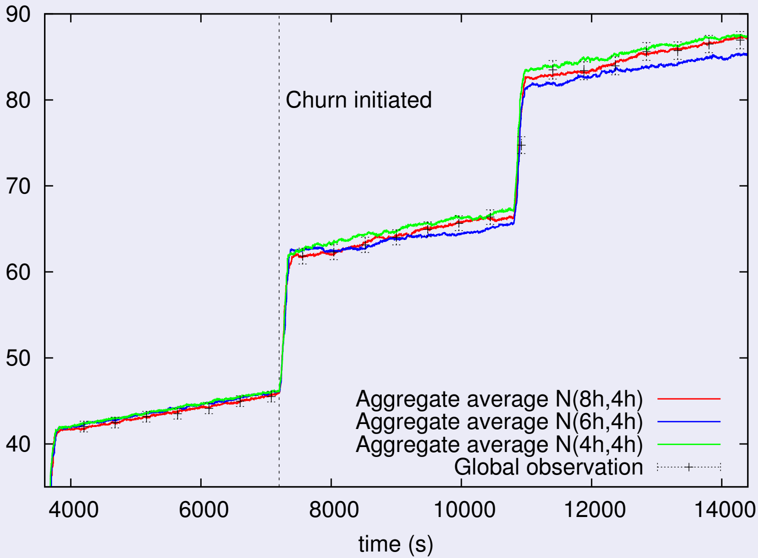


Dynamic node population

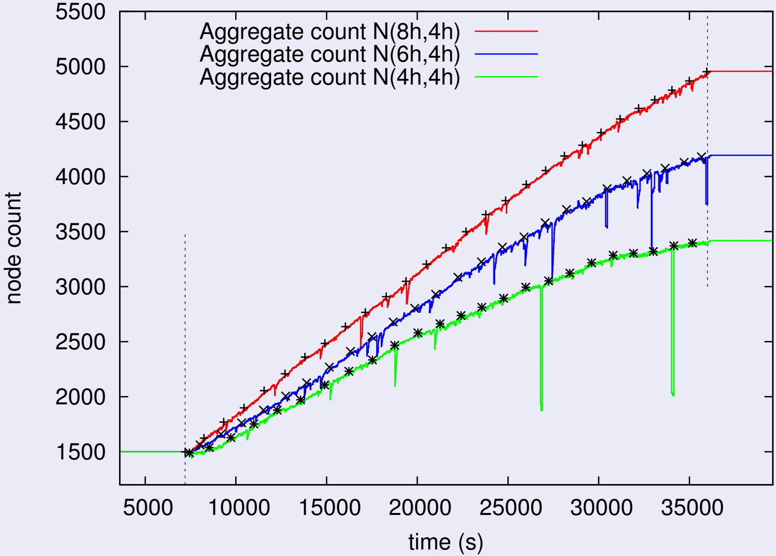
Experimental setup

- BA graph, $m_0 = 5, m = 3$
- 1500 nodes at time zero
- Poisson arrivals with $1/\lambda = 5s$.
- Node lifetime drawn from $\mathcal{N}(\mu, \sigma)$
- Initial node lifetime (zero population) drawn from uniform $[0, \mu]$ distribution.
- Churn interval $t = [2h, 10h]$
- Failure detection latency: $100ms + \mathcal{N}(0s, 100ms)$.

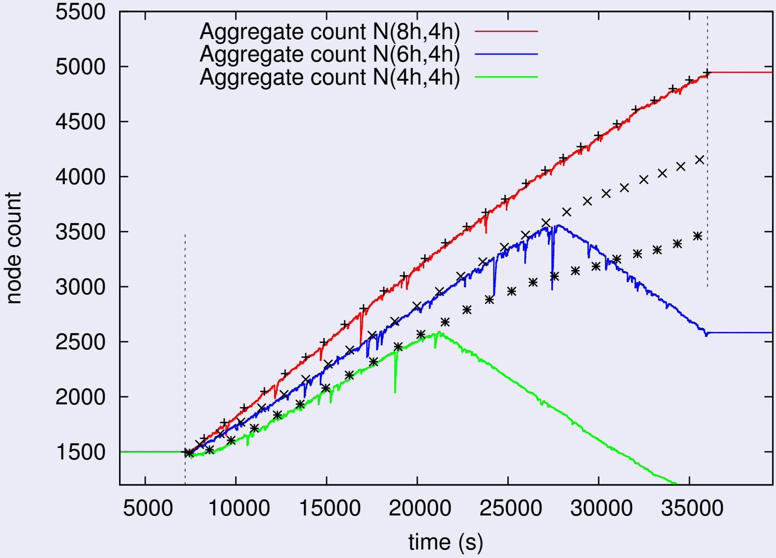
Aggregate – AVERAGE



Aggregate – COUNT



Aggregate – COUNT. Slow failure detection.



failure detection: $1s + \mathcal{N}(0s, 1s)$.

Conclusions

- **Motivation**: Allow easy construction of random-graph based simulations in OMNeT++
  - Abstract away from complexities of networks/systems, providing means of evaluating protocols with emphasis on end systems.
- **Toolbox**: Provide a set of components to facilitate simulation based on *random graph models* in OMNeT++
  - **Generic node class** (example only)
  - **Node factory**
  - **Topology manager** with **plug-in generators**
- **Demonstration application:** GAP dynamic aggregation protocol.
- **Generally applicable** tool for graph-based simulation research
  - May even be used for applications unrelated to physical networks.
  - OMNeT++ as a tool to study social networks?