Naps: Scalable, Robust Topology Management in Wireless Ad Hoc Networks

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What is Naps?

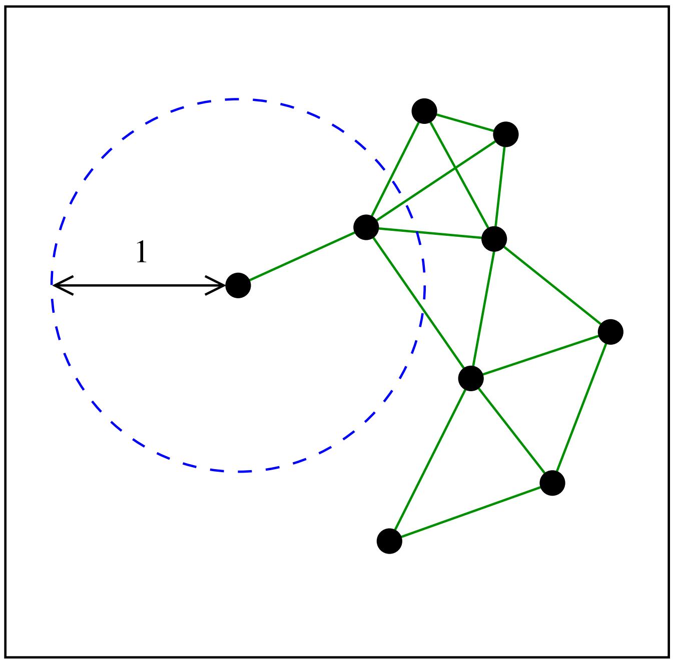
- Naps is a simple, randomized algorithm that “thins” an ad hoc network to a desired density of nodes per unit area without knowledge of the underlying density or node location.
- Potential applications: reducing contention among radios, smoothing sensing coverage
- Application in this paper: power saving
  - Nodes deployed at density λ
  - Density $\lambda_t < \lambda$ sufficient for multi-hop routing connectivity
  - Use Naps to thin network to density λ_t
  - Thinned nodes “sleep” (turn off their radios)

Model

Geometric random graph:

- Nodes distributed uniformly at random in a square region
- Average of λ nodes per unit area
- Unit radius connectivity

Naps performs well empirically even under relaxed assumptions.



Intuition

- $\lambda =$ underlying density, $\lambda_t =$ target density
- Easy way to thin to desired density: leave each node on with probability λ_t/λ (others sleep)
  - Nodes distributed like Poisson process with intensity λ
  - Poisson thinning property: waking set is like Poisson with λ_t
- Problems:
  - Needs global knowledge of λ
  - Node density may vary over space and time
- Naps uses an adaptive local estimate of underlying density

The Naps algorithm in words

Executed at each node:

- Iterate over time periods:
  - Broadcast HELLO message
  - Listen for HELLO messages from neighbors
  - If c HELLO messages received, sleep until end of period
- Initially and every 10 periods thereafter, period length is uniform-random $\in [0, T)$; otherwise period length is T.

Two parameters:

- **Neighbor threshold** c proportional to target density (e.g. $c = 6$)
- **Time period** T controls rate of turnover (e.g. $T = 10$ minutes)

The Naps algorithm in pictures

Here $c = 4$.

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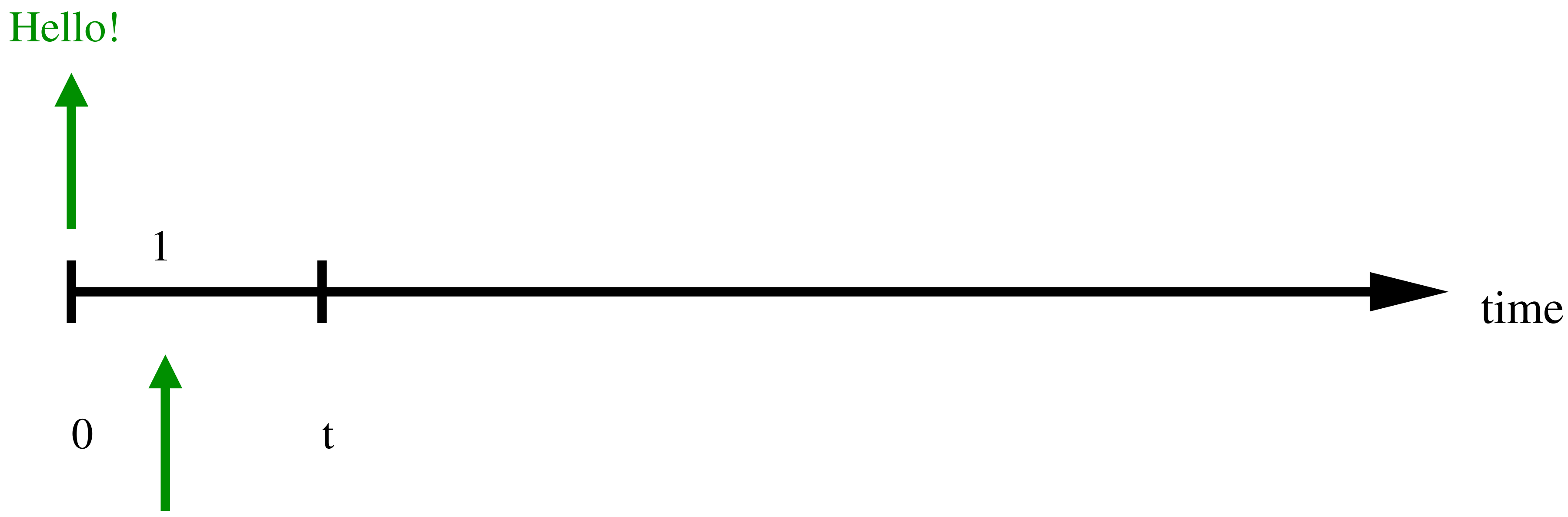

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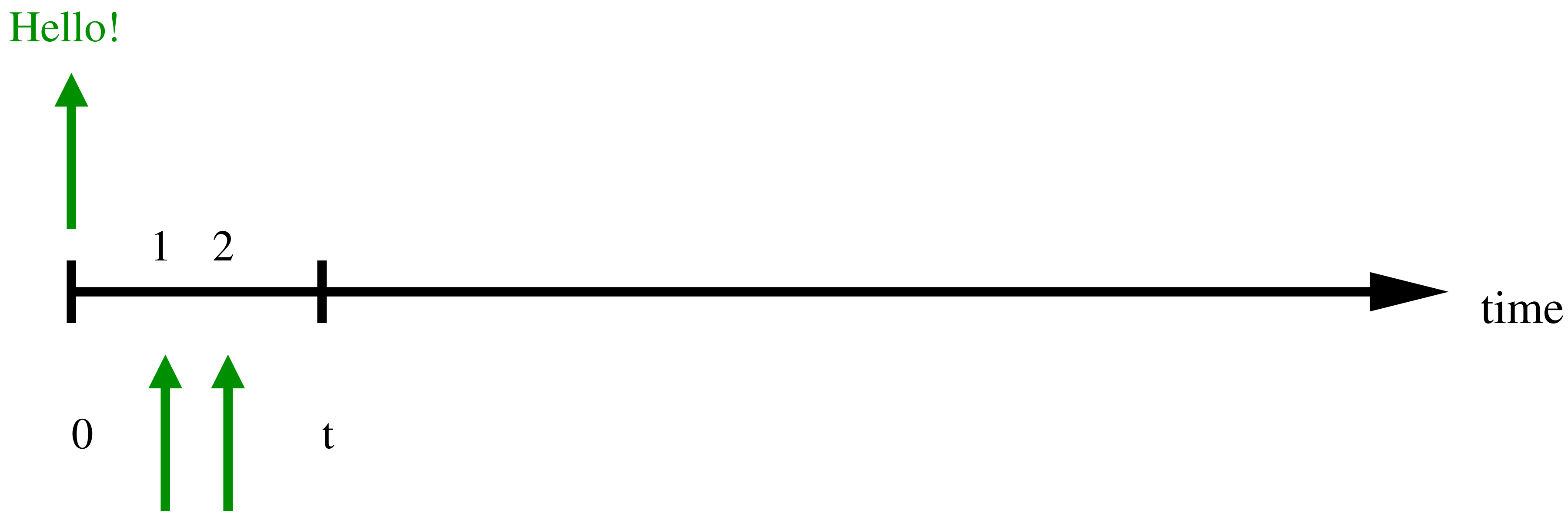

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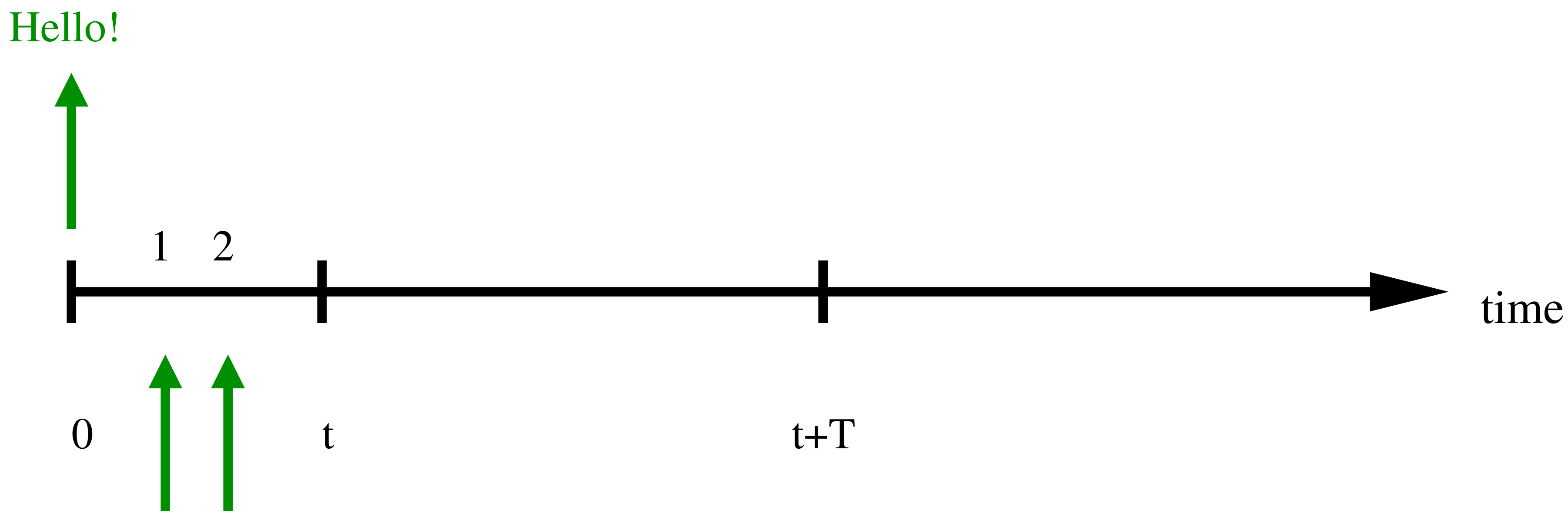

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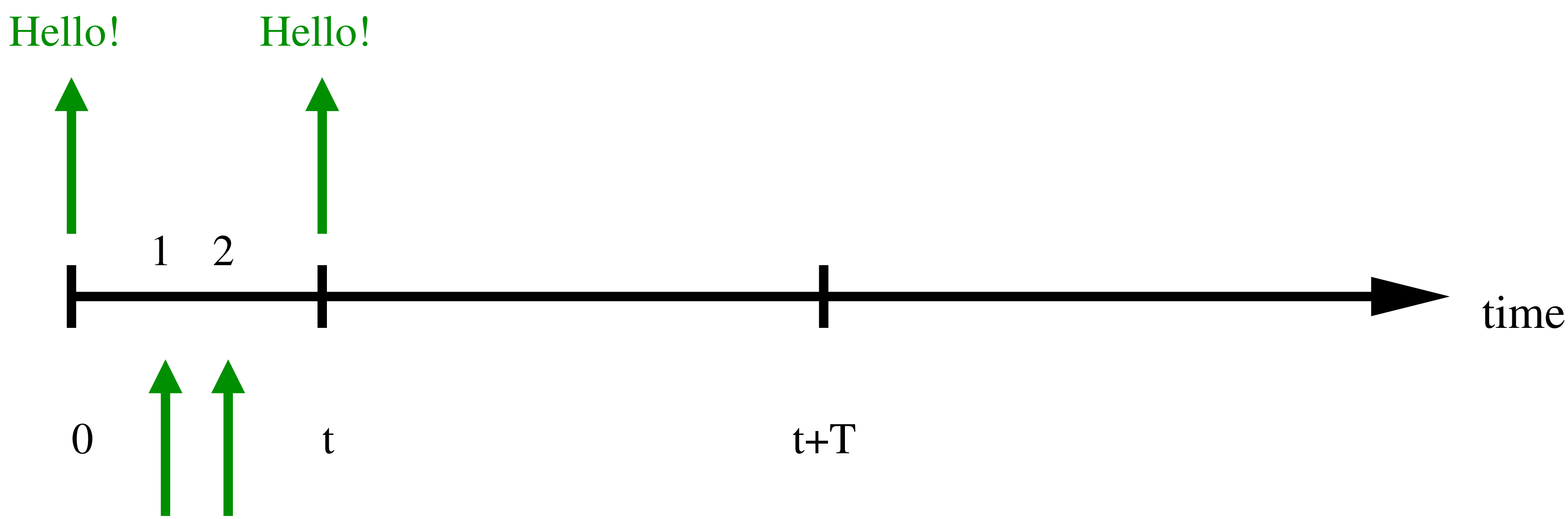

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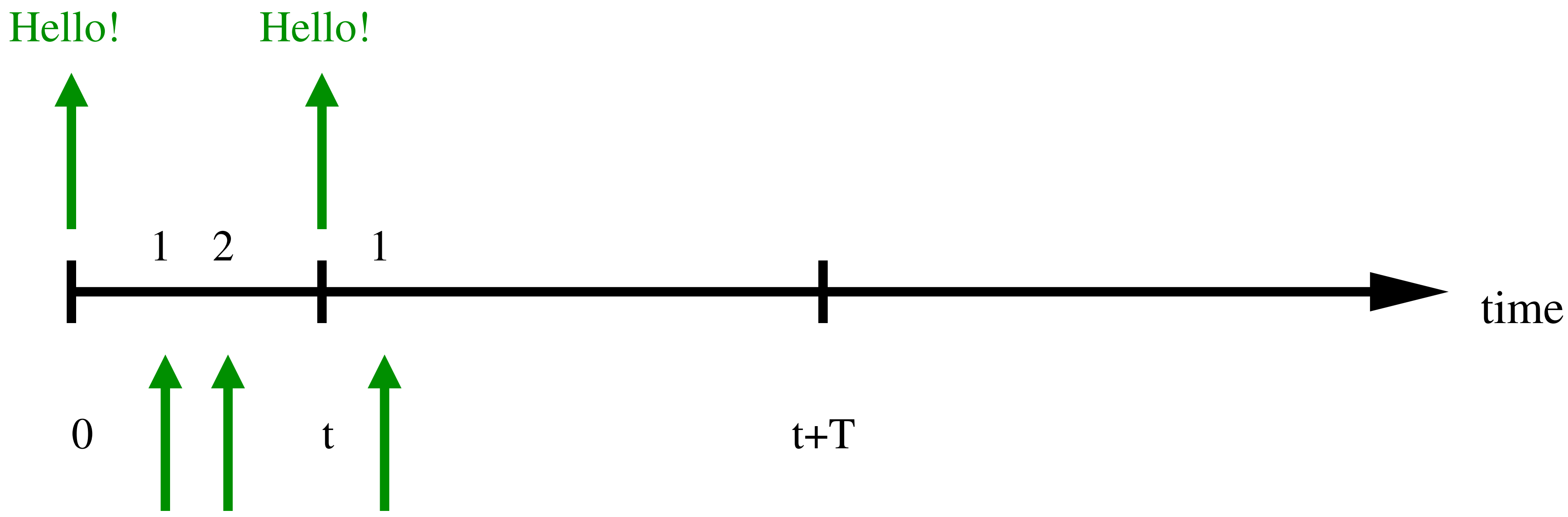

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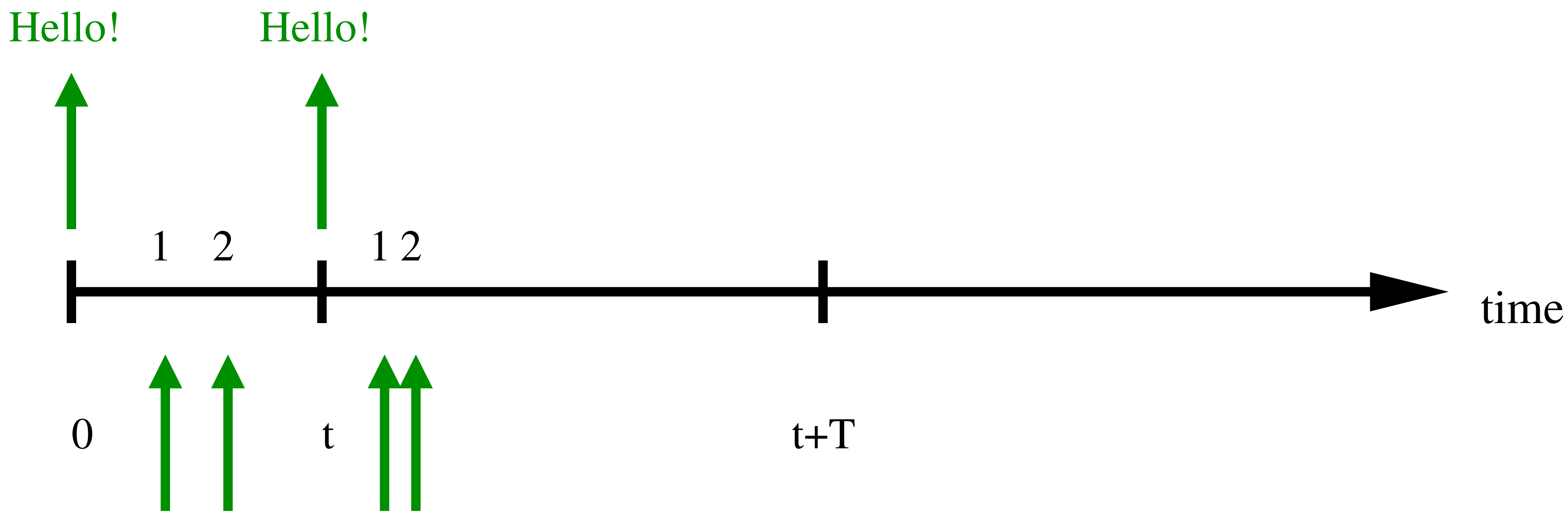

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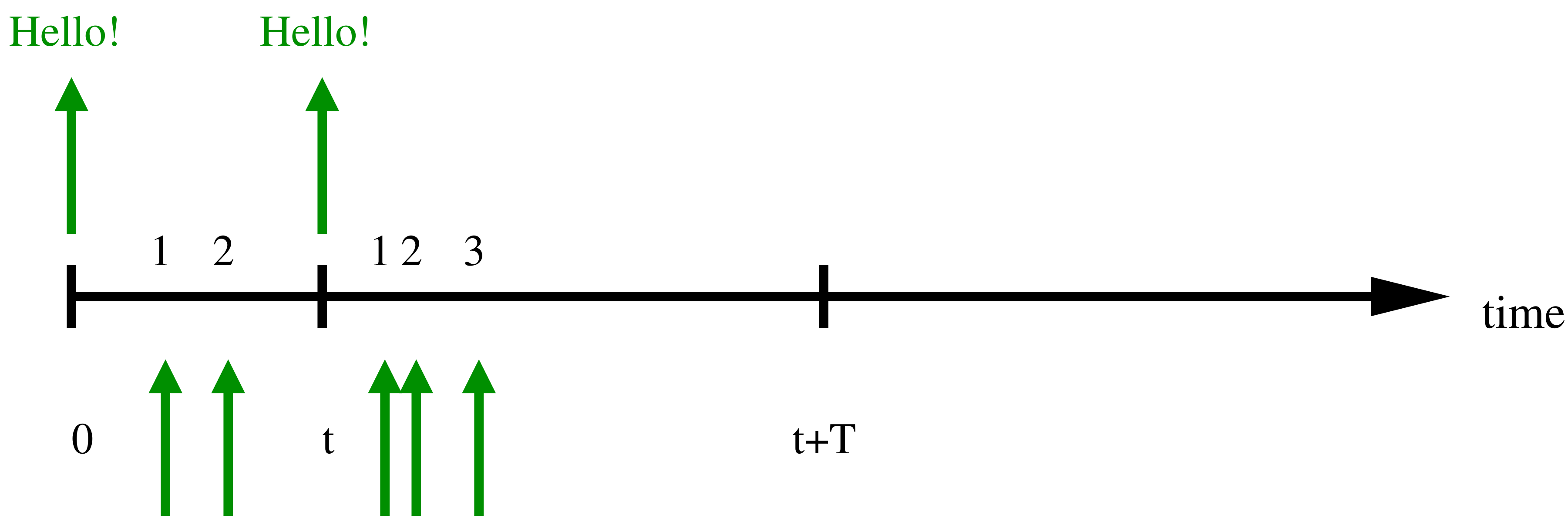

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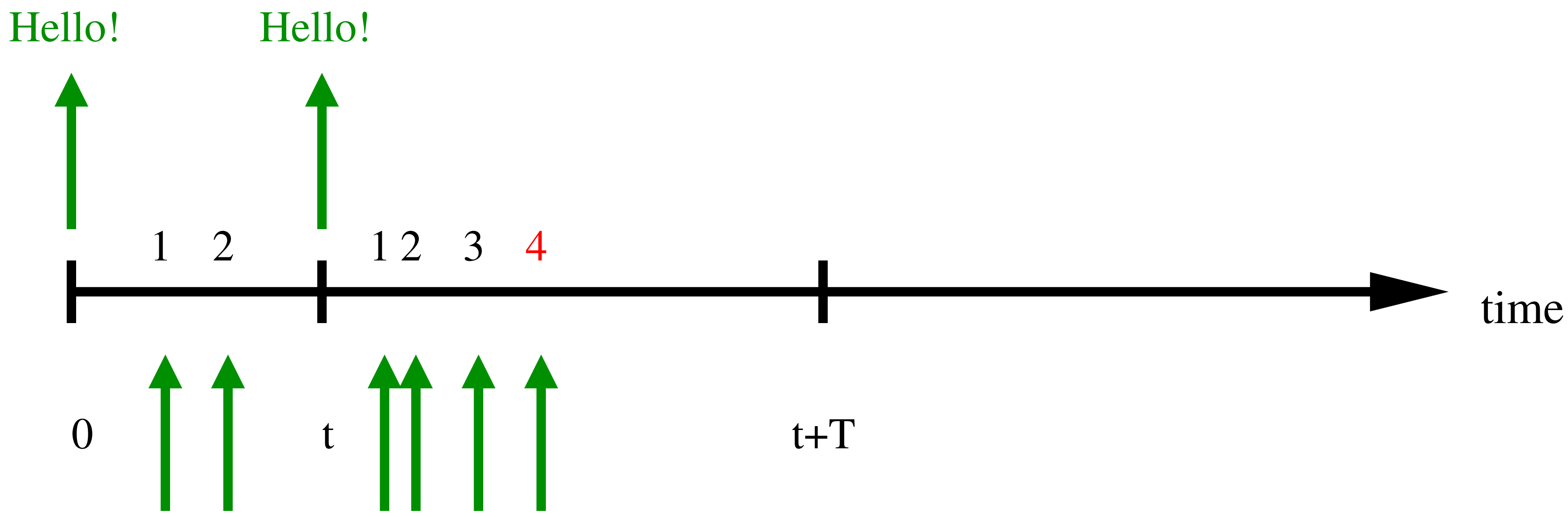

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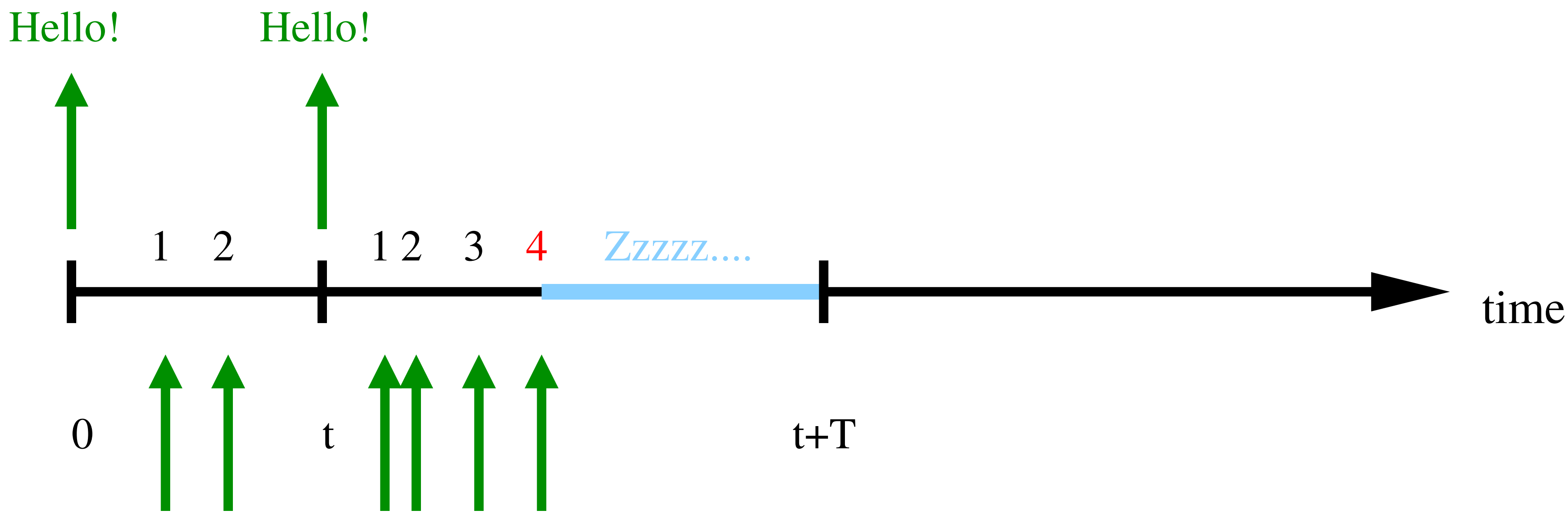

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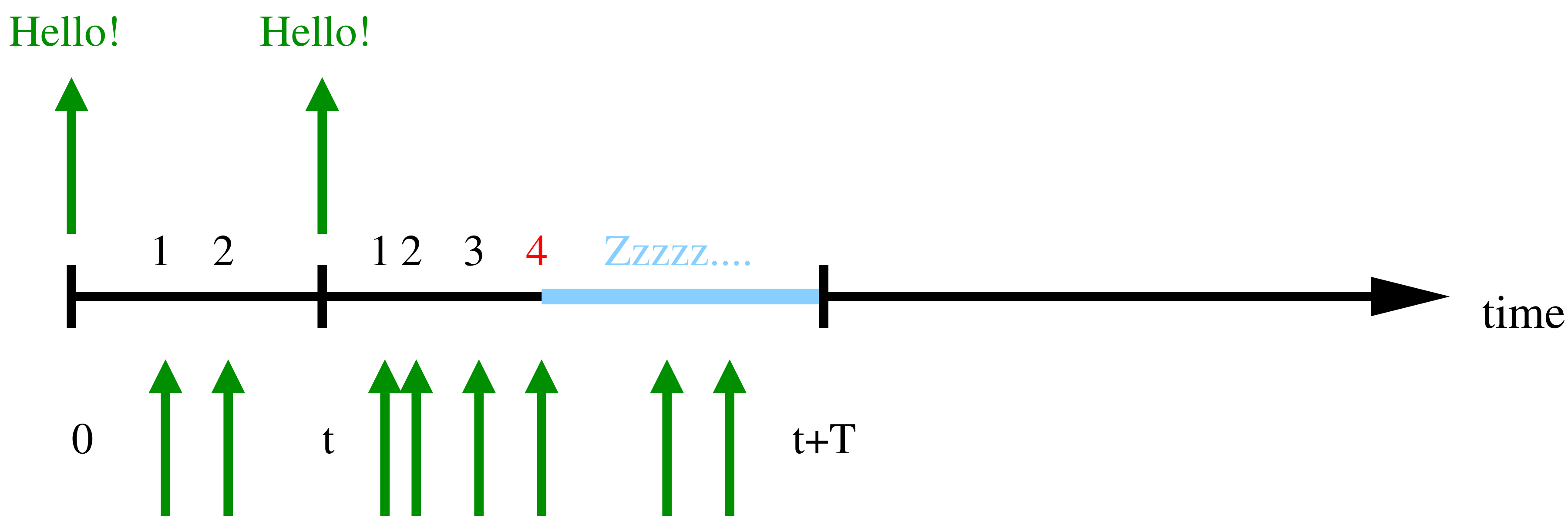

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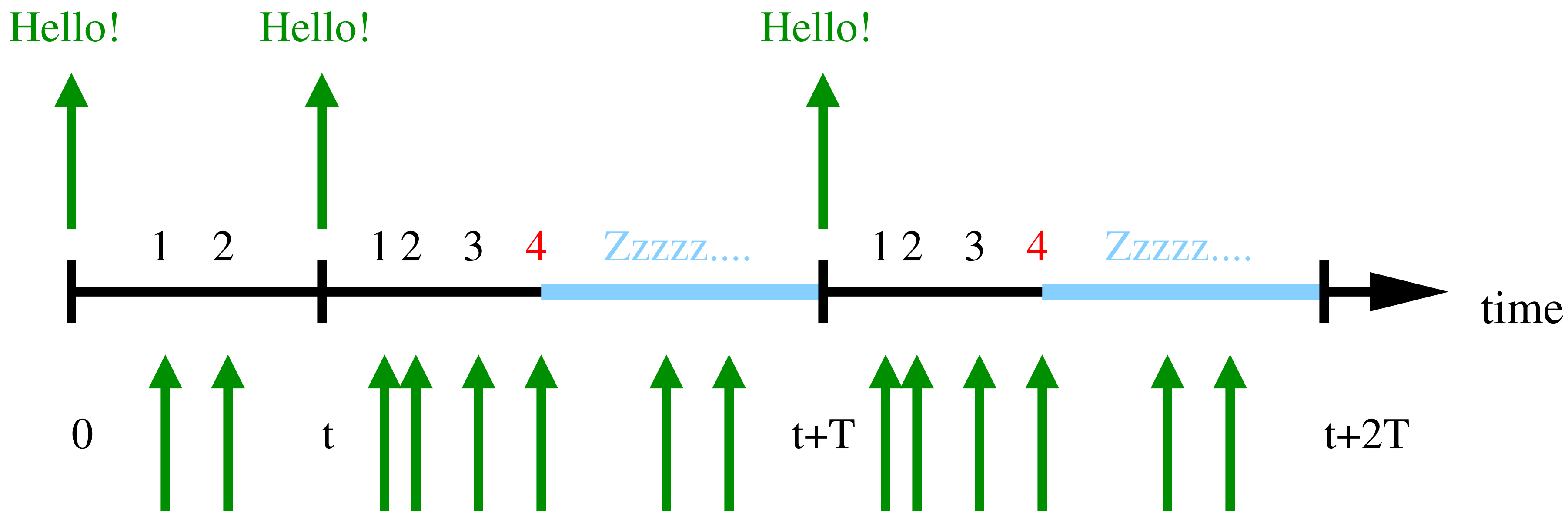


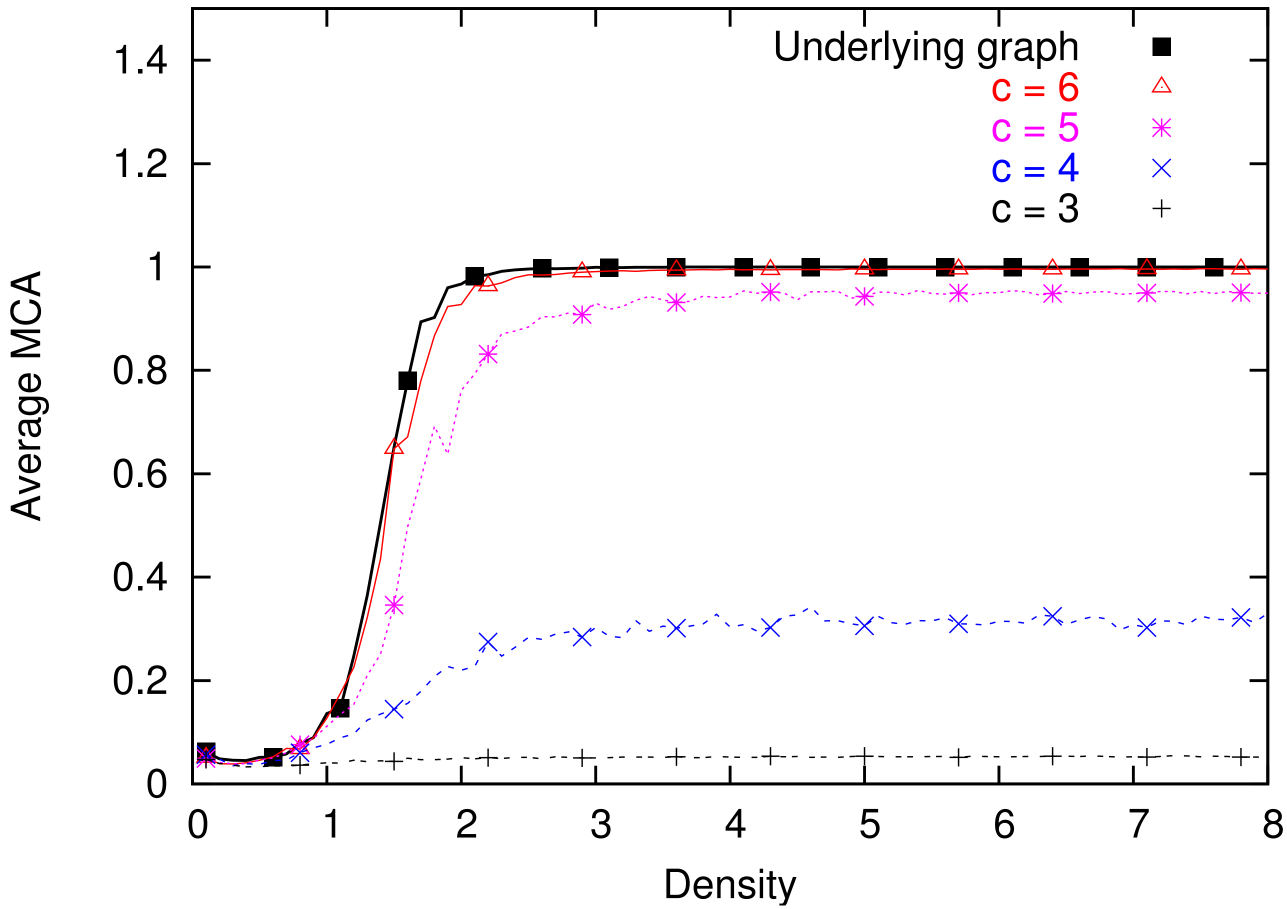
Why it works

- Suppose node v has d neighbors
- HELLO messages received by node v are uniformly distributed
- $\Longrightarrow$ expected time between two messages is $\frac{T}{d+1}$
- Node v stays awake for c of these intervals per period T
- $\Longrightarrow$ awake for fraction $\frac{c}{d+1}$ of time
- $\mathrm{E}[d] = \pi\lambda$
- $\Longrightarrow$ average node stays awake for fraction of time $\approx \frac{c}{\pi\lambda}$
- i.e. for target density λ_t, pick $c = \pi\lambda_t$

Using Naps for power saving

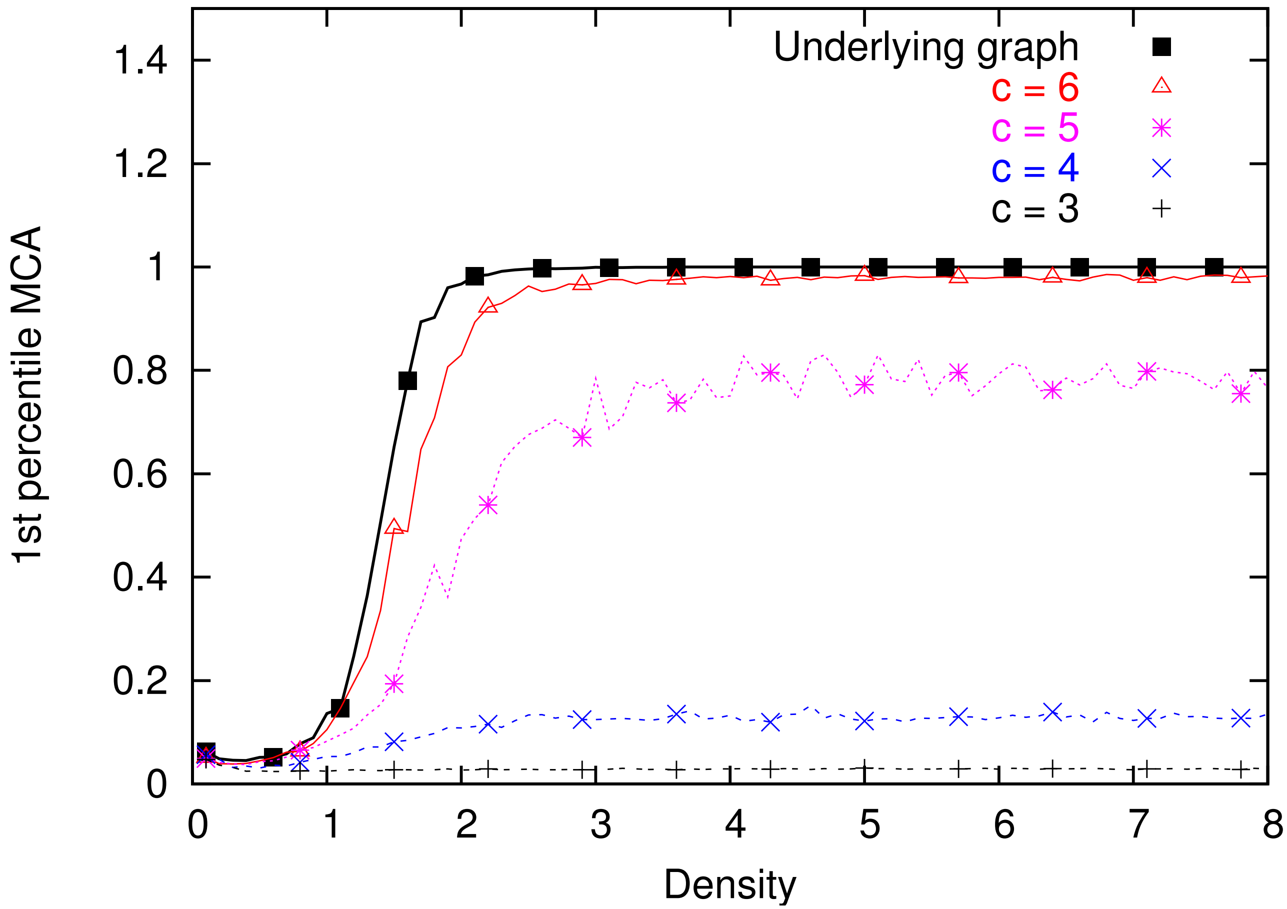
- Goal: Turn off as many nodes as possible such that multi-hop routing still works, i.e.
  - (almost all) waking nodes are in a connected component and
  - (almost every) sleeping node has a waking neighbor
- Property of geometric random graphs: there is a *critical density* λ_c above which a large fraction of nodes are in a connected component w.h.p.
- Set λ_t above critical threshold $\Longrightarrow$ almost all waking nodes are connected
- Random graphs produced by Naps are not geometric random graphs...
- ...but we prove they also have a critical threshold above which connectivity is good.

Simulation: connectivity



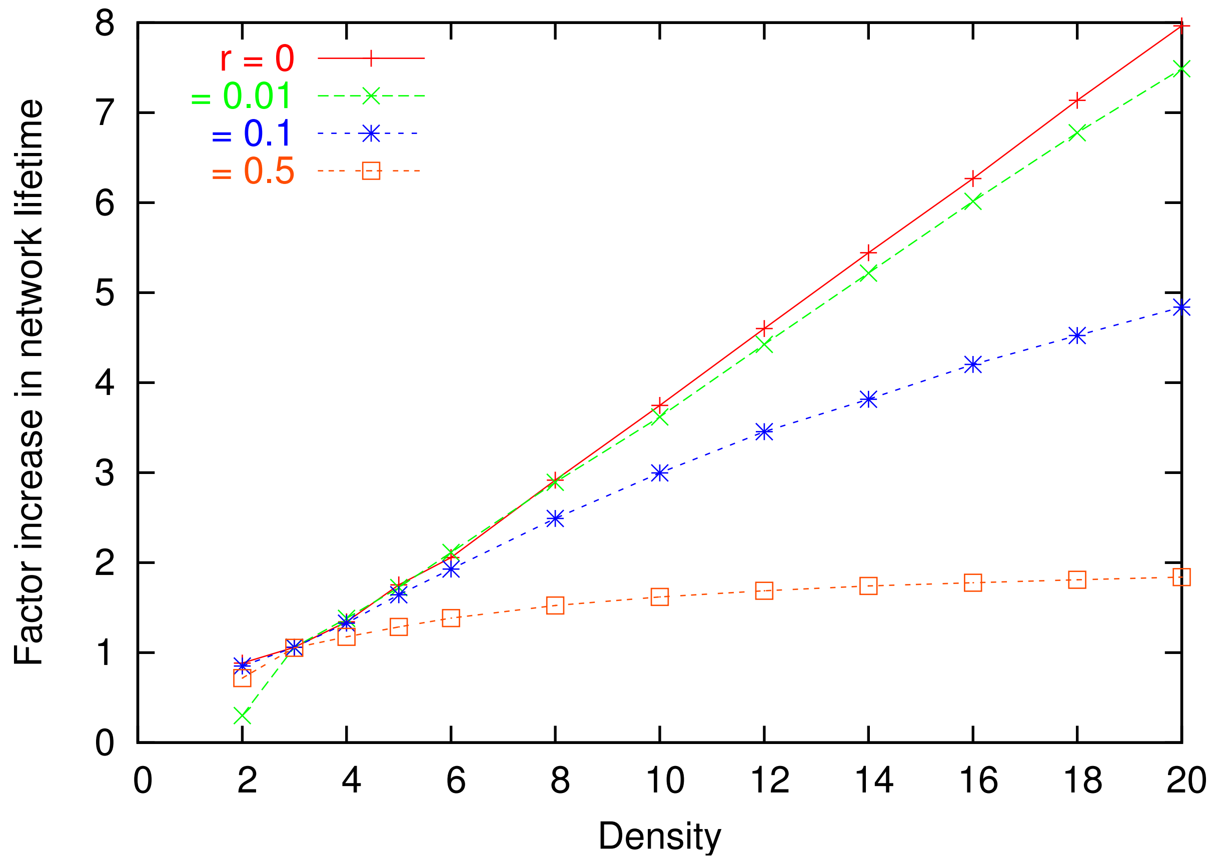
MCA = Maximum Component Accessibility = fraction of nodes in or adjacent to the largest waking component

Simulation: connectivity



Area $= 625$. 1st percentile is minimum of 100 samples within a time period, then averaged over 20 trials.

Simulation: power savings



Network lifetime is time that MCA ≥ 0.9.

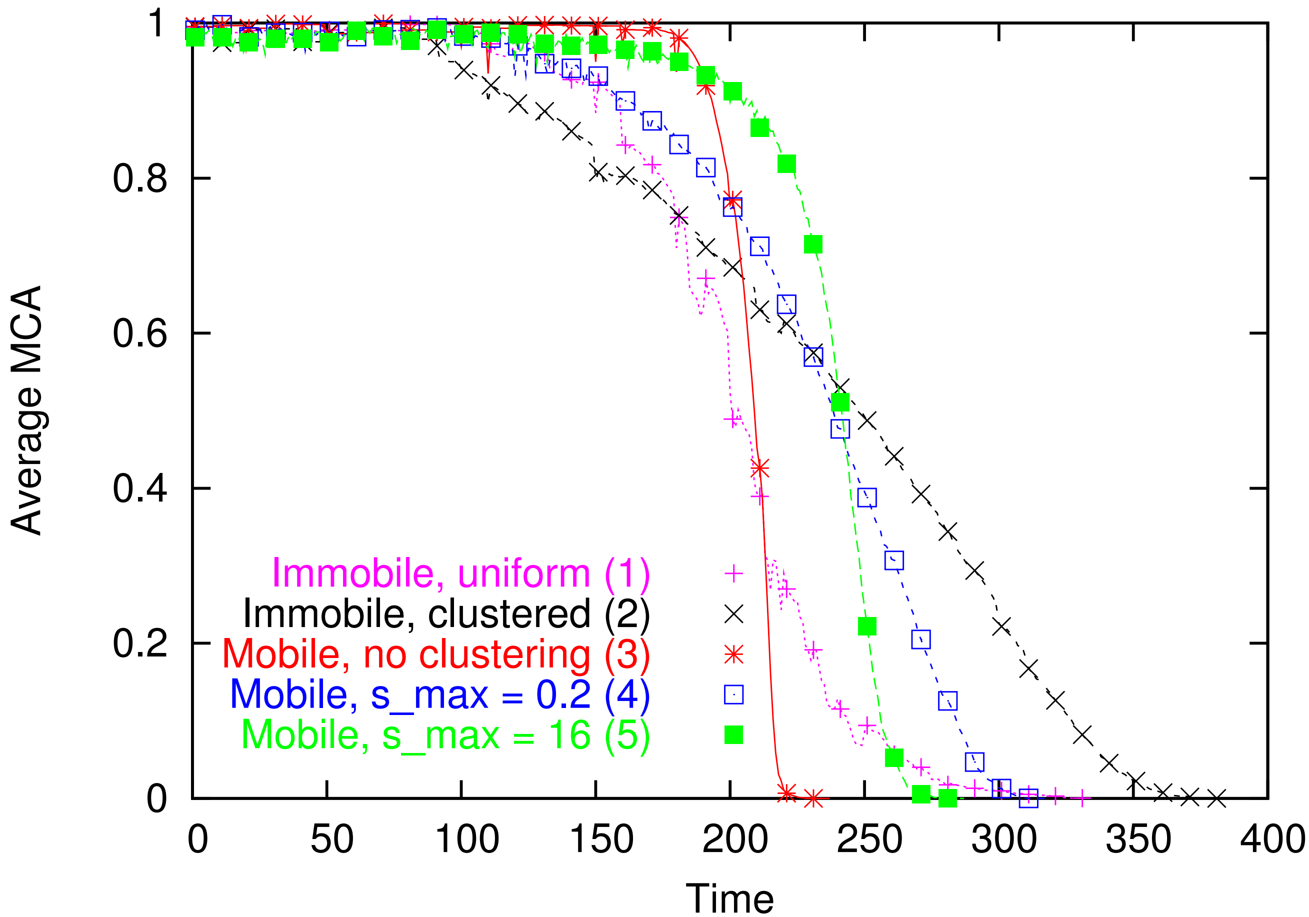
$r =$ ratio of sleeping power to waking power.

Area $= 900$, $c = 6$, waking node lifetime $= 100T$. 5 trials.

Summary

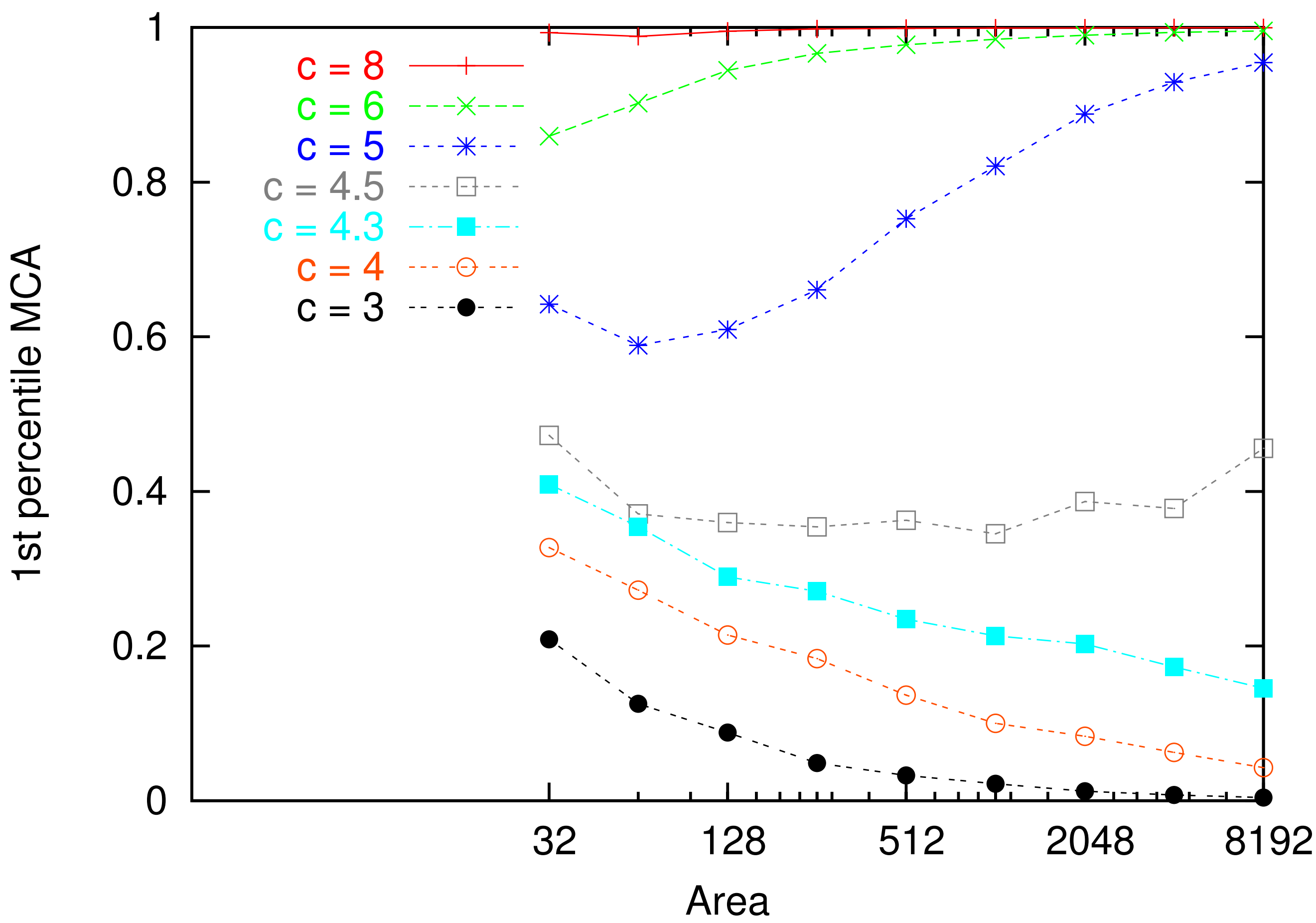
- Naps selects a rotating set of “waking” nodes of a desired density
- Advantages
  - Low communication (one message sent per node, $\Theta(\lambda_t)$ received)
  - Simple, robust (performs *better* in mobile setting)
  - No location information necessary
- Disadvantages
  - Only probabalistic guarantees
  - Isn’t optimal in terms of number of nodes turned off (but more efficent schemes are costly)
- Future work
  - Test performance in a real network
  - Estimate *target* density adaptively

Simulation: mobility



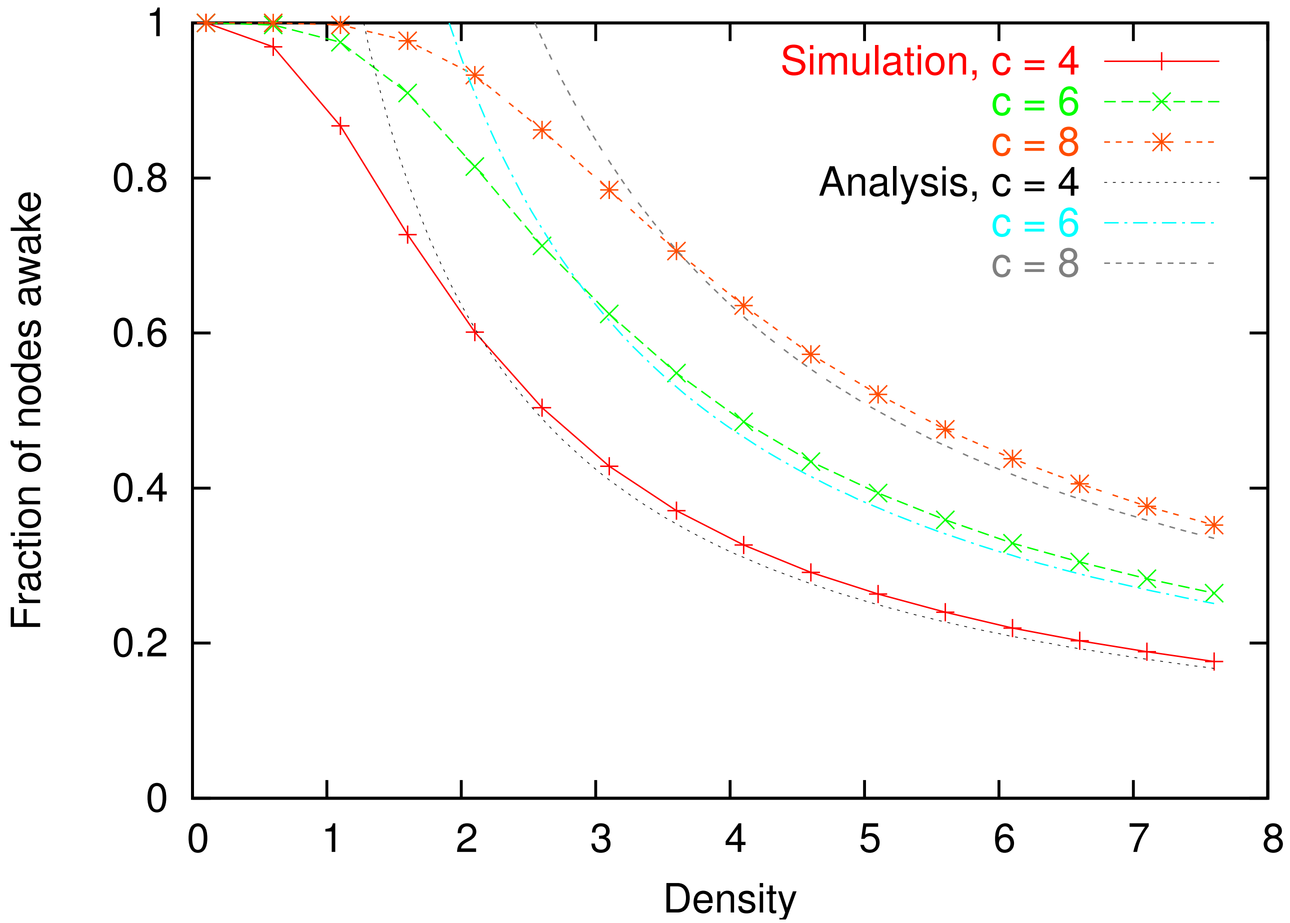
Area $= 256$, $\lambda = 5$, $c = 6$, $r = 0.1$, and waking node survives for time $100T$. Averaged over 5 trials.

Simulation: scaling



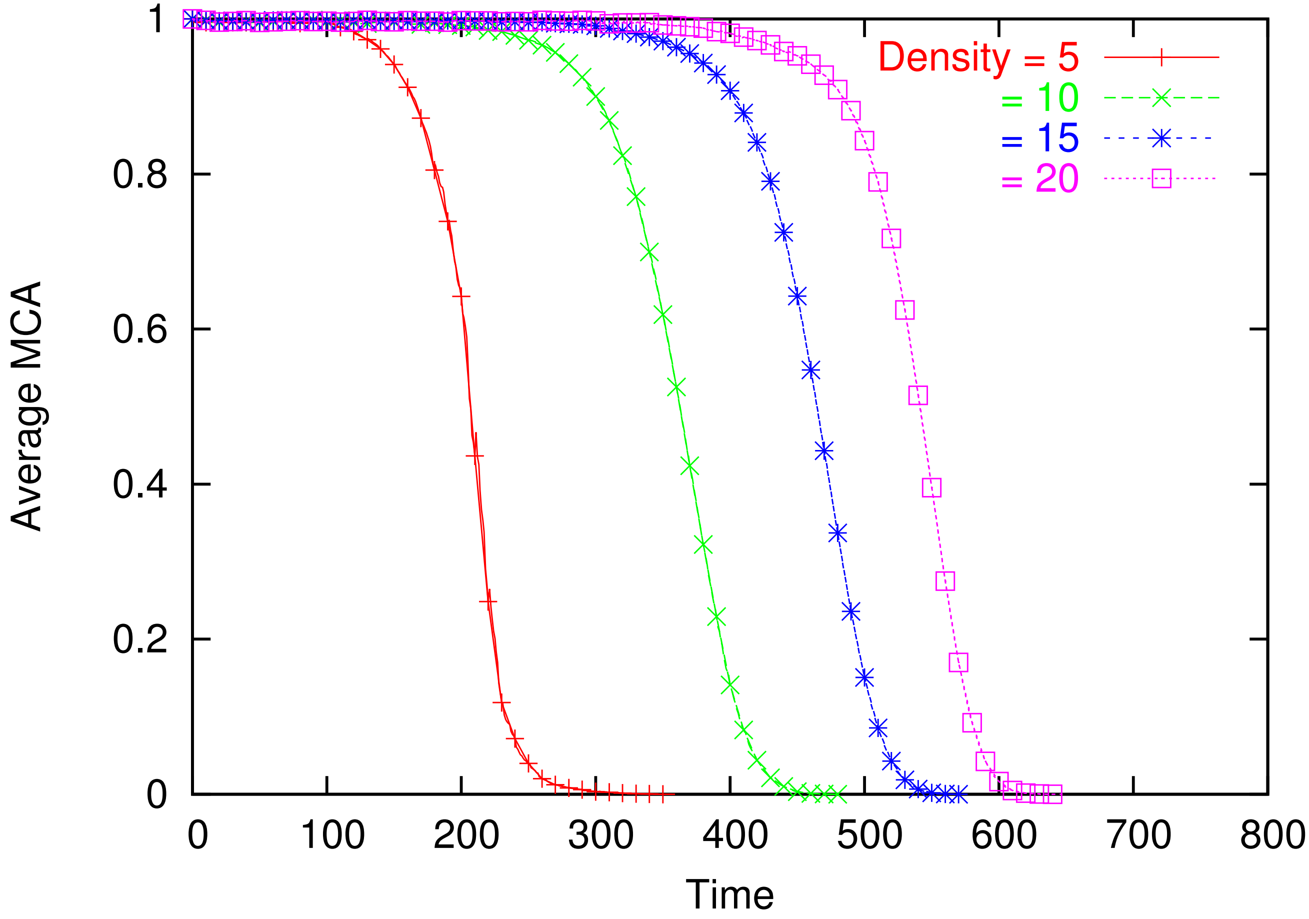
1st percentile is over 100 samples within a time period. $\lambda = 5$.

Simulation: fraction of nodes awake



Area $= 625$.

Simulation: MCA vs. time



Area $= 625$, $c = 6$, $r = 0.1$, and a waking node survives for time $100T$.