Initializing Newly Deployed Ad Hoc and Sensor Networks

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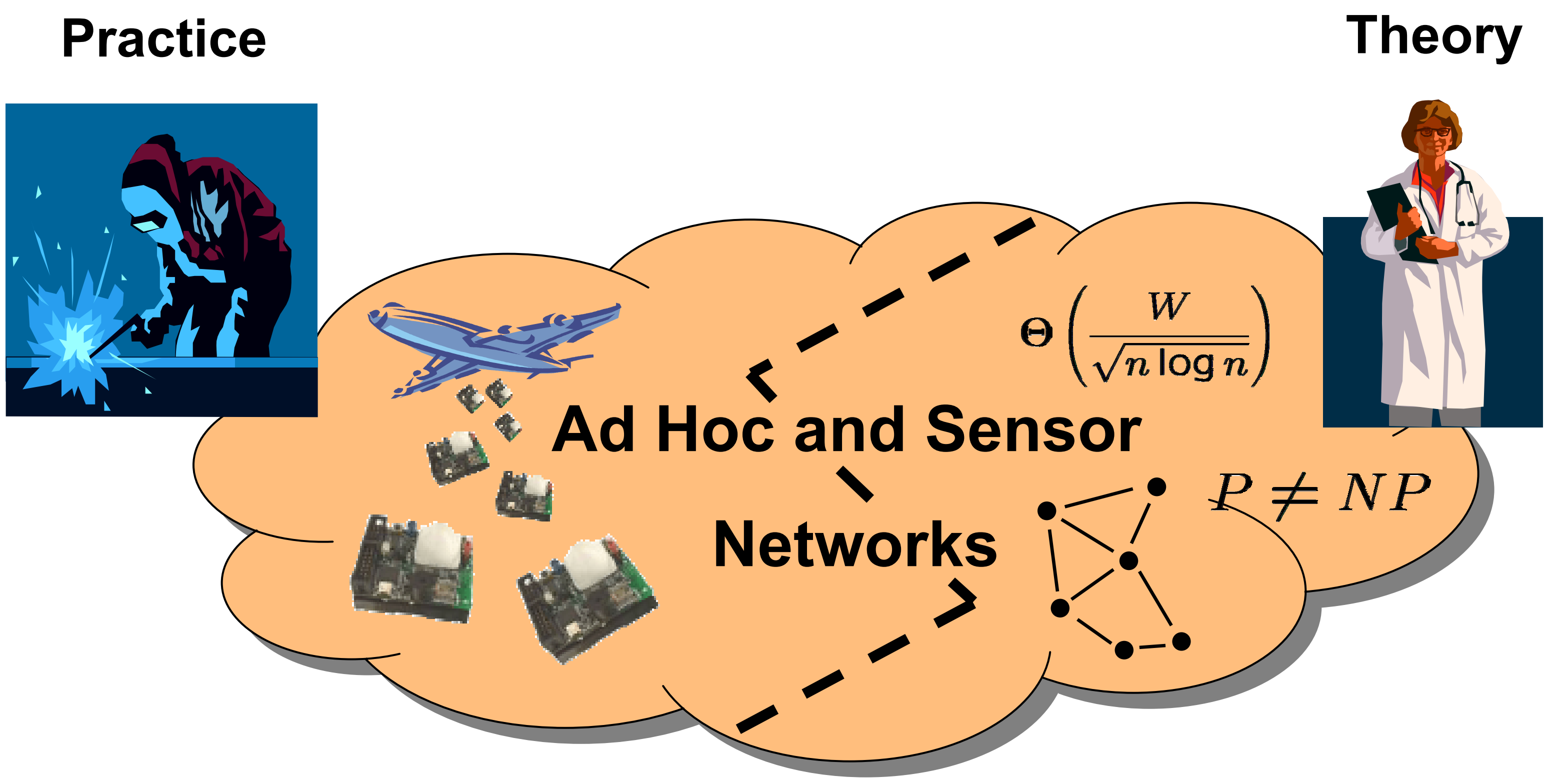
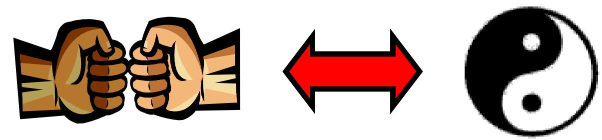
Of Theory and Practice...



There is often a big gap between theory and practice in the field of wireless ad hoc and sensor networks.

Of Theory and Practice...

- What is the reason for this chasm...?



- Theoreticians try to understand the fundamentals
- Need to abstract away a few technicalities...

What are technicalities...???

- Abstracting away too many „technicalities“ renders theory useless for practice!

Random Node Distribution

- Theoreticians often assume that, ...

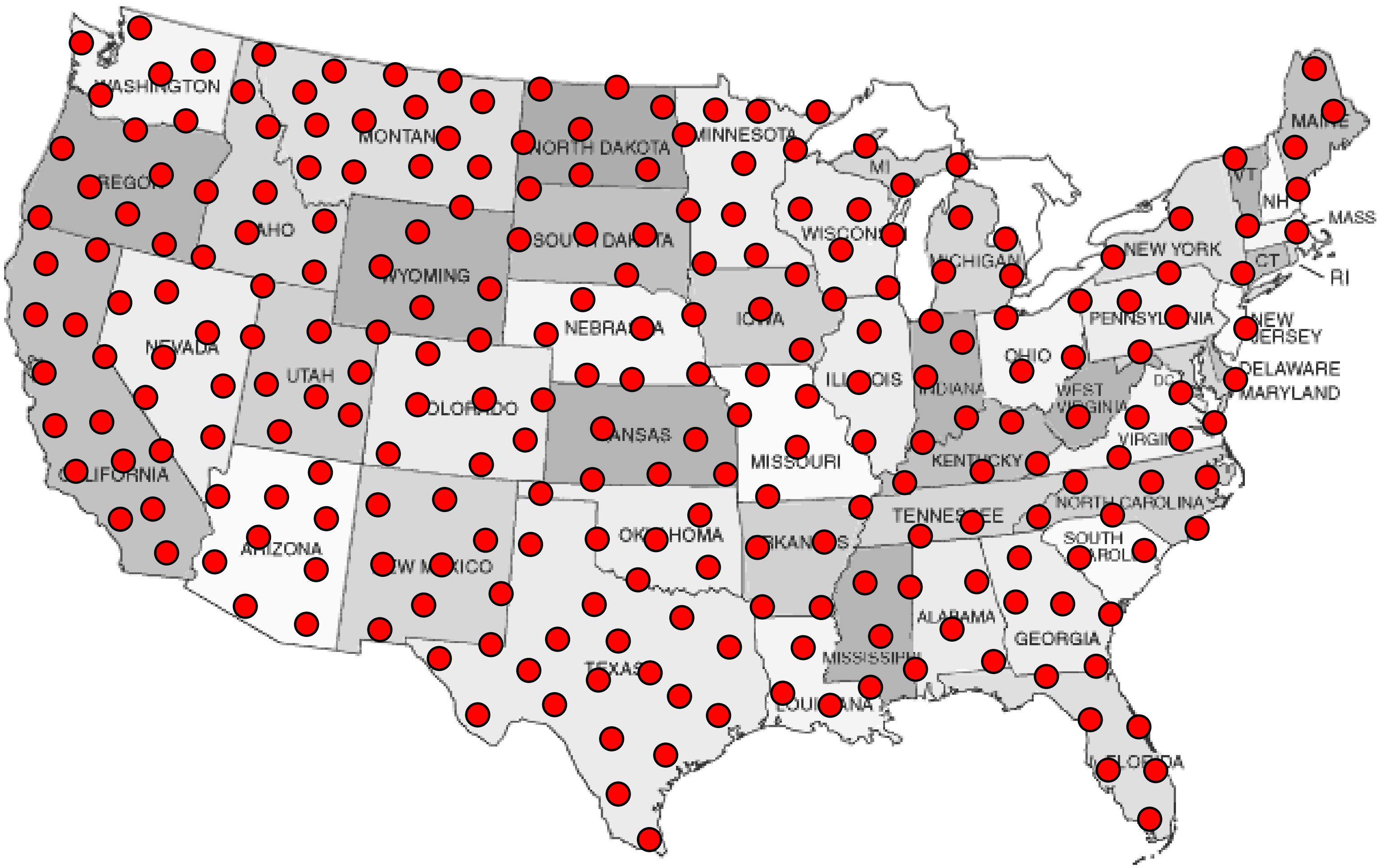
nodes are randomly, uniformly distributed in the plane.

This assumption allows for nice formulas

But is this really a „technicality“...?

How do real networks look like...?

Like this?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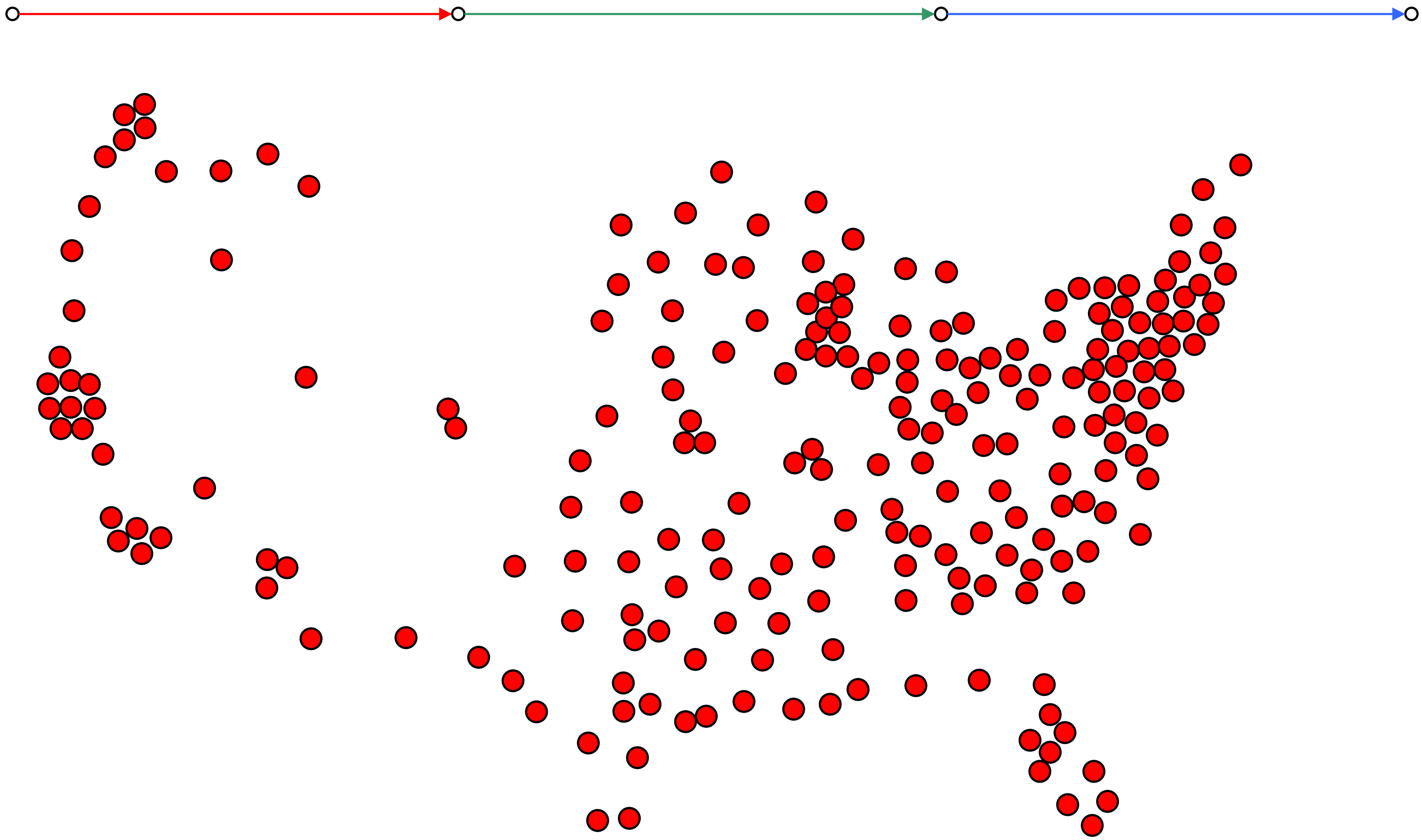
Or rather like this?



Random Node Distribution

- In theory, it is often assumed that, ...

nodes are randomly, uniformly distributed in the plane.

This assumption allows for nice formulas

Most small- and large-scale networks feature highly heterogenous node densities.

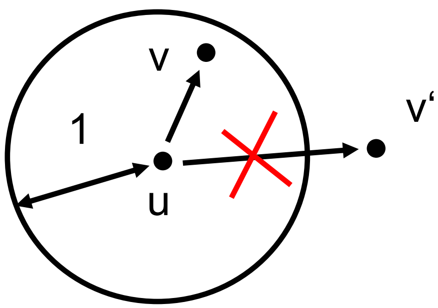
At high node density, assuming uniformity renders many practical problems trivial.

→ Not a technicality!

Unit Disk Graph Model

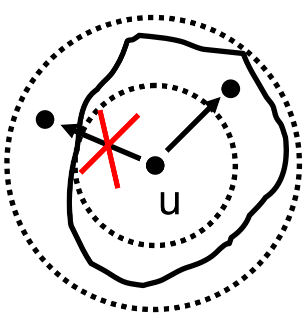
- In theory, it is often assumed that, ...

nodes form a unit disk graph!



Two nodes can communicate if they are within Euclidean distance 1.

This assumption allows for nice results



Signal propagation of real antennas not clear-cut disk!

Algorithms designed for unit disk graph model may not work well in reality. → Not a technicality!

More technicalities...

Excerpts from a typical paper

Algorithm 2 $\mathrm{LP}_{\mathrm{MDS}}$ approximation (Δ known)

$x_i := 0;$
for $\ell := k-1$ to 0 by -1 **do**
    $(*\ \tilde{\delta}(v_i) \leq (\Delta+1)^{(\ell+1)/k},\ z_i := 0\ *)$
    for $m := k-1$ to 0 by -1 **do**
        $(*\ a(v_i) \leq (\Delta+1)^{(m+1)/k}\ *)$
        send color_i to all neighbors;
        $\tilde{\delta}(v_i) := \left|\{j \in N_i \mid \mathrm{color}_j = \text{`white'}\}\right|;$
        if $\tilde{\delta}(v_i) \geq (\Delta+1)^{\ell/k}$ **then**
            $x_i := \max\left\{x_i, \frac{1}{(\Delta+1)^{m/k}}\right\}$
        fi;
        send x_i to all neighbors;
        if $\sum_{j \in N_i} x_j \geq 1$ **then** $\mathrm{color}_i :=$ 'gray' **fi**;
    od
    $(*\ z_i \leq 1/(\Delta+1)^{(\ell-1)/k}\ *)$
od

More technicalities...

6: **send** color$_i$ to all neighbors;

How do you know your neighbors ???

How can you exchange data with them ???
→ Collisions (Hidden-Terminal Problem)

Most papers assume that there is a MAC-Layer in place!

This assumption may make sense in well-established, structured networks,...

...but it is certainly invalid during and shortly after the deployment of ad hoc and sensor networks.

More technicalities...

Excerpts from a typical paper

Algorithm 2 LP_{MDS} approximation (Δ known)

$x_i := 0$;
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      $x_i := \max\left\{x_i, \frac{1}{(\Delta+1)^{m/k}}\right\}$
    fi;
    send x_i to all neighbors;
    if $\sum_{j \in N_i} x_j \geq 1$ **then** $\text{color}_i :=$ 'gray' **fi**;
  od
  $(*\ z_i \leq 1/(\Delta+1)^{(\ell-1)/k}\ *)$
od

More technicalities...

$$2{:}\ \textbf{for}\ \ell := k-1\ \text{to}\ 0\ \text{by}\ -1\ \textbf{do}$$

How do nodes know when to start the loop ???

What if nodes join in afterwards ???

→ Asynchronous wake-up!

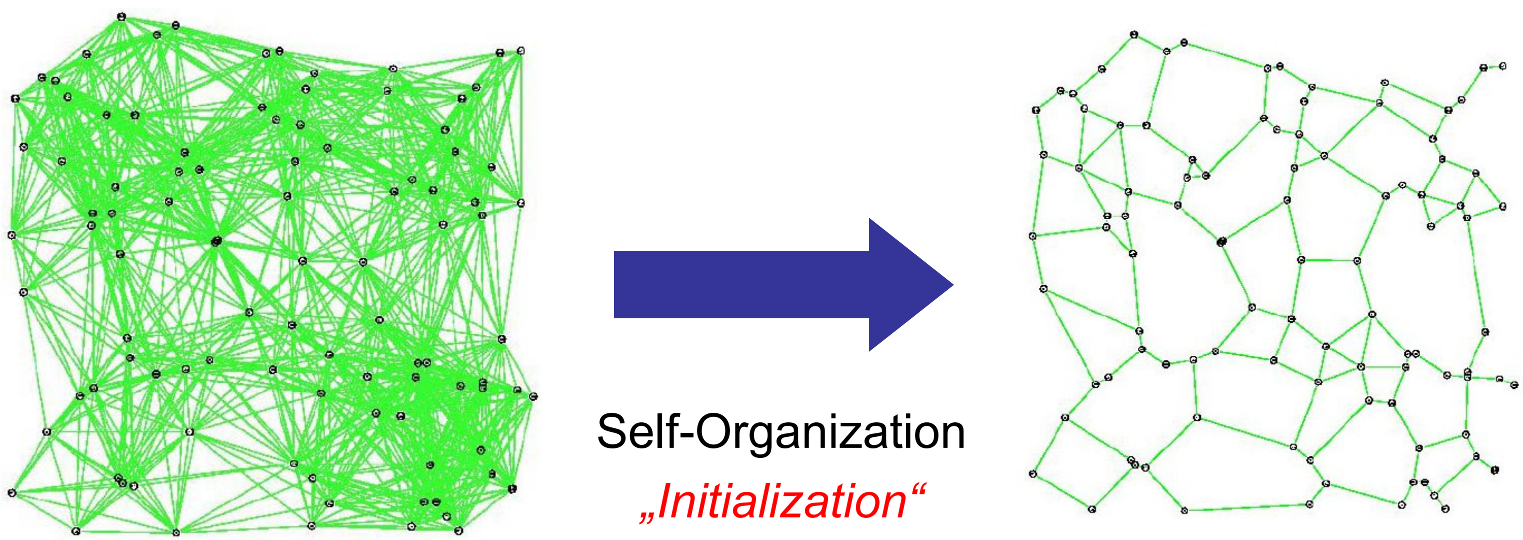
Paper assumes that there is a global clock and synchronous wake-up!

This assumption greatly facilitates the algorithm's analysis...

...but it is certainly invalid during and shortly after the deployment of ad hoc and sensor networks.

Deployment and Initialization

- Ad Hoc & Sensor Networks → no built-in infrastructure
- During and after the deployment → complete chaos
- Neighborhood is unknown
- There is no existing MAC-layer providing point-to-point connections!



Deployment and Initialization

- Initialization in current systems often very slow (Bluetooth)

- Ultimate Goal: Come up with an efficient MAC-Layer quickly.
- Theory Goal: Design a *provably* fast and reliable initialization algorithm.

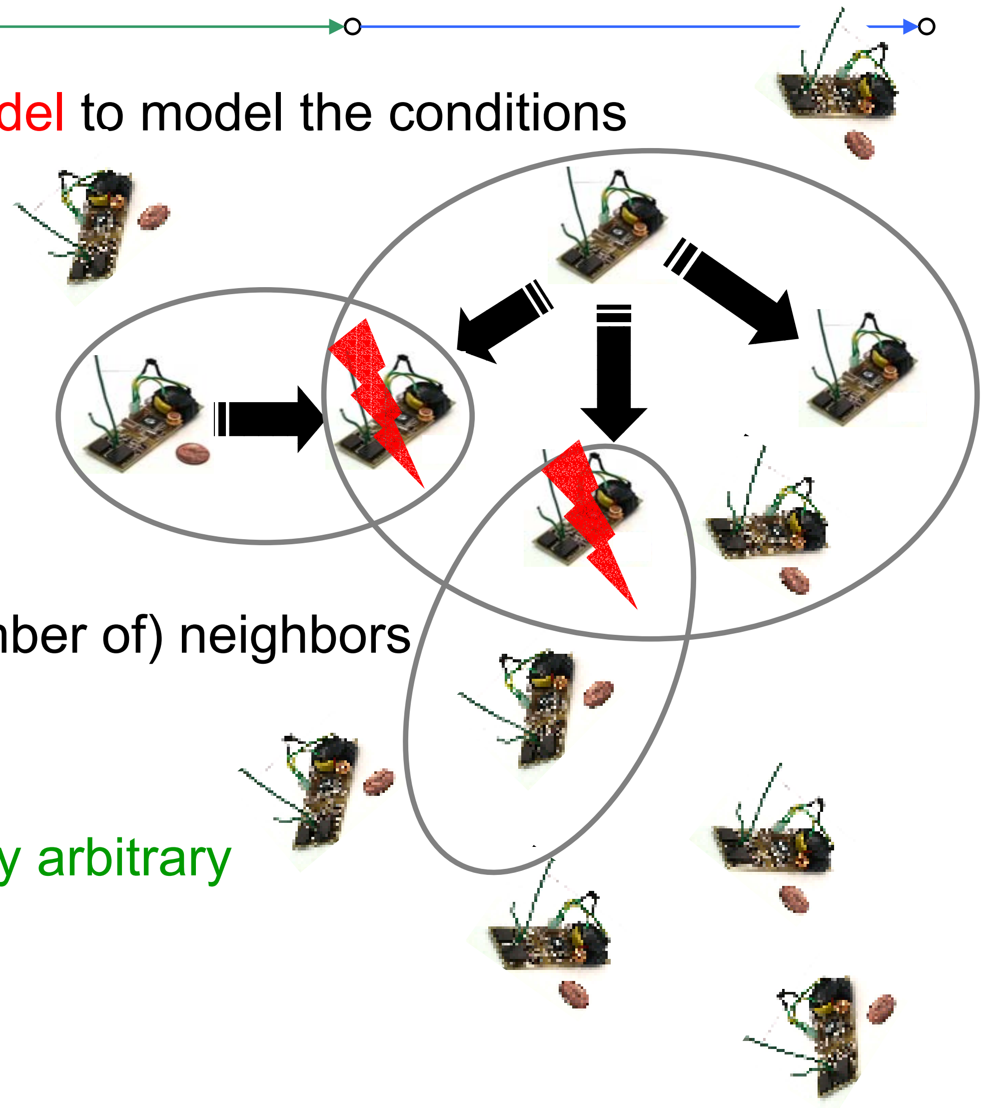
We have to consider the relevant technicalities!

We need to define a model capturing

the characteristics of the initialization phase.

Unstructured Multi-Hop Radio Networks – Model (1)

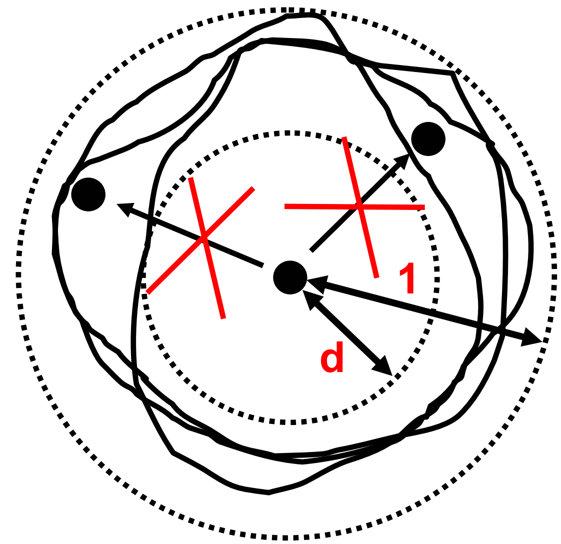
Adapt classic Radio Network Model to model the conditions immediately after deployment.



- Multi-Hop
  - Hidden-Terminal Problem
- No collision detection
  - Not even at the sender!
- No knowledge about (the number of) neighbors
- Asynchronous Wake-Up
  - No global clock!
- Node distribution is completely arbitrary
  - No uniform distribution!

Unstructured Multi-Hop Radio Networks – Model (2)

- Quasi Unit Disk Graph (QUDG) to model wireless multi-hop network
  - Two nodes can communicate if Euclidean distance is $\leq$ d
  - Two nodes cannot communicate if Euclidean distance is >1
  - In the range [d..1], it is unspecified whether a message arrives [Barrière, Fraigniaud, Narayanan, 2001]



- Upper bound N for number of nodes in network is known
  - This is necessary due to Ω(n / log n) lower bound [Jurdzinski, Stachowiak, 2002]

Q: Can we efficiently (and provably!) compute an *MAC-Layer* in this harsh model?

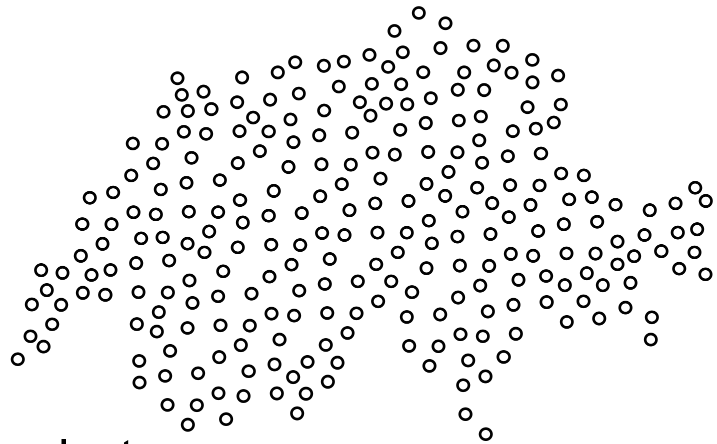
Q: Can we efficiently (and provably!) compute an *initial structure* in this model?

A: Yes, we can!

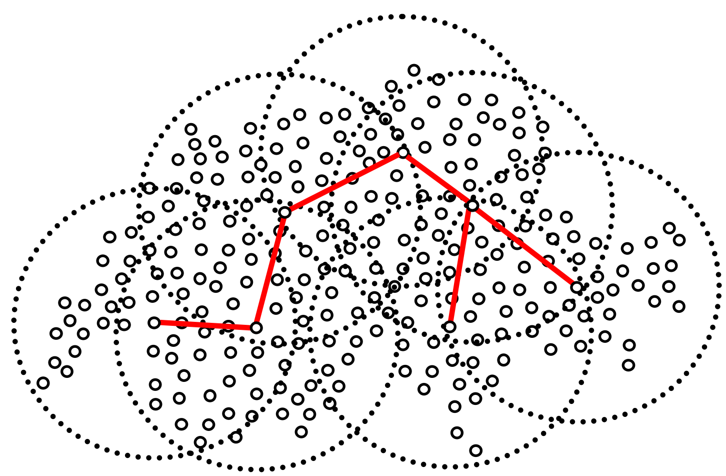
A: Hmm, ...

The Importance of Being Clustered...

- Clustering
  - Virtual Backbone for efficient routing
    → *Connected Dominating Set*
  - Improves usage of sparse resources
    → *Bandwidth, Energy, ...*
  - Spatial multiplexing in non-overlapping clusters
    → *Important step towards a MAC Layer*



Clustering



Clustering helps in bringing structure into Chaos!

Dominating Set

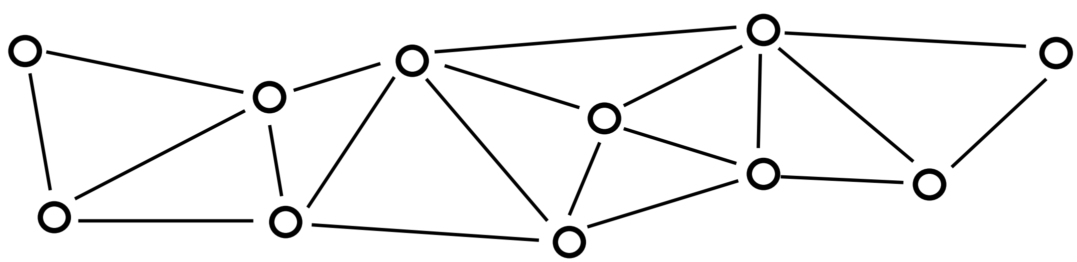
- Clustering:
  - Choose clusterhead such that:

    Each node is either a clusterhead or has a clusterhead in its communication range.

- When modeling the network as a graph G=(V,E), this leads to the well-known Dominating Set problem.

Dominating Set:

- A Dominating Set DS is a subset of nodes such that each node is either in DS or has a neighbor in DS.
- Minimum Dominating Set MDS is a DS of minimal cardinality.



Yet Another Dominating Set Algorithm...???

- There are many existing DS algorithms
  - [Kutten, Peleg, Journal of Algorithms 1998]
  - [Gao, et al., SCG 2001]
  - [Jia, Rajaraman, Suel, PODC 2001]
  - [Wan, Alzoubi, Frieder, INFOCOM 2002 & MOBIHOC 2002]
  - [Chen, Liestman, MOBIHOC 2002]
  - [Kuhn, Wattenhofer, PODC 2003]
  - .....

- Q: Why yet another clustering algorithm ?
- A: Other algorithms - with theoretical worst-case bounds - make too strong assumptions! (see previous slides...)

  → Not valid during initialization phase!

Clustering Algorithm - Results

- With three communication channels

In expectation, our algorithm computes a $O\left(\frac{1}{d^2}\right)$ approximation for MDS in time

$$O\left(\frac{\log N}{d^2}\left(\log \Delta + \frac{\log N}{\log\log N}\right)\right)$$

N : Upper bound on number of nodes in the network

Δ : Upper bound on number of nodes in a neighborhood (max. degree)

d : Quasi unit disk graph parameter

- Typically, d is a constant between 0.5 and 1.
  → Constant approximation!
- The time-complexity thus reduces to

$$O\left(\frac{\log^2 N}{\log\log N}\right) \text{ for } 1 \leq \Delta \leq N^{1/\log\log N}$$

$$O(\log N \log \Delta) \text{ for } N^{1/\log\log N} \leq \Delta \leq N$$

Overview

- Motivation
  Model

- Algorithm
  Analysis

- Conclusion
  Outlook

Clustering Algorithm – Basic Idea

- Use 3 independent communication channels Γ_1, Γ_2, and Γ_3.
  → Then, simulate these channels with a single channel.

- For the analysis: Assume time to be slotted
  → Algorithm does not rely on this assumption
  → Slotted analysis only a constant factor better than unslotted (ALOHA)

Clustering Algorithm – Basic Structure

Upon wake-up do:

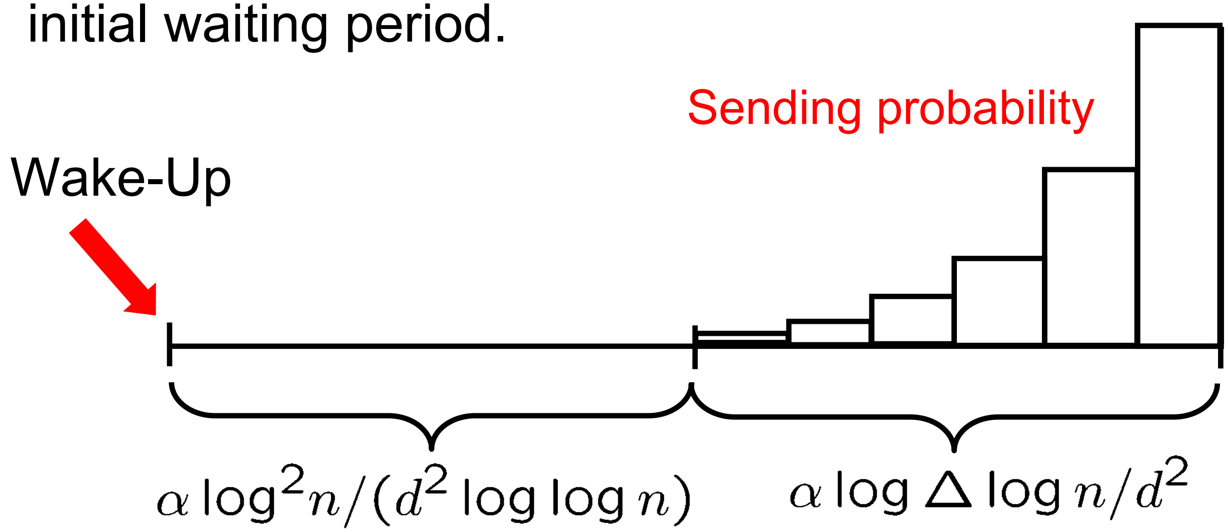
1) Listen for $\alpha \cdot \log^2 N/(d^2 \log\log N)$ time-slots on all channels
   upon receiving message → become dominated
   → stop competing to become dominator

2) For j=log Δ downto 0 do
   for $\alpha \cdot \log N/d^2$ slots, send with prob. $p_1 = \eta d^2 2^{-\log \Delta + j}$
   upon sending → become dominator
   upon receiving message → become dominated
   → stop competing to become dominator

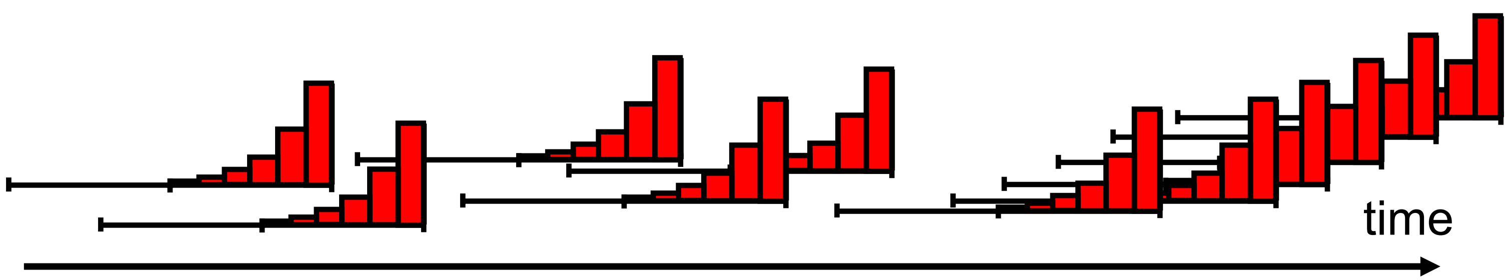
3) Additionally, dominators send on Γ_2 and Γ_3 with prob.
   $p_2 = \eta d^2 \log\log N/\log N$ and $p_3 = \eta d^2 \log\log N/\log^2 N$.

Clustering Algorithm – Basic Structure

- Each node‘s sending probability increases exponentially after an initial waiting period.

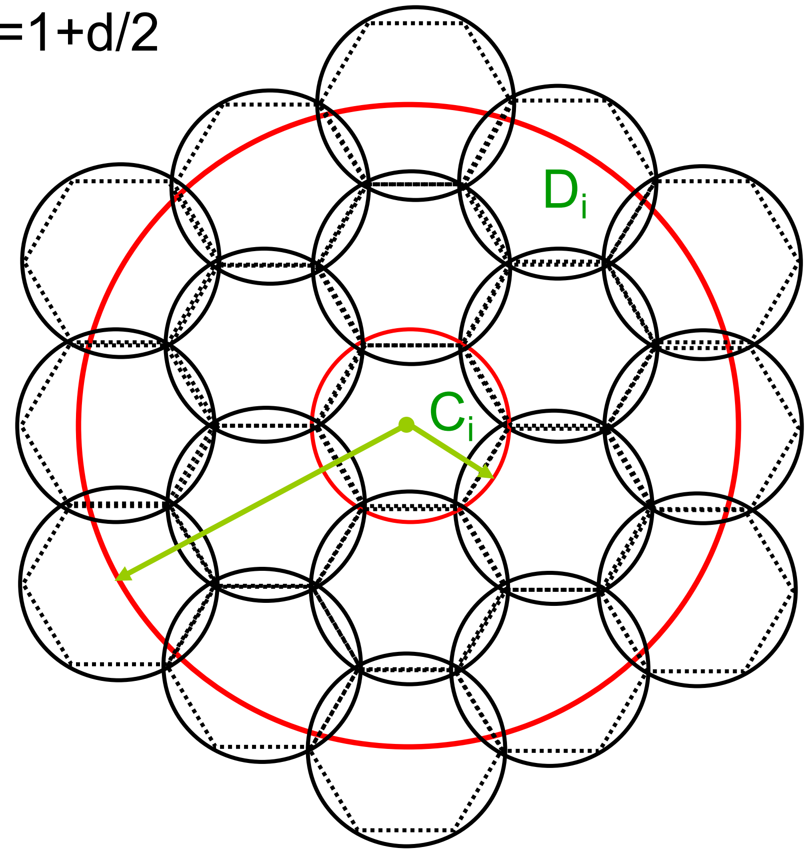


- Sequences are arbitrarily shifted in time (asynchronous wake-up)



Analysis - Outline

- Cover the plane with (imaginary) circles C_i of radius r=d/2
- Let D_i be the circle with radius R=1+d/2



- A node in C_i can hear all nodes in C_i
- Nodes outside of D_i cannot interfere with nodes in C_i

- We show: Algorithm has O(1) dominators in each C_i
- Optimum needs at least 1 dominator in D_i

Constant Approximation for constant d

Analysis - Outline

1. Bound the *sum of sending probabilities* in a circle C_i

   Remember: Due to asynchronous wake-up, every node may have a different sending probability

2. Bound the number of collisions in C_i before C_i becomes cleared

3. Bound the number of sending nodes per collision

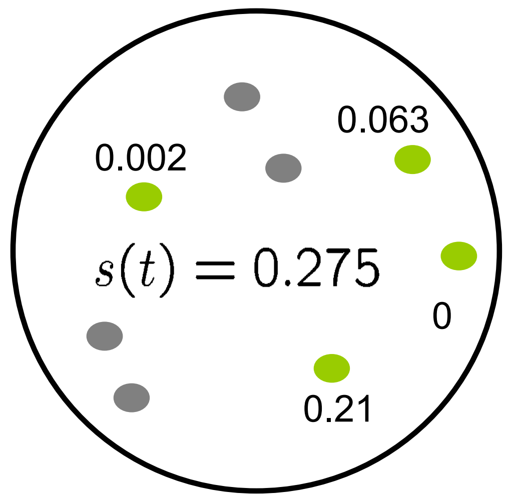
4. Newly awakened, already covered nodes will not become dominator

Analysis

Lemma 1: *Bound sum of sending probabilities in C_i*

- *Def:* Let $s(t)$ be the sum of sending probabilities of nodes in a circle C_i at time t, i.e.,

$$s(t) := \sum_{k \in C_i} p_k(t)$$

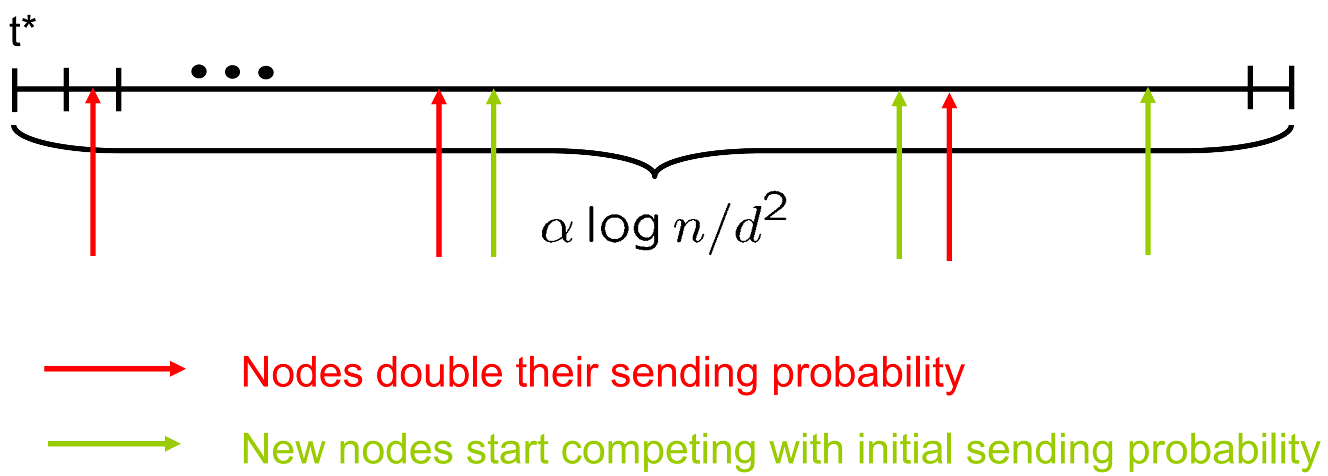


For all circles C_i and all times t, it holds that $s(t) \leq 3\eta d^2$ w.h.p.

Analysis

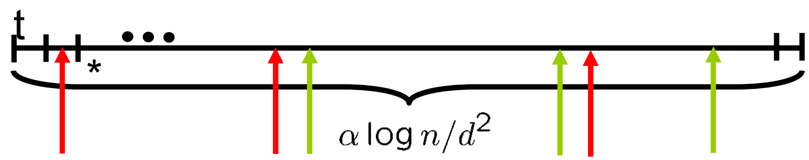
- Proof of Lemma 1:

- Induction over all time-slots when (for the first time) $s(t) > \eta d^2$ in a circle C_i. (Induction over multi-hop network!)
- Let t* be such a time-slot
- Consider interval $[t^*, \ldots, t^* + \alpha \log n / d^2 - 1]$



Analysis

- Proof of Lemma 1 (cont)
- Existing nodes can at most double
- New nodes send with very small probability



$$s(t + \alpha \log n/d^2 - 1) \leq 3\eta d^2$$

→ Next, we show in the paper that i$[t^*, \ldots, t^* + \alpha \log n/d^2 - 1]$ there will be at least one time-slot in which no node in $D_i \setminus C_i$, and exactly one node in C_i sends.

→ After this time-slot, C_i is *cleared,* i.e., all (currently awake) nodes are decided.

→ Sum of sending probabilities does not exceed $3\eta d^2$

Analysis

Lemma 1:
Bound on sum of sending probabilities

⇒

Lemma 2:
Bound number of collisions before C_i is cleared

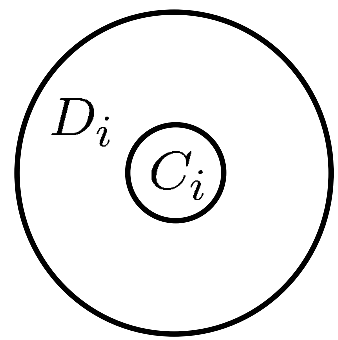
- Define events:

  X : More than one node in C_i is sending

  Y : At least one node in C_i is sending

  Z : Some node in $D_i \setminus C_i$ is sending

  A : Exactly one node in D_i is sending



- Compute probability:

$$P[A|Y] = \ldots = \left(1 - \frac{P[X]}{P[Y]}\right)(1 - P[Z])$$

Analysis

Lemma 2

Let C be the number of collisions in a circle C_i. The expected number of collisions in C_i before its clearance is $E[C] < 5$ and $C < 6 \log n$ with high probability.

Lemma 3 (Computed using Lemma 1)

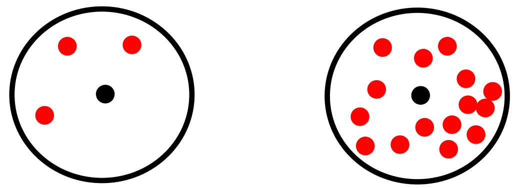
Let D be the number of nodes in a circle C_i sending in a time-slot. Let Φ be the event of a collision in C_i. Given a collision, the expected number of sending nodes is $E[D|\Phi] \in O(1)$ and $D|\Phi < 3 \log n / \log \log n$ with high probability.

Analysis

Lemma 4

- It remains to be shown that only O(1) nodes waking up after the clearance become dominator.
- D : Number of dominators in the range of a newly awakened node.
- Distinguish two cases:
  - Case 1: $1 \leq D \leq c \log n$
    → Consider channel Γ_2
  - Case 2: $c \log n \leq D \leq c' \log^2 n$
    → Consider channel Γ_3
- Compute probability, that one dominator sends alone on Γ_2 or Γ_3.

Case 1 Case 2



$$P_1 = D \cdot q \cdot (1-q)^{D-1} = \ldots \in \Omega(\log^{-1} n)$$

→ Since waiting-period is $O(\log^2 n / \log\log n)$ long, at least one message will eventually arrive at the node.

Analysis - Results

- For each circle C_i holds:
  - Number of dominators before a clearance in O(1) in expectation
  - Number of dominators after a clearance in O(1) w.h.p
  - → Number of dominators in C_i in O(1) in expectation

- Optimum has to place at least one dominator in D_i.

In expectation, the algorithm compute a $O(1/d^2)$ approximation.

- Reasonable values of d are constant → Constant approximation!

Three Channels → Single Channel

- Three independent communication channels not always feasible
- Simulation with a single channel is possible within O(polylog(n)).
- Idea:
  - Each node simulates each of its multi-channel time-slots with O(polylog(n)) single-channel time-slots.
  - It can be shown that result remains the same.

Algorithm compute a O(1/d^2) approximation for MDS in polylogarithmic time even with a single communication channel.

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Simulation

- The hidden constants in the big-O notation are quite big.
- Simulation shows that this is an artefact of „worst-case“ analysis.
- In reality, it is sufficient to set $\alpha := 10$.

  → Running time is at most $t < 10 \cdot \log^2 n$

Example: Scatterweb, Embedded Sensor Nodes

TU Berlin

Transmission rate :	115 kb/s
Switch time trans → recv :	20 μs
Switch time recv → trans :	12 μs
Paketsize of algorithm :	~20 Byte

→ Lenght of one time-slot is < 3 ms

Initializing 1000 nodes takes time < 3 seconds!

Comparison: For 2 nodes, Bluetooth takes about 20 seconds!

Conclusion and Outlook

- Initialization of ad hoc and sensor network of great importance!
- Relevant technicalities must be considered!

In this work:

- A model capturing the characteristics of the initialization phase
- A fast algorithm for computing a good dominating set from scratch
- An application of the algorithm

In our MASS 2004 paper:

- A fast algorithm for computing more sophisticated structures (MIS)

GOAL

A fast algorithm for establishing a MAC Layer from scratch!