The Complexity of Connectivity in Wireless Networks
The paper

- Joint work with Thomas Moscibroda
  - Former PhD student of mine
  - Now researcher at Microsoft Research, Redmond
  - Infocom 2006 presentation by Thomas
  - Some slides by Thomas. Thanks!

- Paper is about wireless networking in general
  - This talk: new introduction/motivation for sensor networks
Today, we look much cuter!

And we’re usually carefully deployed

Radio
Processor
Memory
Power
Sensors
Data Gathering in Wireless Sensor Networks

• Data gathering & aggregation
  – Classic application of sensor networks
  – Sensor nodes periodically sense environment
  – Relevant information needs to be transmitted to sink

• Functional Capacity of Sensor Networks
  – Sink periodically wants to compute a function $f_n$ of sensor data
  – At what rate can this function be computed?

$fn(1), fn(2), fn(3)$
Data Gathering in Wireless Sensor Networks

Example: simple round-robin scheme
→ Each sensor reports its results directly to the root one after another

Simple Round-Robin Scheme:
→ Sink can compute one function per n rounds
→ Achieves a rate of $1/n$
There are better schemes using Multi-hop relaying, In-network processing, Spatial Reuse, Pipelining.

Data Gathering in Wireless Sensor Networks

sink

\[ f_n^{(1)} \]
\[ f_n^{(2)} \]
\[ f_n^{(3)} \]
\[ f_n^{(4)} \]
\[ t \]
Capacity in Wireless Sensor Networks

At what rate can sensors transmit data to the sink?
Scaling-laws → how does rate decrease as \( n \) increases…?

\[ \Theta \left( \frac{1}{n} \right) \quad \Theta \left( \frac{1}{\sqrt{n}} \right) \quad \Theta \left( \frac{1}{\log n} \right) \quad \Theta (1) \]

Answer depends on:
- Function to be computed
- Coding techniques
- Network topology
- Wireless communication model

Only perfectly compressible functions (max, min, avg, …)
No fancy coding techniques

Roger Wattenhofer @ WISARD 2008 – 7
“Classic” Capacity…

The Capacity of Wireless Networks
Gupta, Kumar, 2000

[Arpacioglu et al, IPSN’04]
[Giridhar et al, JSAC’05]
[Barrenechea et al, IPSN’04]

[Liu et al, INFOCOM’03]
[Grossglauser et al, INFOCOM’01]

[Toumpis, TWC’03] [Gamal et al, INFOCOM’04]
[Barrenechea et al, IPSN’04]

[Kodialam et al, MOBICOM’05]
[Gastpar et al, INFOCOM’02]

[Li et al, MOBICOM’01] [Mitra et al, IPSN’04] [Zhang et al, INFOCOM’05]

[Bansal et al, INFOCOM’03] [Dousse et al, INFOCOM’04]

[Yi et al, MOBIHOC’03] [Perevalov et al, INFOCOM’03] etc…
Worst-Case Capacity

- Capacity studies so far make very strong assumptions on node deployment, topologies
  - randomly, uniformly distributed nodes
  - nodes placed on a grid
  - etc...

What if a network looks differently...?
Like this?
Or rather like this?
Worst-Case Capacity

- Capacity studies so far have made very strong assumptions on node deployment, topologies
  - randomly, uniformly distributed nodes
  - nodes placed on a grid
  - etc...

We assume arbitrary node distribution

What if a network looks differently...?

Classic Capacity

How much information can be transmitted in nice, well-behaving networks

Worst-Case Capacity

How much information can be Transmitted in any network
Models

• Two standard models in wireless networking

Protocol Model (graph-based, simpler) <-> Physical Model (SINR-based, more realistic)
Protocol Model

- Based on graph-based notion of interference
- Transmission range and interference range

Algorithmic work on worst-case topologies usually in protocol models (unit disk graph, …)

R(x) is in interference range of y. R(x) and R(y) cannot simultaneously receive!
Physical Model

- Based on signal-to-noise-plus-interference (SINR)
- Simplest case:
  \[ \rightarrow \text{packets can be decoded if SINR is larger than } \beta \text{ at receiver} \]

\[ \frac{P_u}{d(u,v)^\alpha} + \sum_{w \in V \setminus \{u\}} \frac{P_w}{d(w,v)^\alpha} + N \geq \beta \]

- Power level of sender \( u \)
- Received signal power from sender
- Path-loss exponent
- Noise
- Received signal power from all other nodes (= interference)
- Minimum signal-to-interference ratio
- Distance between two nodes
Models

- Two standard models of wireless communication
  - **Protocol Model** (graph-based, simpler)
  - **Physical Model** (SINR-based, more realistic)

- Algorithms typically designed and analyzed in protocol model

**Premise:** Results obtained in protocol model do not divert too much from more realistic model!

**Justification:**
Capacity results are typically (almost) the same in both models (e.g., Gupta, Kumar, etc...)
Example: Protocol vs. Physical Model

A sends to D, B sends to C

Assume a single frequency (and no fancy decoding techniques!)

Is spatial reuse possible?

- Protocol Model: NO
- Physical Model: YES

Let $\alpha=3$, $\beta=3$, and $N=10nW$
Transmission powers: $P_B = -15 \text{ dBm}$ and $P_A = 1 \text{ dBm}$

SINR of A at D:
$$\frac{1.26mW/(7m)^3}{0.01\mu W + 31.6\mu W/(3m)^3} \approx 3.11 \geq \beta$$

SINR of B at C:
$$\frac{31.6\mu W/(1m)^3}{0.01\mu W + 1.26mW/(5m)^3} \approx 3.13 \geq \beta$$

In Reality!
This works in practice!

- We did measurements using standard mica2 nodes!
- Replaced standard MAC protocol by a (tailor-made) „SINR-MAC“
- Measured for instance the following deployment...

- Time for successfully transmitting 20'000 packets:

<table>
<thead>
<tr>
<th>Node</th>
<th>Time required (s)</th>
<th>Messages received</th>
</tr>
</thead>
<tbody>
<tr>
<td>u₁</td>
<td>721</td>
<td>19999</td>
</tr>
<tr>
<td>u₂</td>
<td>778</td>
<td>18984</td>
</tr>
<tr>
<td>u₃</td>
<td>780</td>
<td>16519</td>
</tr>
<tr>
<td>u₄</td>
<td>267</td>
<td>19773</td>
</tr>
<tr>
<td>u₅</td>
<td>268</td>
<td>18488</td>
</tr>
<tr>
<td>u₆</td>
<td>270</td>
<td>19498</td>
</tr>
</tbody>
</table>

Speed-up is almost a factor 3
Upper Bound Protocol Model

- There are networks, in which at most one node can transmit!
  → like round-robin
- Consider exponential node chain
- Assume nodes can choose arbitrary transmission power

\[ d(\text{sink}, x_i) = (1 + 1/\Delta)^{i-1} \]

- Whenever a node transmits to another node
  → All nodes to its left are in its interference range!
  → Network behaves like a single-hop network

In the **protocol model**, the achievable rate is \( \Theta(1/n) \).
Lower Bound Physical Model

• Much better bounds in SINR-based physical model are possible (exponential gap)
• Paper presents a scheduling algorithm that achieves a rate of $\Omega(1/\log^3 n)$

In the physical model, the achievable rate is $\Omega(1/\text{polylog } n)$.

• Algorithm is centralized, highly complex $\rightarrow$ not practical
• But it shows that high rates are possible even in worst-case networks

• Basic idea: Enable spatial reuse by exploiting SINR effects.
Scheduling Algorithm – High Level Procedure

- High-level idea is simple
- Construct a hierarchical tree $T(X)$ that has desirable properties

1) Initially, each node is active
2) Each node connects to closest active node
3) Break cycles → yields forest
4) Only root of each tree remains active

The resulting structure has some nice properties
→ If each link of $T(X)$ can be scheduled at least once in $L(X)$ time-slots
→ Then, a rate of $1/L(X)$ can be achieved

Can be adjusted if transmission power limited

Phase Scheduler: How to schedule $T(X)$?
Scheduling Algorithm – Phase Scheduler

- How to schedule $T(X)$ efficiently
- We need to **schedule links of different magnitude simultaneously**!
- Only possibility: senders of small links must **overpower their receiver**!

If we want to schedule both links…

1) … $R(x)$ must be **overpowered**
   → Must transmit at power more than $\sim d^\alpha$

2) If senders of small links overpower their receiver…
   … their “safety radius” increases (spatial reuse smaller)
Scheduling Algorithm – Phase Scheduler

1) Partition links into sets of similar length

2) Group sets such that links a and b in two sets in the same group have at least $d_a \geq \left(\xi \beta\right)^{\xi (\tau_a - \tau_b)} \cdot d_b$

→ Each link gets a $\tau_{ij}$ value → Small links have large $\tau_{ij}$ and vice versa
→ Schedule links in these sets in one outer-loop iteration
→ Intuition: Schedule links of similar length or very different length

3) Schedule links in a group → Consider in order of decreasing length (I will not show details because of time constraints.)

Together with structure of $T(x)$ → $\Omega(1/\log^3 n)$ bound
### Worst-Case Capacity in Wireless Networks

<table>
<thead>
<tr>
<th>Networks</th>
<th>Max. rate in arbitrary, worst-case deployment</th>
<th>Max. rate in random, uniform deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Model</td>
<td>$\Theta(1/n)$</td>
<td>$\Theta(1/\log n)$</td>
</tr>
<tr>
<td>Physical Model</td>
<td>$\Omega(1/\log^3 n)$</td>
<td>$\Omega(1/\log n)$</td>
</tr>
</tbody>
</table>

- **Worst-Case Capacity**
- **Traditional Capacity**

The Price of Worst-Case Node Placement
- Exponential in protocol model
- Polylogarithmic in physical model
  (almost no worst-case penalty!)

Exponential gap between protocol and physical model!
Conclusions

• Introduce **worst-case capacity of sensor networks**
  → How much data can periodically be sent to data sink

• Complements existing capacity studies
• Many novel insights

1) Possibilities and limitations of wireless communication
2) Fundamentals of wireless communication models
3) How to devise efficient scheduling algorithms, protocols

**Sensor Networks Scale!**
Efficient data gathering is possible in every (even worst-case) network!

**Protocol Model Poor!**
Exponential gap between protocol and physical model!

**Efficient Protocols!**
Must use SINR-effects and power control to achieve high rate!
Overview of results so far

- Moscibroda, Wattenhofer, Infocom 2006
  - First paper in this area, $O(\log^3 n)$ bound for connectivity, and more
  - This is essentially the paper I presented on the previous slides

- Moscibroda, Wattenhofer, Zollinger, MobiHoc 2006
  - First results beyond connectivity, namely in the topology control domain

  - Practical experiments, ideas for capacity-improving protocol

- Moscibroda, Oswald, Wattenhofer, Infocom 2007
  - Generalization of Infocom 2006, proof that known algorithms perform poorly

- Goussevskaia, Oswald, Wattenhofer, MobiHoc 2007
  - Hardness results & constant approximation for constant power

- Chafekar, Kumar, Marathe, Parthasarathy, Srinivasan, MobiHoc 2007
  - Cross layer analysis for scheduling and routing

- Moscibroda, IPSN 2007
  - Connection to data gathering, improved $O(\log^2 n)$ result

- Locher, von Rickenbach, Wattenhofer, ICDCN 2008
  - Still some major open problems
Main open question in this area

- Most papers so far deal with special cases, essentially scheduling a number of links with special properties. The general problem is still wide open:

- A communication request consists of a source and a destination, which are arbitrary points in the Euclidean plane. Given $n$ communication requests, assign a color (time slot) to each request. For all requests sharing the same color specify power levels such that each request can be handled correctly, i.e., the SINR condition is met at all destinations. The goal is to minimize the number of colors.

- E.g., for arbitrary power levels not even hardness is known…
Thank You!
Questions & Comments?