... an oxymoron?
...as old as society
more recently?
Wireless Communication

EE, Physics
Maxwell Equations
Simulation, Testing
‘Scaling Laws’

Network Algorithms

CS, Applied Math
[Geometric] Graphs
Worst-Case Analysis
Any-Case Analysis
CS Models: e.g. Disk Model (Protocol Model)
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CS Models: e.g. Disk Model (Protocol Model)
EE Models: e.g. SINR Model (Physical Model)
Signal-To-Interference-Plus-Noise Ratio (SINR) Formula

\[
\frac{P_u}{d(u,v)^\alpha} \geq \frac{\sum_{w \in V \setminus \{u\}} P_w}{N + \sum_{w \in V \setminus \{u\}} d(w,v)^\alpha} \geq \beta
\]
Signal-To-Interference-Plus-Noise Ratio (SINR) Formula

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

- **Power level of sender** \(u\)
- **Path-loss exponent** \(\alpha\)
- **Received signal power from sender** \(P_u\)
- **Distance between two nodes** \(d(u,v)\)
- **Noise**
- **Received signal power from all other nodes** (=interference)
- **Minimum signal-to-interference ratio** \(\beta\)
Example: Protocol vs. Physical Model

A ------ 4m ------ B ------ 1m ------ C ------ 2m ------ D

Assume a single frequency (and no fancy decoding techniques!)
Example: Protocol vs. Physical Model

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

Is spatial reuse possible?

- **NO** Protocol Model
- **YES** With power control

Let $\alpha=3$, $\beta=3$, and $N=10\text{nW}$

Transmission powers: $P_B = -15$ dBm and $P_A = 1$ 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:
$$\frac{31.6\mu W/(1m)^3}{0.01\mu W + 1.26mW/(5m)^3} \approx 3.13 \geq \beta$$
This works in practice!

... even with very simple hardware (sensor nodes)

Time for transmitting 20'000 packets:

<table>
<thead>
<tr>
<th>Node</th>
<th>Time required (s)</th>
<th>Standard MAC</th>
<th>“SINR-MAC”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$</td>
<td>721</td>
<td>721</td>
<td>267</td>
</tr>
<tr>
<td>$u_2$</td>
<td>778</td>
<td>778</td>
<td>268</td>
</tr>
<tr>
<td>$u_3$</td>
<td>780</td>
<td>780</td>
<td>270</td>
</tr>
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<table>
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<tr>
<th>Node</th>
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<tr>
<td>$u_4$</td>
<td>19999</td>
<td>19999</td>
<td>19773</td>
</tr>
<tr>
<td>$u_5$</td>
<td>18784</td>
<td>18784</td>
<td>18488</td>
</tr>
<tr>
<td>$u_6$</td>
<td>16519</td>
<td>16519</td>
<td>19498</td>
</tr>
</tbody>
</table>

Speed-up is almost a factor 3

The Capacity of a Wireless Network
Measures for Capacity

Throughput capacity
- Number of packets successfully delivered per time
- Dependent on the traffic pattern
- *E.g.: What is the maximum achievable rate, over all protocols, for a random node distribution and a random destination for each source?*

Transport capacity
- A network transports one *bit-meter* when one bit has been transported a distance of one meter.
- *What is the maximum achievable rate, over all node locations, and all traffic patterns, and all protocols?*

Convergecast capacity
- *How long does it take to get information from all nodes to a sink*

Many more...
Transport Capacity

- \( n \) nodes are arbitrarily located in a unit disk.

- We adopt the protocol model with \( R=2 \), that is a transmission is successful if and only if the sender is at least a factor 2 closer than any interfering transmitter. In other words, each node transmits with the same power, and transmissions are in synchronized slots.

- **Quiz:** What configuration and traffic pattern will yield the highest transport capacity?

- **Idea:** Distribute \( n/2 \) senders uniformly in the unit disk. Place the \( n/2 \) receivers just close enough to senders so as to satisfy the threshold.
Transport Capacity: Example
Transport Capacity: Example
Transport Capacity: Understanding the example

- Sender-receiver distance is $\Theta(1/\sqrt{n})$. Assuming channel bandwidth $W$ [bits], transport capacity is $\Theta(W\sqrt{n})$ [bit-meter], or per node: $\Theta(W/\sqrt{n})$ [bit-meter]

- Can we do better by placing the source-destination pairs more carefully? No, having a sender-receiver pair at distance $d$ inhibits another receiver within distance up to $2d$ from the sender. In other words, it kills an area of $\Theta(d^2)$.

- We want to maximize $n$ transmissions with distances $d_1, d_2, \ldots, d_n$ given that the total area is less than a unit disk. This is maximized if all $d_i = \Theta(1/\sqrt{n})$. So the example was asymptotically optimal.
  - BTW, a fun open geometry problem: Given $k$ circles with total area 1, can you always fit them in a circle with total area 2?
More capacities...

- The throughput capacity of an $n$ node random network is $\Theta \left( \frac{W}{\sqrt{n \log n}} \right)$

- There exist constants $c$ and $c'$ such that:
  - $\lim_{n \to \infty} \Pr \left[ c \frac{W}{\sqrt{n \log n}} \text{ is feasible} \right] = 1$
  - $\lim_{n \to \infty} \Pr \left[ c' \frac{W}{\sqrt{n \log n}} \text{ is feasible} \right] = 0$

- Transport capacity:
  - Per node transport capacity decreases with $\frac{1}{\sqrt{n}}$
  - Maximized when nodes transmit to neighbors

- Throughput capacity:
  - For random networks, decreases with $\frac{1}{\sqrt{n \log n}}$
  - Near-optimal when nodes transmit to neighbors

- In one sentence: local communication is better
Even more capacities...

- Similar claims hold in the physical (SINR) model as well...

- There are literally thousands of results on capacity, e.g.
  - on random destinations
  - on power-law traffic patterns
  - communication through relays
  - communication in mobile networks
  - channel broken into subchannels
  - etc.
Practical relevance?

- Efficient access to media, i.e. MAC layer!

- This (and related) problem is studied theoretically:

  *The Capacity of Wireless Networks*
  Gupta, Kumar, 2000

  [Liu et al, INFOCOM’03]
  [Toumpis, TWC’03]
  [Kodialam et al, MOBICOM’05]
  [Li et al, MOBICOM’01]
  [Bansal et al, INFOCOM’03]
  [Yi et al, MOBIHOC’03]

  [Giridhar et al, JSAC’05]
  [Gamal et al, INFOCOM’04]
  [Kyasanur et al, MOBICOM’05]
  [Mitra et al, IPSN’04]
  [Zhang et al, INFOCOM’05]
  [Dousse et al, INFOCOM’04]
  [Perevalov et al, INFOCOM’03]

  etc…
Network Topology?

- All these capacity studies make very strong assumptions on node deployment, topologies
  - randomly, uniformly distributed nodes
  - nodes placed on a grid
  - etc.

What if a network looks differently...?
 Scaling Laws

“Classic” Capacity

How much information can be transmitted in nice networks?
Scaling Laws

“Classic” Capacity
How much information can be transmitted in nice networks?

Worst-Case Capacity
How much information can be transmitted in nasty networks?
‘Scaling Laws’

Real Capacity

How much information can be transmitted in any network?

“Classic” Capacity

How much information can be transmitted in nice networks?

Worst-Case Capacity

How much information can be transmitted in nasty networks?
Convergecast Capacity in Wireless 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?
Convergecast Capacity in Wireless 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 $1/n$
Convergecast Capacity in Wireless Networks

There are better schemes using Multi-hop relaying
In-network processing
Spatial Reuse
Pipelining

sink

\[ f_n^{(1)} \]
\[ f_n^{(2)} \]
\[ f_n^{(3)} \]
\[ f_n^{(4)} \]
\[ t \]
At what rate can sensors transmit data to the sink? Scaling-laws $\rightarrow$ how does rate decrease as $n$ increases...?

$\Theta(1/n)$, $\Theta(1/\sqrt{n})$, $\Theta(1/\log n)$, $\Theta(1)$
Convergecast Capacity in Wireless Networks

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

\( \Theta(1/n) \)
\( \Theta(1/\sqrt{n}) \)
\( \Theta(1/\log n) \)
\( \Theta(1) \)

Answer depends on:
Function to be computed
Coding techniques
Network topology

\{ 
Only perfectly compressible functions (max, min, avg,...)
No fancy coding techniques
\}
Convergecast Capacity in Wireless Networks

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[Moscibroda, W, 2006]  
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[Moscibroda, W, 2006] | [Giridhar, Kumar, 2005]
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- [Moscibroda, W, 2006] - Worst-Case Capacity
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Convergecast Capacity in Wireless Networks

**Worst-Case Capacity**

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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!**

**References**
- [Moscibroda, W, 2006]
- [Giridhar, Kumar, 2005]
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Any-Case Analysis
Possible Application – Hotspots in WLAN

Traditionally: clients assigned to (more or less) closest access point → far-terminal problem → hotspots have less throughput
Possible Application – Hotspots in WLAN

Potentially better: create hotspots with very high throughput. Every client outside a hotspot is served by one base station. → Better overall throughput – increase in capacity!
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Wireless Algorithms

CS & EE
SINR and more
Worst-Case Analysis
Any-Case Analysis

Mobility increases the capacity of ad hoc wireless networks [Grossglauser, Tse, 2002]

Wireless Algorithms

CS & EE
SINR and more
Worst-Case Analysis
Any-Case Analysis

Distributed Protocols

Mobility increases the capacity of ad hoc wireless networks [Grossglauser, Tse, 2002]

Wireless Communication 101
Signal-To-Interference-Plus-Noise Ratio (SINR) Formula

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

- Power level of sender \( u \)
- Received signal power from sender
- Path-loss exponent
- Received signal power from all other nodes (=interference)
- Noise
- Distances between nodes
- Minimum signal-to-interference ratio
Ratio $\beta$ depends on receiver (hardware, software, parameters)

- Simple solutions have $\beta > 10$
  - But $\beta < 1$ is possible (thanks to forward error correction)
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- Algorithmically speaking, the exact value of $\beta$ does not really matter, thanks to SINR robustness
  - [Halldorsson, W, 2009] and [Fanghänel, Kesselheim, Räcke, Vöcking, 2009]
  - Model not only robust with regard to $\beta$, but also with regard to other constant factor disturbances, for instance, wind, constant antenna gain, etc.
  - Concretely: If we adapt model by factor $\phi$, results will change at most by factor $\phi^2$. 
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Modulation and demodulation

Modulation in action:

Radio transmitter

Radio receiver
Digital modulation

- Modulation of digital signals known as Shift Keying

- Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference

- Frequency Shift Keying (FSK):
  - needs larger bandwidth

- Phase Shift Keying (PSK):
  - more complex
  - robust against interference
Phase Shift Keying 101

amplitude domain

frequency spectrum

phase state diagram

BPSK (robust, satellites)

QPSK

QAM (large $\beta$)
Signal-To-Interference-Plus-Noise Ratio (SINR) Formula

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

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

(BTW: \( d^\alpha \) has nothing to do with energy consumption)
Path-loss-exponent $\alpha$
Path-loss-exponent $\alpha$
Path-loss-exponent $\alpha$

\[ P_r = P_s G_s G_r \frac{\lambda^2}{(4\pi)^2 d^2 L} \]

[Diagram showing different regions labeled as 'sender', 'receiver', 'interference', 'noise', 'received power', 'distance', 'LOS', 'NLOS', with numerical values and a 15-25 dB drop indicated]

\[ P_r = \frac{P_s G_s G_r h_s^2 h_r^2}{d^4} \]
Path-loss-exponent $\alpha$

$P_r = \frac{P_s G_s G_r \lambda^2}{(4\pi)^2 d^2 L}$

$P_r = \frac{P_s G_s G_r h_s^2 h_r^2}{d^4}$

$\alpha \geq \text{Dimension}$

$2^{nd}$ law of thermodynamics.
Wireless Propagation Depends on Frequency

- VLF: 300 Hz to 30 kHz
- LF: 30 kHz to 3 MHz
- MF: 3 MHz to 30 MHz
- HF: 30 MHz to 300 MHz
- VHF: 300 MHz to 3 GHz
- UHF: 3 GHz to 30 GHz
- SHF: 30 GHz to 300 GHz
- EHF: 300 GHz to 3 THz
- infrared: 3 THz to 30 THz
- visible light: 30 THz to 300 THz

- Twisted pair
- Coax

- ISM: Industrial, Scientific, and Medical

- AM
- SW
- FM
Path-loss-exponent $\alpha$: Near-Field Effects

$$P_r = \frac{P_s G_s G_r \lambda^2}{(4\pi)^2 d^2 L}$$

$d << 1?$
Path-loss-exponent $\alpha$: Near-Field Effects

\[ P_r = \frac{P_s G_s G_r \lambda^2}{(4\pi)^2 d^2 L} \]

$d \ll 1$?

---

$1\text{cm}!!$

... in other words, algorithmic papers should rule out near-field effects
Real World Examples
Attenuation by objects

- Shadowing (3-30 dB):
  - textile (3 dB)
  - concrete walls (13-20 dB)
  - floors (20-30 dB)
- reflection at large obstacles
- scattering at small obstacles
- diffraction at edges
- fading (frequency dependent)
Multipath

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction

- Time dispersion: signal is dispersed over time
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- Time dispersion: signal is dispersed over time
- Interference with “neighbor” symbols: Inter Symbol Interference (ISI)
Multipath

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction

-Time dispersion: signal is dispersed over time
- Interference with “neighbor” symbols: Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted. Distorted signal depending on the phases of the different parts
There’s much more...
There’s much more...

MIMO

Analog Network Coding

A B C

$X_1 \rightarrow X_2$

$X_1 + X_2$
Advanced Algorithms?
Problem: More than 1 node may sense problem at the same time. Potentially we have a massive interference problem!
Quiz: How to Build a Multi-Hop Alarm System

Problem: More than 1 node may sense problem at the same time. Potentially we have a massive interference problem!
Quiz: How to Build a Multi-Hop Alarm System

Problem: More than 1 node may sense problem at the same time. Potentially we have a massive interference problem!

```
root
1 hop
2 hops
3 hops
```

rx or alarm?

tx ‘wave’ on freq $f_0$ (FSK)

...followed by verification (1% false positives outdoors)

[Flury, W, 2010]
Media Access: Theory and Practice

[Sommer, W, 2010]
Media Access: Theory and Practice

[Sommer, W, 2010]
Ultrasound

(A different kind of communication)

[Sommer, W, 2010]
Ultra-Wideband (UWB)

- An example of a new physical paradigm.
- Discard the usual dedicated frequency band paradigm.
- Instead share a large spectrum (about 1-10 GHz).

- Modulation: Often pulse-based systems. Use extremely short duration pulses (sub-nanosecond) instead of continuous waves to transmit information. Depending on application 1M-2G pulses/second.

\[ 	ext{PPM} \quad \text{PAM} \quad \text{OOK} \]
Summary
Thank You!
Questions & Comments?

Roger Wattenhofer