Eidgenössische Technische Hochschule Zürich
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Informatik
Computer Science

In Defense of Wireless Carrier Sense

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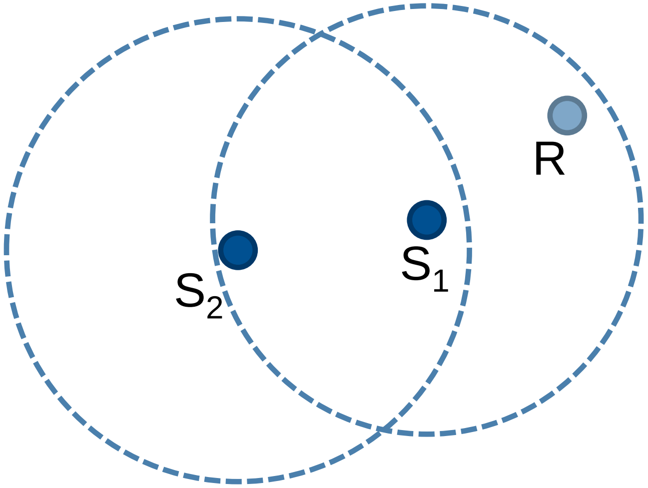
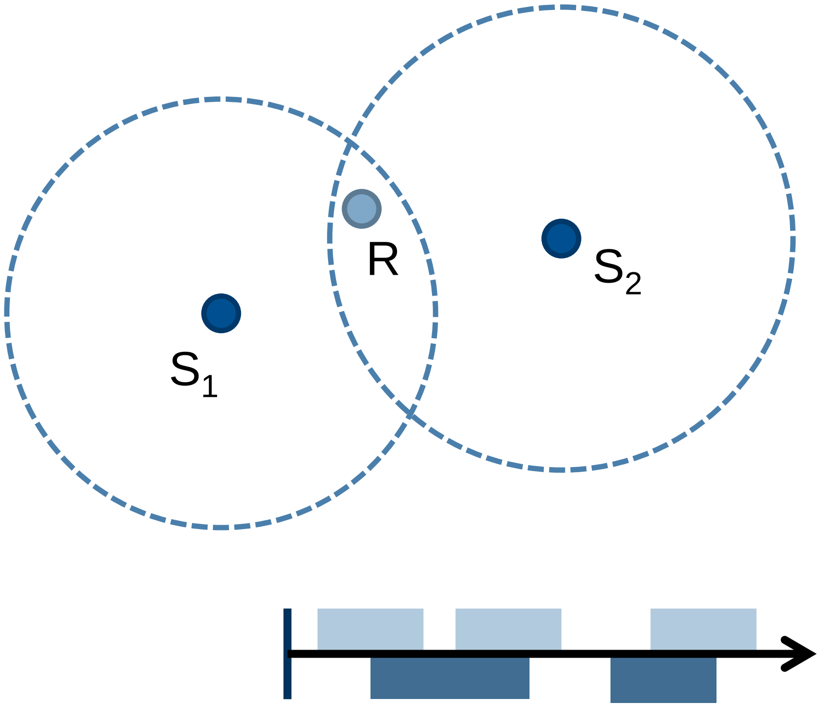
So what is Carrier Sense?

- Problem: One medium (wire, frequency, …) shared between multiple senders
- Possible solution: Listen on medium before transmitting
- Monitor for power vs. detect valid packets
- Many variants: CSMA/CD, CSMA/CA, probability-based, fixed-order, …

Problems with Carrier Sense

- Carrier sensing is done by the sender, it cannot determine the signal level at the receiver (→ hidden/exposed node/terminal)





Fixing Hidden Terminal Issues

- Instead of just trying to transmit, schedule transmissions
- Needs a mechanism to coordinate senders
- Hybrid approach taken by WiFi: CSMA/CA & RTS/CTS
  - Sender sends an RTS frame to reserve medium around itself
  - Receiver responds with CTS to also reserve medium around receiver
  - Sender sends data
  - Receiver acknowledges data

Concurrency vs. Multiplexing

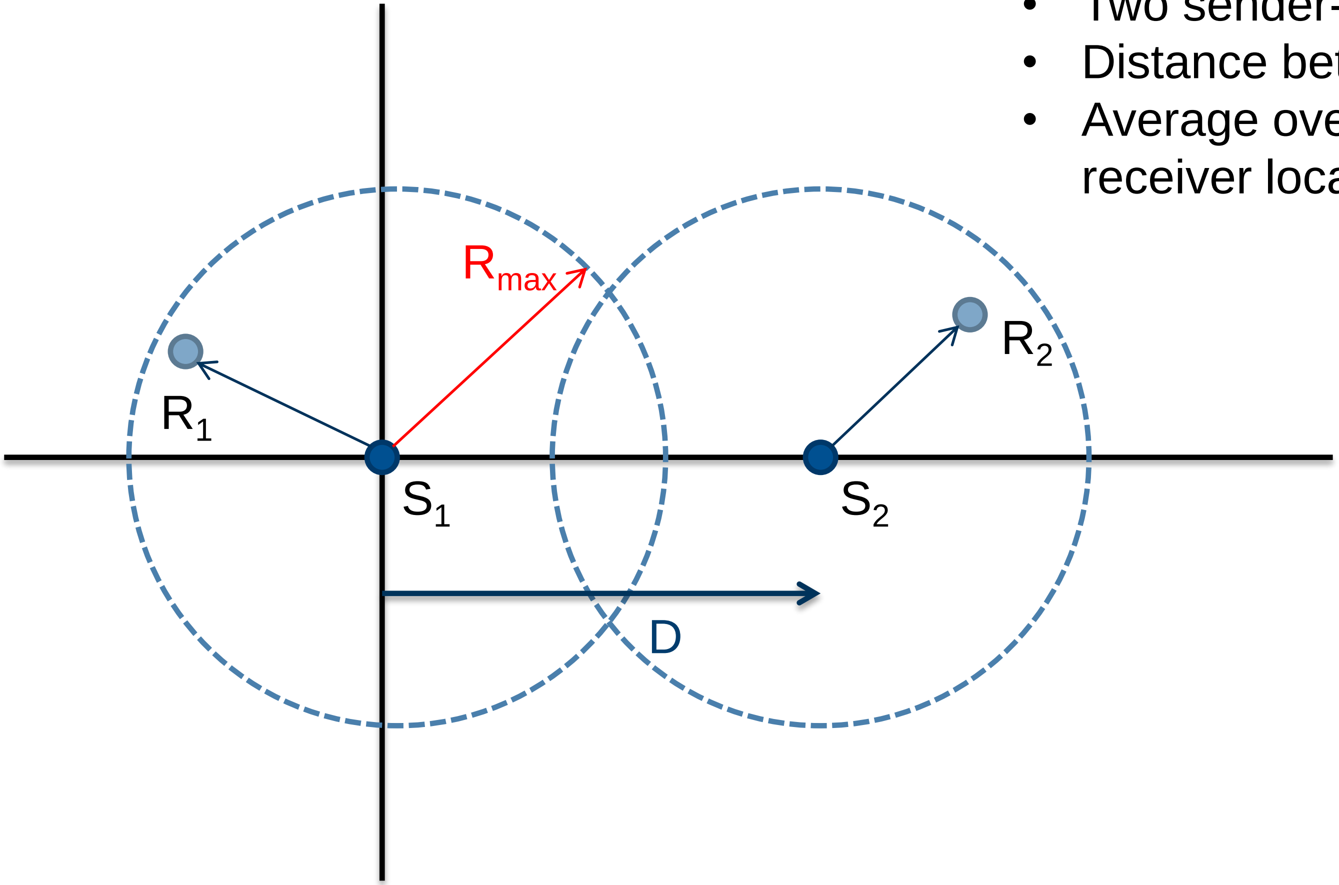
Concurrency	Multiplexing
Senders transmit at the same time	Senders take turns
Interference contributes to noise	No interference
If SINR too low, decoding fails	If SNR too low, decoding fails
Full throughput on both pairs	Throughput only 50% on both pairs

Motivation

- Carrier sense has been challenged in the past and schemes for TDMA, such as WiMAX, have been proposed as an alternative.

- This paper analyses the performance of carrier sense based on a general model to evaluate how close to optimal carrier sense performs

Model



- Two sender-receiver pairs
- Distance between senders: D
- Average over all possible receiver locations within R_{max}

Capacity Model

- Shannon's capacity formula:

$$\frac{Capacity\ [bits]}{Bandwidth\ [Hz]} = \log_2\left(1 + \frac{Signal\ [W]}{Noise\ [W]}\right)$$

usually given in dB:

$$SNR\ [dB] = 10 * \log_{10}\frac{S}{N}$$

Capacity Model

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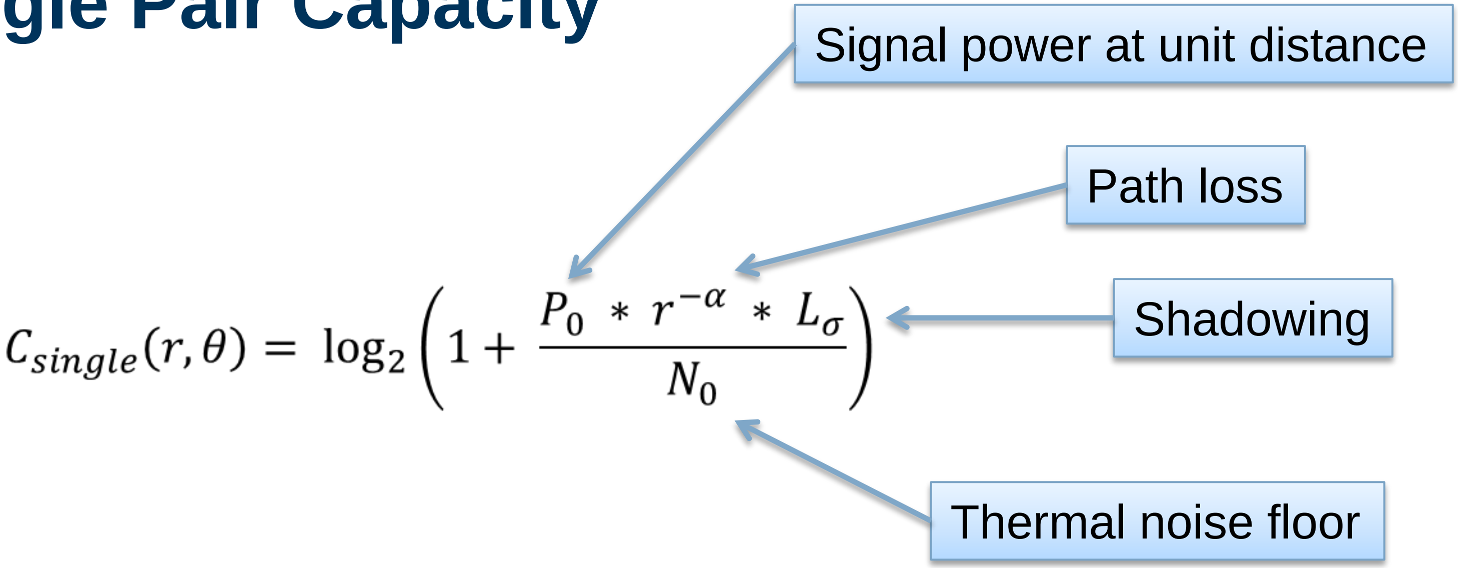
usually given in dB:

$$SNR\ [dB] = 10 * \log_{10}\frac{S}{N}$$

- And with interference:

$$\frac{Capacity\ [bits]}{Bandwidth\ [Hz]} = \log_2\left(1 + \frac{Signal\ [W]}{Noise[W] + Interference\ [W]}\right)$$

Single Pair Capacity



$$C_{single}(r,\theta) = \log_2\left(1 + \frac{P_0 * r^{-\alpha} * L_\sigma}{N_0}\right)$$

Signal power at unit distance

Path loss

Shadowing

Thermal noise floor

Single Pair Capacity

$$C_{single}(r,\theta) = \log_2\left(1 + \frac{P_0 * r^{-\alpha} * L_\sigma}{N_0}\right)$$

Path loss
(α typically varies from 2 to 4)

Free space would have α = 2

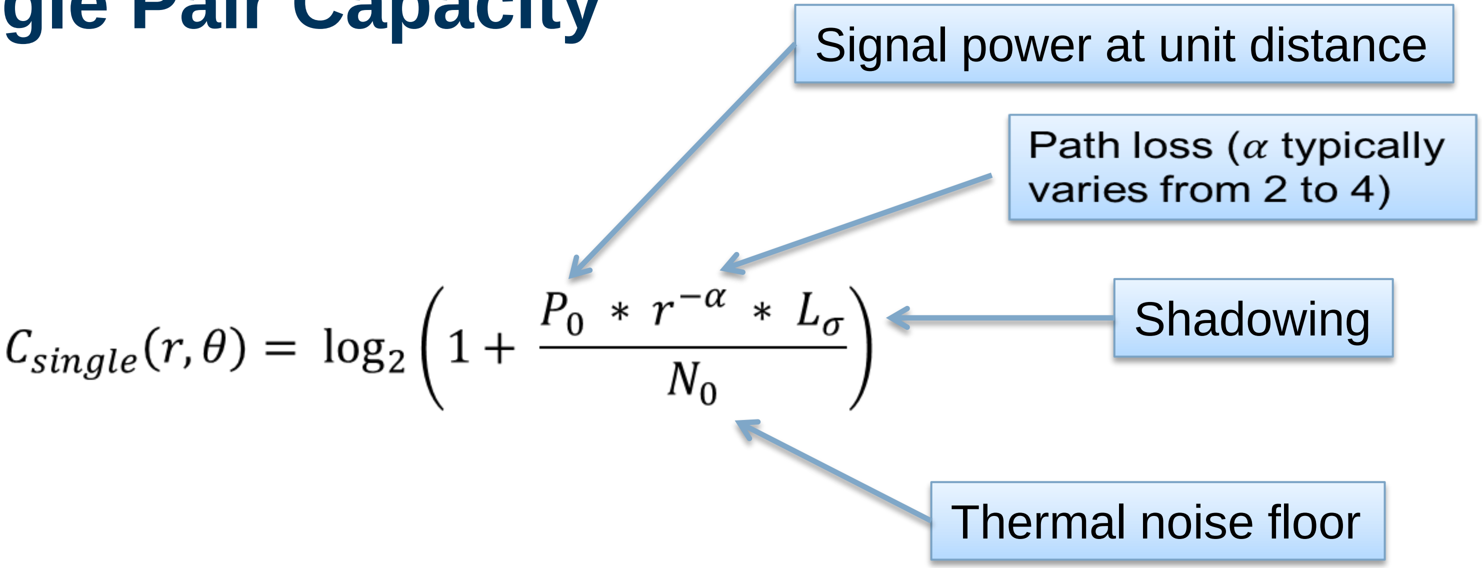
Single Pair Capacity

$$C_{single}(r,\theta) = \log_2\left(1 + \frac{P_0 * r^{-\alpha} * L_\sigma}{N_0}\right)$$

Shadowing

Sample from a random variable with log-normal distribution due to obstacles

Single Pair Capacity



$$C_{single}(r,\theta) = \log_2\left(1 + \frac{P_0 * r^{-\alpha} * L_\sigma}{N_0}\right)$$

Signal power at unit distance

Path loss (α typically varies from 2 to 4)

Shadowing

Thermal noise floor

Signal power can be factored into noise:

$$C_{single}(r,\theta) = \log_2\left(1 + \frac{r^{-\alpha} * L_\sigma}{N}\right) \qquad N = \frac{N_0}{P_0}$$

Two Pair Capacity: Multiplexing

- An ideal MAC gives both pairs half of the capacity with no overhead:

$$C_{multiplexing}(r,\theta) = \frac{C_{single}}{2} = \frac{\log_2\left(1+\frac{r^{-\alpha} * L_\sigma}{N}\right)}{2}$$

Two Pair Capacity: Concurrency

- With both pairs sending concurrently, they contribute to each other’s noise levels:

$$C_{concurrent}(r,\theta) = \log_2\left(1 + \frac{r^{-\alpha} * L_\sigma}{N + P_{other}}\right) = \log_2\left(1 + \frac{r^{-\alpha} * L_\sigma}{N + L'_\sigma * \Delta r^{-\alpha}}\right)$$

$$\Delta r = \sqrt{(r * \cos\theta - D)^2 + (r * \sin\theta)^2}$$

Two Pair Capacity: Carrier Sensing MAC

- Depending on a threshold, either concurrent transmission or multiplexing is chosen:

$$C_{cs}(r,\theta)\begin{cases} C_{multiplexing}(r,\theta) & |D^{-\alpha}\ L_{\sigma} > P_{threshold} \\ C_{concurrent}(r,\theta) & |D^{-\alpha}\ L_{\sigma} < P_{threshold} \end{cases}$$

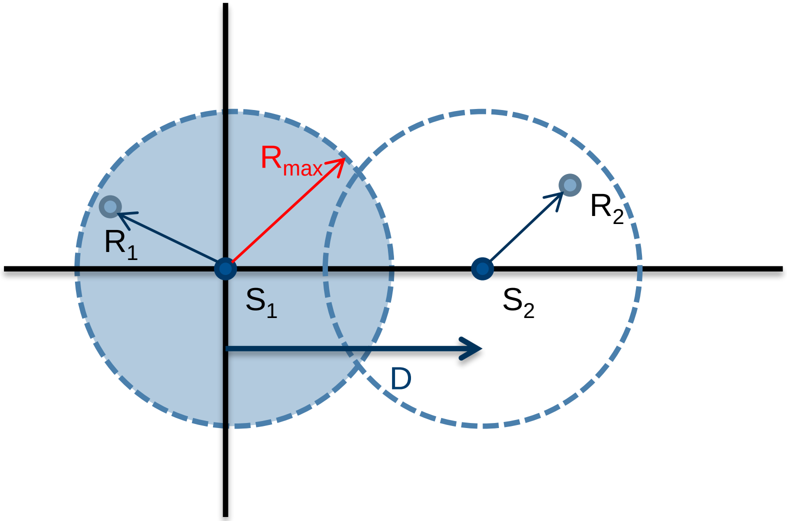
- An optimal MAC would achieve:

$$C_{max}(r_1,\theta_1,r_2,\theta_2) = \frac{1}{2} * \max \begin{array}{l} [C_{concurrent}(r_1,\theta_1) + C_{concurrent}(r_2,\theta_2), \\ C_{multiplexing}(r_1,\theta_1) + C_{multiplexing}(r_2,\theta_2)] \end{array}$$

Average Capacity

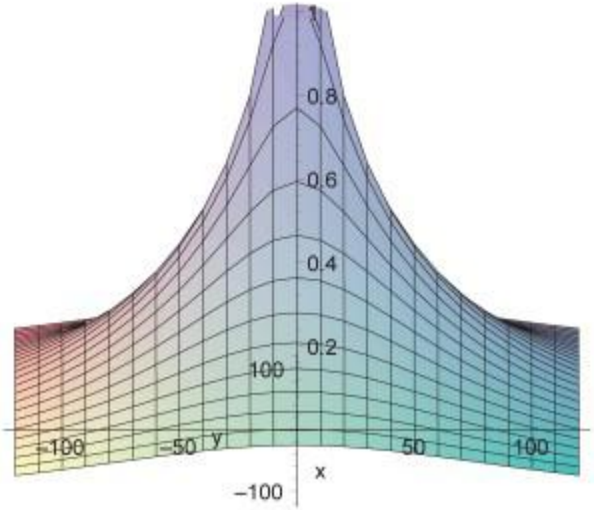
- Average capacity is determined by integrating over the R_{max}-radius circle around the sender:

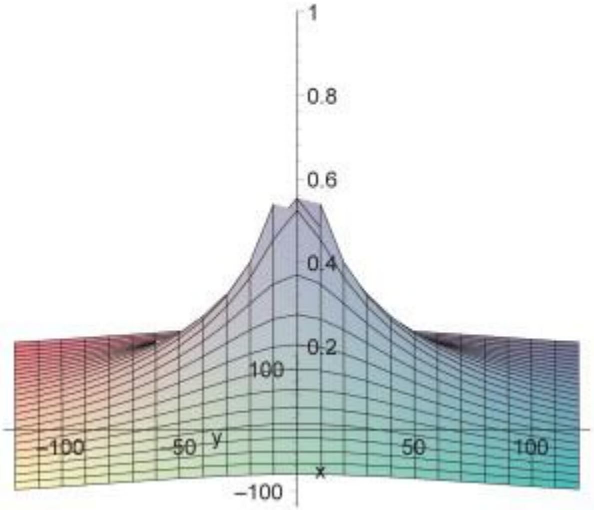
$$\langle C_i \rangle = \frac{1}{\pi {R_{max}}^2} \int_0^{R_{max}} \int_0^{2\pi} C_i(r, \theta) r d\theta dr$$



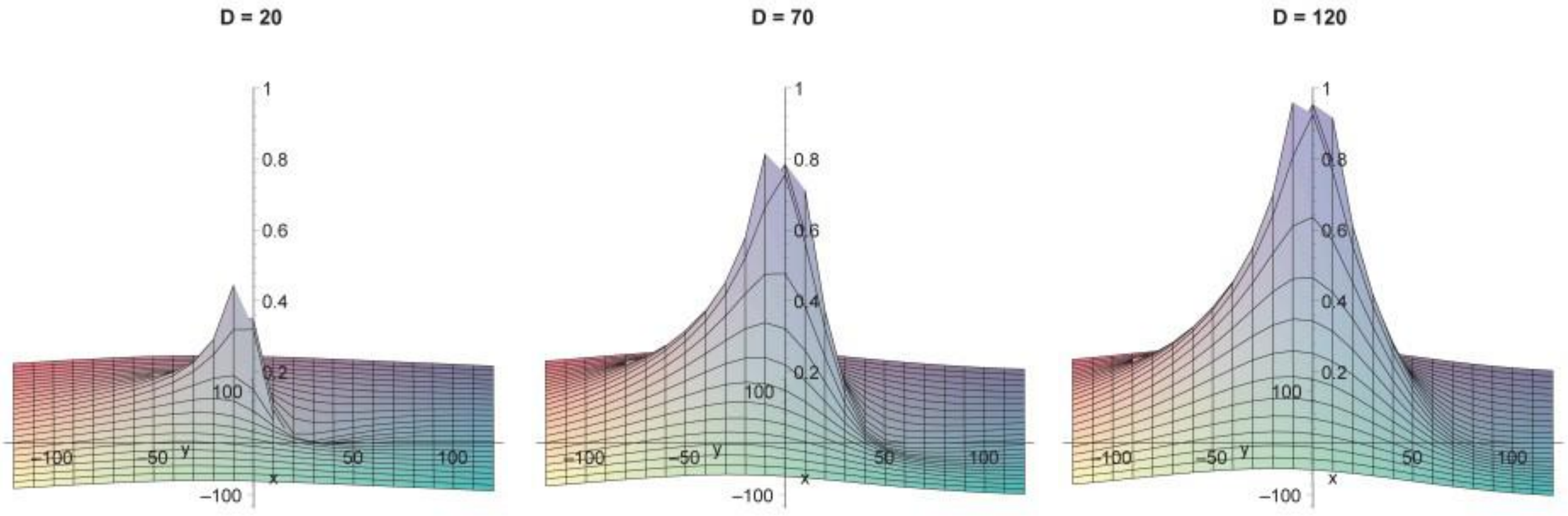
Carrier Sense Performance: Border Cases

Concurrency	Multiplexing
Very far: D = ∞	Very close: D = 0
No Interference → concurrency is optimal	SNR 0dB → multiplexing is optimal

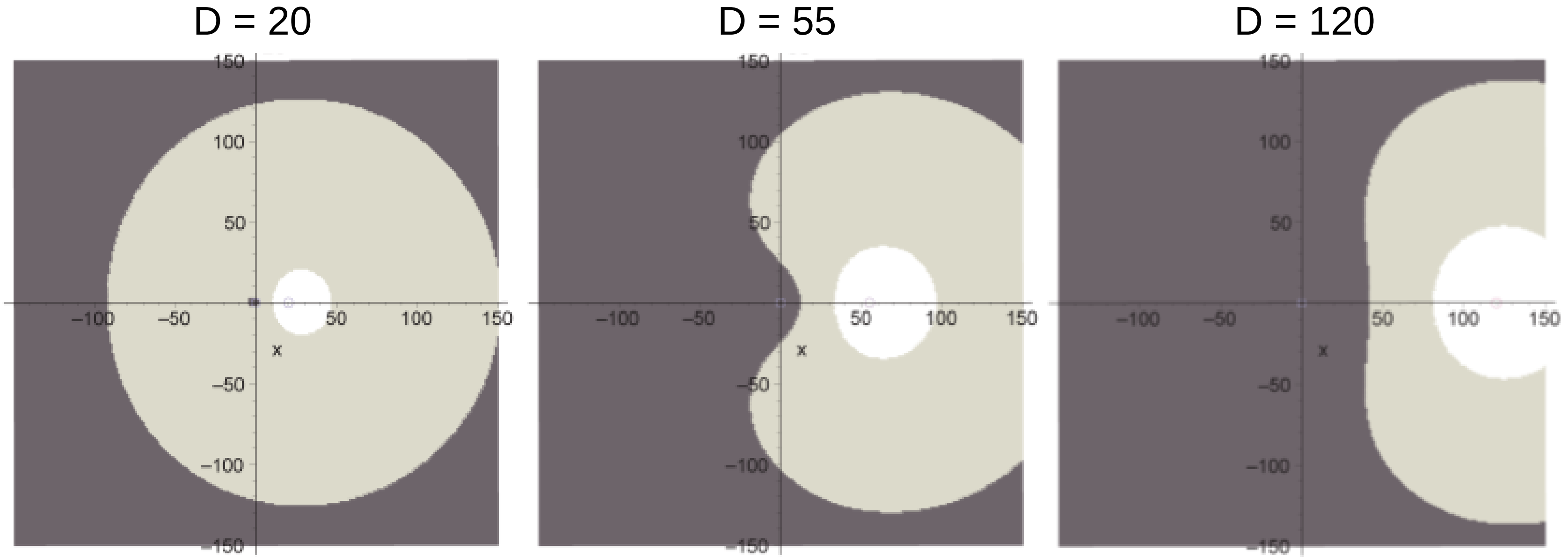




Capacity Landscape



CS Performance: Receiver’s Choice



Dark area:	Receiver prefers concurrency
Light area:	Receiver prefers multiplexing
White area:	Receiver requires multiplexing

Quantitative Results

for α = 3 and σ = 8dB

D R_{max}	20	55	120
20	96%	88%	96%
40	96%	87%	96%
120	89%	83%	92%

Percentage of optimal throughput with threshold = 55

D R_{max}	20	55	120
20 (40)	93%	91%	99%
40 (55)	96%	87%	96%
120 (60)	89%	83%	92%

Percentage of optimal throughput with optimized thresholds

Quantitative Results: Consistency

- Varying α from 2 to 4 and σ from 4dB to 12dB results in little change
- Smaller α tend to make a network look more short range and larger α more long range

Reminder
Signal power = $P_0 * r^{-\alpha} * L_\sigma$
α: path-loss coefficient
σ: shadowing distribution parameter

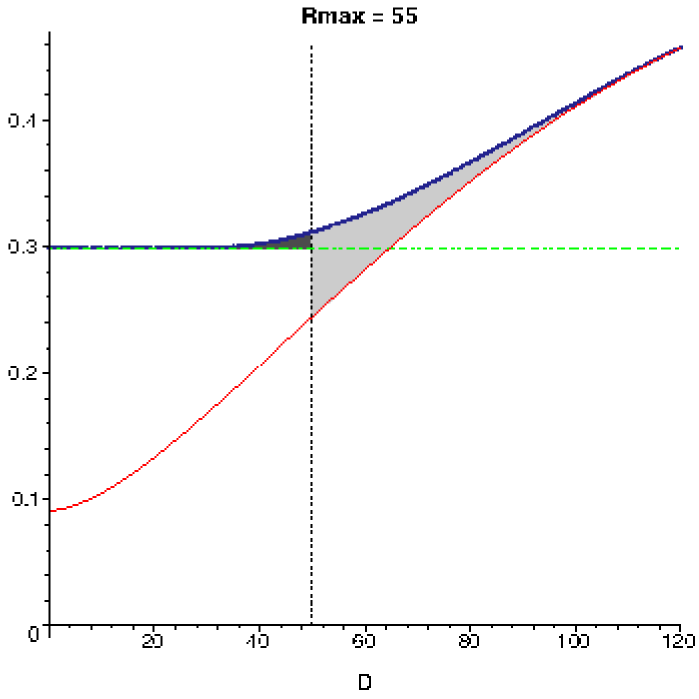
Global Threshold Selection

- Threshold determines efficiency of carrier sense
- Poor threshold choice leads to bad decision when selecting between multiplexing and concurrent transmission
- Manufacturers of wireless chipsets need to select a default threshold

Global Threshold Selection

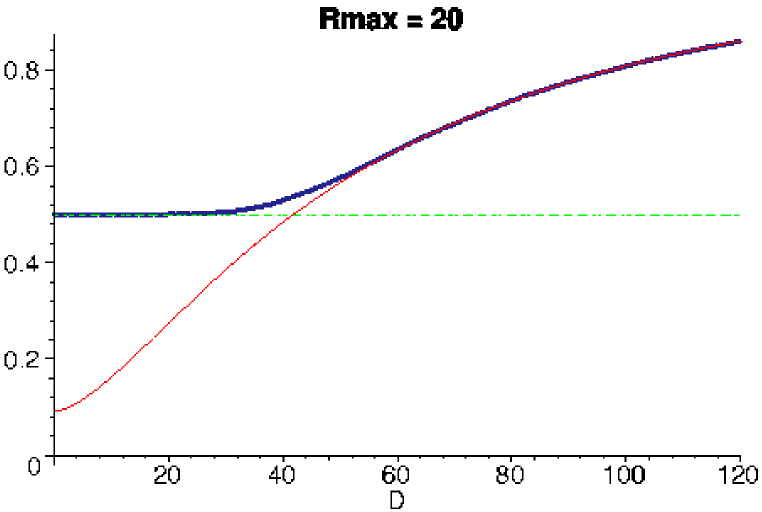
- Multiplexing almost reaches optimal performance with a close interferer. Concurrency does the same with a distant interferer

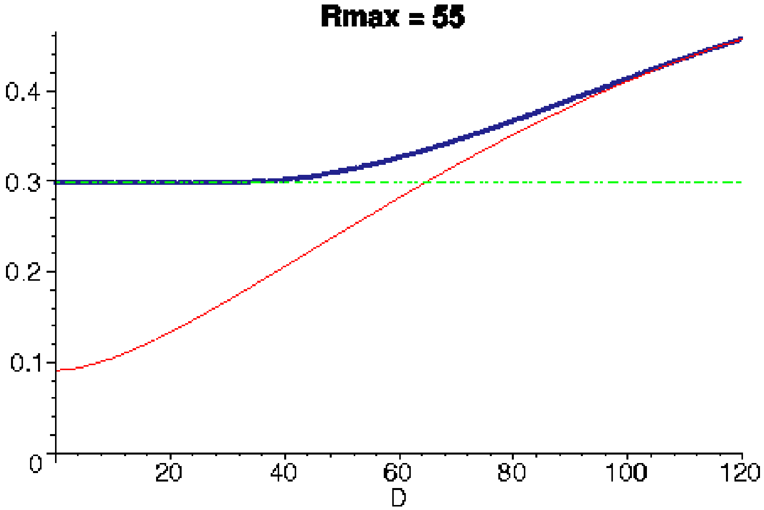
- Transition region is suboptimal, as receivers prefer a different method depending on location

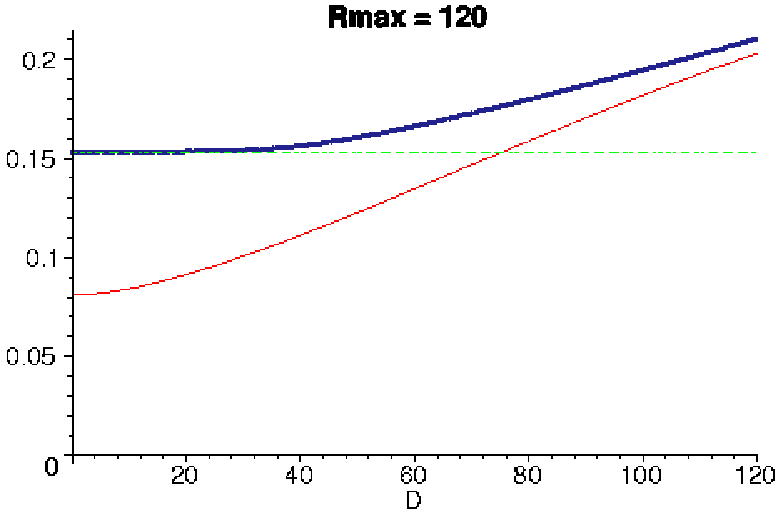


🟦	optimal
🟩	multiplexing
🟥	concurrency

CS Performance: Throughput


Rmax = 20


Rmax = 55


Rmax = 120

Transition Region Performance

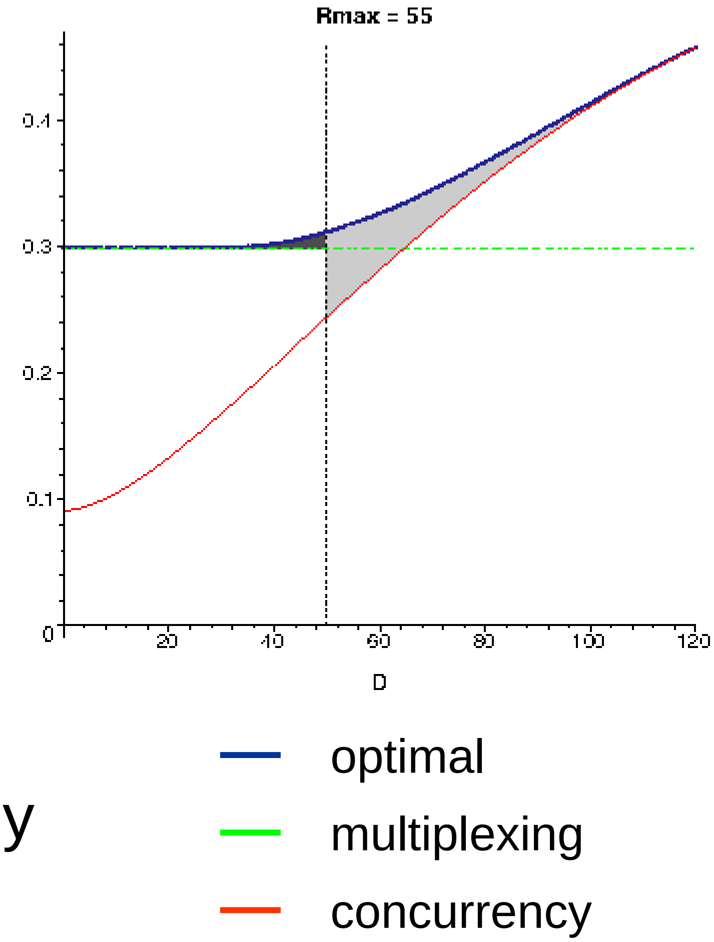
- Adaptive bitrate protocols and the smooth propagation of interference prevent dramatic differences in throughput

- Locality depends on the size (R_{max}) of the network. In short range networks, effects of an interferer are similar for all receiver locations. Long range networks where interference fades out below the noise floor on distant receivers suffer more localized effects

→ Carrier sense is significantly more efficient in short range networks

Picking a Global Threshold

- Optimal threshold is at the intersection of multiplexing and concurrency throughputs
- Requires knowledge of R_{max} and propagation environment
- A good default lies in the middle of optimal thresholds of typical operating parameters supported by the hardware



Long-range vs. Short-range Networks

- Short-range networks usually have the threshold well outside of R_{max}. Long-range networks on the other hand usually have the threshold inside R_{max}, when interference affects a large part of the network.

- Therefore, one can define:

long range $\rightarrow R_{thresh} < R_{max}$
short range $\rightarrow R_{thresh} > 2R_{max}$

Threshold Robustness

- As the quantitative results have shown, performance is good even with suboptimal threshold choice

- This is largely because data networking hardware operates in the regime around 10-25dB SNR

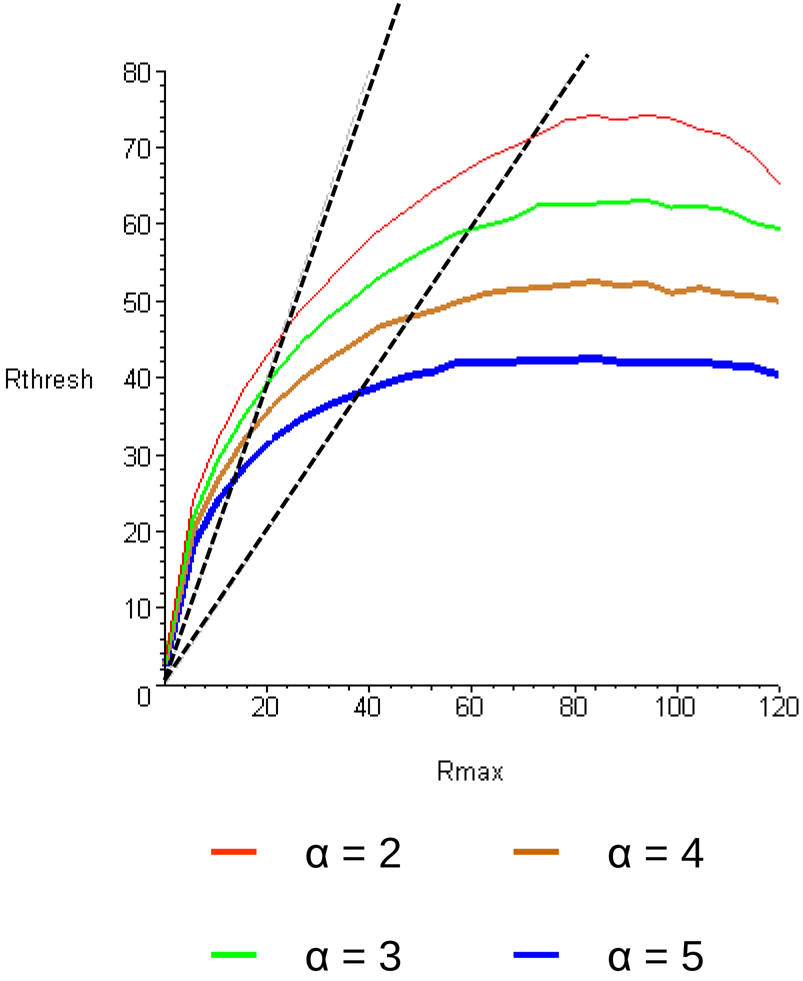
- The range corresponds to the intermediate region between short-range and long-range range limits

Threshold Robustness

- On the left side lies the short-range limiting behaviour with thresholds approaching 0

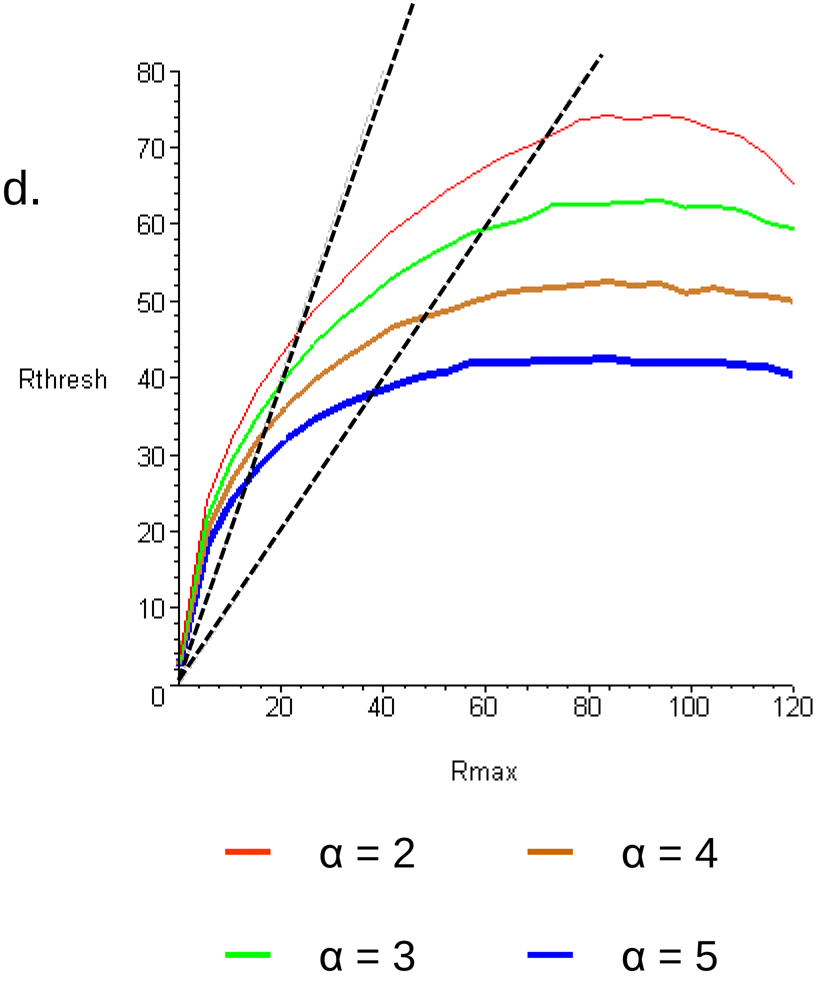
- On the right side lies the long-range limiting behaviour with threshold growth tapering off in R_{max} but spreads out in α

- In between, neatly enclosed by two dashed lines representing $R_{thresh} = R_{max}$ and $R_{thresh} = 2R_{max}$ lies the transition region between the extremes



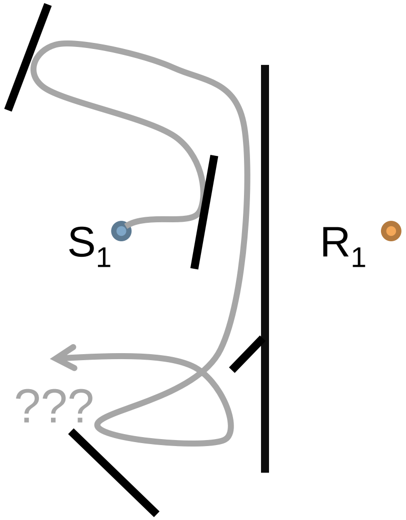
Threshold Robustness

- In the short-range case, carrier sense performs well with an optimal threshold. However, optimal threshold grows rapidly with R_{max}
- In the long-range case, carrier sense performance is suboptimal but robust under varying thresholds.
- In the middle is a compromise of both extremes. This coincidentally is the primary operating regime for wireless network hardware



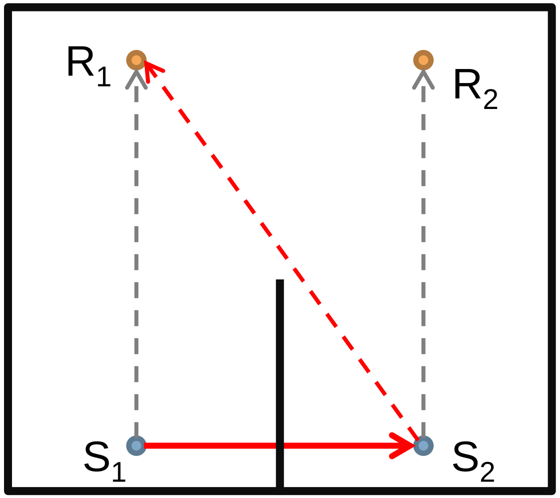
Throughput with Shadowing

- Obstacles produce local differences of signal transmission → Shadowing
- If differences too great, results might be unrealistic as environments without shadowing are rare



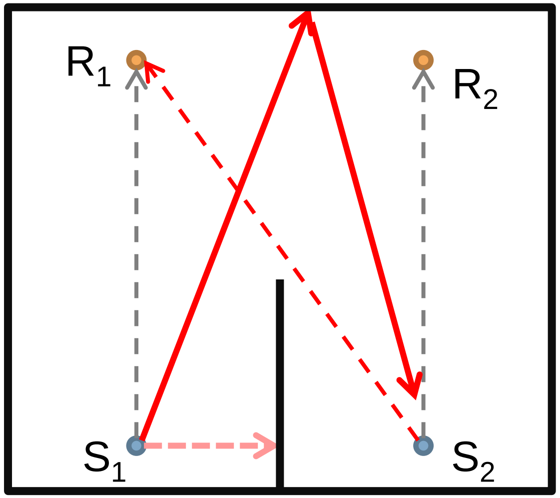
Shadowing: Signal Penetration

- Most building materials are not opaque to radio.
- An interior wall typically attenuates the signal for at most 10dB



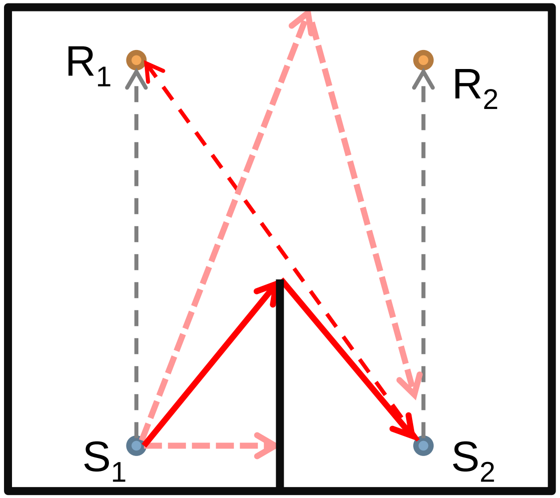
Shadowing: Reflections

- Materials reflect signals to a certain degree
- Reflection typically incur losses of less than 10dB

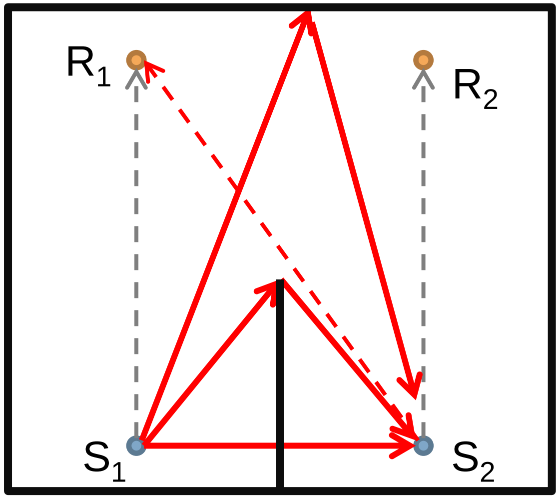


Throughput with Shadowing

- Edges lead to diffraction → Signals can propagate around corners
- Example: 5m to wall, 2.4Ghz → 30dB loss

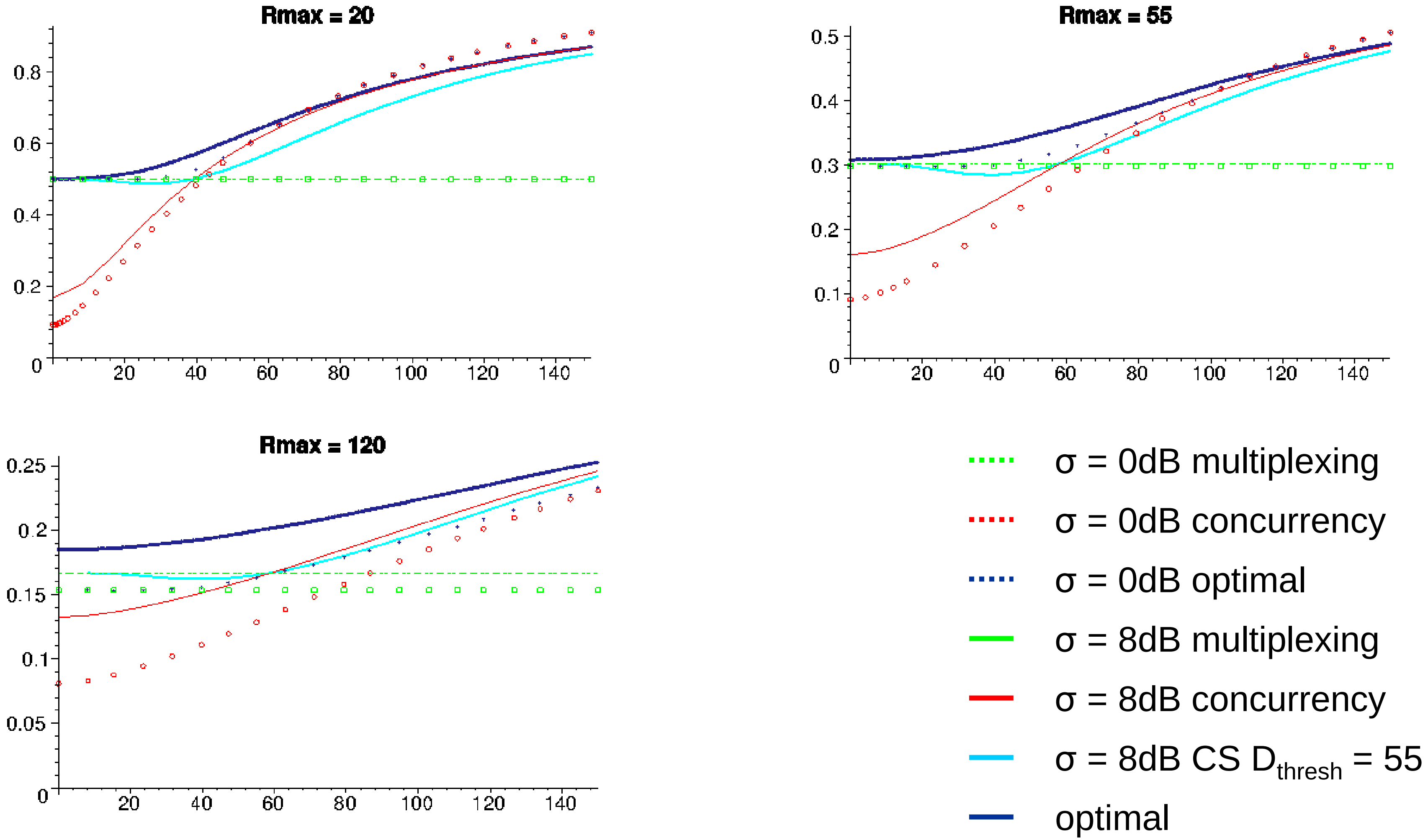


Throughput with Shadowing



- Due to the central limit theorem, we can combine all possible contributions into a single Gaussian random variable
- The resulting lognormal shadowing distribution typically has a standard deviation between 4 and 12dB
- This is not enough to cause substantially different results

Throughput with Shadowing



Experimental Evaluation

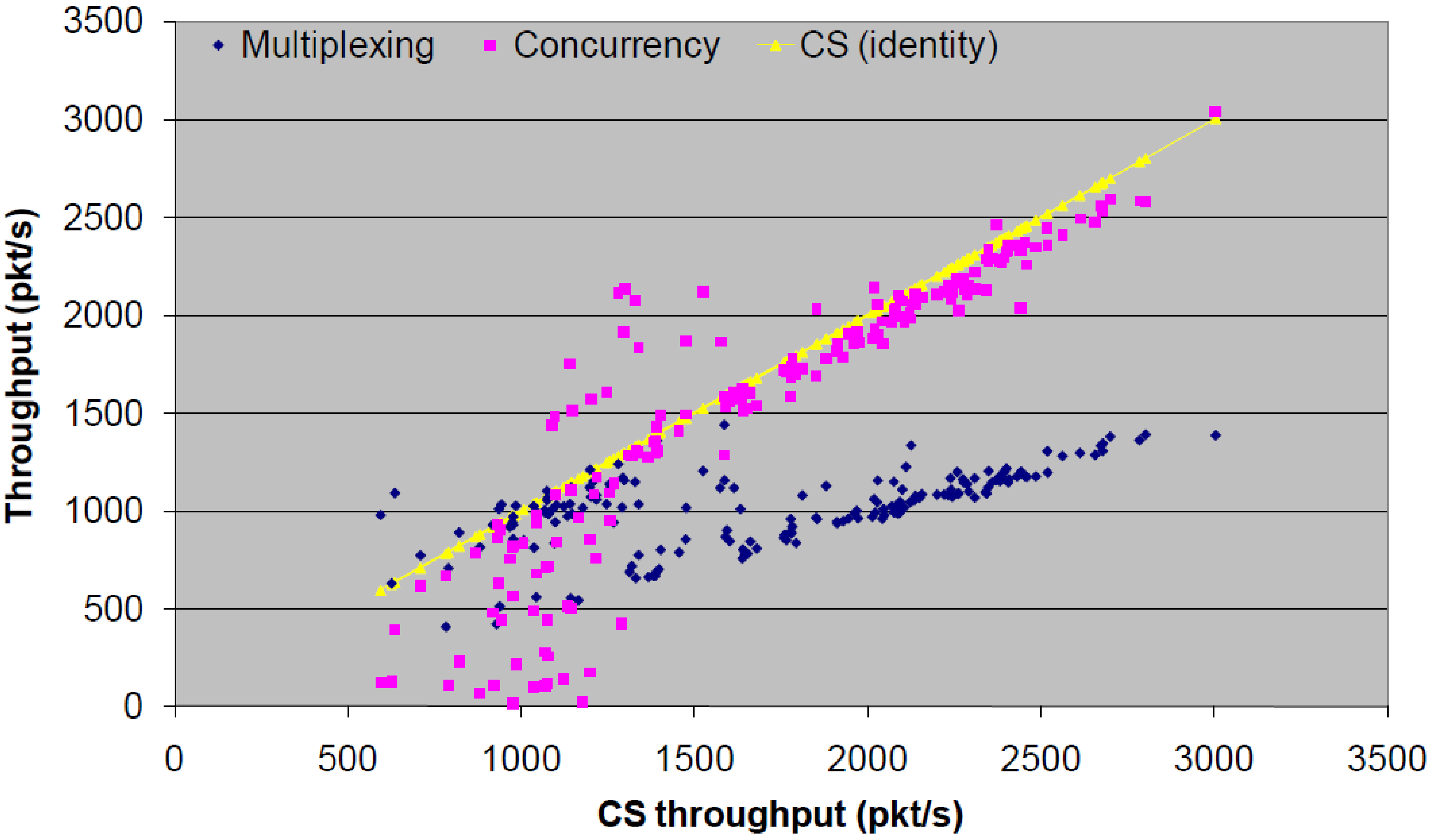
- Indoor testbed of Atheros AR5212 and AR5213 based devices scattered over 2 floors of a modern office building
- Senders continuously transmit 1400-byte packets for 15 seconds
- Concurrency is achieved by turning off hardware carrier sense, multiplexing by first only enabling one sender, then the other
- Runs with 6, 9, 12, 18 and 24 Mbps

Experimental Evaluation

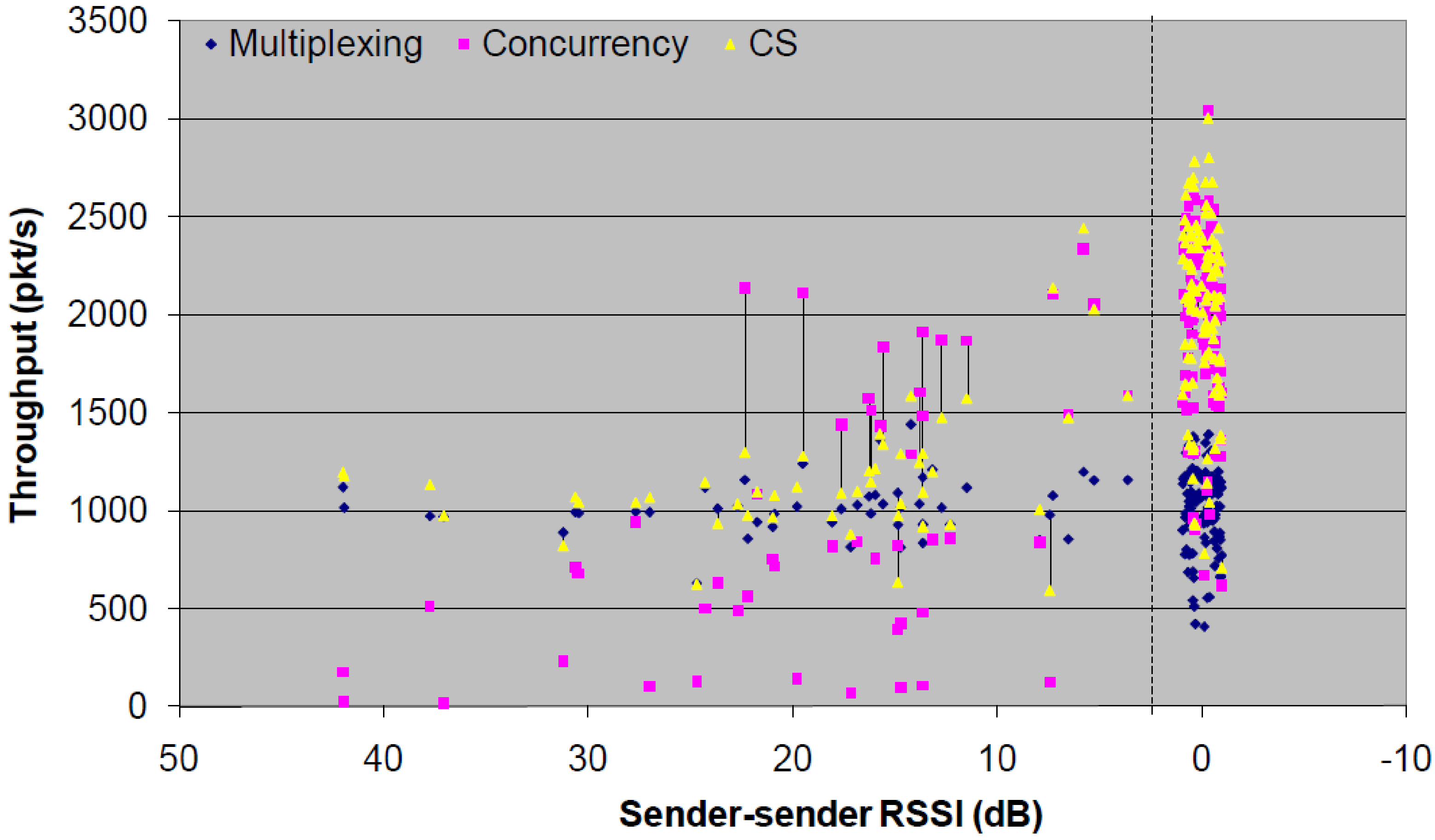
- A short-range network is simulated by only communicating with receivers that receive 94% of packets at 6 Mbps. This results in a SNR of about 27dB which corresponds to $R_{max} = 30$

- A long-range network is simulated by including the receivers that receive 80% to 95% of packets. This results in a SNR of about 16dB which corresponds to $R_{max} = 70$

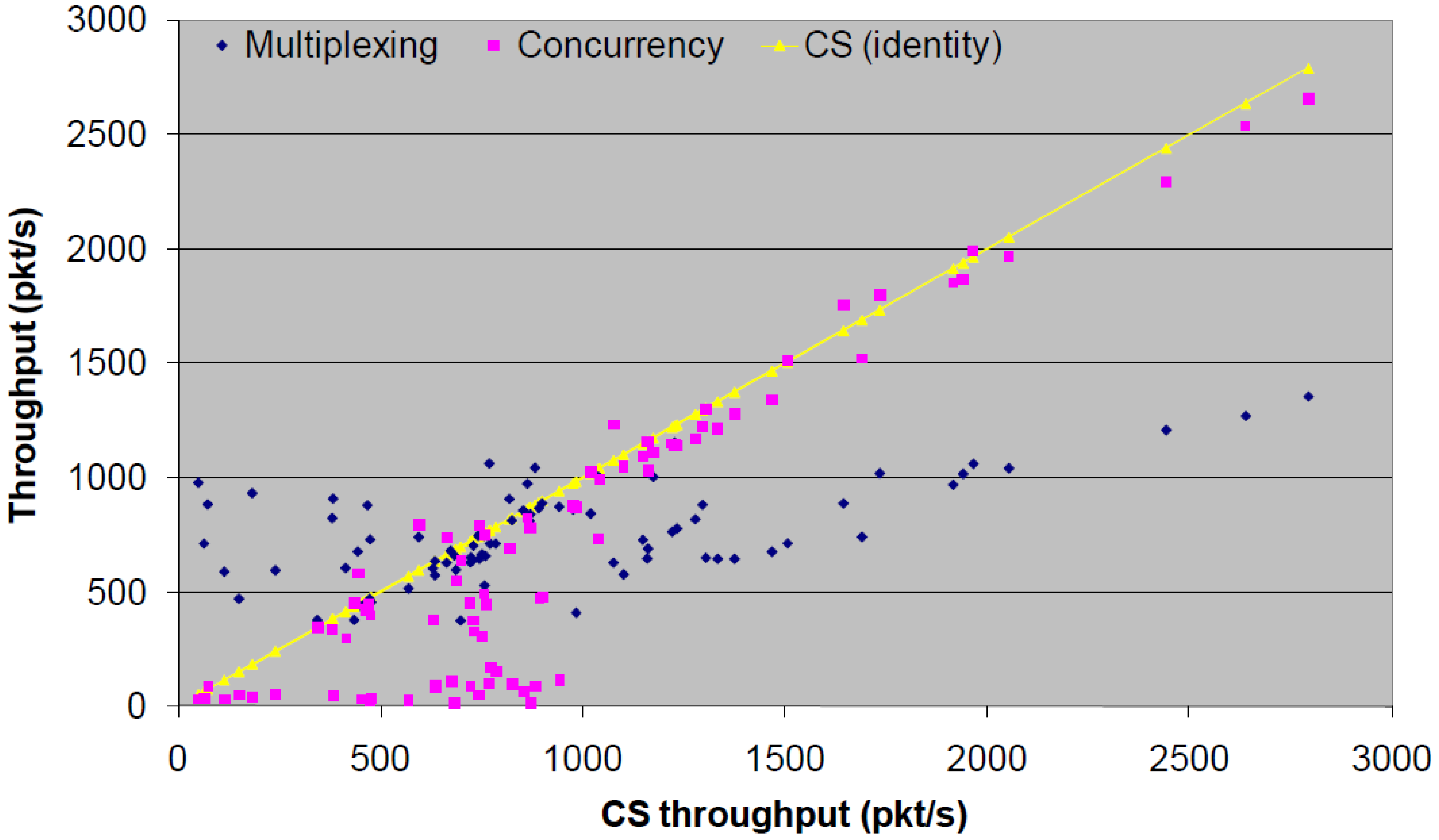
Experimental Evaluation: Short-Range



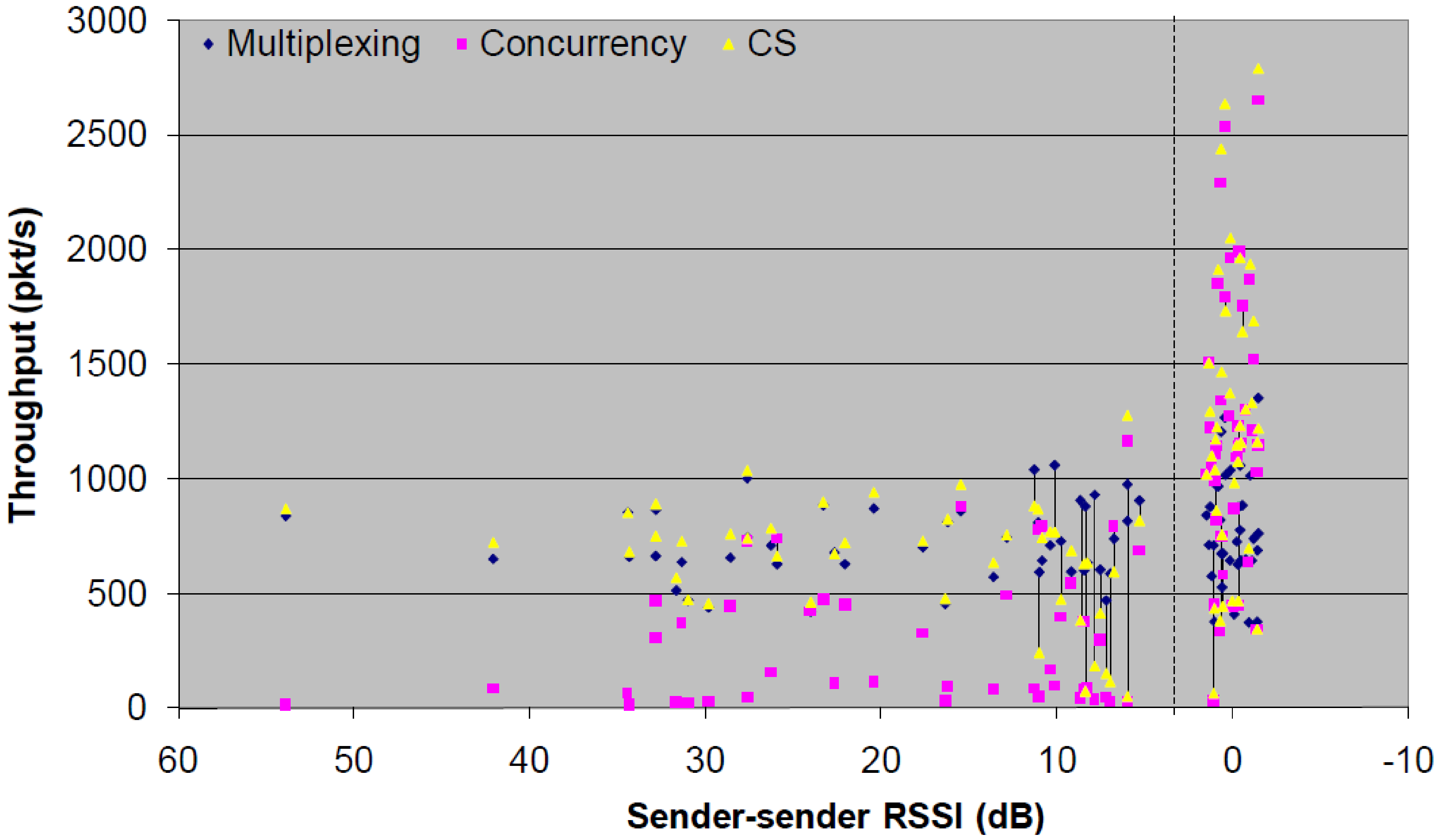
Experimental Evaluation: Short-Range



Experimental Evaluation: Long-Range



Experimental Evaluation: Long-Range



Conclusion

- Carrier sense reaches near-optimal performance in the average case
- Carrier sense performs particularly well in short-range networks
- Shadowing does not introduce dramatic differences