Transmit Only for Dense Wireless Networks

Bernhard Firner

Rutgers University, WINLAB

October 18, 2013

Dense Wireless Networks?

- Wireless devices becoming smaller, cheaper, & more plentiful
- New use cases emerging with 100s or 1000s of devices
  - Agricultural & environmental monitoring
  - Smart-homes, offices, etc
  - Healthcare tracking and monitoring

Dense Wireless Networks?

- Wireless devices becoming smaller, cheaper, & more plentiful
- New use cases emerging with 100s or 1000s of devices
  - Agricultural & environmental monitoring
  - Smart-homes, offices, etc
  - Healthcare tracking and monitoring
  - This dissertation is about networks of these small, wireless devices

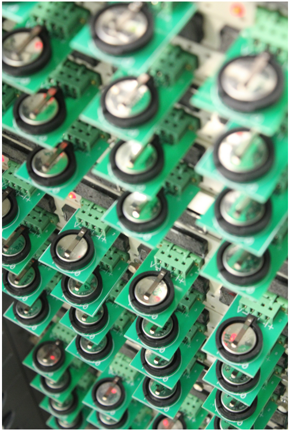
Problem: Wireless Radios Need Batteries

What are these radios doing?

- Frequent, periodic transmissions
- Small packets, little chunks of data
- Data often redundant

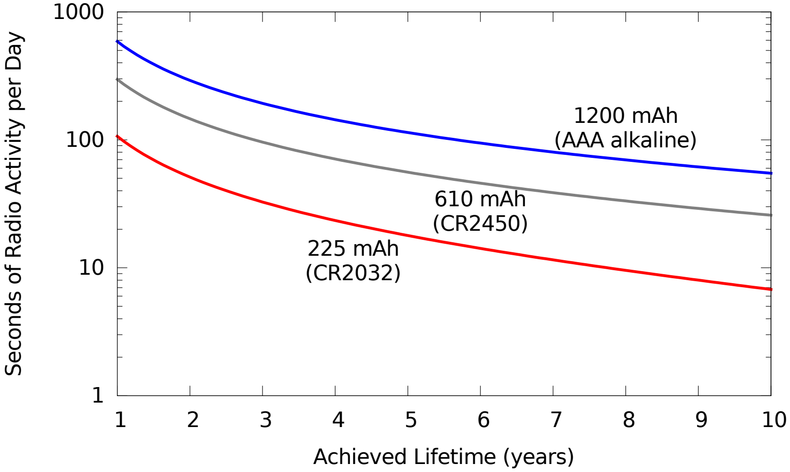
Problem:

- Small, mobile devices need batteries
- Batteries must last for years



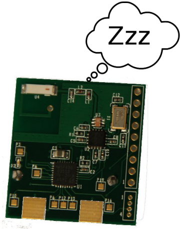
Battery testing by UCL
Mathematical and Physical Sciences

Is Energy a Big Problem? Yes.



Existing Solutions Not Very Low Energy

- Throughput and reliability usually top priorities
- Not good for these kinds of devices
    - Energy costly set-up or scheduling is bad
    - Small packets make overhead relatively worse
        - ACKs and carrier sensing relatively costly
- Most time should be spent sleeping!!!



Transmit Only

- Save energy by *only transmitting*
  - No channel sensing, coordination, etc
  - More time to sleep!
- Trade reliability for lifetime
- Will not sacrifice throughput in dense networks
  - Probabilistically reduce packet losses with the *capture effect*
  - Use multiple receivers to increase capture likelihood

How Does a TO Topology Look?

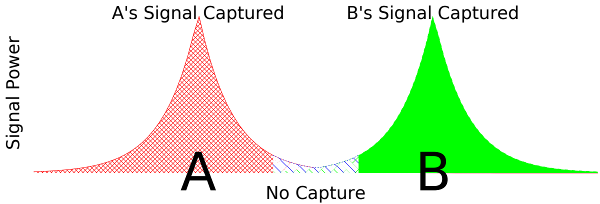
- One-hop from transmitters to receivers
  - Receivers are wire-powered or have batteries with many times the energy of the transmitters
  - Receivers forward data to an aggregation point over a back haul network
- Multiple receivers can hear each transmitter
  - This gives each transmitter multiple chances for capture

Let's Talk About the Capture Effect

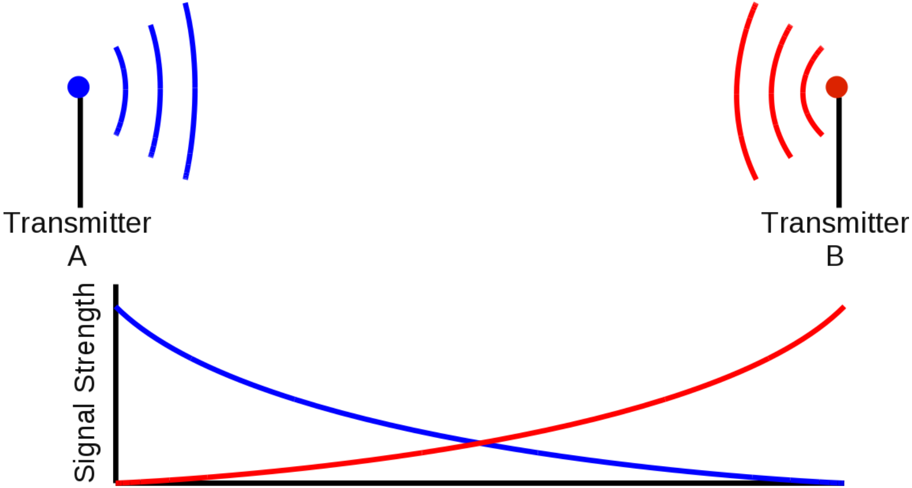
- Exploiting the capture effect is vital to TO
- Let's learn more about it

What Is the Capture Effect?

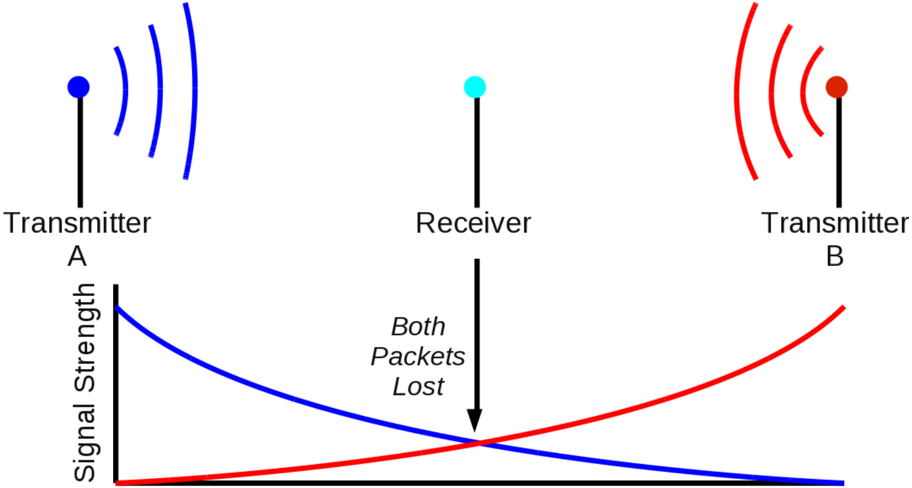
- Occurs during packet collisions
  - Packets have different signal strengths
  - Packet with the strongest signal strength may be *captured*
  - Weaker packets are lost as noise
- The captured packet is received correctly



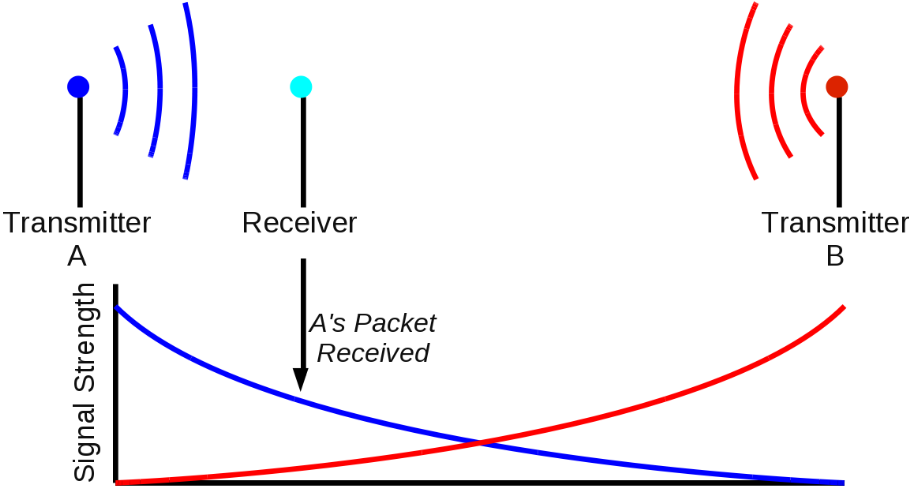
Exploiting the Capture Effect



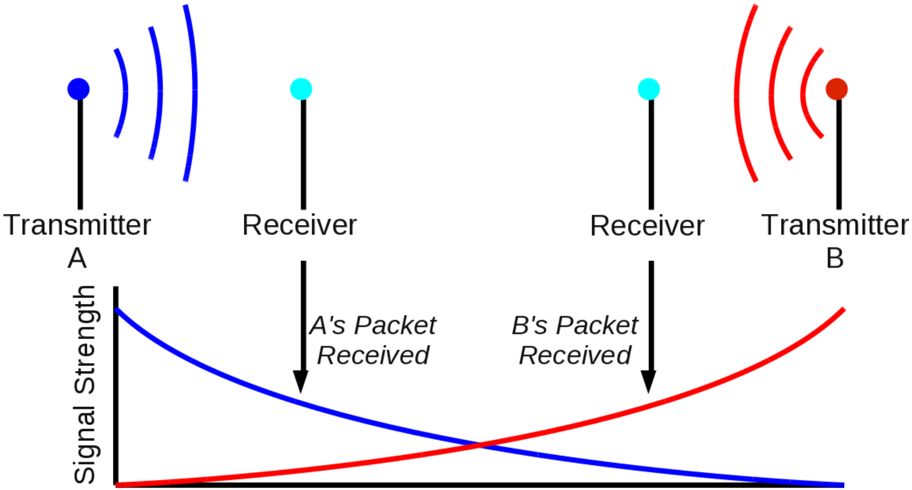
Exploiting the Capture Effect



Exploiting the Capture Effect



Exploiting the Capture Effect

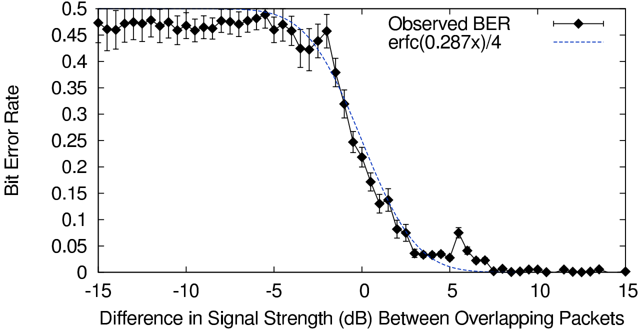


Spatial diversity increases capture gains!

Case Study: Capture in the CC1100 Radio

- CC110x line of radios are common, low power radios
- Experiment: Collide packets and observe the capture threshold
- Experimental parameters:
  - Frequency was 902.1 MHz
  - Modulation was MSK with data whitening enabled
  - Packets were 32 bits preamble, 32 bits sync word, and 16 bits of data

Bit Error Rate (BER) and Capture



- BER derived from bits in data and sync word
- Capture isn't quite a binary event, but BER ≈ 0 at $> +6dB$
- Can consider this the capture threshold for the CC1100

Capture Threshold Is Hardware Dependent

- 6dB in CC1100 radio
- 1dB in some Atheros WiFi cards[1]
- Will refer to a 0dB threshold as “perfect” capture

[1] J. Lee, W. Kim, S.-J. Lee, D. Jo, J. Ryu, T. Kwon, and Y. Choi. An Experimental Study on the Capture Effect in 802.11a networks. In *WinTECH 07: Proceedings of the second ACM international workshop on Wireless network testbeds, experimental evaluation and characterization*, pages 1926, New York, NY, USA, 2007. ACM.

What are TO's Advantages?

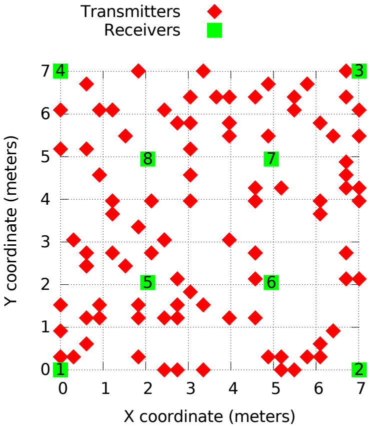
Now we can talk about TO's performance!

- TO on a Single Channel Vs. Multiple Frequencies
  - Can we "capture" more bandwidth on a single channel than in multiple channels?
- TO Vs. Known MAC protocols
  - Is the $\frac{Joules}{Successful\ bit}$ greater in TO compared to e.g. CSMA?

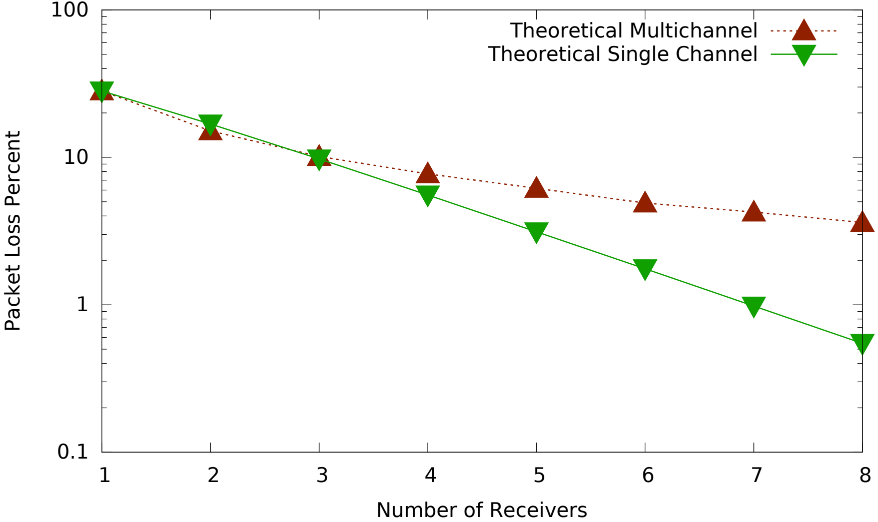
Why Not Use Multiple Channels?

Let's check!

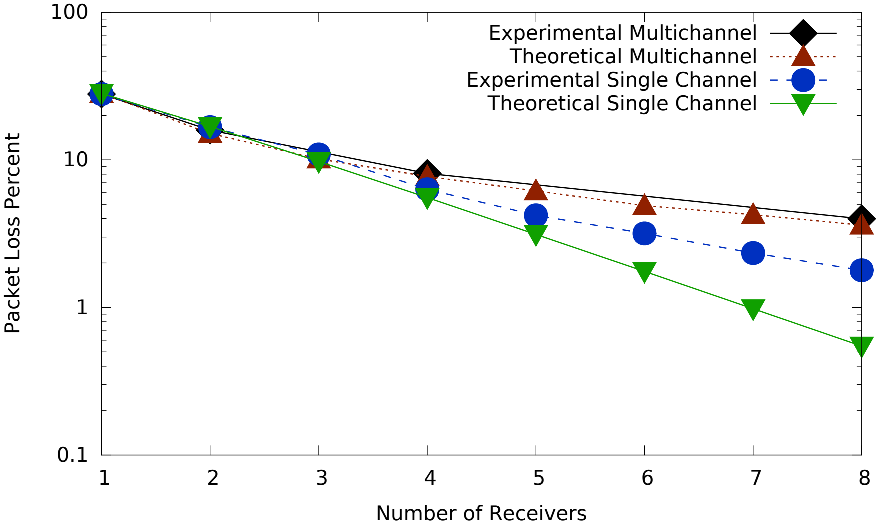
- 100 transmitters, offered load of 30%
- 8 receivers
- Test all combinations
  - 1 channel with 8 receivers
  - 2 channels with 4 receivers
  - ...
  - 8 channels with 1 receiver



Expected Results (from math)



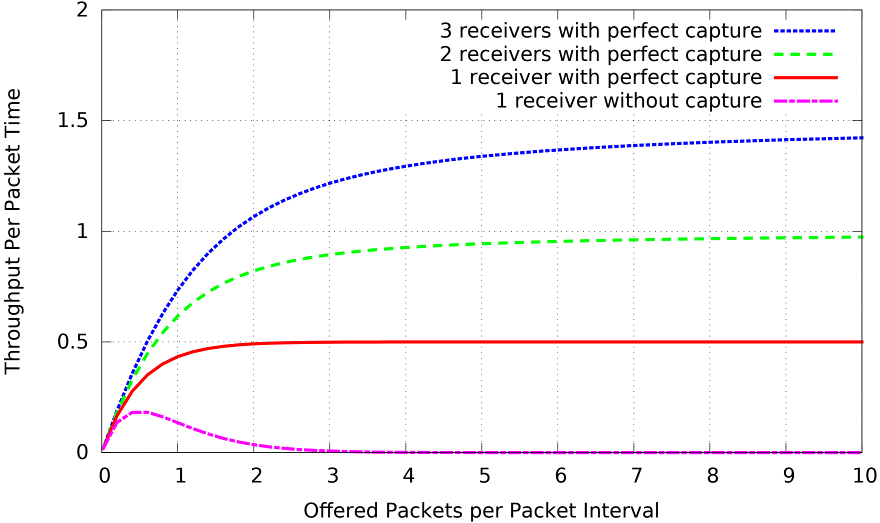
Achieved Results



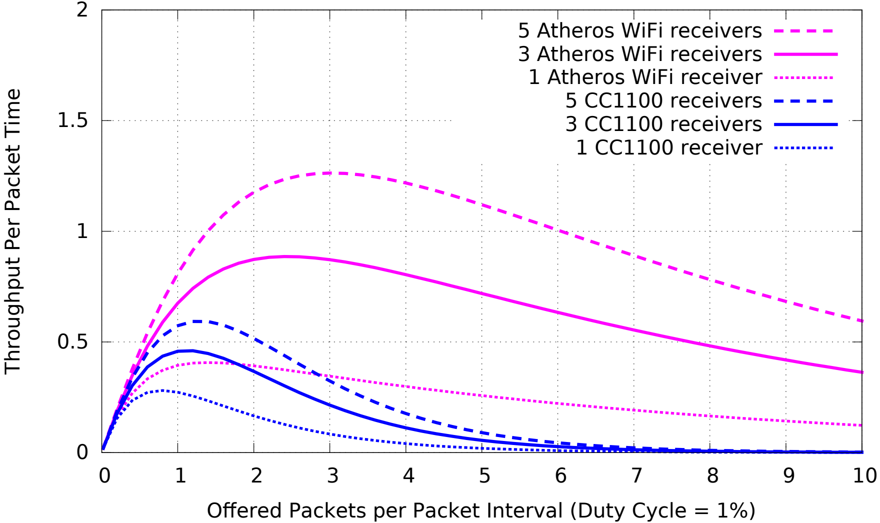
Comparing TO with Existing Protocols

- There are two metrics that we care about
  1. Throughput
  2. Energy efficiency: $\frac{Joules}{Successful\ bit}$

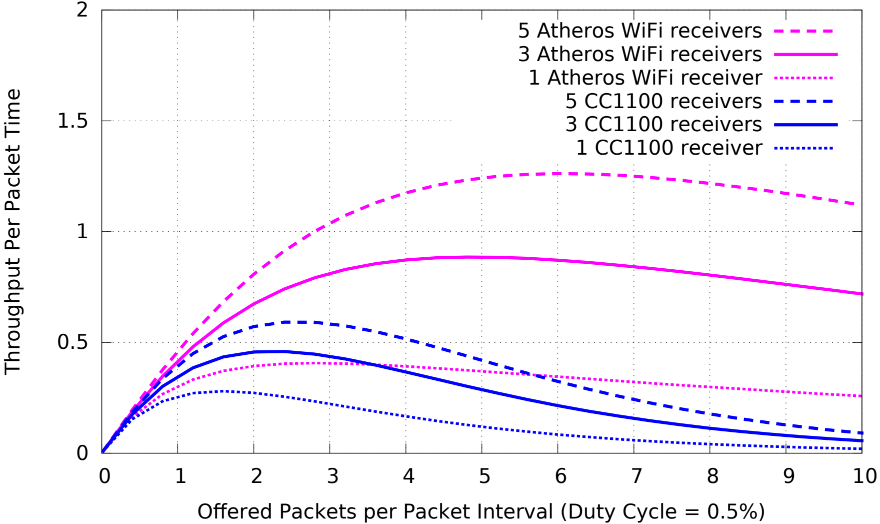
TO Throughput with Perfect Capture



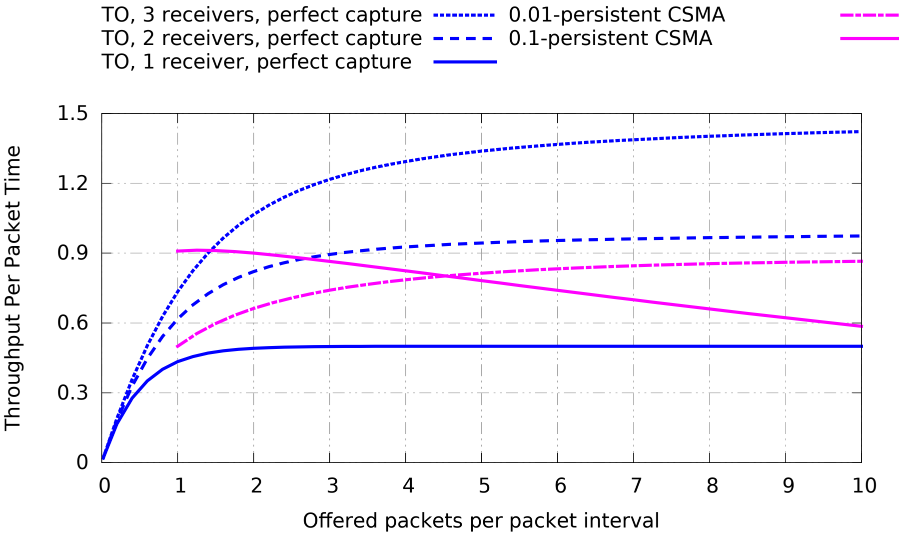
TO Without Perfect Capture



Smaller Packet Size

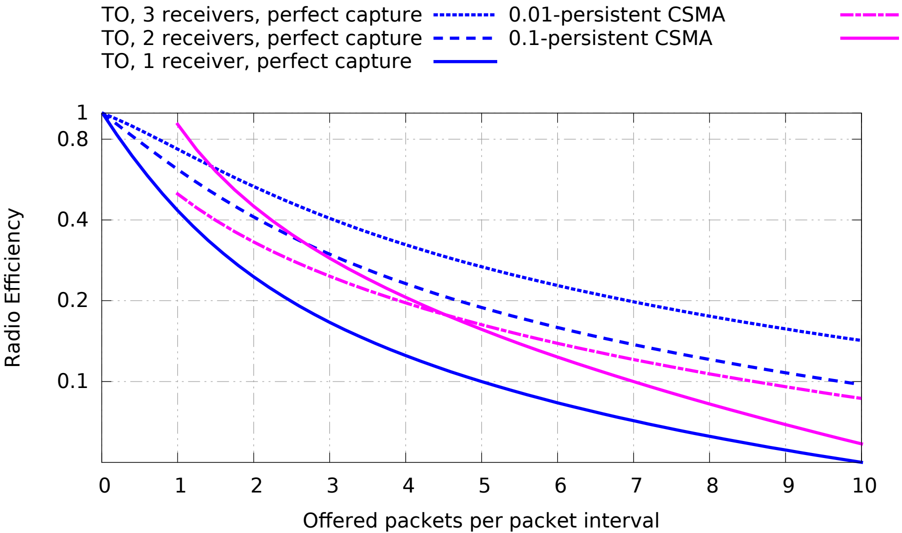


TO Versus CSMA: Throughput

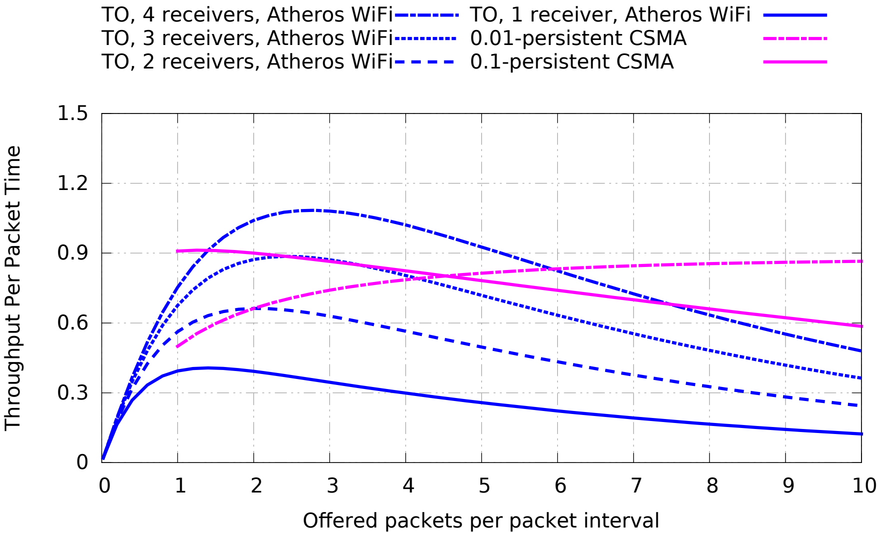


RUTGERS WINLAB

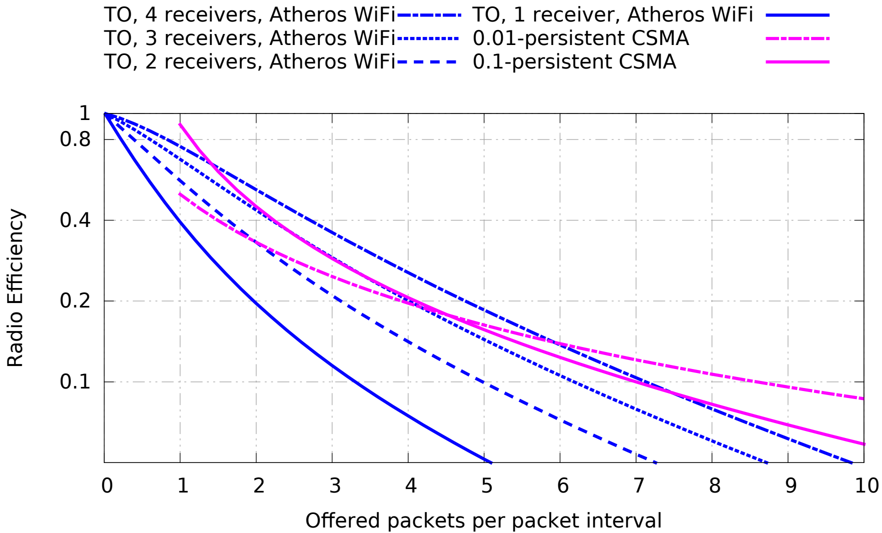
TO Versus CSMA: Energy Per Bit



Imperfect TO Versus CSMA: Throughput



Imperfect TO Versus CSMA: Energy Per Bit

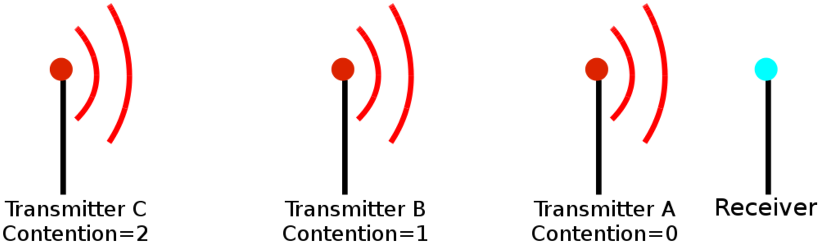


TO in Practice

- TO looks good in theory
- Need to have some guidelines when using it in practice
  - Is there a way to see if TO is a good fit for a topology?
  - Where do receivers go?
  - Will we need an impractical number of receivers?

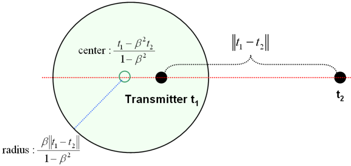
Optimizing Transmitter Capture

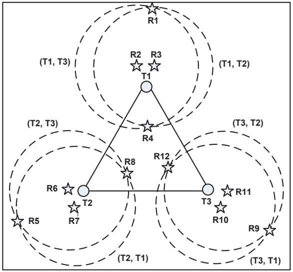
- Difficult to estimate performance with so many parameters
- Better to find a single parameter to optimize
    - Contention!
- A is in contention with B if A's packet will not be captured over B's packet at all receivers



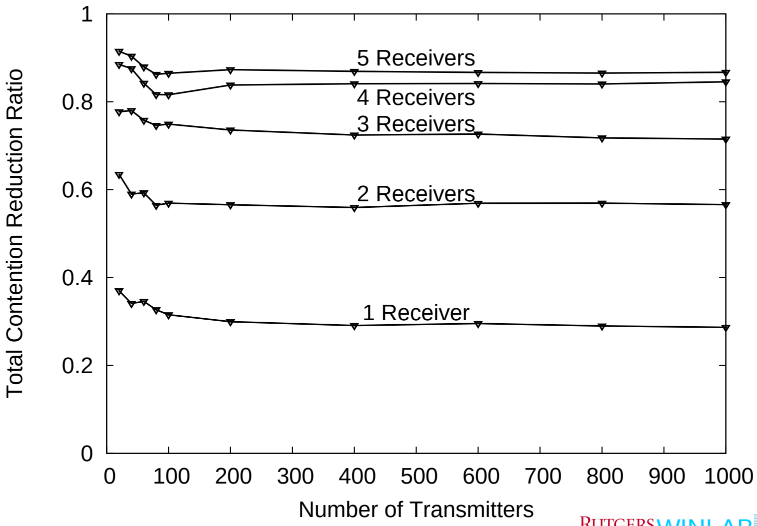
Placing Receivers to Limit Contention

- Identify "capture disks" for each transmitter pair
- Mark the centers of disks and the intersection points between disks as possible receiver locations
- Greedily choose solution points, remove already covered disks, and repeat until contention reaches the desired level

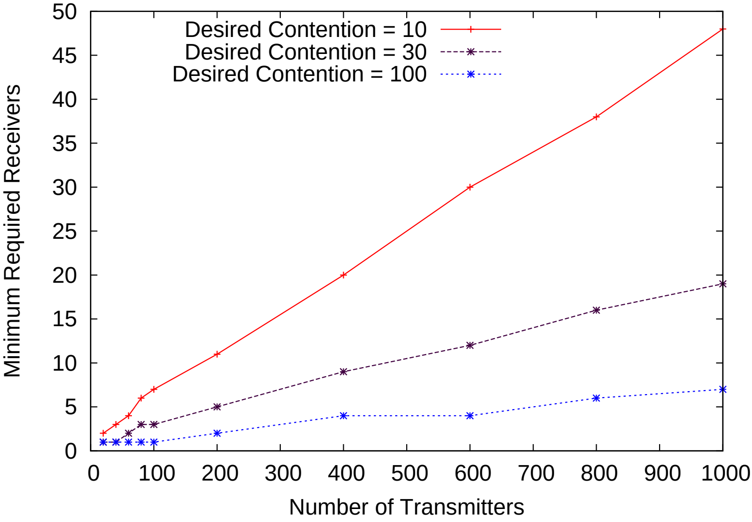




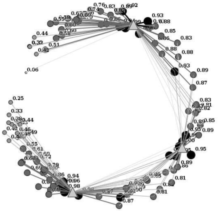
Simulated Results:
Transmitters in a uniform random distribution in a square



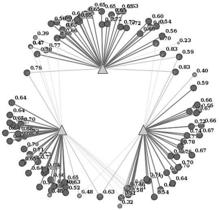
Receiver to Transmitter Growth is Slow



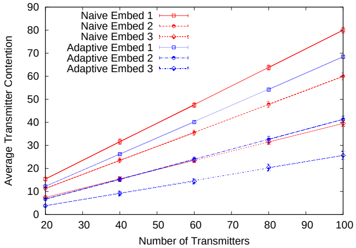
Simulating Receiver Location Gains



Our Placement



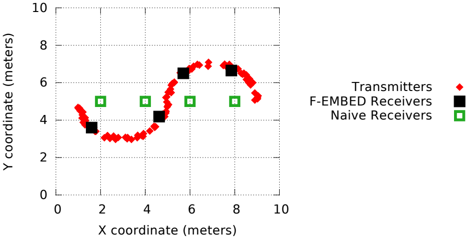
RSS Placement



Performance

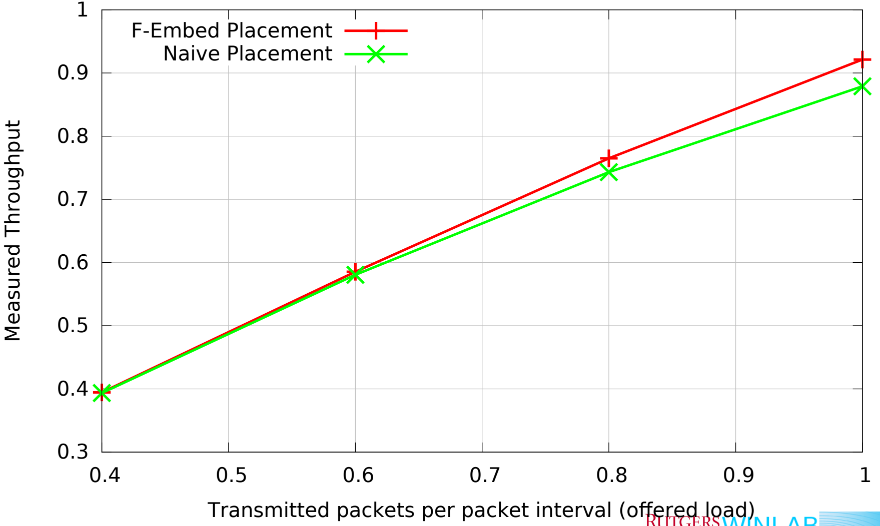
Real-World Testing

Transmitters in a uniform random distribution along a sine wave



- Packet duration $\delta = 1 millisecond$
- Packet interval $\tau = 0.5 seconds$
- 200 to 500 transmitters (offered load 0.2 to 1.0)

Outdoor Results:
Capture Aware Placement Much Better



Math Section

We will now explore the mathematical models used in the first part of the talk.

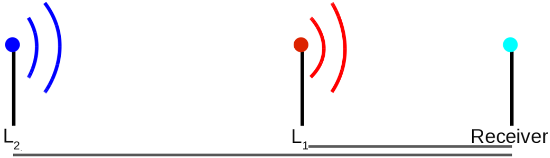
Predicting Capture Likelihood

- Capture occurs at a relative dB amount, Δ.
- Translates to a relative distance, called K (from 0 to 1)
  - Assume propagation follows $1/r^{\alpha}$

$$\frac{1}{l_1^{\alpha}} \geq \frac{10^{\Delta/10}}{l_2^{\alpha}}$$

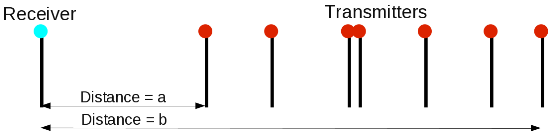
$$l_1 \leq l_2 10^{-\Delta/10\alpha}$$

$$l_1 \leq l_2 K, \text{where K} = 10^{-\Delta/10\alpha}$$



Capture Probability

- Assume transmitters are uniform randomly distributed around the receiver
- Closest transmitter's distance is a
- Furthest transmitter's distance is b
- Integrate to find the probability that the ratio of two transmitter's distances is $\leq K$



Capture Probability

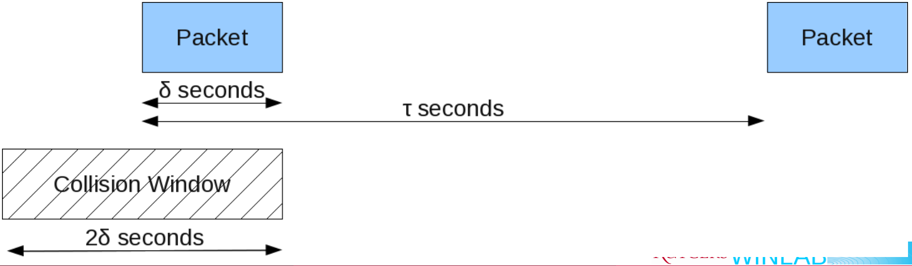
- Assume transmitters are uniform randomly distributed around the receiver
- Closest transmitter's distance is a
- Furthest transmitter's distance is b
- Integrate to find the probability that the ratio of two transmitter's distances is $\leq K$

$$\begin{aligned} & \int_{a/K}^{b} \frac{1}{b-a} \int_{a}^{Kx} \frac{1}{b-a}\, dy\, dx \\ = & \quad \frac{K}{(b-a)^2}\left(b - \frac{a}{K}\right)^2 \\ = & \quad \frac{K}{2} \text{ if a} = 0. \end{aligned}$$

The General TO Model

- Some terms:
  - δ: the packet duration
  - τ: the packet transmission interval
- TO is unslotted, a collision occurs when packets overlap

$$P_{2-way-collision} = \frac{2\delta}{\tau}$$



Multi-Way Collisions

With N transmitters, a transmitter's packet is received if no collisions occur, the probability of which is

$$P_{succ} = (1.0 - \frac{2\delta}{\tau})^{N-1}$$

With Capture and Multiple Receivers

The probability of packet loss from a collision is simply a binomial random variable with the addition of the capture probability with each collision magnitude.

$$P_{loss} = \sum_{i=1}^{N-1} \left(\frac{2\delta}{\tau}\right)^{i} \left(1 - \frac{2\delta}{\tau}\right)^{N-i-1} \binom{N-1}{i} (1 - P_{capture})$$

$P_{capture}$ with Multiple Receivers

With *perfect capture* a receiver will always correctly decode one of the packets in a collision. In this case the probability of any transmitter involved in an n-way collision having its packet captured is simply $1/n$. Given n transmitters and r receivers the probability of a particular transmitter not having its packet captured is

$$1 - P_{perfect-capture}(n, r) = (1 - 1/n)^r$$

Non-Ideal Capture

For simplicity we will assume that the probability of capture at different receivers is independent. We will use the K threshold probability from before. The probability of the strongest signal being captured is simply K^{n-1} (since it is captured over $n-1$ signals). When we consider the possibility of capture at any of r receivers when n transmitters collide we find

$$1 - P_{capture}(n,r) = (1 - P_{strongest} P_{strongest\ captures})^r$$
$$1 - P_{capture}(n,r) = \left(1 - \frac{K^{n-1}}{n}\right)^r$$

Summary (for anyone who just woke up)

- Transmit Only (TO) sacrifices packet delivery guarantees for energy efficiency
- TO also delivers good throughput by exploiting the capture effect across multiple receivers
- The dissertation presents a model that covers everything from single receiver ALOHA without capture to multi-receiver TO with imperfect capture
- Models have been backed up by several experiments that confirm TO is viable