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THE STATE UNIVERSITY
OF NEW JERSEY

The Case for
Transmit Only Communication

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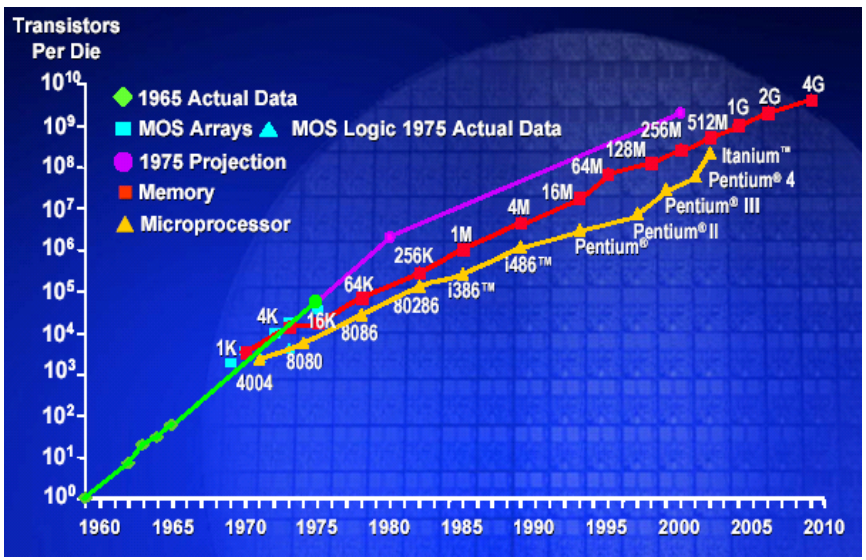
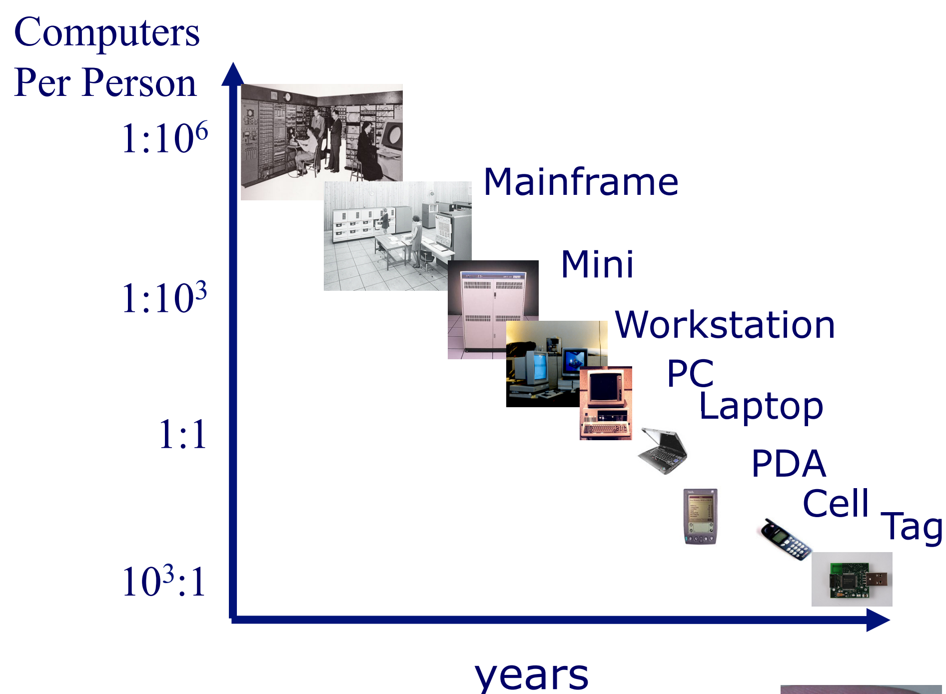
The Opportunity

Moore's Law: transistor # on cost-effective chip doubles every 18 months

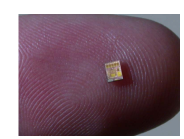


Today: 1 million transistors per $

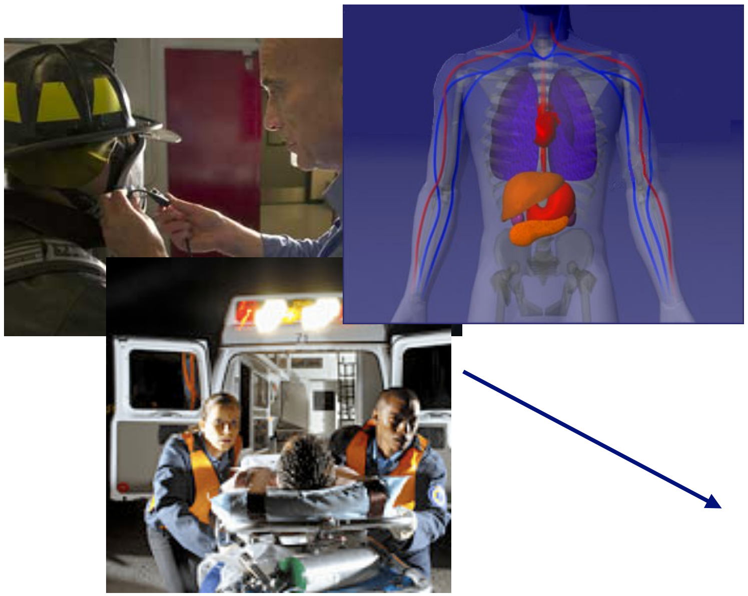
Bell's Law: a new computer class emerges every 10 years



Same fabrication technology provides CMOS radios for communication and micro-sensors

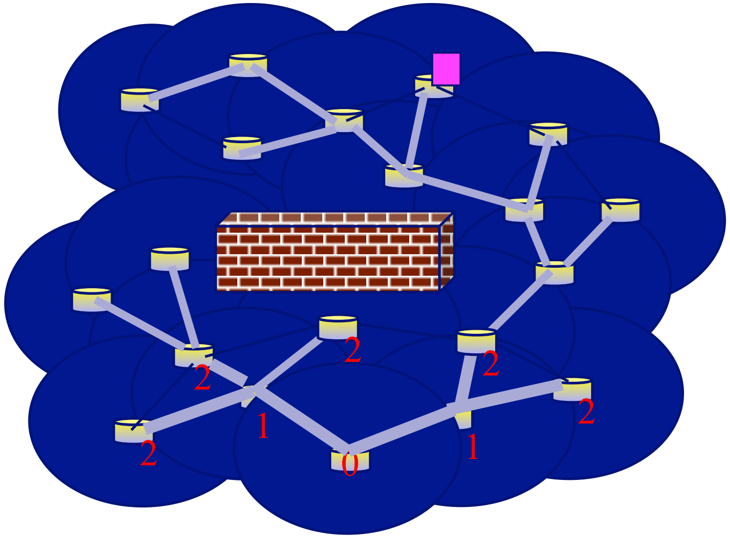


The Vision




What's happening?
@summerfrog2
Coffee is ready! --message at Fri Mar 25 10:52:46 EDT 2011
Tweets from @summerfrog2

Down the garden path of sensor networks



Programming a sensor network:

- Multi-hop
- Ad-hoc
- Aggregation and compression
- Energy conservation of whole application is paramount
- Novel operating systems, programming languages and environments

A rose by any other name

- 1999 Smart Dust
- 2000 Sensor Networks
- 2004 Internet of Things
- 2005 Ambient Intelligence
- 2009 Swarms

- ~15 years on, we still have not realized the vision.

What happened?

Problems

- **Problems people talked about:**
  - Energy conservation
  - Scaling number of sensors
  - Efficiency of code／data size in small sensors
  - Routing
- **More meaningful problems:**
  - Too expensive for application domains
  - Difficult to develop applications
  - Can't re-use infrastructure
  - Not general purpose

When less is better

- 1 level of the system performs 1 goal
  - Move other functionality to other layers
  - Overall system improvement!
- Architecture: RISC vs. CISC
  - Focus on instruction throughput, move abstraction to language/ compiler
- Networks: IP vs. ISDN/ATM
  - Focus on packet switching, move circuits and sessions to endpoints
- Operating systems: Unix vs. Multics
  - Focus on process execution and I/O, move object persistence to the database

Transmit Only Approach

- **Key insight: sensed data is in a class where small losses can be tolerated. Probabilistic reception is OK.**
  - **Similar to audio, video, and multi-player games, not documents.**
- **Sensors only sense and transmit with specified periods**
  - **Sensors are at most 1 hop**
  - **Add small amount of randomization to prevent collision periodicity.**
- **A small set of receivers cooperate to reconstruct sensed data**
  - **Connected by a powerful back-haul network**
  - **Back-haul bandwidth > sensor bandwidth**

TO - less is better

- **Everything that doesn't transmit an application bit is overhead**
- **Removed:**
  - **Sensing the channel before transmission (for CSMA protocols)**
  - **Acknowledgements (for RTS/CTS protocols)**
  - **Precise clocks and synchronization (for TDMA protocols)**
  - **Signal feedback (MIMO physical layers)**

Transmit Only as less is better

- **Focus on getting the sensed data:**
  - Everything else is overhead
- **Saves energy on the sensor**
  - Receiving has similar energy costs per bit-time as transmit
- **Simplify the sensors**
  - Fewer components
  - Cheaper components
  - Smaller sensors
- **Simplify the programming model**
  - Aggregation layer's interface to the sensors becomes much simpler.

Challenges

- Semantic: Some data loss OK?
- Wireless Channel Utilization
  - Are we really limited to 18% efficiency?
- Receiver Network:
  - Complexity?
  - Energy use?
  - Number and coverage?
  - Connectivity?
- Manageability
  - Change parameters on the sensor?
- Security
  - How to perform lightweight unidirectional security?

Outline

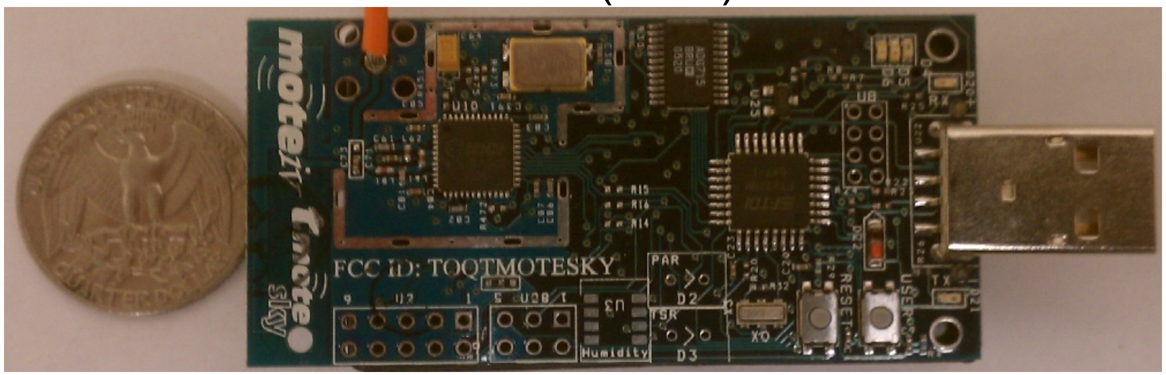
- **Improvements from sensor simplification**
- **Recovering channel efficiency exploiting the capture effect**
- **Simplifying the programming model**
- **Example applications**

Sensor simplicity

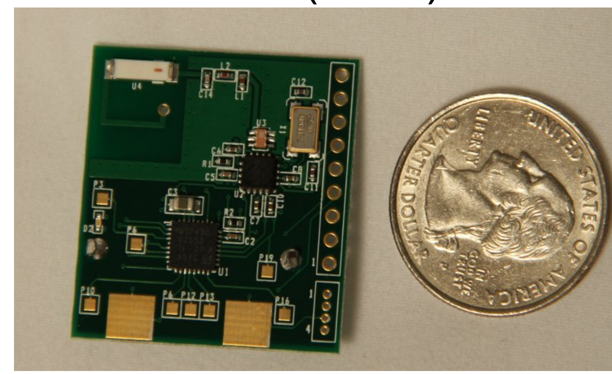
- Sensor node cost is a limitation for many applications
  - Applications enabled at sensor cost of $100, $10, $1, 10¢, 1¢ ?
- Cost assumptions based on scaling Moore's law omit real constraints
  - 15 years show these constraints are fundamental
- Cost is driven by the number and type of components, not Moore's law!
- TO reduces costs by several factors
  - enough to expand the application space ($80->$10)
- Marginal costs will only go down if there is a true single-chip sensor
  - But high fixed costs remain a barrier for a true single chip solution!

Two wireless sensor boards

Classic
TelosB (2004)



Transmit-Only
TO-PIP(2013)

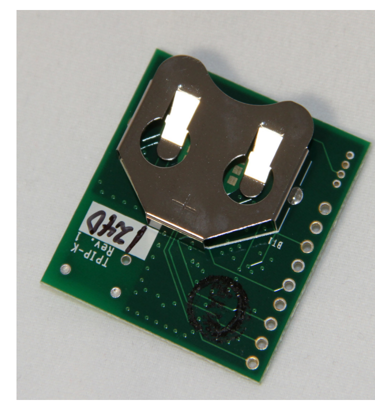


Antenna

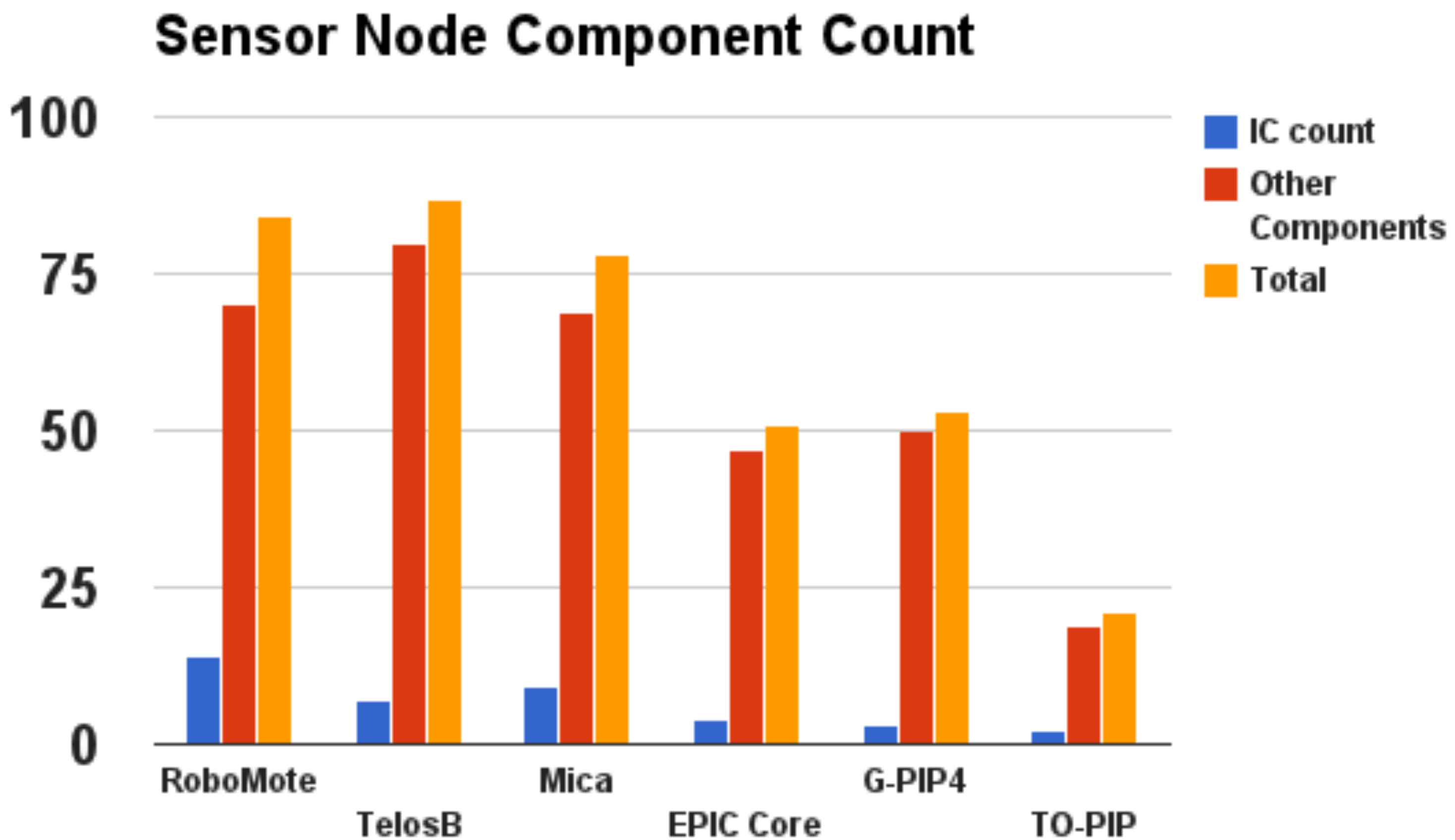
Radio

Micro controller

Battery



Component counts



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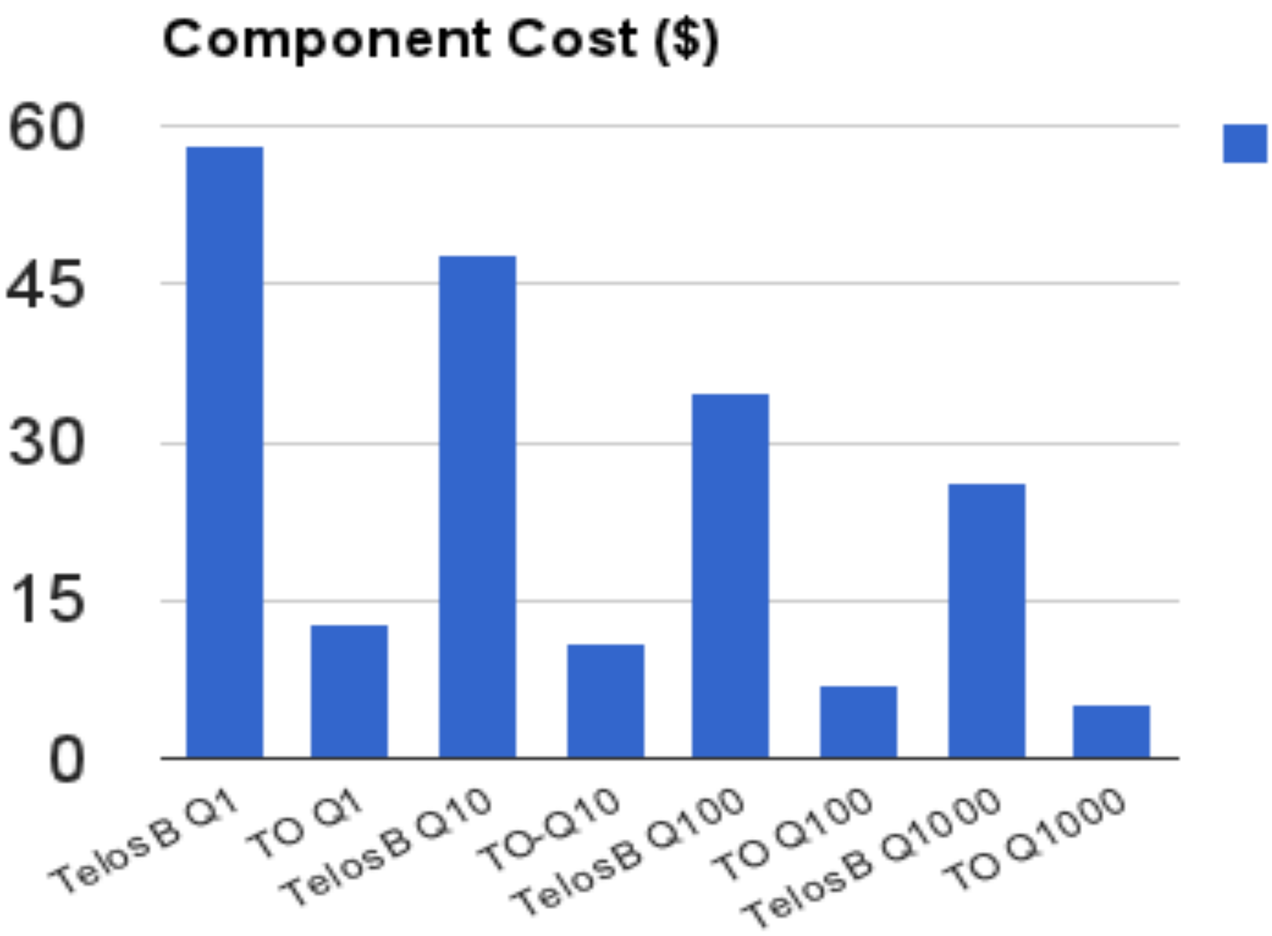
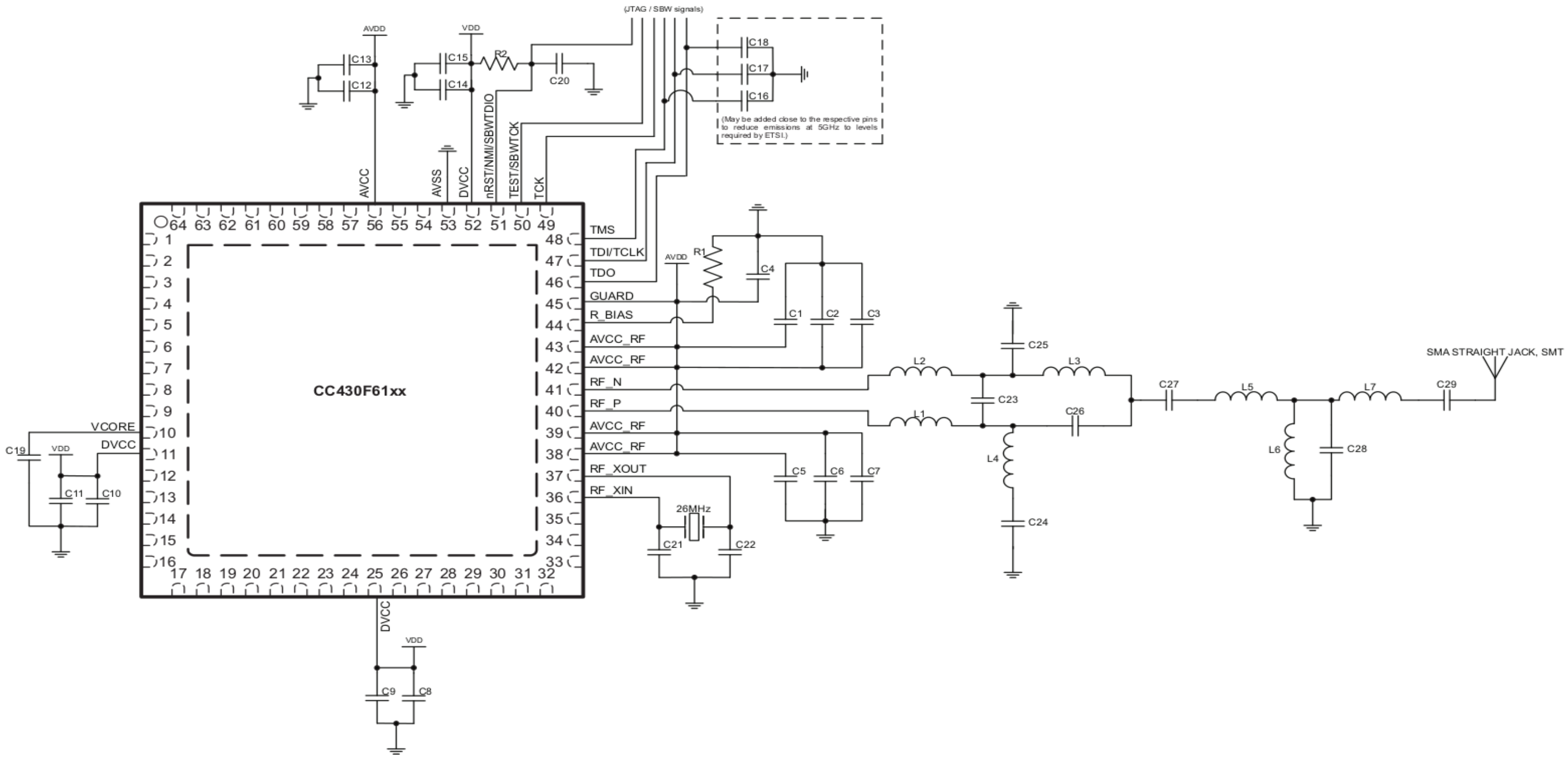
Component Cost vs. Volume



Problems with existing Systems on a Chip

- **CPU+Radio: 1 chip, but 39 components**
- **Analog components do not scale with Moore's Law!**



Comparison transmitting @ 1/second

- **Lifetime:**
  - TO-PIP: 2.2 years
  - TelosB: 3-4 months
- **Size:**
  - TO-PIP: 1.1 x 1.2 x 0.21 in
  - TelosB: 2.25 x 1.2 x 0.69 in
- **Component cost @ quantity 1000**
  - TO-PIP: $5.09
  - TelosB: $26.23

- **What about channel efficiency and the receiver network?**

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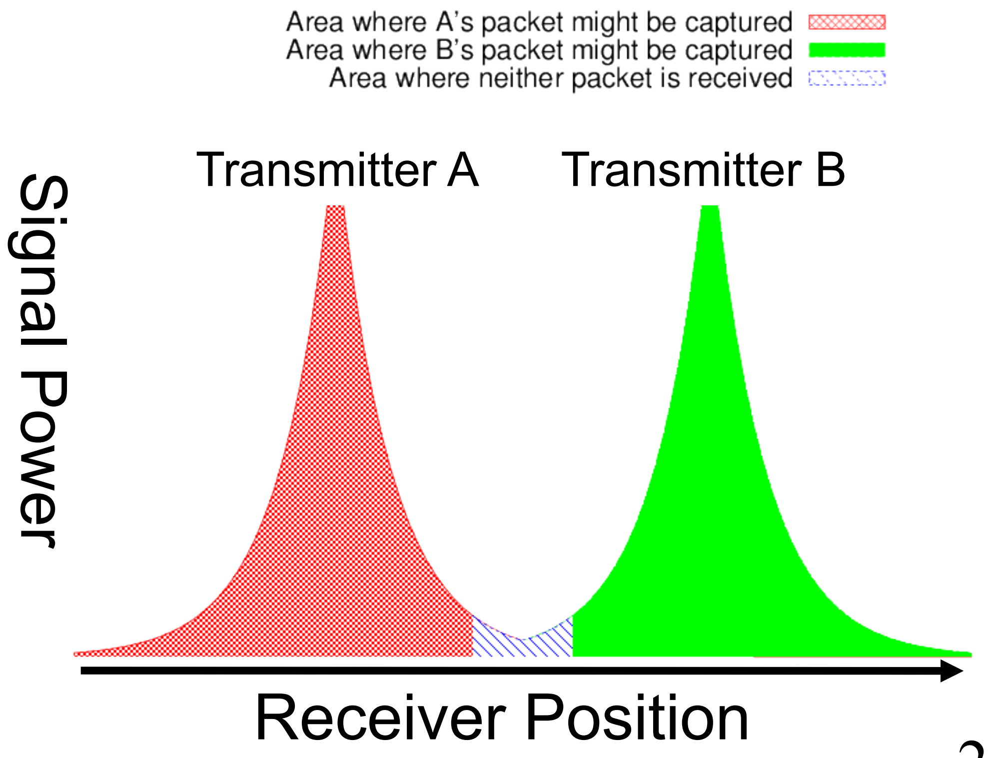
Improving Channel Capacity

- **Unslotted aloha: simply transmit packet when ready**
  - **Similar to TO on the transmit side**
- **Traditional analysis shows unslotted aloha efficiency is 18%**
  - **Probability of a collision grows with number of transmitters**
- **Do we need to sacrifice this much efficiency?**
  - **Carrier Sense Multiple Access (CSMA) efficiency:**
  - **Time-Division Multiple Access (TDMA) efficiency: 95+ %**

The Capture Effect

- **Radios utilize EM waves**
- **A stronger wave overpowers a weaker one**
- **Simultaneous reception of packets with different signal powers means we can recover the symbols in the stronger wave**

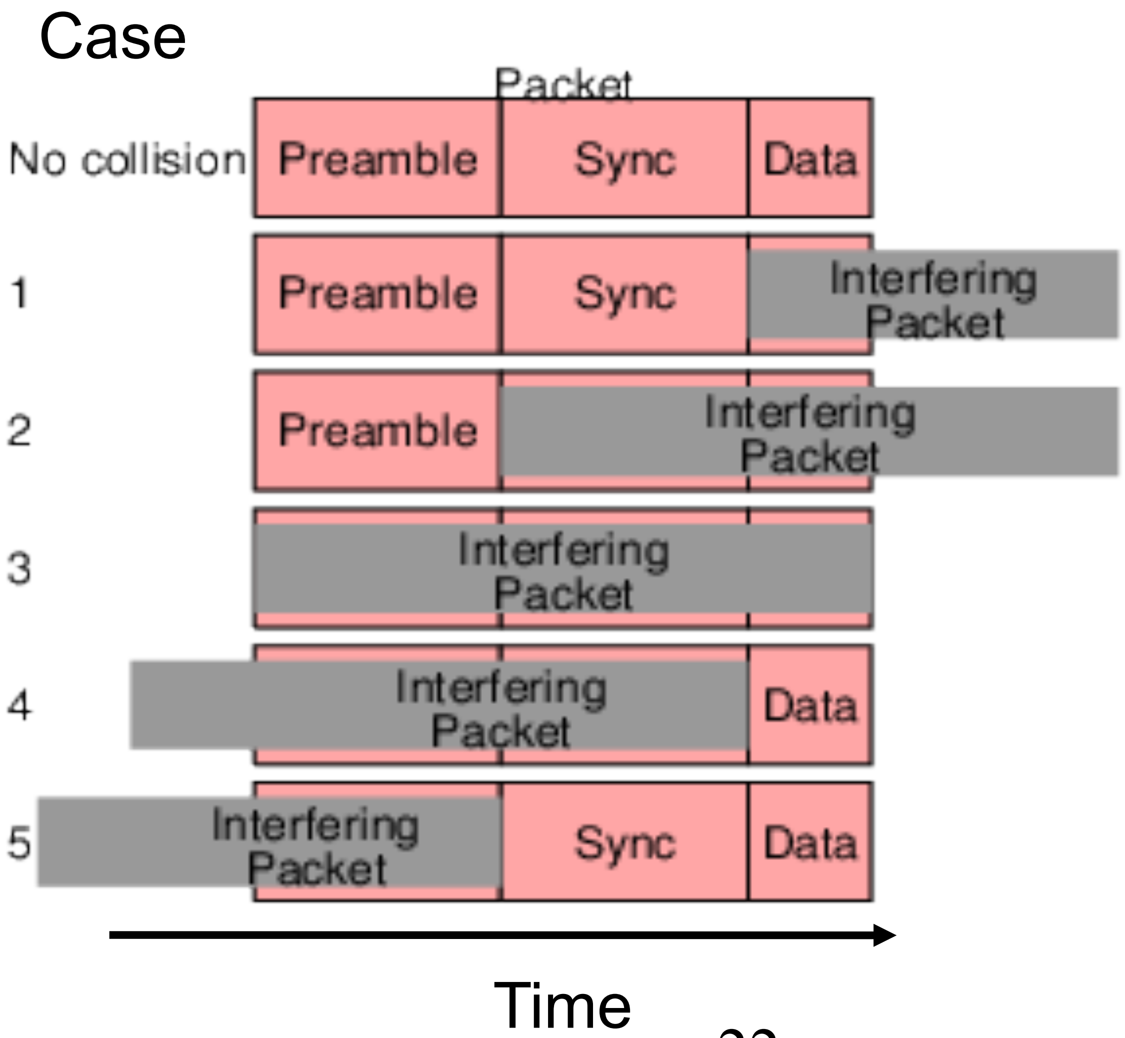


Two methods to leverage the capture effect

- **Message in Messaging**
  - **Sense when the stronger signal arrives, and start decoding then**
- **Receiver Placement**
  - **Put receivers in physical locations where they will receive stronger signals.**

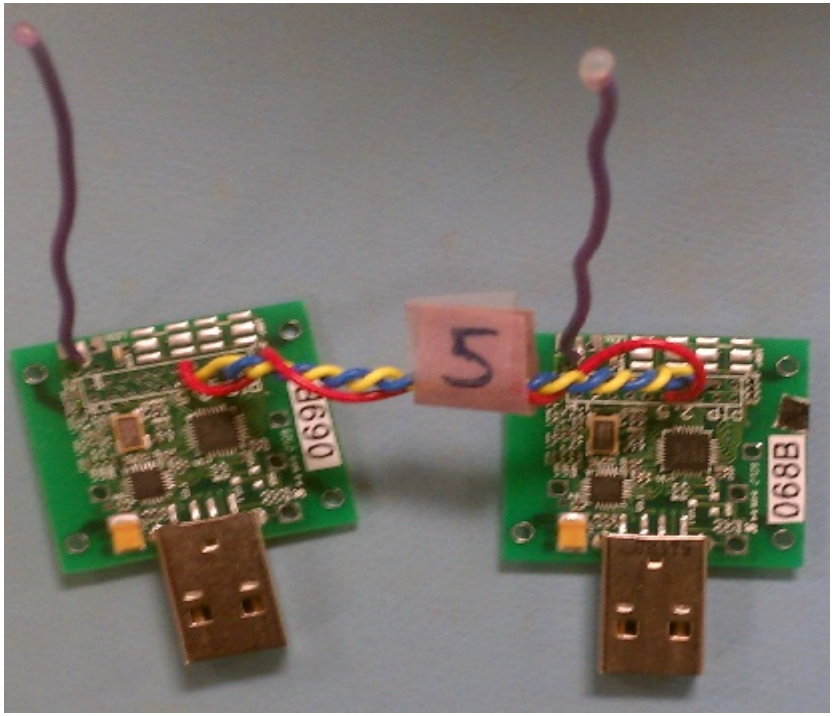
Message in Messaging

stronger packet (pink)
interfering one (grey)



Building a MiM receiver from 2 single receivers

- **If I see a preamble, tell other radio to start**
  - **If the second packet is stronger, the other will receive it.**
- **Tell other radio when I recognized a packet correctly**
  - **Allows aborts of a bad packet, restart to catch a new one.**



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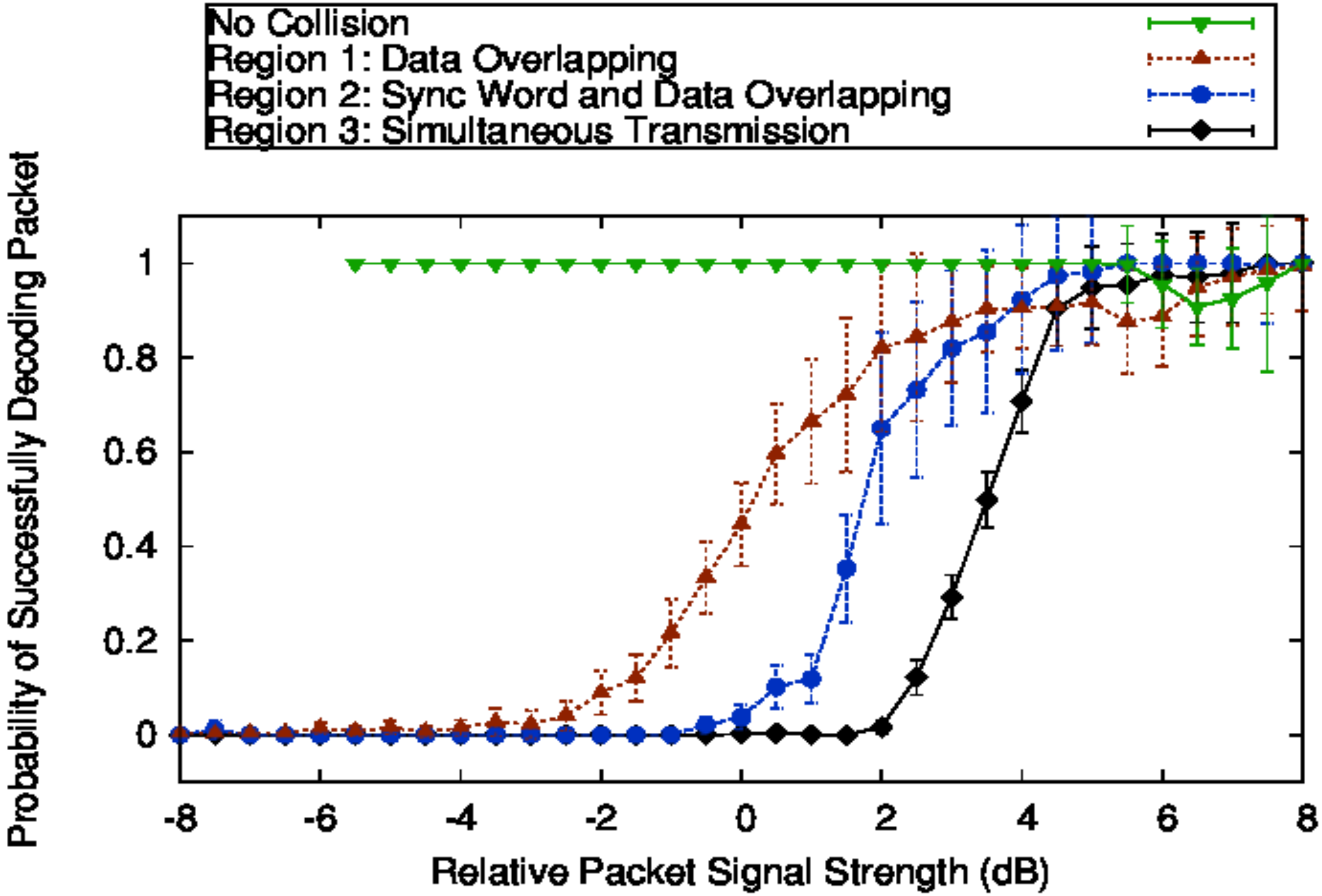
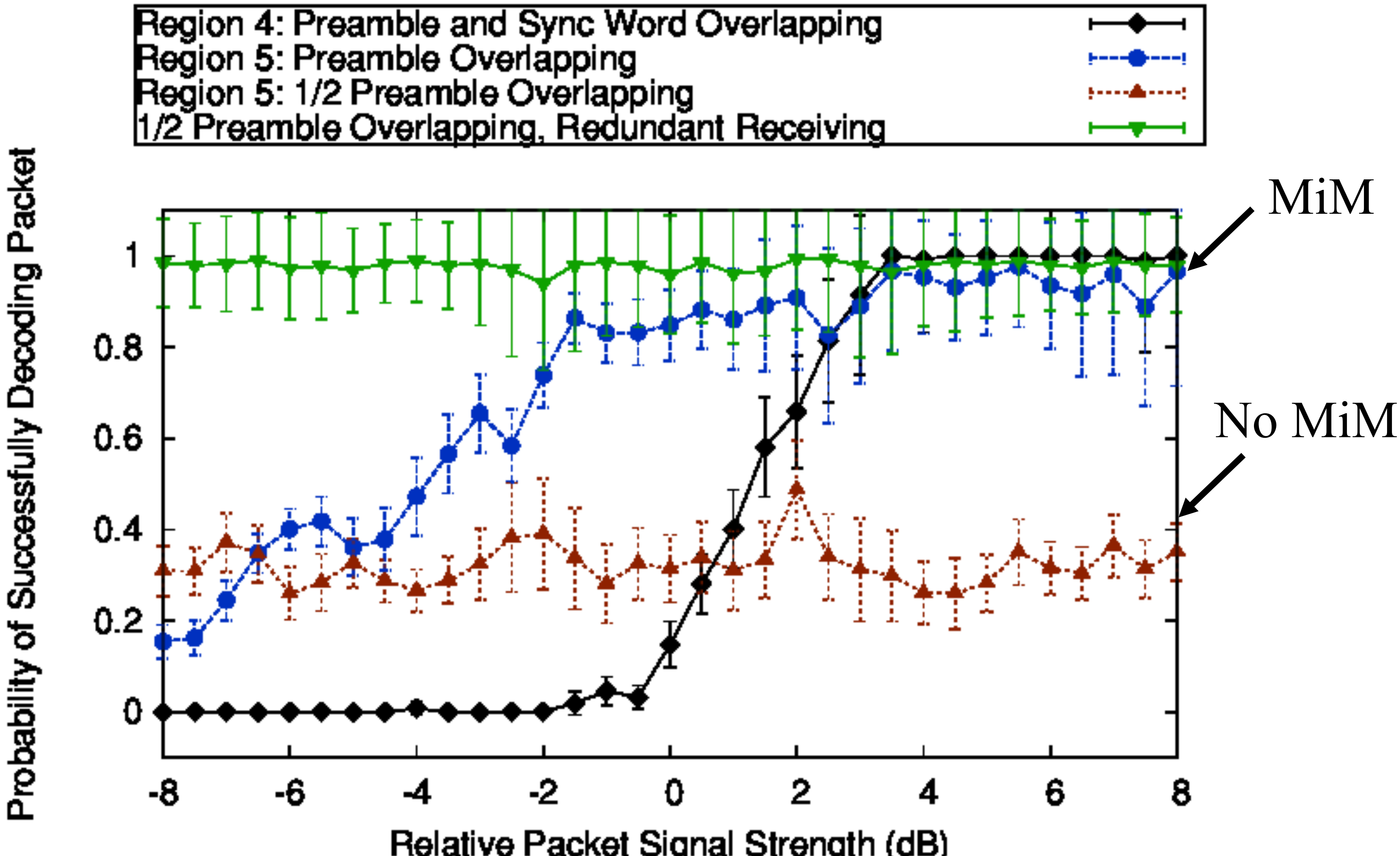
Impact of collisions – stronger packet first

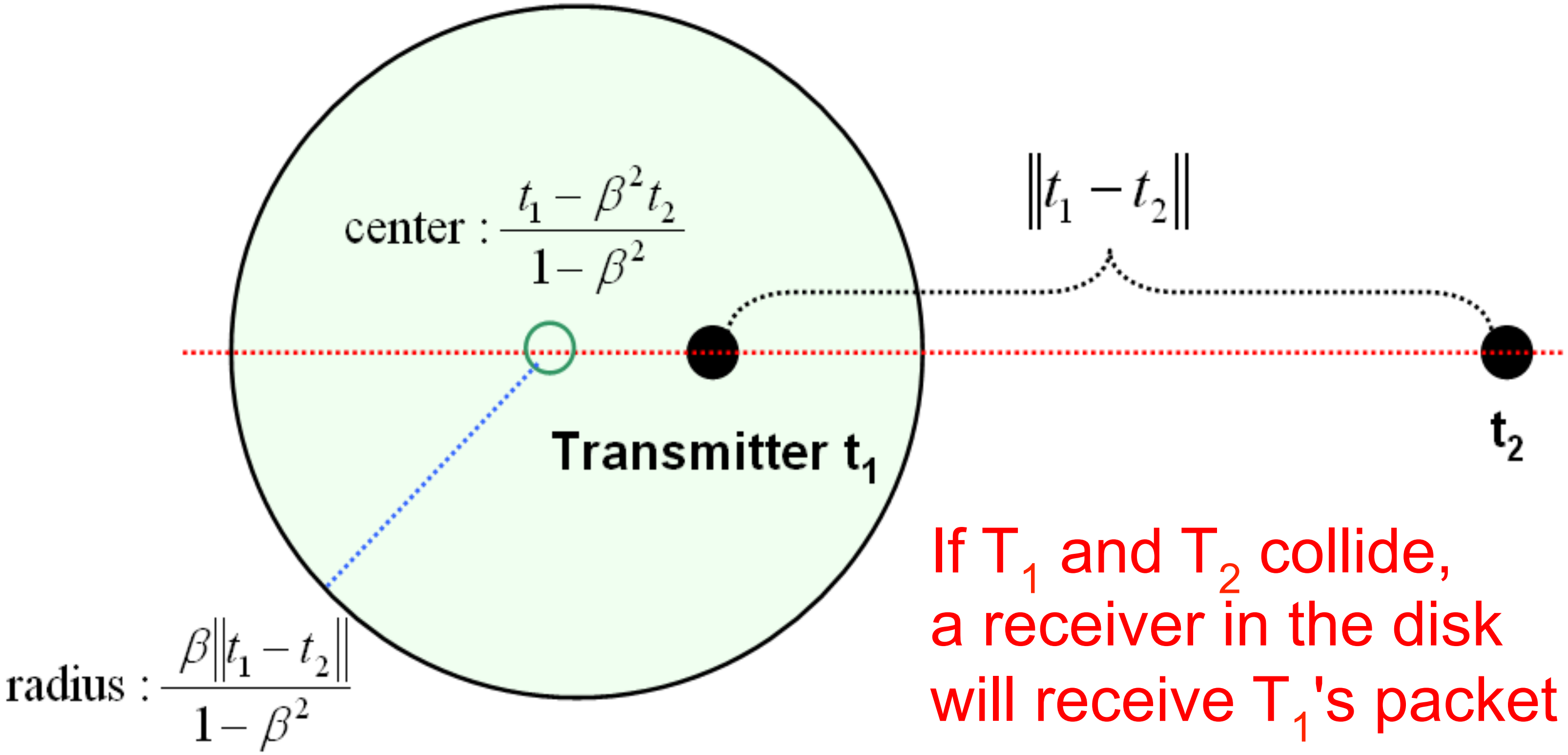


Impact of Collisions – weaker first (with MiM)



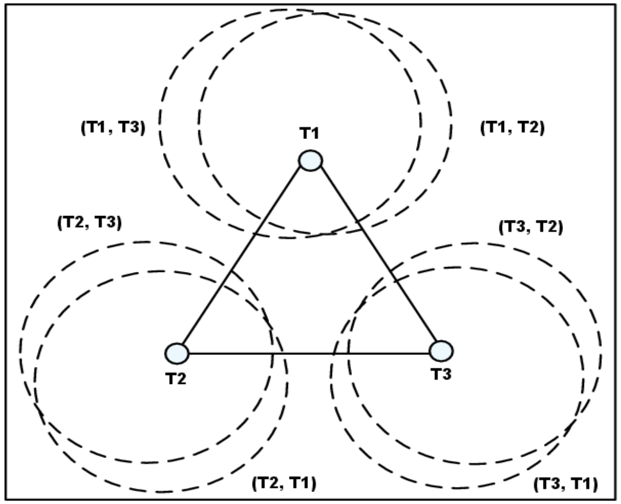
Receiver Placement

- Given the locations of the transmitters, choose the physical locations that minimize contention
- A Capture Disk:

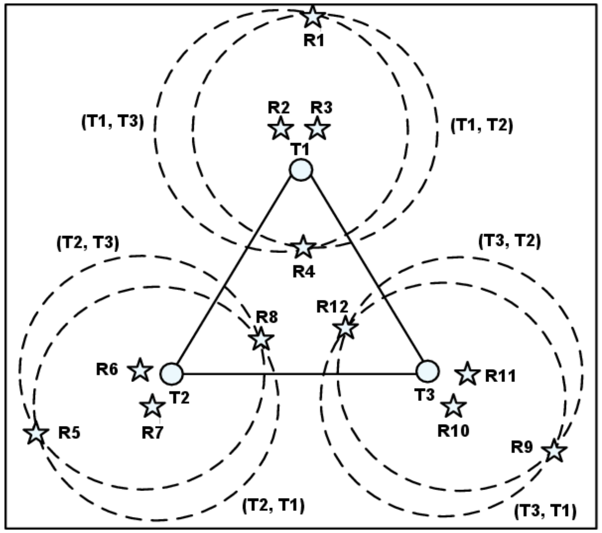


F-Embed algorithm

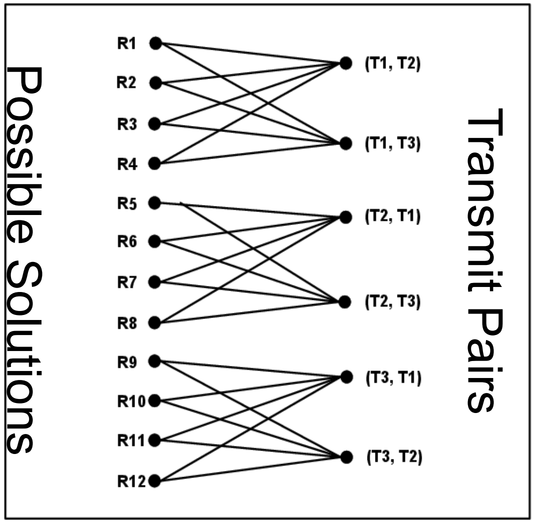
1. Pairwise Capture Disks



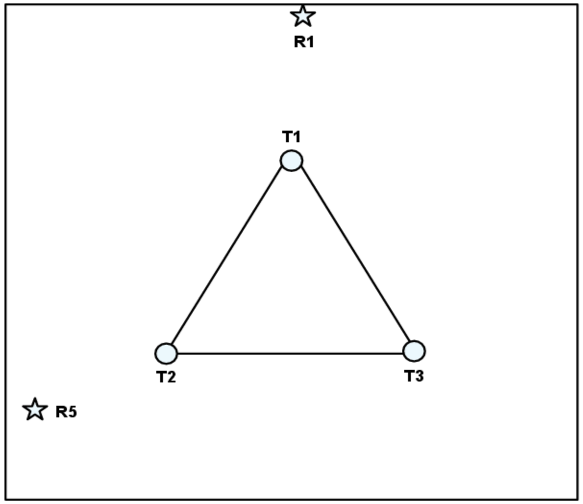
2. Possible Solution Points



3. Bipartite Graph



4. Top-N locations

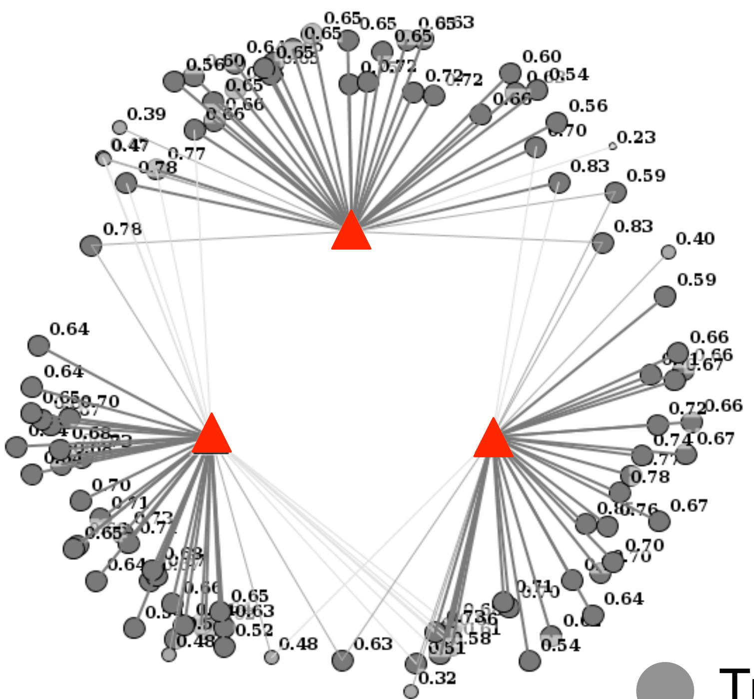


Exact solutions and approximations

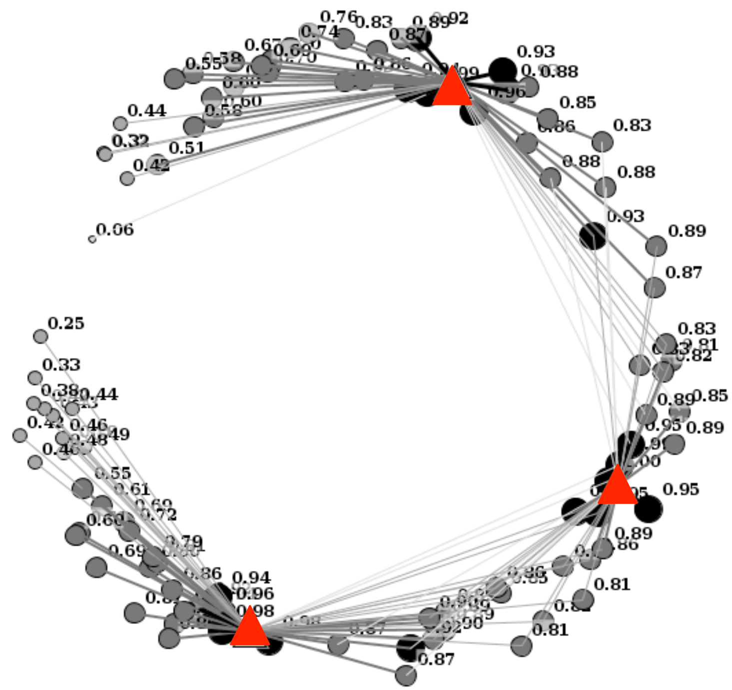
- Exact solution is NP-hard
- F-Embed is 2-approximation (bounded 50% of exact)
- F-Embed is $O(R^*T^6)$ in number of Receivers/Transmitters
  - Scales with number of capture disks
  - Too slow for more than few 100's of transmitters
- Use a gridded approximation:
  - Divided plane into a mesh of test points (candidate solutions)
  - Scales with $C^*O(n^2)$

Intuition: place receivers in the densest region

Naive Placement



F-Embed Placement

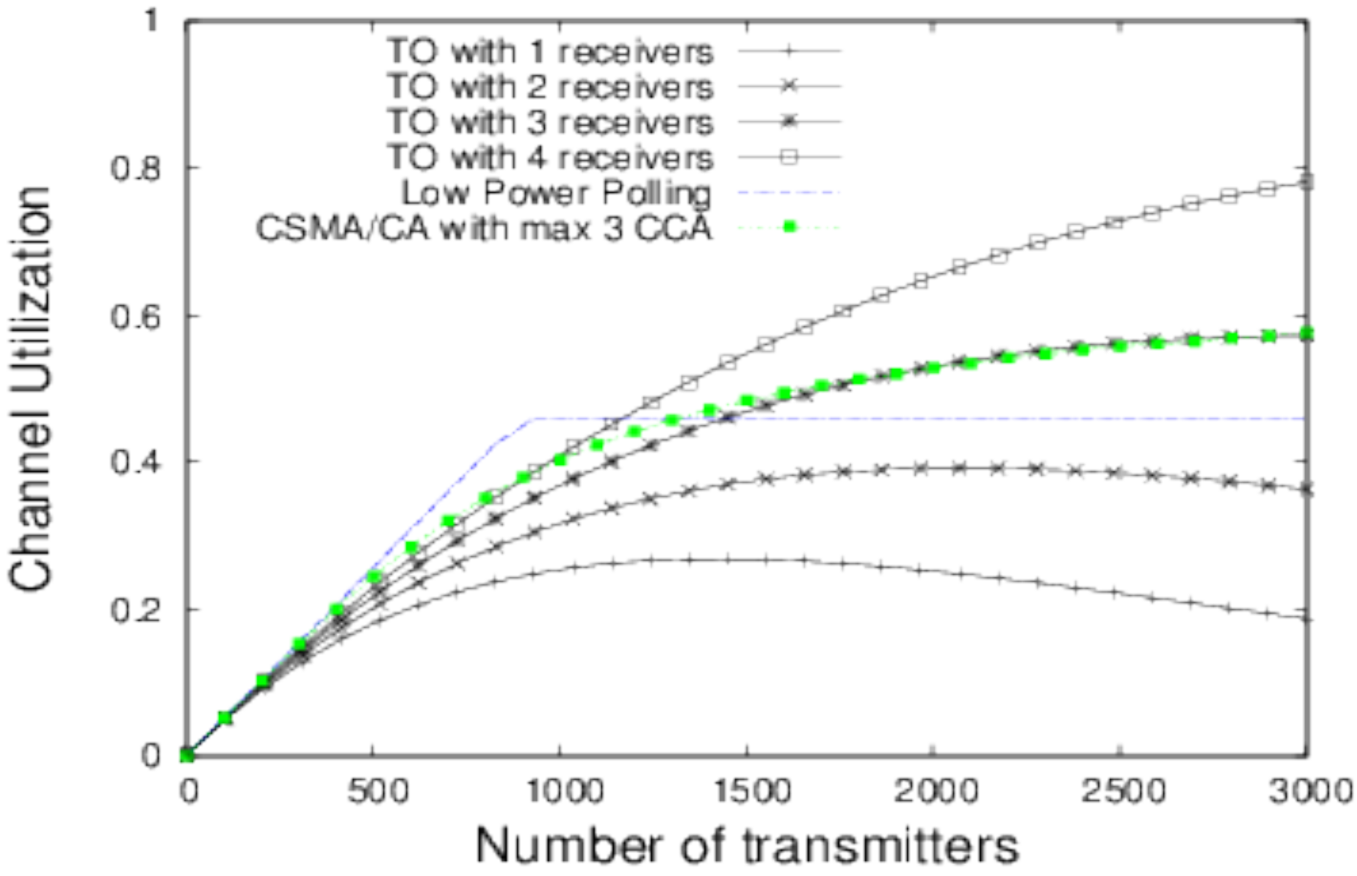


Transmitter

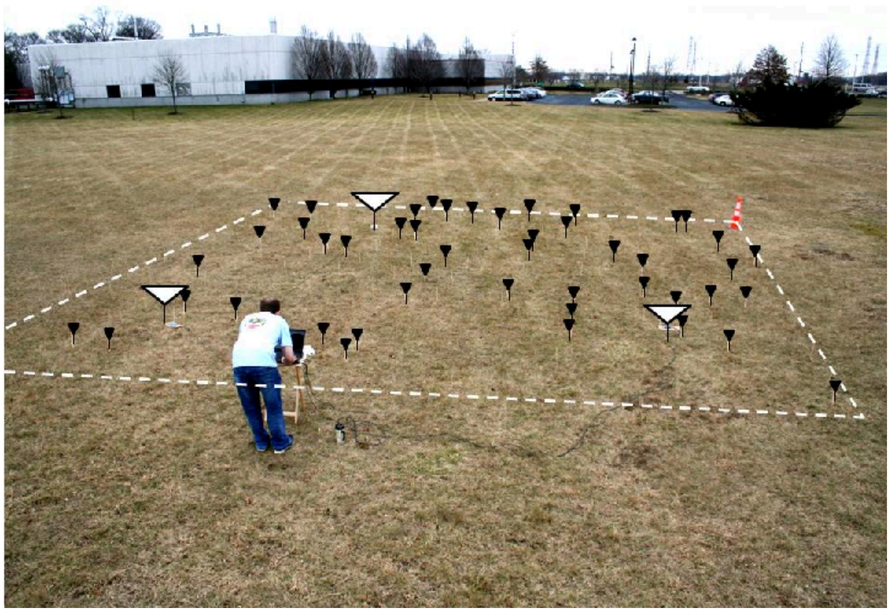
Receiver

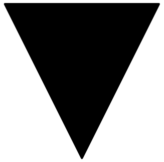
Capture Probability

Channel Utilization at Scale

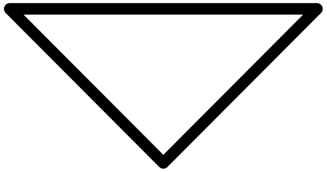


Experiment with 500 Transmitters



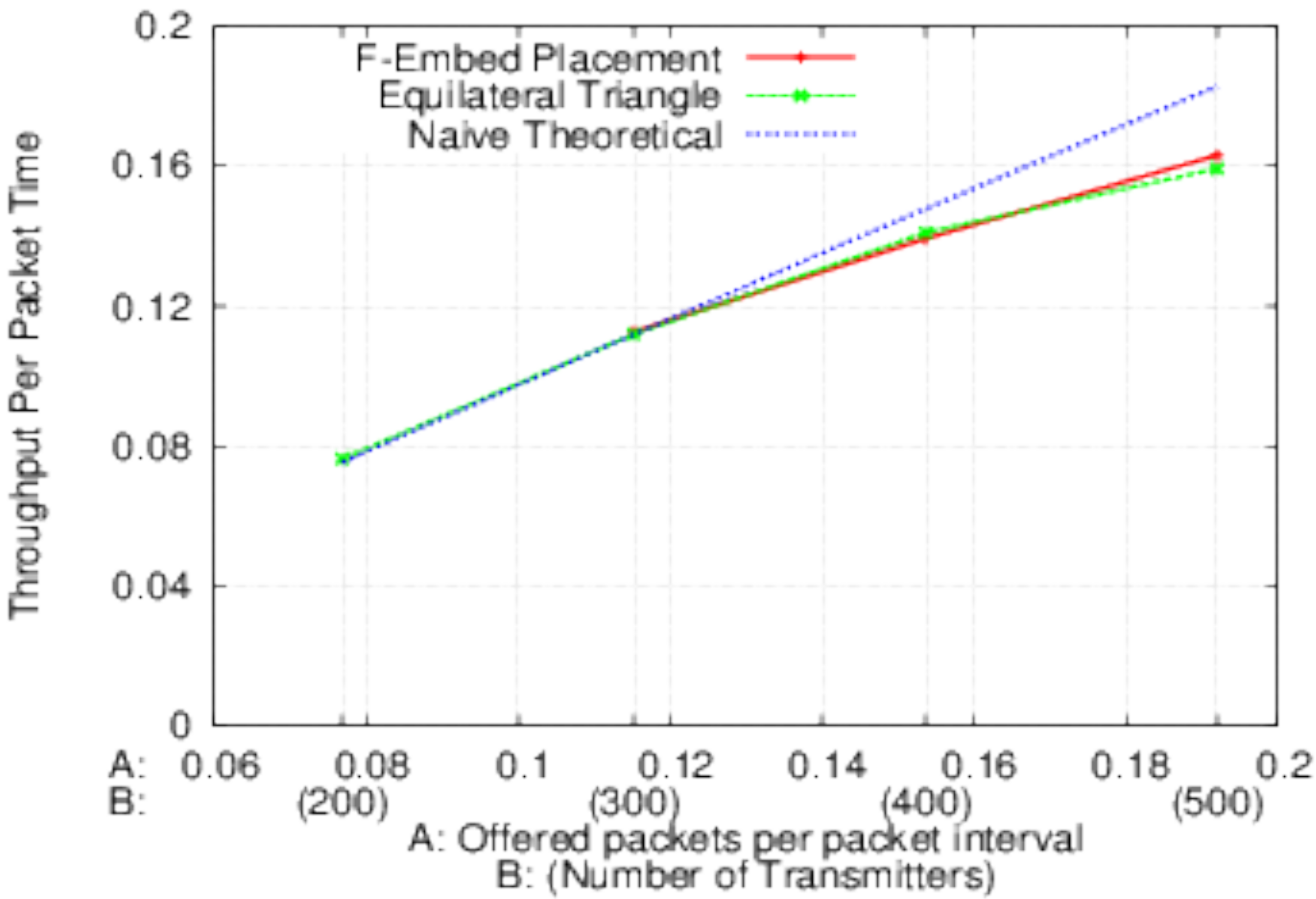


Bundle of 10 transmitters

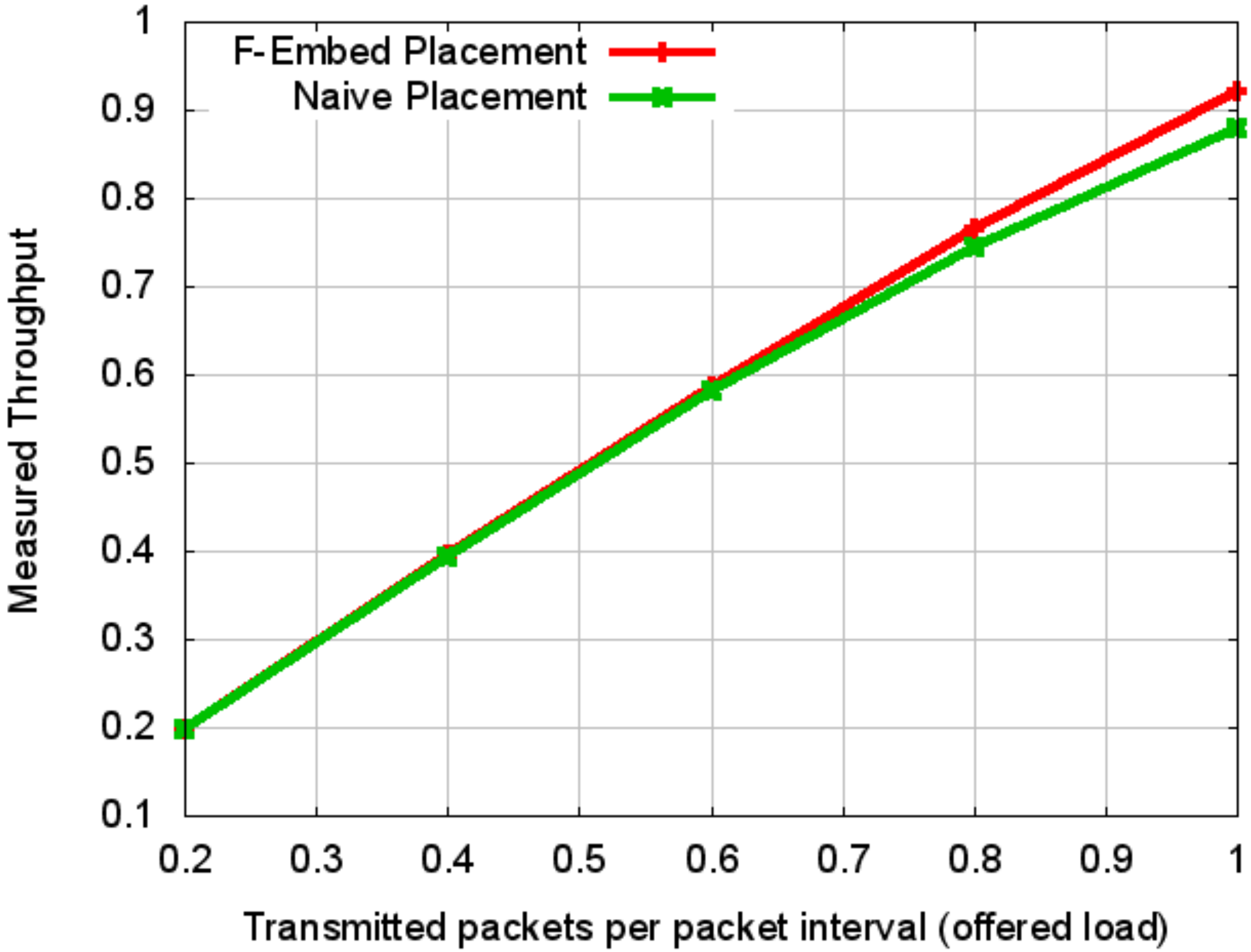


MiM Receiver

Theoretic predictions vs. experiment

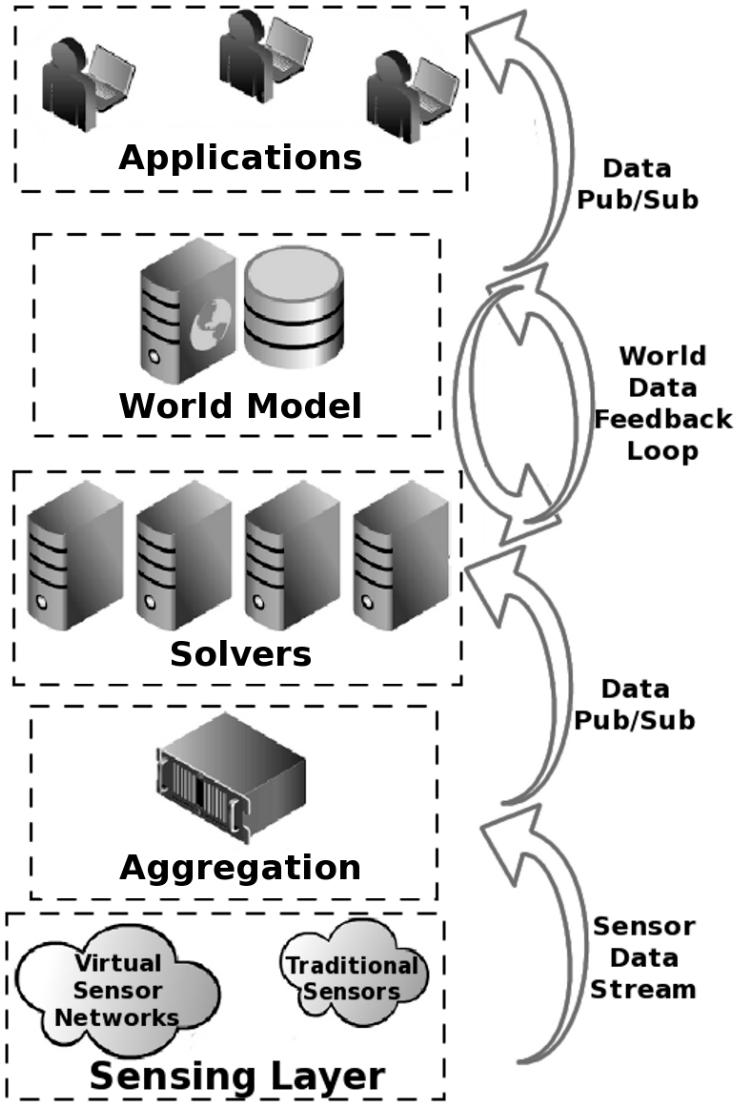


Sine-Wave Deployment



Connecting TO networks via the Owl Platform

- **Sensors connect to an intermediate layer that hides details**
- **Solvers build higher-level representations from low-level ones**
- **A uniform model of the world allows sharing**
- **Applications run in standard environments in the cloud**



Example Applications

- **Leak detection**
  - Sense standing water, email/SMS if water detected
- **Office space assignment**
  - Sense door open/closes, assign new students to lightly used offices
- **Fresh Coffee**
  - Sense temperature of coffee pot, email/SMS if a temp spike
- **Chair Stolen**
  - Email/SMS if a chair is moved away from the owner's cubicle
- **Loaner Bicycle Inventory**
  - Count # of bicycles in a room to see if one is available.

Conclusions

- **Channel Utilization**
  - **Close to 100%**
- **Receiver Network:**
  - **1%-5% of the number of transmitters for realistic loads**
  - **Simple**
  - **Needs continuous power**
  - **3-4x sensor input bandwidth**
- **Manageability**
  - **Change parameters on the sensor?**
- **Security**
  - **How to perform lightweight unidirectional security?**

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Future Directions

- **Kickstarter.com project to build base station, sensors coming soon!**
- **Adding a control channel:**
  - **Transmit mostly**
- **Constrained receiver placement**
  - **What if only specific areas (near power plugs)**
- **Mobile Transmitters and Receivers**
- **Lightweight unidirectional encryption**
  - **How to insure 3rd parties can't eavesdrop?**
- **Long data sets**
  - **For example, fountain codes for video streams**

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Thank you!

Naive analytic model

Similar to simple aloha protocol models

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

δ=packet time (length)
τ=interval time
c=# of contenders

Modeling the Capture Effect

$$P_{succ} = 1.0 - \left(1.0 - \frac{2\delta}{\tau}(1 - 0.5)^M\right)^N$$

δ=packet time (length)
τ=interval time
0.5=chance of capture at a receiver
M=# of receivers
N=# of transmitters