Design of a VLSI Based, Energy Aware Sensor Node

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Protocol Objectives

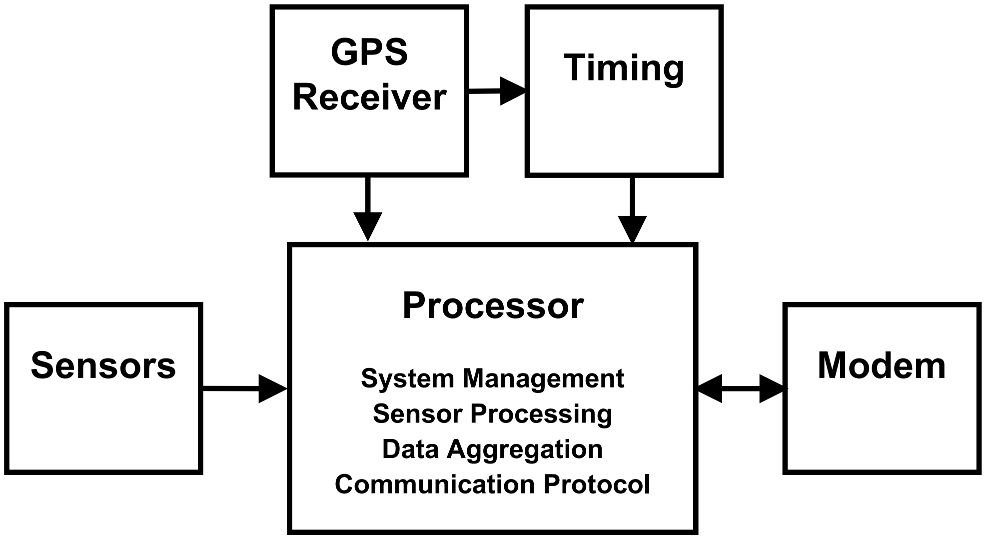
- Support a very large number (1000-10,000) of nodes.
- Perform an important mission.
- Is flexible enough to accommodate different requirements.
- Conserves energy to prolong network life.
- Is easily and inexpensively implemented in VLSI hardware.

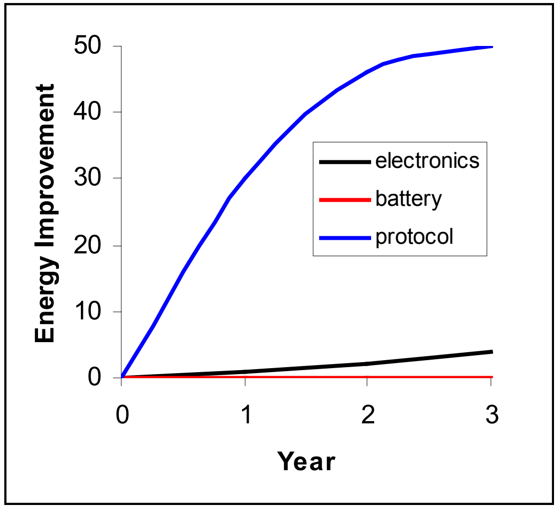
Enable the deployment of effective sensor networks.

State of the Art

Current State	New Technology
can support a very large number (1000-10,000) of nodes	
20-100 nodes	eliminate global effects
	eliminate duplicate data
	data ooze
support a militarily significant mission	
single purpose sensor systems	cooperative sensors
single point sensing	area surveillance (airports)
low sample rate to get long life	barrier surveillance (pipelines, borders)
surveyed emplacement	automated deployment (TMD dispersion)
flexible to accommodate different requirements	
general purpose or single use	parameterized protocol
minor modifications of commercial protocols (802.11)	synchronous/asynchronous switching
	variable coding
conserves energy to prolong network life	
sleep modes	duty cycle management
low energy=low capability	high capability used sparingly
high capability=high energy	
is easily and inexpensively implemented in VLSI hardware	
system not integrated	system on a chip
integrated modules (modem, GPS)	

Our Approach: Careful Component Management





- High capability components used sparingly
  - reduce total energy consumption by managing the components
  - only power components when required
  - reduce duty cycle as low as possible
  - communication protocol is key, at all levels

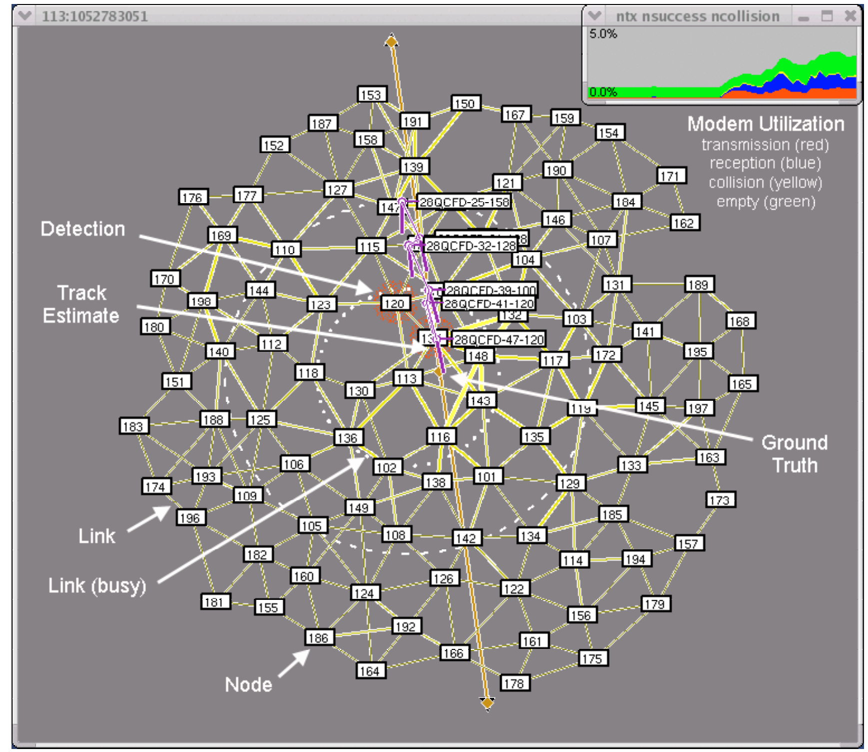
Manage and minimize component use.

Reference mission: area surveillance system

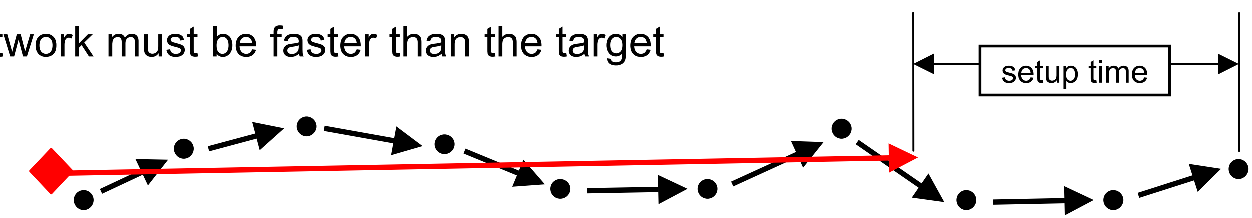
Detect and track targets in a secure area

Mission Design Guidelines

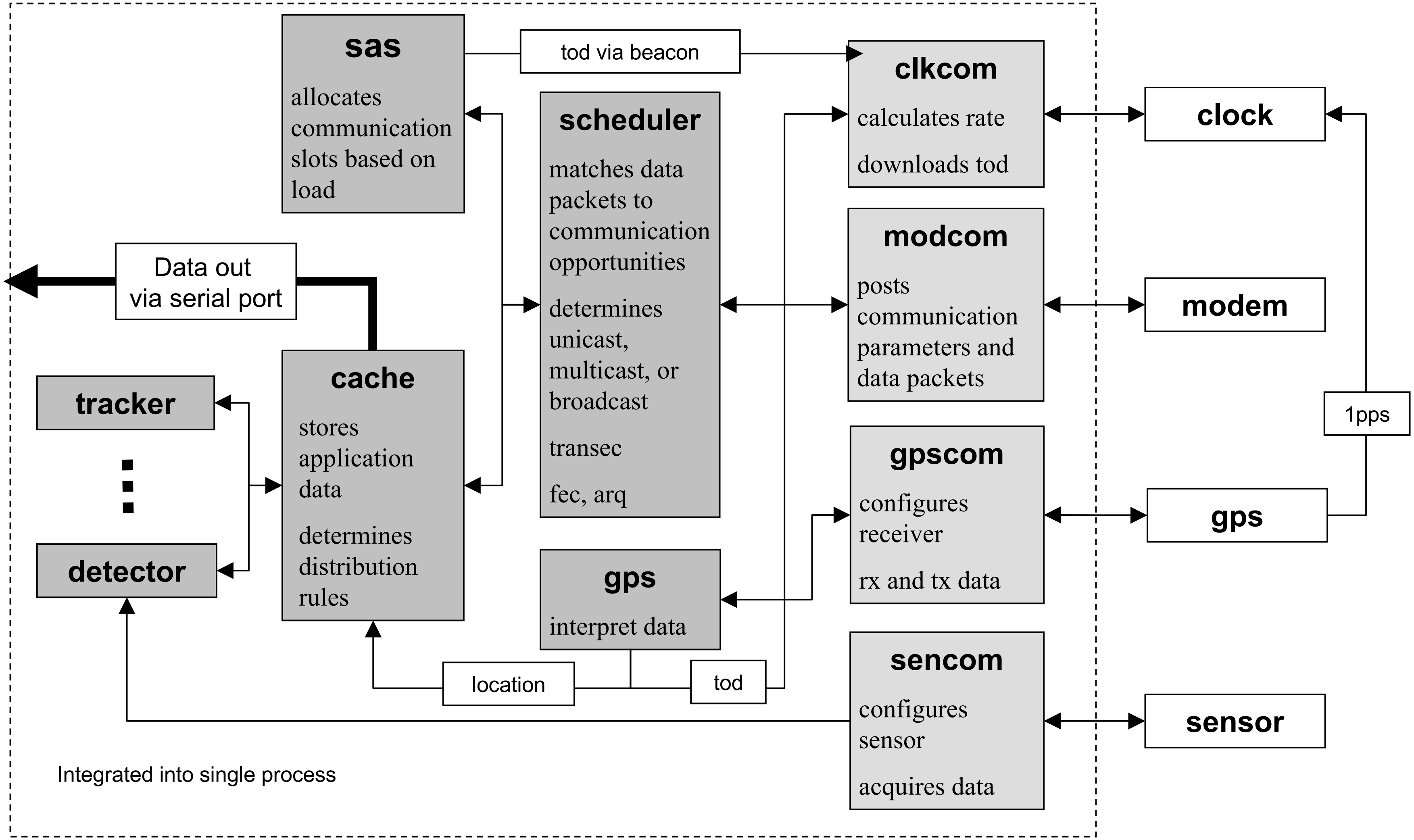
Sensor calibration time	1-10 s
Target speed	5 m/s
Node spacing	10-30 m
Node location accuracy	1-5 m
Critical data latency	1 s/hop or less
Critical data bandwidth	100-200 Byte/s/node
Overhead data latency	30 s
Overhead data bandwidth	0 Byte/s



network must be faster than the target



Major Modules and Data Flow



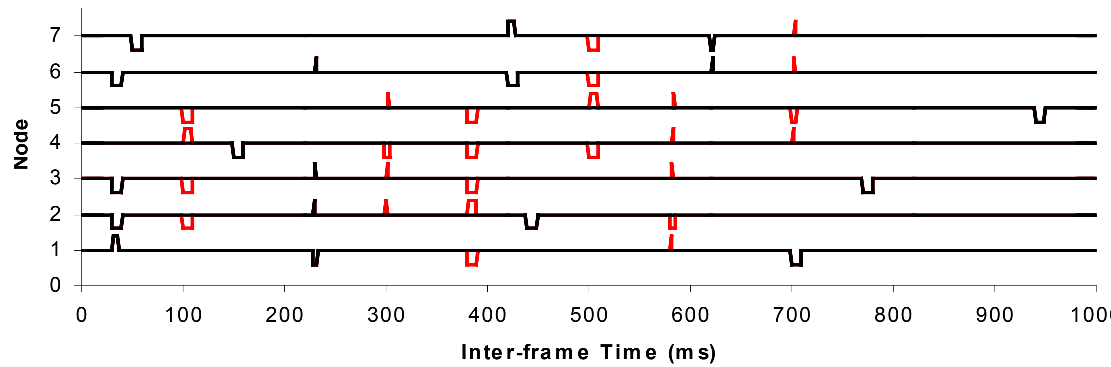
Common software

Interface software real or simulated

Firmware and hardware or simulated environment

SAS Medium Access Protocol

- Blended medium access protocol
  - Asynchronous: contention, low cost, for low load and low importance
  - Synchronous: reserved channel, high cost, for high load or high importance
  - Configuration options and real time situation determine blend
- Communication space divided into slots
  - time x channel (TDMA with DFS)
  - distributed allocation of slots
    - by transmitter or receiver
    - unicast, multicast, or broadcast
  - schedule shared with neighbors, and neighbors of neighbors



Blended protocol optimizes performance and power consumption.

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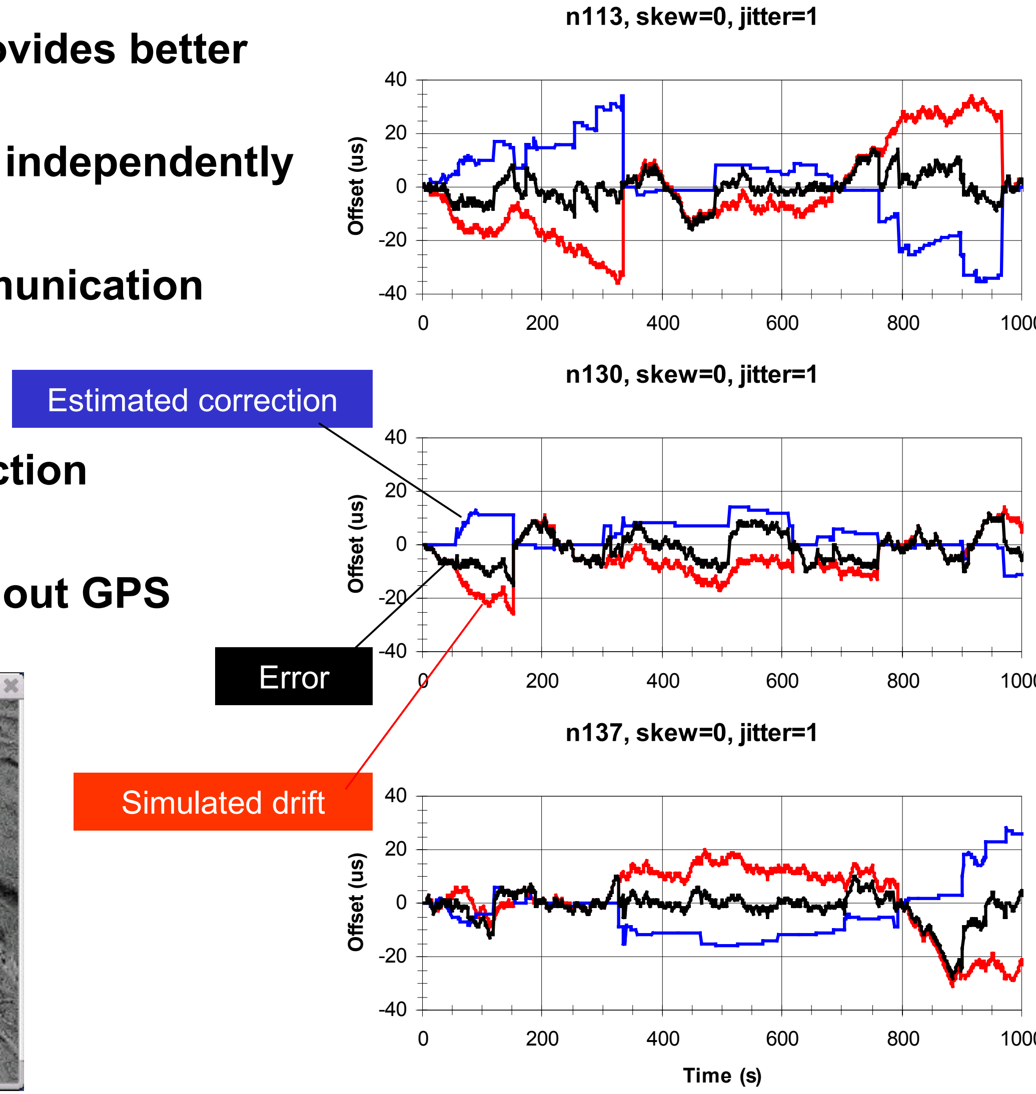
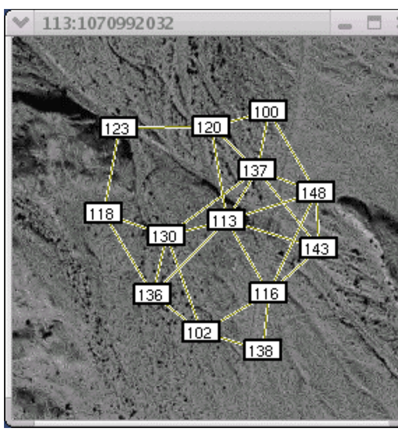
Configurable Capacity Change Conditions

- **Slot definitions are coordinated locally and cooperatively**
  - **schedule modified as local conditions change**
  - **no central, high energy control node**
- **Slots are added for a variety of reasons**
  - **high rate of collisions on listen slots**
    - **adds a listen slot to more evenly spread the load and reduce the loss due to collisions**
  - **high listen slot utilization**
    - **adds a listen slot to avoid collisions before they happen**
  - **high outgoing load**
    - **adds transmit slots either to an individual, a group, or to all nodes to reduce the backup**
  - **discovery of a new neighbor**
    - **adds a point-to-point transmit slot to move the current schedule of all neighbors**
  - **signal from another module of impending critical data**
    - **adds a transmit slot in advance of data being generated to produce the lowest latency for impending critical data**

Distributed Time Synchronization

- Weighted mean of clocks provides better estimate of true time
  - Calculated on each node independently
  - N neighbors + own
- Requires node to node communication
  - even if no data to send
  - uses more energy for tx
- Lessens need for GPS correction
  - uses less energy
  - some nodes can run without GPS





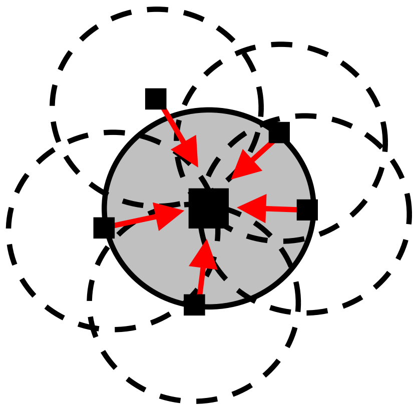
Data Cache

- Data storage - retain information as long as it’s valid
  - small distributed database/shared information space
  - producer and consumer do not directly communicate
  - real time notification of changes
- Data dissemination - distribute data to where it’s needed
  - all data is available for remote access
  - distribution automatically determined to satisfy application queries
  - search and extract (by query with where clause)
  - ooze and route distribution methods
- Primary key for data naming - make sure data is the same everywhere
  - automatic consistency enforcement throughout network
  - data stream merging

Database replication technology provides data reliability.

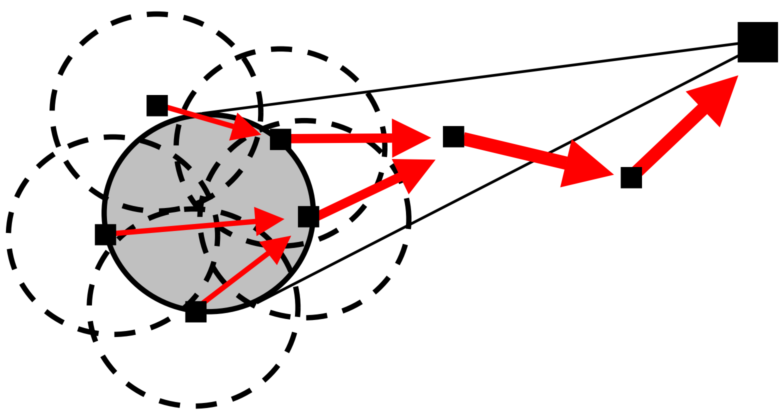
Data Distribution: Ooze or Route

Formation



- Dense, connected queries
- Data disseminated to neighbors
- Cheap, local broadcast (data ooze)
- Own query can be approximated by union of neighbor's
- Used for in-network processing

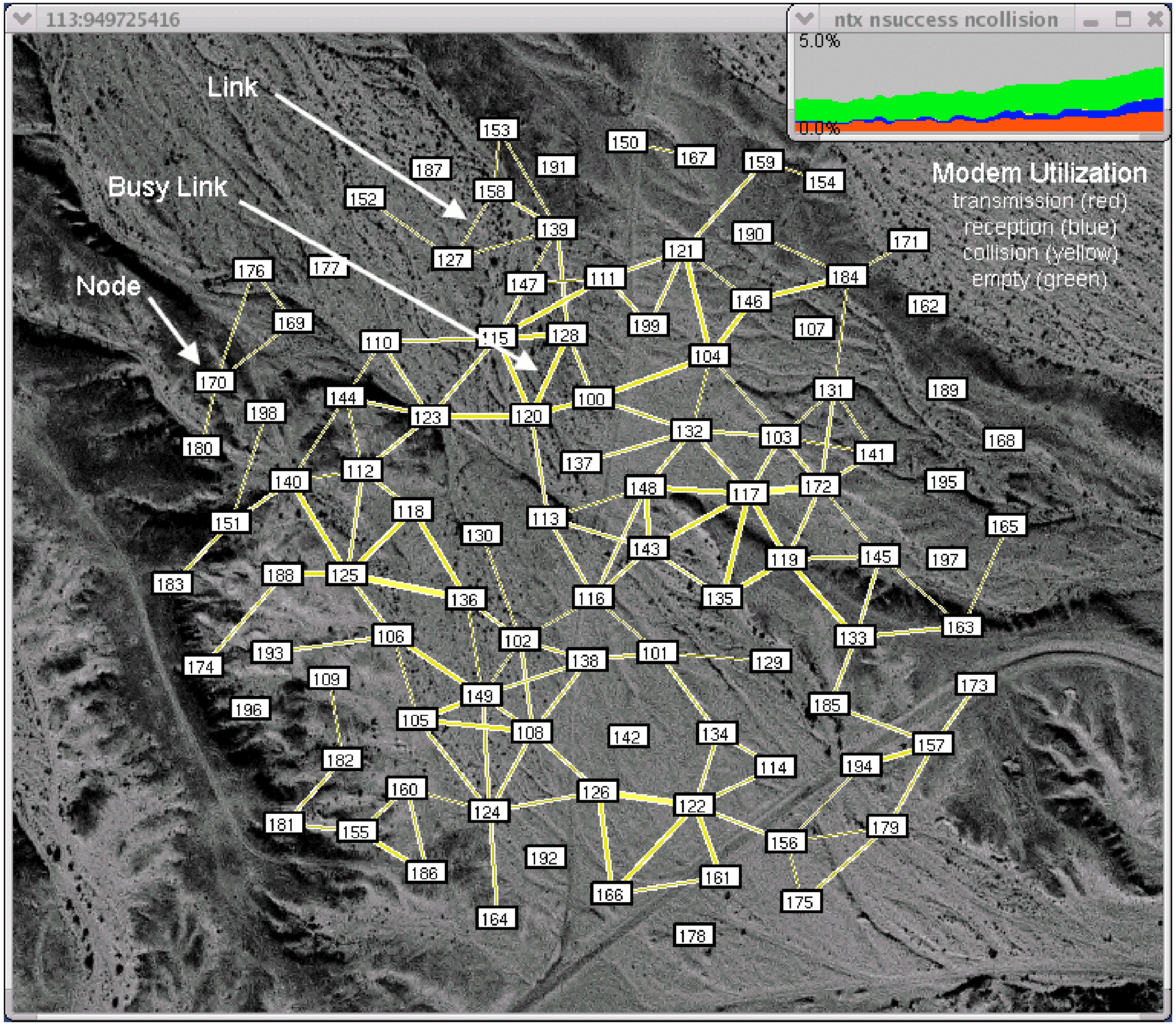
Extraction



- Sparse, disjoint queries
- Data moves across network through many uninterested nodes
- Expensive routing required
  - Global, geographic, or addressed
- Requires knowledge of and evaluation of query at all nodes
- Used for tasking and reporting

Large sensor networks need both data distribution techniques.

Network Formation



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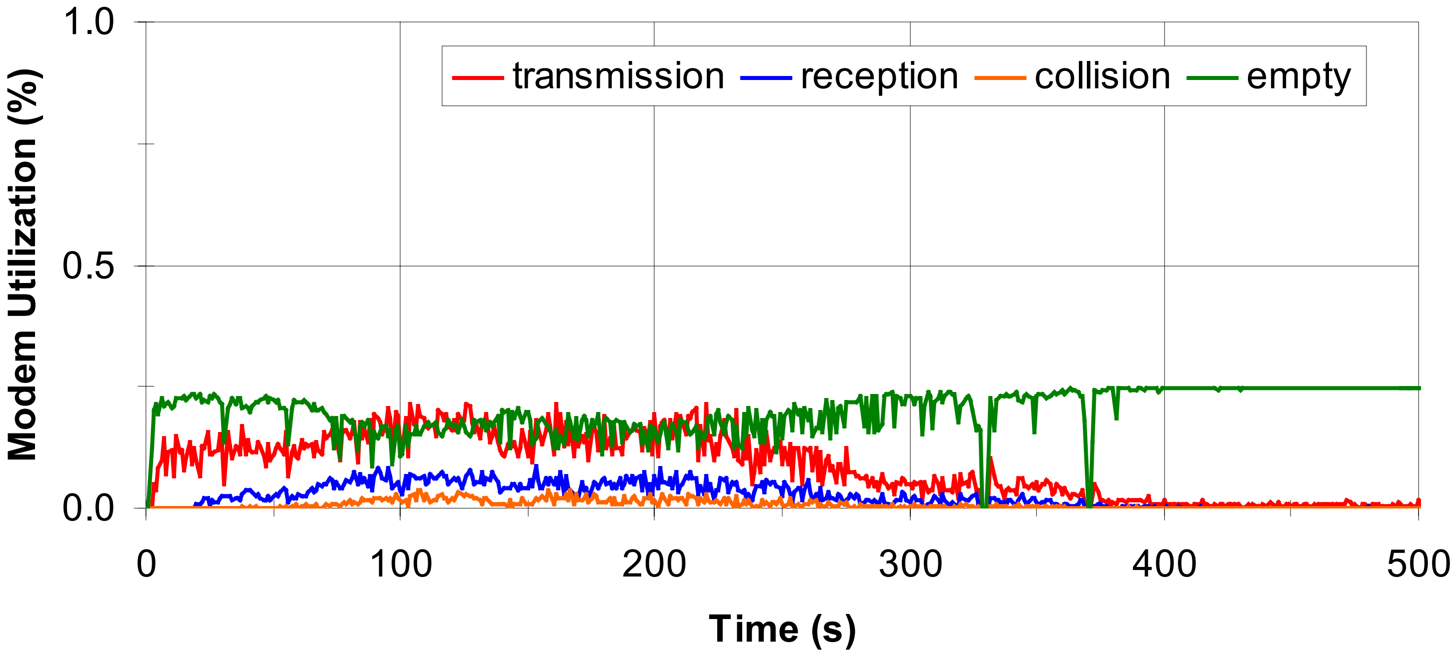
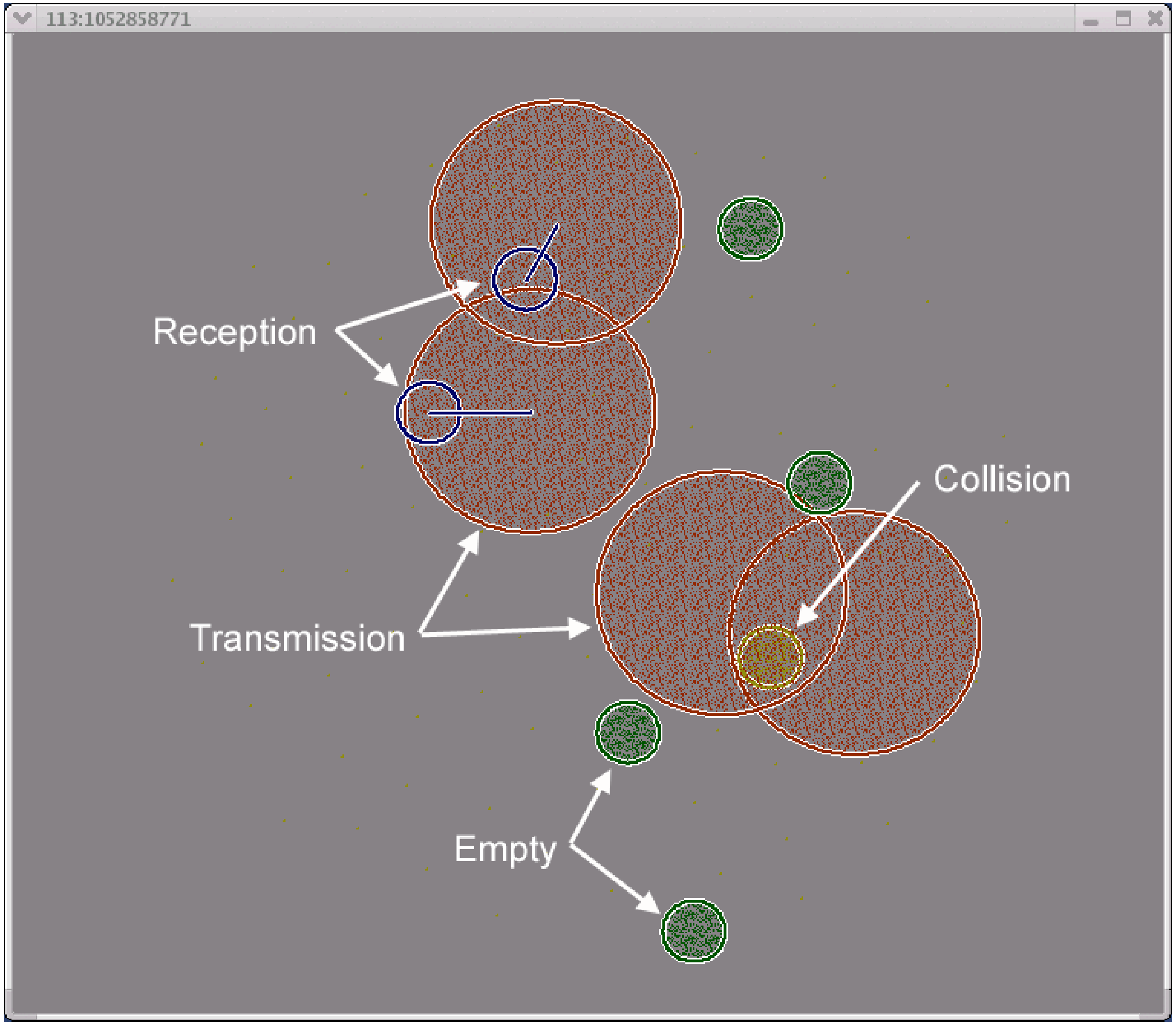
Test Results: Network Formation



- **Balance energy consumption with speed of formation**
  - **1 receive opportunity per frame**
  - **$2^{-(\text{number of neighbors})}$ probability of random transmissions on each frame**
  - **fully formed network in about 4 minutes**
  - **adding more receive opportunities shortens formation time but increases energy consumption**

Modem Duty Cycle



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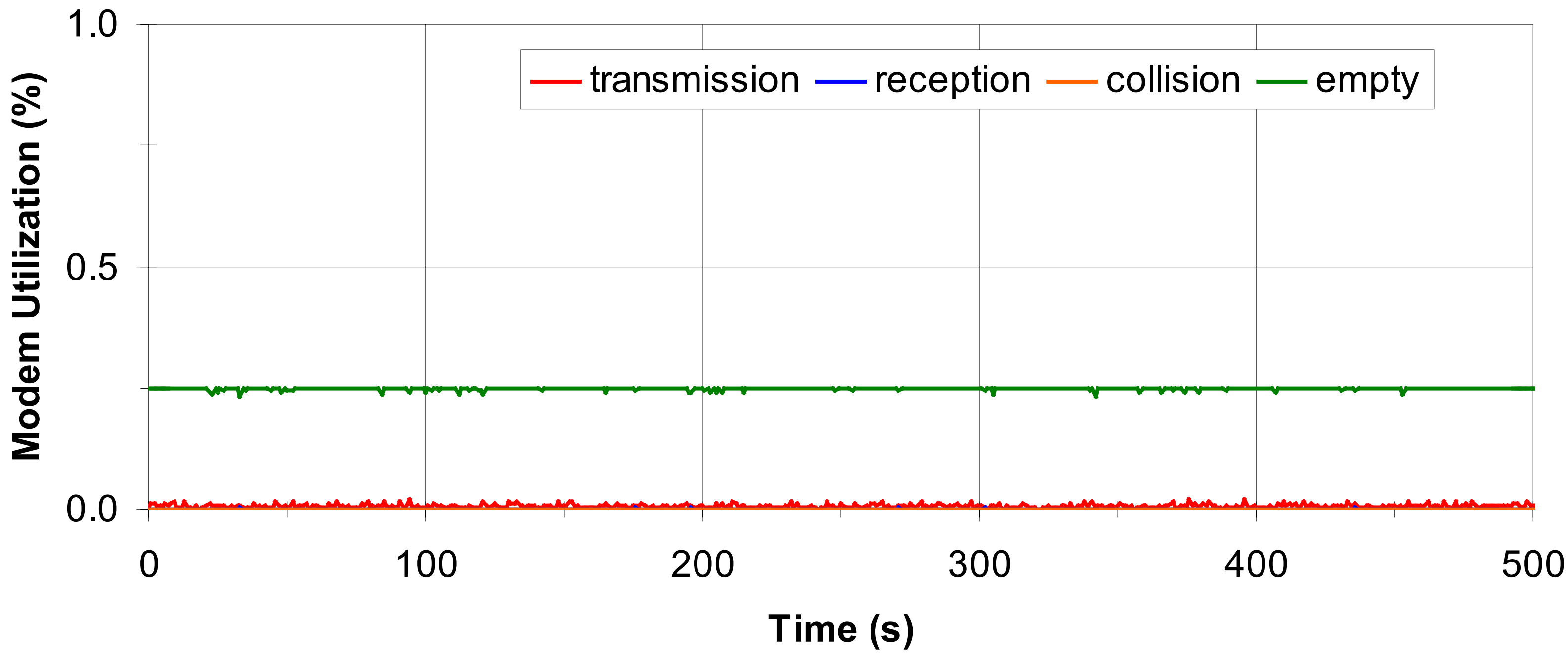
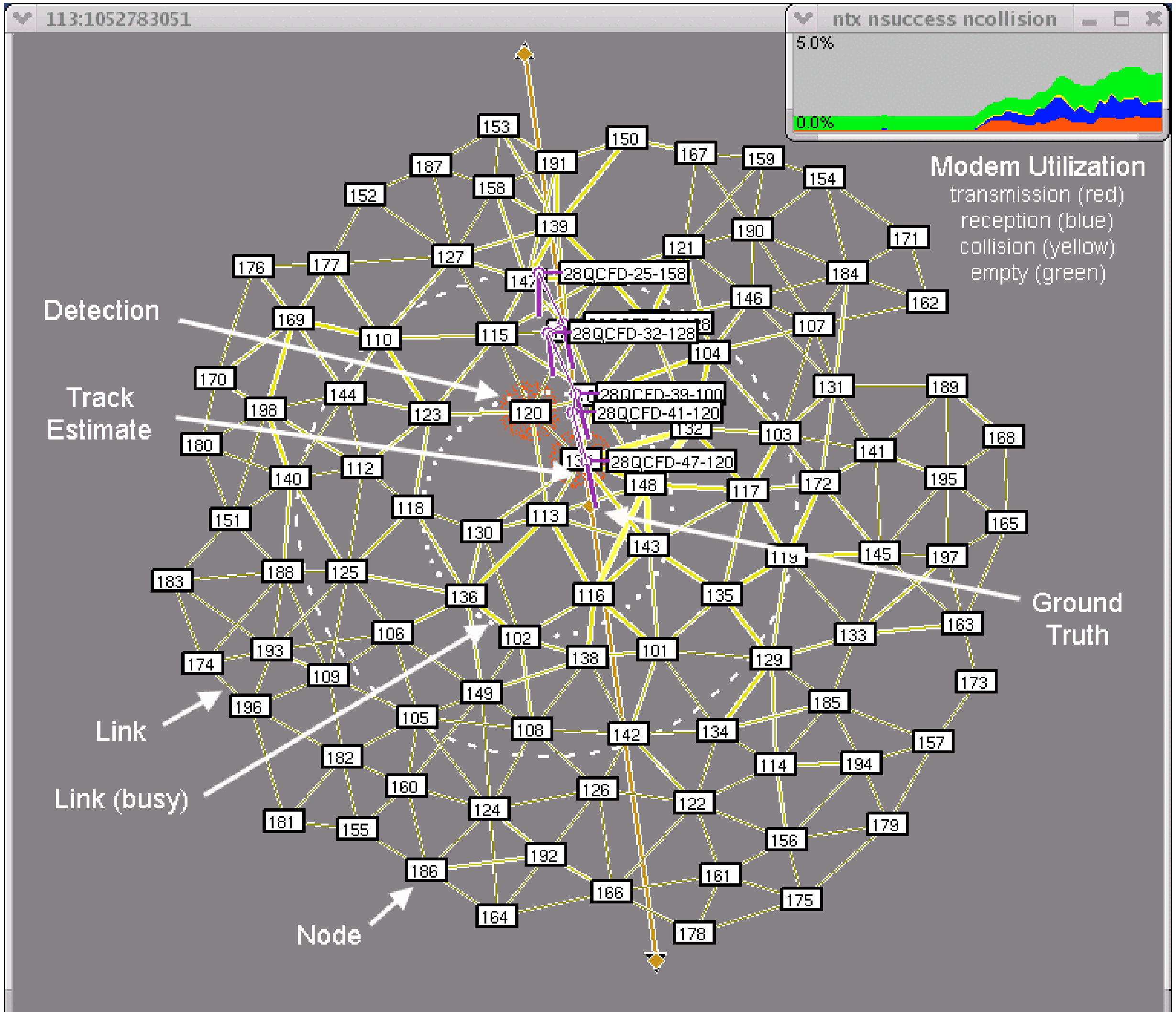
Test Results: Normal Active State



- **over node lifetime, this state is largest energy consumer**
- **low energy and response time are both important**
  - **1 fan-in, contention managed, receive opportunity per frame**
  - **close to 0 transmissions per frame throughout the network**
  - **more fan in slots reduces response time**

Detection and Tracking



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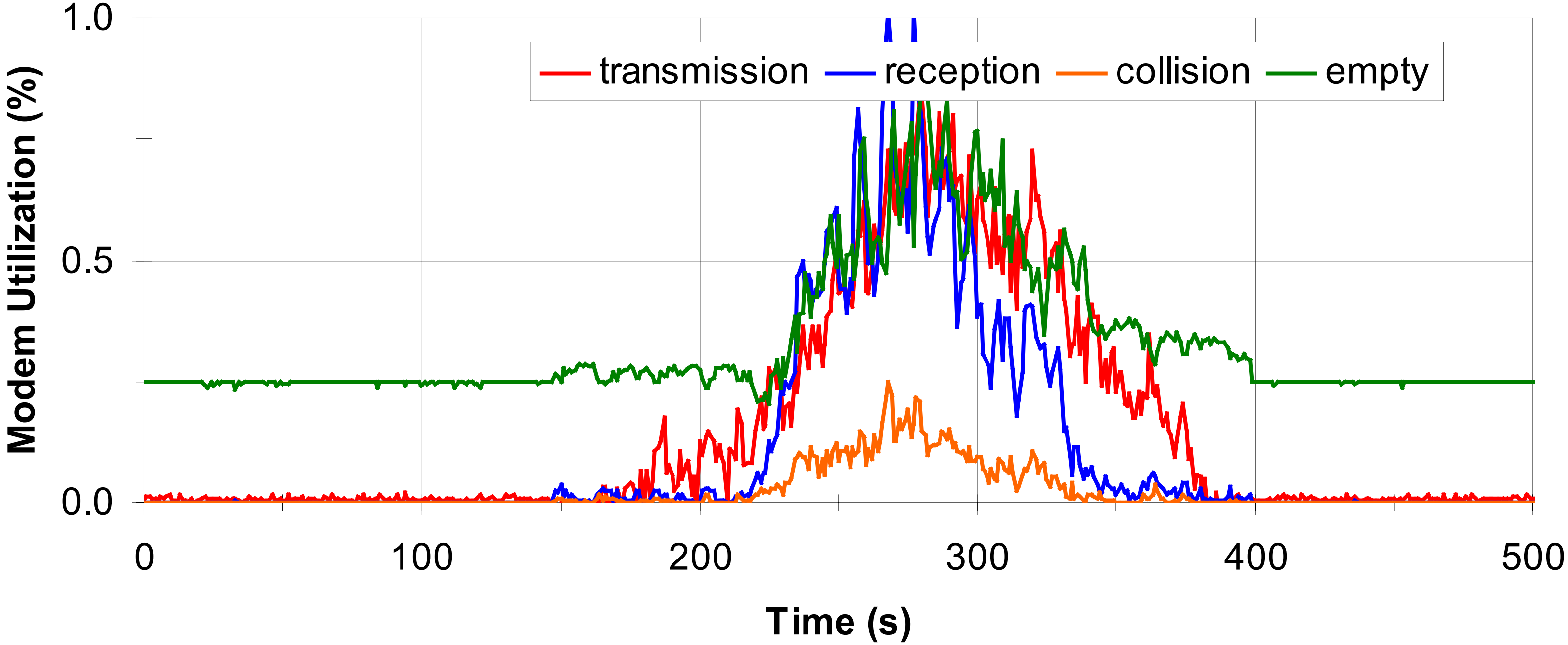
Test Results: Tracking



- **tracker performance degrades quickly with lost or late data**
  - **not a lot of data, but high criticality, requires low latency**
  - **stress test of communication system**
- **tx broadcast slot cued by approaching track**
  - **efficient delivery to multiple neighbors, no collisions, low latency**

Estimated Energy Consumption

Component	Peak (mW)	Dormant (mW)	Active (mW)	Tracking (mW)
Sensor	10	0.00	0	10
Gps	160	0.01	1	1
Modem	264	0.06	2	8
Processor	142	0.35	27	95
TOTAL	576	0.42	30	114
Days (2AA, 2000mAh)	0.3	476.2	6.6	1.7

- **Excellent reduction in modem duty cycle**
- **Well within capabilities of processing cores and components**
- **Energy estimates based on:**
  - **normal, commercially available components**
  - **measured duty cycles (modem), estimated (gps, sensor)**
  - **measured performance (cache, scheduler, sas), estimated (detector, tracker)**
  - **estimated hardware performance**

Measured Energy Consumption

Item	State	Current	Peak Energy	Duty Cycle	Energy	Subtotal	
		(mA)	(mW)		(mW)	(mW)	at 2.27V
Processing			603.820			30.236	5.008%
processor	fast (133Mhz)	266	603.820	0.010000	6.038		10ms
	slow (10MHz)	86	195.220	0.010000	1.952		10ms
	idle (32kHz)	10	22.700	0.980000	22.246		
Communication			621.980			0.596	0.096%
modem	off	0	0.000	0.995600	0.000		
	idle	19	43.130	0.002200	0.095		2 ms startup before each use
	tx	29	65.830	0.000200	0.013		1 slot per every 10th frame
	rx	38	86.260	0.002000	0.173		1 slot per frame
pa	ps=a	245	556.150	0.000200	0.111		
lna		45	102.150	0.002000	0.204		
GPS			351.850			0.946	0.269%
gps	acquisition	143	324.610	0.000000	0.000		only at node start
	tracking	138	313.260	0.002778	0.870		10 seconds every 60 minutes
	antenna/lna	12	27.240	0.002778	0.076		
Sensing			65.830			2.270	3.448%
pir		1	2.270	1.000000	2.270		actually too small to measure
magnetometer		28	63.560	0.000000	0.000		only at node start
temperature		0	0.000	0.003333	0.000		1 measurement every 5 minutes
battery		0	0.000	0.003333	0.000		1 measurement every 5 minutes
TOTAL			1652.560			34.048	2.060%

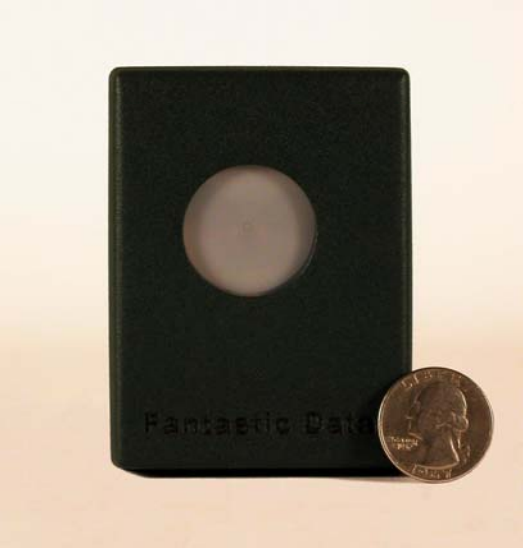
- **Actual current measured with fully assembled unit**
  - **using lab supply (@2.27V) as battery surrogate**
- **Processor idle current is biggest issue**
  - **downsize and modernize in next iteration of design**

Common AA NiMH batteries (2x)		
V	mAh	lifetime (day)
2.4	2000	5.874002298
2.4	2500	7.342502873

Sensor Node Hardware

Sensor Node Hardware Specifications

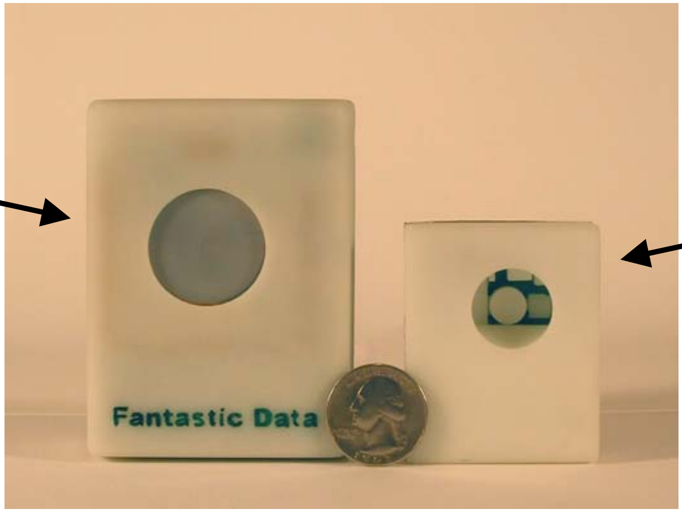
Size	**4 cm x 6 cm x 8 cm** **192 cm^3**
Weight	**140 g (without batteries)** **200 g (with batteries)**
Power	**34 mW (average, 1 s response time)**
Data Rate	**1 Mbps FSK (max, reduced rates available)**
Link Margin	**107 dB, omni directional antenna**
Range	**60 m (at ground level)** **400 m (1 m AGL)**
Detection Range	**20 m (person walking)** **> 50 m (vehicle traffic)**
Location	**± 3 m** **± 2° magnetic orientation, 3 axis**
Time accuracy	**20 ppm (uncorrected)** **40 ppb (single GPS correction)** **150 μs (corrected once per hour)**
Processing Power	**16 kips to 130 Mips** **32 MB RAM (1.5 MB used)** **4 MB Flash (0.6 MB used)** **C/C++, Verilog, VHDL programming**



Conclusion

- **Comprehensive approach optimizes energy consumption**
  - **Not just the communications hardware or sensor by itself**
  - **Protocol is markedly different than the commercial trend but…**
    - **Improves utility in military sensor applications**
    - **Reduces power consumption by eliminating need for data to flow through a hierarchy**
- **Next step: reduce size, weight, power, and cost**
  - **Reduce processor peak capacity, reduce memory**
  - **Single PCB rather than modular stack**
  - **Smaller power supply capacity uses smaller components**
  - **Li+ battery reduces weight but has little impact on volume**

192 cm^3
200 g
34 mW
$1000
available now



64 cm^3
100 g
4 mW
$400
6-12 month lead time

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