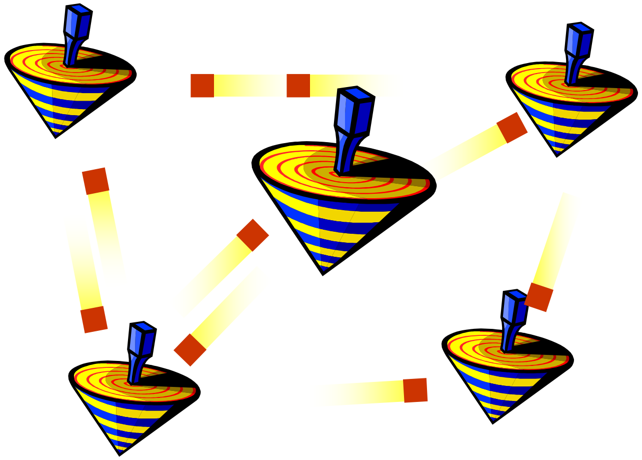
Advanced Technology Office

Connectionless Networking Program

Industry Day Briefing

4 March 2003



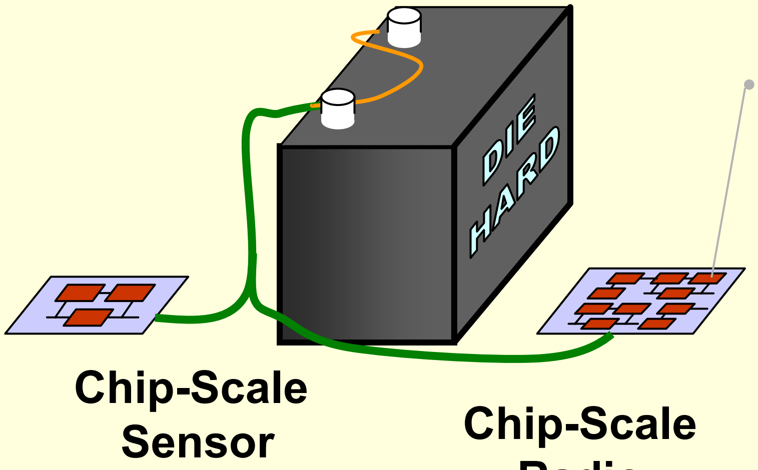
Preston Marshall, Program Manager

703-696-5273, pmarshall@darpa.mil

Connectionless Networking
The Problem

- **Size/Weight/Power of Sensing and RF Components Continue to Drop**
  - **Sensing and RF Components Soon to be Able to Leverage MEMs/Nano Technology**
  - **Digital Processing Power Requirements Drop by Factor of 1.6/Year**
- **Energy Required to Send a Bit Remains Constant**
  - **Driven by Shannon's Law and Physics**
- **Energy Required by RF Link and Network Topology Limits Lifespan, Miniaturization, Covertness, …**

Ad-Hoc, Low Duty Cycle Networks Require a Different Kind of Radio



The Future With Current Approaches

Connectionless Networks
Military Significance

- Required Technology to Deploy Large Number of Autonomous Low Duty Cycle Radio Devices
- Orders of Magnitude Decrease in Required Power & Signature
- Potentially Low Complexity
- Scalable Architecture for Range of Networks
  - Dense (Short Range)
  - Widely Distributed (Medium Range)
  - Very Proliferated (Over >100,000 Radios)

Open Loop/ Connectionless Networking

- Closed Loop Links and Networking Ineffective for Short Duty Cycle Messaging Applications:
  - Acquisition Synchronization Delays and Power
  - Network Setup Delay and Traffic Load
  - End-To-End Acknowledgement Latency
- Open-Loop Potential Savings 10^{4+} in Energy/Time or Increase in "GoodPut"
  - Reduce Link/Net Setup By Up to 10^4
  - Reduce Overhead by Up to 10^3
- Based On:
  - Ability to Pre-Compute and Correct Waveform Frequency, Timing, and Phase for "Instant" Acquisition/Synchronization
  - Processor Intensive Rather Than Data Intensive Routing
  - Availability of State (Relative Position & Velocity) and Time

- SUOSAS Takes Up to 10 Seconds to Setup
- MILSTAR Can Take Minutes
- End-to-End Acknowledgement Greatly Increases Delay
- **Efficiency <0.1% For Short Messages**
  - LPI, LPD, Battery, Complexity Impacts

Military Applications

- Low Duty Cycle (Infrequent Messages)
  - Unattended Sensors
  - "Wooden Round" Weapons
  - "Shout Back" from Weapons
- Proliferated
  - Network Formation Too Complex
- Short Timeline Applications
  - <1 Second from Power Up to Shutdown)
- Low Power and LPD
  - Alternative to Setting Up High Persistence Networks
- Scalable Architecture for Range of Networks

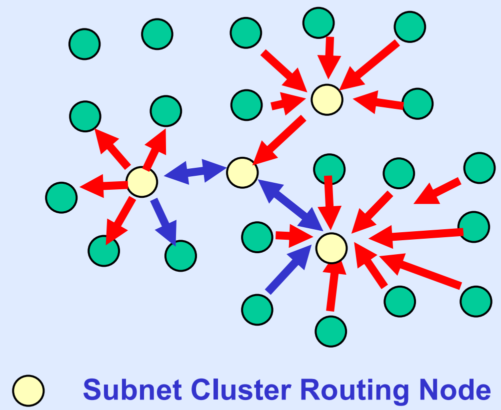
Challenge Assumption That Wireless Systems Should Look Like Wired Ones

Connectionless Networks Program Concept

- Reduce Communications Energy Requirements by at Least 10^2
  - Eliminate Link Acquisition, Synchronization,
  - Leverage Platform Awareness to Pre-Compute Appropriate Communications Parameters
  - Integrate Chip-Level Power Management into Protocol
  - Provide Ad-Hoc Routing Decisions without Routing Info Across Network in Advance
  - Provide High Burst Rate, Low Power/Duty Cycle
- Key Technology Challenges
  - Coherent Carrier Phase Tracking
  - Acquisition-Less Waveforms
  - Power-Sensitive Protocols

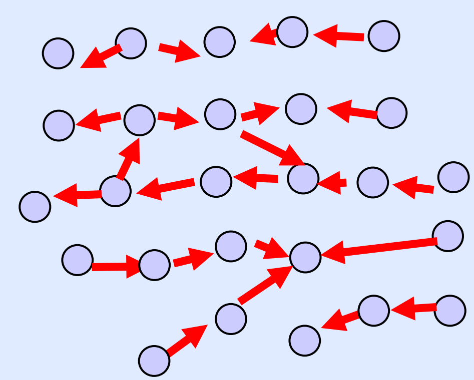
Acquisition-Less Operation is Key to Achieving True Ad-Hoc Networks

Connection-Oriented Networks Force Routing Bottlenecks



Enabling Transition

Ad-Hoc Networks Add Capacity As Node Density Increases



Network Operation is Costly! Steady State SUOSAS Example

- Network Functions Are Dominant Users of Bandwidth
- Fixed Overhead Increasingly Less Efficient as Duty Cycle Decreases
- Closed Loop Mechanisms Require Duplex Operation
- Much of Bandwidth Provides Redundant/Unnecessary Information
  - Headers for Each Level
  - Timing
  - Status

Redundant since information exists in the Integrated system

SUOSAS Aggregate Capability 200 Mbps

512 byte packet, 32 mcps & FEC = 1/2 @ 4000 kbps maximum burst	Bits (in K)	Reduction	% Payload
Transmission Capacity of 50 Radios	200,000		
Half-Duplex Operation	100,000	100,000	
Channel Contention @ 5 Radio Density	40,000	60,000	
UDP Header	39,385	615	34%
IP Header	37,647	1,738	95%
COMSEC Header	36,571	1,076	59%
Radio Network Header	36,120	451	25%
Radio Link Layer Header	35,679	441	24%
Modem Framing & CRC	35,068	611	34%
Forward Error Correction	17,534	17,534	
Waveform Framing	17,491	43	2%
Synchronization Probe Overhead	13,378	4,113	226%
Slot Quantization @ 1.2 ms per Slot	11,378	2,000	110%
Channel Acquisition (RTS/CTS)	6,827	4,551	250%
Frame Acknowledge	5,689	1,138	62%
Average Contention Interval (1.44 slots)	4,588	1,101	60%
Average Number of Transmissions per packet	1,821	2,767	
Candidate Packet Overhead			982%

From SUO SAS TIM, June 12 & 13 2001

Actual Application Data 1.8 Mbps ≈ 0.9 %

- Does Not Include Initial Acquisition, Other Entry Requests, TCP, Routing Table, and Related Bandwidth Requirements
- 10 Second Set-up Time Represents Opportunity Cost of 2 Gigabits of Throughput

Link Formation is Costly!

RF

PHYSICAL 1

LINK 2

NETWORK 3

TRANS-PORT 4

Operations Required Other than Data Transfer

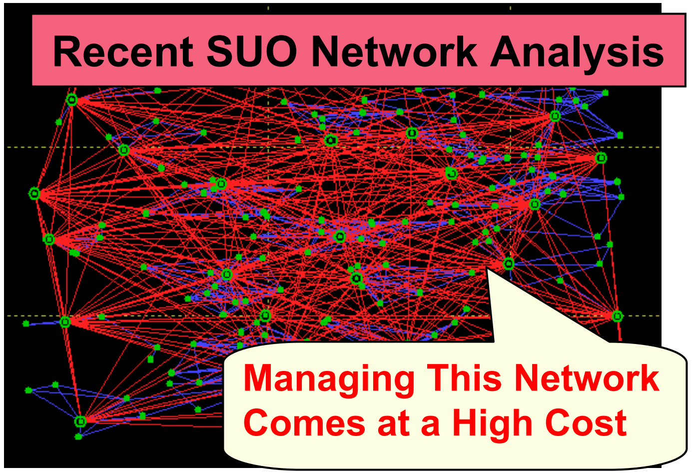
Resolve	Driven By:
Hop Time	Distance/Time Tolerance
Frequency	Relative Velocity
Timing	Distance/Time Tolerance
Phase	Baseband Coherent Tracking
Clock Rate	Relative Closing Velocity
Acquisition Preamble	

Establish	Required For:
Media Access	Slot Assignment, Collision, …

Communicate	Required For:
Address	Assignment within Address Space
Routing	Informing Other Routers of Subnet Path

Function	Required For:
Open Path	Negotiate Window Size
ACK/NAC	Confirm each block

- Even SUOSAS Takes Up to 10 Seconds to Complete Layer 1 to 3
- MILSTAR Can Take Minutes
- End to End Acknowledgement Greatly Increases Delay
- **Efficiency <0.1% For Short Messages**
  - LPI, LPD, Battery, Complexity Impacts

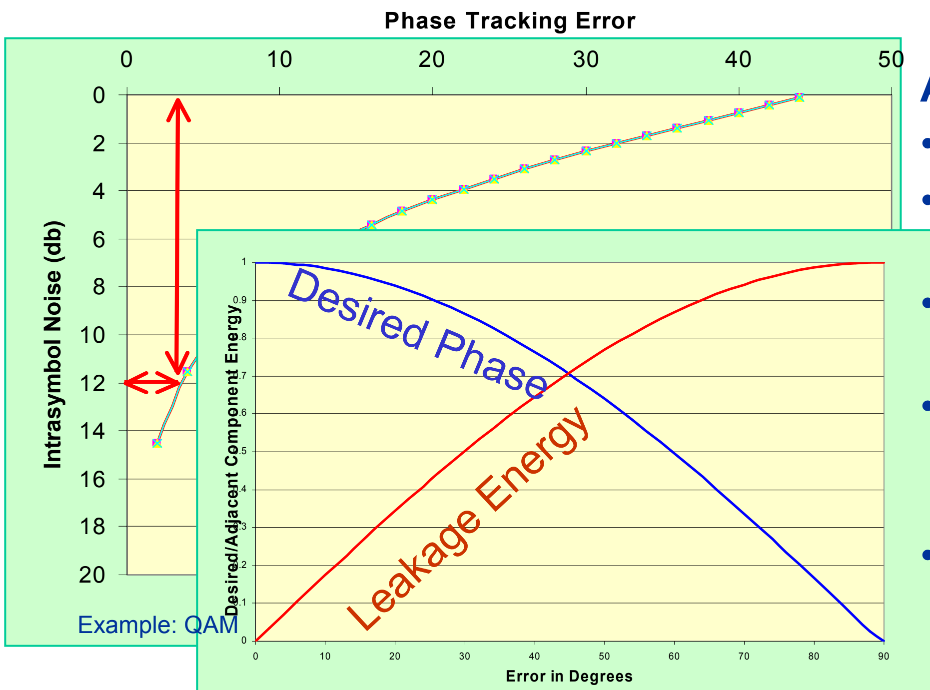


We Use Power/BW on Overhead … Invest in Getting Efficiency from .1% to 10%

Key Technical Challenge
Baseband Coherent Phase Tracking

Challenge

- Phase Modulations Require Receiver to Track Carrier Phase (in advance of Reception)
- Even Small Phase Tracking Tracking Errors Reduce Energy and “leak” Other Phase Energy
  - Self Interference Not Mitigated by Margin
- Self-Interference Drives Signal Sampling rate
  - 12db Threshold Selected for Initial Connectionless Link Analysis
  - $\pm$ 4 º Phase Sampling
    - 45 Time Symbol Rate I,Q Samples



Approach

- Oversample Baseband Signal
- Process Multiple Phase/Epoch Time Assumptions
- Use Error Detection Code to Identify “Correct” Assumption
- Receiver Powered Only During Receive Epochs, and Processing Only After Energy Detected
- Trades Acquisition/Tracking Transmission Energy for Processing
  - Leverage Future Digital Power Reductions

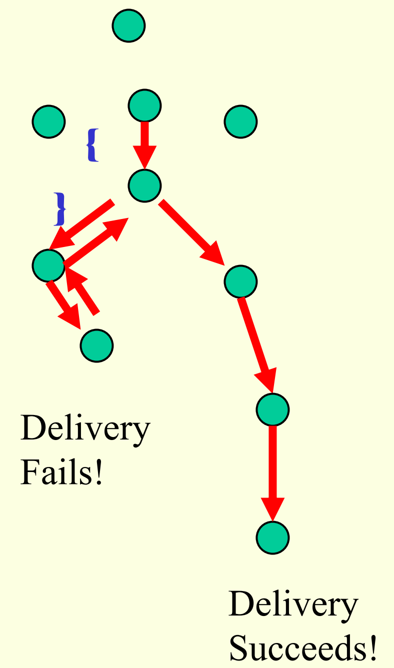
Key Technical Challenge
Routing Approach

Challenge

- Develop Mac Layer and Routing Protocols that are “Power Aware” and Support Power Management at Chip Level
  - Able to Power Down for High % of Time
  - Candidate Research on Routing Performed at Berkeley, BBN, HRL, UCSB,…
  - Low Latency Performance using Many High-Burst Rate Relays

Approach

- Numerous Approaches to Mobile - AdHoc Networks Exist
- Adapt to Exploit Best Features of Physical and MAC Layers

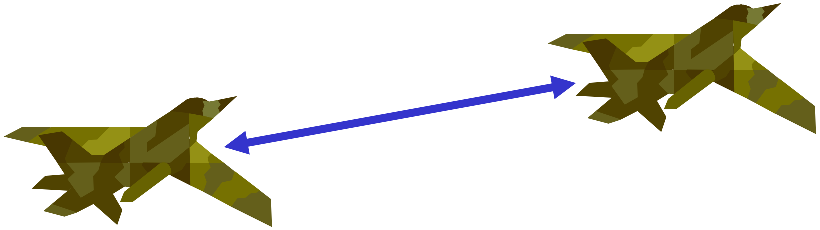


- Nodes Pass to Best Delivery Opportunity
- Nodes pass Message Until Delivery Failure
- Responsibility Passed Back Until Success

Key Technical Challenge
Instantaneous Acquisition

Challenge
- Receivers Must Obtain "Near Perfect" Knowledge of Frequency and Epoch (Block) Time to Initiate Acquisition

Approach
- Leverage of State Vector Knowledge
  - Time to Synchronize with Receiver Epoch Clock
  - Position to Compute Arrival Time Correction
  - Velocity to Compute Doppler and Frame Time Adjustments
  - Acceleration (if Required) for intra-Block Frame Timing Adjustments
  - Relative Distance and Velocity Also Derivable Through Time of Arrival Determination Based on Neighbor "Ping"
- Multiple Hypothesis Detection Resolves Carrier Phase and Accommodates Tolerances



Military Applications

- Low Duty Cycle (Infrequent Messages) Applications
  - Unattended Sensors
  - "Wooden Round" Weapons
    - Quick Turn-on, Reporting, and Operation (ex. A Mine)
  - "Shout Back" from Weapons During Endgame
- Proliferated
  - Network Formation Too Complex
- Short Timeline Applications
  - <1 Second from Power Up to Shutdown)
- Low Power and LPD
- Alternative to Setting Up High Persistence Networks
- Scalable Architecture for Range of Networks
  - Dense (Short Range)
  - Widely Distributed (Medium Range)
  - Very Proliferated (Over >100,000 Radios)

Connectionless Networking Energy Usage Model

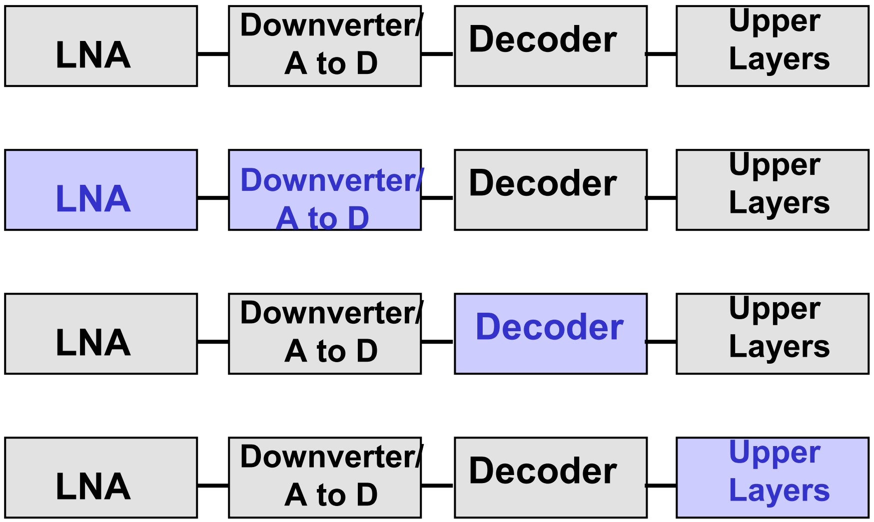
Receiver

> 99.8% — Normal State – All Powered Down

< 0.2% — Front End Powered for Position/Time Ambiguity Period

< 10^{-4} — Decoder Powered Only After Energy Detected for Valid Block Period

< 10^{-5} — Upper Layers Powered After Receipt of Valid Block



Transmitter

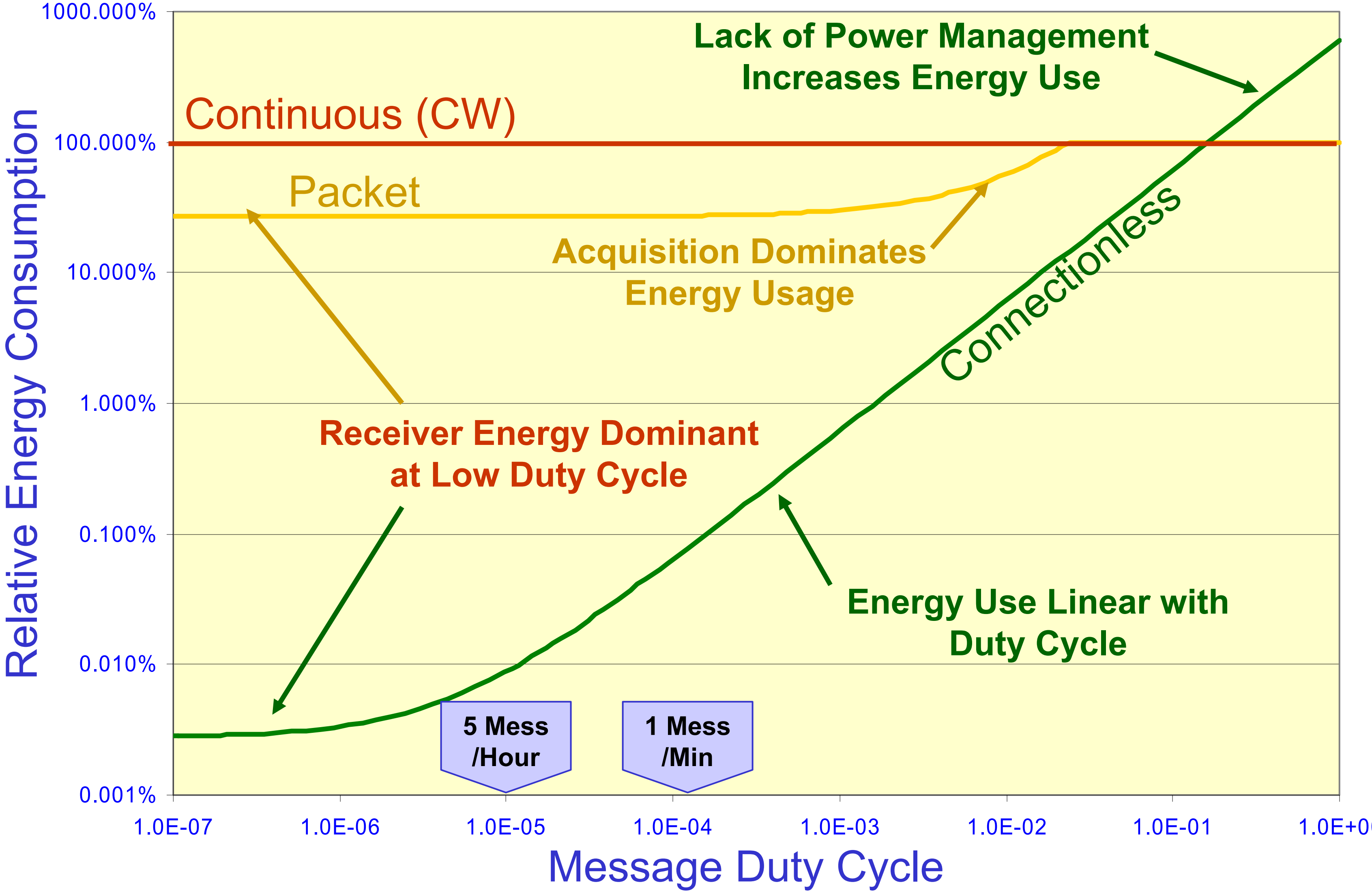
< 10^{-5} — Powered Only When Transmitting Message Local Application or as Intermediate Relay

Lowest Latency Networks Have High Instantaneous Bandwidth with Low Duty Cycle!

Values Based on 100 Transmissions/Day

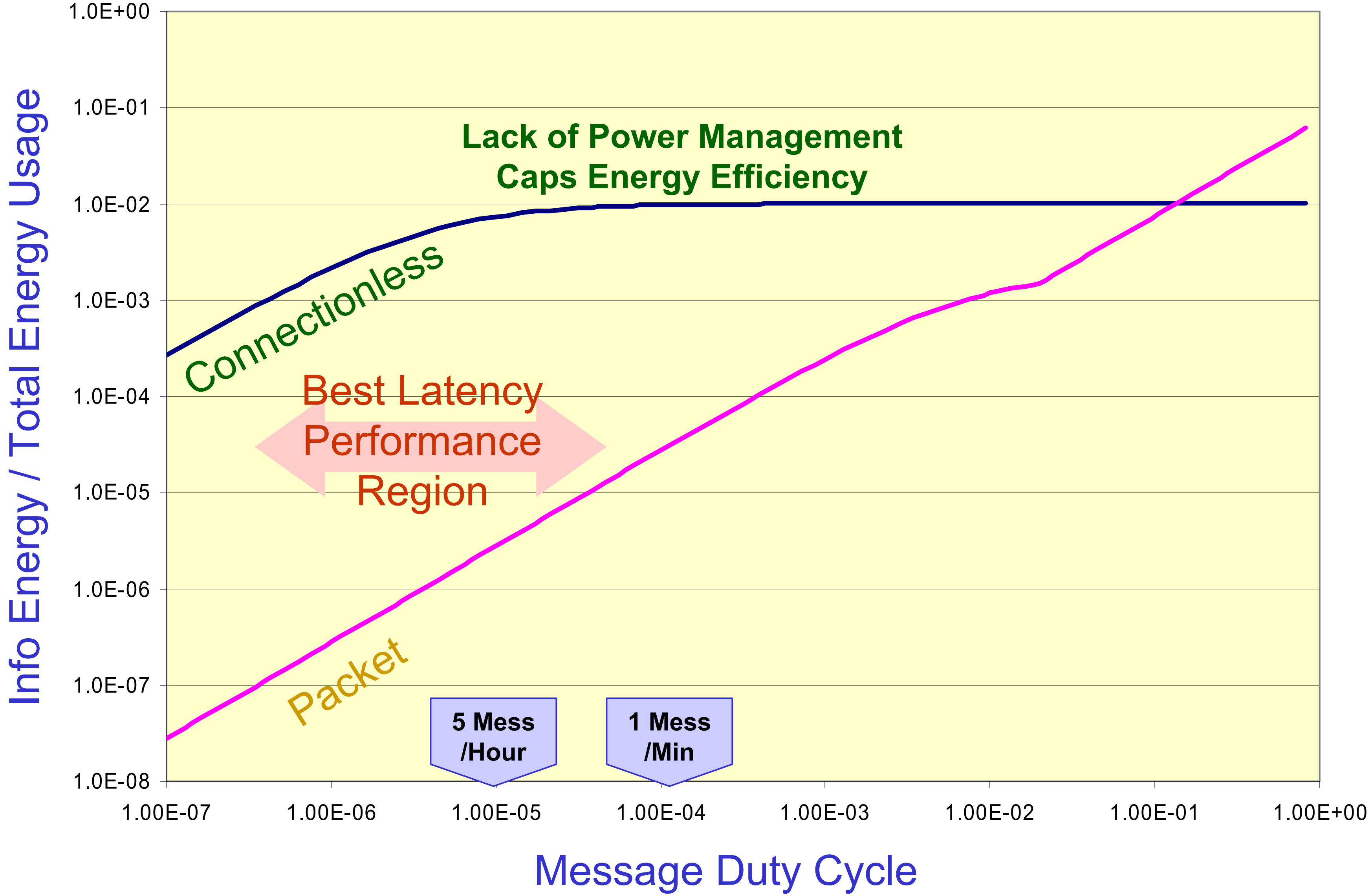
Clock and Control Circuitry Not Shown and Are Always Powered

Connectionless Networking Relative Energy Use



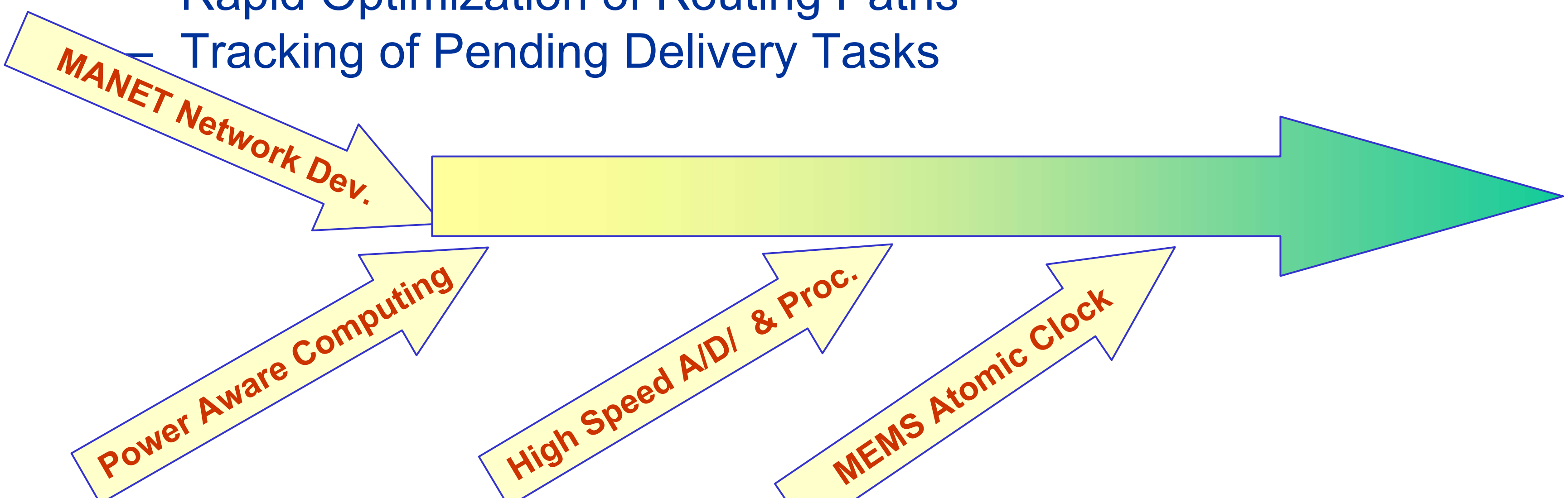
Duty Cycle is Based on a 3 Mbps Network Link Layer

Connectionless Networks Information Energy Efficiency



Technology Augmentation

- Low Power High Speed A/D Processing (eg ABCS)
  - Multiple Hypothesis Signal Acquisition, Timing
  - High Burst Rate Communications
- High Accuracy, Low Drift Time Reference (eg Chip Scale Atomic Clock)
  - Inherent Epoch, Slot, Crypto, Synchronization Timing
- Computing Resources (FPGA, Low Power Processing)
  - Rapid Optimization of Routing Paths
  - Tracking of Pending Delivery Tasks



Augmenting Technology Available or In-Process

Connectionless Networks Implementation Layers

Threshold: Collective Improvement in 10^2 for Single Messages

Each Can Be Addressed Independently

Eliminate Link Synchronization/ Acquisition Process	• Pre-Correct Doppler/Arrival Time –Velocity, Position Knowledge to Refine Frequency and Time • Multiple Hypothesis Coherent Tracking • "Power Off" at Most Time	Savings From 10 to 10^4
Eliminate Media Access Control Messages	Synchronize Message Timing	Savings from 3 to 10 Times
Avoid Exchange of Routing Information	Peer-Peer Ad-Hoc and Dynamic Routing	Savings from 10 to 10^3
Eliminate End to End Acknowledgement	Neighbor to Neighbor Handoff	Linear Latency Improvement

"Highly Assured "Open Loop" Communications"

Go/No Go Thresholds

Metric	Definition	Phase 1	Phase 2	Objective	Rationale
Acquisition Time for Phase-Based Modulations	Time required between initiating transmission of the signal, and the initiation of information bearing transmission	0.0 seconds	0.0 seconds	0.0 seconds	The ability to instantly transmit information is critical to network latency, energy performance, and hardware simplification.
Energy Effectiveness for Low Duty Cycle12 Operations	Total Energy Used for system based on waveform, protocol and hardware/software design analysis	$10^{2.5}$ reduction in Predicted Energy Use3	Included in Go/No Below	Included in Go/No Below	Initial development focus on technology development that can achieve greatly more efficient protocol and waveform operation, based on best available current technology.
Energy Efficiency	Total transmit Energy to establish the network, deliver the message (including intermediate routing), and provide any required transport layer functionality	Not Evaluated	At least 1% Energy Efficiency 4Over For Duty cycles above 10^{-5}	At least 3% Energy Efficiency Over Three Orders of magnitude of Net Duty Cycle	Achieve absolute measure of network operation over very wide range of network operating conditions. % basis allows technology to be applied to any application (short range WLAN, Point to Point, etc.)

1 Duty cycle is defines as the ratio of average time that individual nodes are only providing application-layer information bearing transmissions compared to the total network operating time. This includes header, FEC, addressing, etc., but does not include network setup, routing information exchange, "keep alive" signaling, synchronization and timing signals, MAC-Layer messaging and other non-application layer bearing exchanges and transmissions.

2 Low Duty Cycle is defined to a Duty Cycle less than 10^{-2}.

3 Relative reduction is used in order to develop a measure that is independent of the specific link. Changing antenna, range, propagation conditions, waveform all can impact absolute power usage, so we use a measure that is independent of these factors, and holds them constant for a given application.

4 Energy efficiency is the ratio of energy that is transmitting the actual information, to the total energy used for other non-information-bearing uses, such as Forward Error Correcting, Acquisition, Synchronization, Framing, Overhead, etc. as well as non-transmitting components, such as receiver and modem components. This measure has the benefits described in the prior footnote of being independent of a specific link

CN Program Schedule

FY03	FY04	FY05	FY06

Technology Push

Acq | Phase I

PI Meetings

Technology Lab Demos

12-16 month PoP

- Model Layer Design and Performance Prediction
- Model Acquisition and Media Access Design, Network and Transport Design

  Several Technology Investigators ~ 4-8

Estimated Value
- $4.3M

Prototype Device Dev. And Testing

Acq | Phase II

•Demonstrate Acquisition and Media Access, Network and Transport Technology in Lab Setting

Subsystem Lab Demos

Subsystem Demos

18-24 month PoP

- Laboratory Demonstration of Performance

  System Integrator Teams ~ 2-3

Estimated Value
- $14.5M
- $ Un-priced Phase III Option.

Technology Integration & System Demonstration

12 month PoP

Acq | Phase III

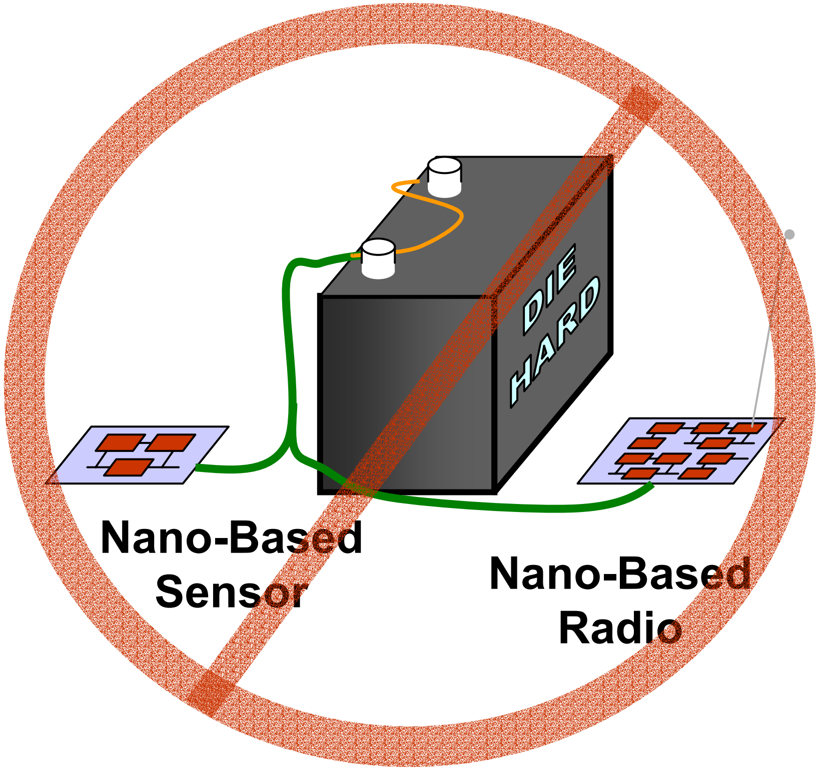
Final Demo

Demonstrate Integrated Network Performance in realistic operating environment

- Field Demonstration

  Single System Integrator

Estimated Value
- $8M


DIE
HARD
Nano-Based
Sensor
Nano-Based
Radio