

Beyond the Third Generation of Wireless Communications

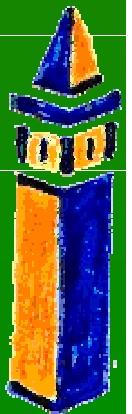
ICICS 99, Singapore

Jan M. Rabaey
BWRC

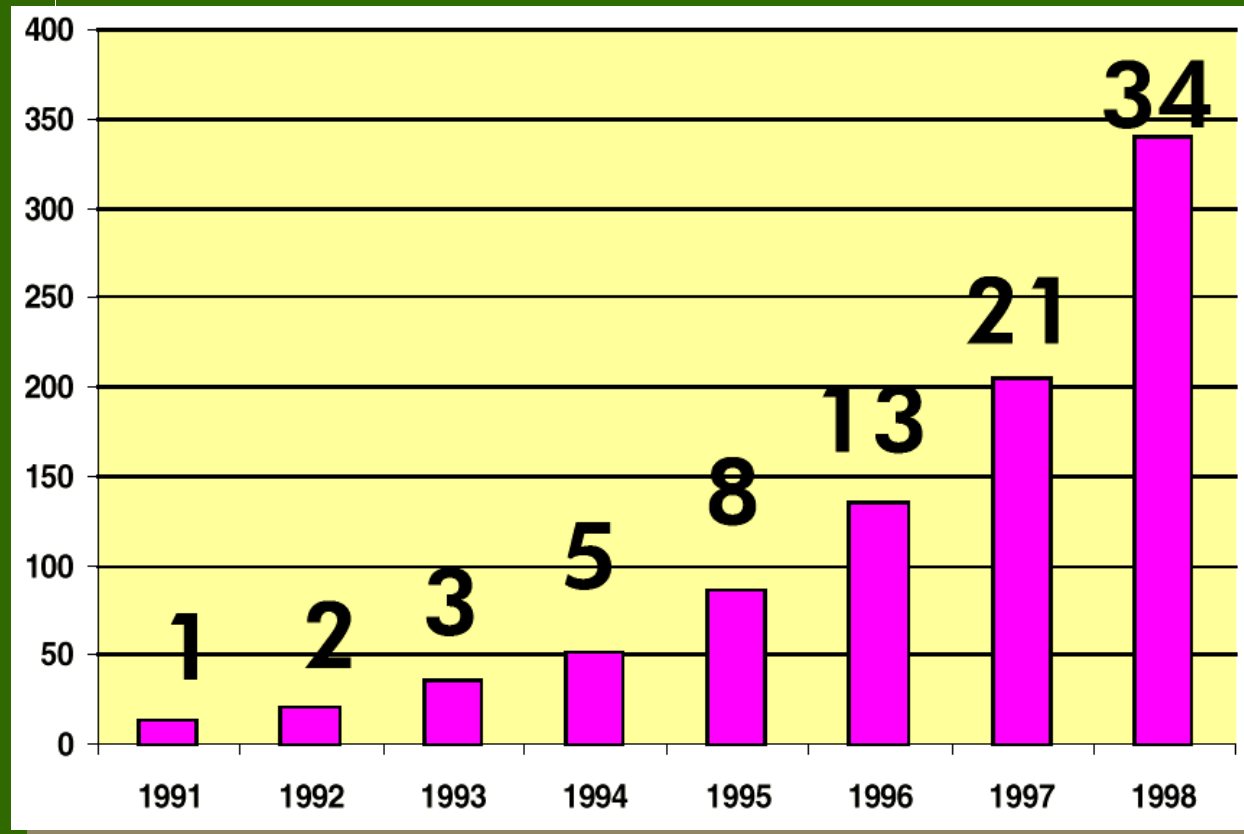
University of California @ Berkeley

<http://bwrc.eecs.berkeley.edu>

Berkeley Wireless
Research Center



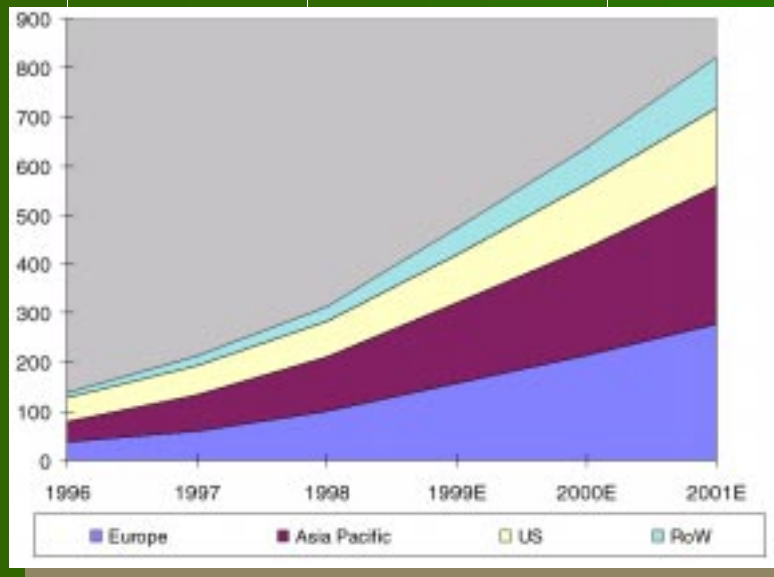
What is the relation between wireless and Fibonacci?



World Wireless Subscriber Growth (in tens of millions)

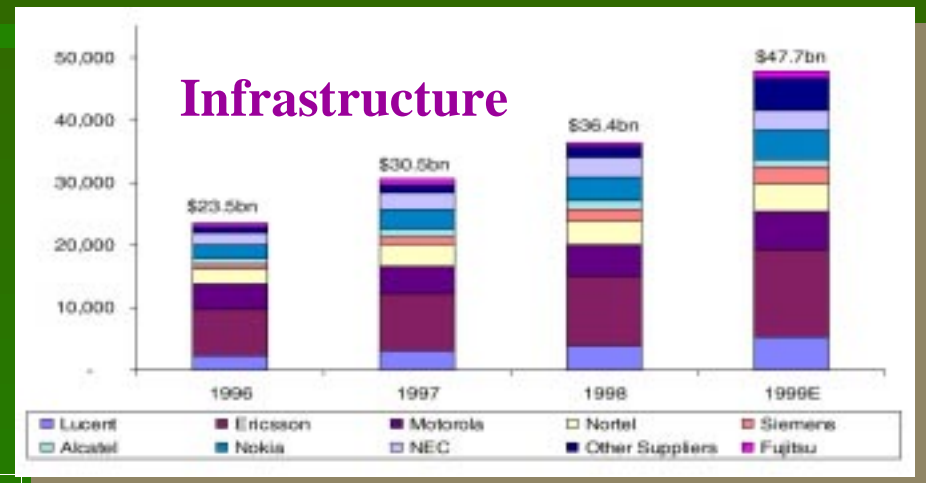
Source: Goldman-Sachs

The sky (or the air) is the limit

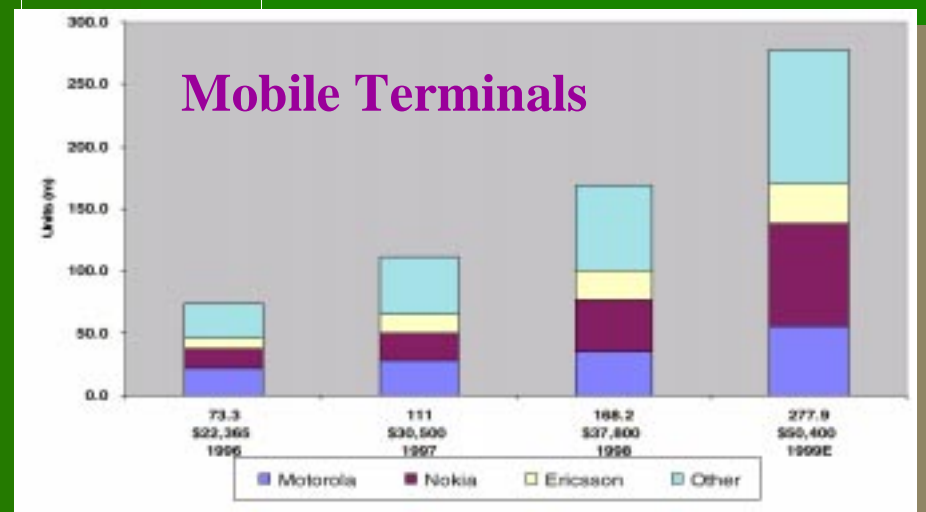


Wireless subscribers (projected)

Source: Goldman-Sachs



Total wireless business: \$ 98 bn



What is next?

The data wave gets unplugged

Example: More than 2 billion SMS messages in Europe monthly



Concentrates industry on connectivity, interoperability

Piques consumer interest in data services

2000

GPRS

Begins process of shift to packet-based systems

Initial support for business wireless e-mail service

2001



Simplifies connectivity between wireless devices

Supports a wide range of consumer, office applications

2002



3G

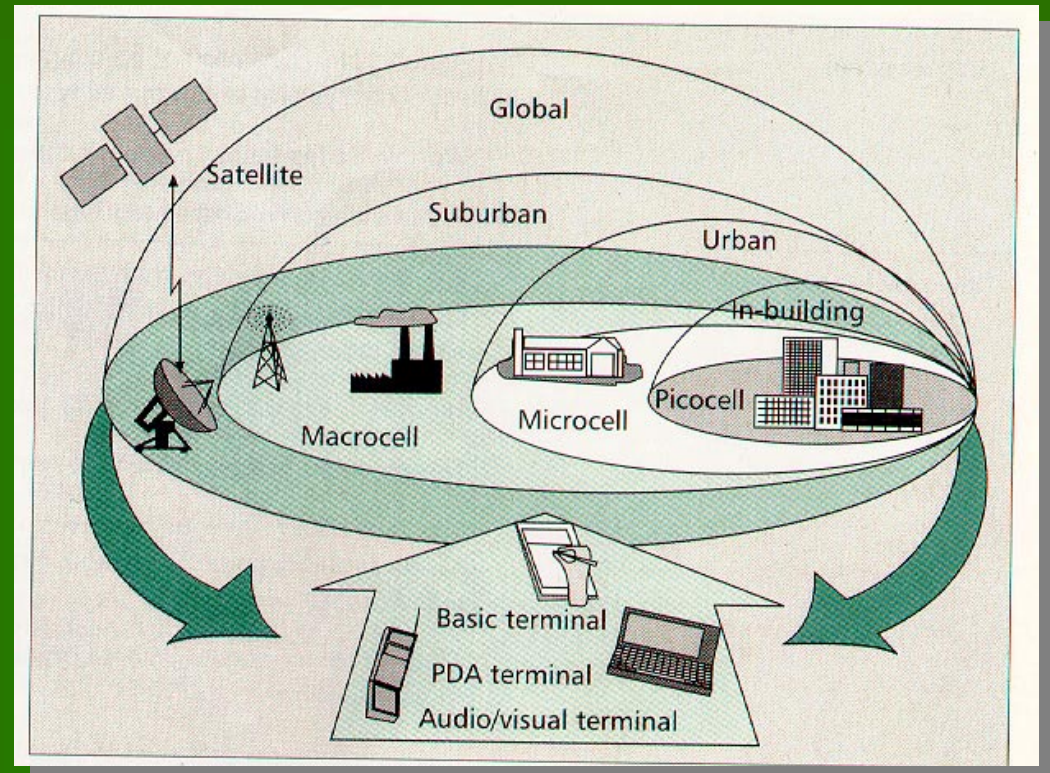
Data speeds reach meaningful levels for streaming

Platforms and technologies evolve, reaching cost for mass market

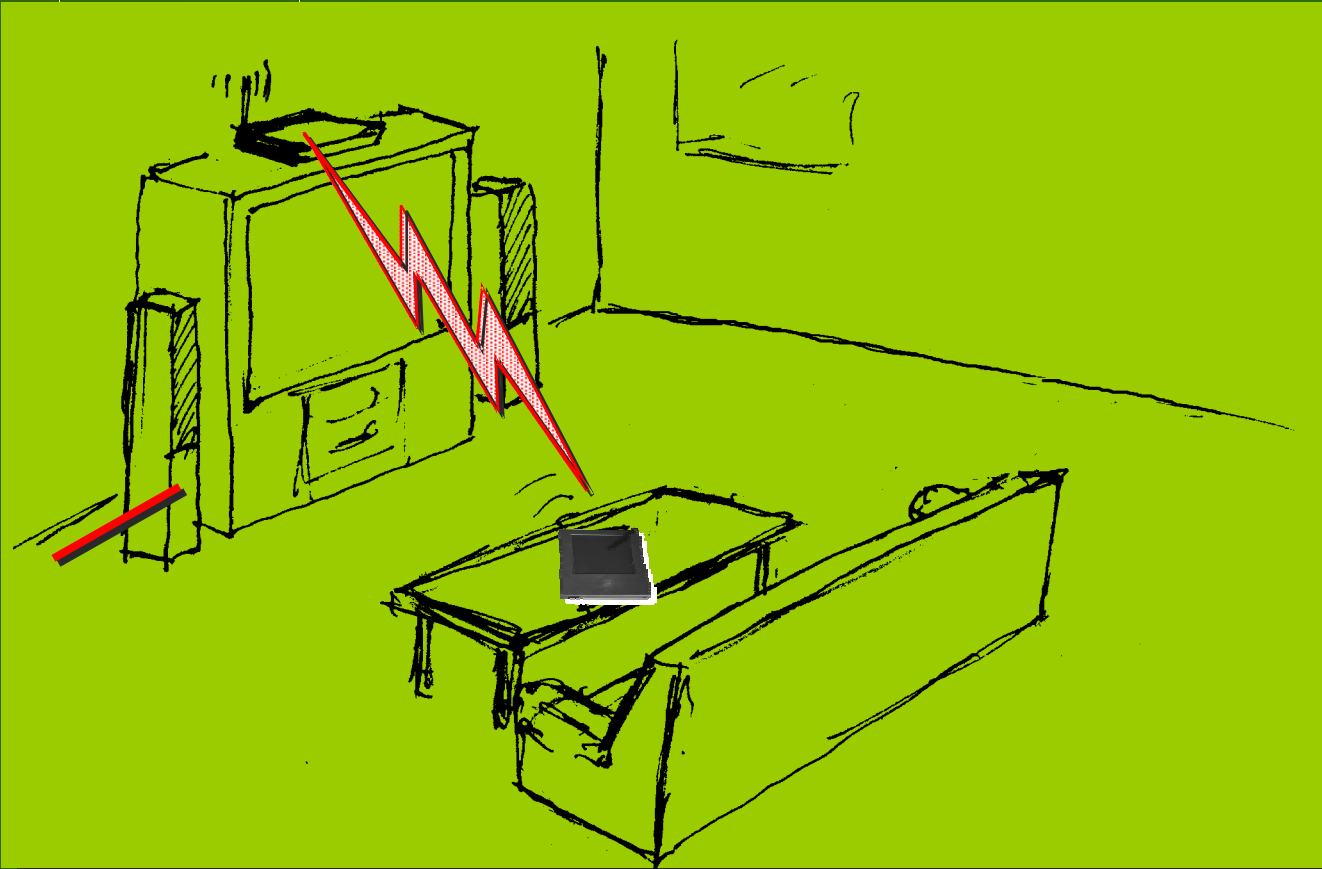
2003

Third Generation Wireless Network (UMTS-UTRA 2000)

- Small, lightweight pocket communicator, that will offer services “anywhere, anytime”
- Mobile Internet access, high speed data, video conferencing, roaming, virtual home environment
- Rates between 340 Kb/sec to 2 Mbit/sec
- Unification of the many diverse systems (paging, cordless, cellular, mobile satellite) into a seamless radio infrastructure



From Handsets to Mobile Devices



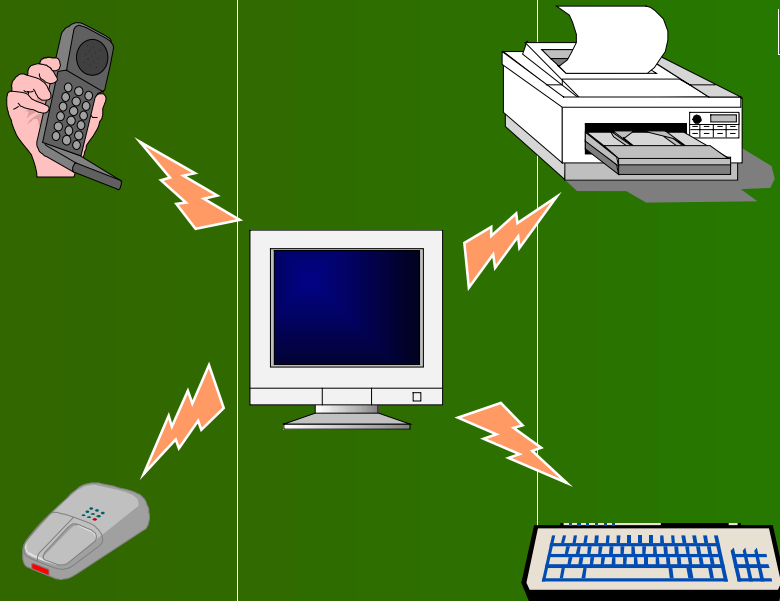
Berkeley Infopad,
1990-1996

Internet access the most important driver
(text, graphics, multimedia)

The Wire Replacement

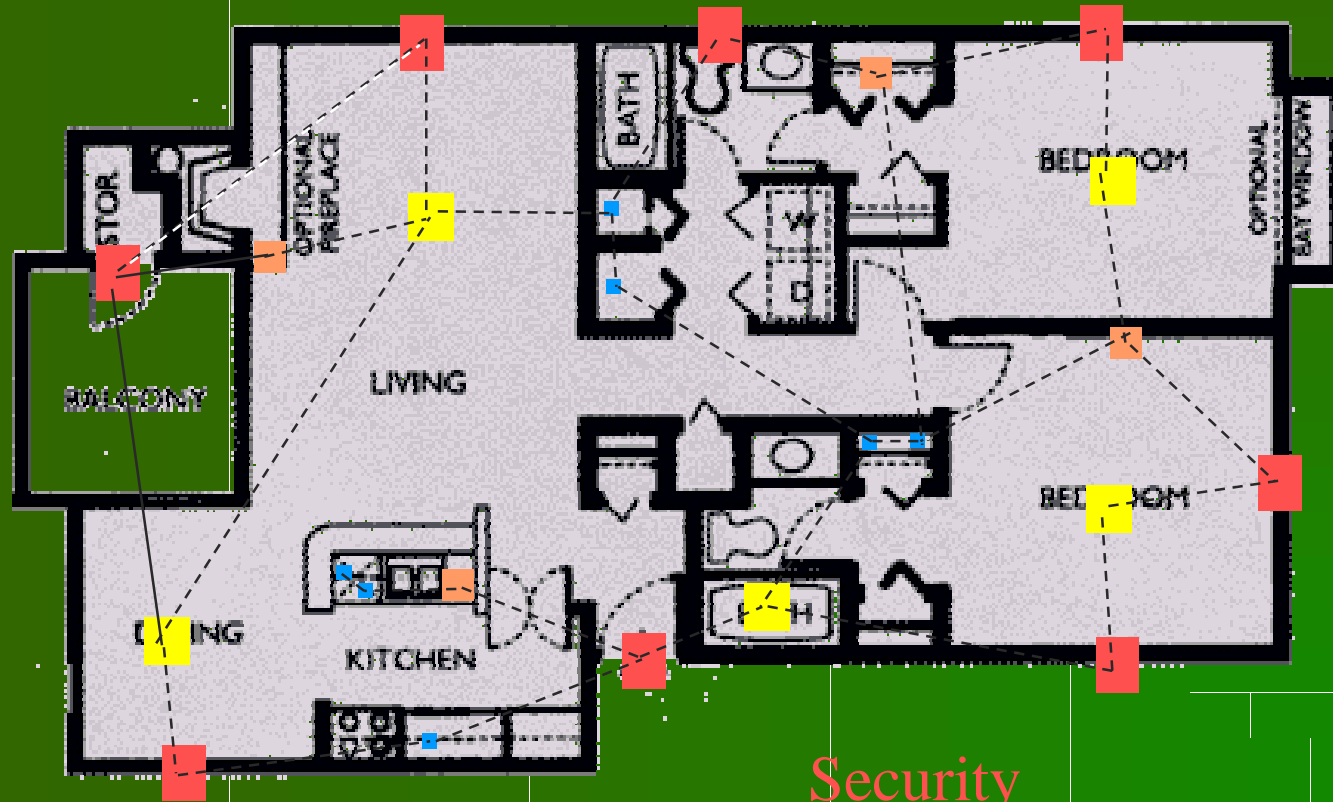
Example: Bluetooth

- Initiative by Intel, Ericsson, Nokia, IBM, and Toshiba
- Original Goal: provide wireless interface between PC and periphery based on picocell technology
 - Small cells of 10 m
 - 10 picoNets/cell
 - Located in ISM band (2.45 GHz) (as do microwave ovens)
 - Point-to-point network configuration
 - FFH/DS spread-spectrum radio's (1400 hops/sec)
 - 432 kbs full-duplex, 721/56 kbs asymmetric half-duplex
 - 0 dBm (1 mW) output power
 - 80 mW and 300 μ W in send- and listening modes, respectively



Other Approaches: HomeRF, HomeRF-lite, 802.11

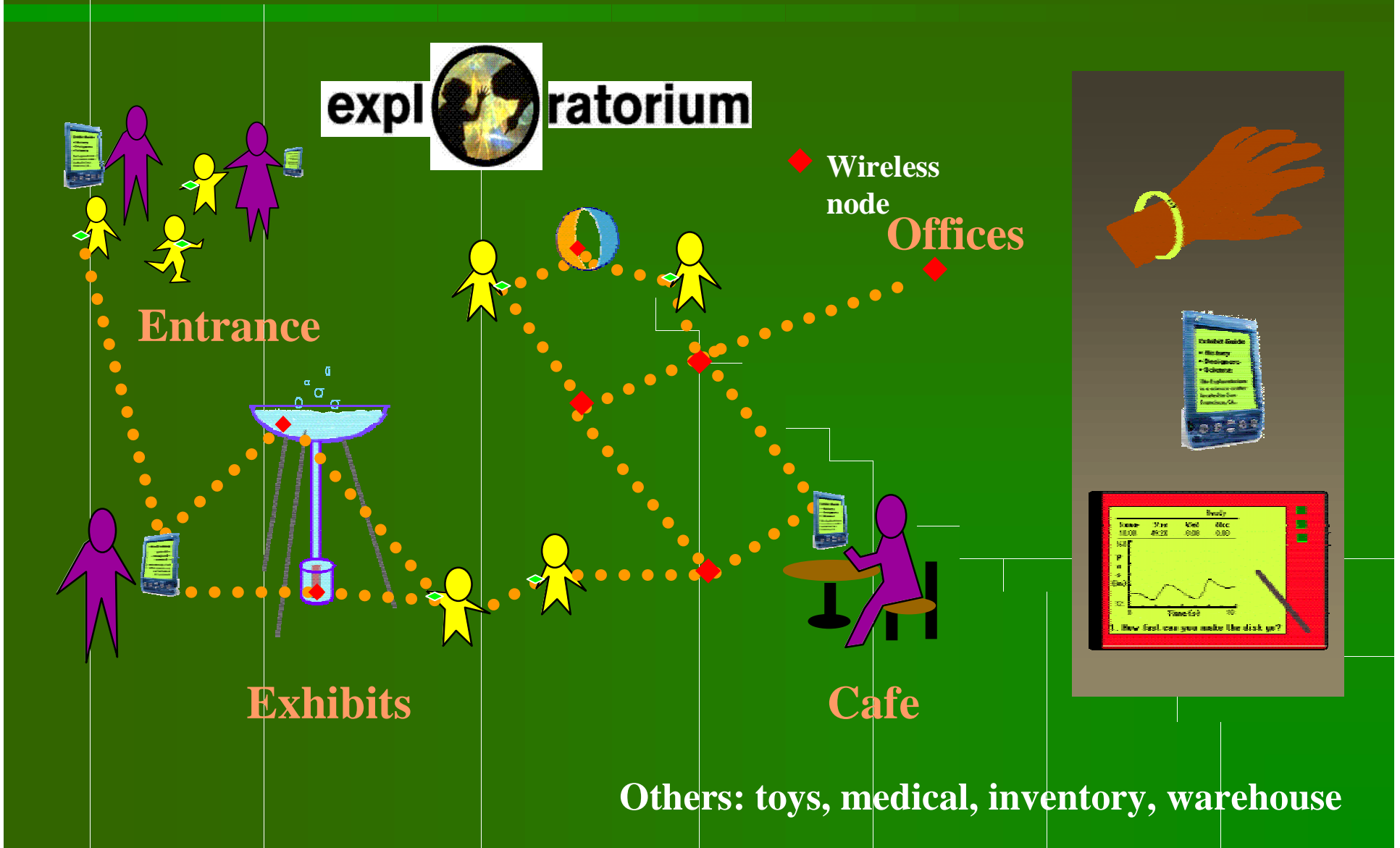
The Smart Home



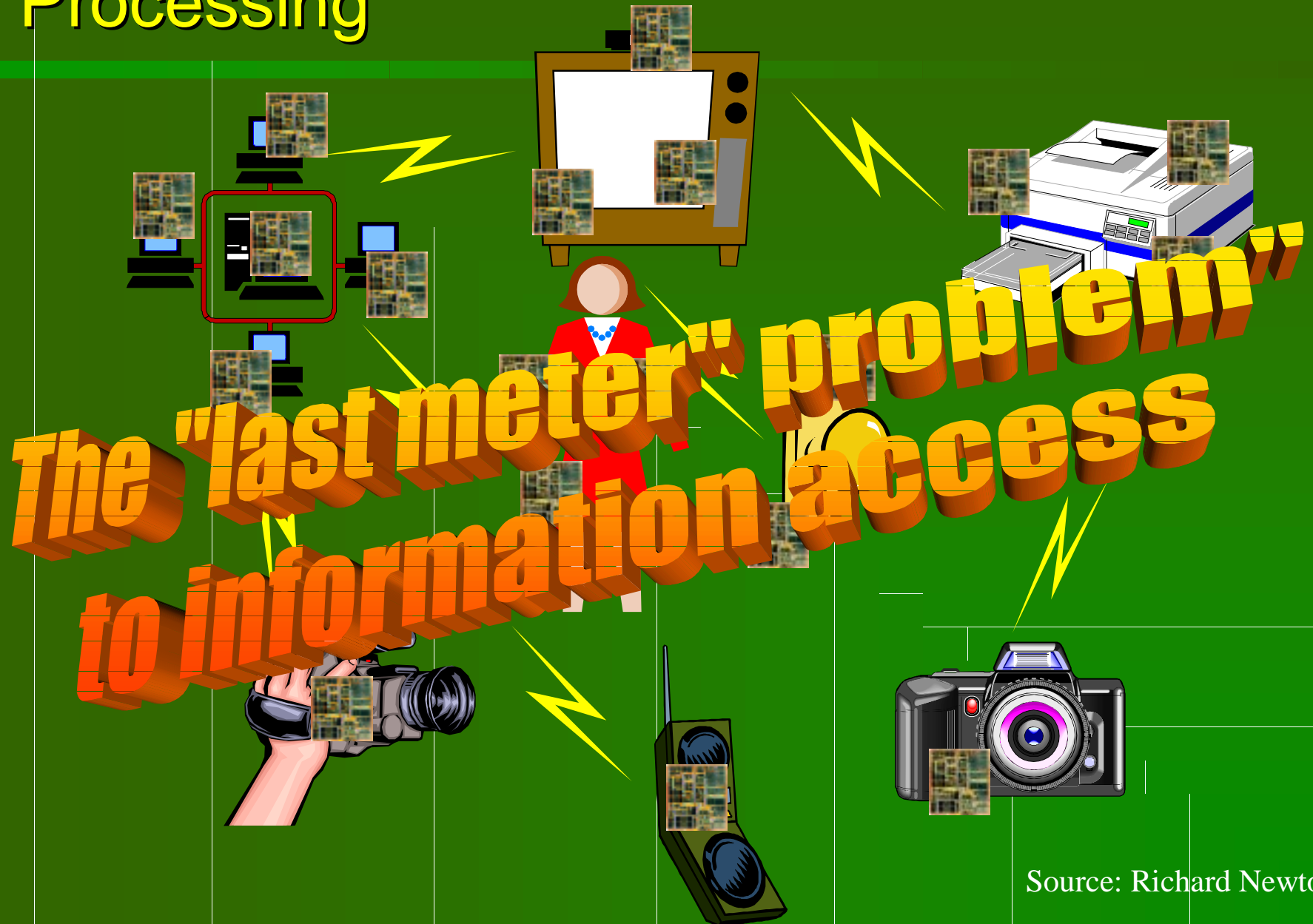
Dense network of
sensor and monitor nodes

Security
Environment monitoring and control
Object tagging
Identification

The Interactive Museum



The Distributed Approach to Information Processing



Source: Richard Newton

4th Generation Challenges

The BWRC Perspective

- Ubiquitous services put wireless spectrum at a premium
 - Effective use of ether hampered by standardization and fragmentation
 - Current spectral efficiency far below theoretical limits
- Ubiquitous wireless networking requires steep reduction in cost and energy dissipation
 - To be acceptable, radio cost has to be between 50 cents and 5\$
 - Frequent battery replacement on 100's of devices unacceptable

Spectrum at a Premium

The existing standards approach wastes spectrum and can't track the changes in implementation and usage

- CMOS implementation results in radio computational capabilities expanding with Moore's law (or even faster ...)
- Future applications are moving from well understood voice to data with unknown requirements
- Ad hoc, self organizing and inexpensive infrastructure moves wireless system implementation from providers to users

Universal Spectrum Sharing

- Provides a strategy (etiquette) for **peaceful uncoordinated coexistence** in unlicensed RF bands
- Allow a wide range of individual (local) system optimizations in a framework which yields fairness and globally maximal utilization
 - Have a minimum level of constraints to allow maximum flexibility in implementation
 - Allow rapid exploitation of new technologies
 - Be extensible to new applications

Example Etiquette

- Use transmit power as a constraint which encourages “good behavior”
- Good behavior means
 - *localization* in time-frequency-spatial signal space which allows other users to coexist without interference
 - *stationary* or predictable behavior which facilitates adaptation by other users
 - *alignment* to a time and frequency structure which facilitates co-existence

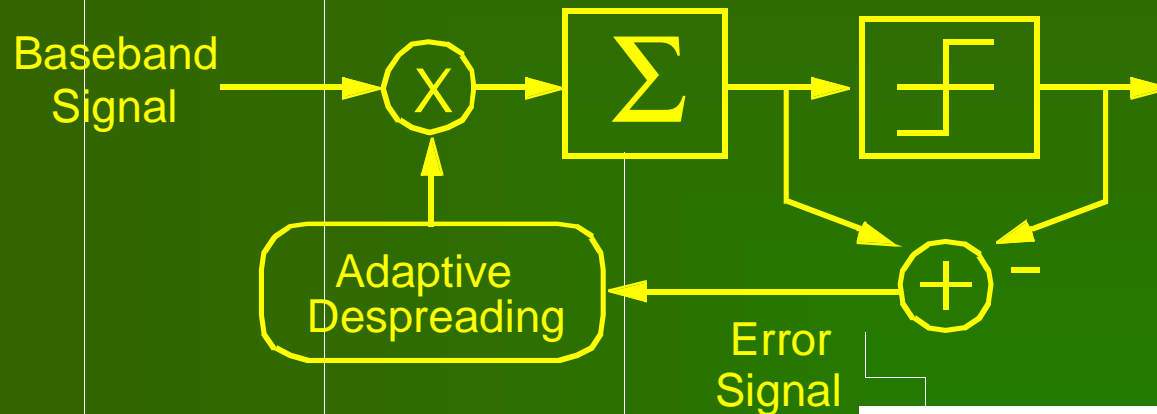
Enabled by Progress in Communication Theory and Algorithms

- Multipath-Fading Mitigation
- Multipath-Fading Exploitation
- Interference Suppression
- Interference Avoidance
- Channel Error-Control Coding
- Adaptive Transmission Rate

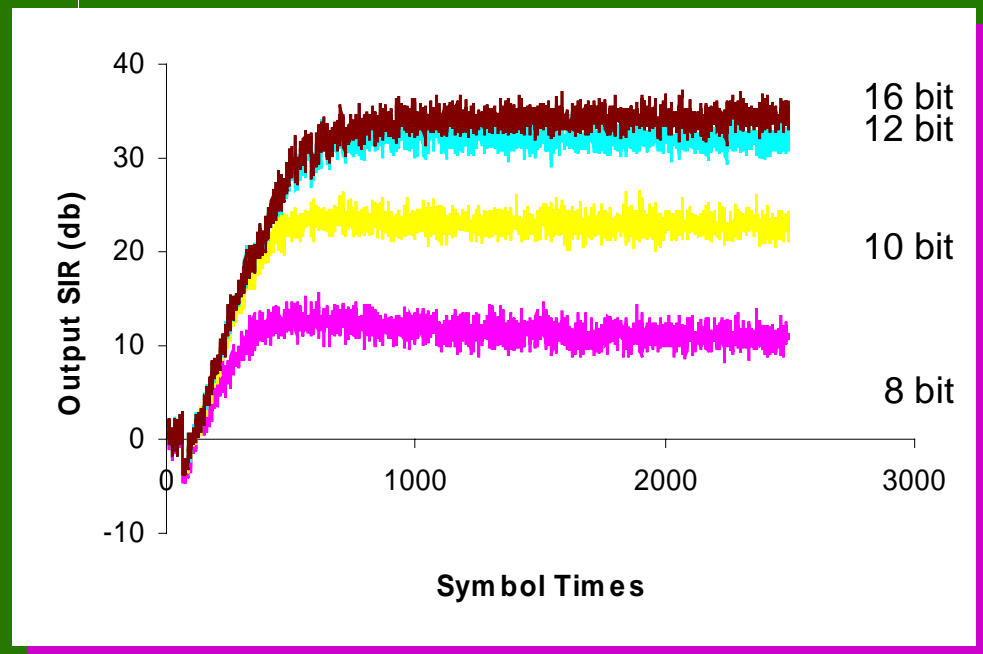
Motivations

- Increase system data rate without sacrificing any bandwidth
- Relax requirements in speed and/or power of the analog circuitry of TX and RX
- Increase reliability through (spatial) diversity

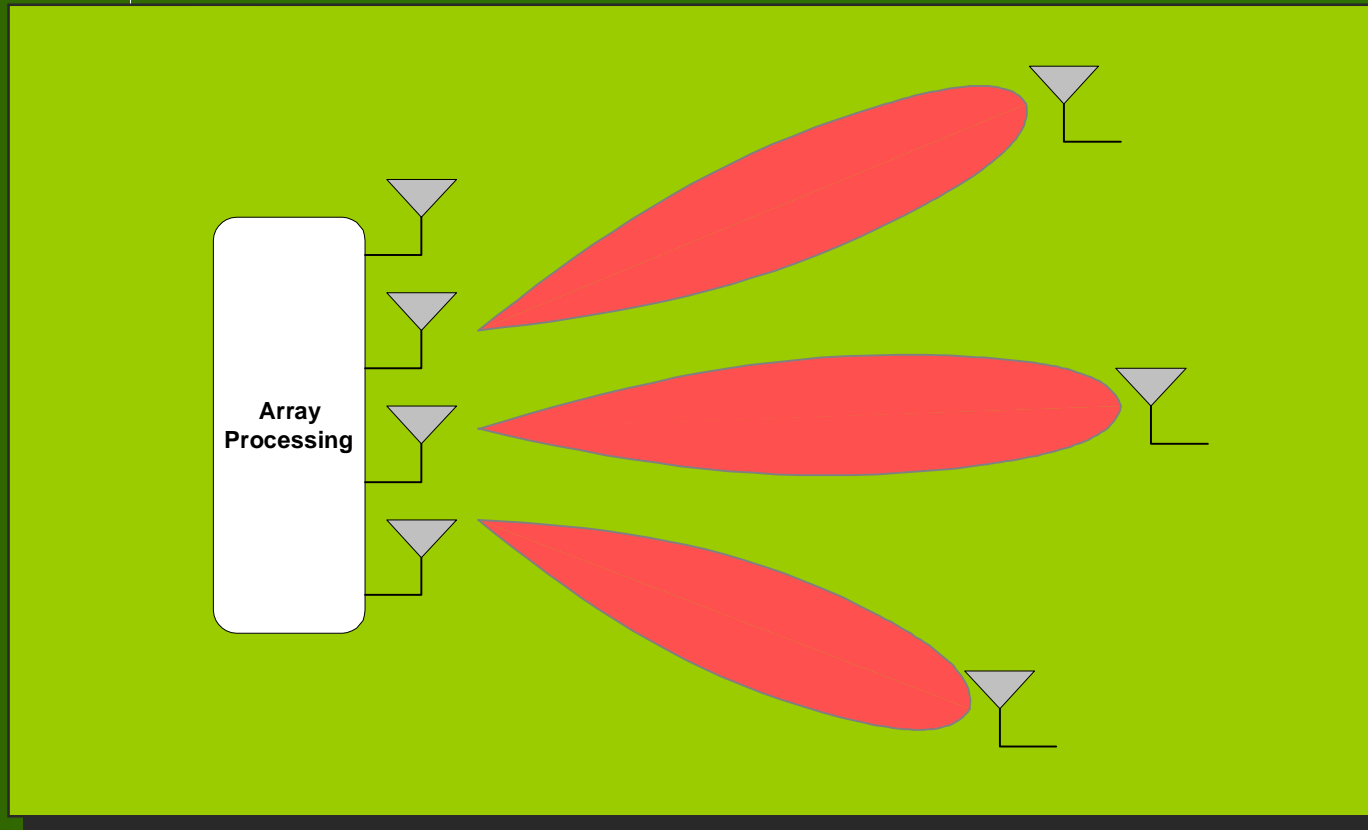
Example 1: Adaptive Multi-User Detection for CDMA



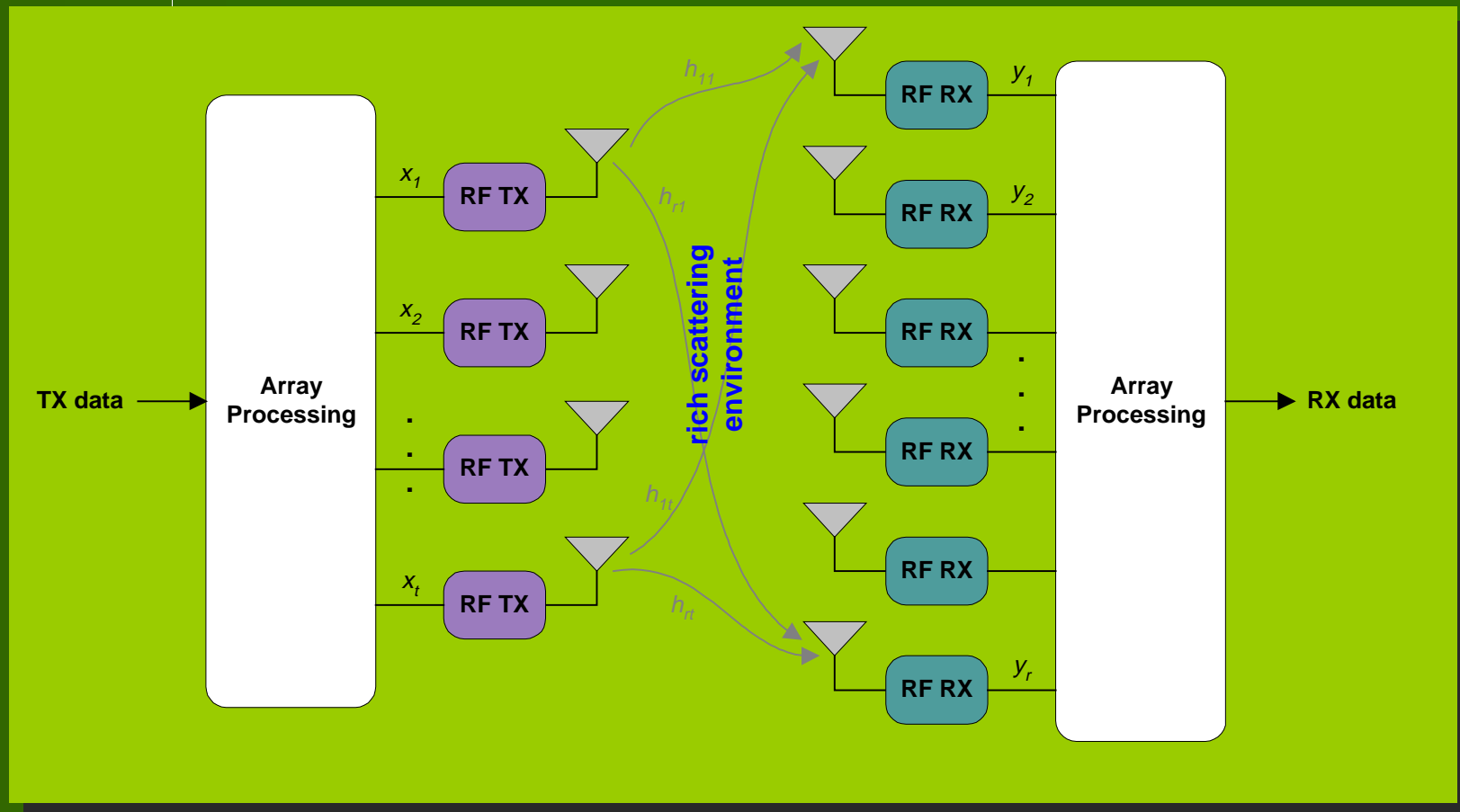
- Tracks changes in channel, environment, and interfering users
- Uses common error metrics such as MSE, and common algorithms such as LMS and RMS



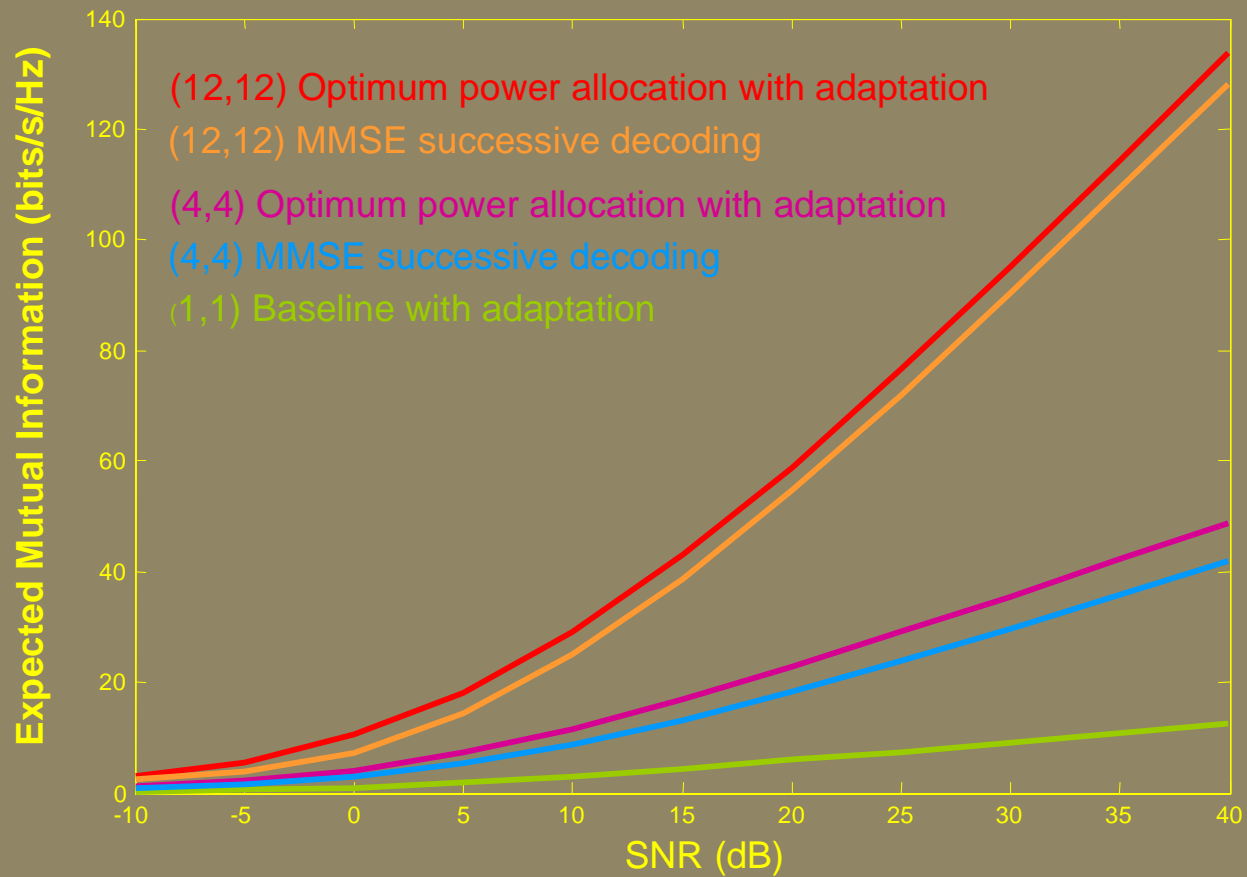
Example 2: Spatial Channels



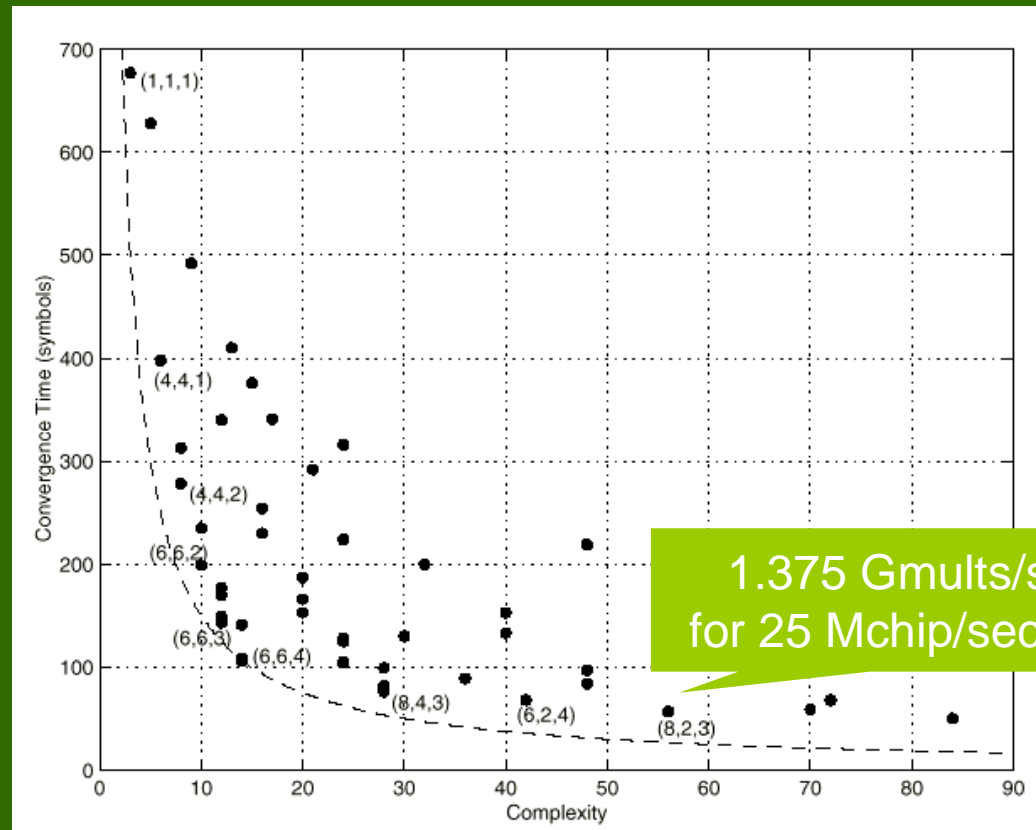
Multiple Antennae System



Capacity Gain



The Down side: Algorithmic Complexity



1.375 Gmults/sec
for 25 Mchip/sec rate

Block RLS using Gram-Schmidt Decomposition

Digital Baseband Processing Requirements

	Wide-band CDMA			FDMA Multiple Antenna
	Matched Filter	Blind MMSE	Exact Decorrelator	SVD
Performance Bits/sec/Hz	1	2	2	6
Multiplications	124	496	230,000	736
Memory	248	1240	640,000	2120
ALU	124	502	240,000	800
Word Length	8-bit	12-bit	16-bit	16-bit

Silicon technology tracking Moore's Law

Silicon in 2010

Die Area: 2.5x2.5 cm

Voltage: 0.6 - 0.9 V

Technology: 0.07 μm

	Density (Gbits/cm ²)	Access Time (ns)
DRAM	8.5	10
		10
		1.5

2.5 times memory
5 times clock rate

	Density (Mgates/cm ²)	Max. Power (W/cm ²)	Clock Rate (GHz)
Custom	25	54	3
Std. Cell	10	27	1.5
Gate Array	5	18	1
Single-Mask GA	2.5	12.5	0.7
FPGA	0.4	4.5	0.25

NTRS Processor 2010



Pentium II @ 2010

Devices: 7,500,000

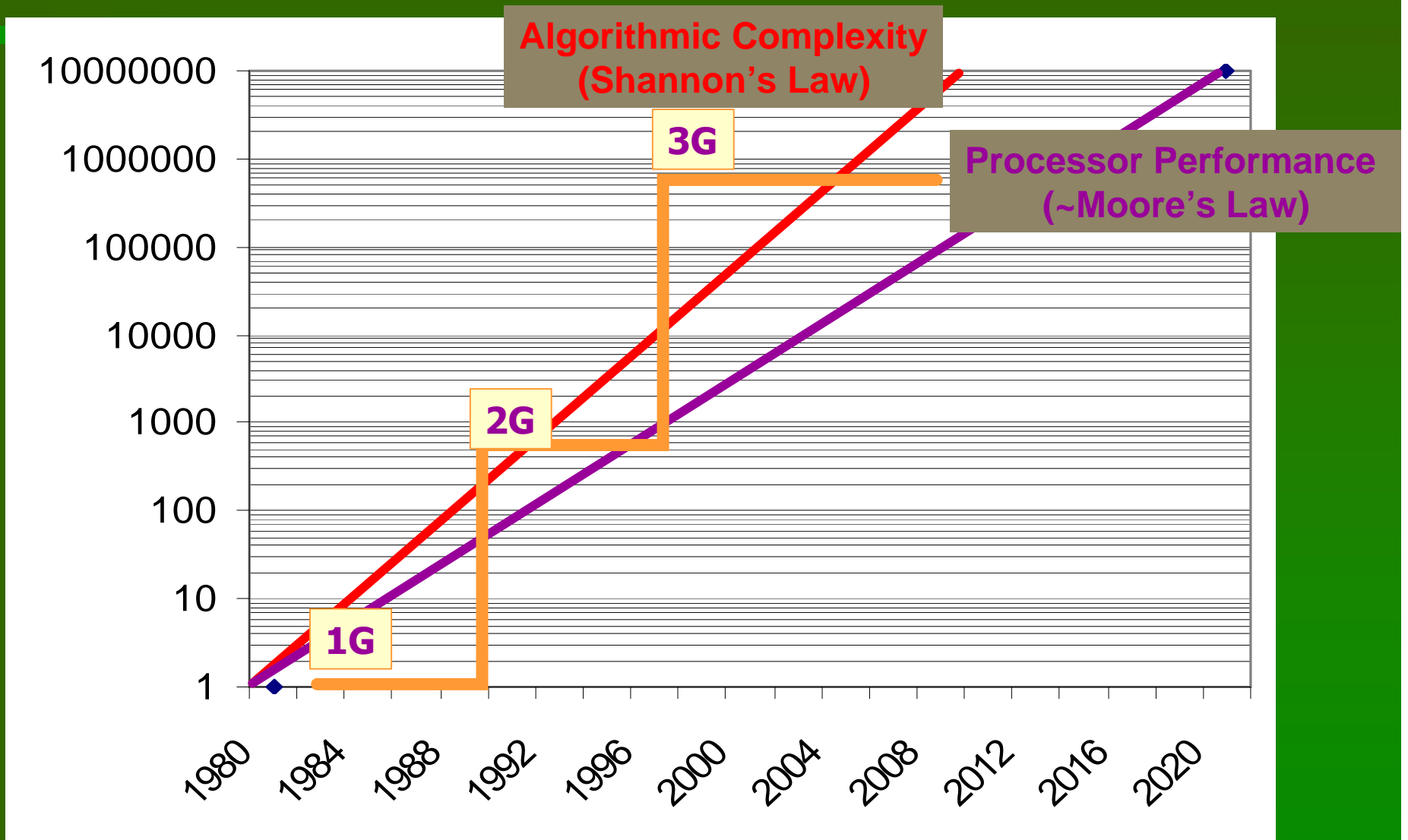
Devices: 900M

Performance > 50 GOPS 1 GHz for 200mW

Power Dissipation: 175W²

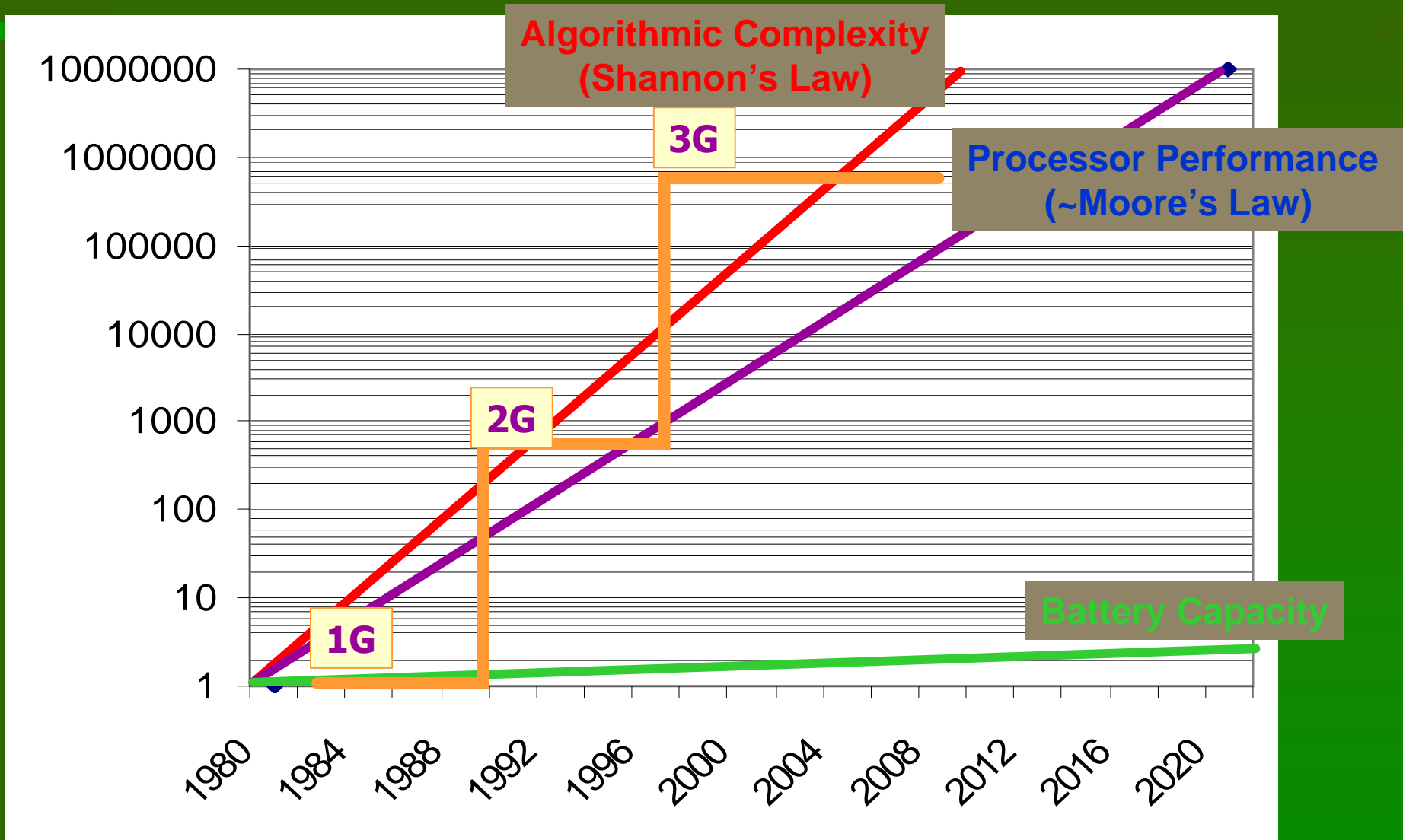
Chip Size: 6mm²

Shannon beats Moore's law



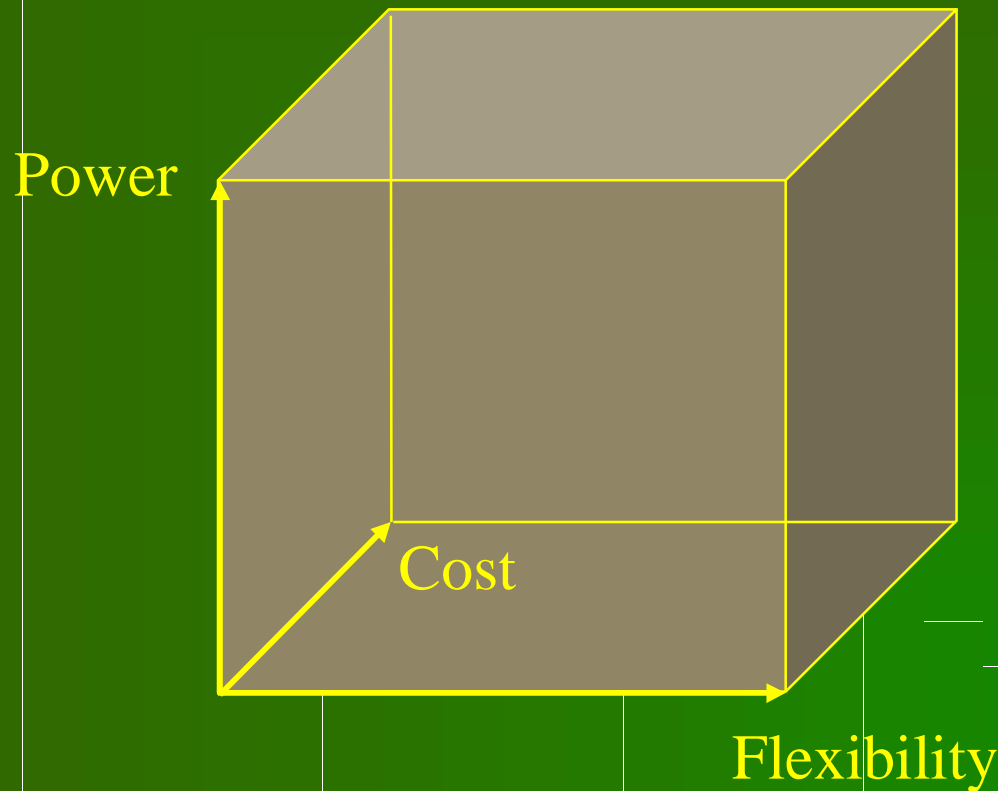
Courtesy: Ravi Subramanian, morphICs Tech. Inc

Energy to Play a Major Role



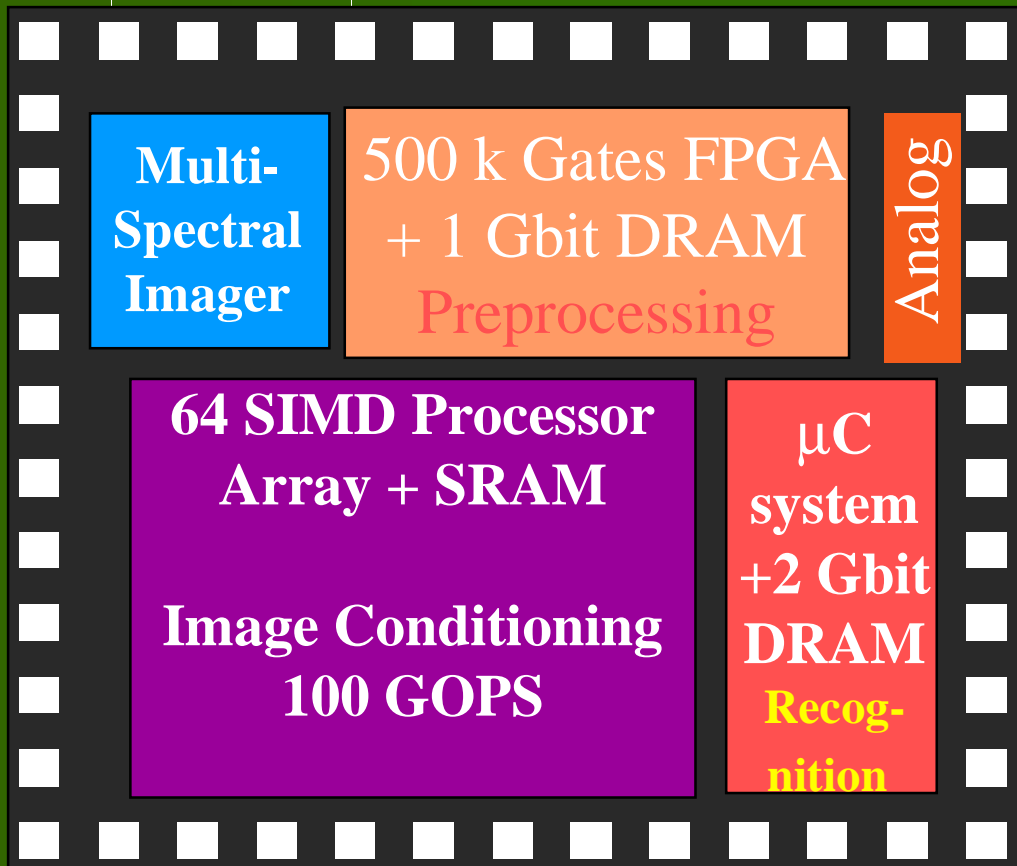
Courtesy: Ravi Subramanian, morphICs Tech. Inc

Wireless System Design Metrics



**Performance as a Functionality Constraint
("Just-in-Time Computing")**

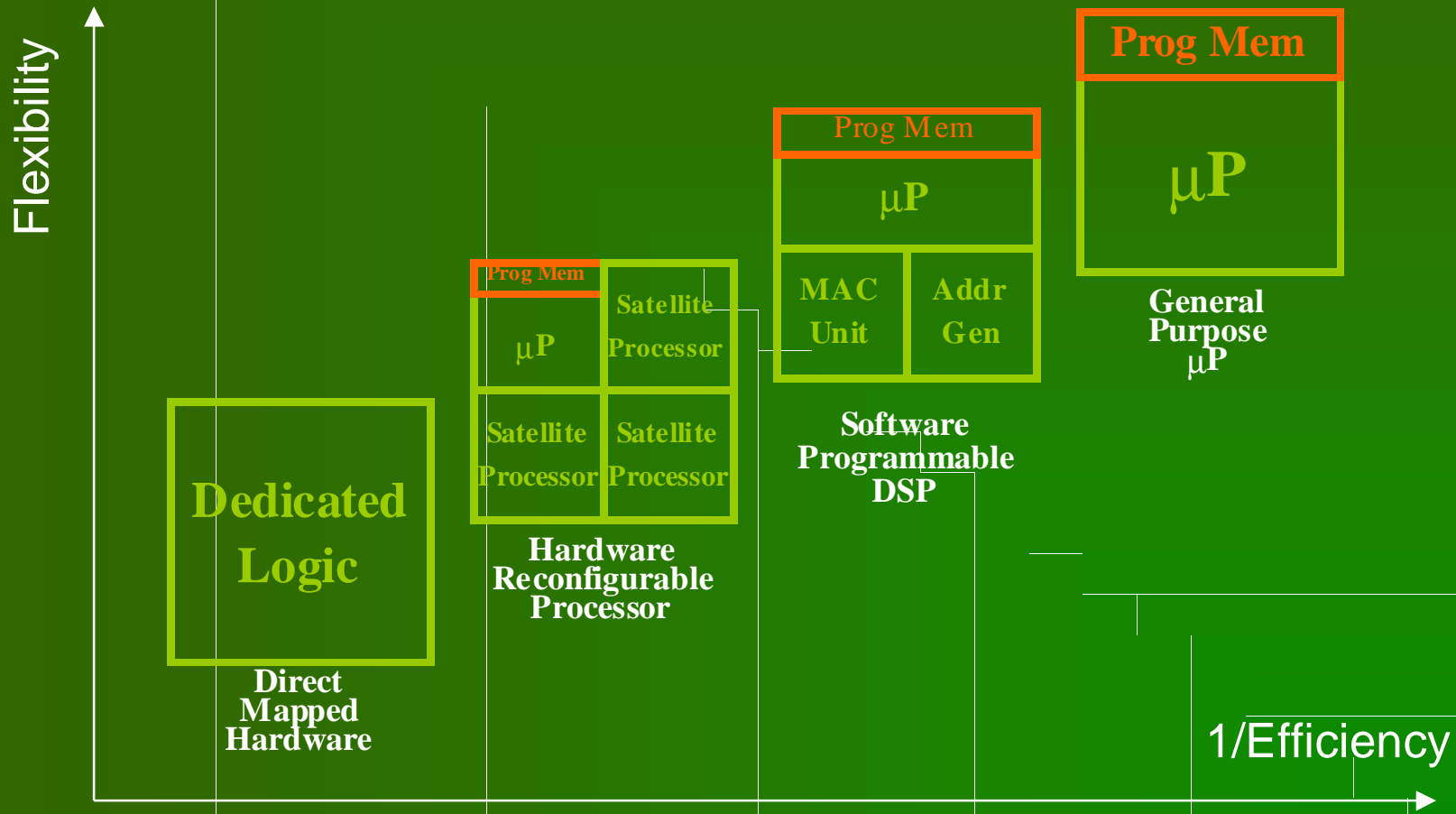
The System-on-a-Chip



SOC anno 2010

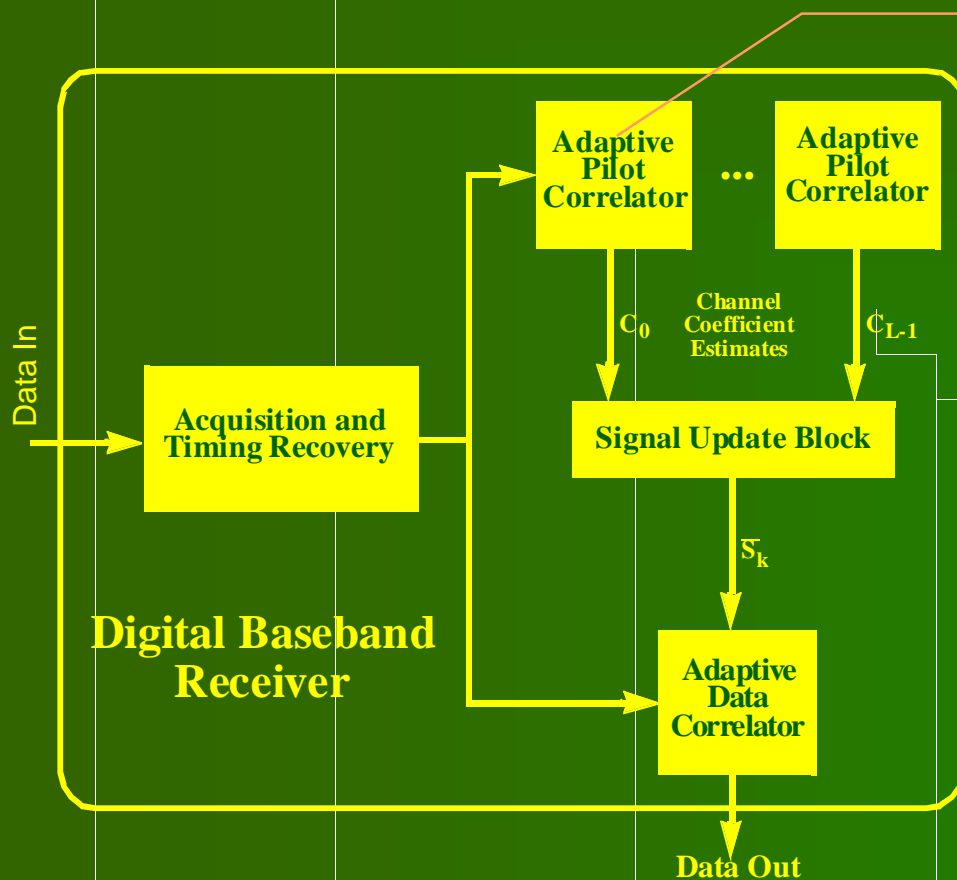
- Embedded applications where **cost, performance, and energy** are the real issues!
- DSP and control intensive
- Mixed-mode
- Combines programmable and application-specific modules
- Software plays crucial role

Picking the Correct Architecture



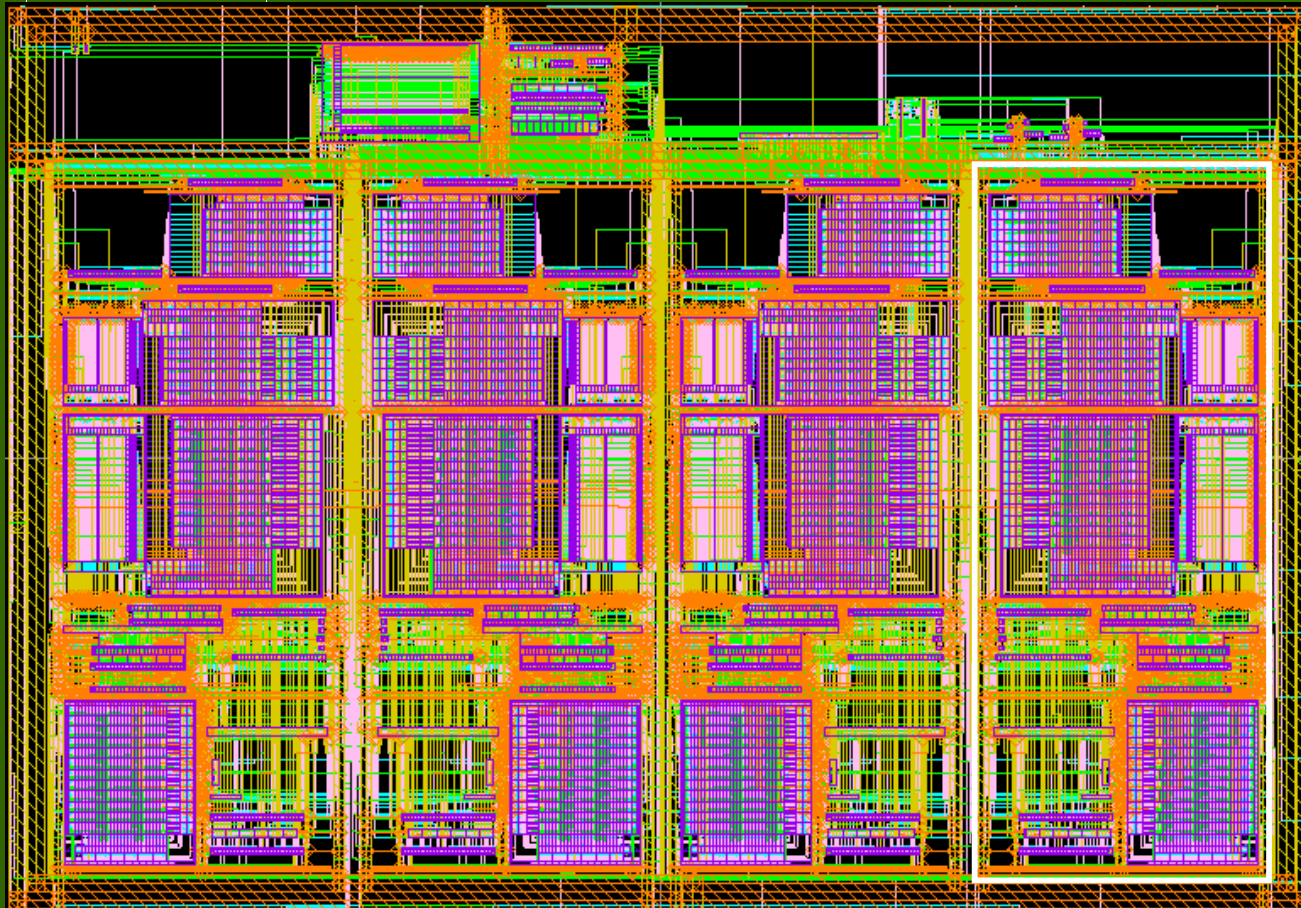
Choosing the Correct Implementation Architecture

300 million multiplications/sec
357 million add-sub's/sec



	DSP Implementation	Direct Mapped Implementation
Adaptive Pilot Correlator	Power Consumption: 460mW Area: 1089mm ²	Power Consumption: 3mW Area: 1.3mm ²
Digital Baseband Receiver	Power Consumption: 1500mW Area: 3600mm ²	Power Consumption: 10mW Area: 5mm ²

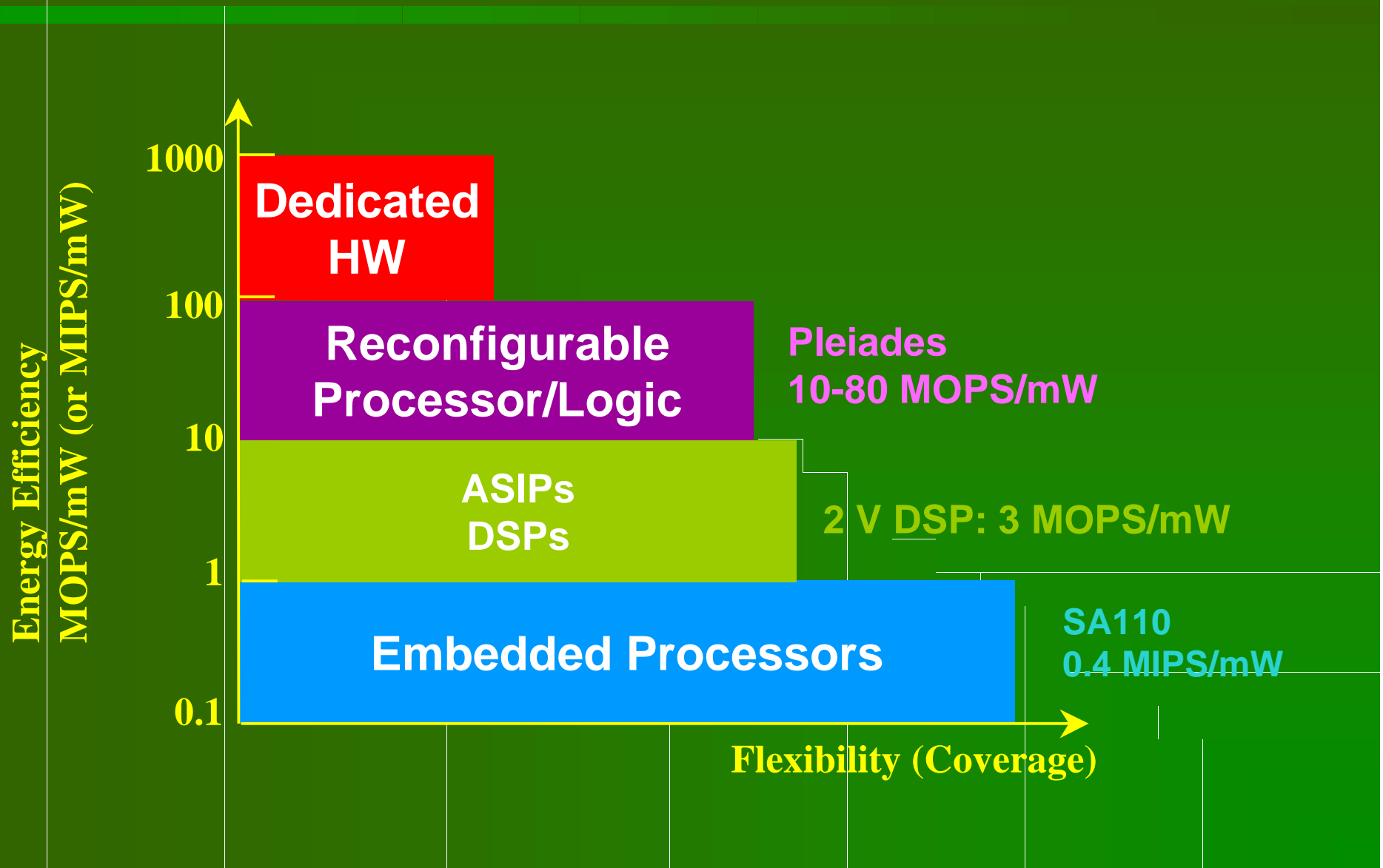
Adaptive Multi-User Detection A Direct Mapping Approach



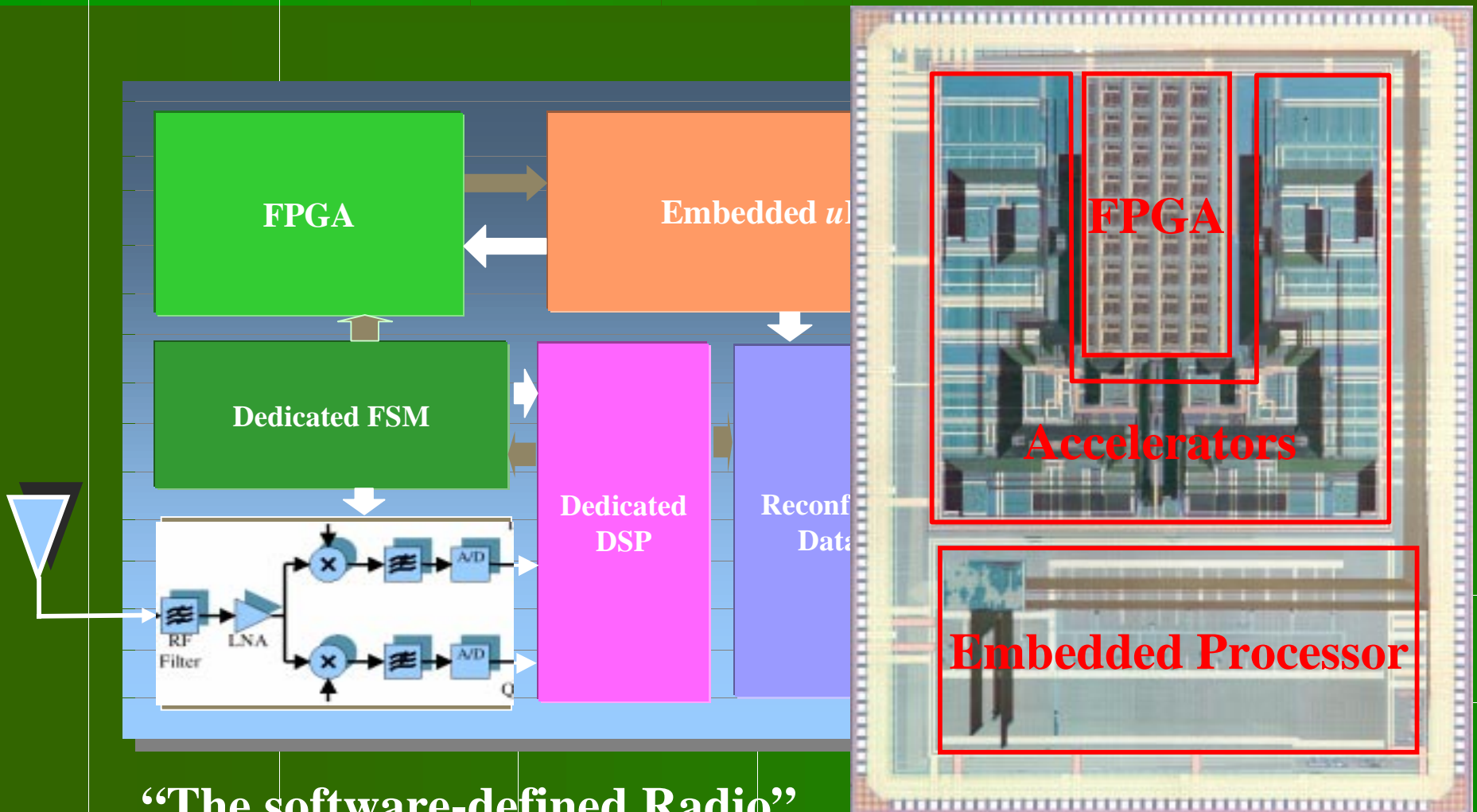
Correlator

Power and area are dominated by MACs and multipliers
Only 36% of power of DSP-processor solution going into arithmetic

The Energy-Flexibility Gap



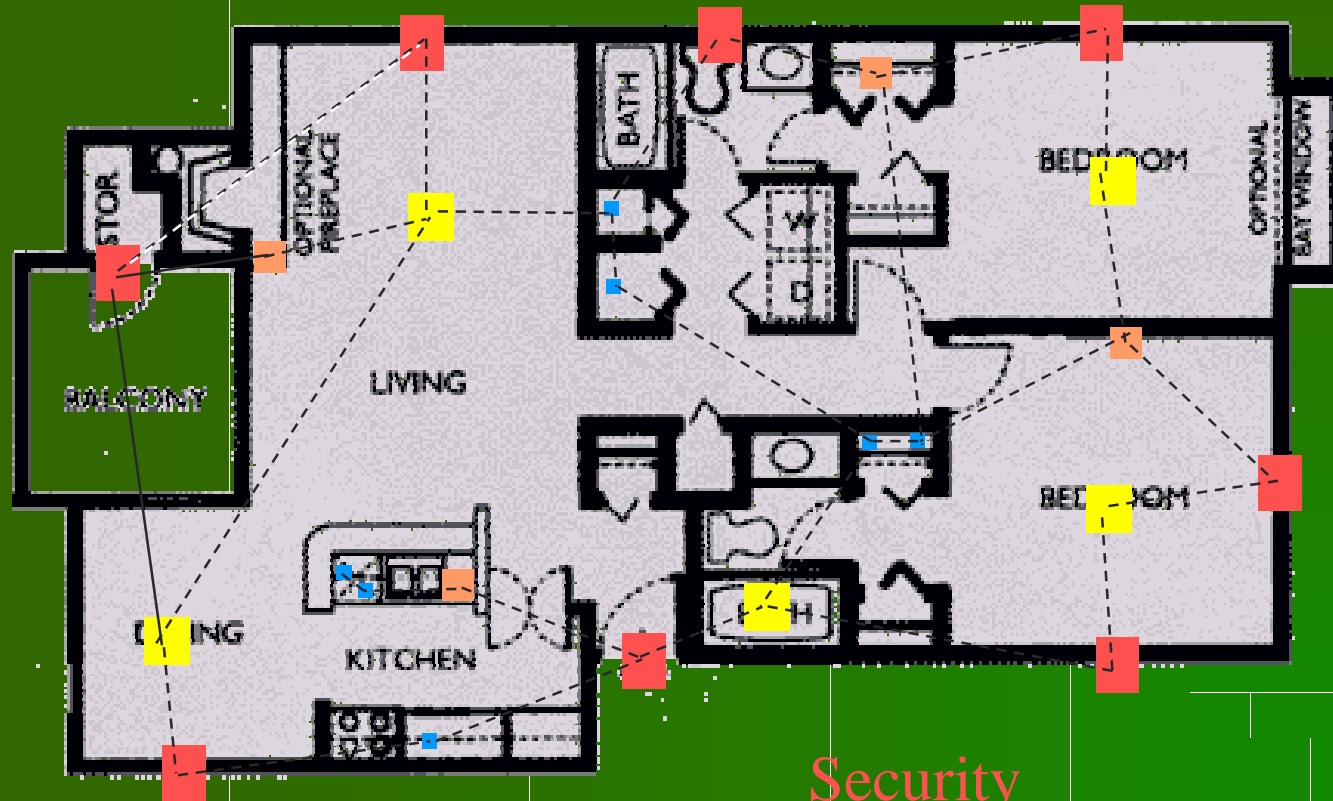
Future Wireless Modem



“The software-defined Radio”

Example: Berkeley Maia Processor

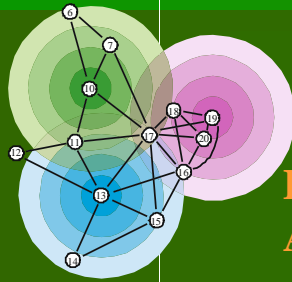
The Energy Problem Revisited



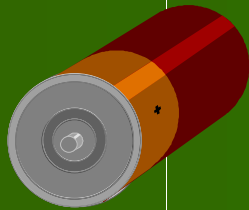
Dense network of
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Security
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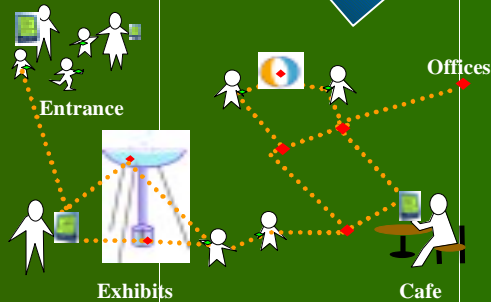
Energy Minimization starts at the System Level



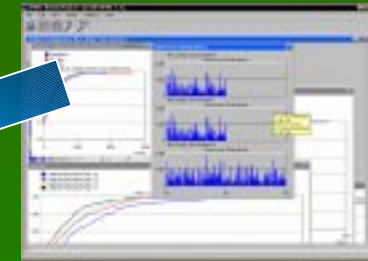
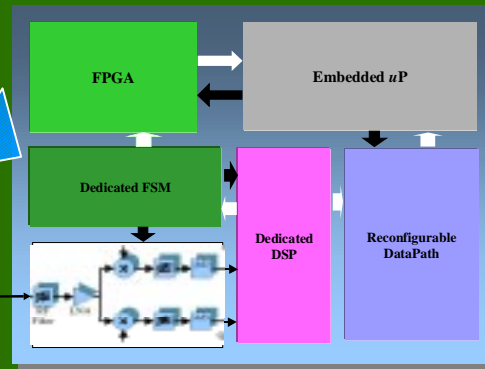
Positioning Network Architecture



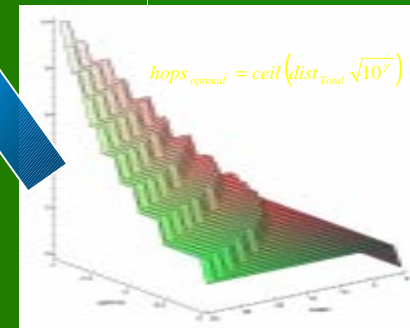
Energy Constraints



Use Cases

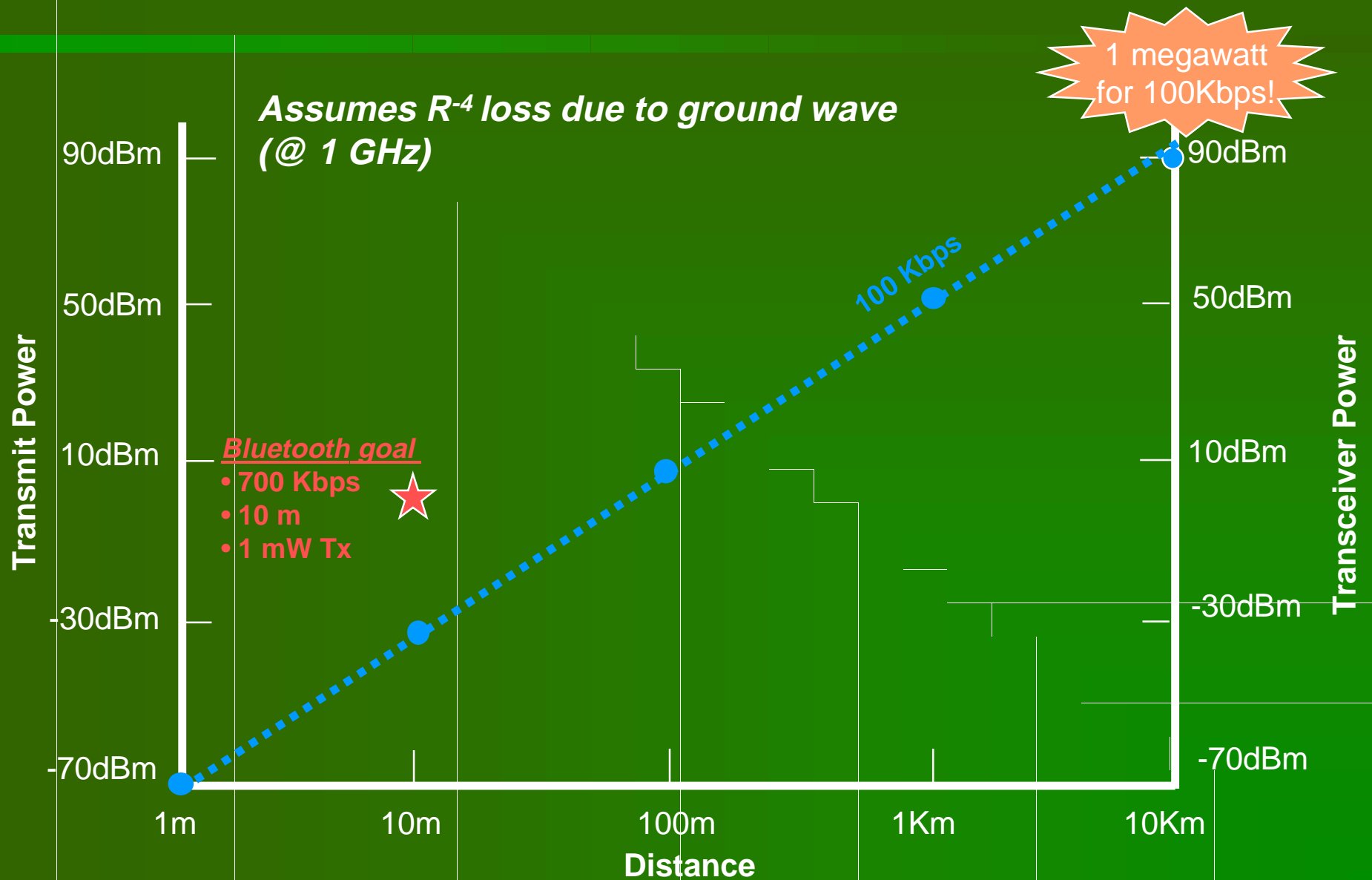


Traffic Analysis



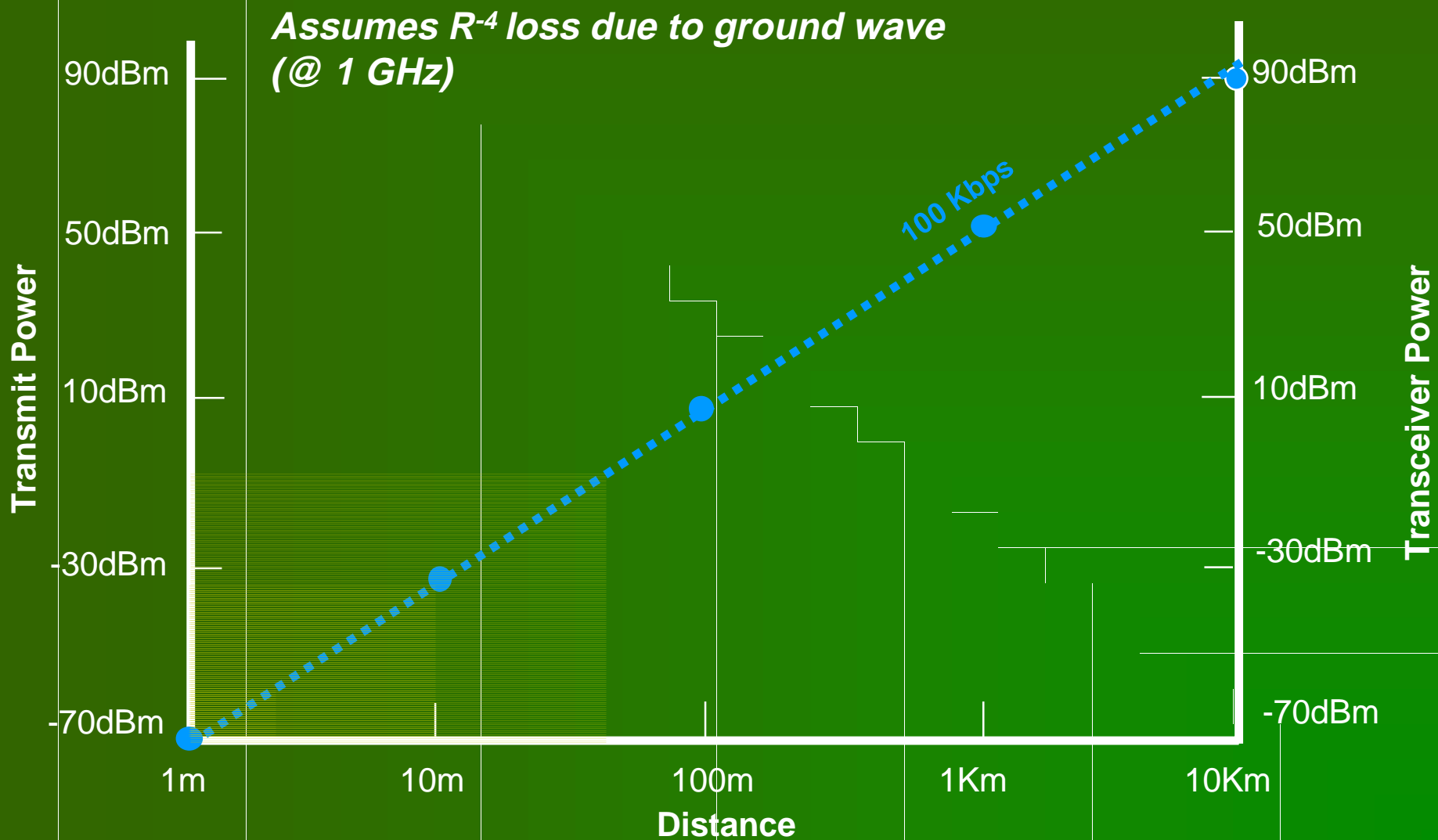
Environment Analysis

The Cost of Communication



PicoRadio Energy Optimization

The Varying Communication Distance



Communication versus Computation

- Computation cost (2004): 60 pJ/operation
- Communication cost (thermal energy minimum):
 - 100 m distance: 20 nJ/bit @ 1.5 GHz
 - 10 m distance: 2 pJ/bit @ 1.5 GHz
- Computation versus Communications
 - 100 m distance: 300 operations == 1 bit
 - 10 m distance: 0.03 operation == 1 bit

Computation/Communication requirements vary with distance, data type, and environment

Requires Adaptive and Time-Varying Solution!

Communicating over Long Distances

Multi-hop Networks

Source



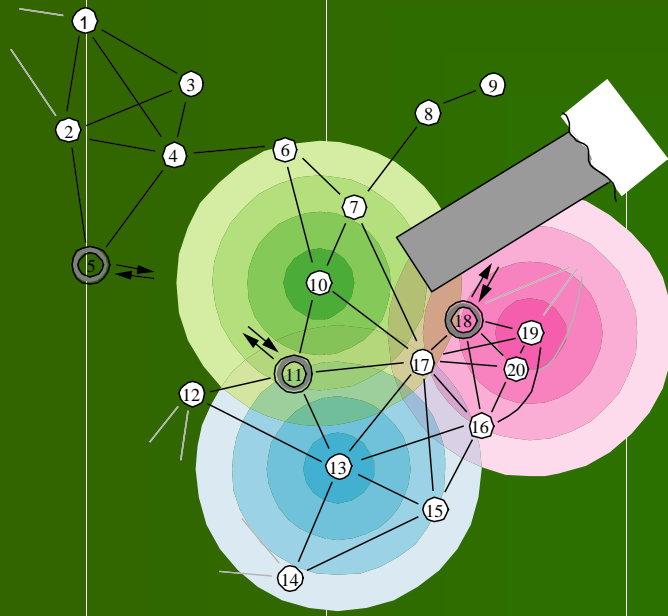
Dest



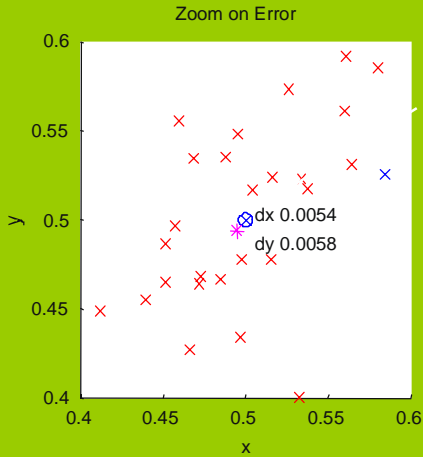
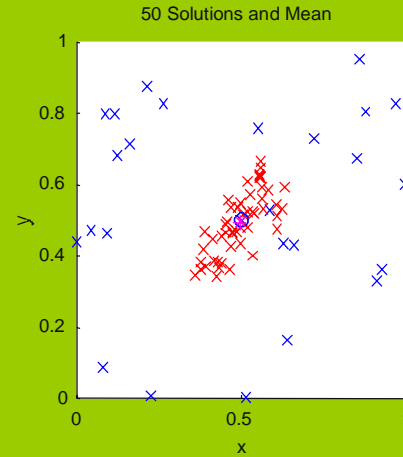
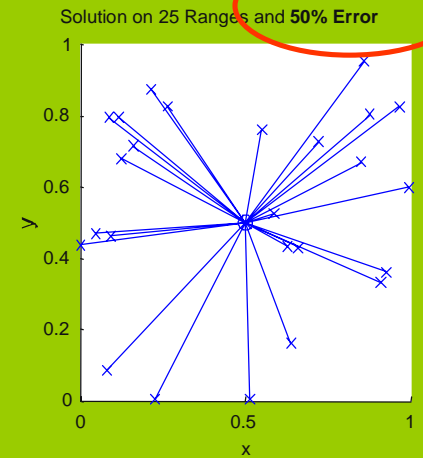
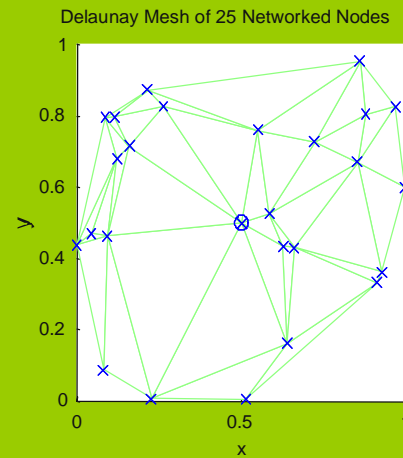
Example:

- 1 hop over 50 m
1.25 nJ/bit
- 5 hops of 10 m each
 $5 \times 2 \text{ pJ/bit} = 10 \text{ pJ/bit}$
- Multi-hop reduces transmission energy by 125!
(ignoring overhead and cost of retransmissions)

Joined Networking-Positioning



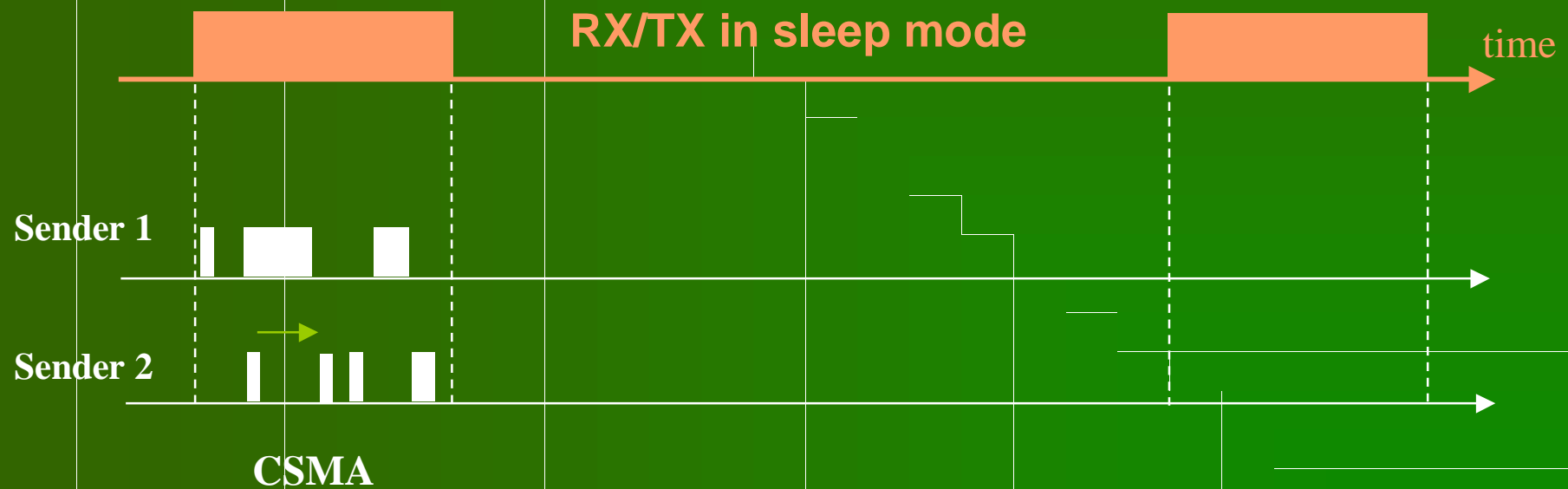
- Ubiquitous radio networks offer accurate localization with minimal overhead
- Potential to substantially reduce networking overhead!



1% error

Maximizing Sleep Mode

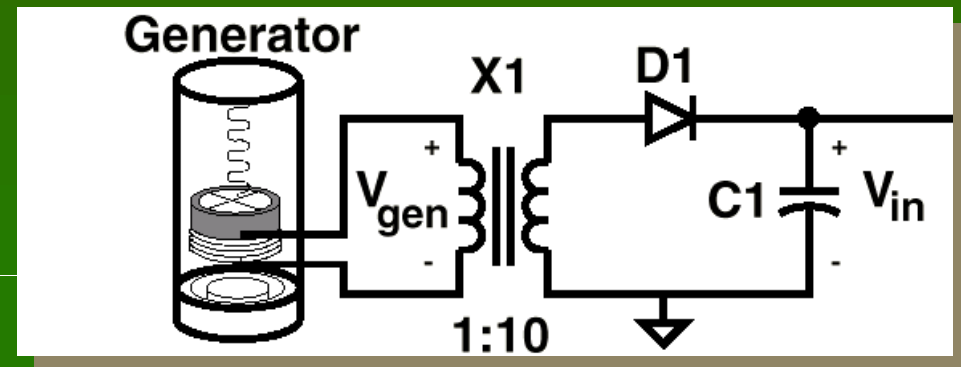
Best addressed at the **media-access** (MAC) layer of the protocol stack



Example: Collision-sense multiple access (CSMA) with overlaid locally-synchronized TDMA framing

The Holy Grail: Energy Scavenging

Energy Sources	Power (Energy) Density
Batteries (Zinc-Air)	1050 -1560 mWh/cm ³
Batteries (rechargeable Lithium)	300 mWh/cm ³ (3 - 4 V)
Solar	15 mW/cm ² - direct sun 1mW/cm ² - ave. over 24 hrs.
Vibrations	0.05 - 0.5 mW/cm ³
Inertial Human Power	
Acoustic Noise	3E-6 mW/cm ² at 75 Db 9.6E-4 mW/cm ² at 100 Db
Non-Inertial Human Power	1.8 mW (Shoe inserts)
Nuclear Reaction	80 mW/cm ³ 1E6m Wh/cm ³
One Time Chemical Reaction	
Fluid Flow	
Fuel Cells	300 - 500 mW/cm ³ ~4000 mWh/cm ³



Integrated micro-vibrator provides 10-100 μ W of free power (equivalent to 2340 free DSP operations/sec) [Amirtharajah & Chandrakasan, DISPS99]

Summary

- Wireless communications is in for a tremendous growth in the next decade
- The opportunity lies in the “last meter”: providing access to ubiquitous distributed sensor, monitor and access devices
- Energy, cost, and spectrum limitations open the door for novel and innovative system concepts and implementations
- The sky (air) is really the limit