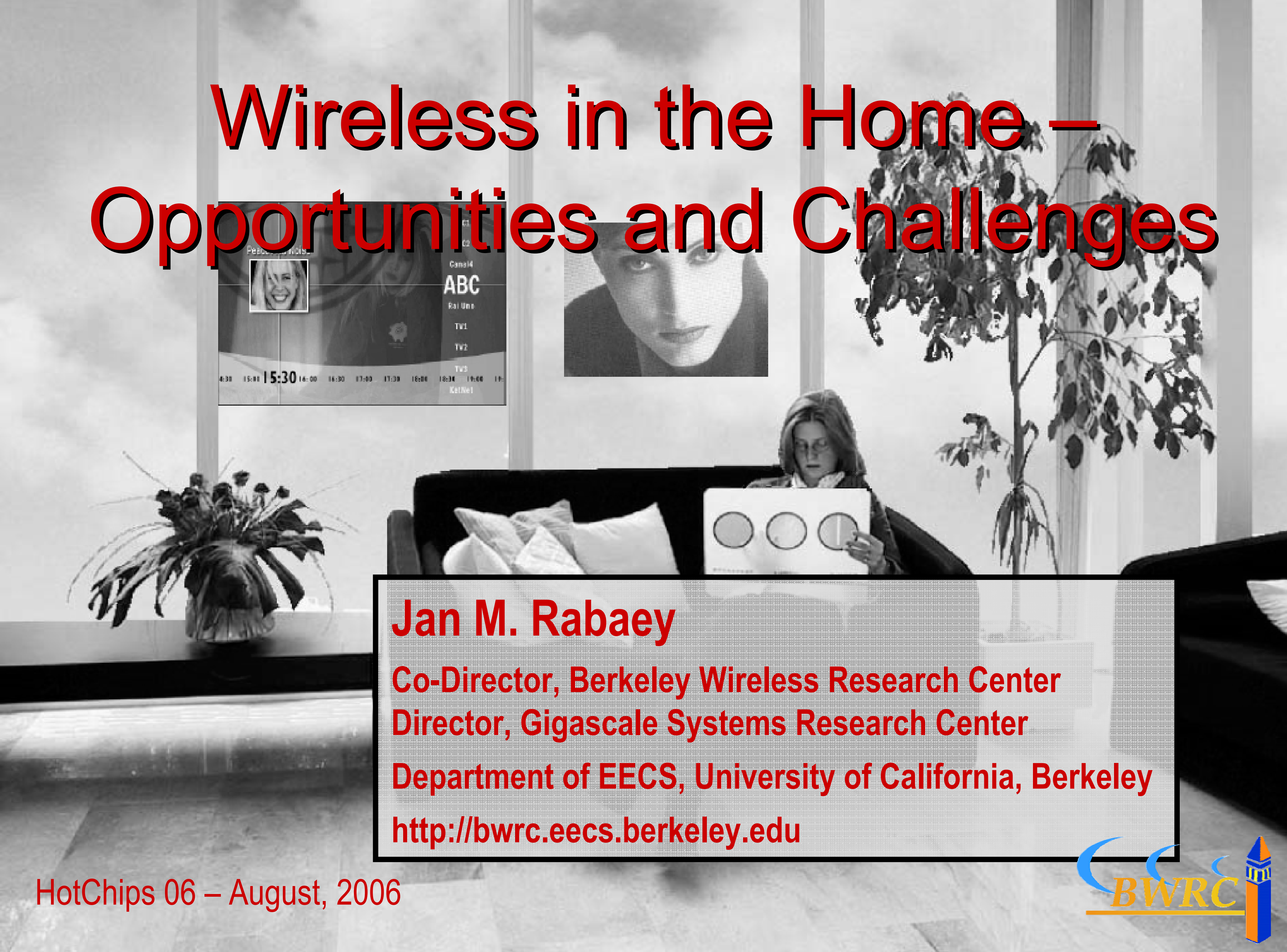

Wireless in the Home – Opportunities and Challenges

Jan M. Rabaey

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http://bwrc.eecs.berkeley.edu

HotChips 06 – August, 2006

Acknowledgements

- The contributions of Danijela Cabric, Domine Leenaerts (Philips), Ali Niknejad, Bob, Brodersen, John Wawrzynek, Yuri Markovski, Chris Baker and Adam Wolisz to this tutorial are greatly acknowledged.

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Berkeley Wireless Research Center (BWRC)

A Partnership of UC Researchers, Industry, and Government

Goal: Explore challenges and opportunities for
Future Integrated Wireless Systems in a pre-competitive setting

- **Participating Members**
  - Agilent Technologies
  - Cisco Systems
  - Conexant Systems
  - Hitachi Ltd
  - Infineon Technologies
  - Intel Corporation
  - STMicroelectronics
  - Samsung Electronics
  - Sun Microsystems
  - Toshiba
- **Associate Members**
  - Atmel Corporation
  - Cadence Design Systems
  - Ericsson Radio Systems
  - Fujitsu Laboratories
  - Hughes Research Labs
  - NEC Corporation
  - Philips Research
  - Qualcomm Incorporated
  - Synopsys, Inc
  - Texas Instruments
  - Xilinx Incorporated

- 60+ Graduate Students, 11 Faculty
- 11,000 ft^2, Downtown Berkeley, 1 block from campus
- Approx M$ 6 budget

Wireless – What Comes Into Mind

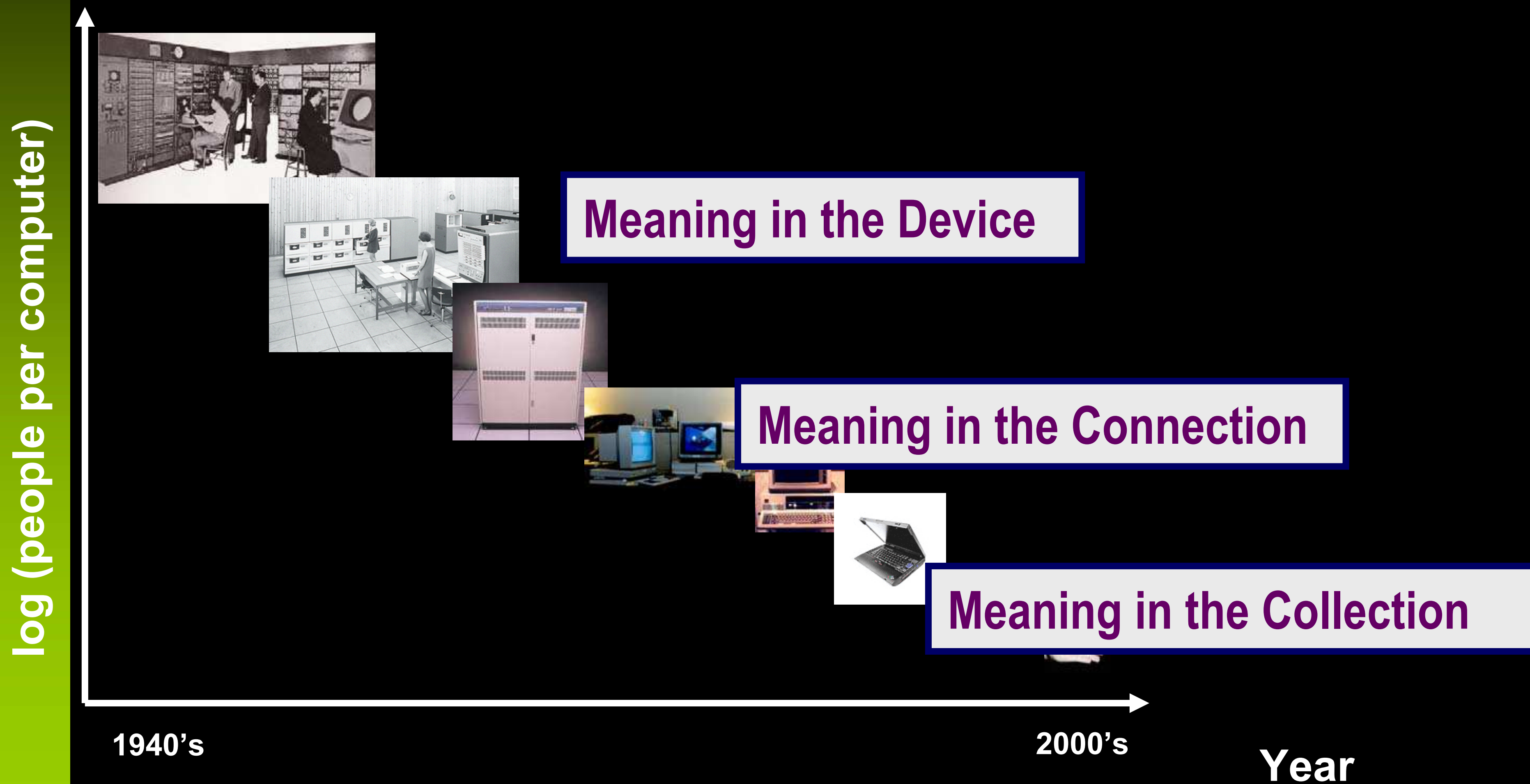
This is not what this tutorial is all about …

The Real Future of Wireless Infrastructure

Ubiquitous Wireless Multimedia Networking

Value is in ad-hoc connection of gadgets, not in individual components (…)

Bell's Law: A New Computer Class Every 10 Years



Courtesy: R. Newton

The Real Future of Wireless Infrastructure

- **All multimedia (consumer) components of the future WILL support some type(s) of wireless connectivity**
  - Avoid the cost of wiring
  - Easier deployment and expansion
  - Enable mobility – no more “men on a leash”
  - Enable “collaborative” paradigms
- **The number of components connected this way will by ORDERS OF MAGNITUDE exceed the number of cell phones!**

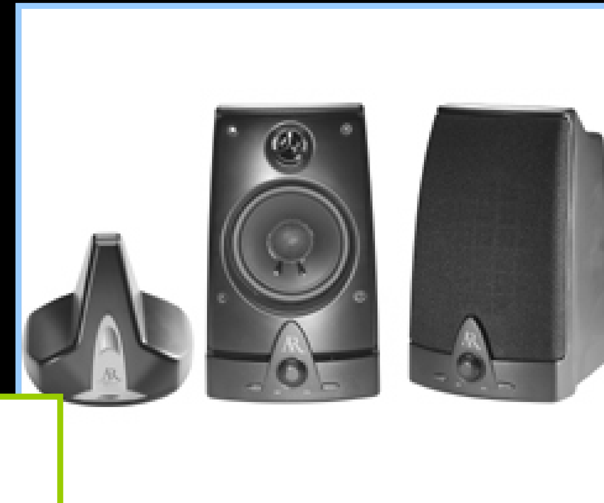
Wireless infrastructure developments should be driven by the demands of such an environment

BWRC

The Consumer World is Taking Notice

Sony 802.11 TV

Sony Wireless Speakers (900 MHz)



Philips 802.11 TV Tuner

NEC 3G/802.11 cell phone

Canon Wireless Camera

Enabling "Ambient Intelligence"

- An environment where technology is embedded, hidden in the background
- An environment that is sensitive, adaptive, and responsive to the presence of people and objects
- An environment that augments activities through smart non-explicit assistance
- An environment that preserves security, privacy and trustworthiness while utilizing information when needed and appropriate

Courtesy: Fred Boekhorst, Philips, ISSCC02

The "Ambient Intelligent" Home as the (a) Future of Wireless Infrastructure

A multimedia environment that
- adapts to capabilities at hand
- is aware of space and topology
- is intuitive and self-configuring

Courtesy Fred Boekhorst, Philips

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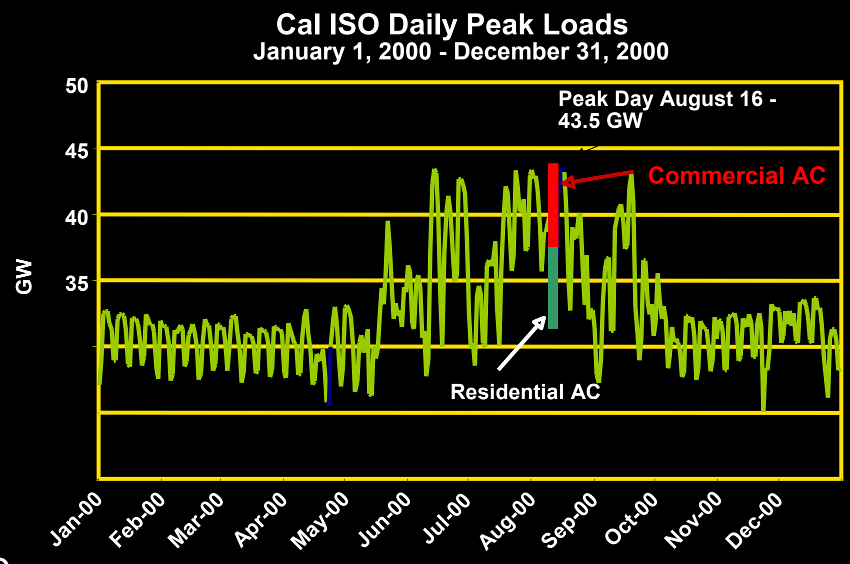
Closely Related to the Smart Home and Wireless Sensor Networks

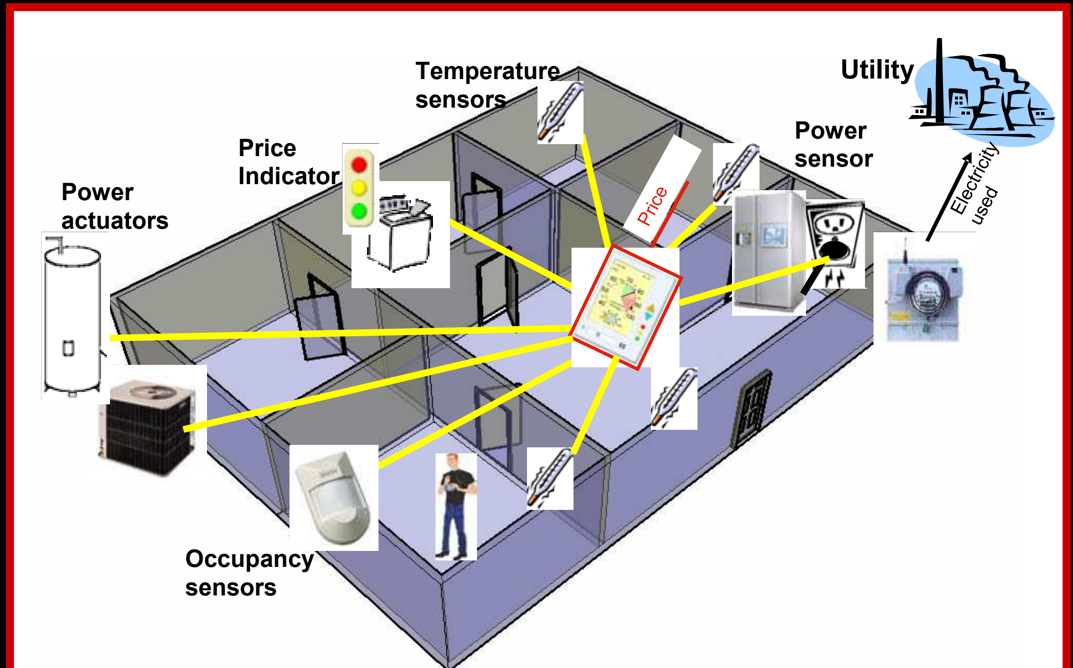
- Energy management
- Environment control
- Security
- Health Care
- Advanced user interfaces
- Sense of presence and space

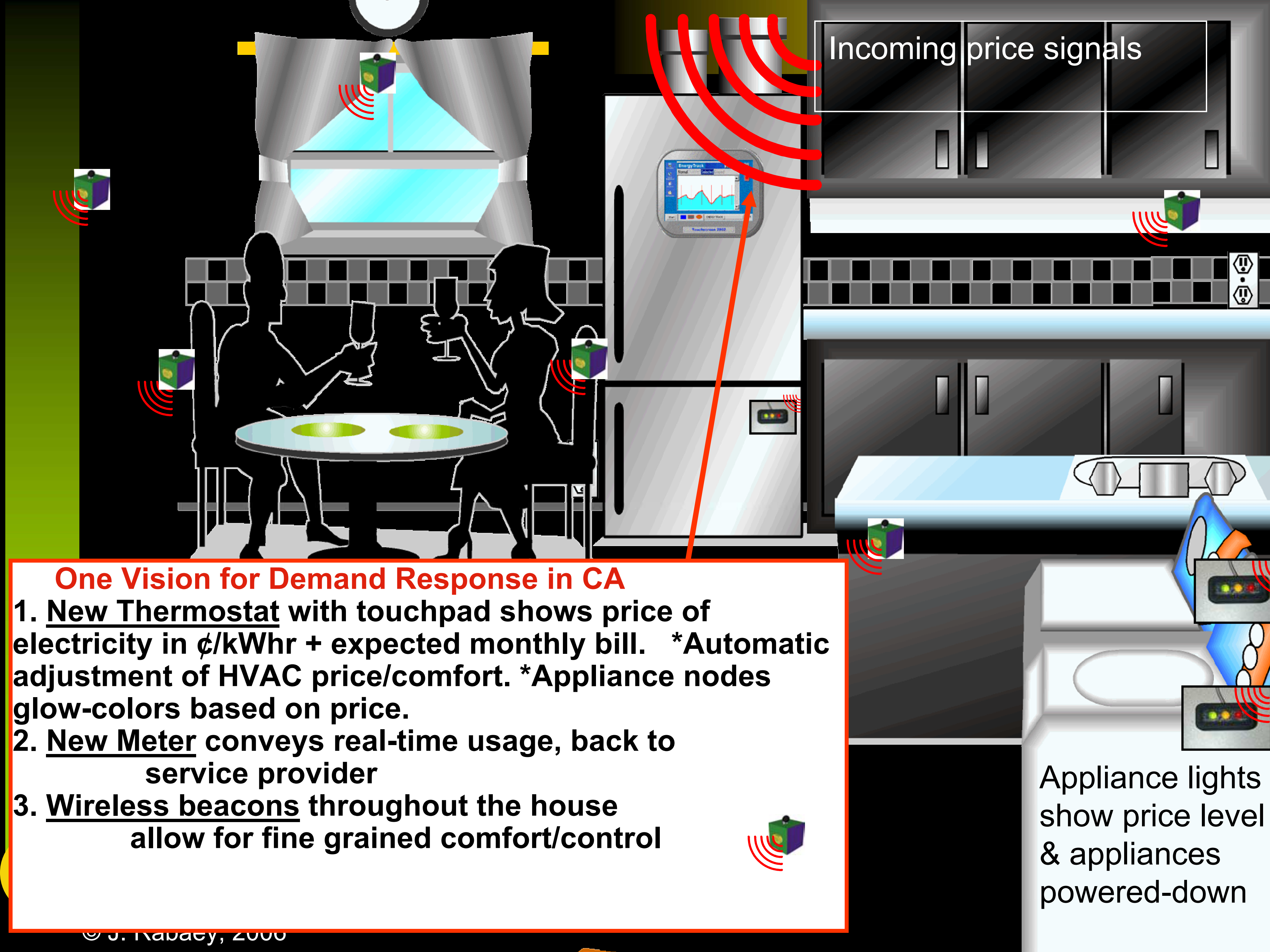
Energy Management and Conservation as an Initial Driver

Demand response:
Make energy prices dependent upon time-of-use

- Advanced thermostats operate on required level of comfort, energy cost, weather forecast and distributed measurements to offload peak times
- Appliances are energy and cost aware







One Vision for Demand Response in CA

1. <u>New Thermostat</u> with touchpad shows price of electricity in ¢/kWhr + expected monthly bill. *Automatic adjustment of HVAC price/comfort. *Appliance nodes glow-colors based on price.
2. <u>New Meter</u> conveys real-time usage, back to service provider
3. <u>Wireless beacons</u> throughout the house allow for fine grained comfort/control

In Contrast: The Home of Today

Houses a range of wired and wireless networks

- Wired voice (traditional telephone)
- Wireless voice (cellular)
- High speed data (cable, DSL)
- Multimedia broadband (cable, satellite)
- Multimedia (wired)
- Security (wired, wireless)
- Climate Control (wired)
- Home automation (X10, others)

All of which are fully disconnected

The Two Faces of Ambient Intelligence

Multimedia Networks

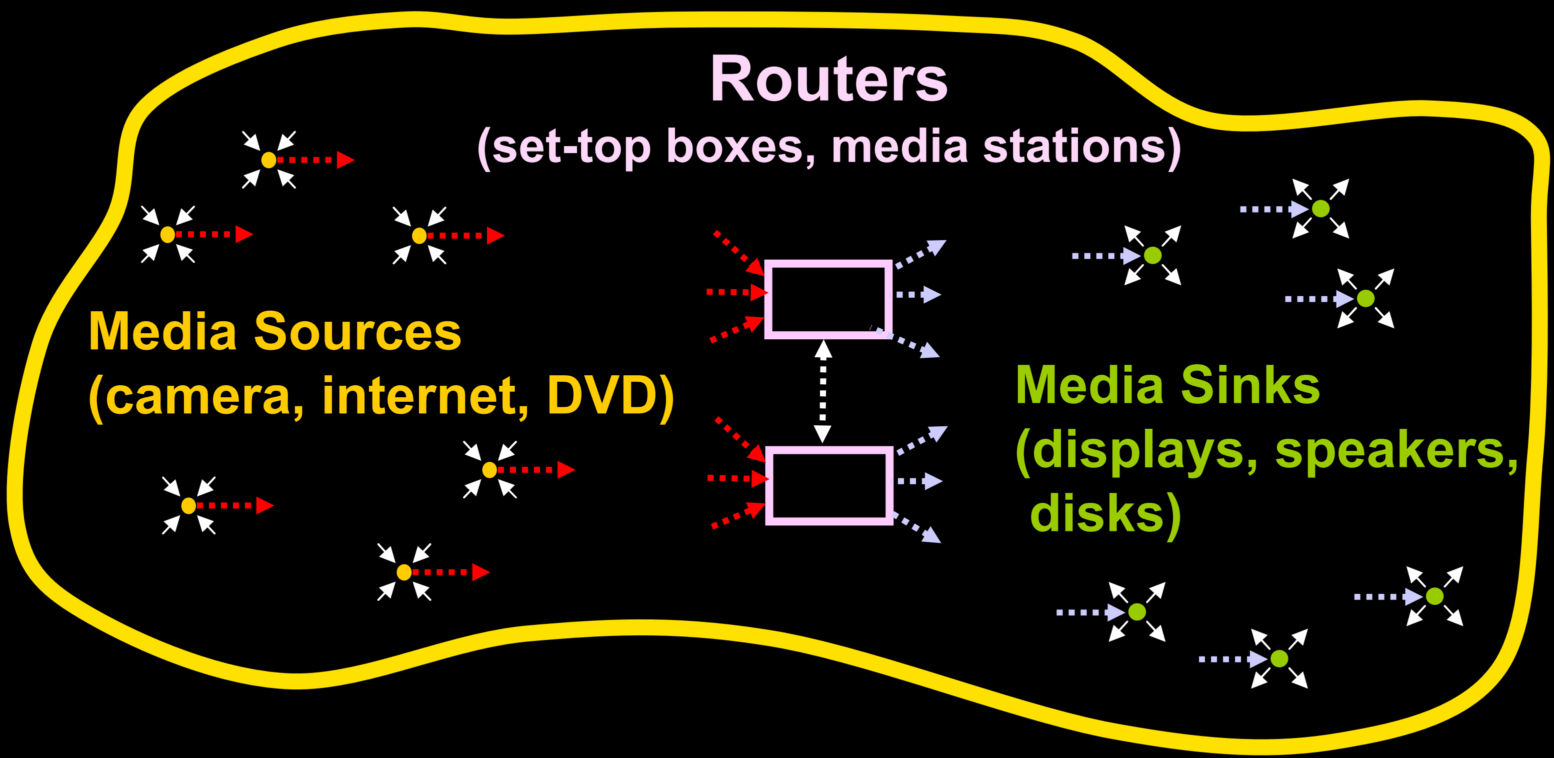
Sensor and Actuator Networks

Synergistic to each other

Providing the contents

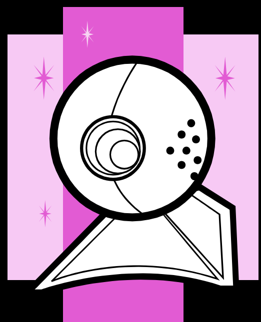
Creating the ambient

Ubiquitous Wireless Multimedia Networks
Providing the Contents

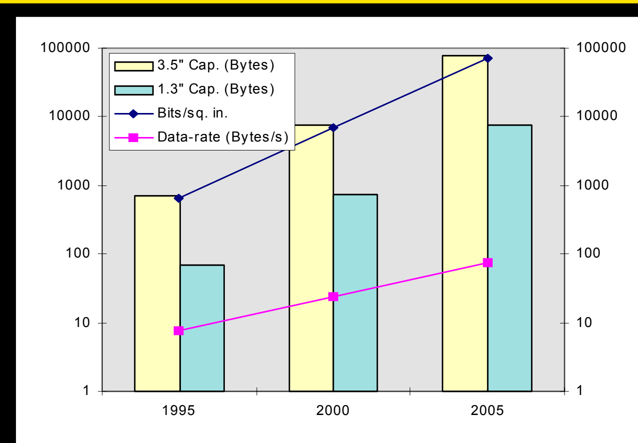


A collection of cooperating algorithms (routers) designed to provide a human observer the best possible media experience, bringing contents from distributed media sources and sinks.

Enabled by Synergetic Technology Advancements




Ubiquitous media I/O

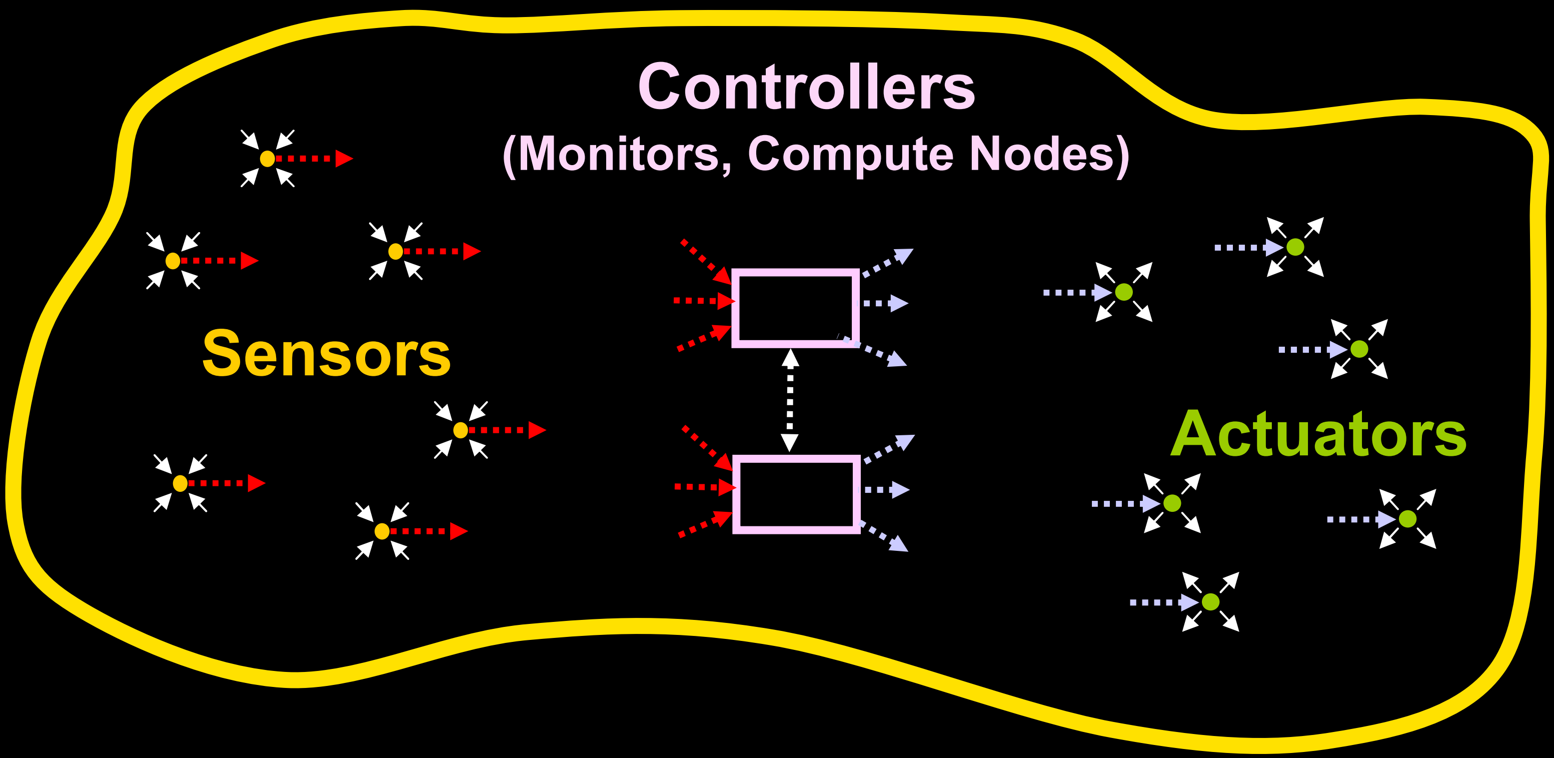


Plenty of cheap storage

Aggressive
signal processing

Wireless galore

Wireless Sensor and Actuator Networks
Providing the Ambient

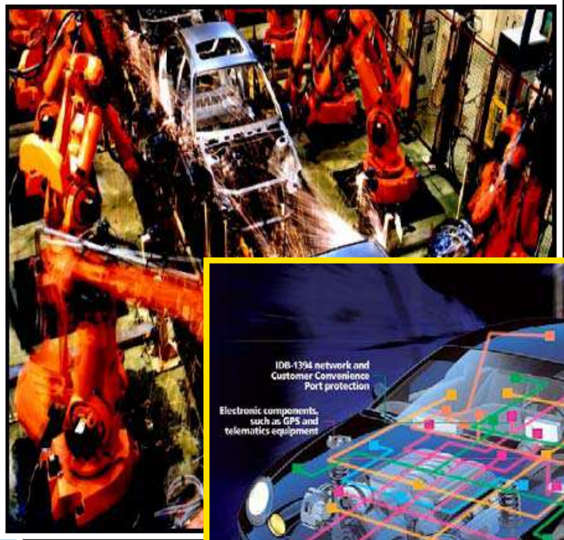


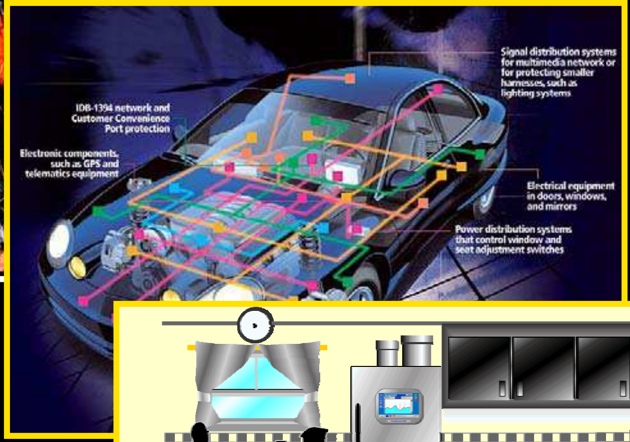
A collection of cooperating algorithms (controllers) designed to achieve a set of common goals, aided by interactions with the environment through **distributed** measurements (sensors) and actions (actuators).

Creating a Whole New World of Applications

From Monitoring

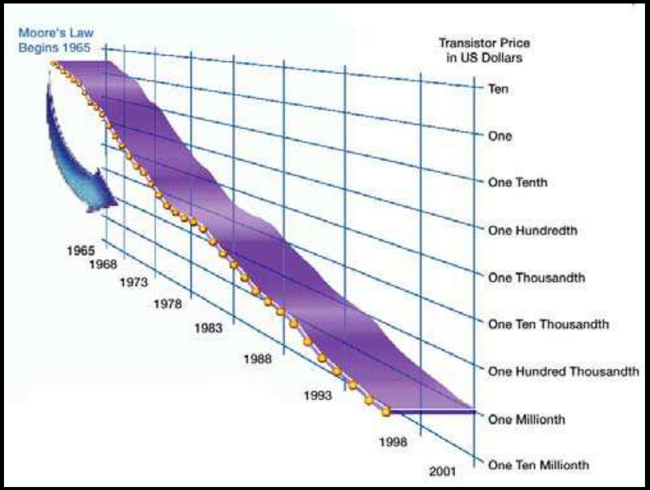
To Automation



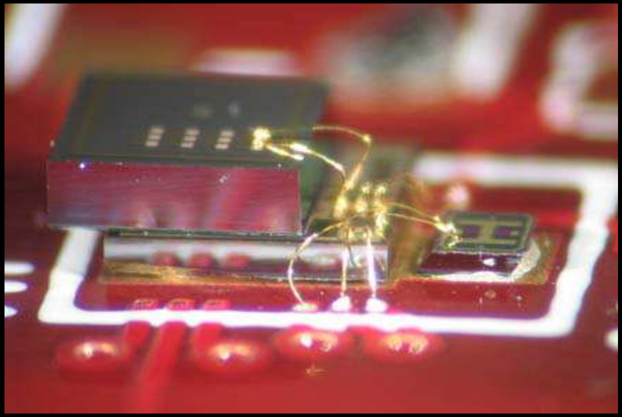


Enabled by Synergetic Technology Advancements

Moore's law and size



Moore's law and cost



True system integration

Ubiquitous wireless as the glue

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The Ambient Wireless Home

The Overall Challenge:
Creating an environment where novel wireless devices can be brought in seamlessly and easily with no or little configuration or management, while guaranteeing the quality of the experience

In Detail:

- Reliability and QOS
- Compatibility and Portability
- Configuration, Management and Control
- *Security and Privacy*

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Tutorial Outline

- Reliability and QoS
  - Trends and Developments in High-Data Rate Wireless
  - Trends and Developments in Low-Data Rate Wireless
- Portability
- Configuration, Management and Control

Reliability and QoS In Wireless Multimedia

Redundancy the best means in providing a reliable and enjoyable user experience

- Dependable system operation best supported by the availability of ample and redundant source, processing and destination functions.
- Providing ample redundant bandwidth and connectivity the simplest and most effective technique to ensure QOS in a “best-effort” way.

The Bandwidth Challenge

Current LAN/PAN Wireless Standards

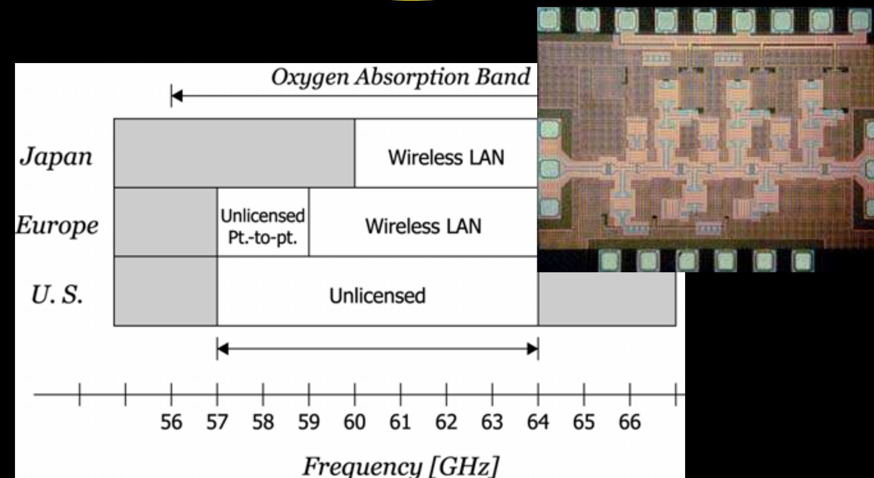
Technology	Data Rate (Mb/sec)	Range (Meters)
Blue Tooth	1-2	100
IrDA	4	1-2
Ultra Wide Band	*100-500*	*10*
802.11a	54	20
802.11b	11	100
802.11g	54	50
802.11n	*108*	*50*

Largely deficient for support of multiple simultaneous streams and QOS guarantees

Conjecture: Wireless Bandwidth will be Free!

Improved spectral efficiency

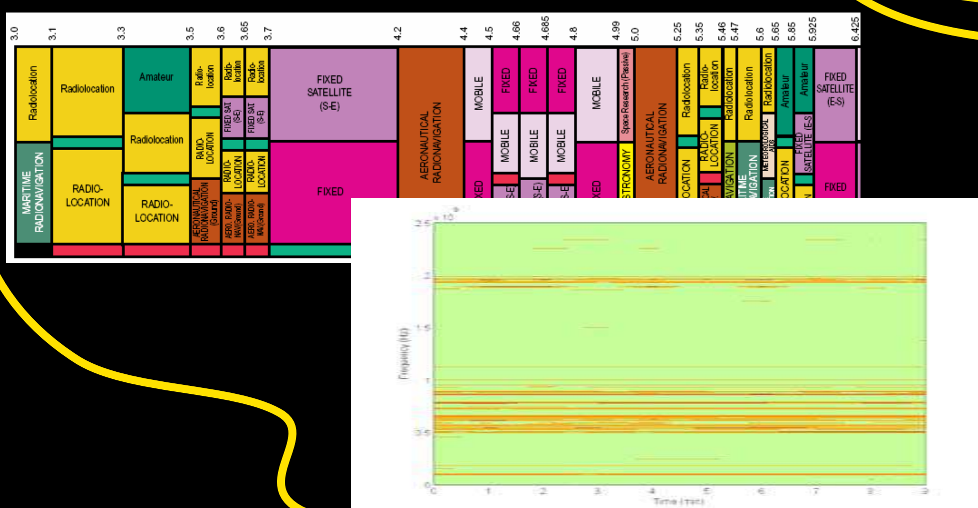
MIMO to the rescue (802.11n)



New frequency realms

4 to 7 Ghz available at 60 GHz

Possible in today's CMOS!



Spectrum recycling

aka "Cognitive radio"

Temporarily re-use idle spectrum

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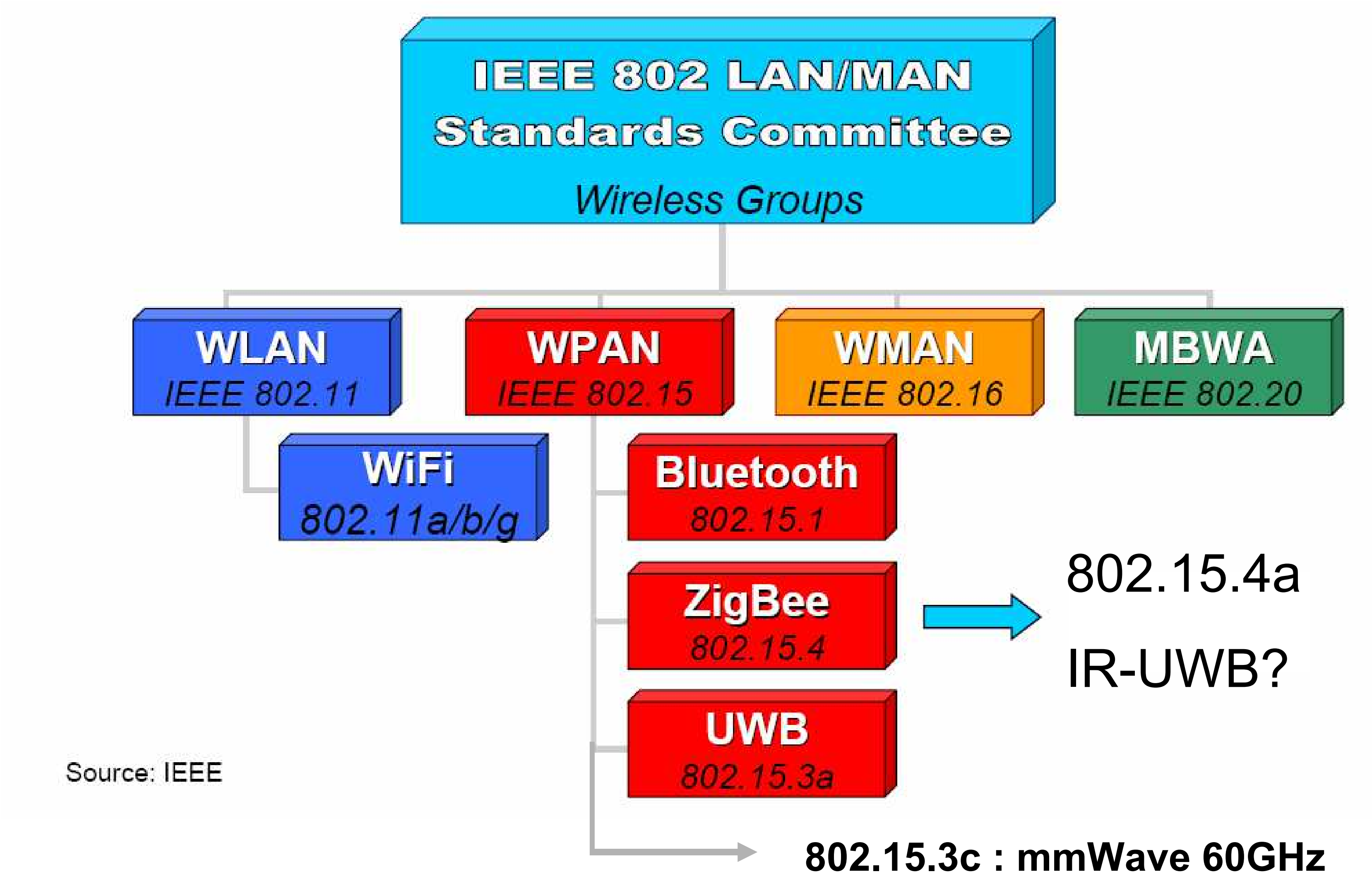
Overview standards

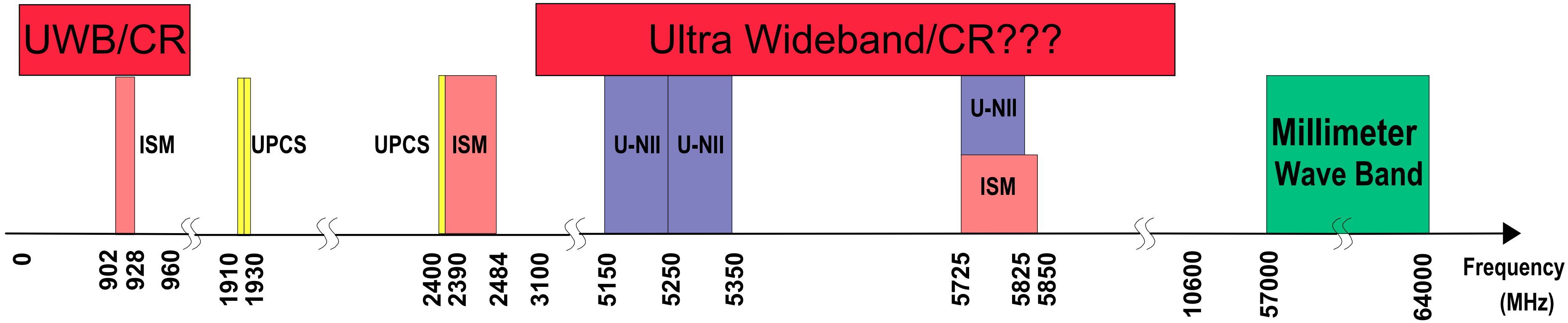


802.15.4a

IR-UWB?

802.15.3c : mmWave 60GHz

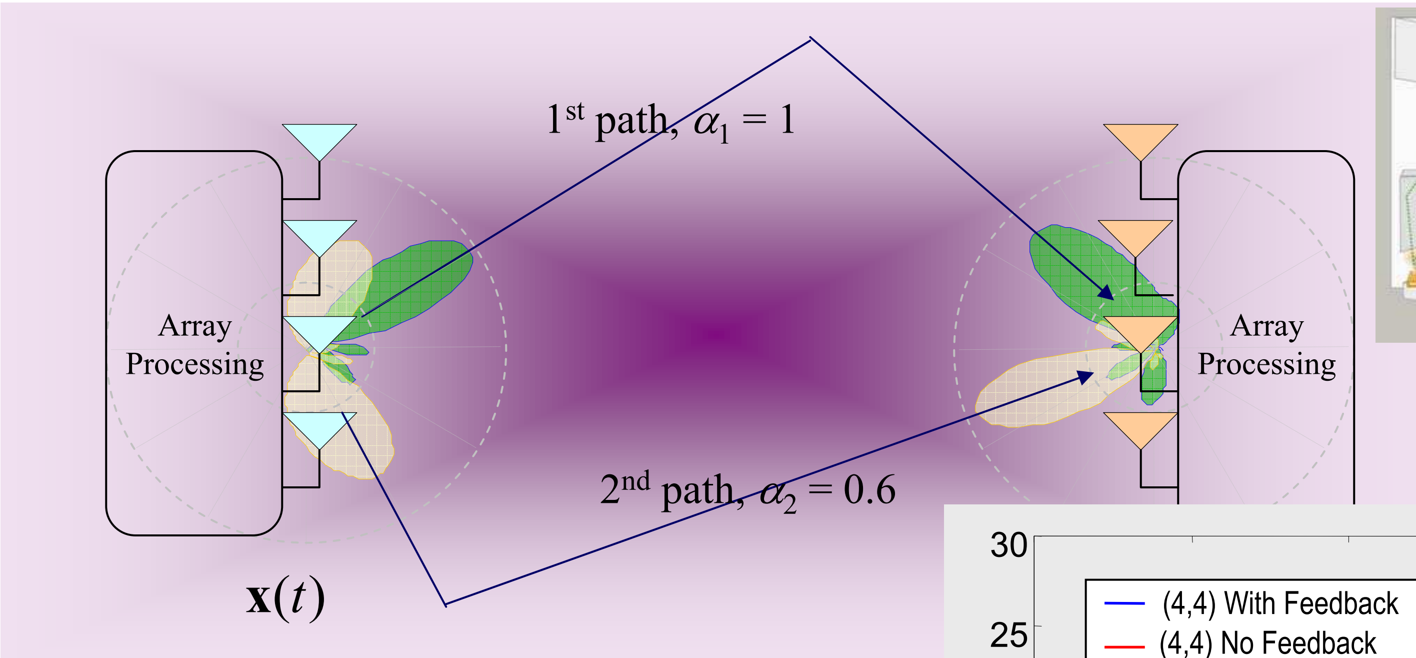
New FCC Spectrum Regulation Strategy

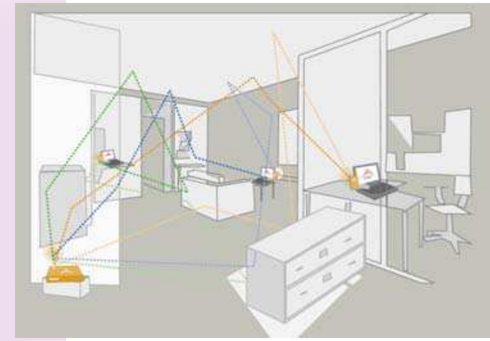


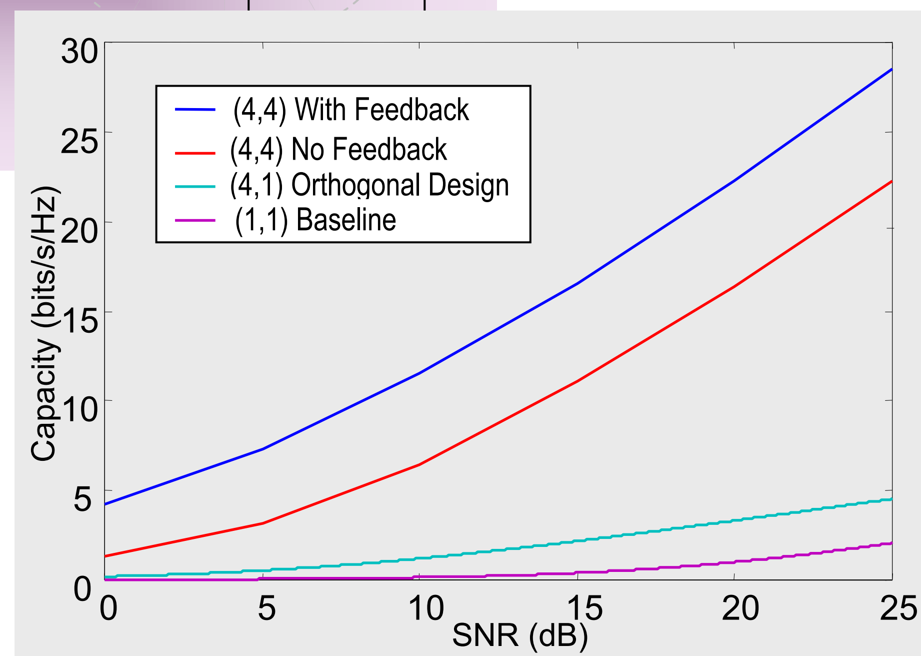
	ISM (1986)	UPCS (1994)	U-NII (1997)	Millimeter Wave (1998)	Ultra Wideband (2002)	Cognitive Radio (2005?)
Link Control		➔				
Modulation	➔					
Total Transmit Power	➔	➔	➔	➔		
Power Spectral Density	➔	➔	➔	➔	➔	
Antenna Gain	➔	➔	➔			
Out of Band Emission	➔	➔	➔			

Addressing the interference

Improving Spectrum Utilization

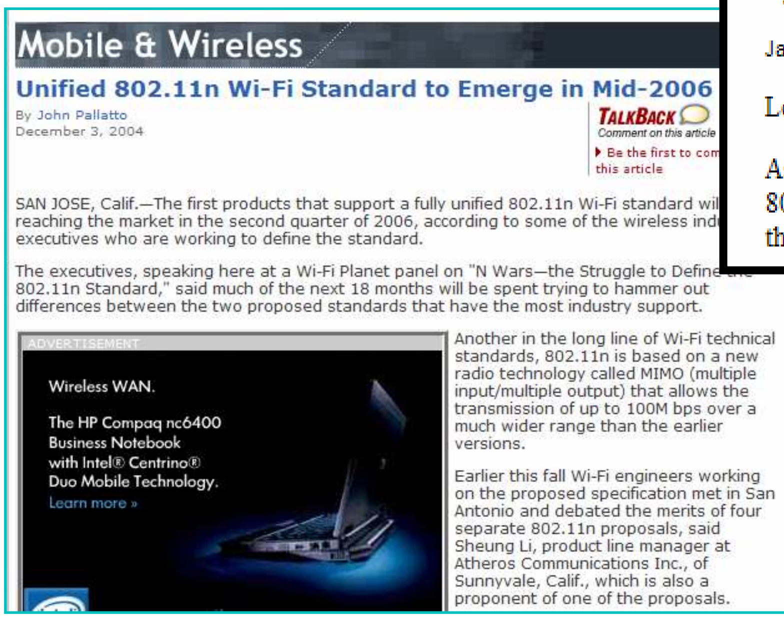






- Multi-antenna approach exploits multi-path fading by sending data along good channels
- Results in large theoretical improvements in bandwidth efficiency for fading channels
- But…computationally hungry

802.11n



Mobile & Wireless

Unified 802.11n Wi-Fi Standard to Emerge in Mid-2006

By John Pallatto
December 3, 2004

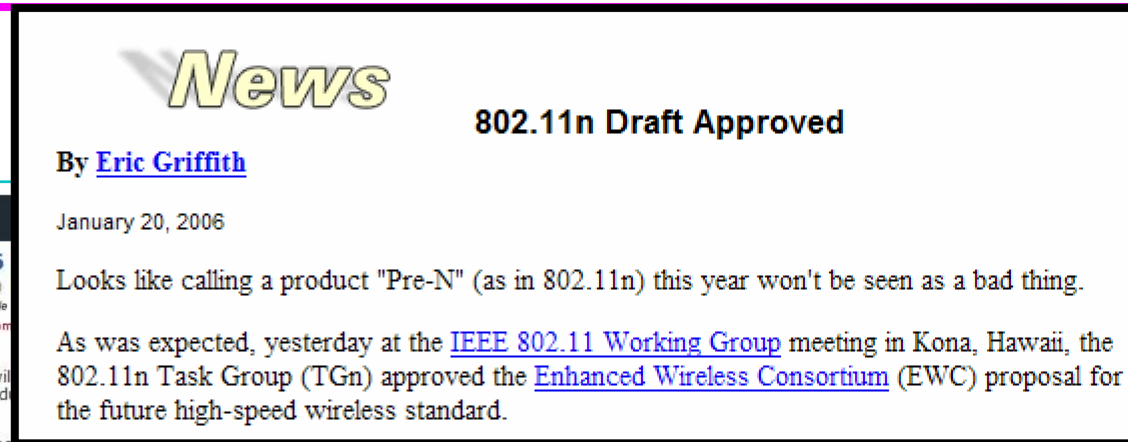
TalkBack
Comment on this article
Be the first to com
this article

SAN JOSE, Calif.—The first products that support a fully unified 802.11n Wi-Fi standard wil reaching the market in the second quarter of 2006, according to some of the wireless ind executives who are working to define the standard.

The executives, speaking here at a Wi-Fi Planet panel on "N Wars—the Struggle to Define the 802.11n Standard," said much of the next 18 months will be spent trying to hammer out differences between the two proposed standards that have the most industry support.

Another in the long line of Wi-Fi technical standards, 802.11n is based on a new radio technology called MIMO (multiple input/multiple output) that allows the transmission of up to 100M bps over a much wider range than the earlier versions.

Earlier this fall Wi-Fi engineers working on the proposed specification met in San Antonio and debated the merits of four separate 802.11n proposals, said Sheung Li, product line manager at Atheros Communications Inc., of Sunnyvale, Calif., which is also a proponent of one of the proposals.



News

802.11n Draft Approved

By Eric Griffith

January 20, 2006

Looks like calling a product "Pre-N" (as in 802.11n) this year won't be seen as a bad thing.

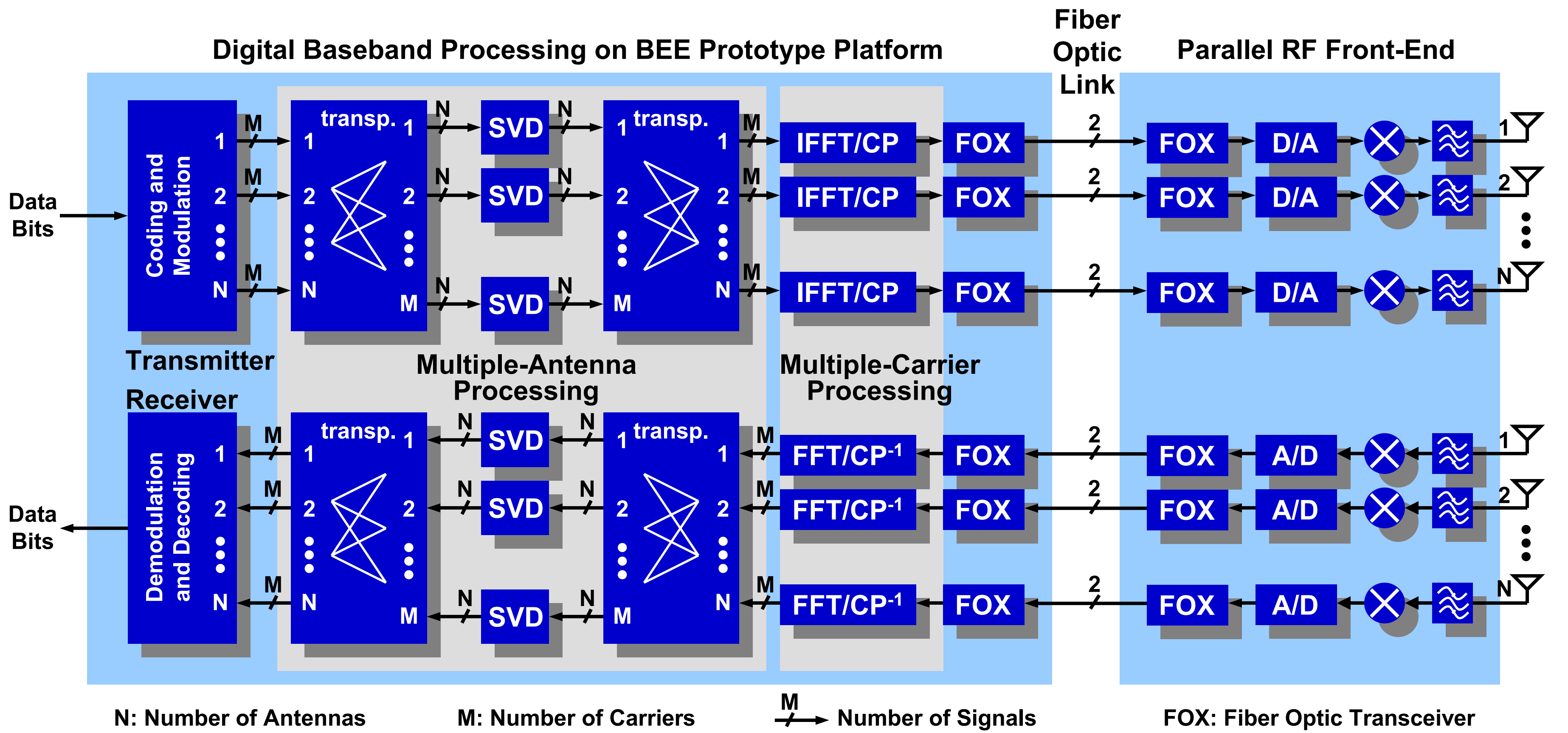
As was expected, yesterday at the IEEE 802.11 Working Group meeting in Kona, Hawaii, the 802.11n Task Group (TGn) approved the Enhanced Wireless Consortium (EWC) proposal for the future high-speed wireless standard.

Belkin (Airgo) Pre-n

Result: Higher DataRates (108 Mbit/sec), Better Coverage
Also: Higher power dissipation (not too attractive for small mobiles)

MIMO Challenge: Complexity

- Fully parallel front-end with up to 16 transmit/receive antennas
- Different MEA algorithms like Singular Value Decomposition (SVD), Beam-forming



New Paradigms

- **Underlay** - restrictions on transmitted power and operation over ultra wide bandwidths **(UWB Radios)**
- **Far away -** 7 GHz at 60 GHz of unlicensed spectrum **(60 GHz Radios)**
- **Overlay -** Sharing with primary high priority users and interference avoidance through spectrum sensing **(Cognitive Radios)**

Future Wireless Systems

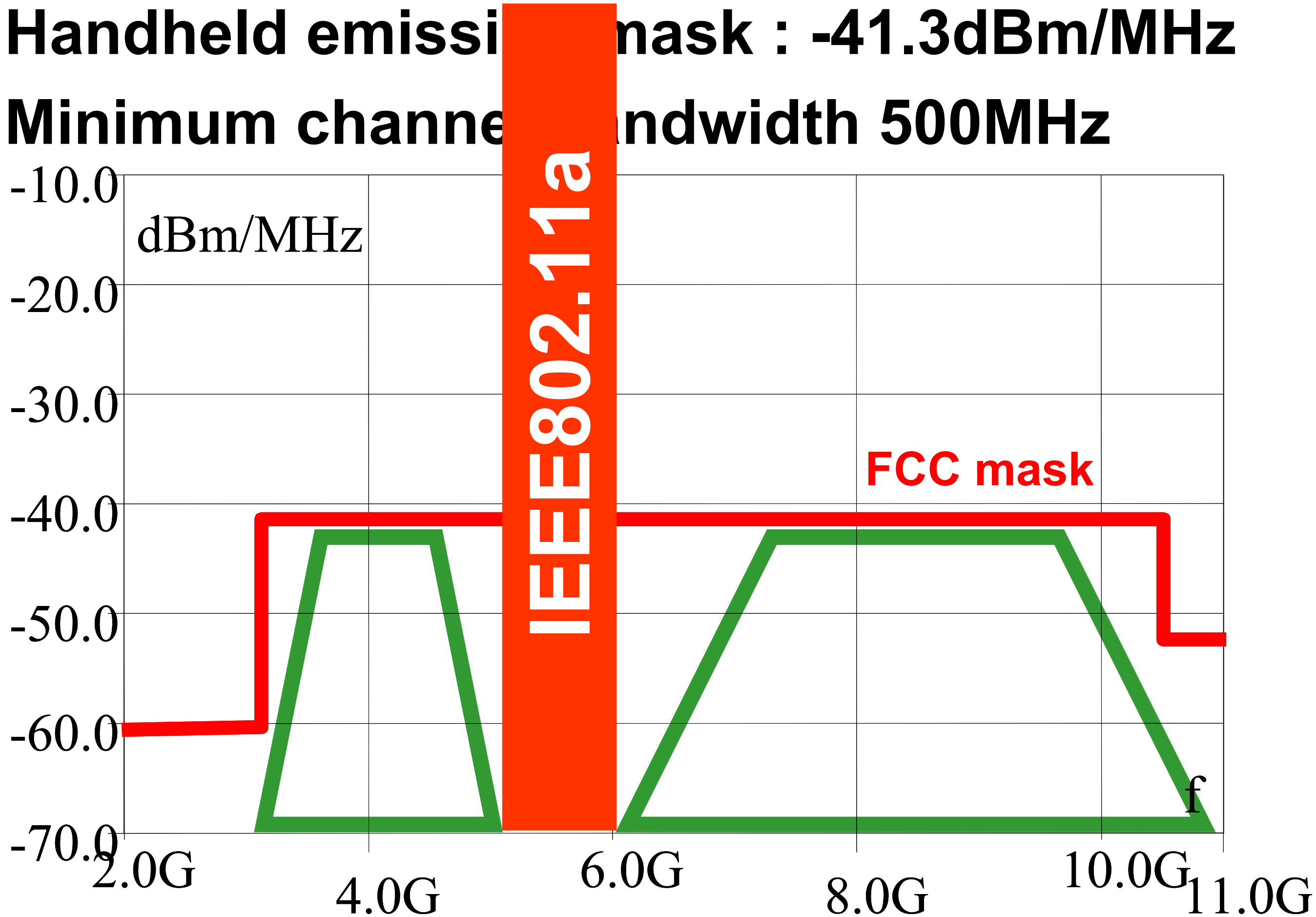
	UWB	60 GHz	*CR**
Spectrum Access	underlay	unlicensed	*overlay*
Carrier	[0-1], [3-10] GHz	[57 – 64] GHz	*[0-1], [3-10]GHz*
Bandwidth	> 500 MHz	> 1GHz	*> 1GHz*
Data Rates	~ 100 Mb/s	~ 1 Gb/s	*~ 10 - 1000 Mb/s*
Spectrum Efficiency	~ 0.2 - 1 b/s/Hz	~ 1 b/s/Hz	*~ 0.1 - 10 b/s/Hz*
Range	1 to 10 m	~ 10 m	*1m to 10 km*

New Circuit and Architecture Challenges

- RF implementation:
  - » Wideband and high linearity
  - » 60 GHz CMOS circuits
- Mixed signal baseband:
  - » Analog/digital system partitioning
  - » ADC: Wideband and high resolution
- Digital signal processing:
  - » Non-sinusoidal wireless transmission
  - » Detection of weak signals

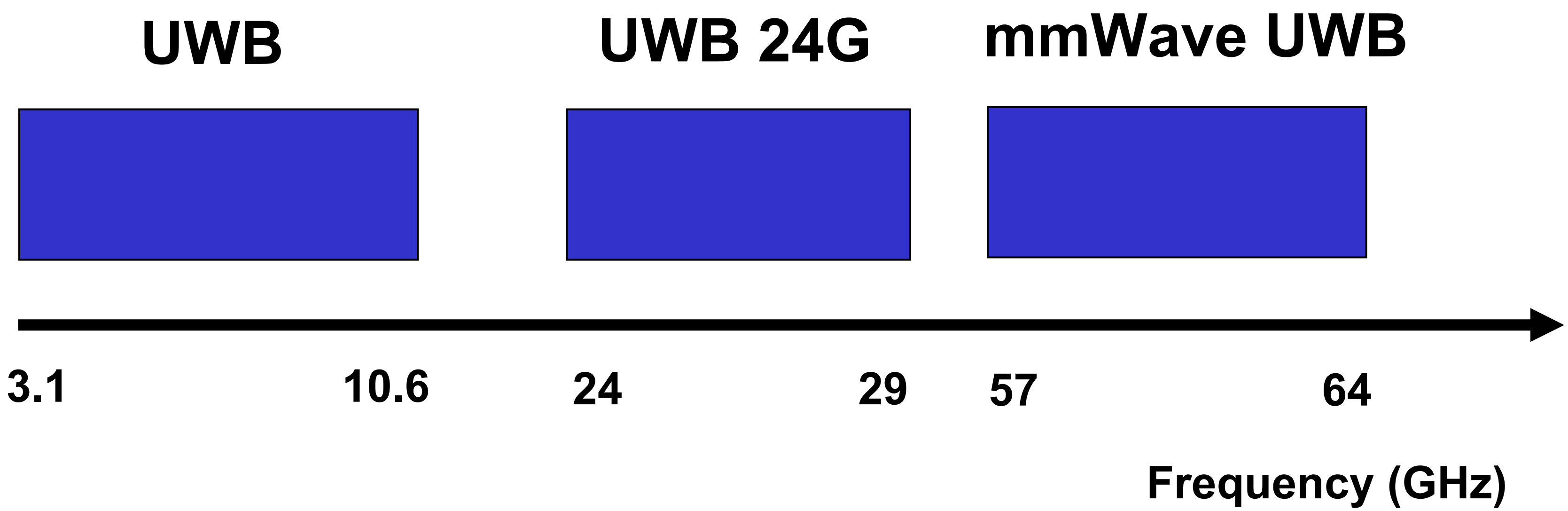
Federal Communication Commission (FCC)

- FCC opened spectrum from 3.1GHz – 10.6GHz
  - Handheld emissi mask : -41.3dBm/MHz
  - Minimum channe ndwidth 500MHz



Federal Communication Commission (FCC)

- FCC opened also other spectra under similar conditions

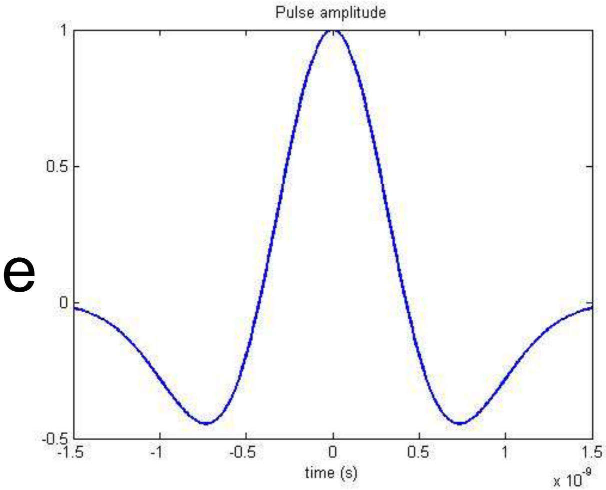


UWB communication proposals

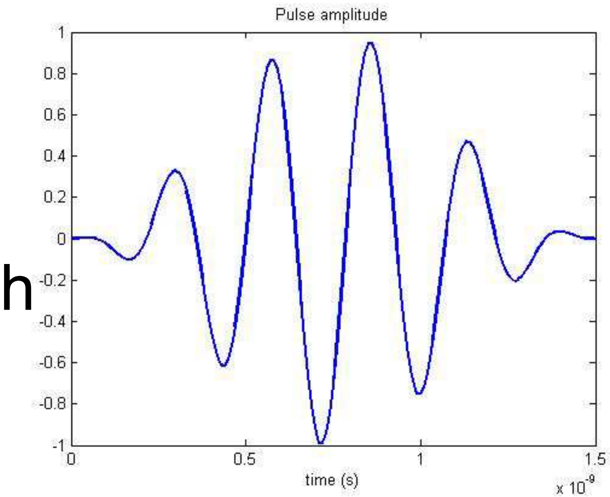
- Time Hopped UWB (probably IEEE802.15.4a)
  - First proposals
  - Old concept (radar)
  - Impulse Radio (IR-UWB)
  - *Low/moderate data rate*
- DS-CDMA UWB (IEEE802.15.3a)
  - *High data rate*
  - UWB Forum supporting DS-UWB
- Multi-Band OFDM UWB (IEEE802.15.3a, ECMA-368)
  - *High data rate*
  - MBOA (MBO Alliance)

Impulse radio UWB (IR-UWB)

- Carrier-less
  - Dedicated pulse generator
  - Short Gaussian-shaped time pulse
  - Low pulse repetition



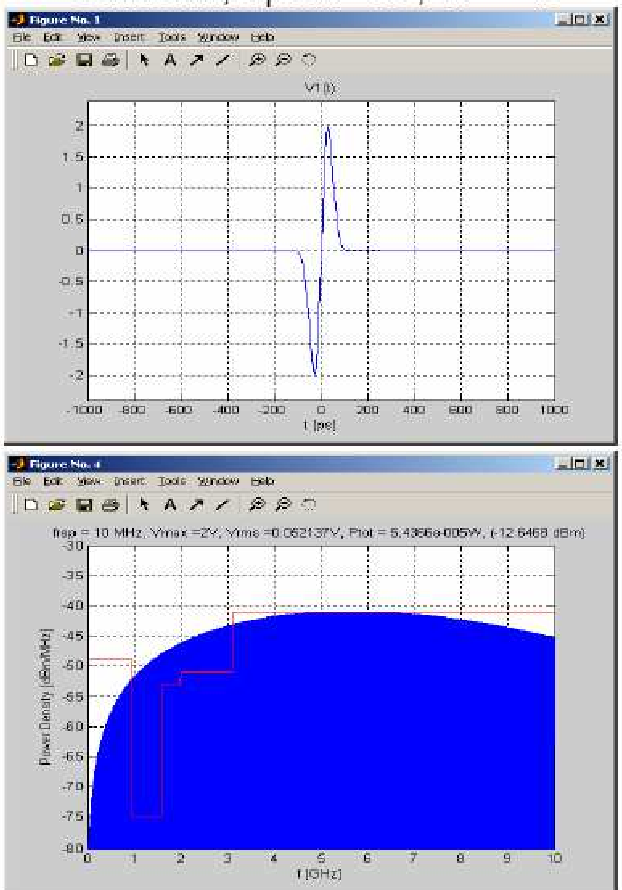
- Carrier-based
  - Quenched oscillators
  - Quench time: frequency bandwidth
  - Oscillation: carrier frequency



IR-UWB: pulse choice

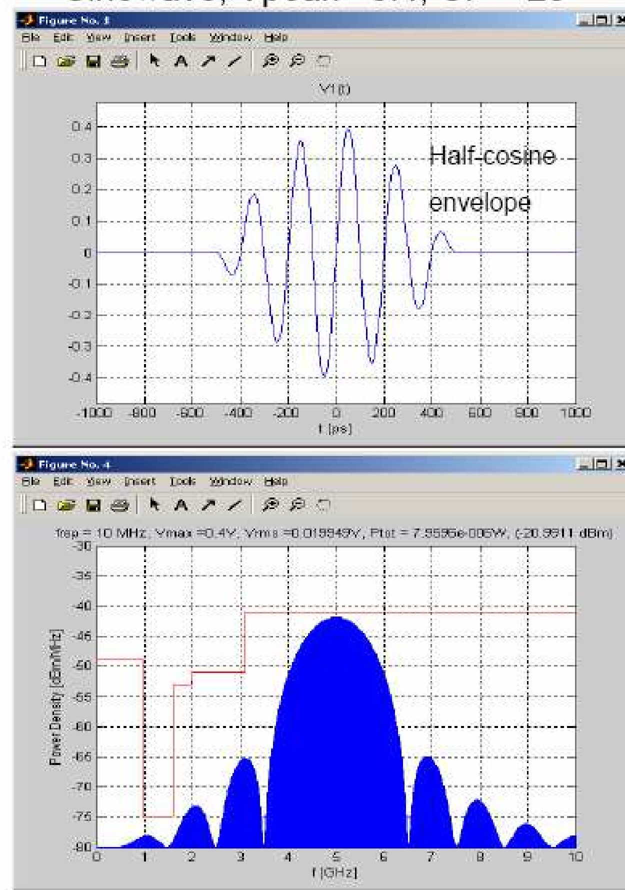
Carrier-less

Gaussian, Vpeak =2V, CF = 40

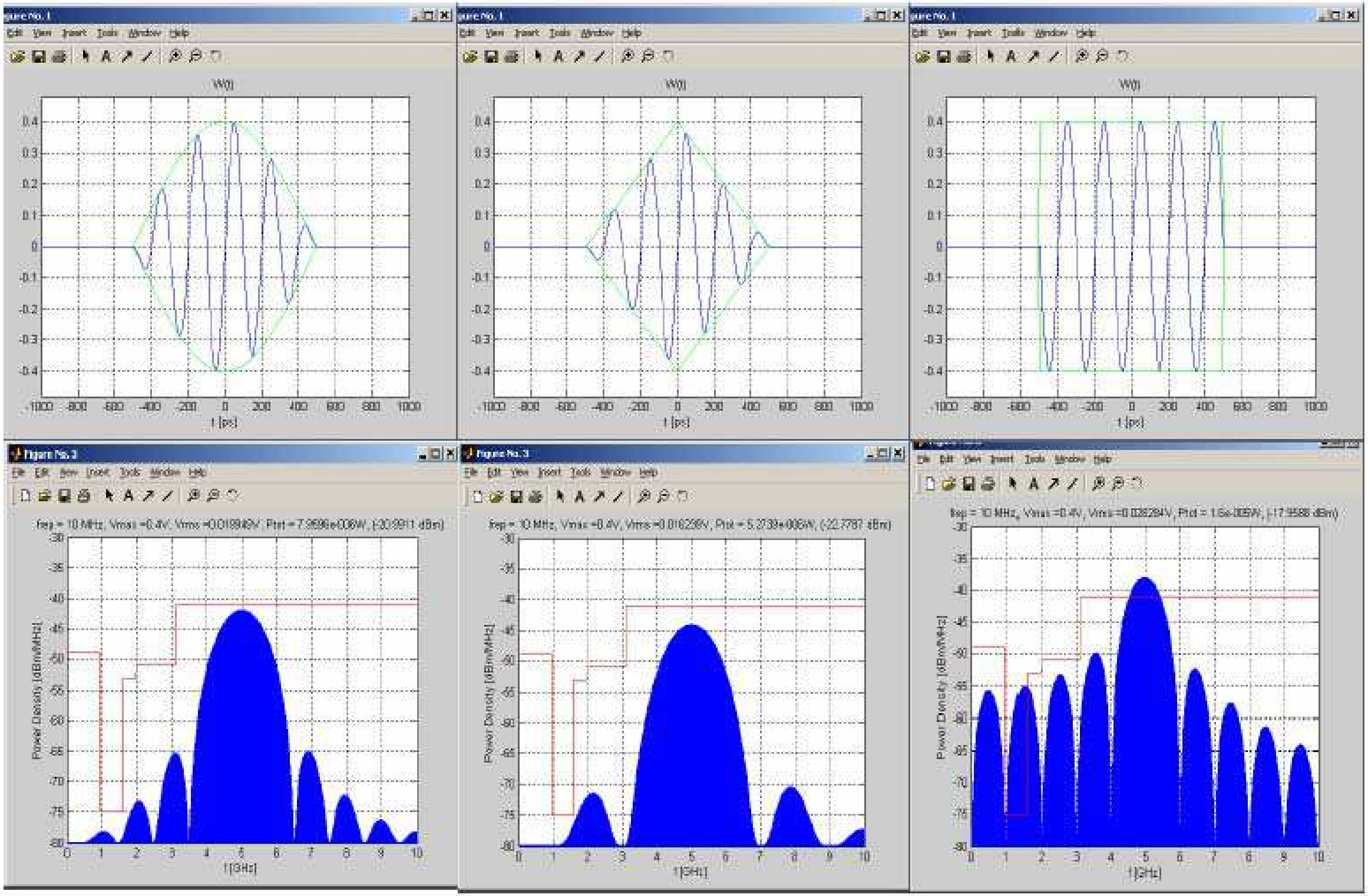


Carrier-based

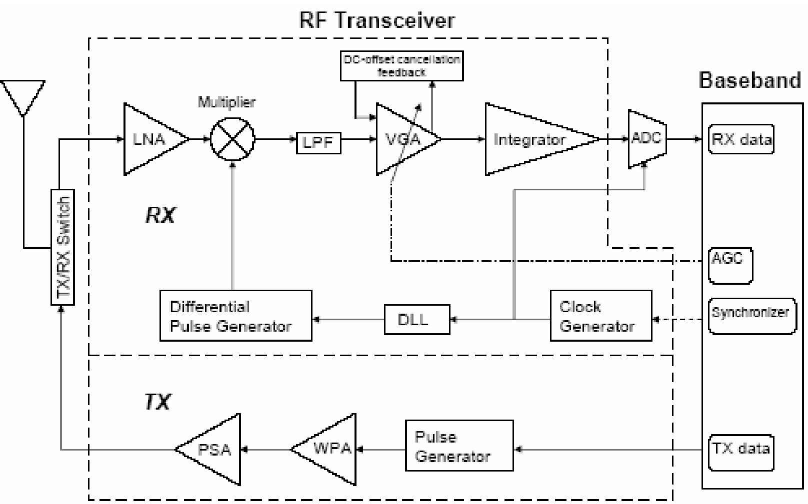
Sinewave, Vpeak =0.4, CF = 20

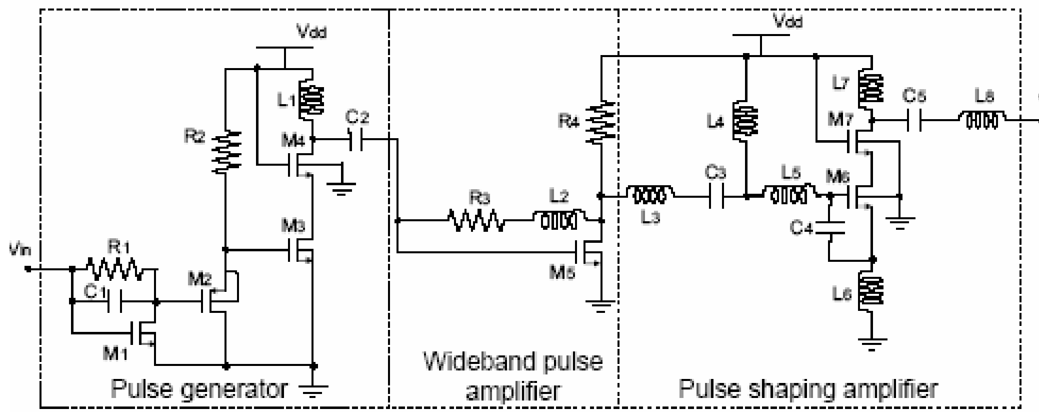


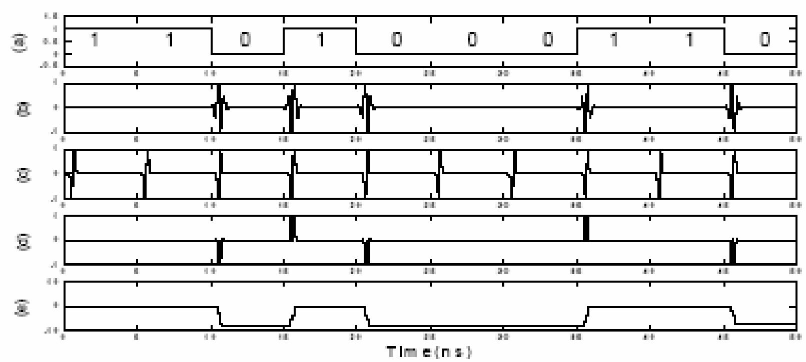
IR-UWB: envelope choice



Carrier-less IR-UWB





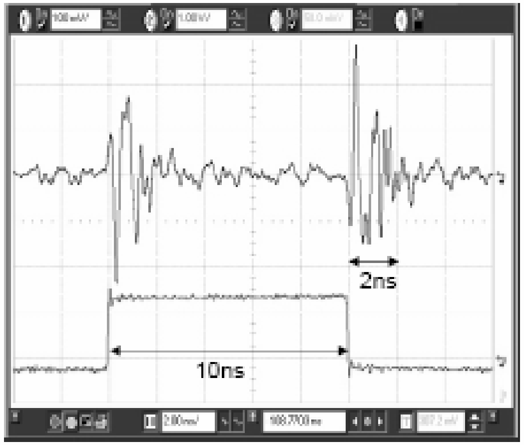


0.18μm CMOS

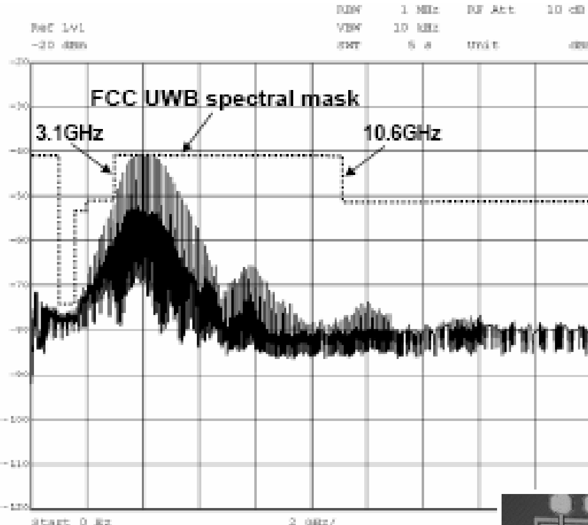
Zheng, ISSCC2006

PPM/BPSK modulation, 400MPulses/s

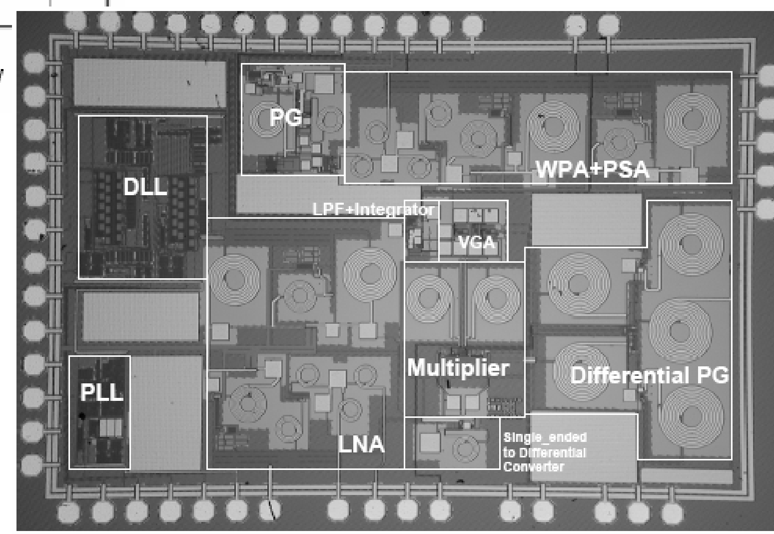
Carrier-less IR-UWB



Time domain pulses

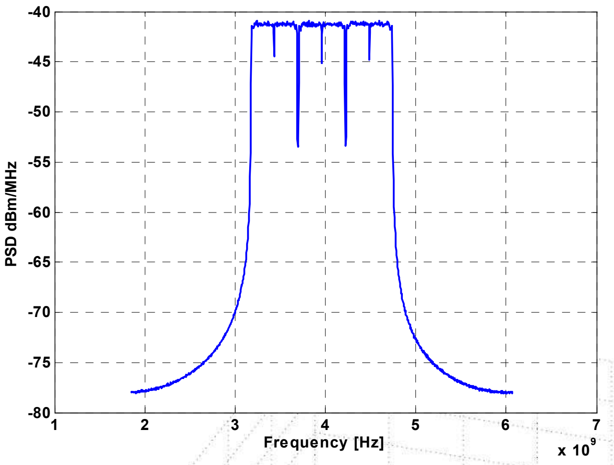


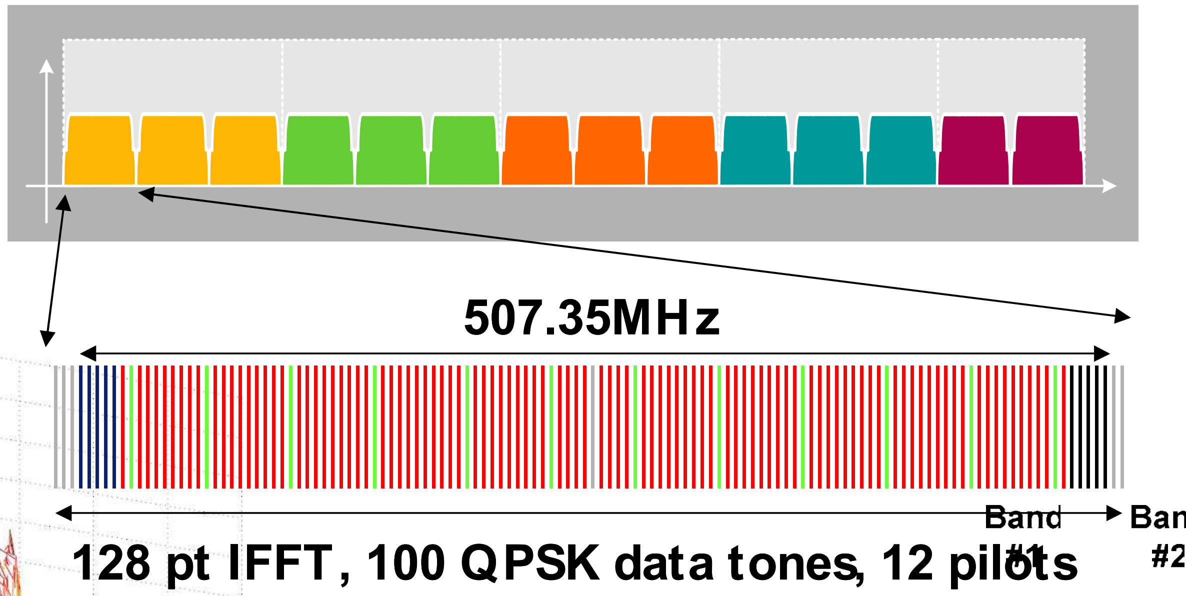
Power spectrum density

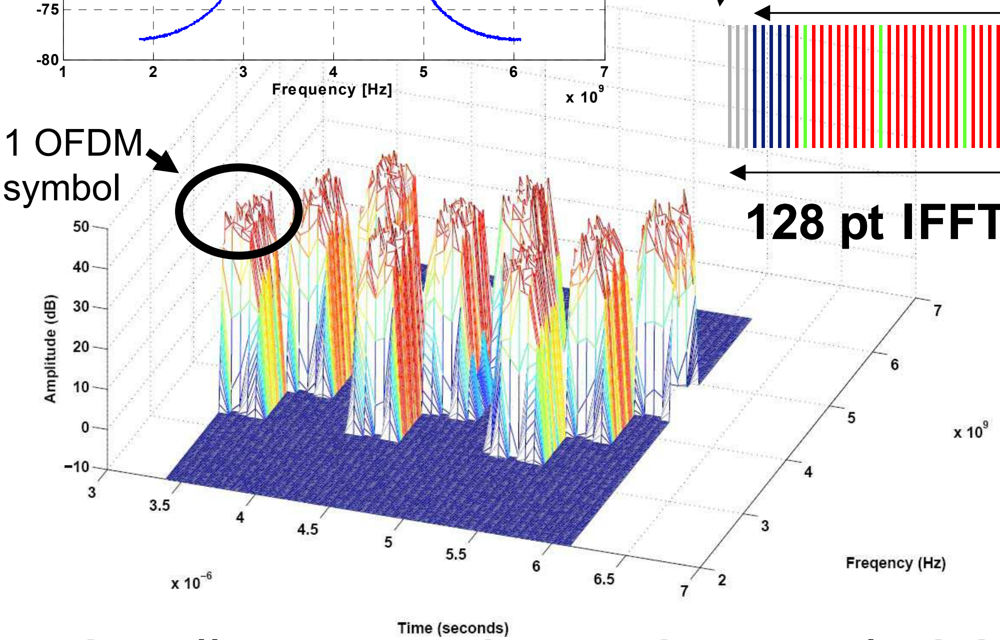


Zheng, ISSCC2006

MB-OFDM UWB: system concept



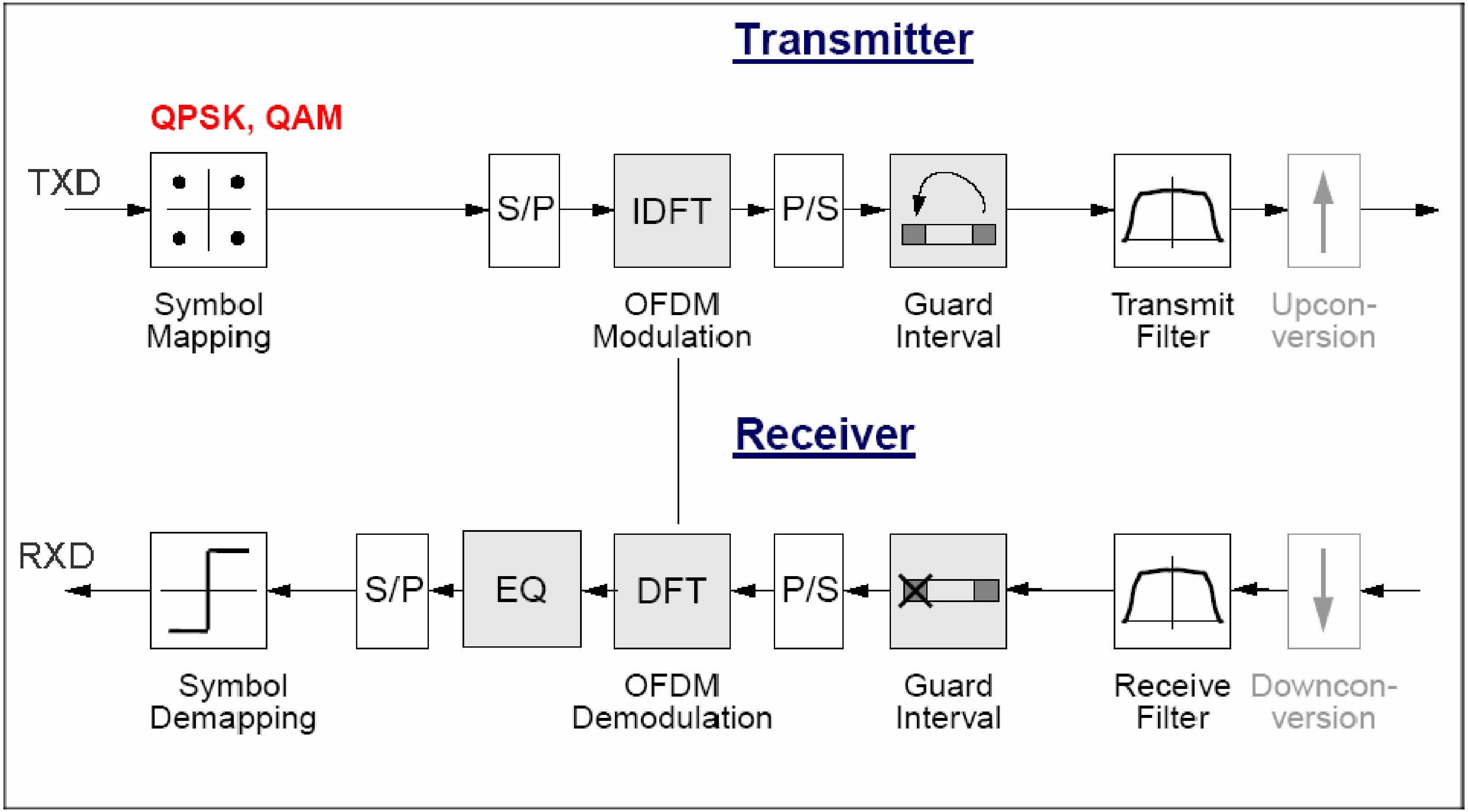




Time frequency coding to allow multiple acces

http://www.ecma-international.org/publications/standards/Ecma-368.htm

MB-OFDM UWB: system concept



UWB RF Transceivers : comparison

	[1]	[2]	[3]	[4]	This work
Technology	0.13μm CMOS	90nm CMOS	0.13μm CMOS	0.18μm CMOS	0.25μm SiGe BiCMOS
NF (dB)	6-7	6.9	4.1	4.7	4.5
iIP3 (dBm)	-15	-16	-22	-0.8	-6
iIP2 (dBm)				+22	+25
EVM (dB)	-19.5	-28	-27	-28.6	-24
P_{out} (dBm)		-3.8	+5	-12.6	-6
TX OIP3		8.6		11.8	12
P diss Rx (mW) Pdiss Tx (mW)	100mA @ 3.3/1.5V 70mA @ 3.3/1.5V	224 131	237 284	412 397	199 190
Chip area (mm^2)	2	4.5	6.6	16	4

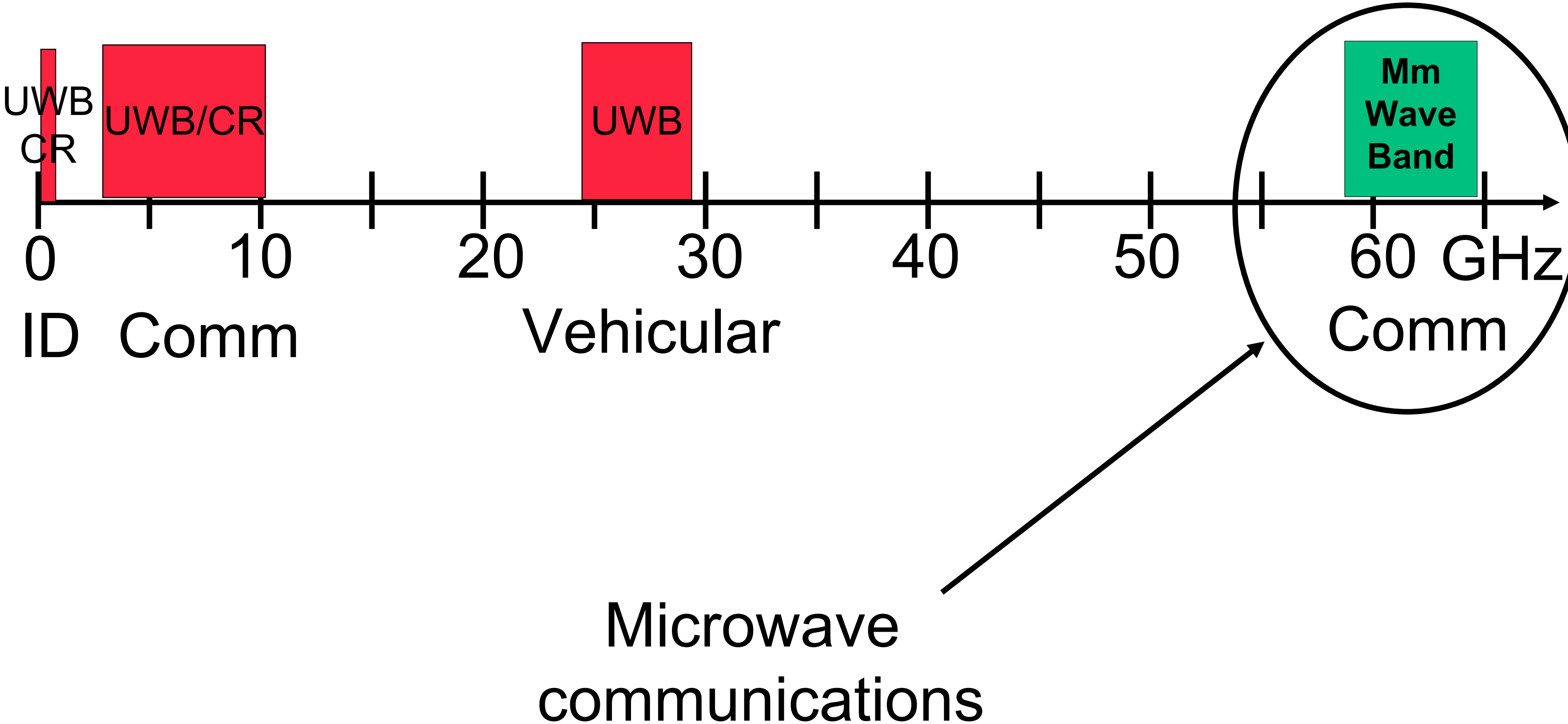
[1] Aytur, ISSCC2006
[2] Tanaka, ISSCC2006
[3] Sadner. ISSCC2006
[4] Lo, ISSCC2006

Concluding remarks on MB-UWB

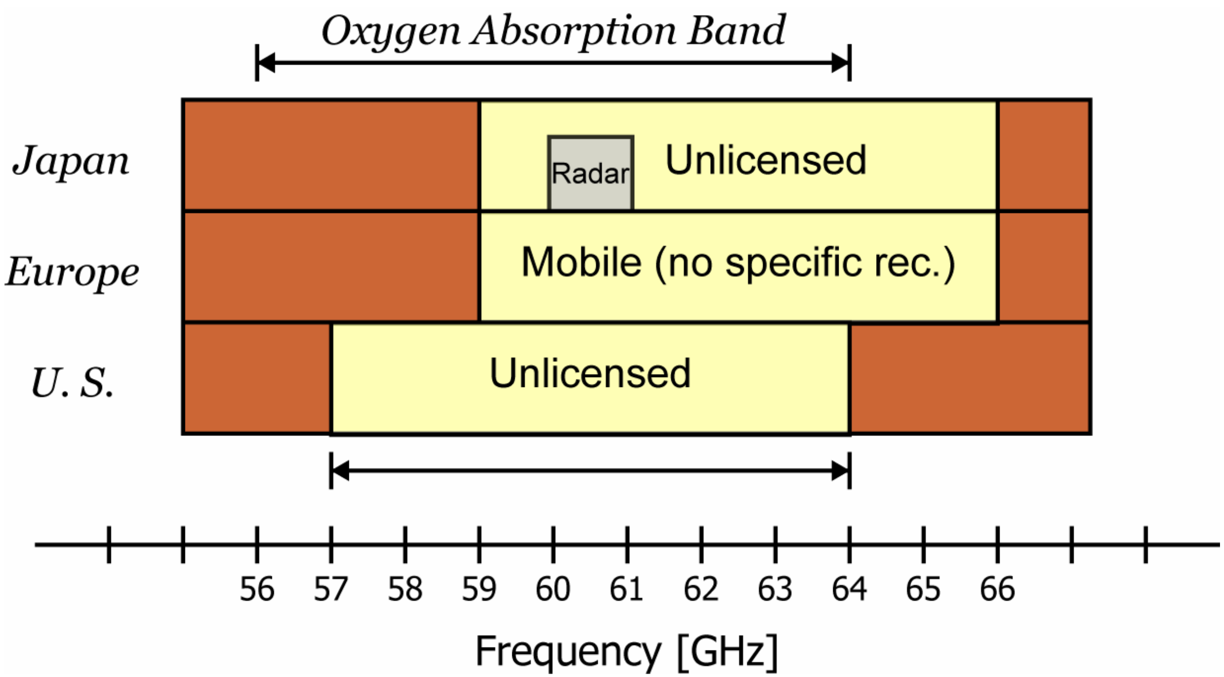
- Complete fully integrated systems have been demonstrated up to 480 Mbps
- First silicon was SiGe, but CMOS is coming
- Challenging is combination of linearity and noise over wide bandwidth
- Co-existence with WiMAX is issue in Europe

UWB Killer App: Wireless USB

Next lets look at the 60 GHz band…



Why is the 60 GHz band so interesting?



Lots of Bandwidth!!!

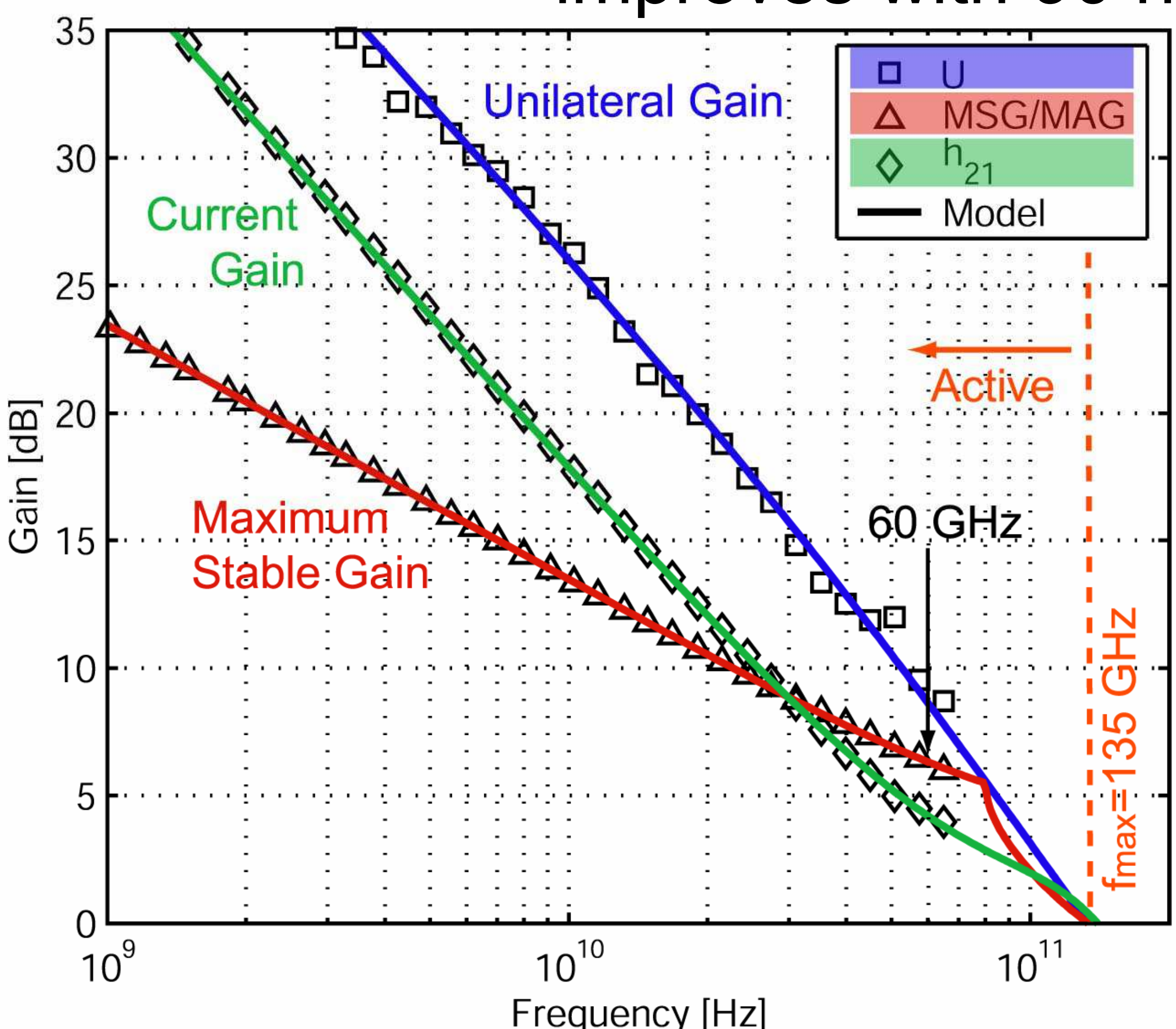
- 7 GHz of unlicensed bandwidth in U.S. and Japan
- Spectrum efficiency no longer primary concern

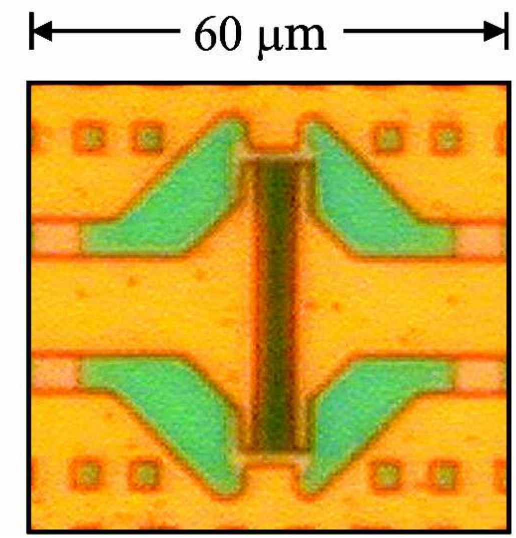
Challenges of Gb/s links at 60 GHz

- CMOS circuit design at 60 GHz
  - » CMOS device modeling and performance
  - » CMOS microwave circuit design methodology
- Power-efficient baseband architecture for Gigabit/second links
  - » Optimized analog and digital circuit partitioning

60GHz CMOS Device Performance

130nm CMOS has a gain of 7dB at 60 GHz and improves with 90 nm





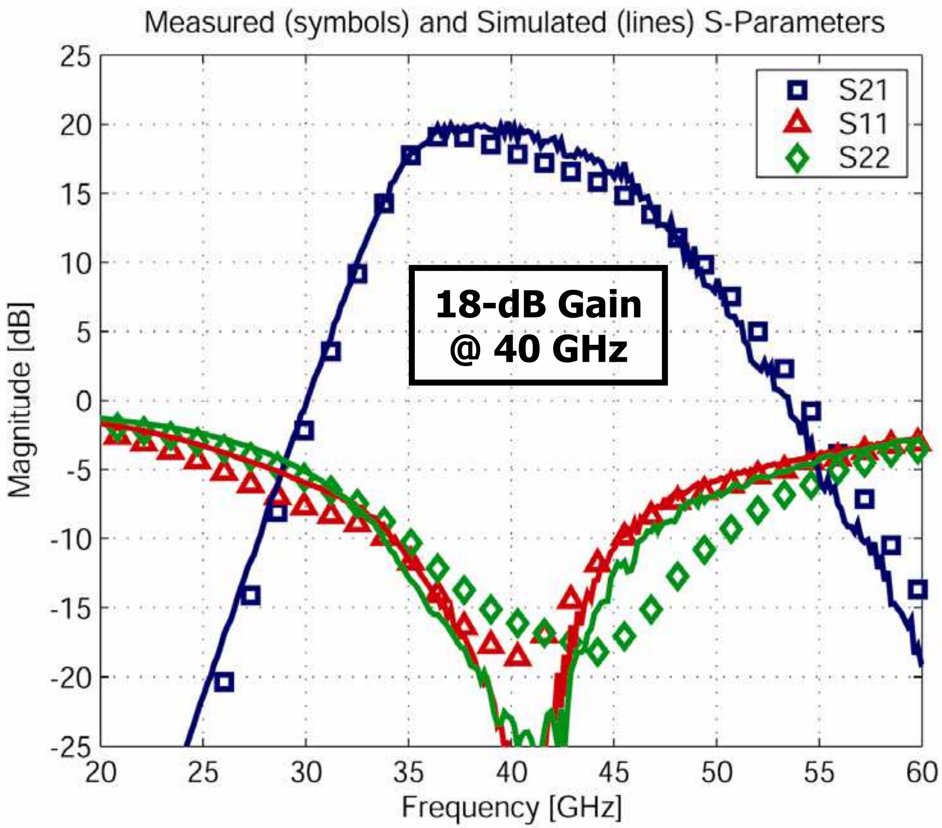
V_{GS} = 0.65 V

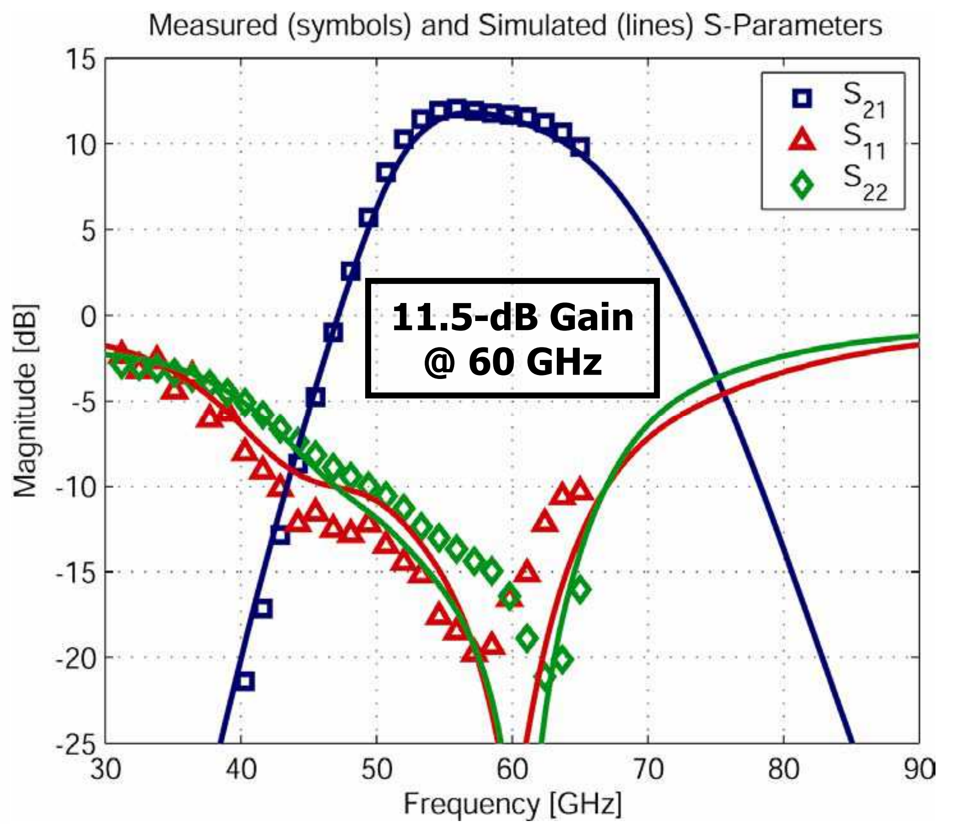
V_{DS} = 1.2 V

I_{DS} = 30 mA

W/L = 100x1u/0.13u

Circuits can be modeled

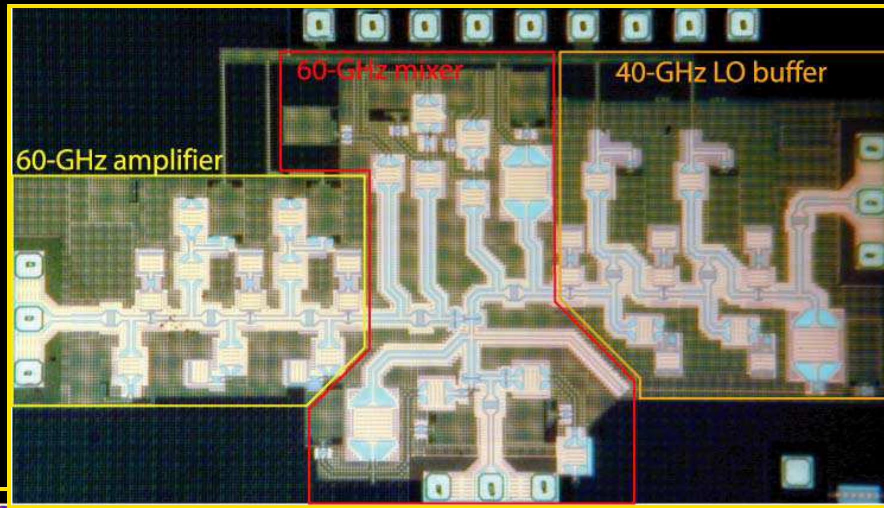


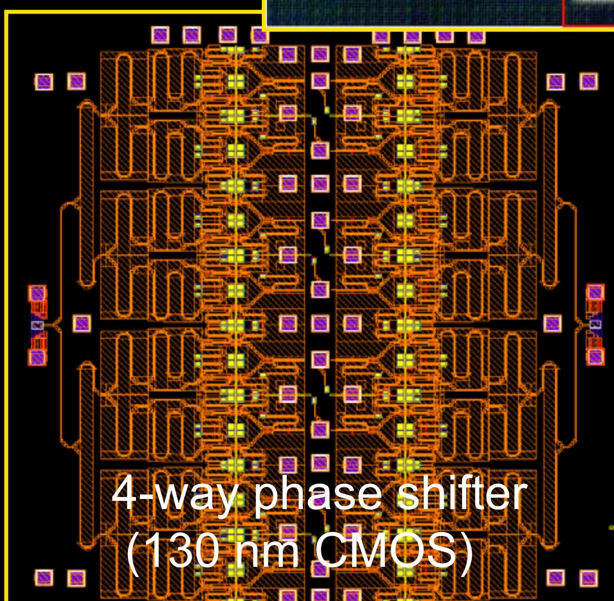


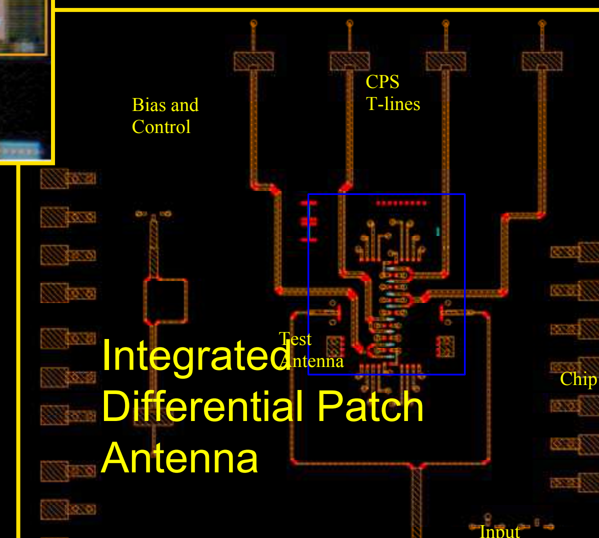
- Use of transmission line interconnect allows control of electrical and magnetic fields

C.Doan et al, JSSC Jan. 2005

And Designed







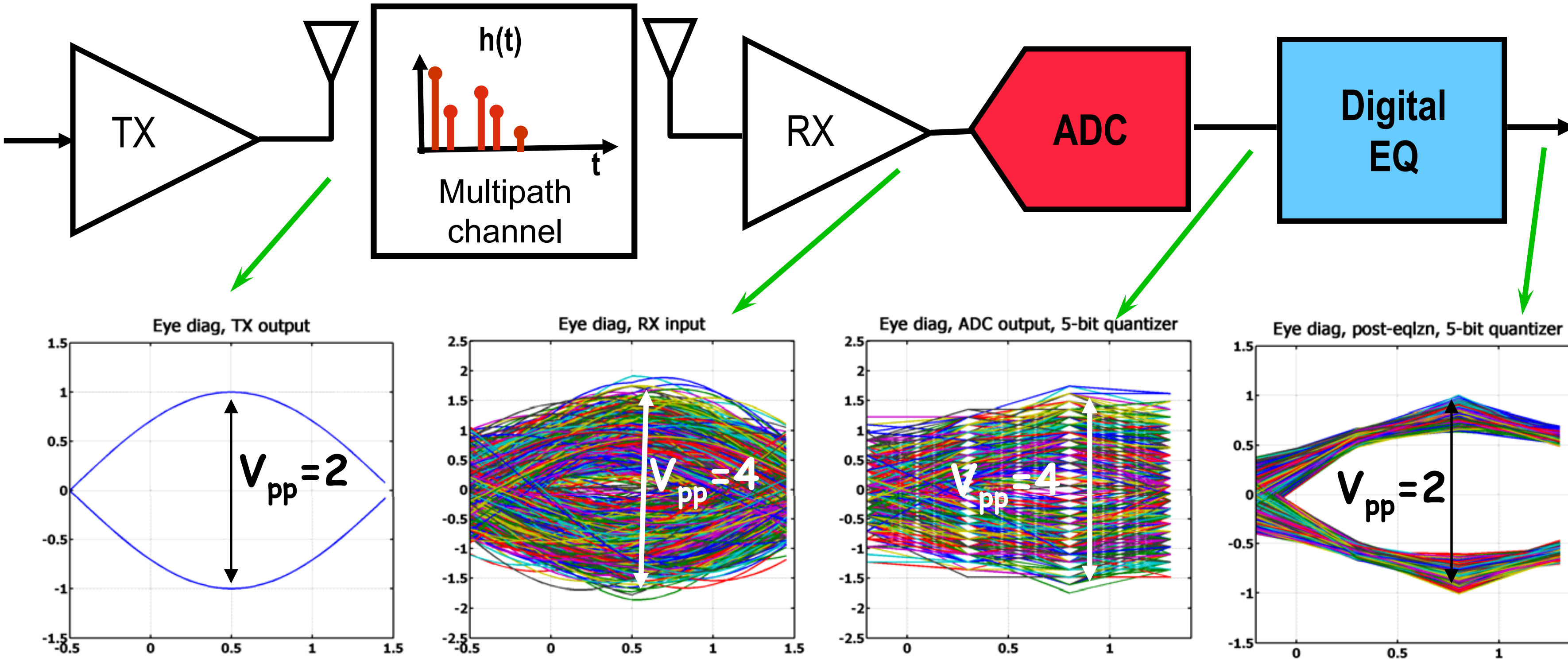
Feasible in today's 130/90 nm CMOS technologies

How best to use the 7 GHz of bandwidth to achieve a Gigabit/sec link?

- “Simple” modulation scheme like FSK simplifies circuit requirements
  - Linearity, PA efficiency, noise, phase noise
- But, still need high-speed ADCs (power hungry)
- Minimize ADC resolution to solve power problem
  - From 6 bit to 4 bit 10x power reduction possible

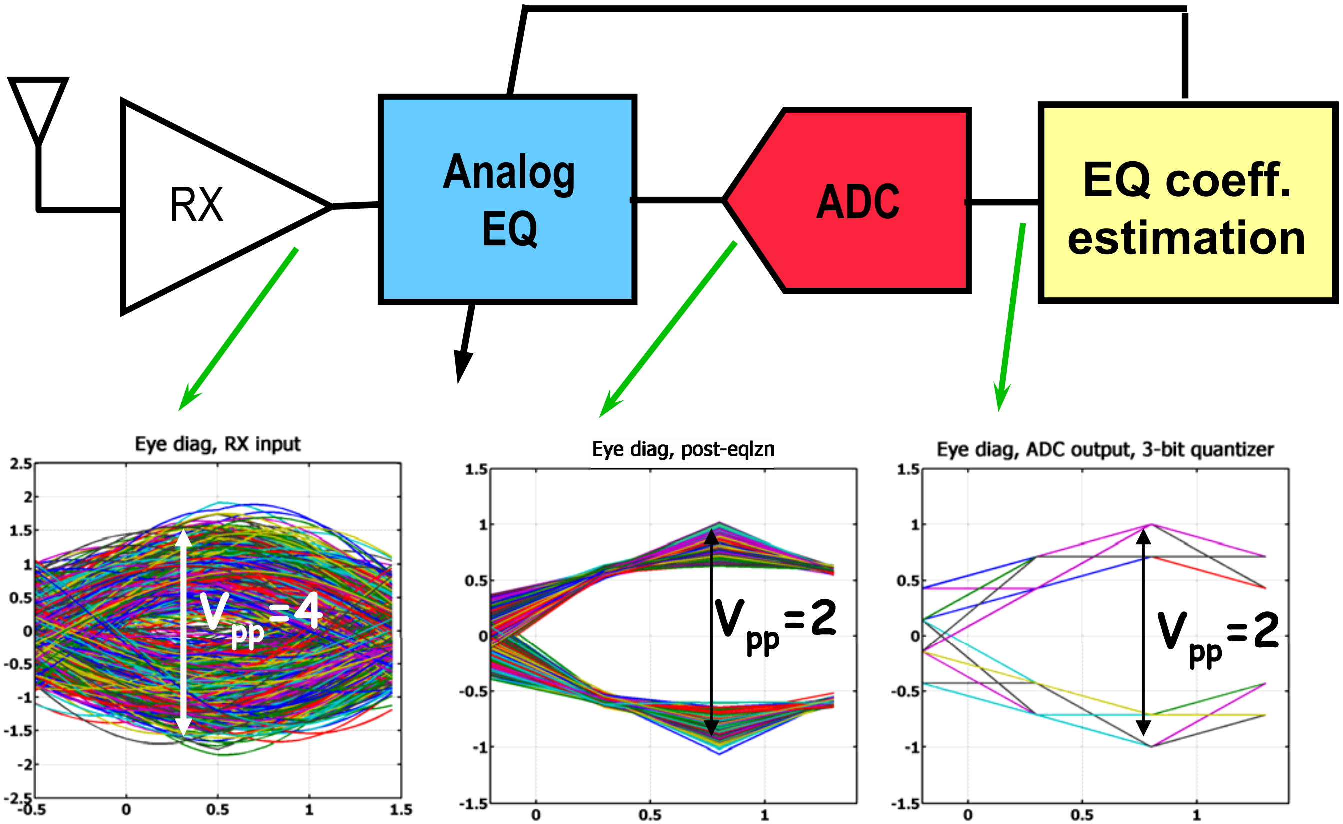
Reduce the dynamic range prior to ADC!

Multipath increases dynamic range



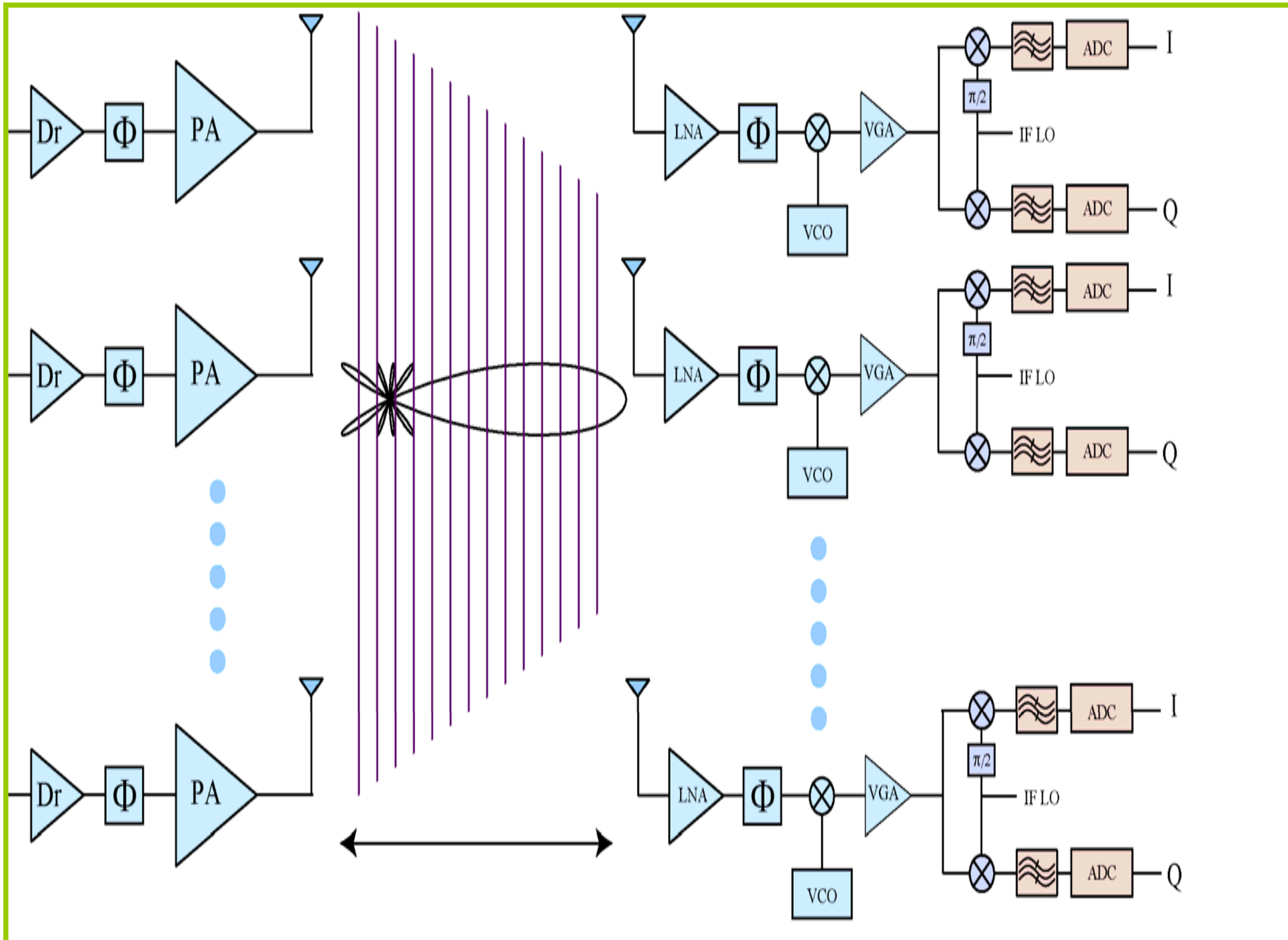
- Digital equalization removes ISI but needs more bits in ADC

Implement equalizer in analog domain



- ESTIMATE coefficients in digital domain, CORRECT in analog domain
- Common approach in high speed optical and wired links

Combating Multi-Path using MIMO



60 GHz Wireless Transceivers

- Implementation in 90 nm CMOS definitely possible
- Variety of transceivers in the making by established companies as well as start-up’s
- IEEE 802.15.3c working group looking at standardization
- Great opportunity for the development of in-room Gbit/sec wireless LANs
- Not for the faint of heart – TRX power will be in the Watt range

A New Approach - Cognitive Radios

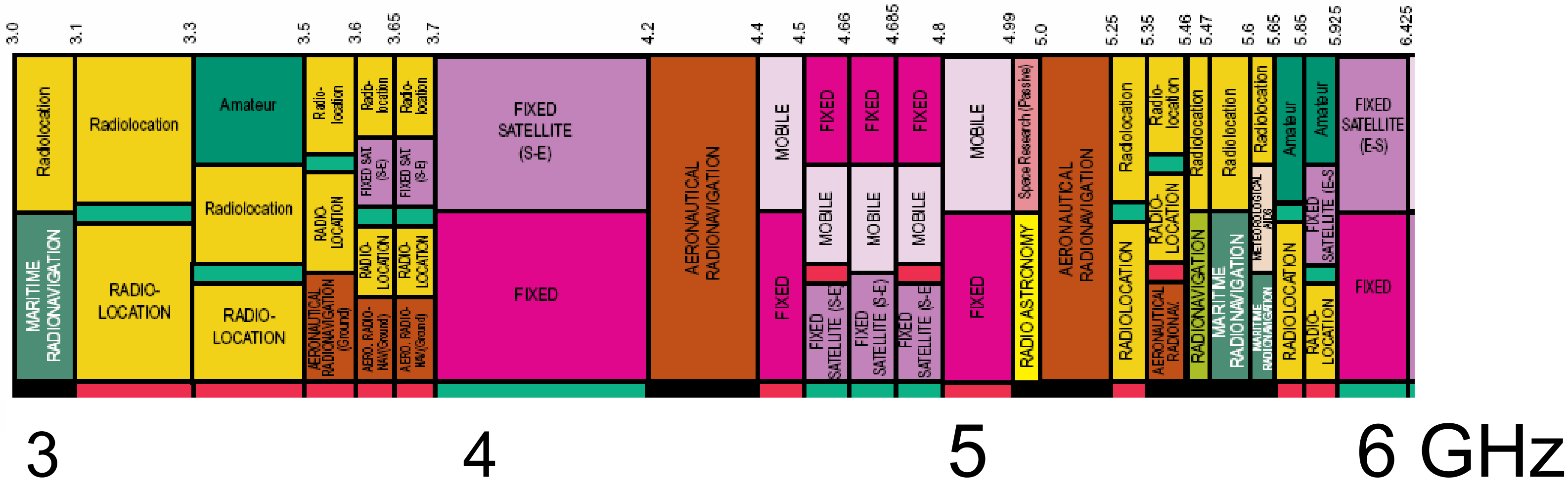
According to the FCC:

"*We recognize the importance of new cognitive radio technologies, which are likely to become more prevalent over the next few years and which hold tremendous promise in helping to facilitate more effective and efficient access to spectrum*"

Federal Communications Commission,

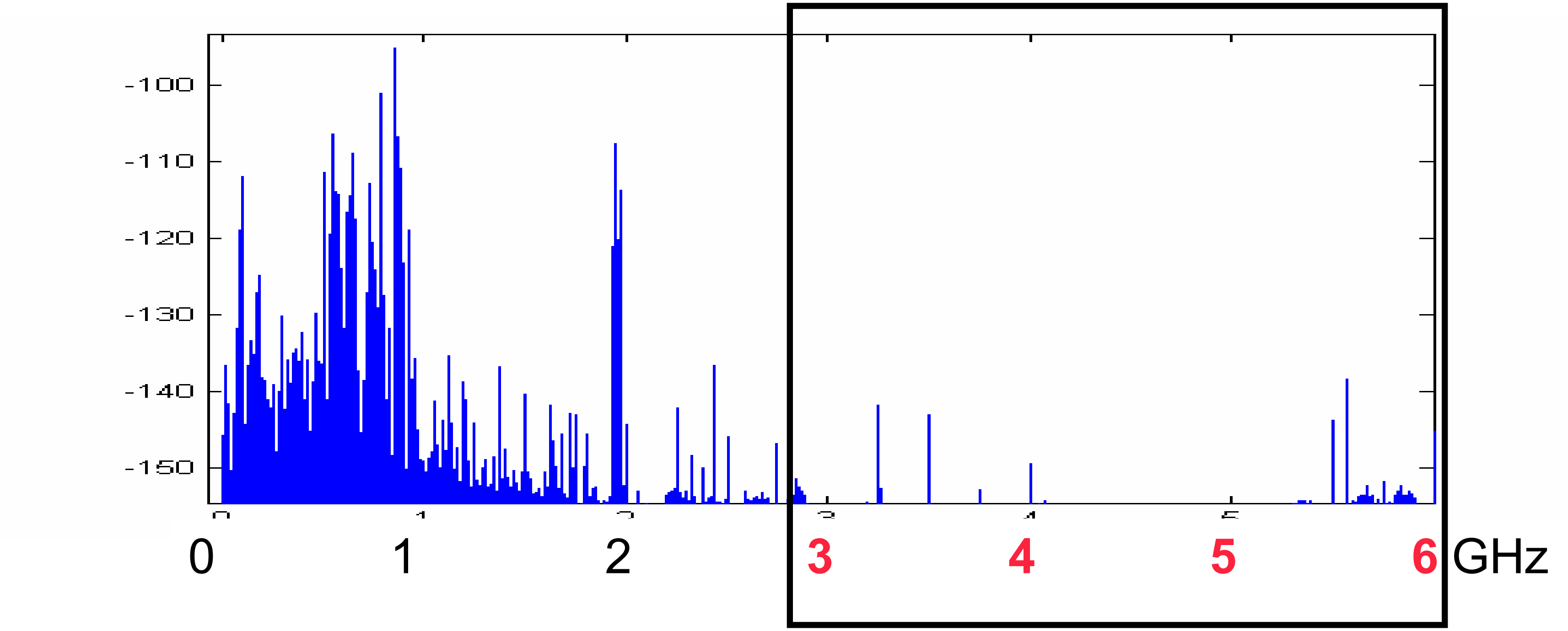
ET Docket No. 03-108, Dec 30th 2003

The spectrum shortage….



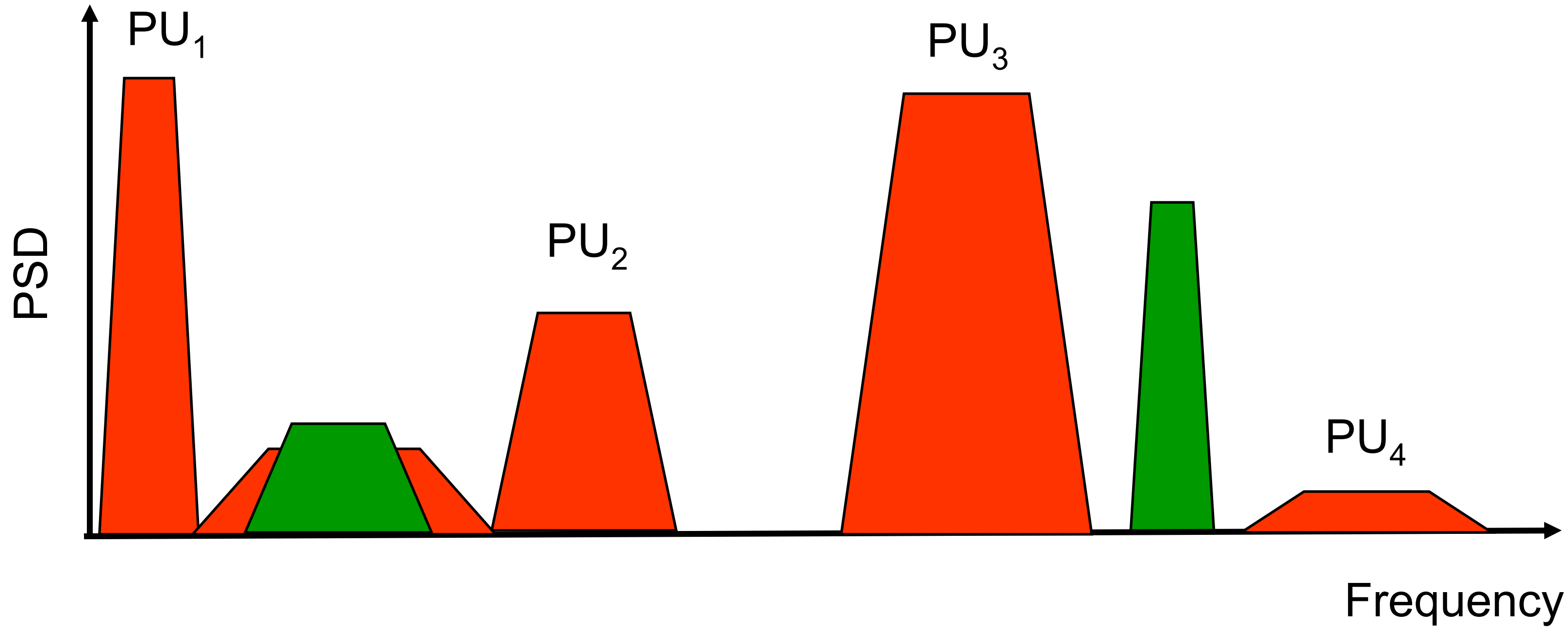
- All frequency bands up to 60 GHz (and beyond) have FCC *allocations* for multiple users
- The allocation from 3-6 GHz is typical - seems very crowded….

The reality…



- Even though the spectra is allocated it is almost unused
- Cognitive radios would allow unlicensed users to share the spectrum with primary users

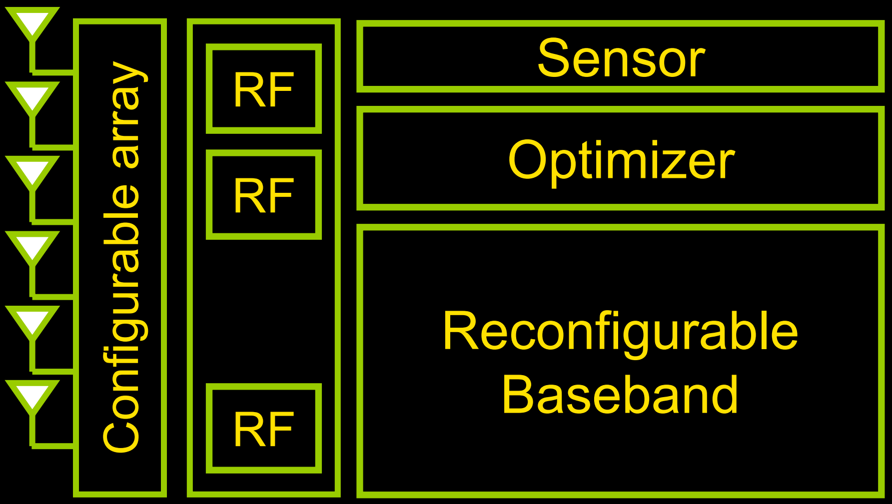
How does a Cognitive Radio operate?

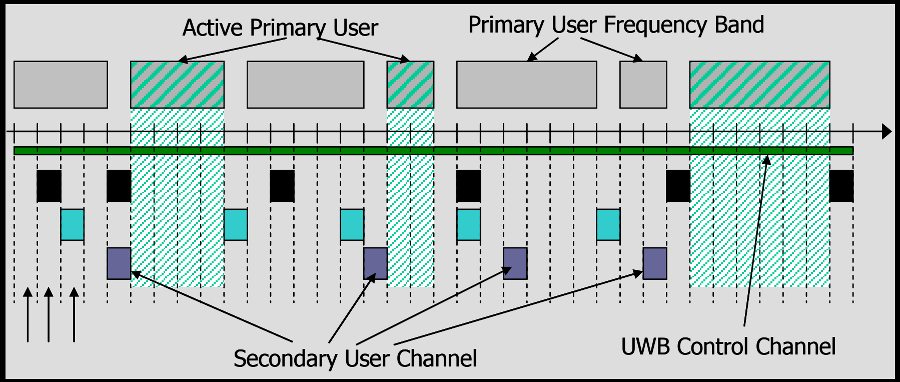


- **sense** the spectral environment over a wide bandwidth
- reliably **detect** presence/absence of primary users
- **transmit** in a primary user band only **if detected as unused**

Opportunity: Cognitive Radios

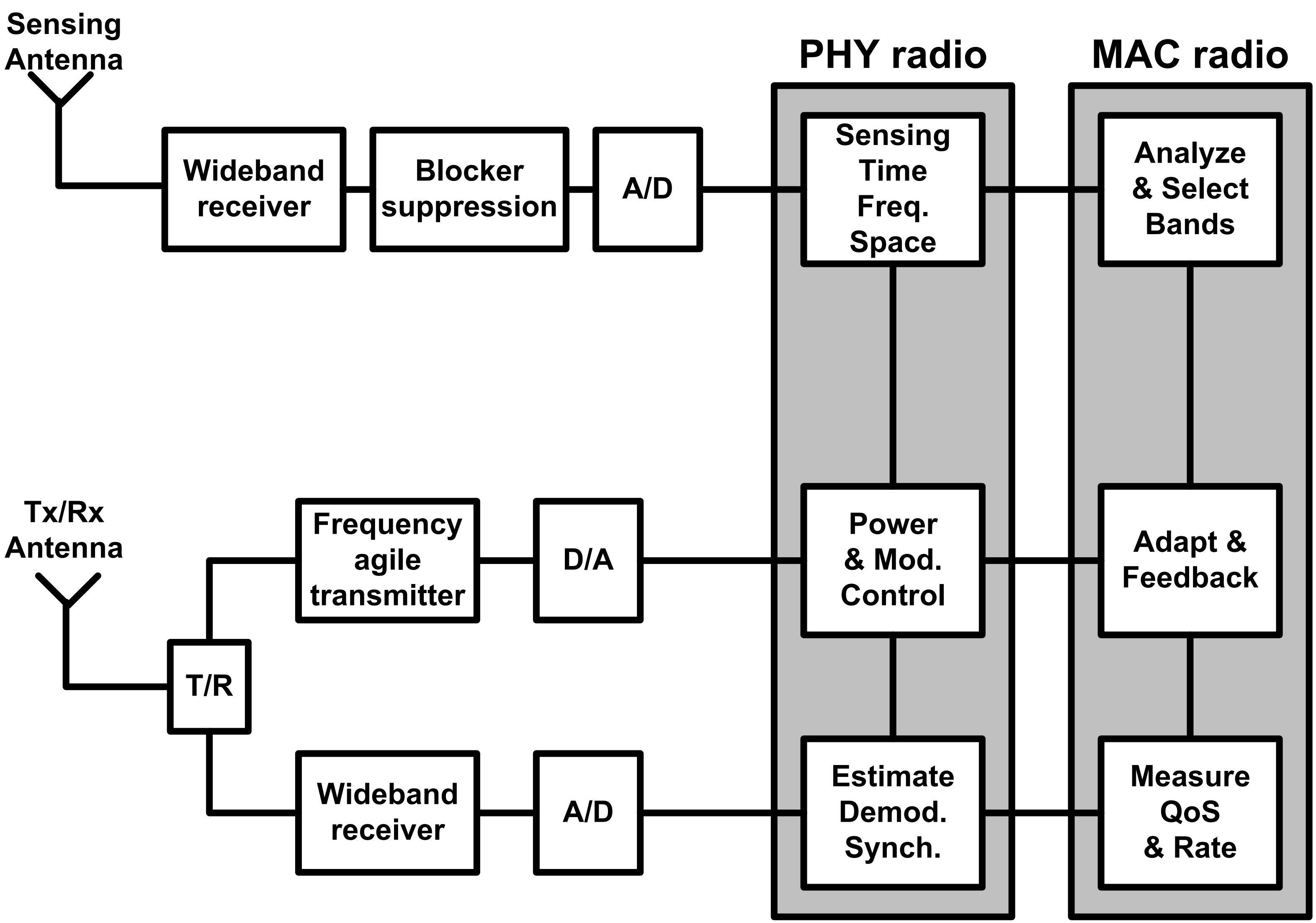
- **Requirements**
  - Co-exist with legacy wireless systems
  - Use their spectrum resources
  - Do not interfere with them
- **Properties**
  - RF technology that "listens" to huge swaths of spectrum
  - Knowledge of primary users' spectrum usage as a function of location and time
  - Rules of sharing the available resources (time, frequency, space)



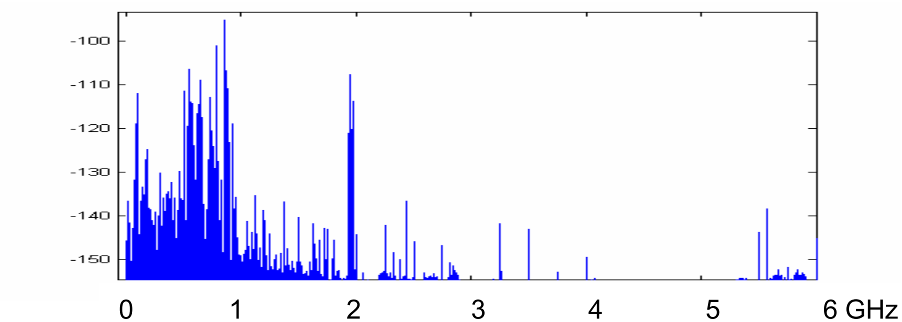


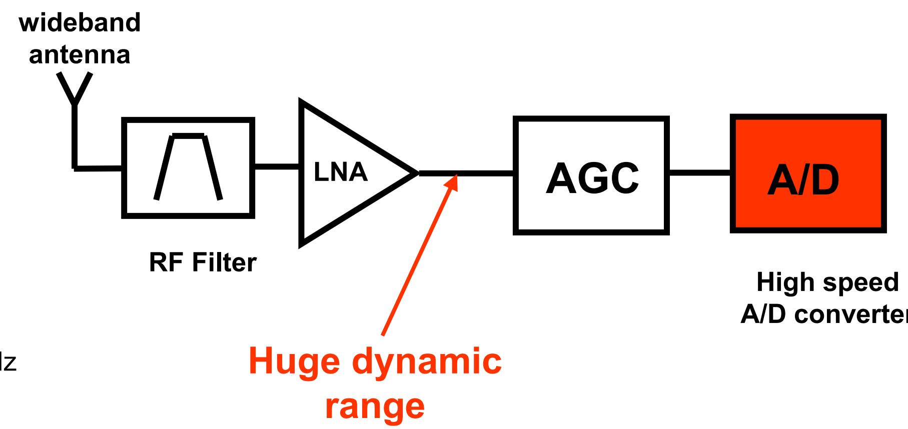
Current focus: The Television Bands

Cognitive Radio Architecture



Wideband Sensing Radio





Challenging specifications:

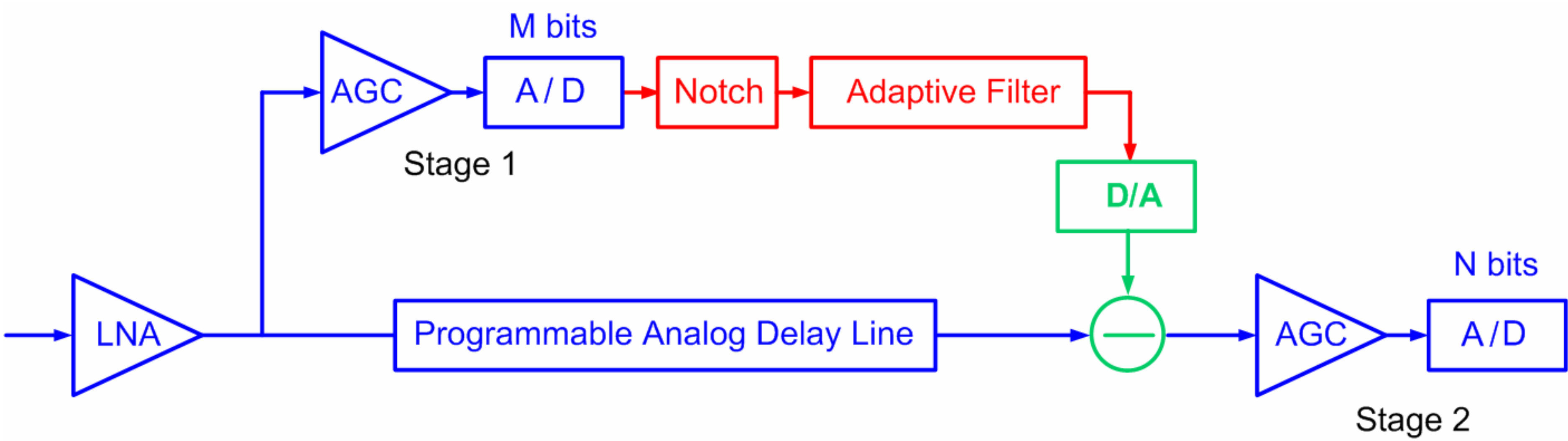
- **Multi-GHz A/D -> Nyquist sampling**
- **High A/D resolution (> 12 bits)**

Dynamic range reduction:

- **Frequency: RF MEMS filter bank**
- **Time: Active cancellation**
- **Spatial: Filtering using multiple antennas**

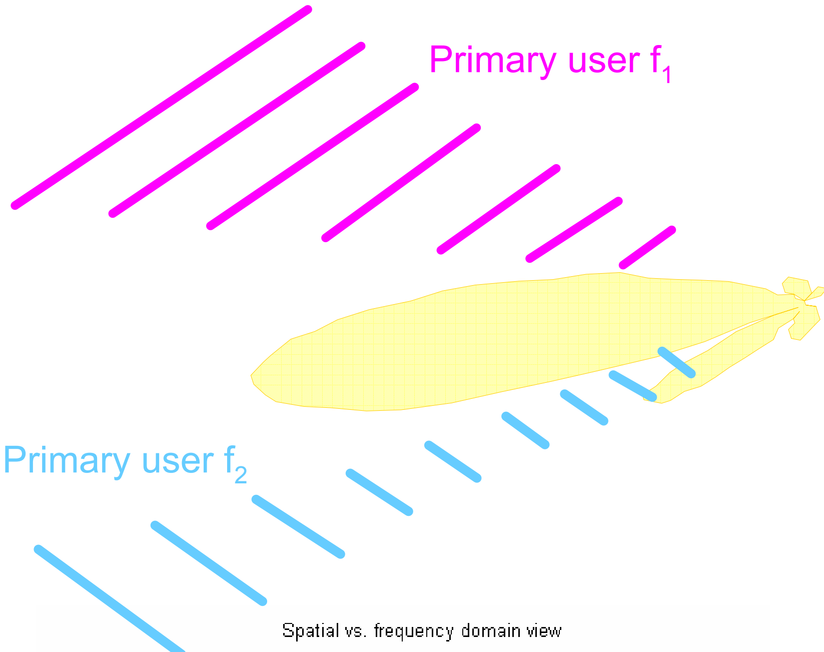
Time Domain Interference Cancellation

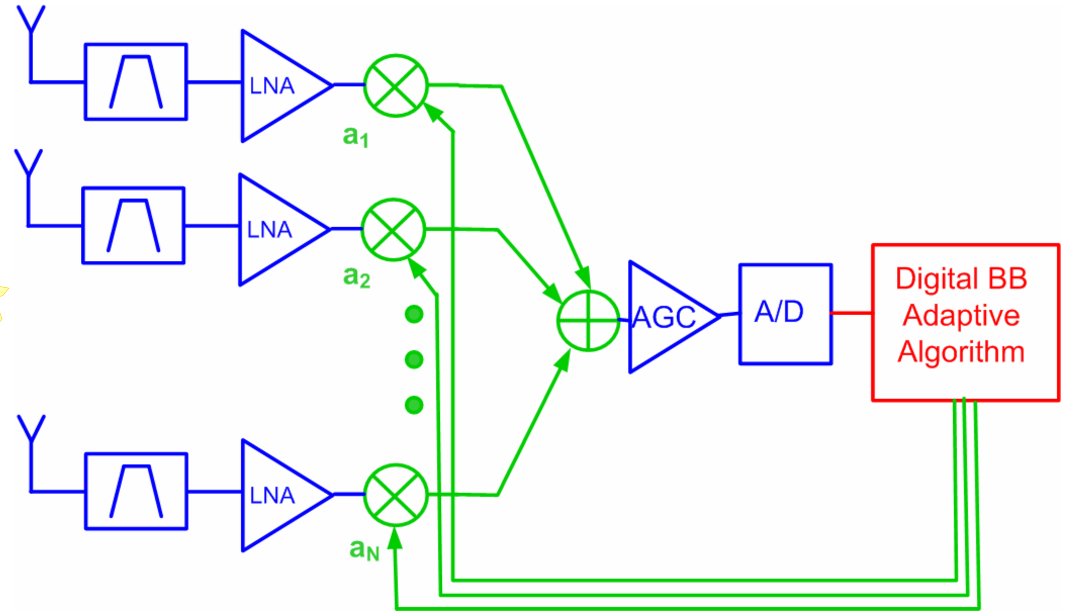
- **Mixed signal approach**
  - Flexibility offered by adaptive digital signal processing
- **Feed forward architecture with 2 stage low resolution A/D conversion to achieve overall high resolution $2^M+2^N << 2^{M+N}$**

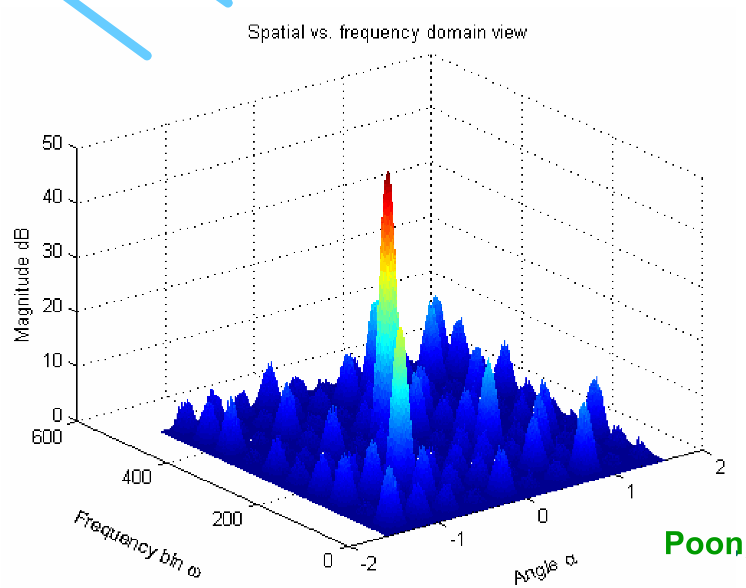


[Yang, Brodersen]

Spatial filtering can reduce dynamic range





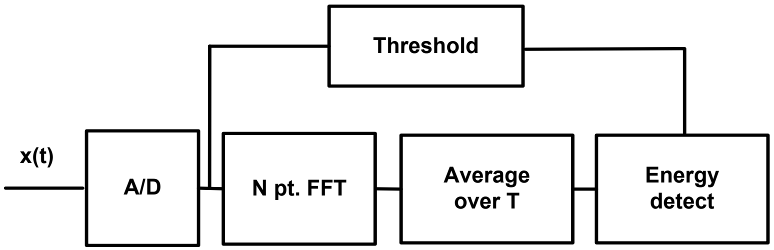


- Point antenna array at cognitive radio transmitter – avoid interferers
- Combine antenna outputs in analog domain to reduce dynamic range

Poon, Tse, Brodersen[2004]

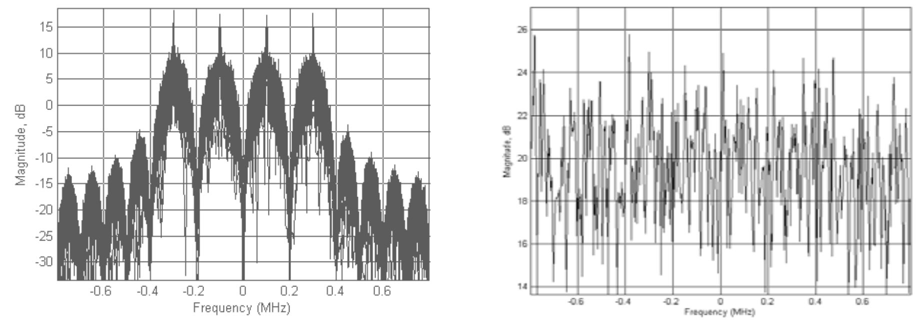
Signal processing can improve sensing of weak signals

Energy Detector



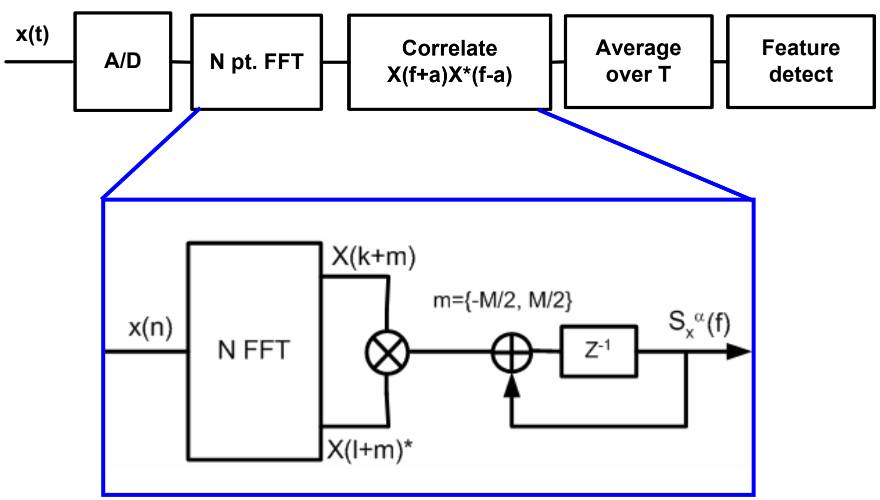
High SNR

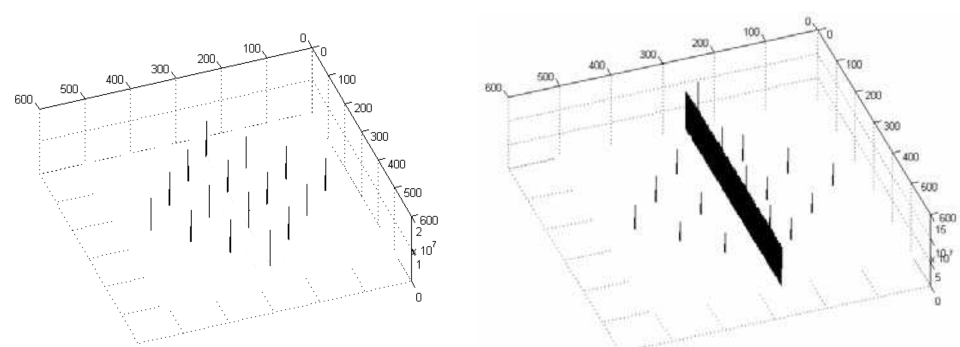
Low SNR



Spectrum density

Cyclostationary Detector





Spectral correlation

Cognitive Radio - Challenge

- Homogenous ad-hoc cognitive radios for opportunistic spectrum use may be possible, but are going to be complex and probably expensive devices.
- Non-frequency-specific sensing infrastructure, coordination bands, and a small amount of backhaul capability may enable non-interfering use by relatively cheap mobile devices.

Ananth Sahai, Wireless Foundations, UCB

Assuming stand-alone low-power cognitive radio's for mobile applications is probably too much to ask
More plausible:
- **Collaborative sensing by multiple devices**
- **Sensing performed by the backbone (Infrastructure)**

Current Status

IEEE 802.18 Working Group

Recent FCC Activity Related to Cognitive Radio cadence

- December 20, 2002, NOI[11]: *Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band*, FCC-02-328.
  - Opens the question of **using fallow TV band channels** for unlicensed services on a non-interference basis.
  - In the NOI, para.16, the FCC states "Specifically, **an unlicensed device should be able identify unused frequency bands** before it can transmit." (i.e. DFS and IPD).

FCC Creates Part 15.244 in TV Band cadence

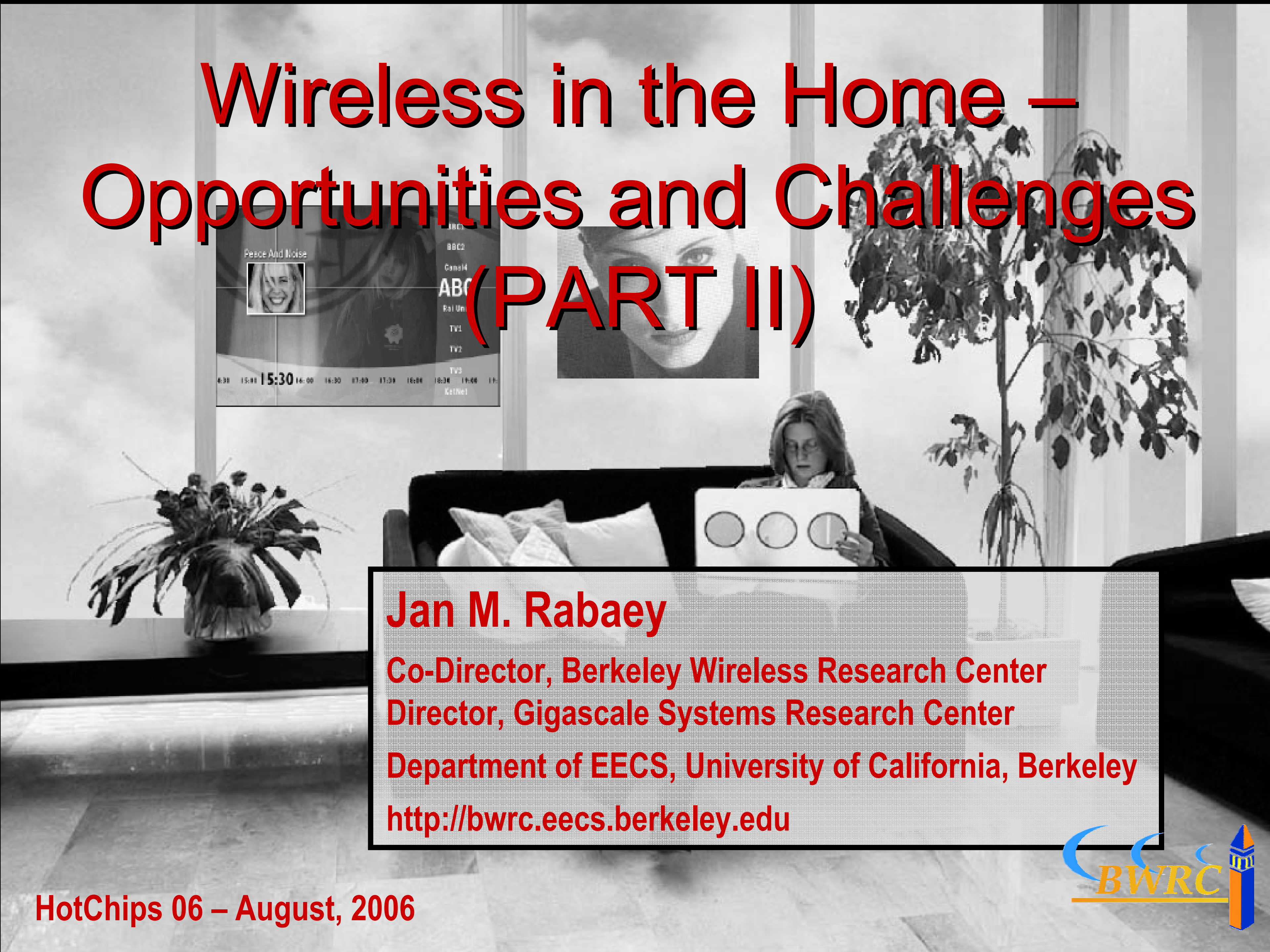
Part 15.244 Device Types

1. Personal/Portable Devices
   - 100 mW peak transmitter power, 400 mW peak EIRP (6 dBi antenna)
   - May transmit only when receiving a control signal from one of the following sources: a TV Broadcast station, an FM Broadcast station, or an unlicensed transmitter indicating available TV channels.
2. Fixed Access Devices
   - 1 W peak transmitter power, 4 W peak EIRP (6 dBi antenna)
   - Must meet one of the following criteria
     a) Include a GPS receiver and means of determining vacant TV channels in the area
     b) Be installed by professionals to operate only on unused channels.

Courtesy: J. Notor, Cadence

High Data Rate Wireless In the Home Summary

- Number of new initiatives will make both wireless LANs and point-to-point connections at high data rates (> 500 MB/sec) possible in the next decade
- Data rates high enough to support multiple HDTV channels at the same time, providing ample redundancy and avoiding data congested channels
- Common requirements: complex processing, high bandwidth front-end, mostly digital implementations
- Not a single unified standard, but many alternatives with different application purpose, data rates and power/size design points
- Trend towards more flexibility in implementation and multi-standard modules



Wireless in the Home – Opportunities and Challenges (PART II)

Jan M. Rabaey

Co-Director, Berkeley Wireless Research Center
Director, Gigascale Systems Research Center

Department of EECS, University of California, Berkeley

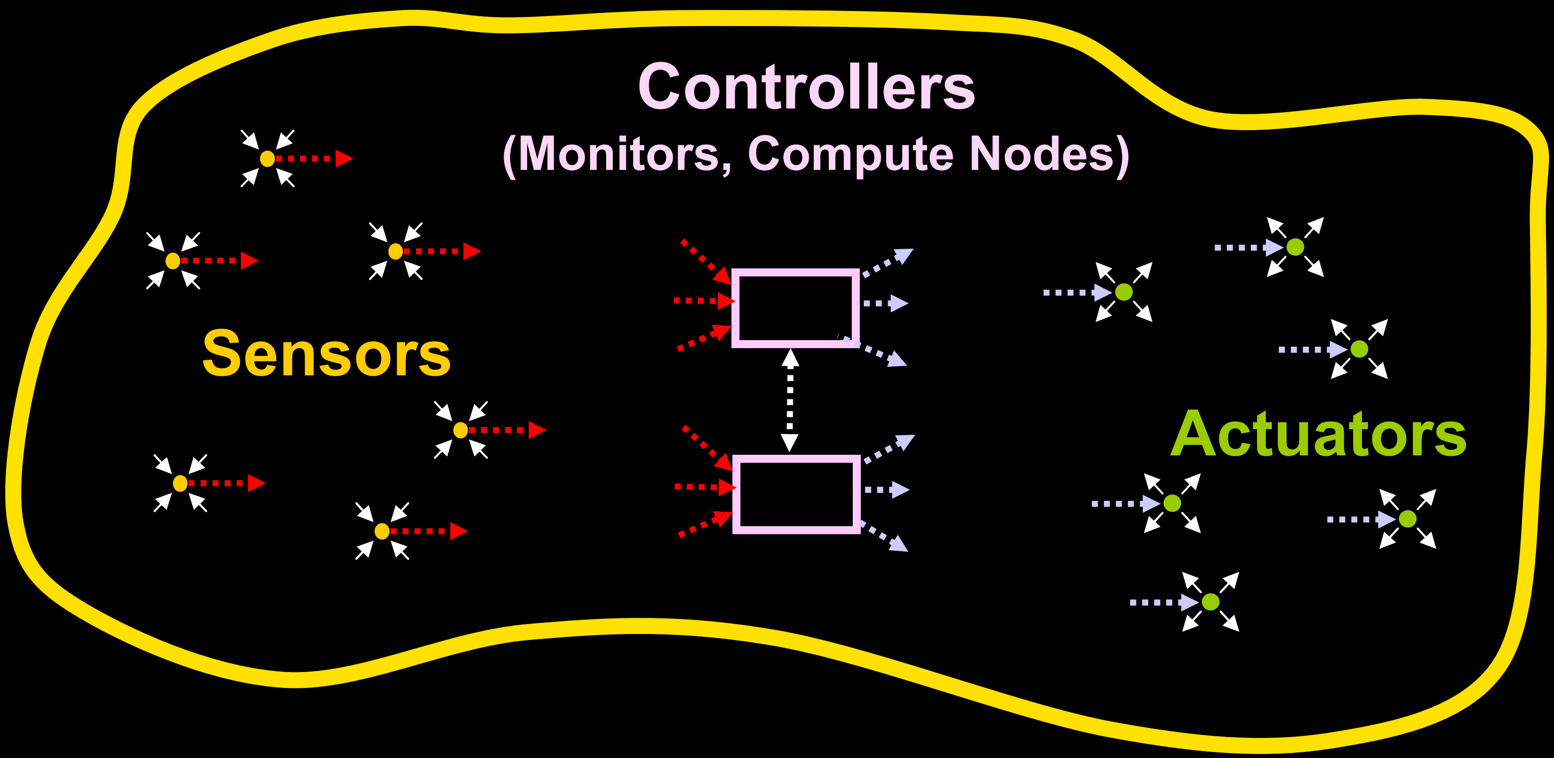
http://bwrc.eecs.berkeley.edu

HotChips 06 – August, 2006

Tutorial Outline

- Reliability and QoS
  - Trends and Developments in High-Data Rate Wireless
  - Trends and Developments in Low-Data Rate Wireless
- Portability and scalability
- Configuration, Management and Control

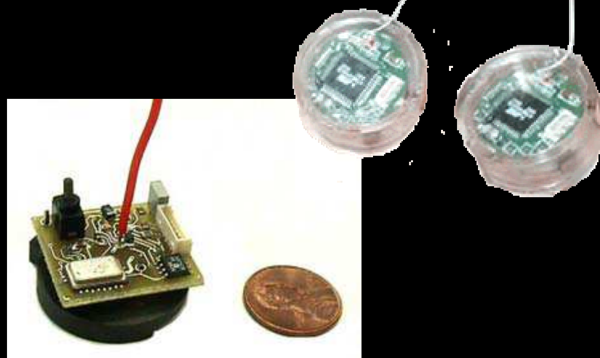
Wireless Sensor and Actuator Networks
Providing the Ambient



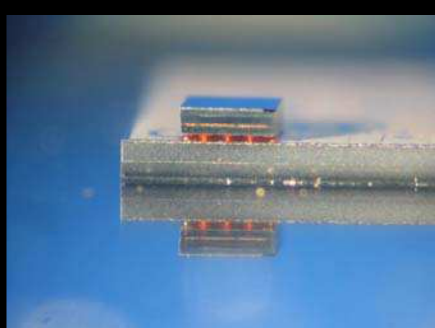
A collection of cooperating algorithms (controllers) designed to achieve a set of common goals, aided by interactions with the environment through **distributed** measurements (sensors) and actions (actuators).

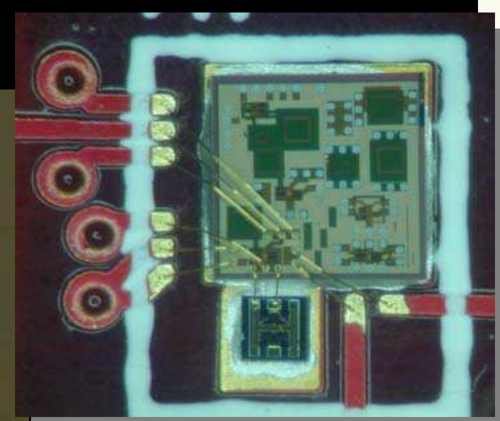
How to Make Electronics Truly Disappear?

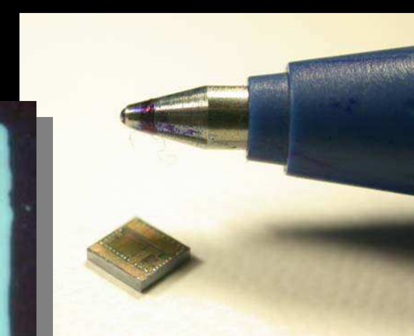
From 10's of cm^3 and 10's to 100's of mW



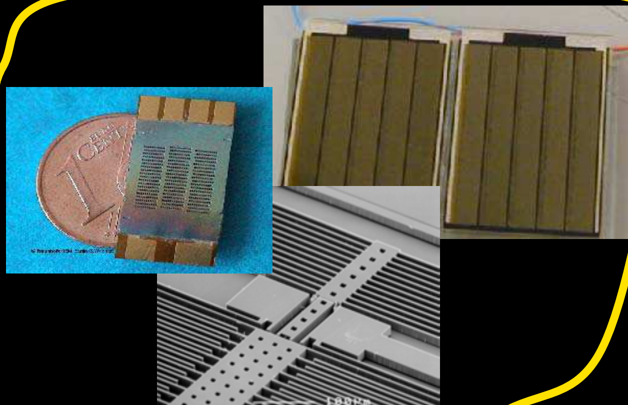
To 10's of mm^3 and 10's of μW





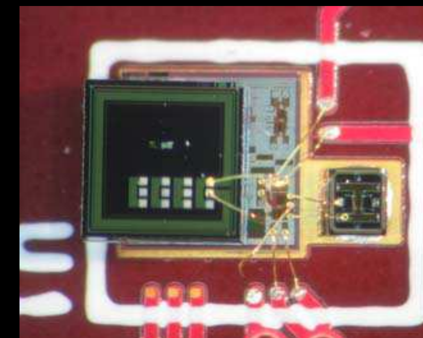


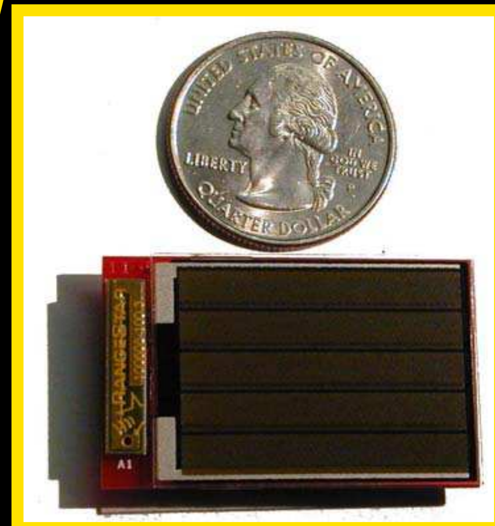
Adopt Non-Orthodox Technologies and Approaches



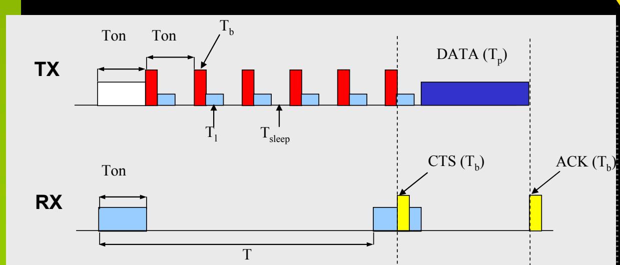
Energy scavenging

Simple radio's with minimal external components

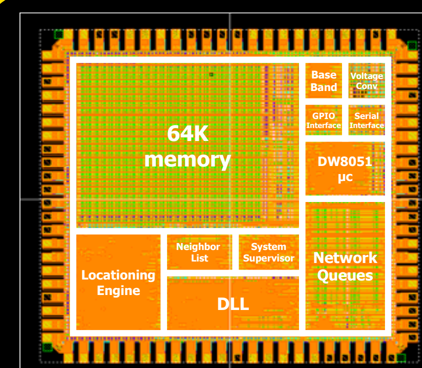




A 100 μW self-contained sensor node



Architectures that maximize standby time

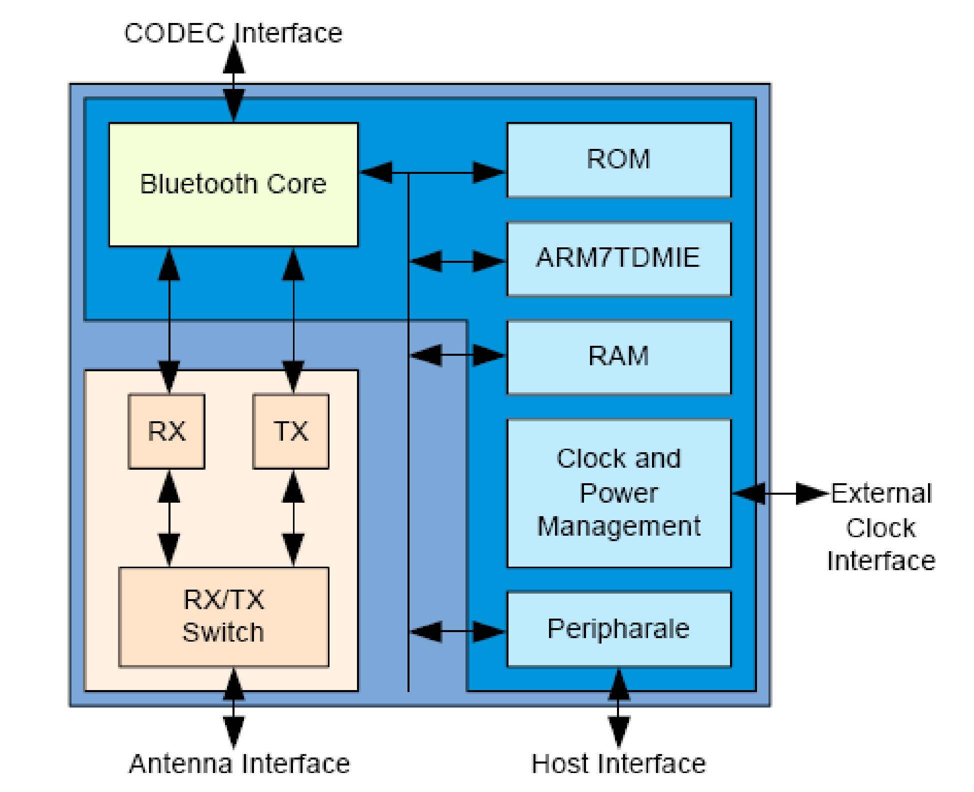


Ultra-low power processors with low standby power

Industrial State-of-the-Art

- Low-data rate short-distance wireless only started receiving attention over the last decade
- Bluetooth as the front-runner (finally successful)
  – However its focus (wire replacement) limits its application scope
- 802.15.4 (most often called Zigbee) designed specifically for low cost / low power applications
  – Limited in-road so far
  – Power numbers ok but marginally meeting the application requirements
- 802.15.4a (UWB low-data rate) under development
- Very often, companies use proprietary protocols in the 800 MHz unlicensed band – simple, low-power, cheap

Bluetooth



- Intended for wire replacement
- Fast frequency hopping (1600 hops/sec, 79 channels with 1 MHz spacing
- **Gaussian filtered binary FM modulation, GFSK.**
- **Gross symbol rate is 1Mb/s.**
- **A Time-Division Duplex scheme.**
- 2.4 GHz ISM band

- **-83 dBm sensitivity,**
- **25 mA transmit and 37 mA receive current consumption (at 1.8V supply)**
- **4$ in volume**

Bluetooth (cntd)

Power Class	Maximum Output Power	Nominal Output Power	Minimum Output Power[1)]	Power Control
1	100 mW (20 dBm)	N/A	1 mW (0 dBm)	4 to +20 dBm -30[2)] to 0 dBm, Optional
2	2.5 mW (4 dBm)	1 mW (0 dBm)	0.25 mW (-6 dBm)	-30[2)] to 0 dBm, Optional
3	1 mW (0 dBm)	N/A	N/A	-30)[2] to 0 dBm, Optional

802.1.5.4 (Zigbee) – Some History

HomeRF Working Group disbands

By Richard Shim
Staff Writer, CNET News.com
Published: January 7, 2003, 5:50 PM PST

TalkBack | E-mail | Print

A consortium of companies promoting a wireless home networking specification to compete with Wi-Fi disbanded at the beginning of the year, representing its commercial end.

The HomeRF Working Group is no longer developing, promoting or distributing the HomeRF specification, Ken Haase, the former chairman and a product marketing director at Proxim, confirmed late Tuesday. But HomeRF will be available through university partners who may study and expand upon it.

The group requested that its Web site be taken down on the first of the year, according to Web hosting company Kavi.

"There is nothing formally being done to evolve the HomeRF from a commercial standpoint...there is no formal entity driving the spec," Haase said.

The news is the final blow for HomeRF and its battle against Wi-Fi for market

---

Philips Semiconductors

WI CON

Philips RF-Lite Program
Firefly

- History:
  - Started life as HomeRF-Lite, a subgroup of the HomeRF organization
    - Gathered Market Requirements, stable
      - Very low cost
      - Low data rates
      - Low power consumption
    - Focus for making contacts
    - Technical Requirements agreed
  - Now spun off from HomeRF to form "Firefly"
    - Separate IP agreement required (outside HomeRF terms of reference)
    - HomeRF focus on SWAP-CA
- Objective:
  - Facilitate the creation of standard(s) radio system to meet the agreed market requirements

Let's make things better. PHILIPS

Philips Semiconductors

WI CON

Philips RF-Lite Program
Firefly - Market Requirements

- The numbers...
  - 10k-115.2kbps data throughput
  - 10-75m coverage range (home/garden)
  - Support for 32-254 nodes
  - Support for 4 *critical* devices
  - 4-100 co-located networks
  - 0.5-2 year battery life
  - Up to 5ms^{-1} permitted mobility
  - Module cost: $1.5-$2.5 in 2003!

PS – XX.XX.XX-11

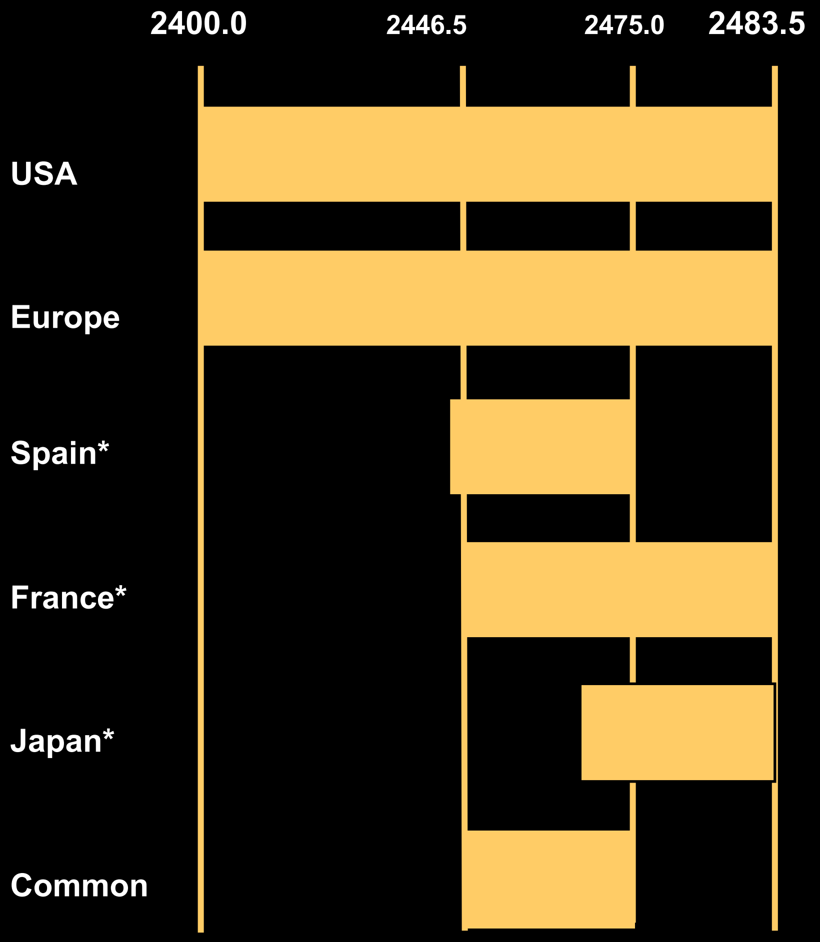
Let's make things better. PHILIPS

802.15.4

- Data rates of 250 kbps, 40 kbps, and 20 kbps.
- Two addressing modes; 16-bit short and 64-bit IEEE addressing.
- Support for critical latency devices, such as joysticks.
- CSMA-CA channel access.
- Automatic network establishment by the coordinator.
- Fully handshaked protocol for transfer reliability.
- Power management to ensure low power consumption.
- 16 channels in the 2.4GHz ISM band, 10 channels in the 915MHz I and one channel in the 868MHz band.

Frequency Bands

- 2.4GHz ISM band
  - Channel spacing: 4MHz
  - F = 2404 + 4k MHz with k = 0, 1, …, 25
  - Common band:
    - USA, Europe including France and Spain
    - 2446.5 – 2475.0 MHZ
    - k = 15, …, 22; equals 8 channels
- 915MHz ISM band USA only
- 868MHz Europe



* Harmonization with FCC in progress

Chipcon CC2420 Transceiver

- Fast data rate, robust signal
  - 250kbps : 2Mchip/s : DSSS
  - 2.4GHz : Offset QPSK : 5MHz
  - 16 channels in 802.15.4
  - -94dBm sensitivity
- Low voltage operation
  - 1.8V minimum supply

Specifications		Min	Typical	Max	Unit
General:	Frequency range	2400		2483.5	MHz
	Data Rate		250		kbps
	Operating Voltage	2.1		3.6	V
	Operating Temperature	-40		85	°C
RX Mode:	Receiver Sensitivity		-94		dBm
	Adjacent Channel Rejection, +5 MHz		46		dB
	Adjacent Channel Rejection, -5 MHz		39		dB
	Alternate Channel Rejection, + 10 MHz		58		dB
	Alternate Channel Rejection, - 10 MHz		55		dB
Power Supply:	Current Consumption, RX		19.7		mA
	Current Consumption, TX, -10 dBm		11		mA
	Current Consumption, TX, -5 dBm		14		mA
	Current Consumption, TX, 0 dBm		17.4		mA
	Current Consumption, Voltage Regulator Off			1	µA

Software assistance for low power microcontrollers

128byte TX/RX buffers for full packet support

Automatic address decoding and automatic acknowledgements

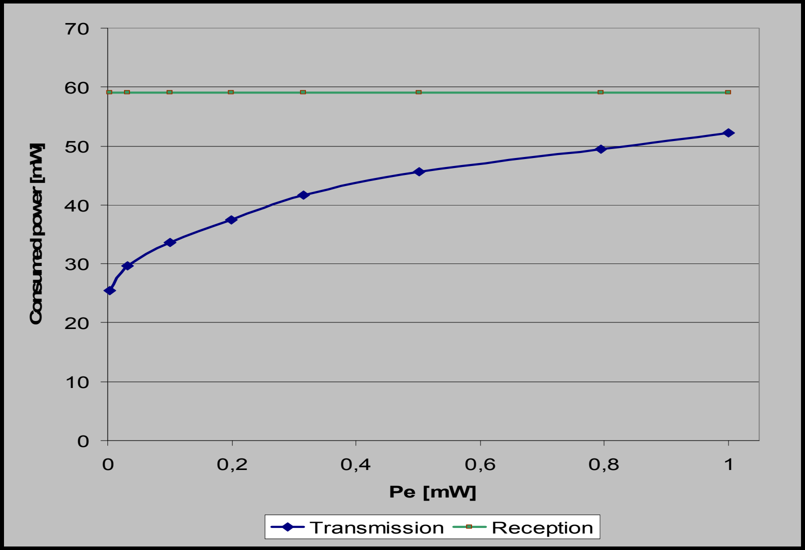
Hardware encryption/authentication

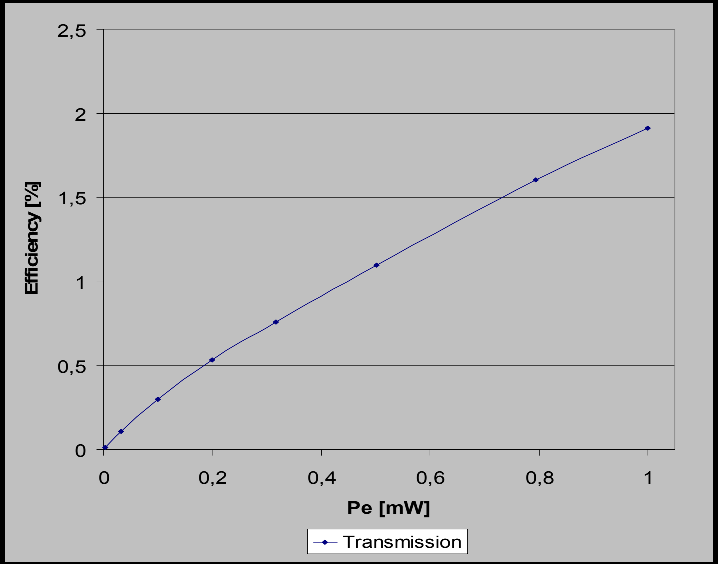
Link quality indicator (assist software link estimation)

samples error rate of first 8 chips of packet (8 chips/bit)

The power efficiency challenge

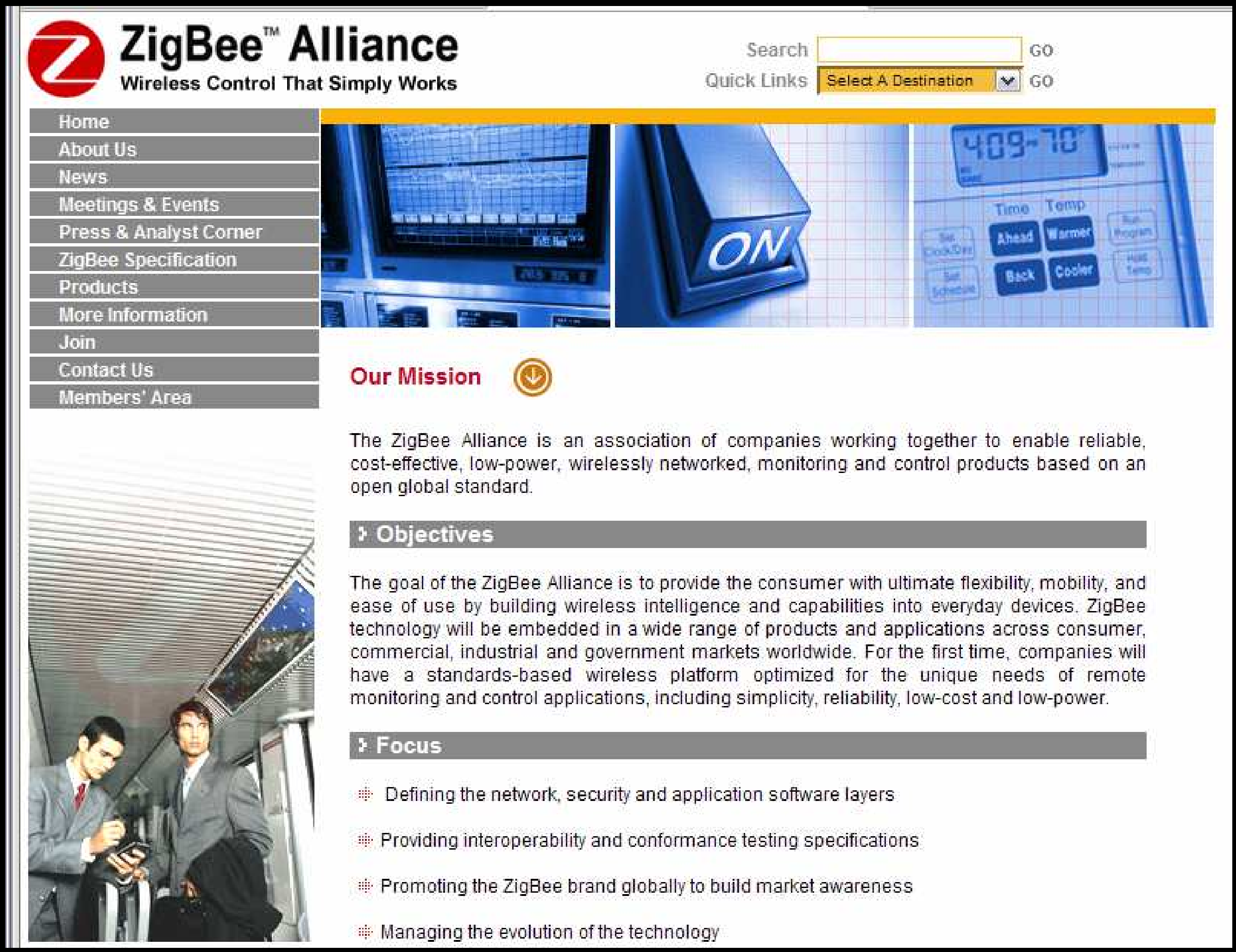
- Power consumption of the CC2420 radio transceiver (IEEE802.15.4 compliant):
  - RX power of 59.1 mW, TX power between 25.5 mW and 52.2 mW
  - Emitted power P_e between 3 μW and 1 mW
  - Efficiency $\eta = P_e / TX$ in the interval < 0.1 %, 2 % >





- ~ Half the RX power needed for modulation/demodulation

Zigbee Alliance



802.15.4a

IEEE 802.15

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IEEE 802.15 WPAN Low Rate Alternative PHY Task Group 4a (TG4a)

Friday, 21 July 2006

Overview

The IEEE 802.15 Low Rate Alternative PHY Task Group (TG4a) for Wireless Personal Area Networks (WPANs) has defined a project for an amendment to 802.15.4 for an alternative PHY.

The principle interest is in providing communications and high precision ranging / location capability (1 meter accuracy and better), high aggregate throughput, and ultra low power; as well as adding scalability to data rates, longer range, and lower power consumption and cost. These additional capabilities over the existing 802.15.4 standard are expected to enable significant new applications and market opportunities.

802.15.4a became an official Task Group in March 2004; with its committee work tracing back to November 2002. The committee is actively drafting an alternate PHY specification for the applications identified in accordance with the project timeline.

In March 2005, we selected our baseline specification without enacting our down-selection procedures, and as a result, we confirmed the baseline with 100% approval. The baseline is two optional PHYs consisting of a UWB Impulse Radio (operating in unlicensed UWB spectrum) and a Chirp Spread Spectrum (operating in unlicensed 2.4GHz spectrum). The UWB Impulse Radio will be able to deliver communications and high precision ranging. New

802.15.4a

- Update
- Profile

Update:

IEEE 802.15.4a Update

The 802.15.4a international task group has made tremendous progress over the last few months, building momentum for next generation wireless technology for asset tagging, asset tracking, and technology for industrial controls and factory and home automation. The committee had 26 PHY proposals and has concluded a baseline standard which includes 2 optional radios. The radios are based on Impulse Radio UWB and the other is a chirp spread spectrum operating at 2.4GHz. The UWB radio is neither MBOA nor DS-UWB technology, rather it is a return to traditional impulse radio approaches to ultrawideband technology; it will operate in the 3GHz to 5GHz unlicensed spectrum. The primary advantages to UWB are low cost, long battery life, multipath immunity and the ability to have communications and simultaneous precision ranging capabilities, on the order of 1/3 meter accuracy. The committee is actively developing this draft standard which is likely to emerge in mid 2006 as an approved IEEE specification. NOTE - the 802.15.4 standard was adopted by the Zigbee Alliance, and it is likely 15.4a will be too; however, the 15.4a technology serves a combined active RFID and Zigbee marketplace. For more information on IEEE 802.15.4a please visit the official webpage (http://www.ieee802.org/15/pub/TG4a.html) or contact Vice Chairman Jason Ellis from Staccato Communications (Jason@staccatocommunications.com).

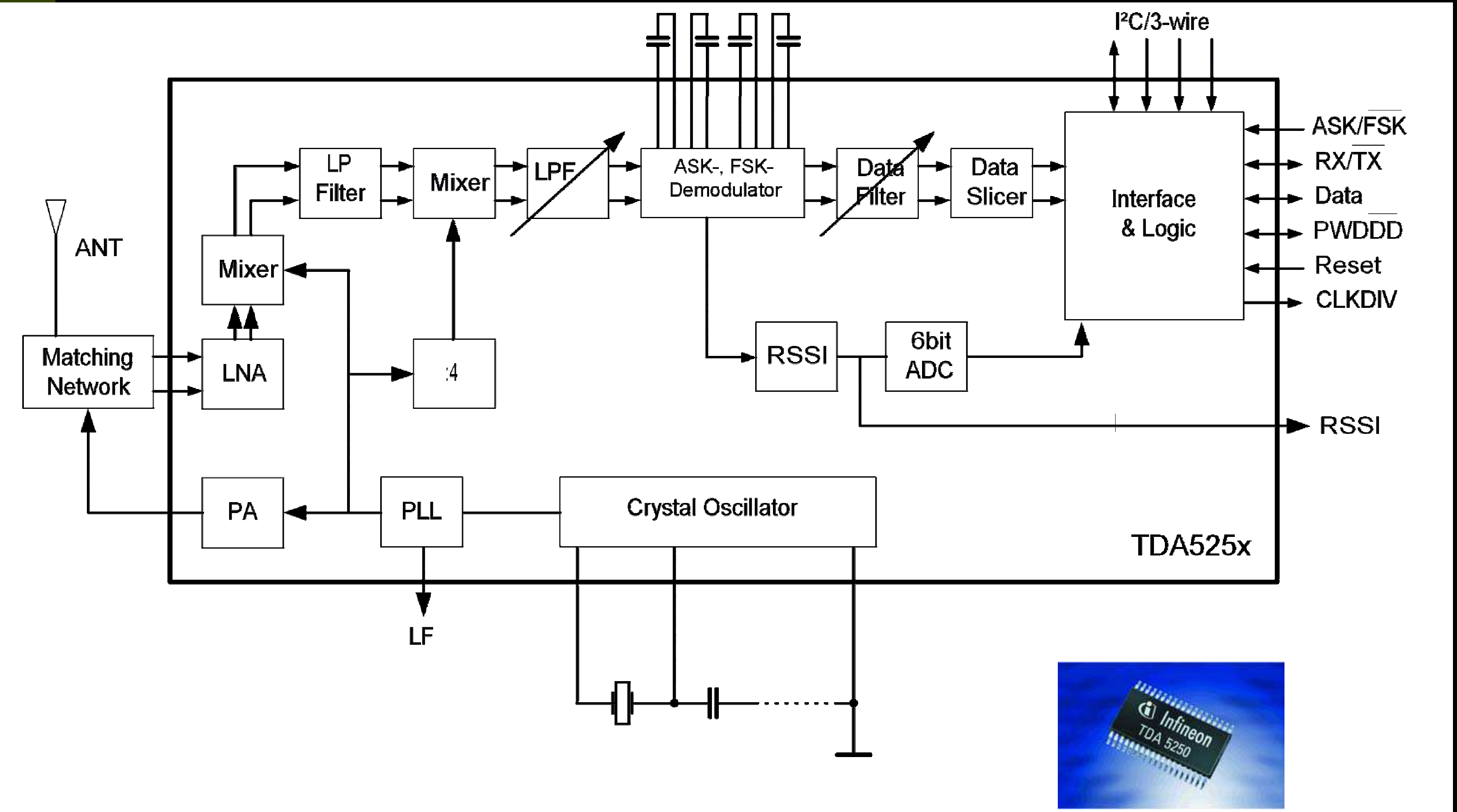
Proprietary Implementations

- Many low-data rate transceivers have been in production for a long time
- Mostly for simple remote control operations
- Operating in 400 MHz – 800 MHz unlicensed bands
- Simple OOK-FSK modulation
- Cheap, but not very sophisticated (no power control, no error control)

Example: Infineon TDA525x

- Technology 0.5µ 25GHz BiCMOS-Process
- Frequency bands 315MHz (TDA5251)
- 433MHz (TDA5255)
- 868MHz (TDA5250)
  915MHz (TDA5252) (from Q2/05)
- Data rate 1..64 KBit/s
- Deviation / Mod. index 10..150KHz / mH > 2
- Sensitivity ASK: < -110 dBm @ 50W, BER = 10-3
- FSK: < -100 dBm @ 50W, BER = 10-3
- Transmit power Pout up to +13 dBm @ 50 W
- Supply voltage: 2.1..5.5V
- Current consumption TX: typ. 10mA RX: typ. 8 mA @ 3V
- Power down max. 100nA
- Temperature range -40°C / +85°C
- Self-polling with fast data rate detection easing CSMA protocol implementation, on-chip data and channel filters set via I²C or SPI bus

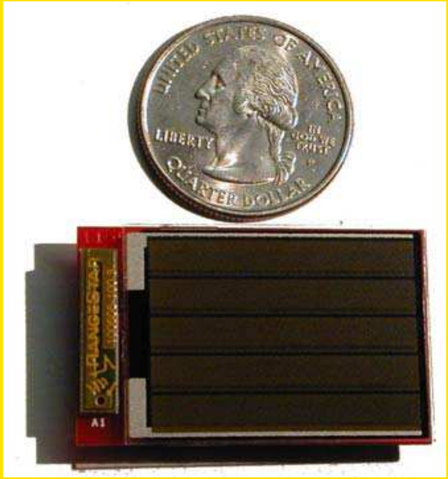
TDA525x Block Diagram



Ultra Low-Power Miniature Wireless Nodes

Meso-scale low-cost wireless transceivers for ubiquitous wireless data acquisition that

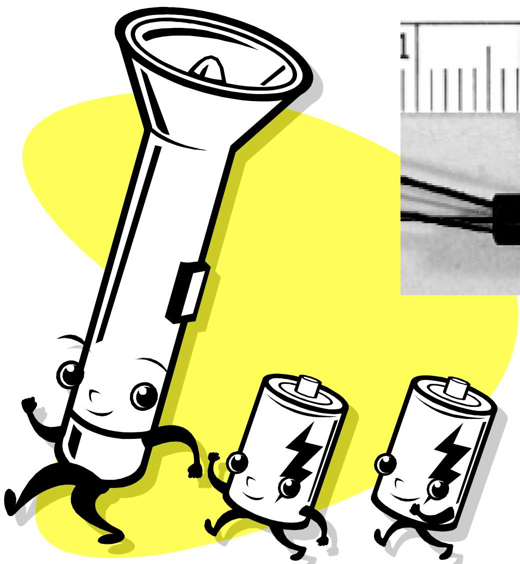
- are fully integrated
  - Size smaller than 1 cm^3
- are dirt cheap ("the Dutch treat")
  - At or below 1$
- minimize power/energy dissipation
  - Limiting power dissipation to 100 μW enables energy scavenging
- and form self-configuring, robust, ad-hoc networks containing 100's to 1000's of nodes

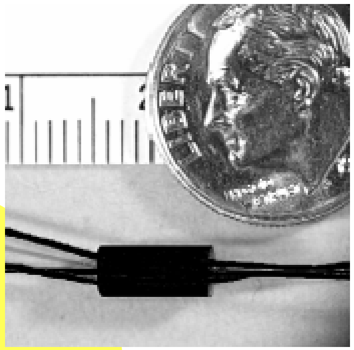


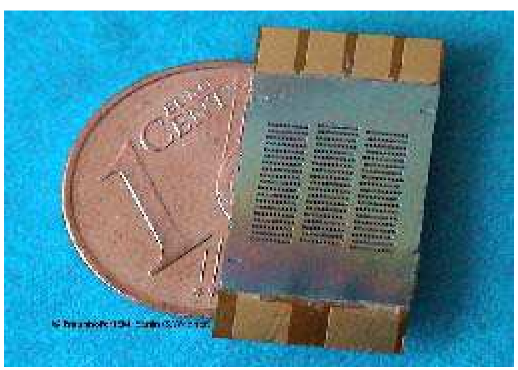
What can one do with 1 cm^3?

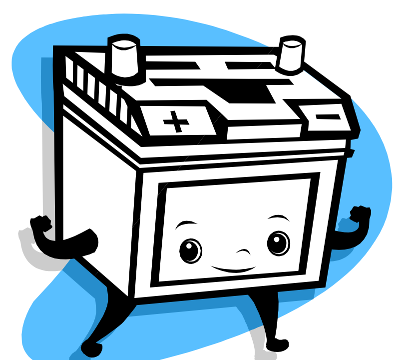
Energy Storage

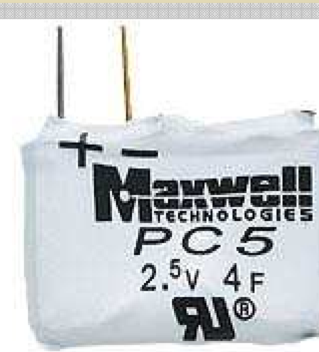
	J/cm^3	$\mu W/cm^3/year$
Micro Fuel cell	3500	110
Primary battery	2880	90
Secondary battery	1080	34
Ultra-capacitor	100	3.2





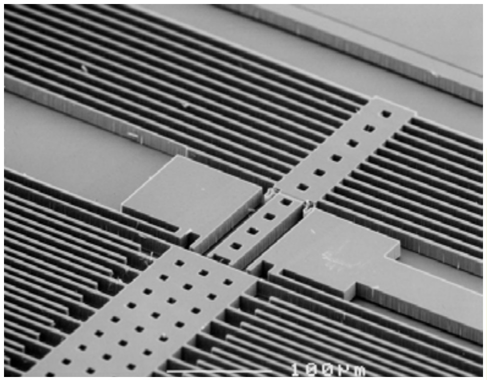


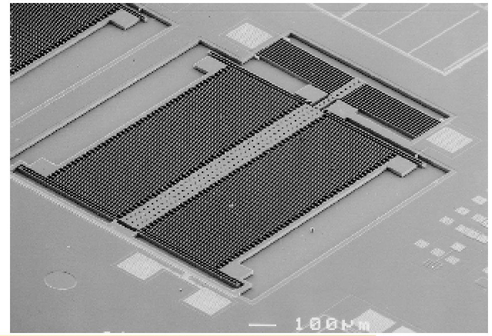


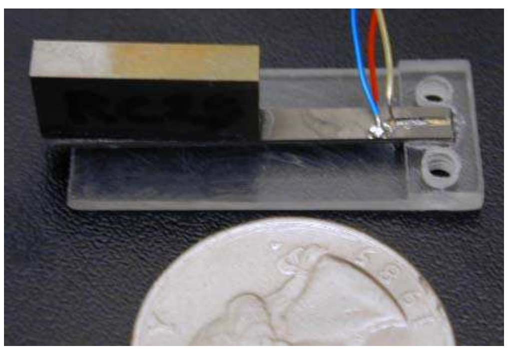


What can one do with 1 cm^3?

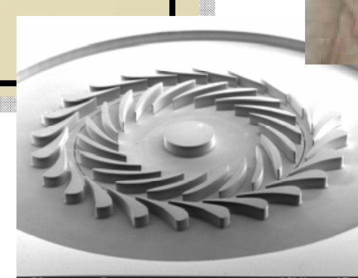
Energy Generation





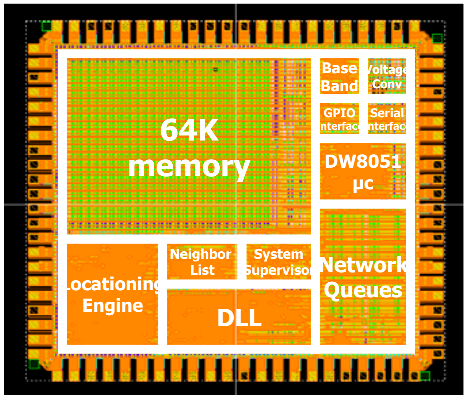


	$\mu W/cm^3$
Solar (outside)	15,000
Air flow	380
Human power	330
Vibration	200
Temperature	40
Pressure Var.	17
Solar (inside)	10

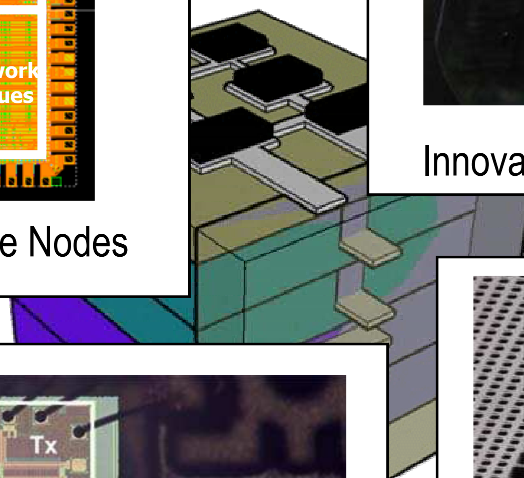


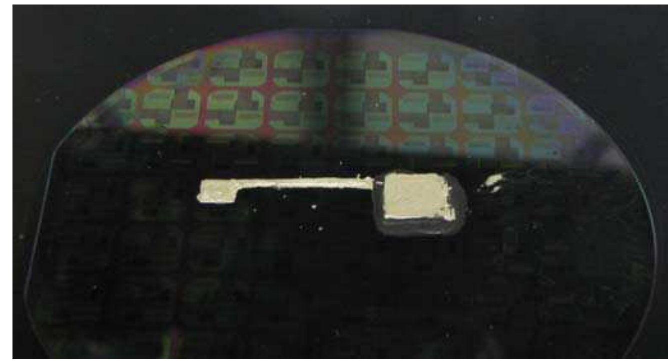
Towards a sub-100 μW Node

“The Art of Creativity”

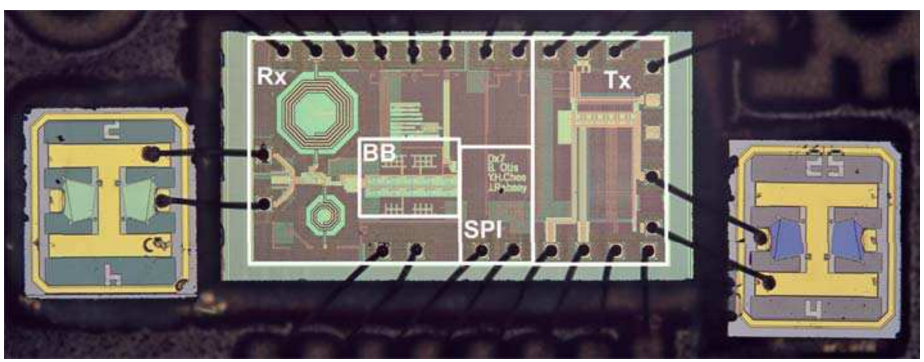


Ultra Low Power Compute Nodes

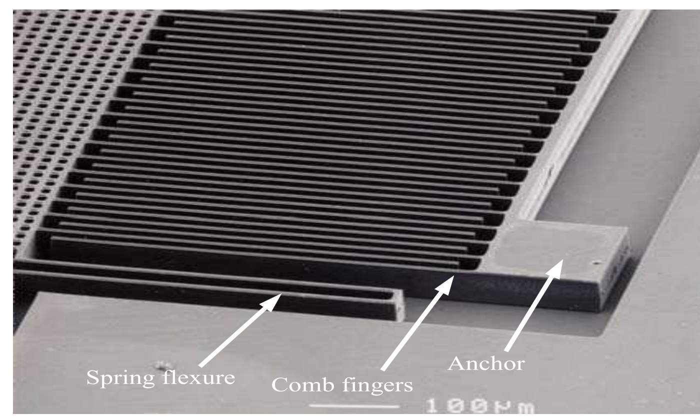




Innovative energy sources



Novel miniature wireless transceivers

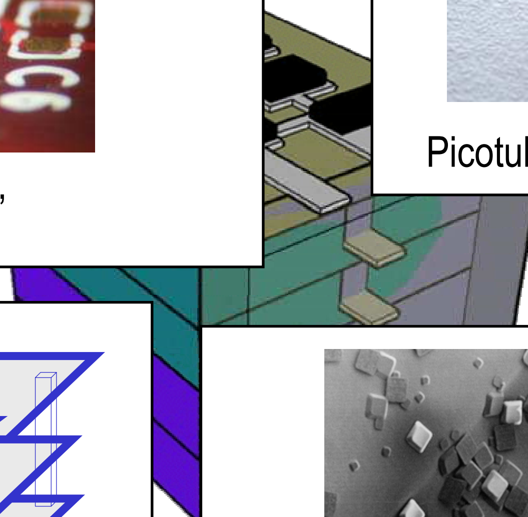


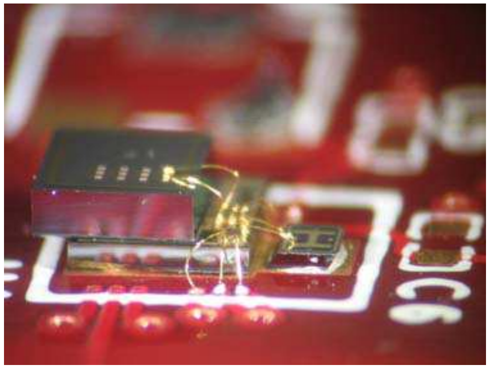
Integrated Sensors

BWRC

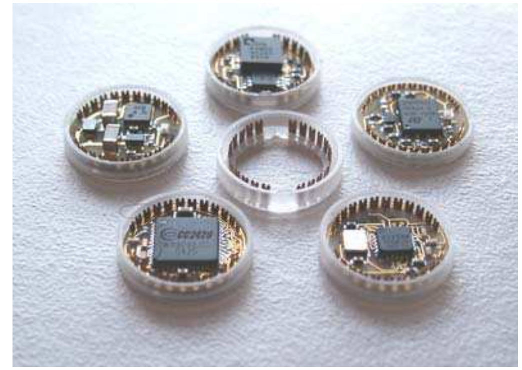
Towards a sub-100 μW Node

"Innovative Packaging"

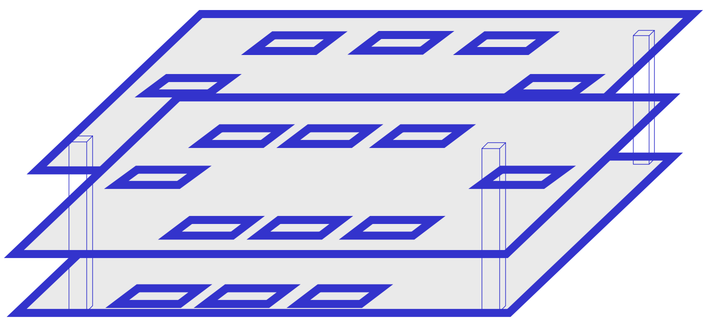




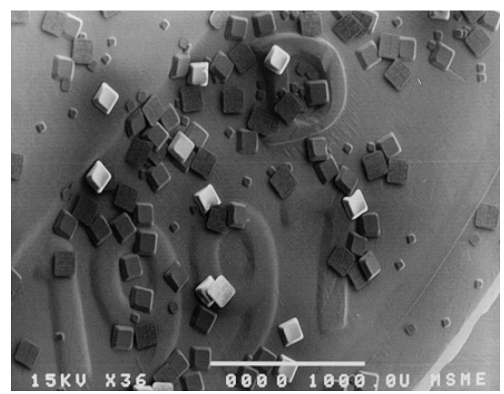
"2.5/3D Integration"



Picotubes (Philips "sand" modules)

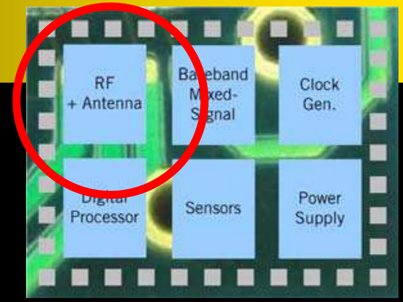


"Wireless Attanets"



Self-assembly

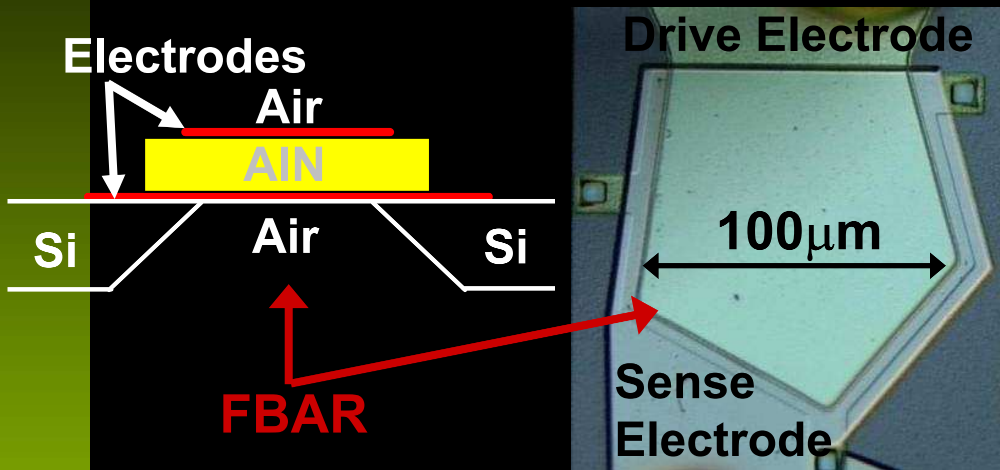
Ultra-Low Power RF?



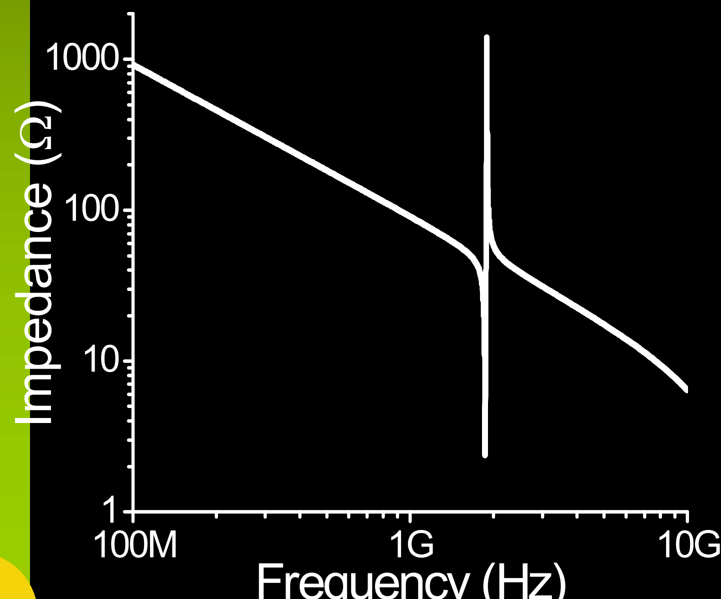
Absolutely!

- Aggressive use of passives
- Unorthodox architectures to create gain (receiver) or increase efficiency (transmitter) at low voltage/current levels
- Efficient oscillators are essential!

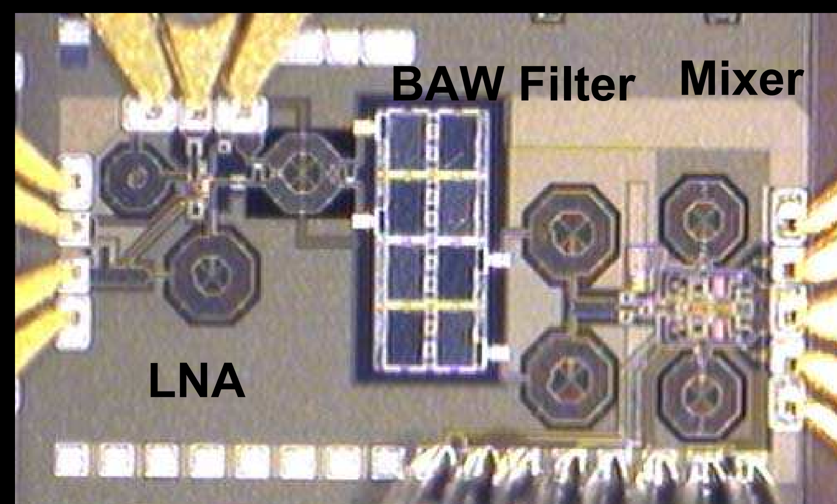
Extensive Use of (Innovative) Passives



- **High Q-factor**
- **Small form factor**
- **MEMS/CMOS co-design**
- **Integration into IC process**



Ruby et. al. (Ultrasonics Symposium 2001)

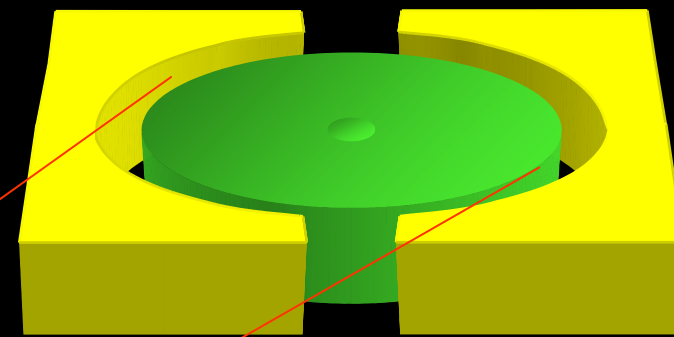


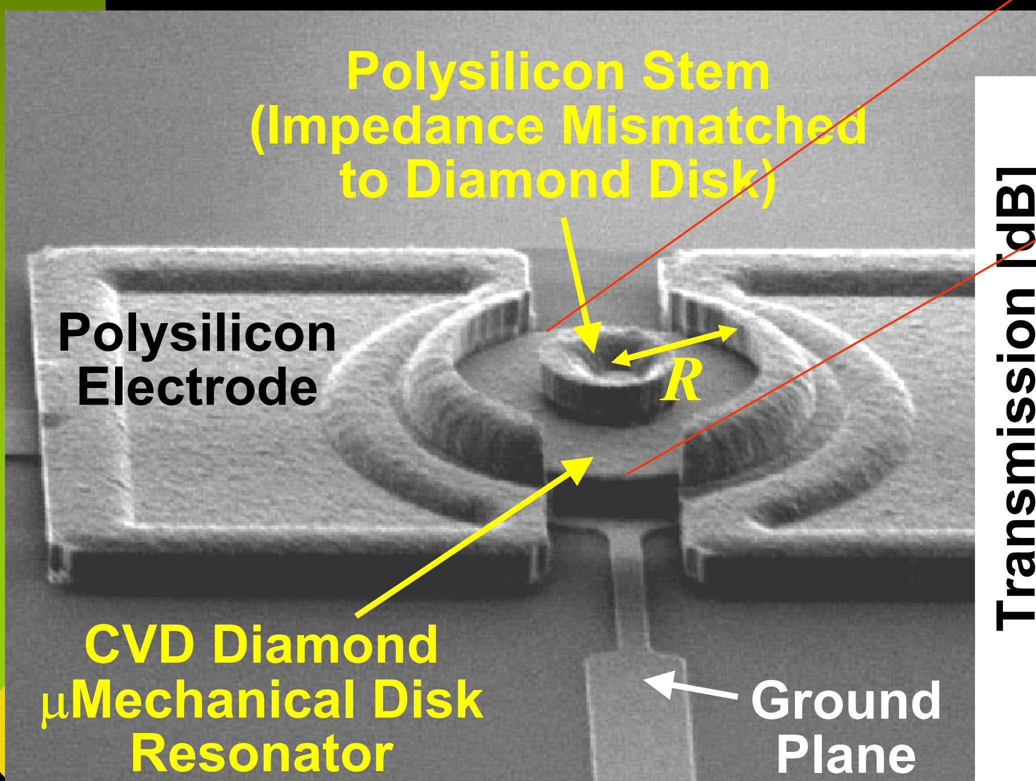
Carpentier et. al. (ISSCC 2005)

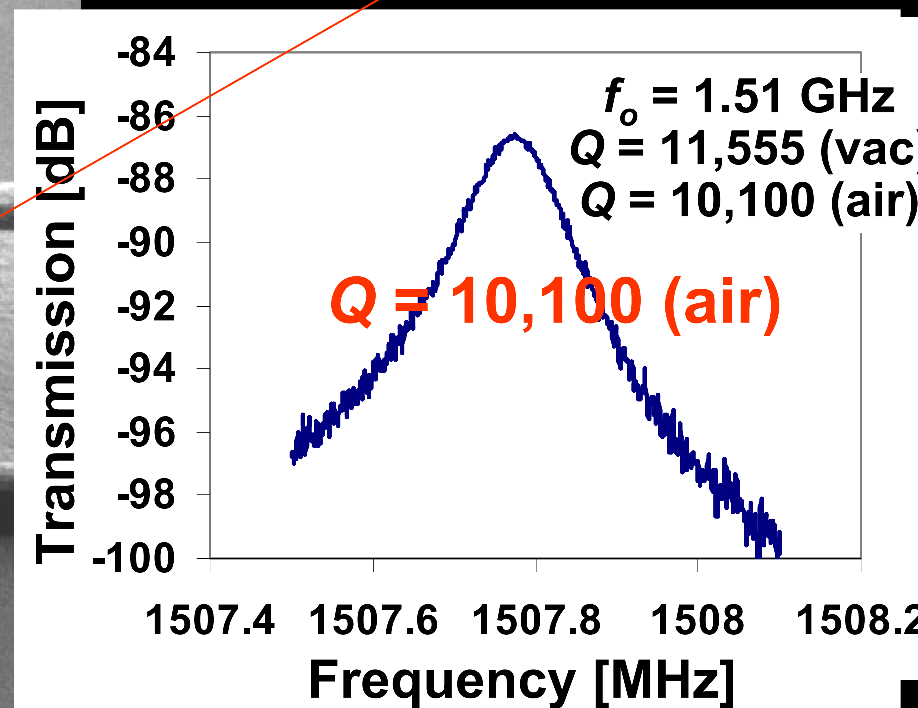
Other options: RFMEMS

1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

- *Below*: 20 μm diameter disk

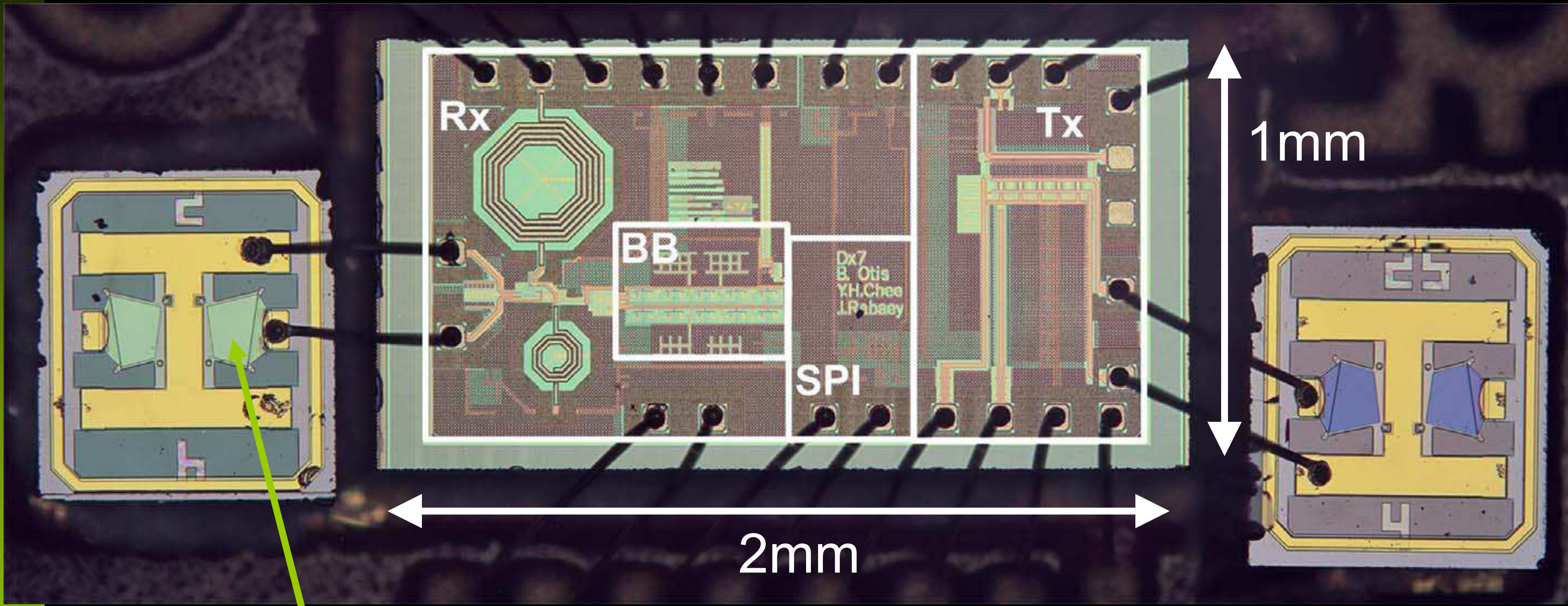


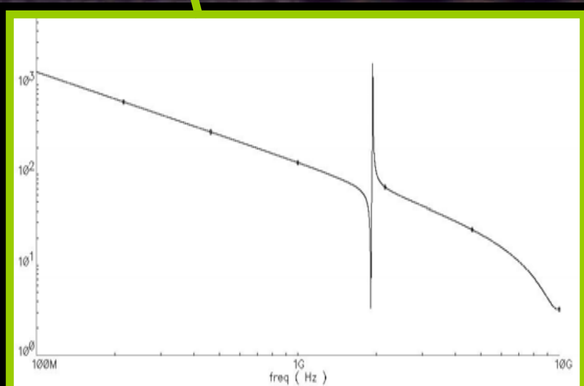




[Wang, Butler, Nguyen MEMS'04]

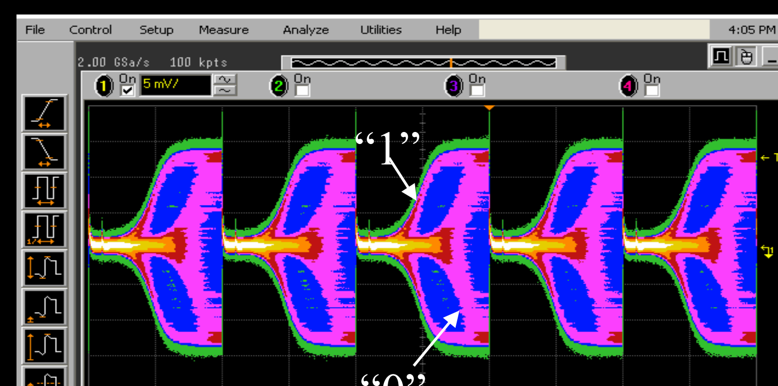
Example: 400 μW Super-regenerative Receiver





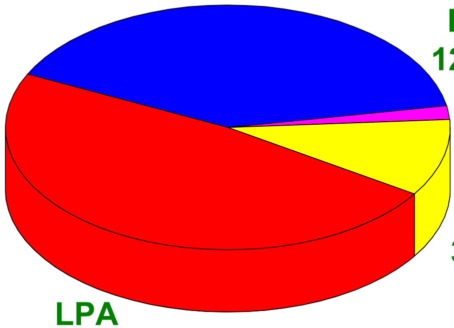
FBAR: Very high selectivity at RF frequencies

Gain with minimum current?
Use oscillator!



Improving TX Efficiency

MICROS[1] Direct Conversion TX
(30mW, η=3.3%)

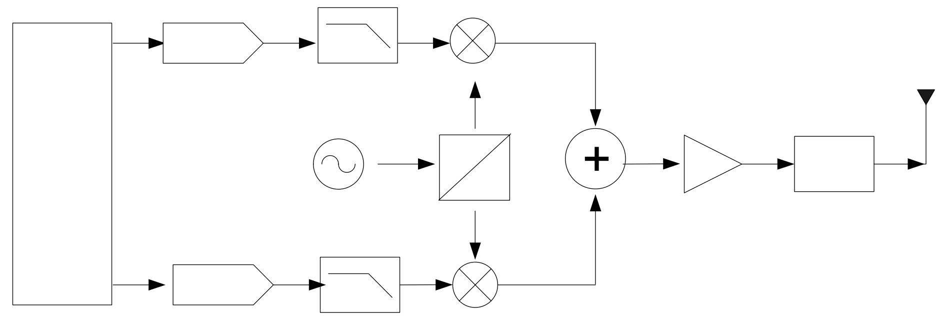


Freq. Syn.
12mW (40%)

Modulator
0.54mW (2%)

Mixer
3.06mW (10%)

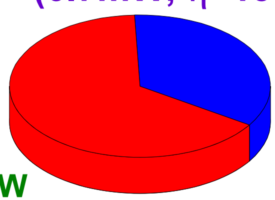
LPA
14.4mW (48%)



4.5X

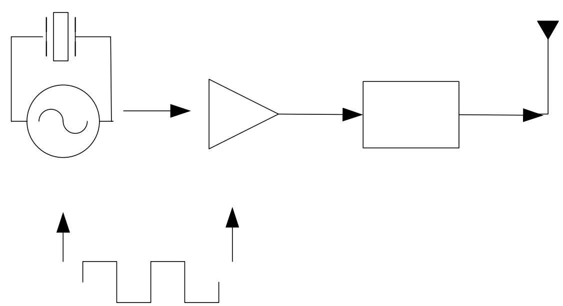
17X

Direct Modulation TX[2]
(6.7mW, η=15%)



Oscillator
2.32mW (35%)

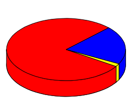
LPA
4.35mW
(65%)



- Reduced Complexity
- RF MEMS Oscillator
- Capacitive Transformer

3.7X

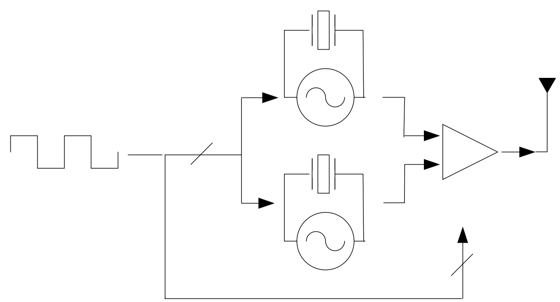
Active Antenna TX
(1.8mW, η=52%)



LPA
1.43mW (79%)

Oscillator
0.36mW (20%)

Antenna Loss
0.03mW (1%)



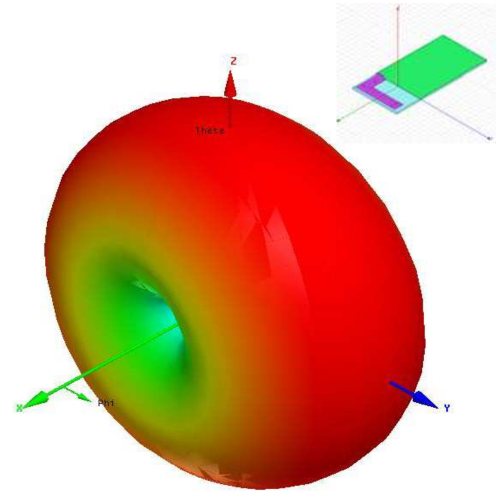
- Active Antenna
- TX Chain co-design
- Lower Power Oscillator
- Low VDD

[1]P. Choi et. al, ISSCC 2003
[2]B. Otis, **Y.H. Chee**, et. al, VLSI 2004

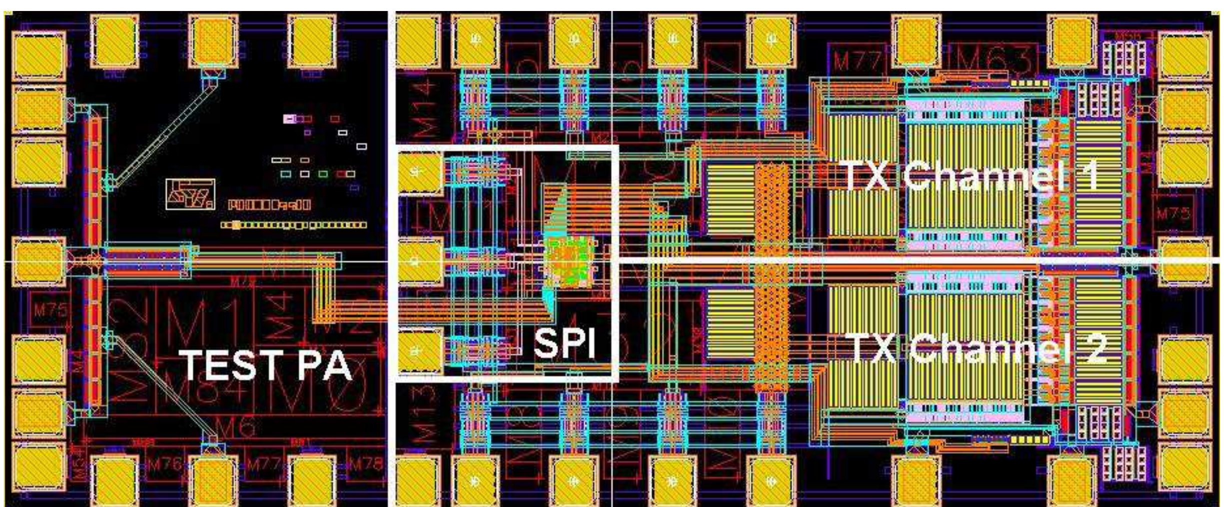
Y.H. Chee

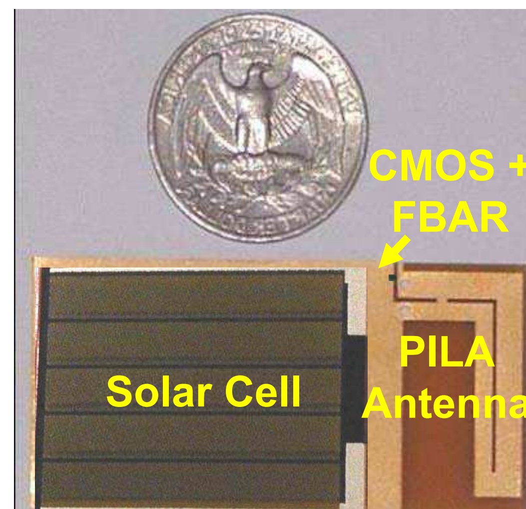
Active Antenna Transmitter

Technology	ST 0.13μm CMOS
Carrier Frequency	1.9 GHz
Supply voltage	0.6V
Startup time	1 μs
Data rate	100 kbps
η @ P_{out} = 0.94mW	52%
Power Consumption	1.8 mW
Die Size (TX)	0.8mm x 1.25mm
Packaging	Chip-on-Board
External Components	2 FBARs (1 per channel)

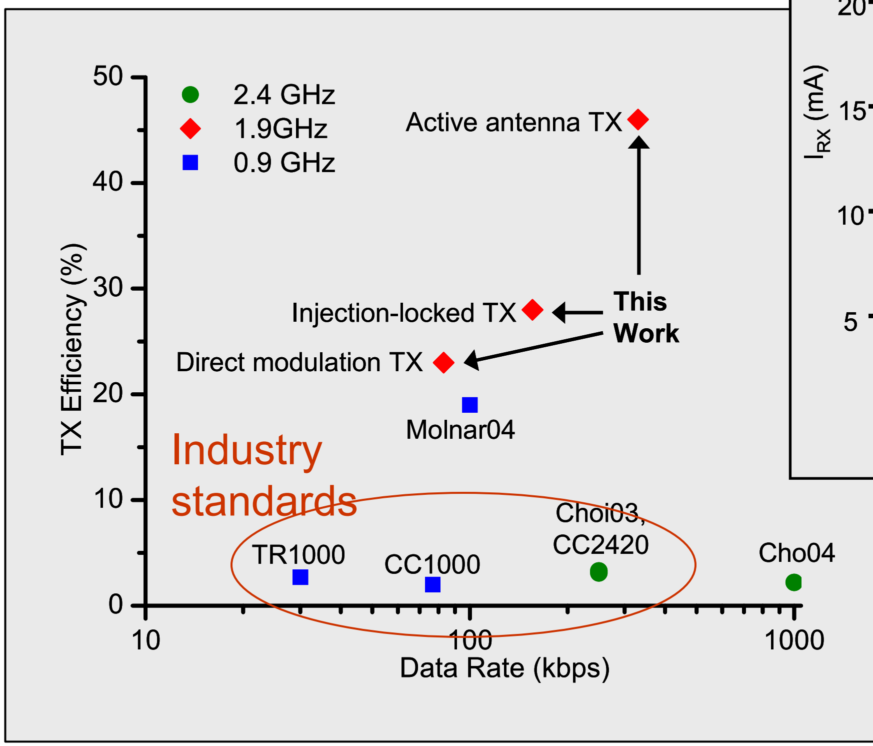


- Directivity = 1.734
- Radiation η = 98%

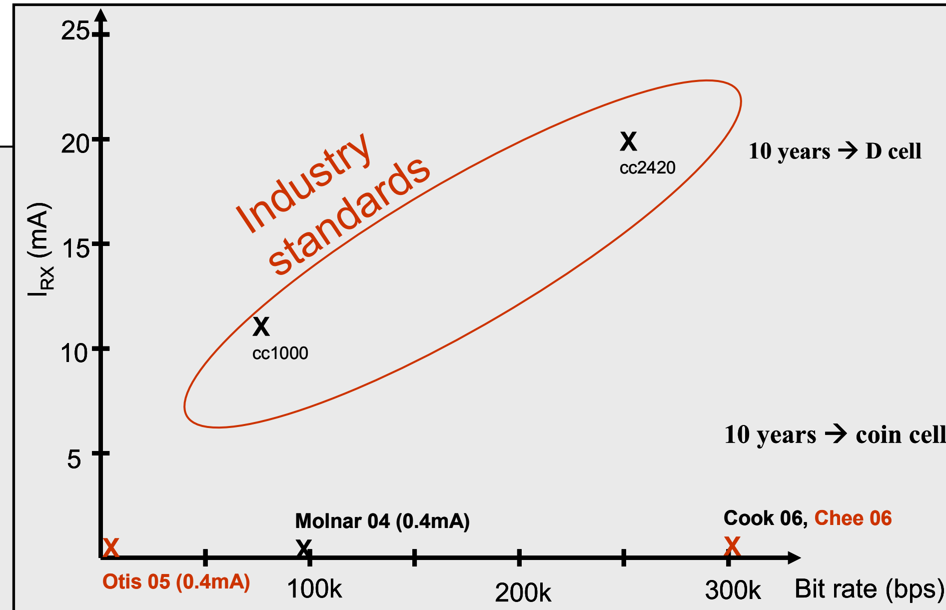




TRX Performance



0 dbM Transmitters



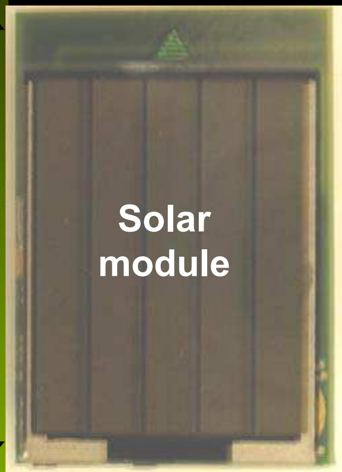
Ultra Low Power Receivers

Courtesy: Y.H Chee, B. Otis, K. Pister

BWRC

Leading to Small Integrated Nodes

Back (with solar module)

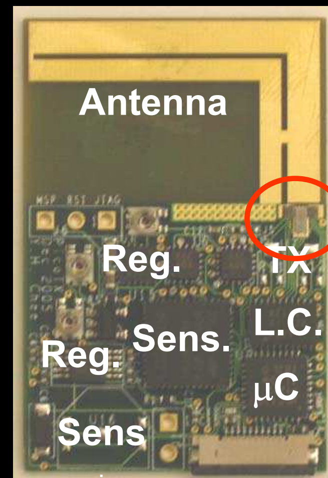


38mm

25mm

Back

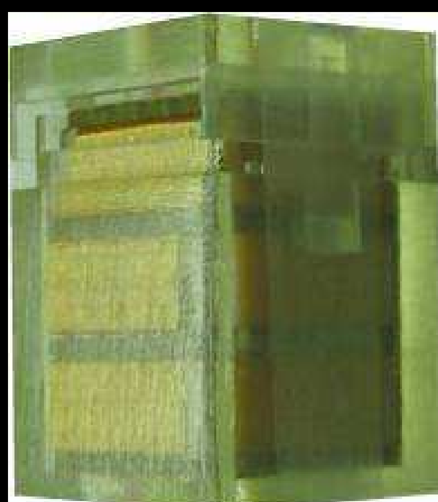
Front



Performance Summary

Standby current	2.8 µA
Active current	4.86 mA
Power down current	2 µA
Duty cycle (with 100 µW)	0.8%
Received power at 10m	-54 dBm

1 cm^3 PicoCube



Modular packaging

Providing Reliability

Unreliability is intrinsic to the disappearing electronics concept.

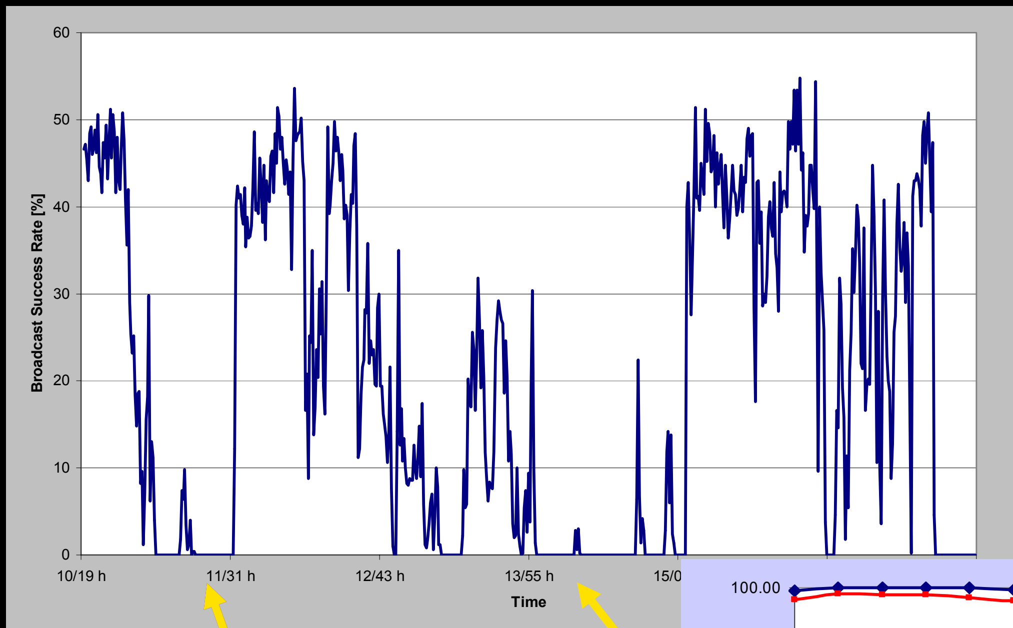
- Nodes may appear at will, may move, may fail and (temporarily) run our of energy
- Problem aggravated by cost, power and size constraints

The wrong answer: over-design

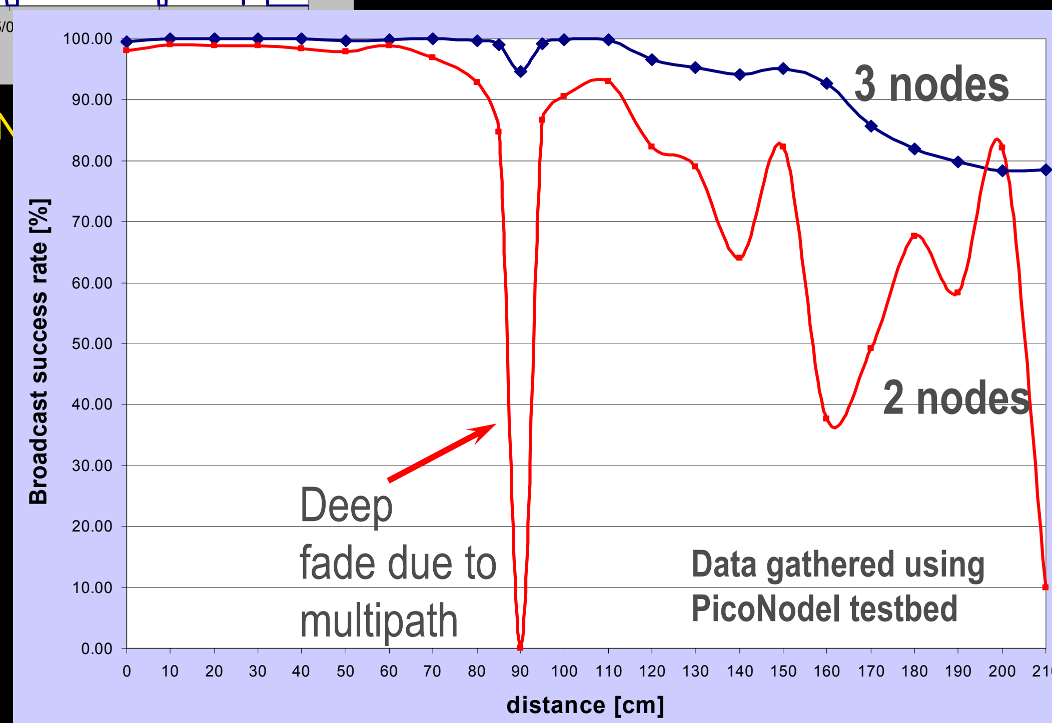
The right answer: exploit nature of Ambient Intelligence

BWRC

Example: ULP Radios are Unreliable



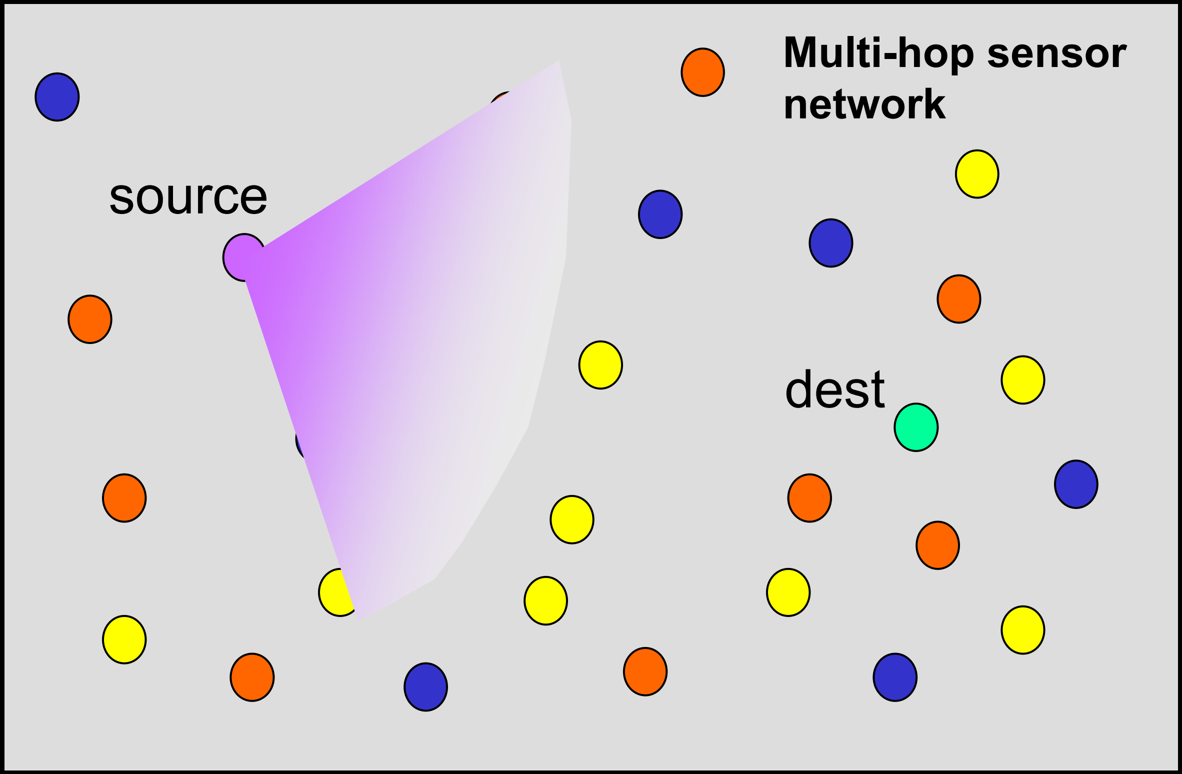
PicoRadio Meeting



But …
Adding spatial diversity

Reliability through Redundancy

Redundancy is a core concept of Sensor Networks,
enabling high quality reliable service with cheap unreliable components.

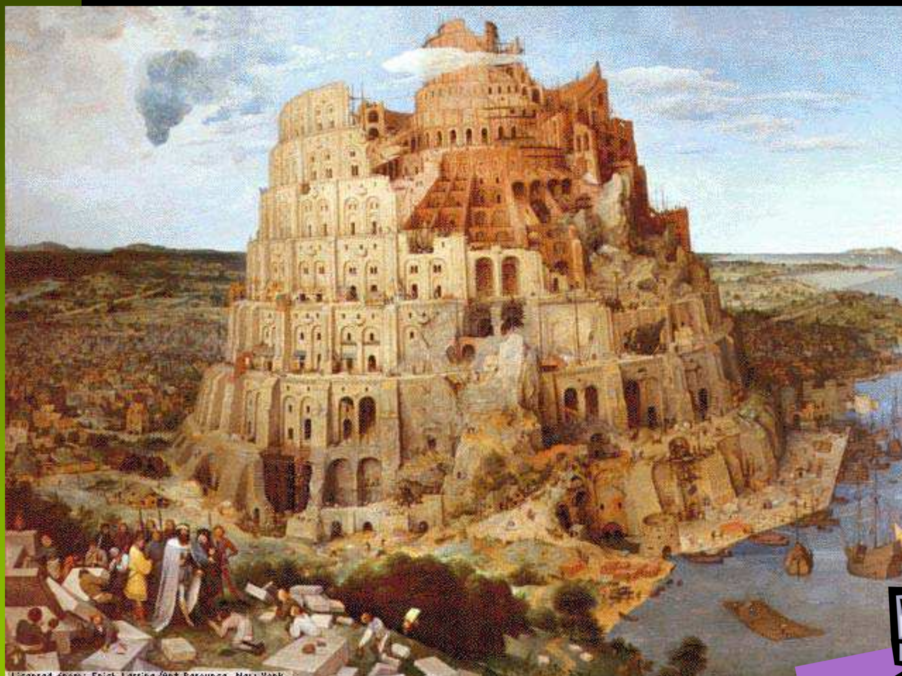


Opportunistic routing: choose any node that is available and goes in the right direction.
Reduces energy and latency as well.

Courtesy Rahul Shah, UCB

The Portability and Scalability Challenge

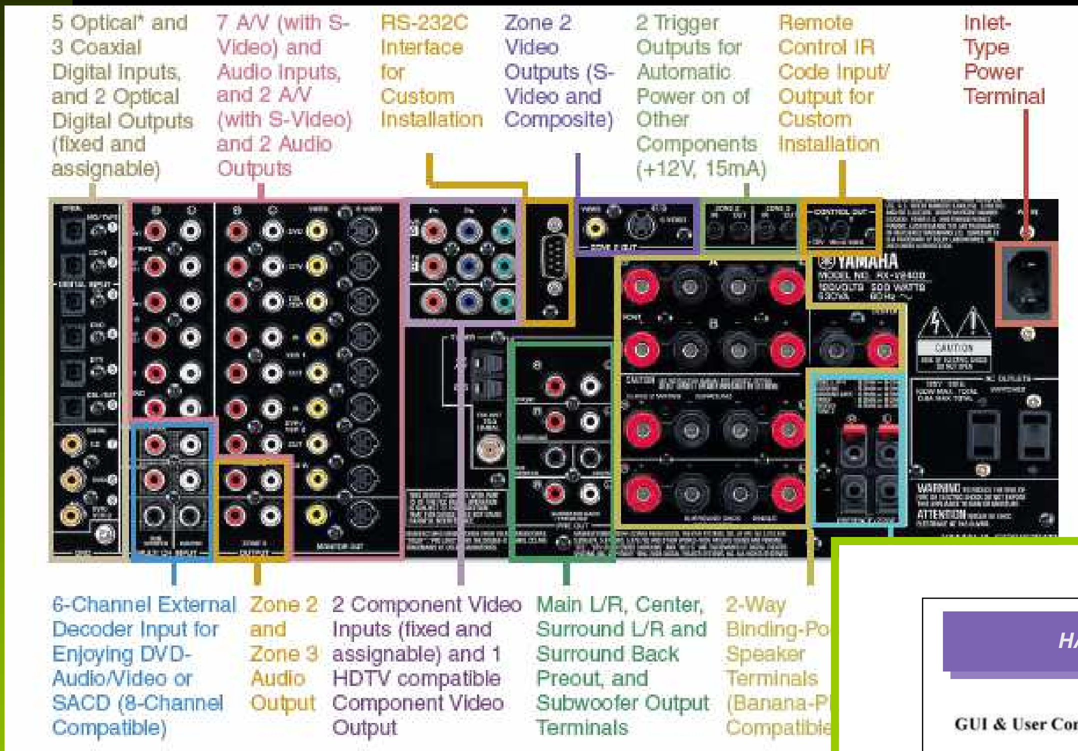
The Home Network as the new Tower of Babel



- New devices are entering the home environment at an ever increasing rate.
- Standards are proliferating – interconnect, recording and playback, display
- Devices do not necessarily interconnect easily

BWRC

The Current Options

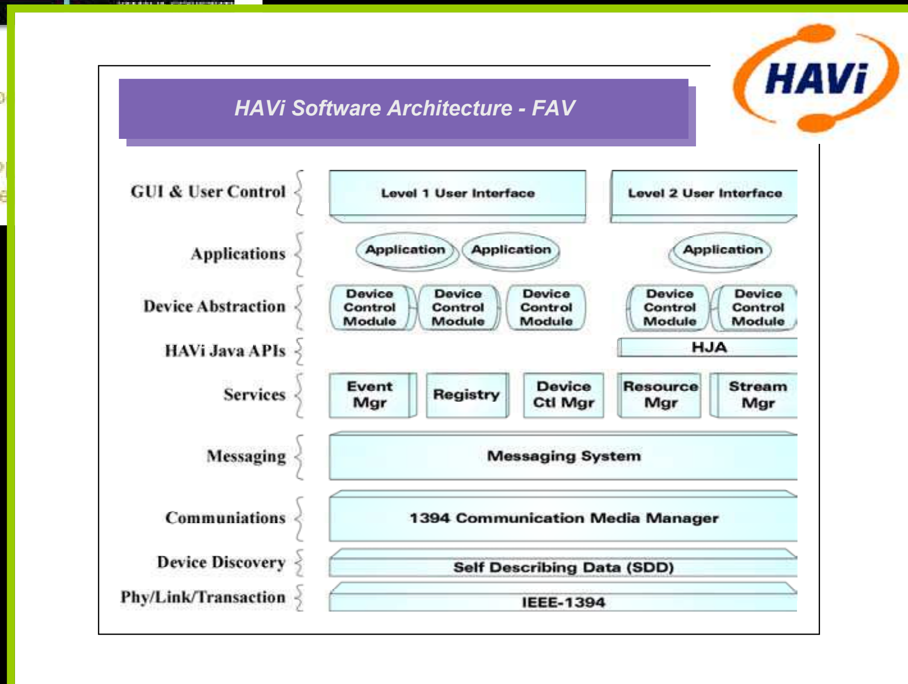


Cover all the bases …

- Clearly not scalable, extensible and upgradable
- Not applicable to light-weight devices

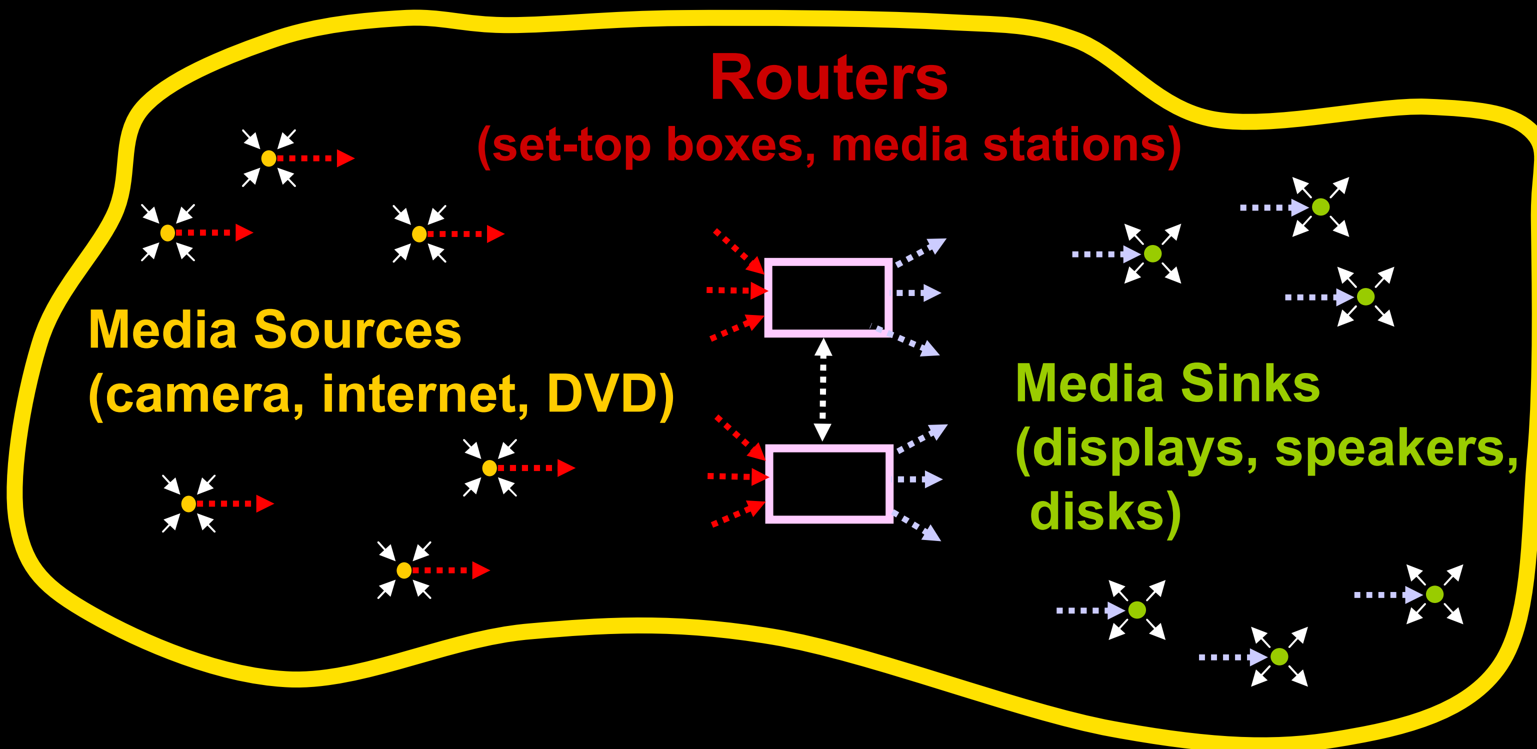
Stovepipe solutions

- Fix the complete stack and hope that the rest of the world will adopt



Dealing with the Myriad of Protocols and Formats

Put the Intelligence in the Network:
"The Universal Content Router (UCR)"



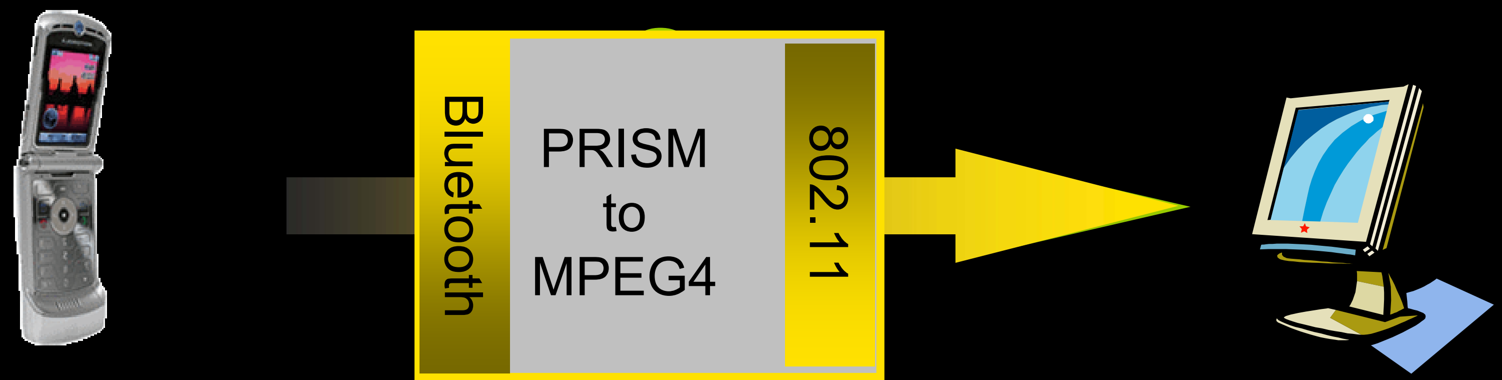
Content routers: Provide on-the-fly protocol conversion and trans-coding based on properties of source and destination devices

"Seamlessly connect everything to anything – or do even better than that"

Mirroring Developments in the Internet

- First Ethernet Implementations:
  - All intelligence in the peripherals
  - Connected by passive medium (thick coax)
- Current internet
  - Peripherals connected through switches and routers

Some Examples

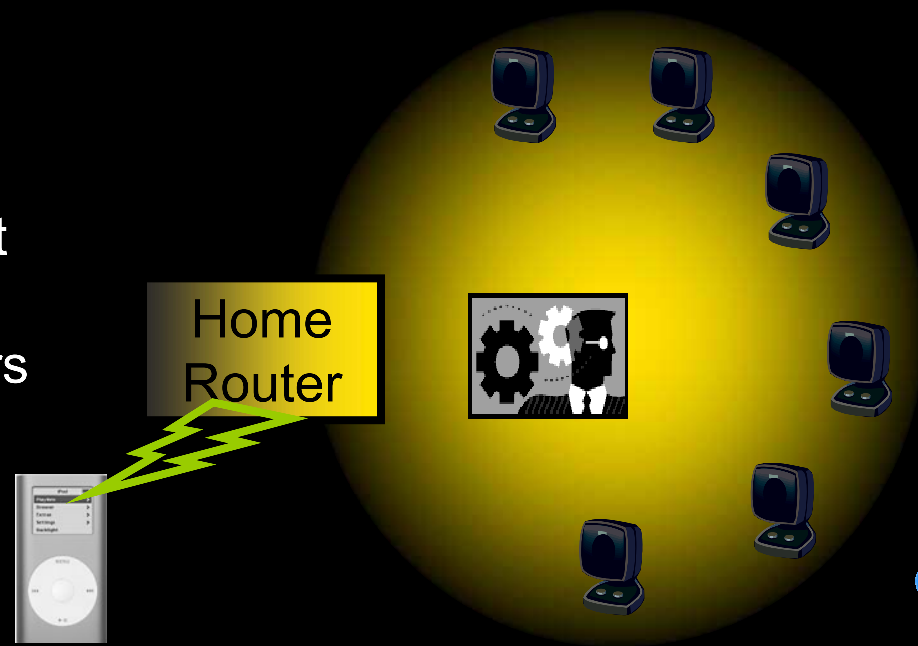


PRISM (light weight video encoder) phone camera with Bluetooth interface

Smart Home Router(s)

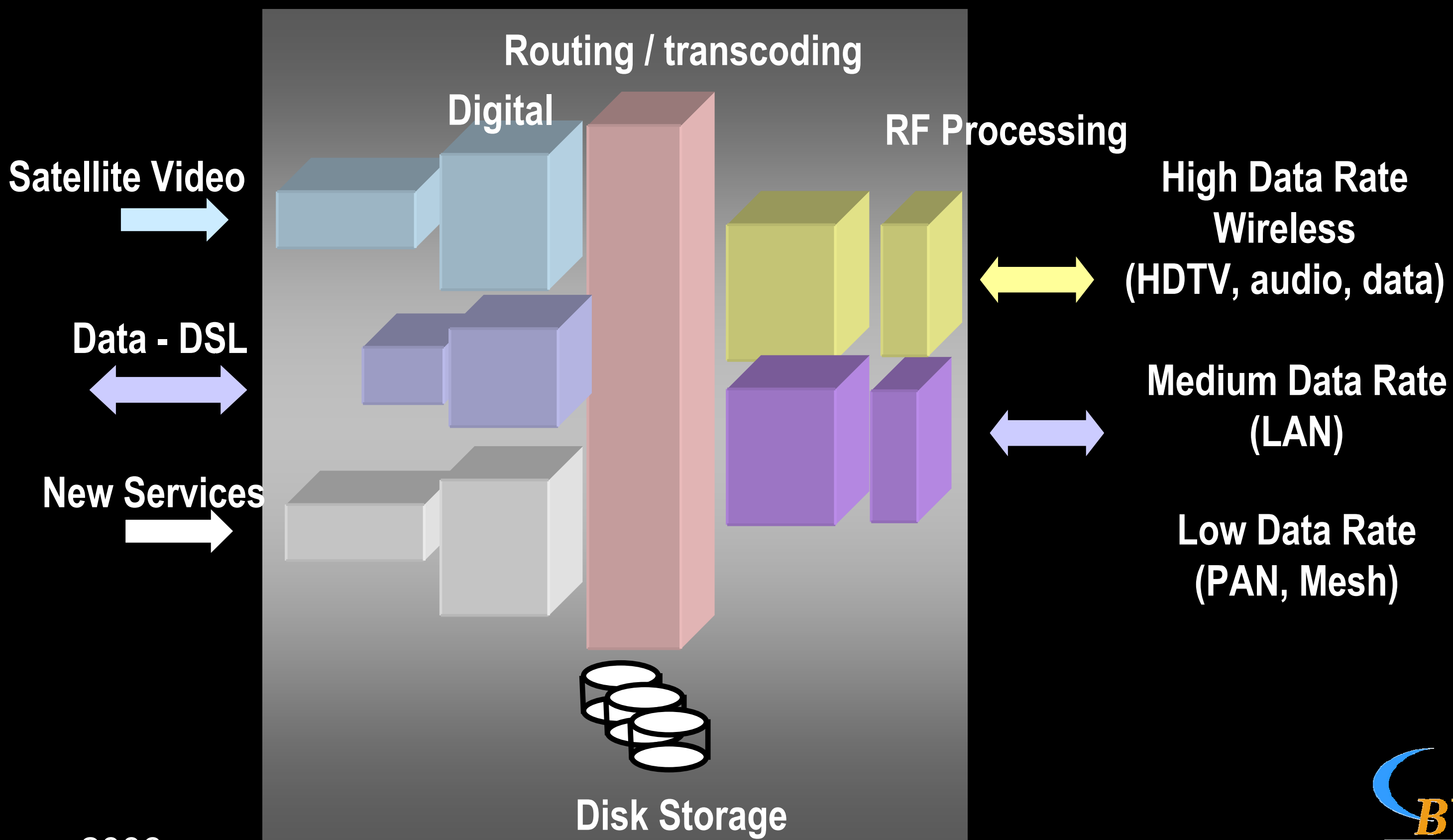
MPEG4 LCD Display with 802.11 interface

Perfect surround at any time using ubiquitous speakers



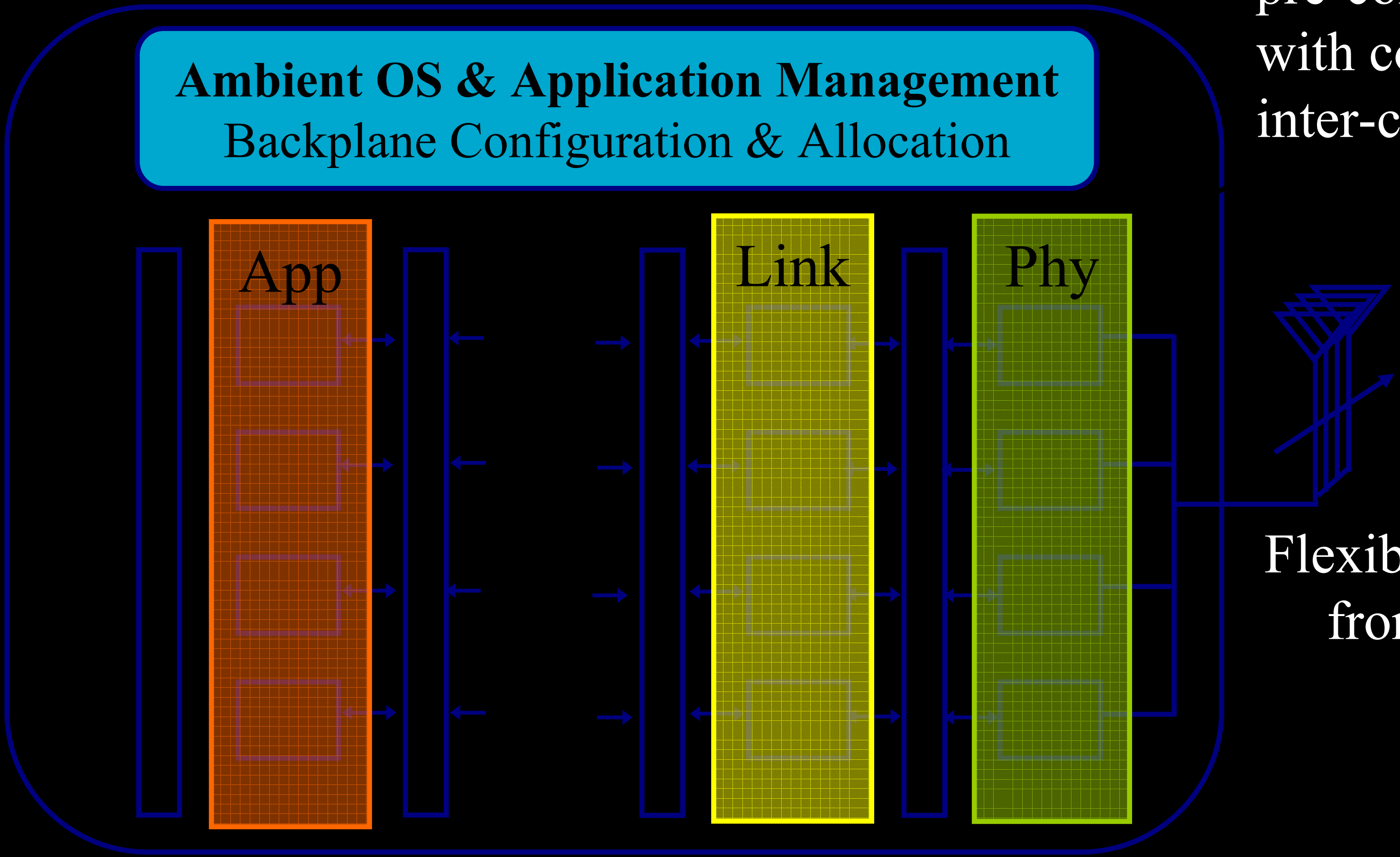
The UCR Implementation Challenge

Must process multiple real-time high-data rate streams from physical interface through protocol stack and signal processing (TOPS) in fully programmable and upgradable fashion at a extremely constrained cost and power budget.



UCR Structure

Configurable fabric / mix
pre-config blocks
with configurable
inter-connect

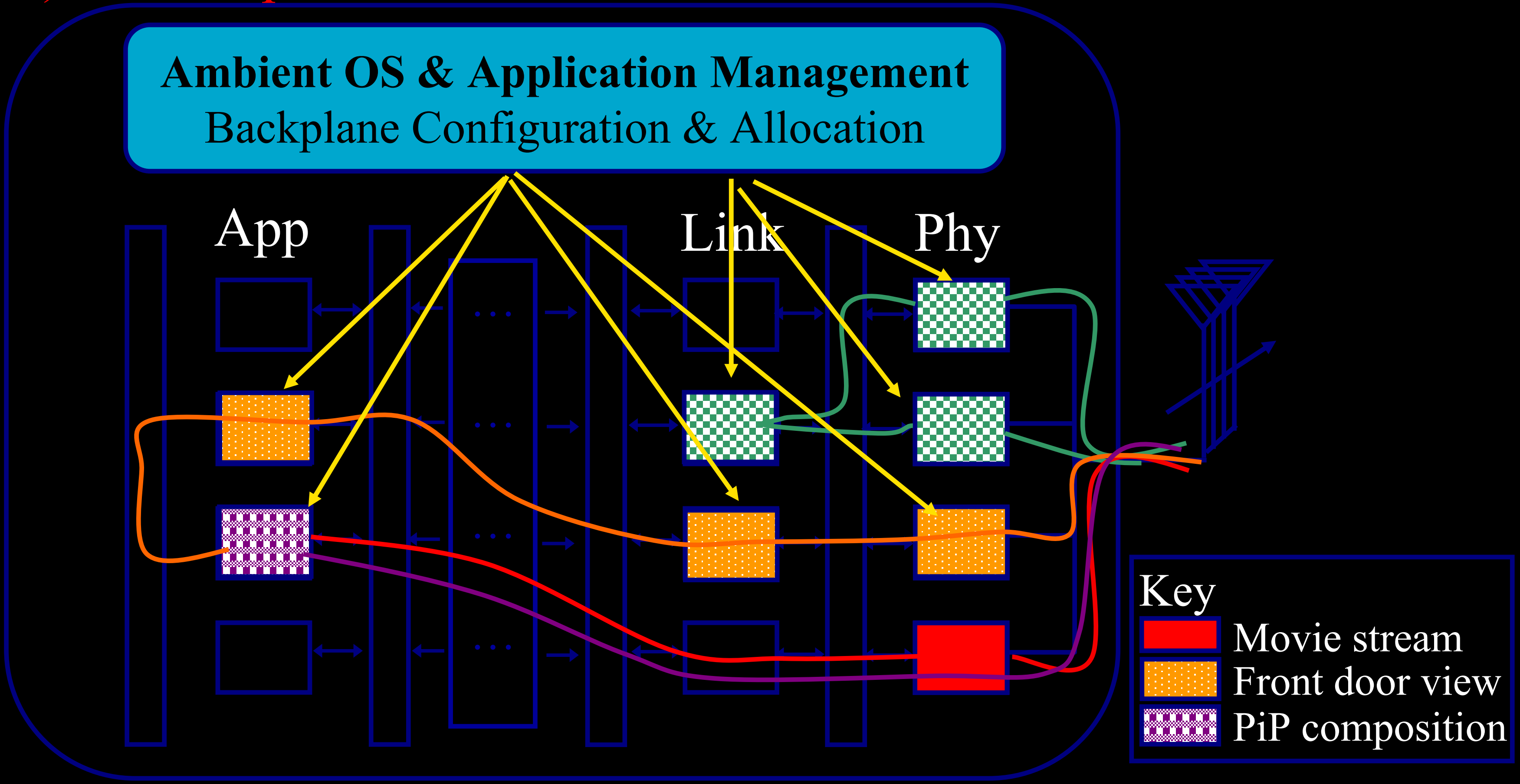


Flexible SDR
front-end

UCR Operation

1) Connecting a bluetooth PDA to a laptop (w/o bluetooth)

2) PiP composition for TV w/o PiP



UCR Desired Properties

- Home infrastructure must be durable (replaced ~10-20 years)
- Must have:
  - Flexible physical connectivity & legacy support
  - Flexible link, transport and presentation protocols
  - Flexible and dynamic routing capabilities
  - Discovery mechanism for new devices & protocols
- Flexibility incurs computation/resource usage overhead

Future Physical Layer Connectivity

- The future is WIRELESS
- Future-proof radio (SDR)

- Scheme for detecting & decoding a new protocol:
  - Continuously scan a wide range of frequencies
  - Upon detecting a new signal:
    - Match new frequency profile with all known profiles (Info can be stored in an online database)
    - *Implements* the closest match & decode the signal
    - If the decoded signal is nonsense, try next closest match

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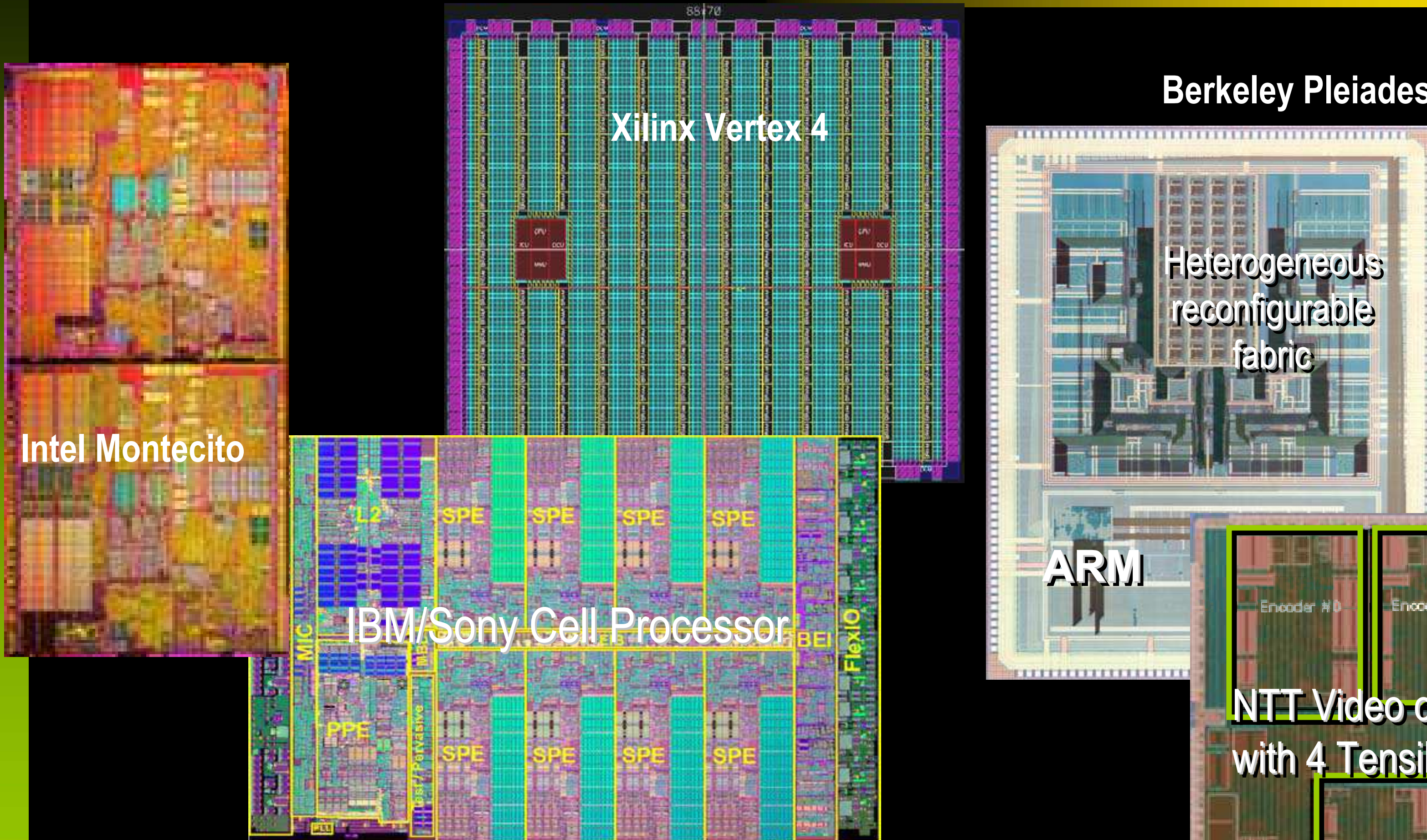
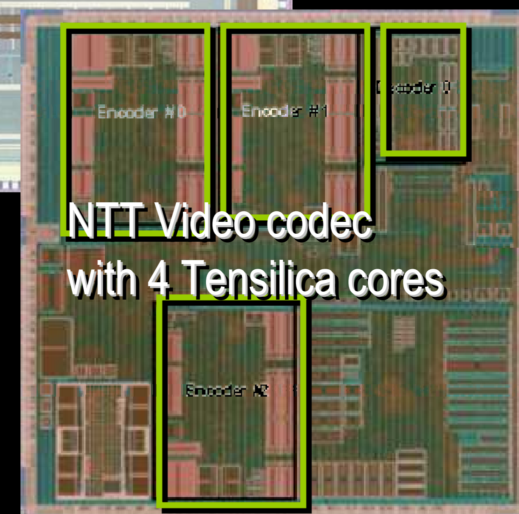
Computation Requirements

- Protocol conversion
  - Computation mostly at PHY layer
  - Standards vary; OFDM steps include: frequency offset correction, a 64-point FFT, channel equalization and QAM demodulation.

	2G	2.5G	3G
Standards	GSM, DSC1800, PCS1900, IS-95B, IS-54B, IS-136, PDC	GPRS, HCSD, IS-95C, IS-136+, IS-136-HS, Compact EDGE	3GPP-DS-TDD, 2GPP -MC, ARIV WCDMA, IS-2000 CDMA, IS-95-HDR
Computation requirement	~100 MIPS	~10,000 MIPS	~100,000 MIPS

A Benchmark for Next-Generation Compute Platforms





The search for the relevant concurrent micro-architecture (energy efficient, flexible, error-resilient, scalable into nanometer scale technologies):
Multi-core versus reconfigurable, homogeneous versus heterogeneous, programmable RF, etc

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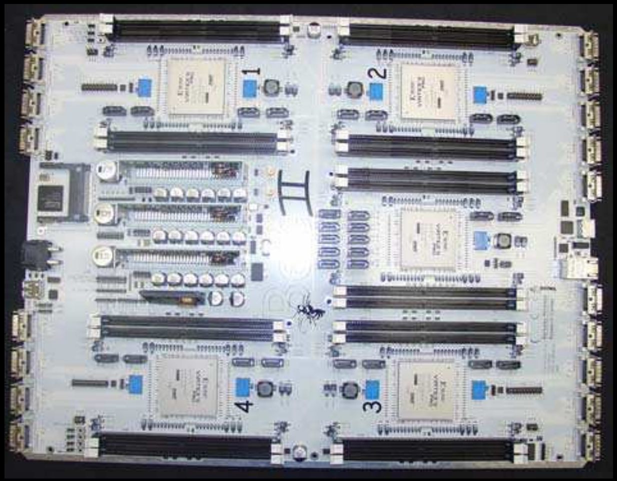
A Platform for Embedded SoC Architecture Exploration



Berkeley BEE-II: 2 TOPs system protytyping environment (Warwrzynek, Brodersen, UCB)

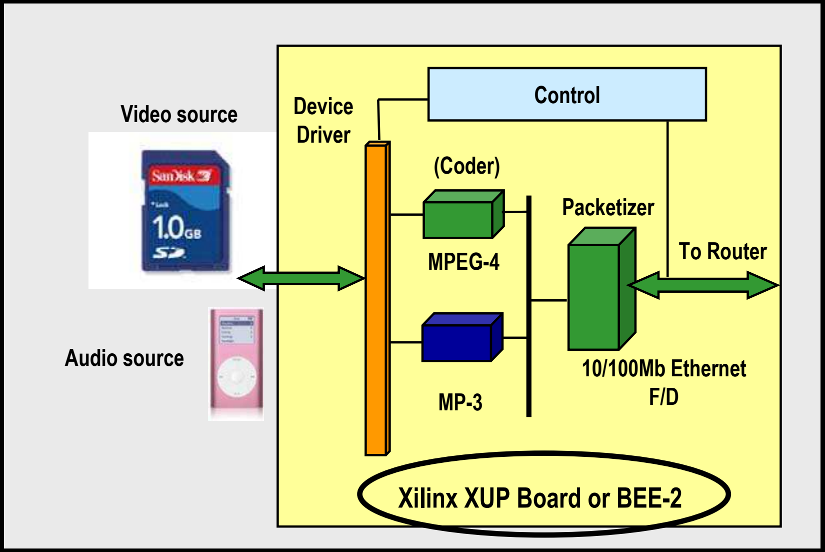
30-40 TOPS (2 TFlops) Rack

Using arrays of FPGAs to emulate and explore virtual architectural models.

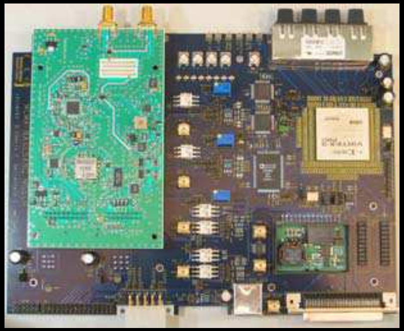
RAMP: A Multi-University Project Targeting the Concurrent Future (Compilers, OS, μArch)

Partially funded by GSRC and BWRC

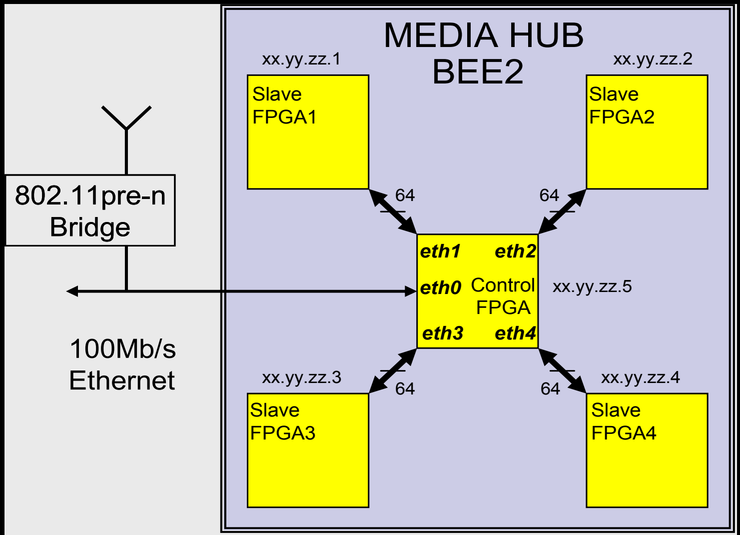
A Prototype Universal Content Router



A dynamically configurable compute platform for home router development



BWRC multi-purpose RF front-end



The Configuration and Control Challenge

Current model:

- Connection oriented

  "Connect the DVD through the AV to the display in the living room"

  Requires intimate knowledge of network – excludes ad-hoc.

- Device, not function dependent

The Computer Industry Response

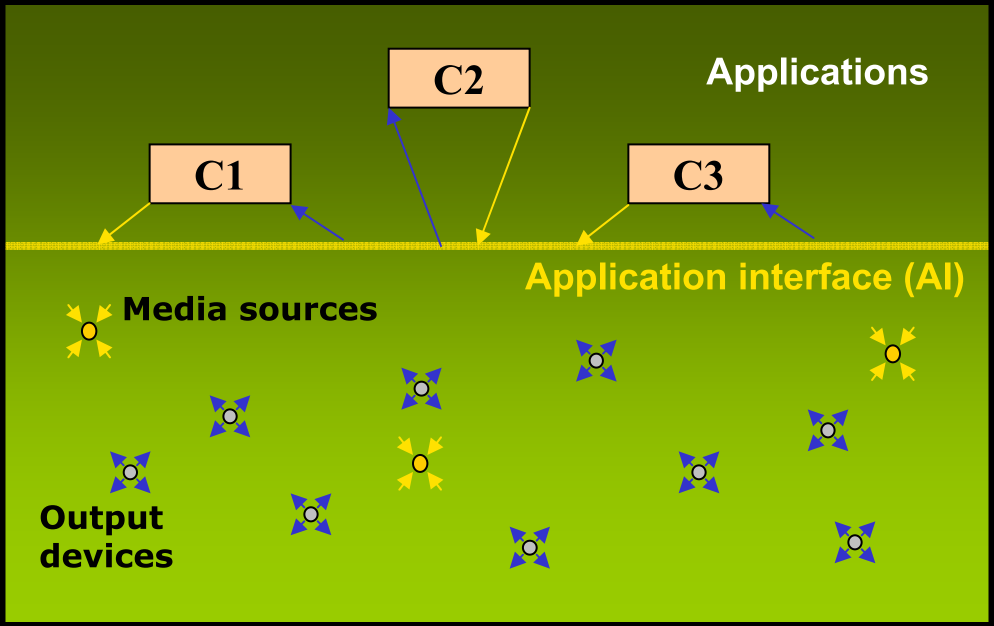
Example: Microsoft MediaCenter

- Standard PC with Windows OS extended with accelerator and enhancements on I/O cards
- Full UI and graphics

But:

- The user is the system and configuration manager (still connection and device oriented)
- Centralized, static, and not spatially aware

The Only Option: Raise the Abstraction Level



Application Interface based on Function "Play *Yesterday* from the *Beatles* at the highest possible fidelity level available now at my current location"

Services dynamically identify capabilities and constraints of present environment, and provide dynamic mapping of function on platform

- Independent of network architecture and hardware platform
- Enabling dynamic deployment, mobility, interoperability and innovation

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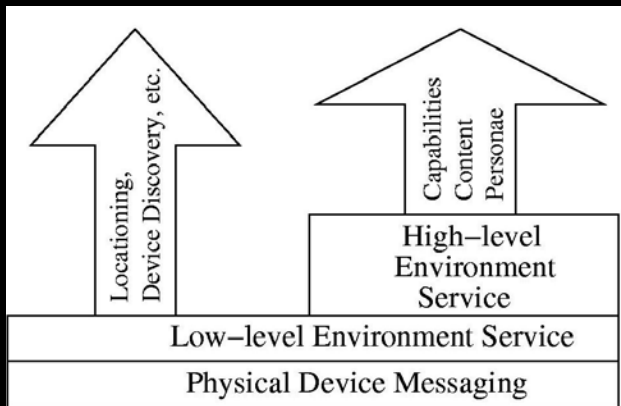
The ZUMA Concept
An Operating System for Wireless Infrastructure of the Future

- Zero-configuration
- Universality
- Multi-user (task) optimality
- Adaptability

Technical Challenges

- Resource Management
  - Type matching, arbitration and allocation, migration for multiple users
- Applications and User Interfaces
  - Multi-modal interfaces (speech, touch, mouse)
  - Decoupling application, UI, and control point
  - Make application easier to write and portable
- Personalization
  - Make ‘user’ a first-class citizen
- Interoperability
  - Discover, integrate, and utilize devices (spans entire networking stack) efficiently
- Adaptation
  - Auto-magically adapt to dynamics of environment (new devices, people)
- Others:
  - Geometry (localization and identification), DRM, AI, wireless spectrum usage, hardware architectures, …

Environment Aware



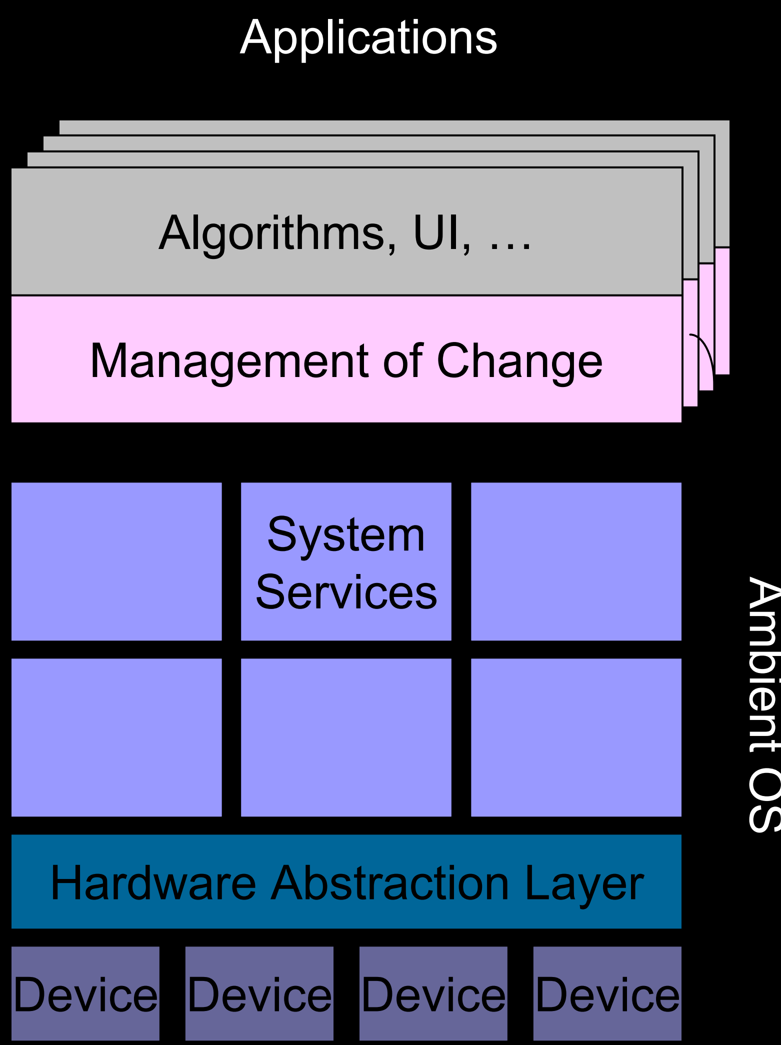
- *Scoped* environment is limited in *time* and *space*
- Dynamic entity with content, capabilities, & personae
- Info service can be queried

- *Example:* Multimedia environment in the home

Content	Capabilities	Personae
• mysong.mp3 • myHomeVideo.mpeg • R-ratedMovie.avi • disneyMovie.mpeg	• Transcoder avi->mpeg • Mpeg player (renderer) • Ipod (audio renderer) • Router (connection)	• HomeOwner •Full access • Guest •Denied access to home video & Ipod

The Zuma Approach

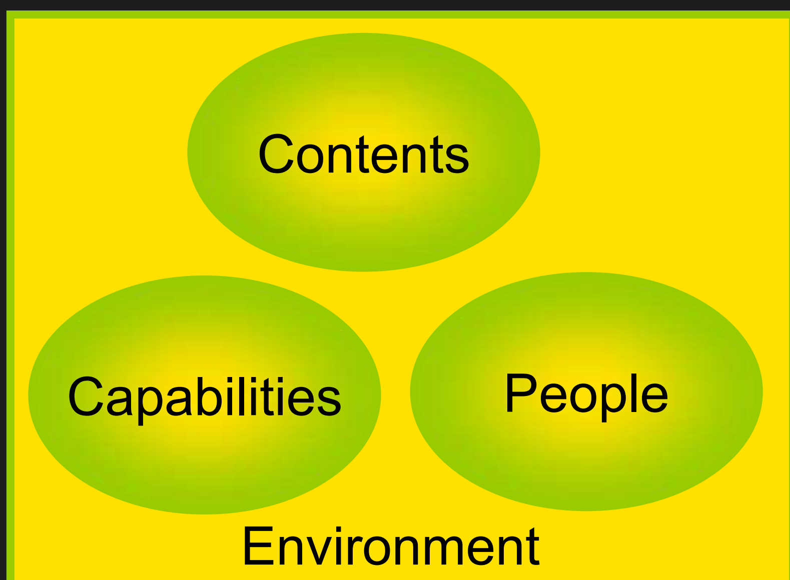
- Who manages the changing environment?
  - User, Application, or System?
  - Often a resource management issue.
- Application responsible for managing change…
- Managing change as a ***System Service***…
  - Factor out common functionality
  - Simplify application
  - Efficient Use of resources

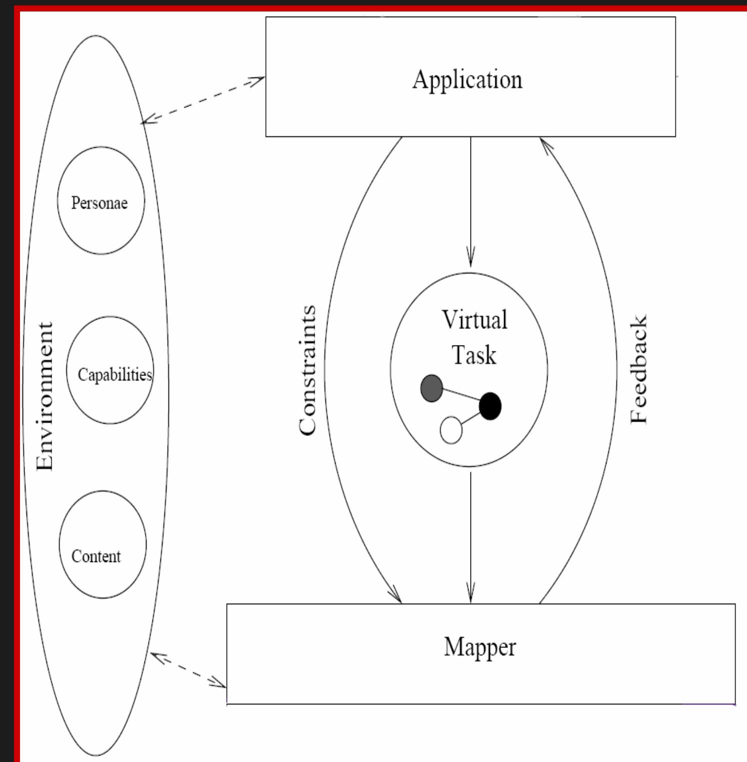


An Operating System for Wireless Infrastructure of the Future

Ambi Environment:
A playground combining available media and data contents, capabilities of the IT platform, and preferences and privileges of people present

Applications





Application reacts to changes in environment (dynamic mapping)

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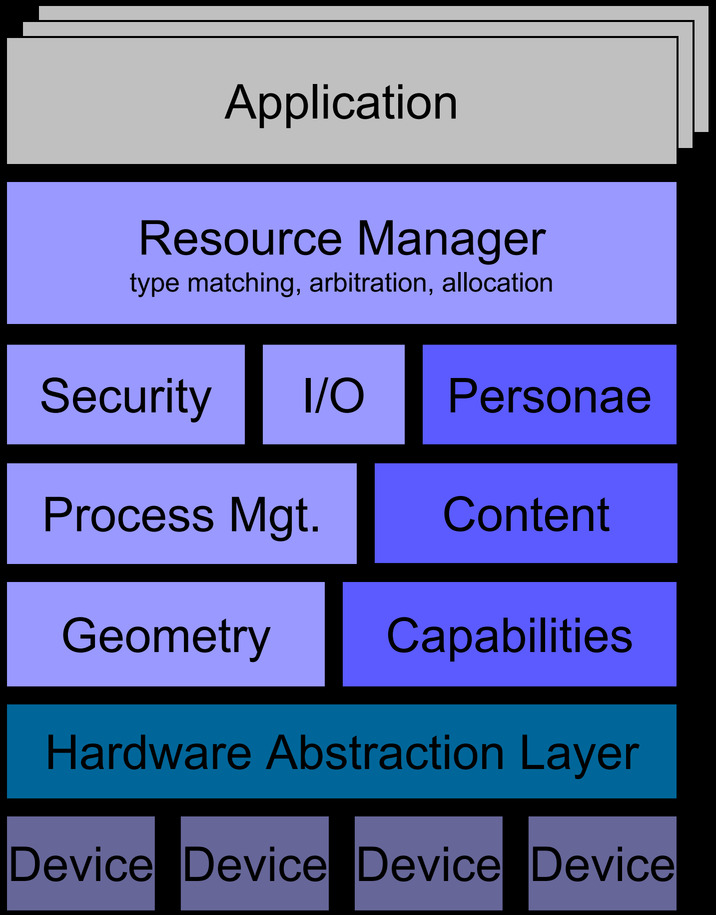
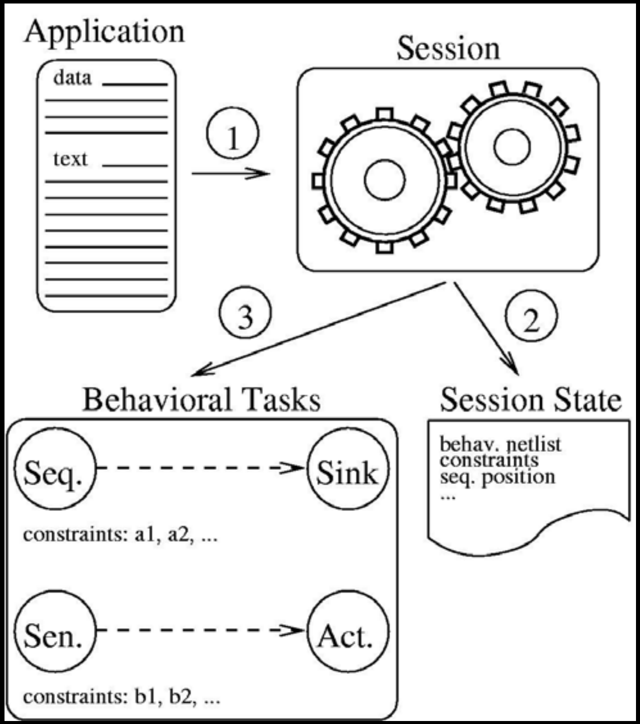
Architecture

- Applications
- High-level Services
  - Personae, content, capabilities
- Low-level Services
  - Resource manager, geometry, security, migration/replication, I/O, etc.
- Hardware Abstraction Layer
  - Common device interface or execution kernel
- Devices
  - Sensors, actuators, rendering, sources, sinks, etc.
- Event mechanism for application and services.



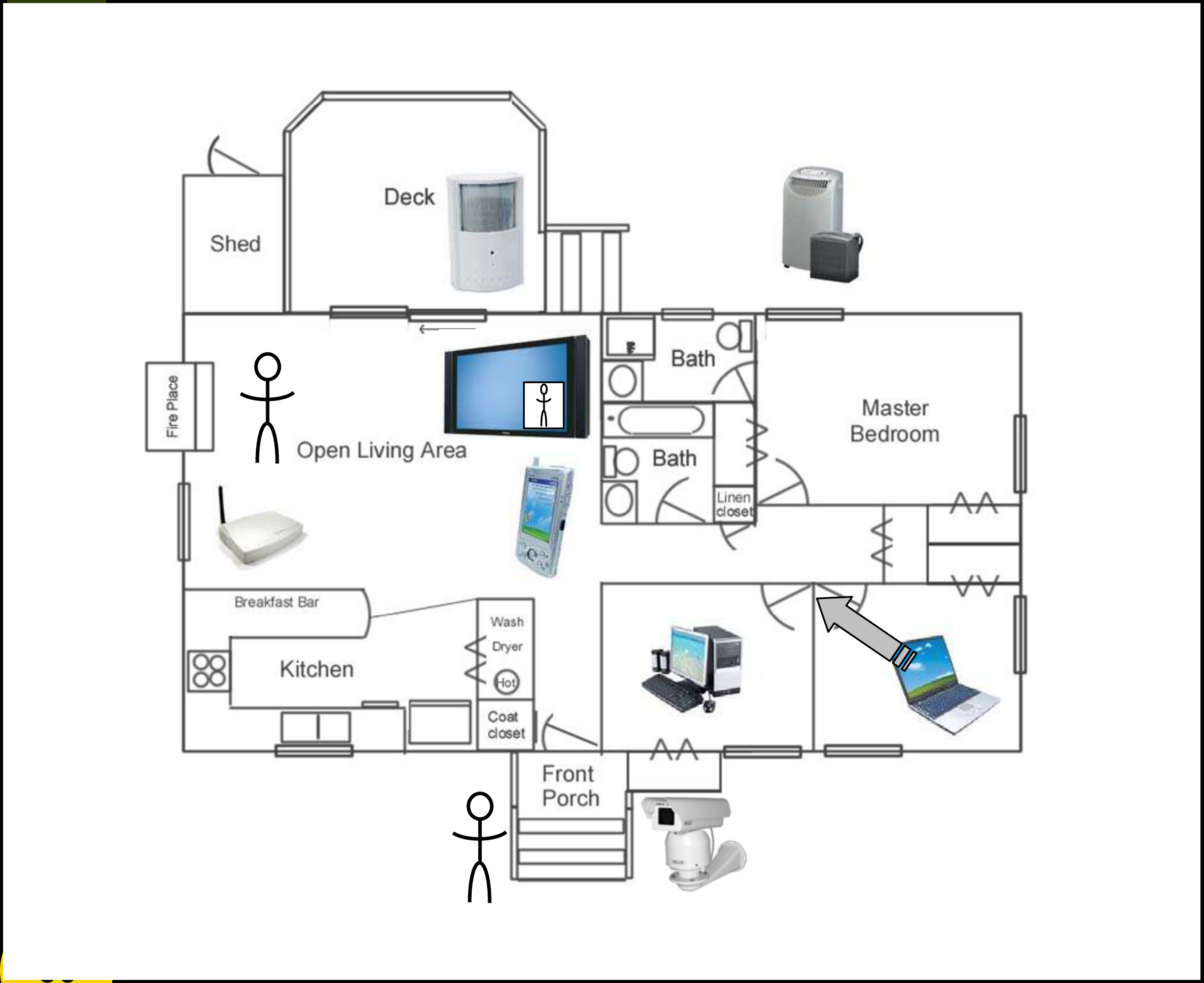
Applications

- An application is a set of behavioral tasks
- *Session* (instantiated app)
  - Queries environment services
  - Elaborates tasks to match current environment (includes trans-coding, finding suitable displays etc)



- *Session state* is stored to enable application migration (position in movie, etc.)

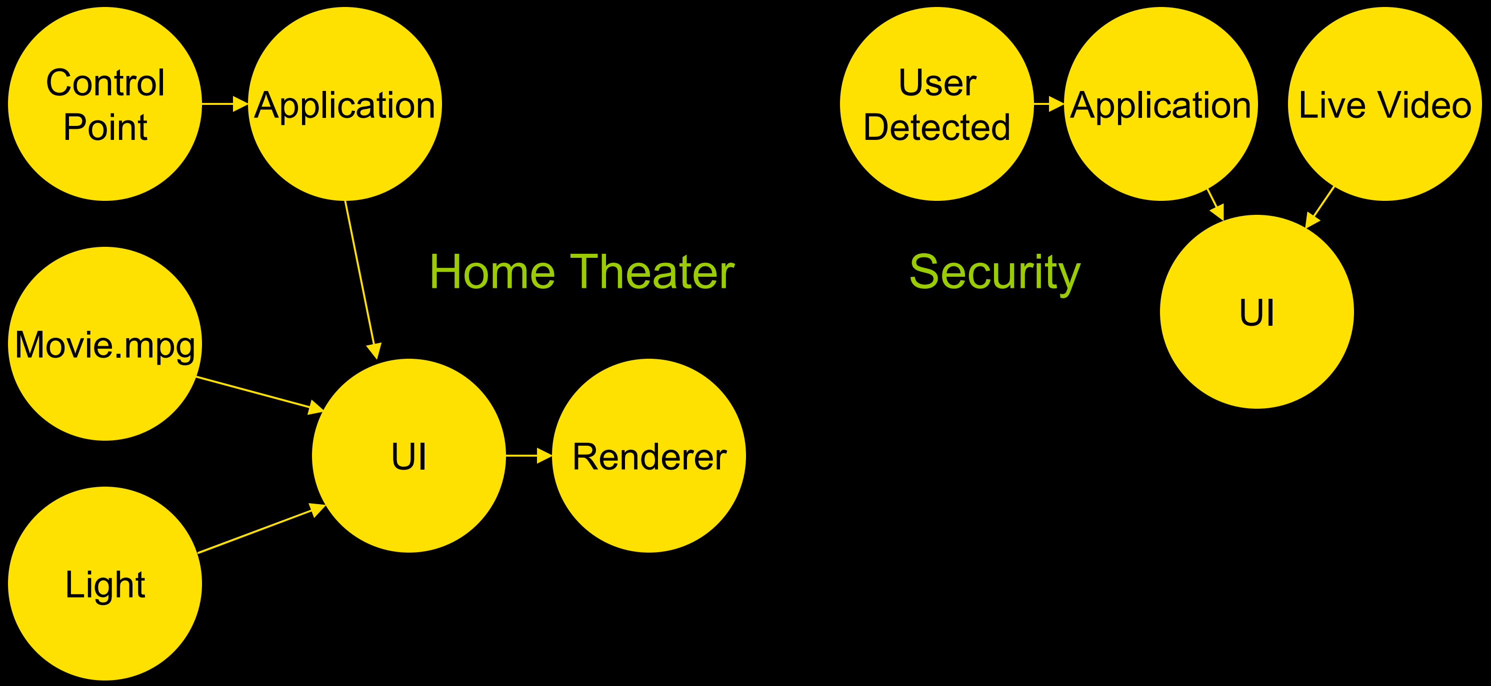
Simple Scenario



- Various Devices
  - Rendering
  - Content sources
  - Control points
  - Compute nodes
  - HVAC
  - Sensing
- Watching streaming video from laptop
- Guest at front porch
- PiP on living area screen

Example

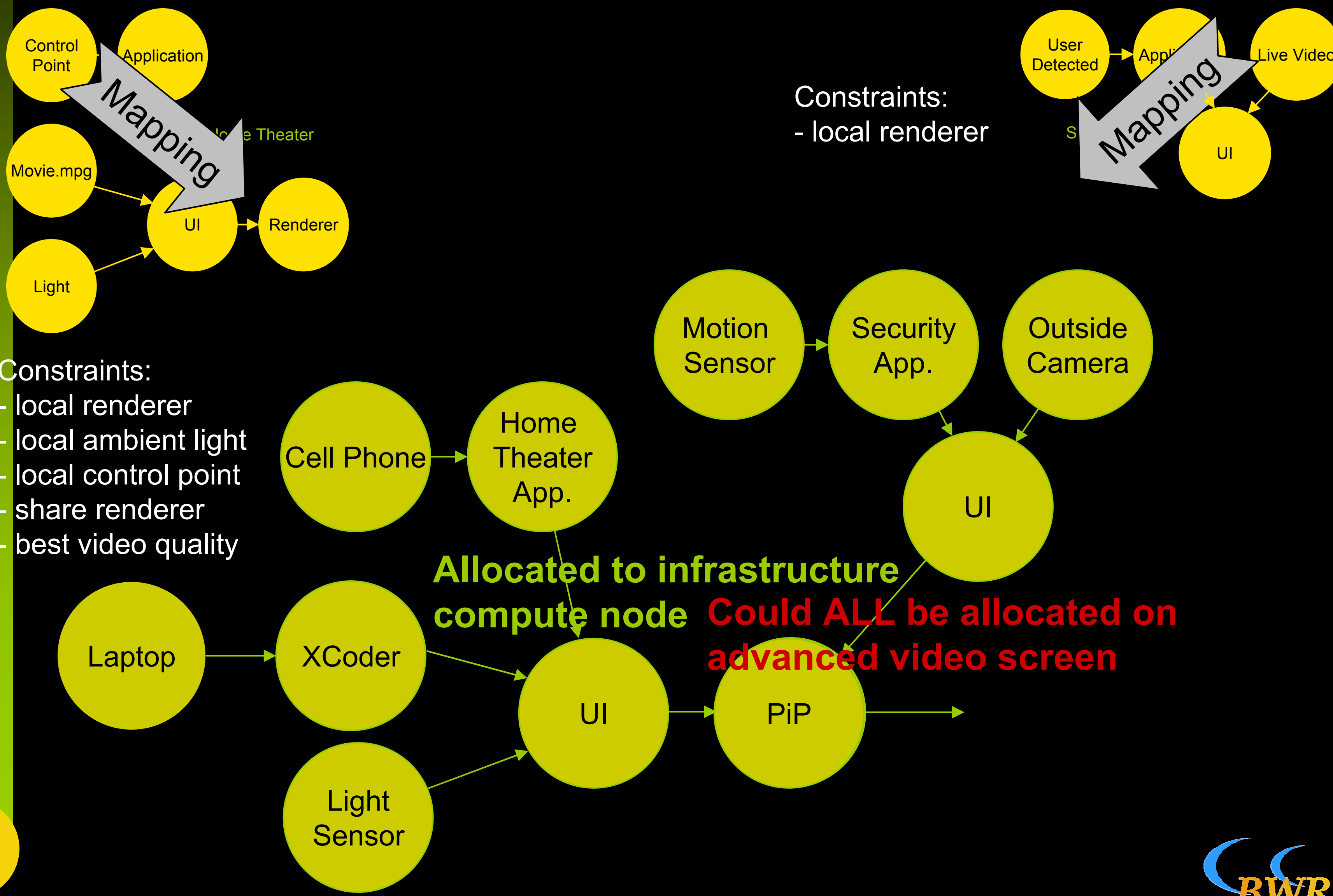
- Initial flow-graphs for application
  - Home theater → streaming video from laptop; monitoring ambient light
  - Security → outside motion sensor and camera



Example

Constraints:
- local renderer

Constraints:
- local renderer
- local ambient light
- local control point
- share renderer
- best video quality

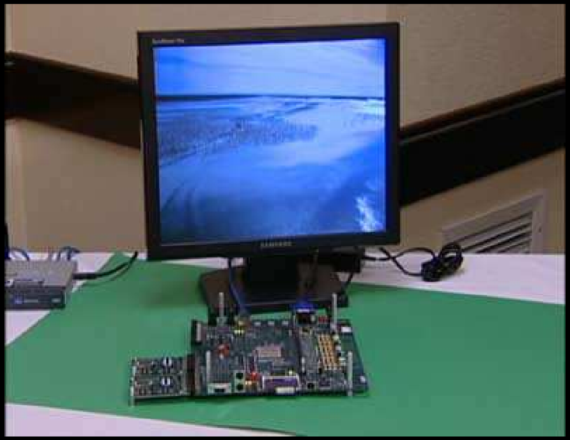


Allocated to infrastructure compute node

Could ALL be allocated on advanced video screen

Status

- Implemented subset of abstractions and resource manager
  - IP network of distributed heterogeneous devices (FPGAs, mobile and compute nodes, COTS)
  - Applications use services to build simple flow-graph.
  - On-the-fly mapping of flow graph with simple constraints (user location and matching media types)
- What's next?
  - Extending resource manager and programming framework
    - Interoperability requires mapping for many layers of networking stack
    - Representation of content, capabilities, and constraints



Summary and Perspectives

- The future of wireless infrastructure is the seamless connection of the myriad of emerging mobile multimedia and sensor devices – the home as the ideal playground
- Putting intelligence in the network can lead to seamless interoperability and enhanced user experience
- Harvesting the offered opportunities requires bold top-down vision with raised levels of abstraction
- Exciting symbiotic relationship between wireless multimedia and sensor networks – creating the true "ambient experience"

Thank you!

"Chaos at least has an open architecture. Chaos has always been the native home of the infinitely possible."
— John Perry Barlow

The contributions of the BWRC and GSRC faculty to this presentation are greatly appreciated. The stimulating discussions with Ken Lutz , Kannan Ramchandran, Alberto Sangiovanni-Vincentelli, John Wawrzynek (UCB) and Adam Wolisz (TU Berlin) are especially valued.