The Future of Spectrum Sharing

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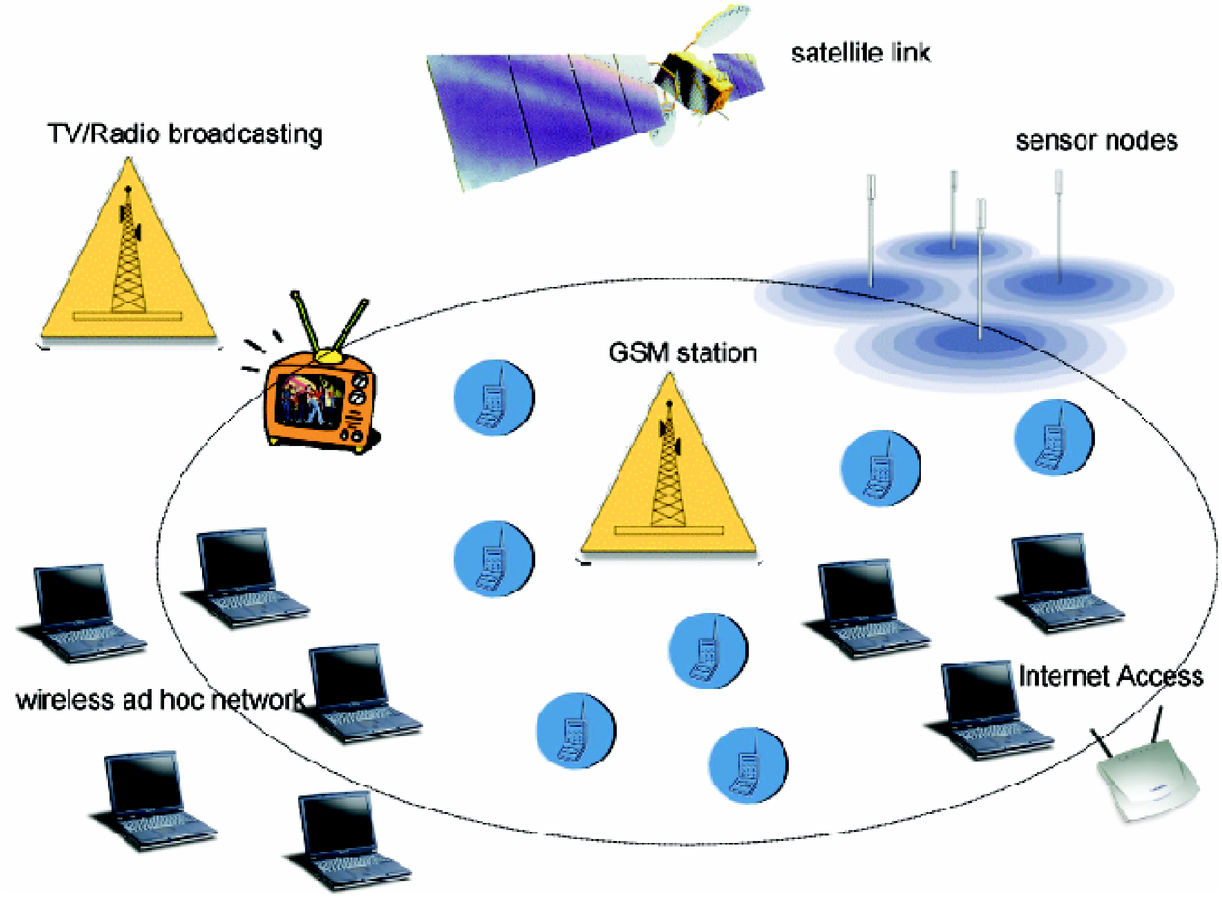
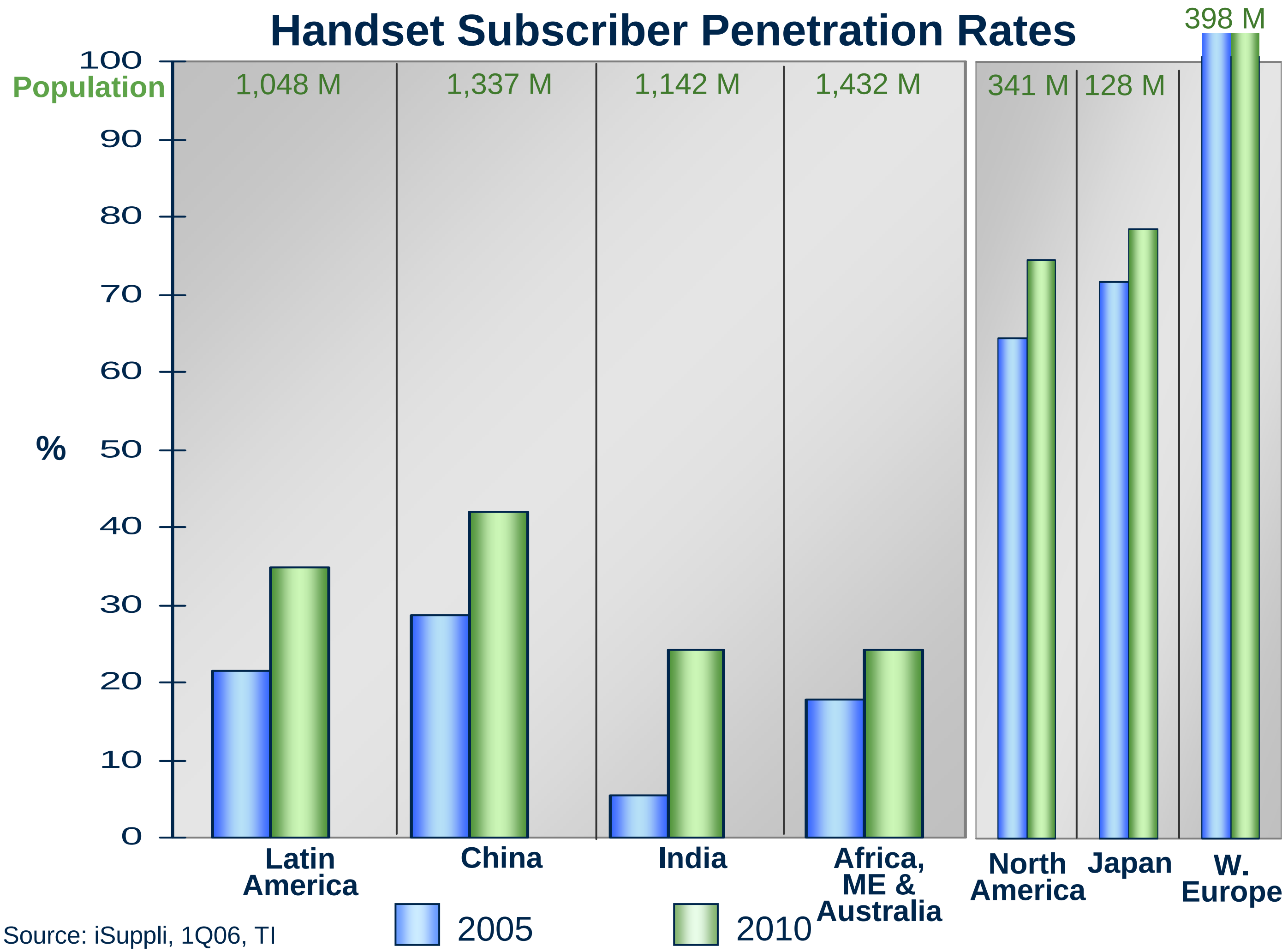
Wireless Explosion



Growing demand for more bandwidth:

- **More users, higher datarates, more applications**
- **Need to find a path to provide >100x growth in this century!**

Mobile Terminal Penetration Rates



Source: iSuppli, 1Q06, TI

Devices Formerly Known as Mobile Phones

- **We rely on mobile phones for daily voice and data communications**
- **They can do much more:**
  - Take pictures, videos, are location-aware
- **Mobile phones are carried by a huge majority of population - like house keys or wallets**

- **In case of a major disaster, we will likely have mobile phones with us**
- **And yet, they won’t work…**

Major Disaster Scenario

- **Many people affected, most survive**
- **10’s or 100’s of thousands may need help**
- **Many may need to be warned of upcoming danger**

San Francisco, 1906

New Orleans, 2005

- **In all recent disasters, wireless communications have failed (Katrina, 9/11, London Underground, NE blackouts, …)**

Why Is Wireless Not Robust?

- **Limited available bandwidth, shared among users**
  - System capacity exceeded in disasters
- **Rigid policies and systems**
  - Cannot change them as needed
- **Traditional narrowband radio architecture**
- **No interoperability between different systems**
- **Little cooperation between devices in one system**
- **Reliance on wired infrastructure**
  - A few disrupted base stations will bring down the system

Outline

- **Traditional ways of sharing spectrum**
- **Approaches to better sharing**
- **Cognitive radio technology**
  - Wideband radio architectures and components
  - Spectrum sensing
- **Collaborative communications systems**
- **Conclusions**

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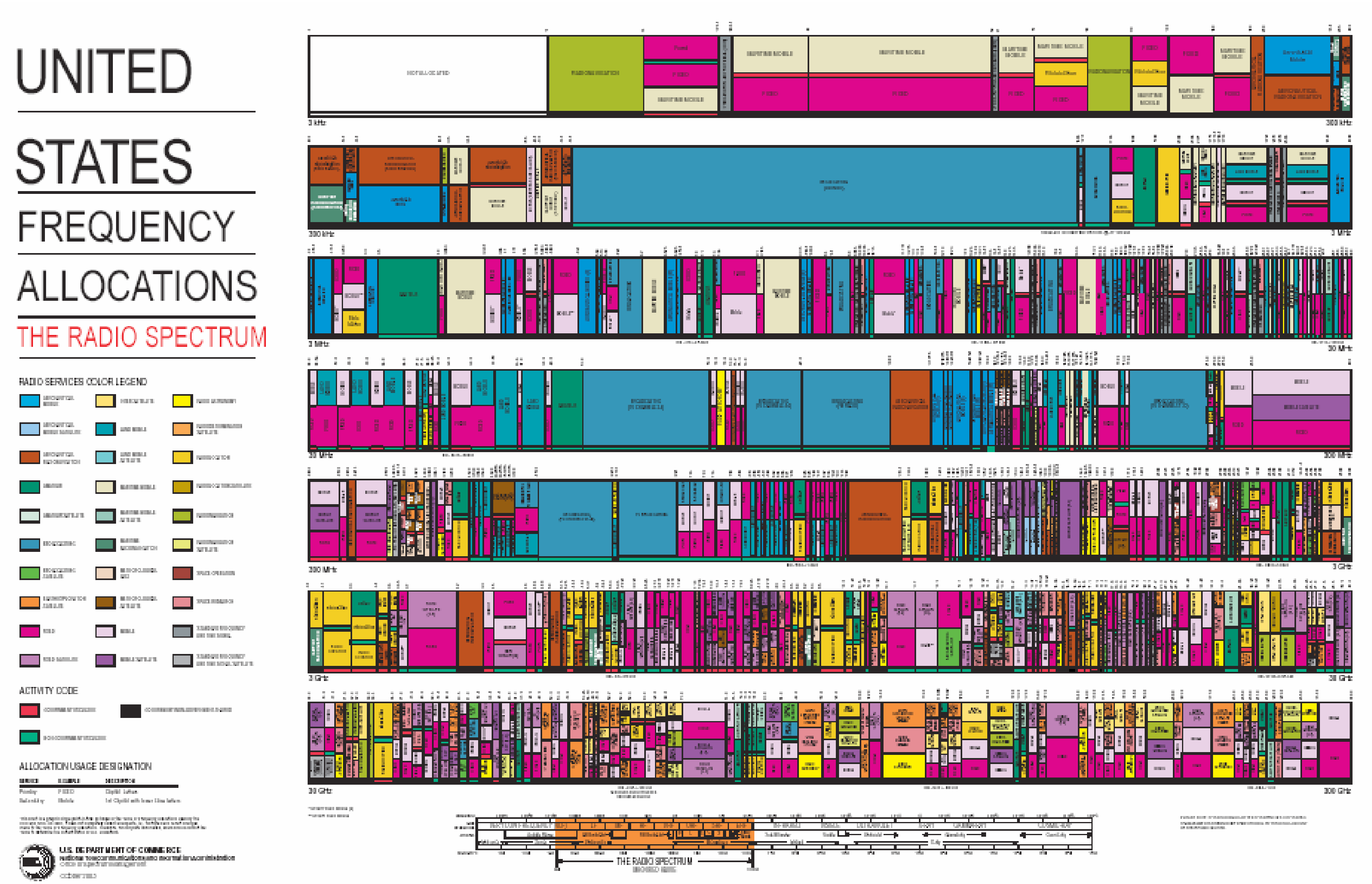
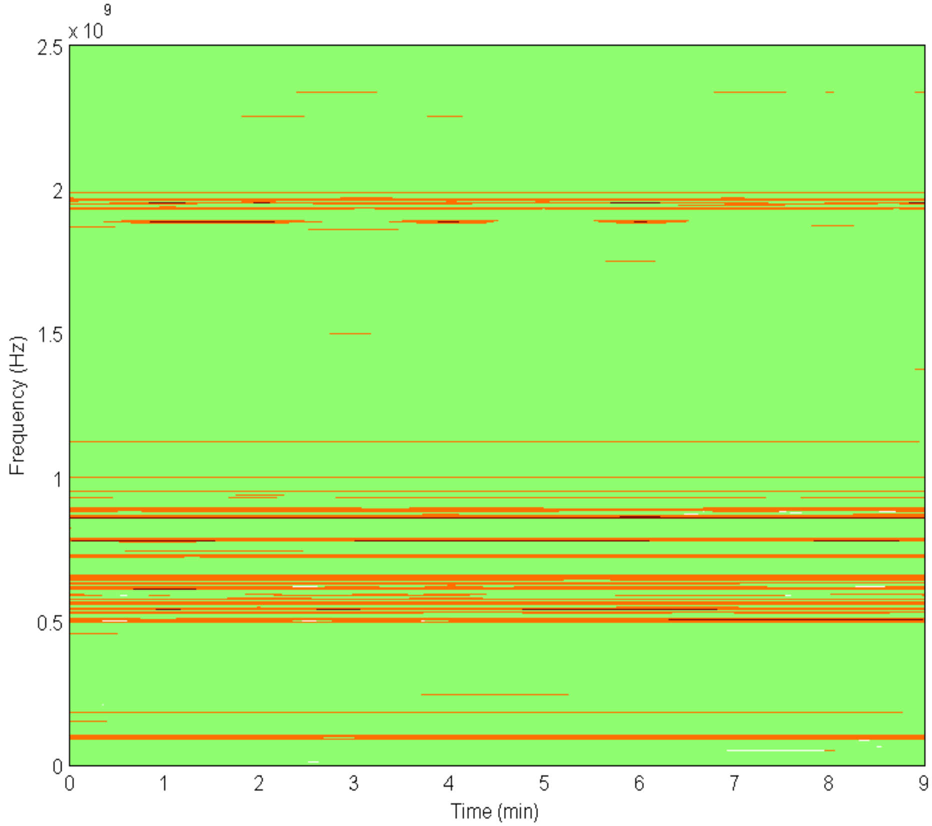
First 100 Years of Spectrum Sharing



The Previous Picture is Misleading

- *Allocated* **does not mean** *licensed*
- *Licensed* **does not mean** *used*



Spectrum usage 0-2.5GHz:

- Used in radio, TV, cellular bands
- Spectrum 2.5 - 5GHz >99% unused

More Spectrum Sharing

- **Cellular bands**
  - Explicit sharing, high spectral efficiency
  - Limited amount of ‘new’ spectrum available at attractive frequencies
- **Unlicensed bands**
  - No license needed to operate a radio; power/power density limits
    - E.g. ISM, U-NII
  - Limited amount of ‘new’ spectrum available at attractive frequencies
  - Lots of unlicensed bandwidth at 60GHz
- **Spectrum reuse**
  - Spectrum underlay (UWB)
  - Spectrum overlay (Cognitive radios)

Public Safety Bands

- There is a perception that public safety communications require dedicated bands
- Many bands available, frequencies incompatible with high volume radios
- Low volumes of dedicated radios, expensive, and lag cutting-edge technology

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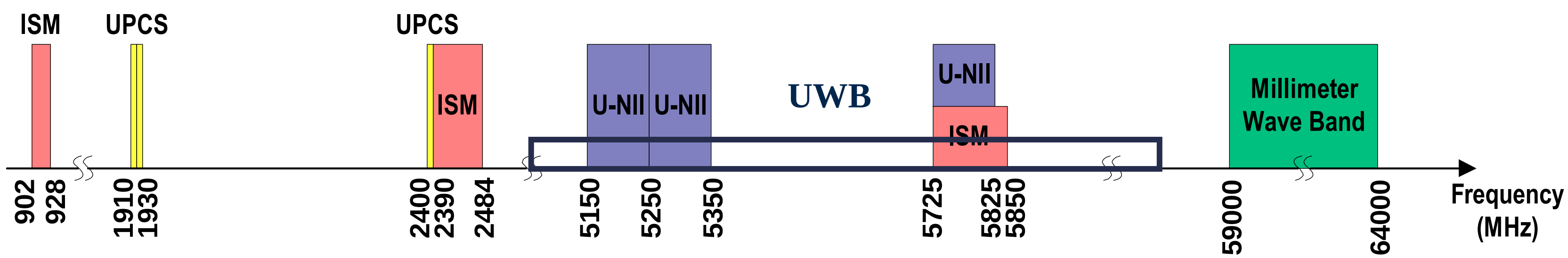
Regulation Has Been Changing



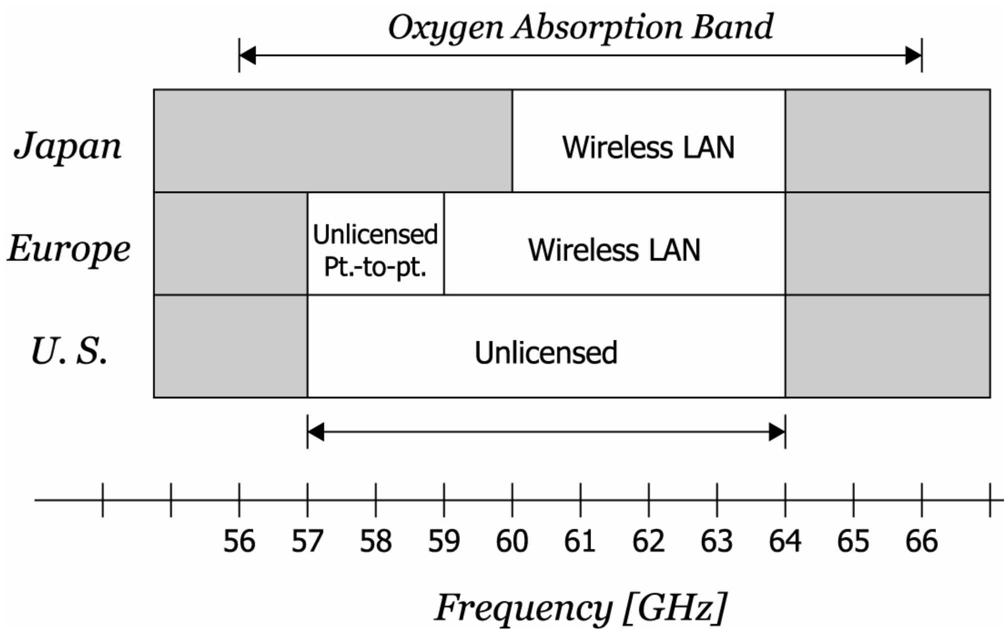
	ISM (1986)	UPCS (1994)	802.11a (1997)	Millimeter Wave (1998)	UWB (2001)
Link Control		✓			
Modulation	✓				
Total Transmit Power	✓	✓	✓	✓	
Power Spect Density	✓	✓	✓	✓	✓
Antenna Gain	✓	✓	✓		
Out of Band Emission	✓	✓	✓		

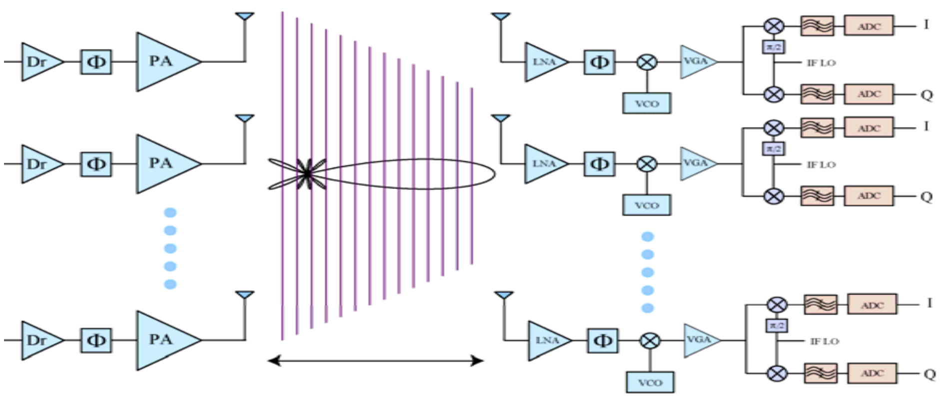
More Sharing

Reference: Part 15 of the FCC Rules, September 2000.

60 GHz Wireless

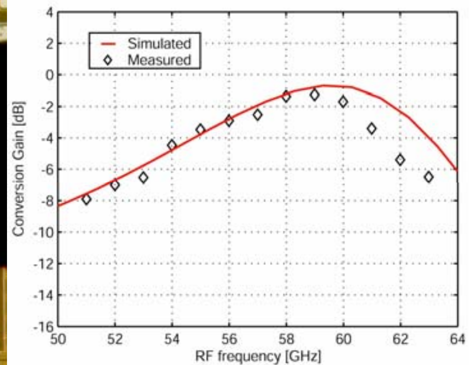
5-7 GHz of Unlicensed Spectrum Worldwide

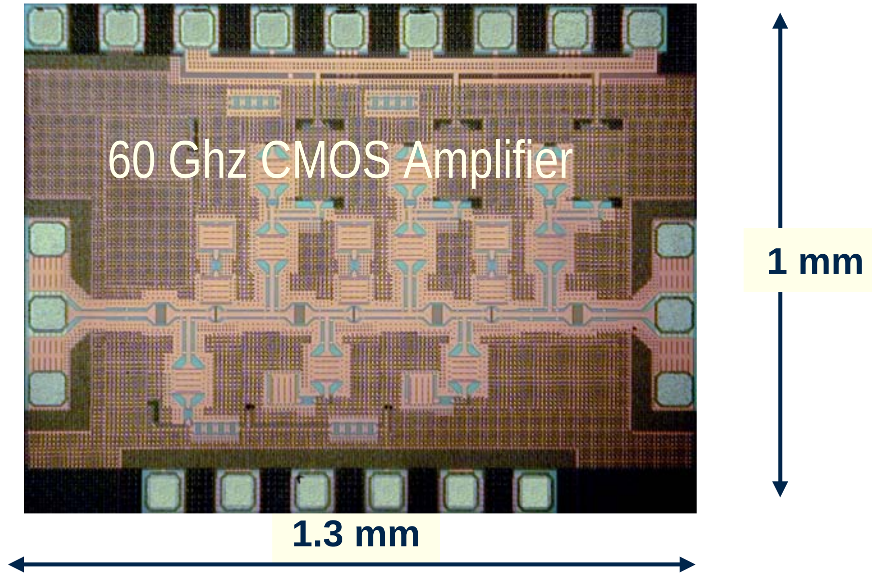


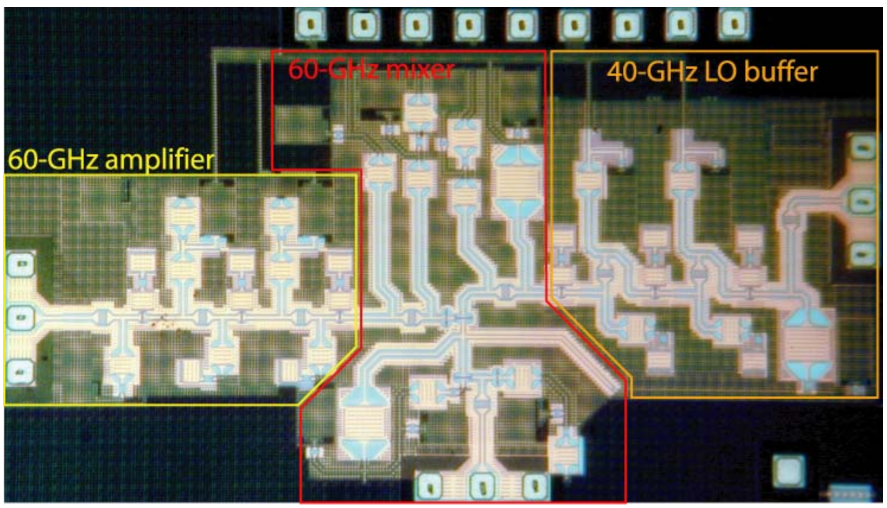


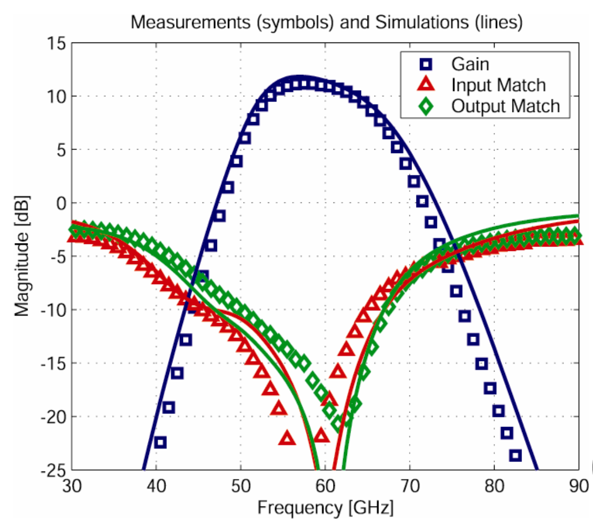
- Antenna arrays for directionality, improved gain and robustness
- Enable a fully-integrated low-cost Gb/s data communication using 60 GHz band.

Possible in Today's CMOS Technology!









Prof. A. Niknejad, UCB

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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"

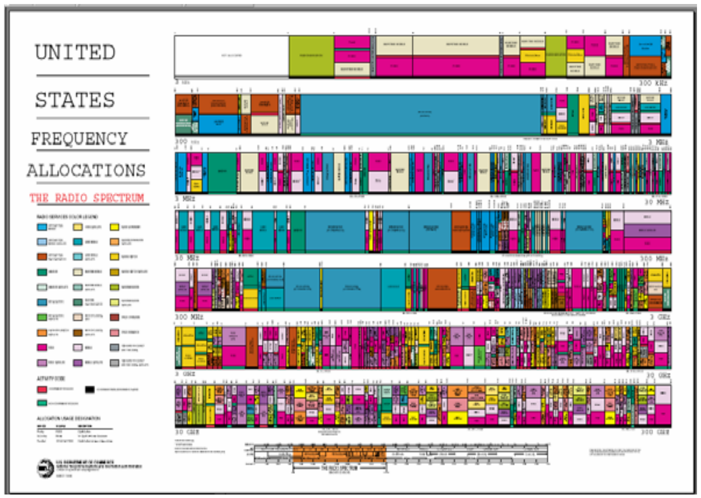
Federal Communications Commission,

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

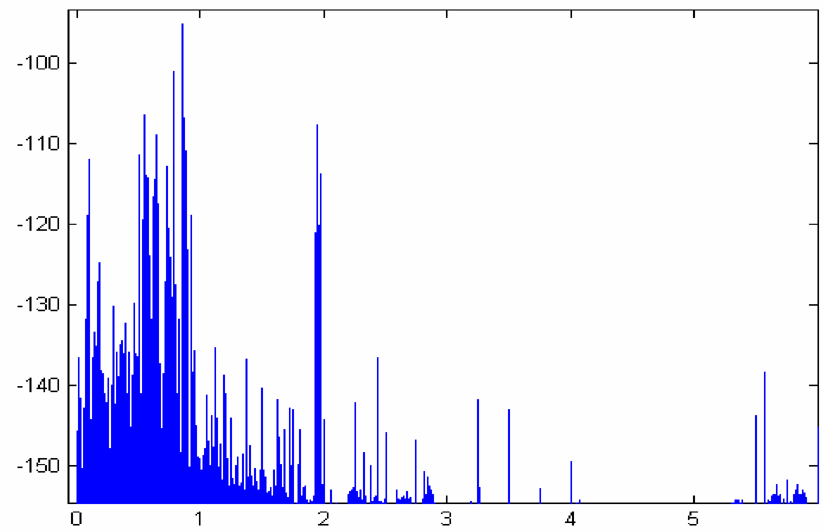
Spectrum Shortage……

- **Existing spectrum policy has full allocation but poor utilization**

Allocation



Utilization

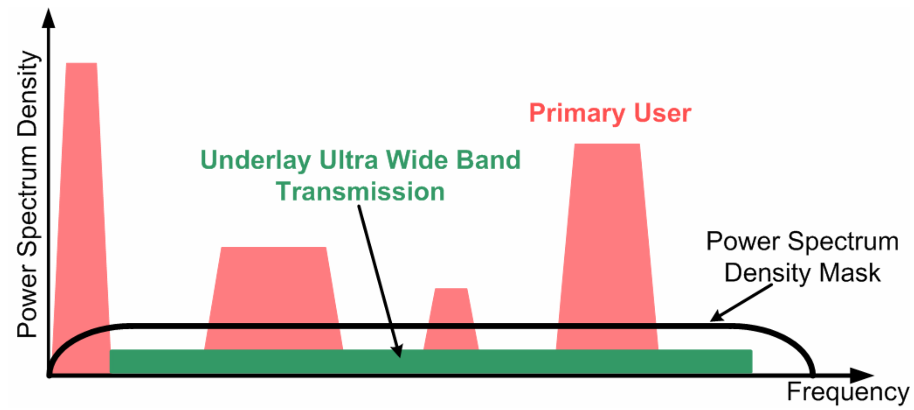


- **The cognitive radio strategy is to find the unused spectrum and to use it without interfering with primary users**

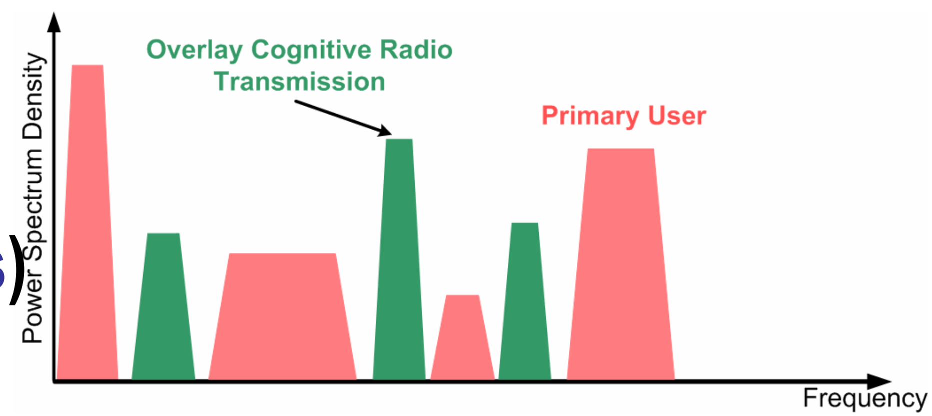
Spectrum Sharing

Allow transmission in allocated bands but avoid interference to primary users

- **Limit power to reduce interference and compensate by the use of wide bandwidths (Ultra Wide Band radios)**



- **Sense primary users and opportunistically transmit in vacant bands (Cognitive radios)**



Cognitive radios could achieve 100 fold increase in system capacity

Government Support for Cognitive Radios

Regulations:

- FCC NPRM (2003) Flexible spectrum use through CR
- FCC NPRM (2004) CR operation in unused TV bands
- FCC FRO (2006) Rules for CR operation in unused TV bands
- FCC NPRM (2006) Public safety network in 700MHz Band

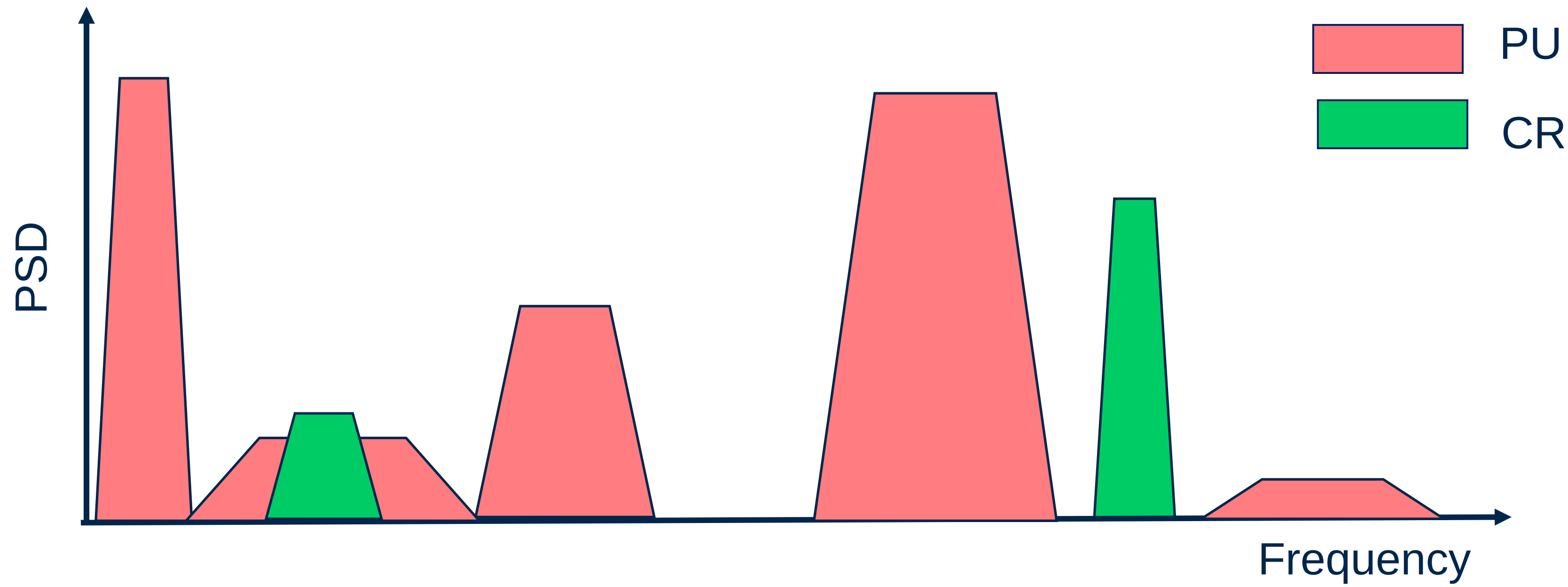
R&D:

- DARPA (XG program) Policy based radios

Industry:

- IEEE 802.22 standard for WRAN in unused TV bands

How Does a Cognitive Radio Operate?



- Sense **the spectral environment over a wide bandwidth**
- Transmit **in “white space” &** Adapt **bandwidth and power**
- Detect **if primary user appears**
- Move **to new white space**

J. Mitola, Ph.D. KTH, 2000

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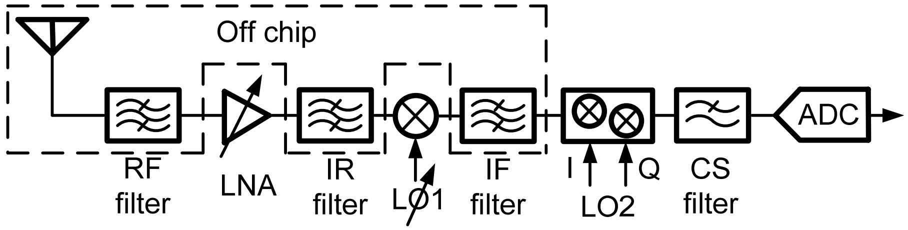
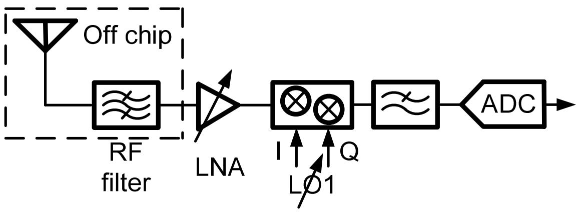
Universal Wireless Terminal

- **Broadband Radio (1-10 GHz, 60 GHz)**
  - Variable center frequency and bandwidth
  - UWB and narrowband capability
- **Operate seamlessly using 3/4G or WLAN/WiFi, WiMAX (or a future system)**
- **Multi-Mode Radio**
  - data, voice, variable data rate
- **Multi-Range**
  - short range (1-10m), long range (km)
- **Dynamic**
  - optimize power consumption for the application
- **Cognitive Capabilities**
  - Spectrum sensing
  - Collaborative communication
- **Use multiple transceivers in various modes:**
  - Simultaneous Tx/Rx in MAN, WAN, and PAN
  - MIMO

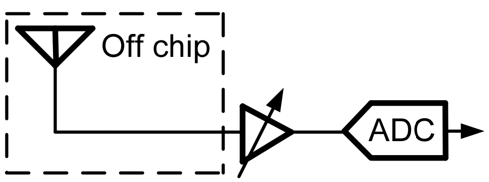
Front-End Migration



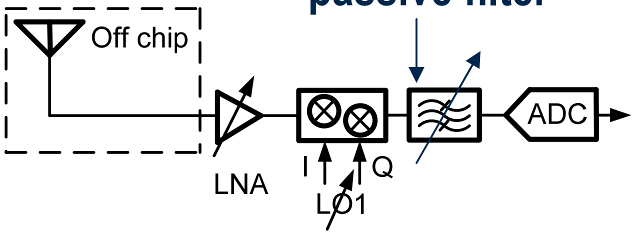
Conventional superheterodyne



Direct conversion



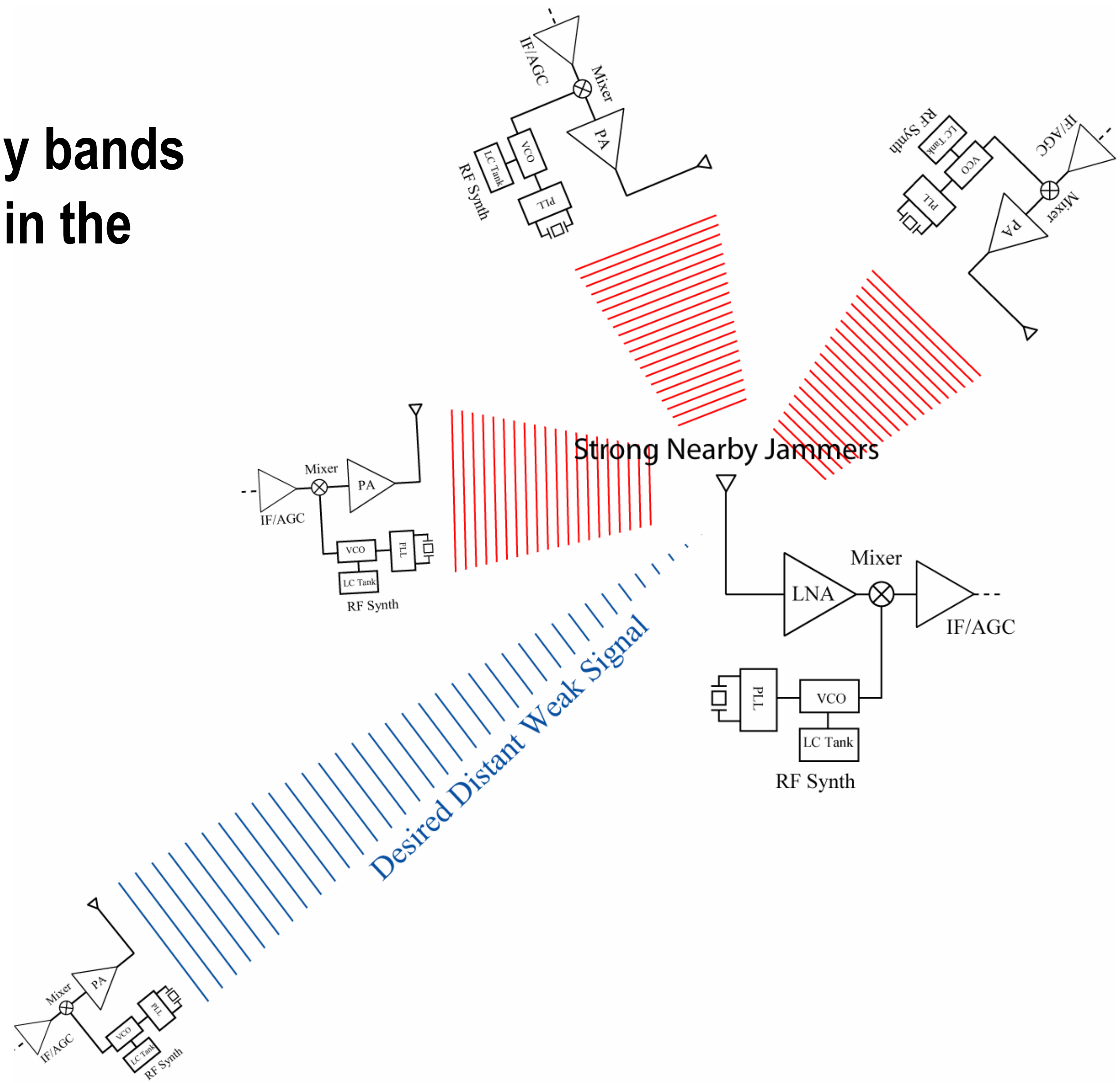
Ideal (imaginary) software defined radio



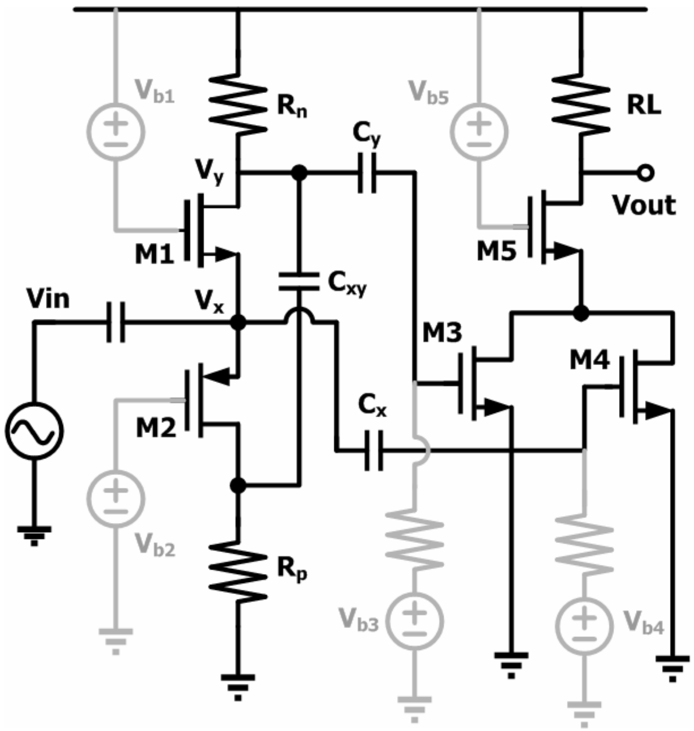
Software defined radio

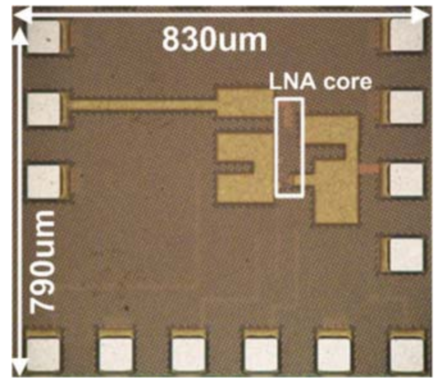
Exacerbated Near/Far Problem

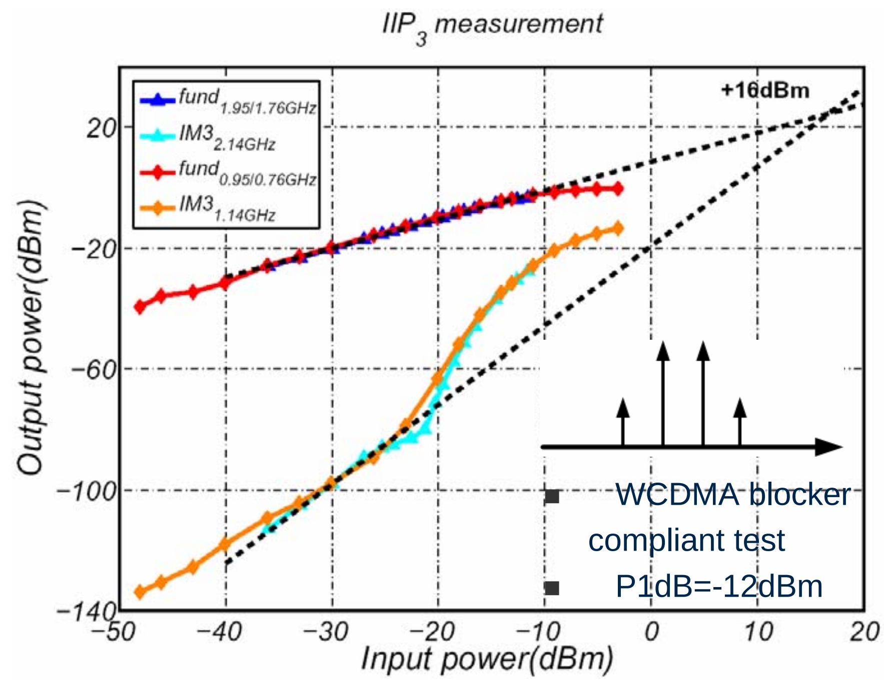
- Broadband input
- Jammers from many bands
- Need high linearity in the front end
  - 20dB IIP3
- Need interference cancellation



Noise/Distortion Cancellation in LNA



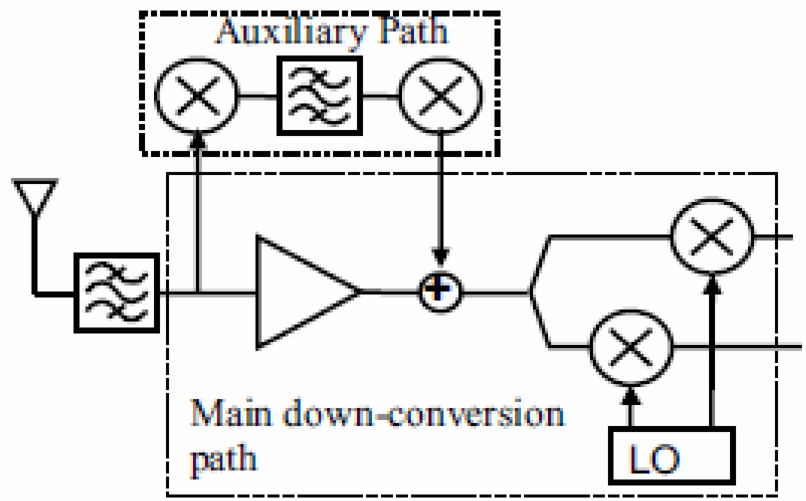




Bandwidth (S11<-8.5dB)	0.8~2.1GHz
Gain (S21)	>8.6dB (add 6dB on-chip)
Noise Figure (NF)	<2.6dB

Chen, Niknejad, RFIC'07

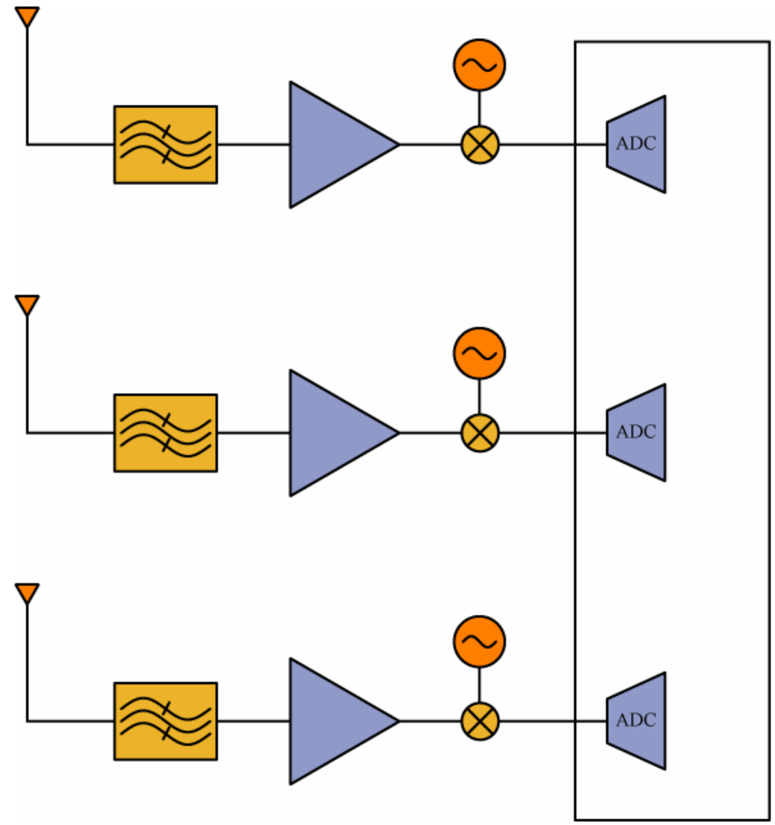
Interference Cancellation



- A broadband front-end is prone to loss of sensitivity due to interference/jammers
- R. Gharpurey, S. Ayazian
- H. Darabi, ISSCC'07

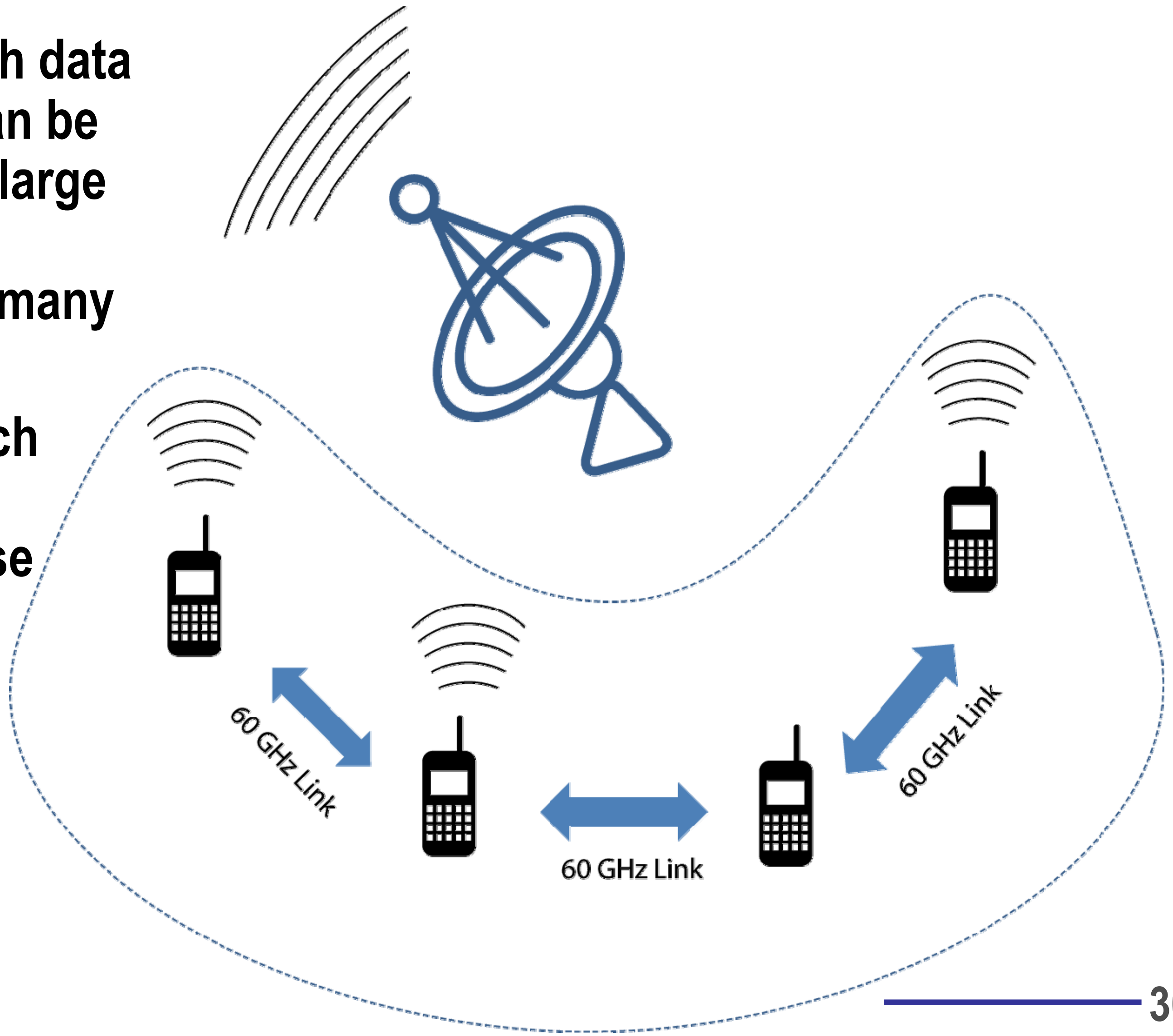
Multi-mode vs. MIMO Mode

- If the radios are built from identical units, then the system can switch between multi-mode operation and MIMO operation



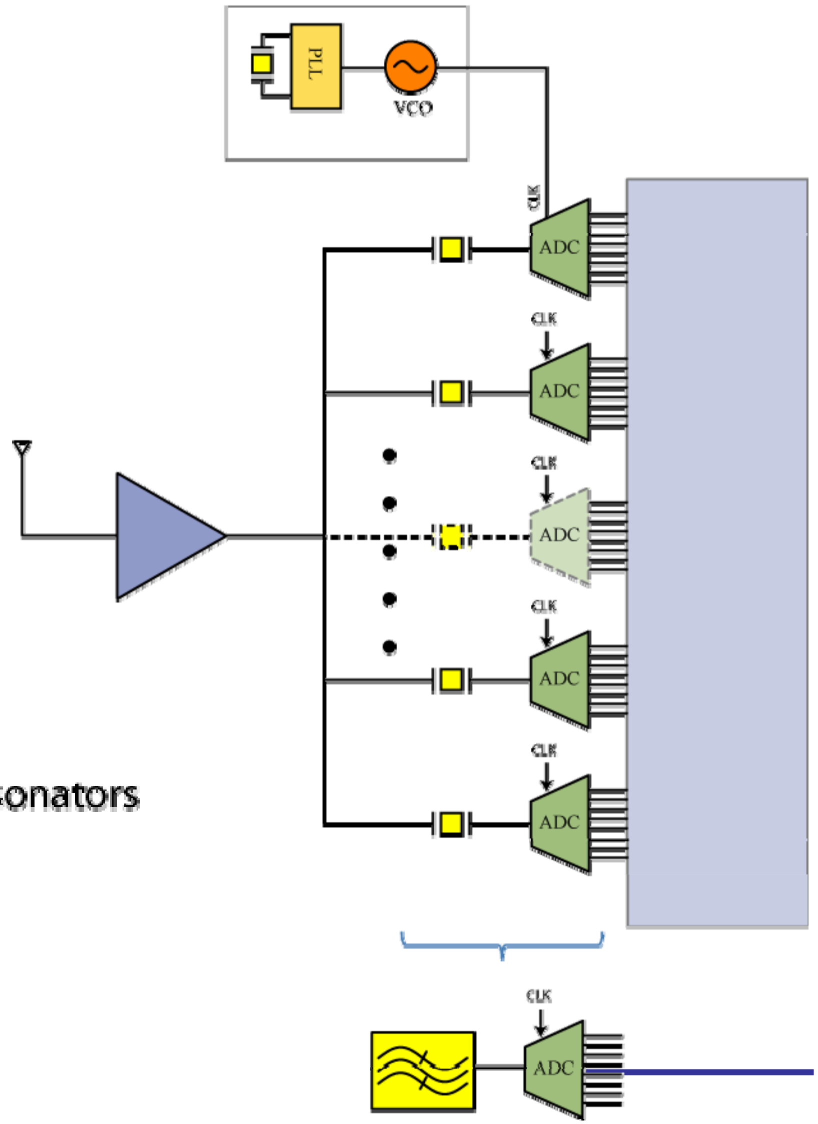
Multi-Terminal MIMO

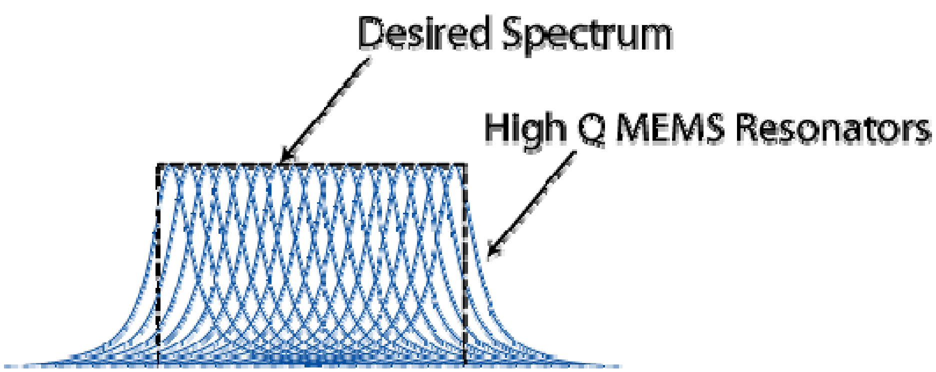
- The short-range high data network (60 GHz) can be exploited to build a large effective aperture antenna array from many terminals
- Users can share each other's terminals to dramatically increase throughput



MEMS Technology

- **Variable center frequency MEMS difficult**
- **Employ bank of resonators and narrowband ADC's**





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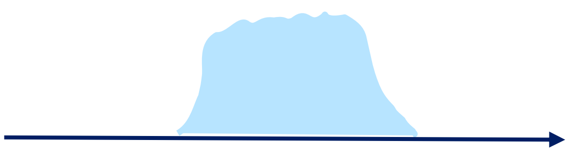
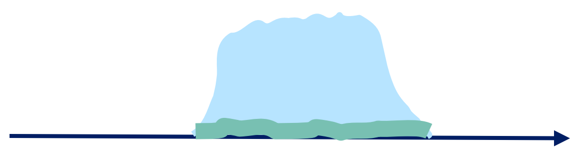
Spectrum Sensing: Detecting Energy

Energy detection has been studied as an hypothesis testing problem



$$H_0: \quad Y(n) = W(n)$$



$$H_1: \quad Y(n) = X(n) + W(n)$$

New requirement:

Meet desired detection and false alarm probabilities in negative SNR regime

P_{fa}= P(decide H_1 | H_0) and P_d= P(decide H_1 | H_1)

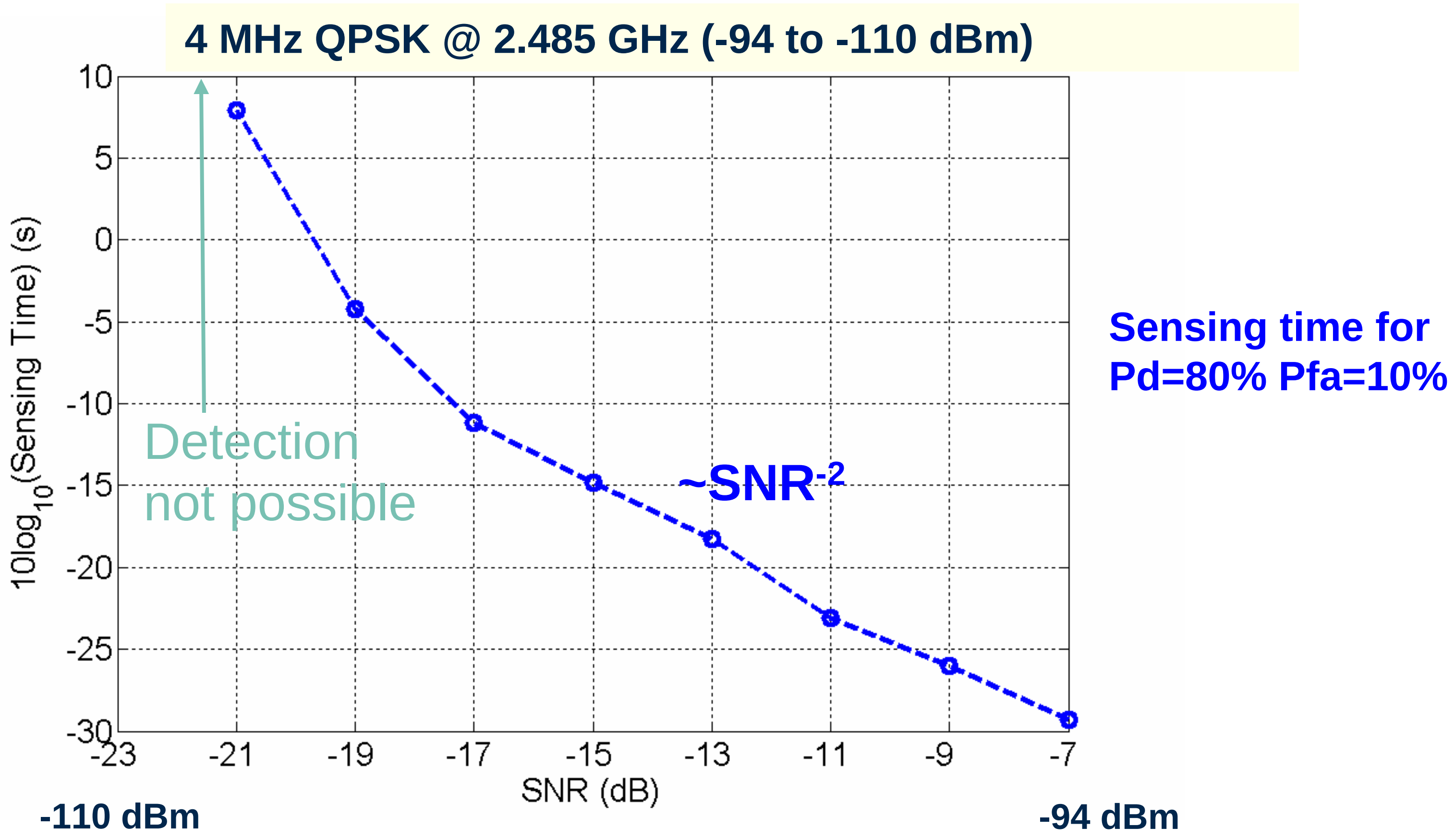
Decision statistics $\varepsilon(N) = \sum_N Y(n)^2$ compared with threshold T

Number of samples N used to meet P_d and P_{fa} scales with SNR as

$$N = 2\left[Q^{-1}(P_{fa}) - Q^{-1}(P_d)\right]^2 SNR^{-2}$$

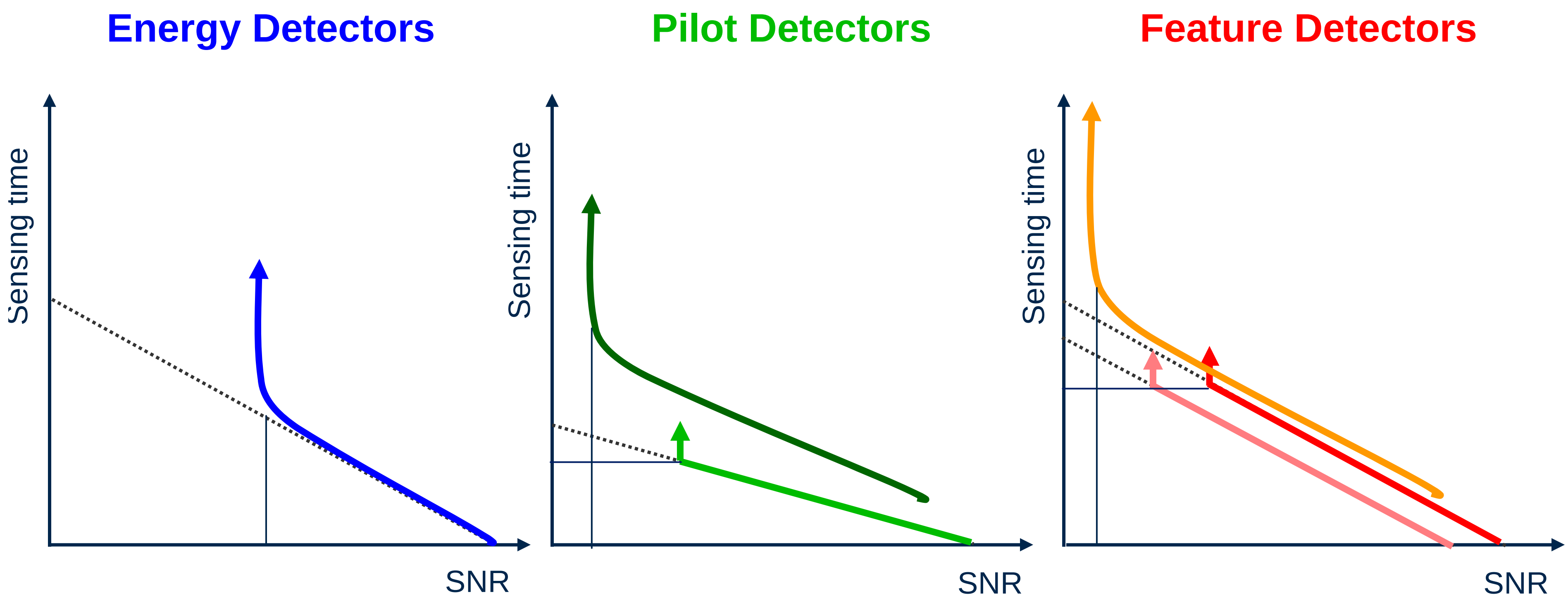
Gaussian assumption for noise and signal and known powers

Energy Detection



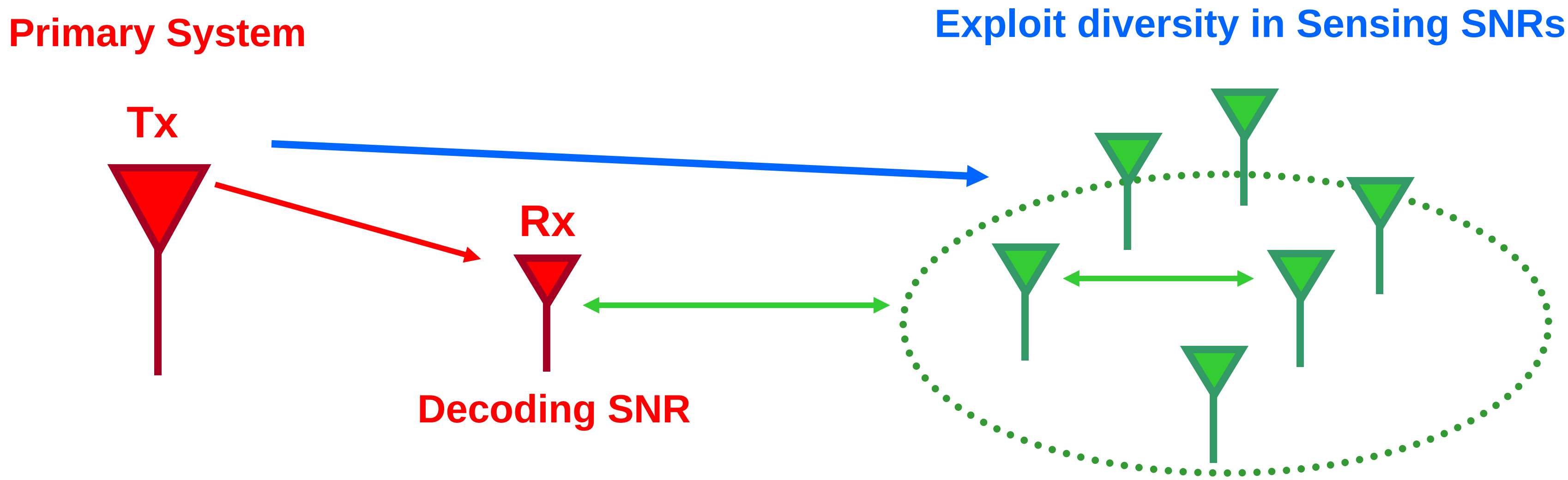
- Theoretical prediction confirmed up to approx. SNR greater than -20 dB
- Beyond -21 dB detection was not possible regardless of sensing time duration

Spectrum Sensors Design



Non - coherent	Coherent	Mixed
Simple	Pilots not always available or very weak	Complex (Gain ~ feature)
Fundamental limit: Noise wall	Need carrier synch. << 1 ppm	Need clock synch. ~1-100 ppm

Using multiple spectrum sensors

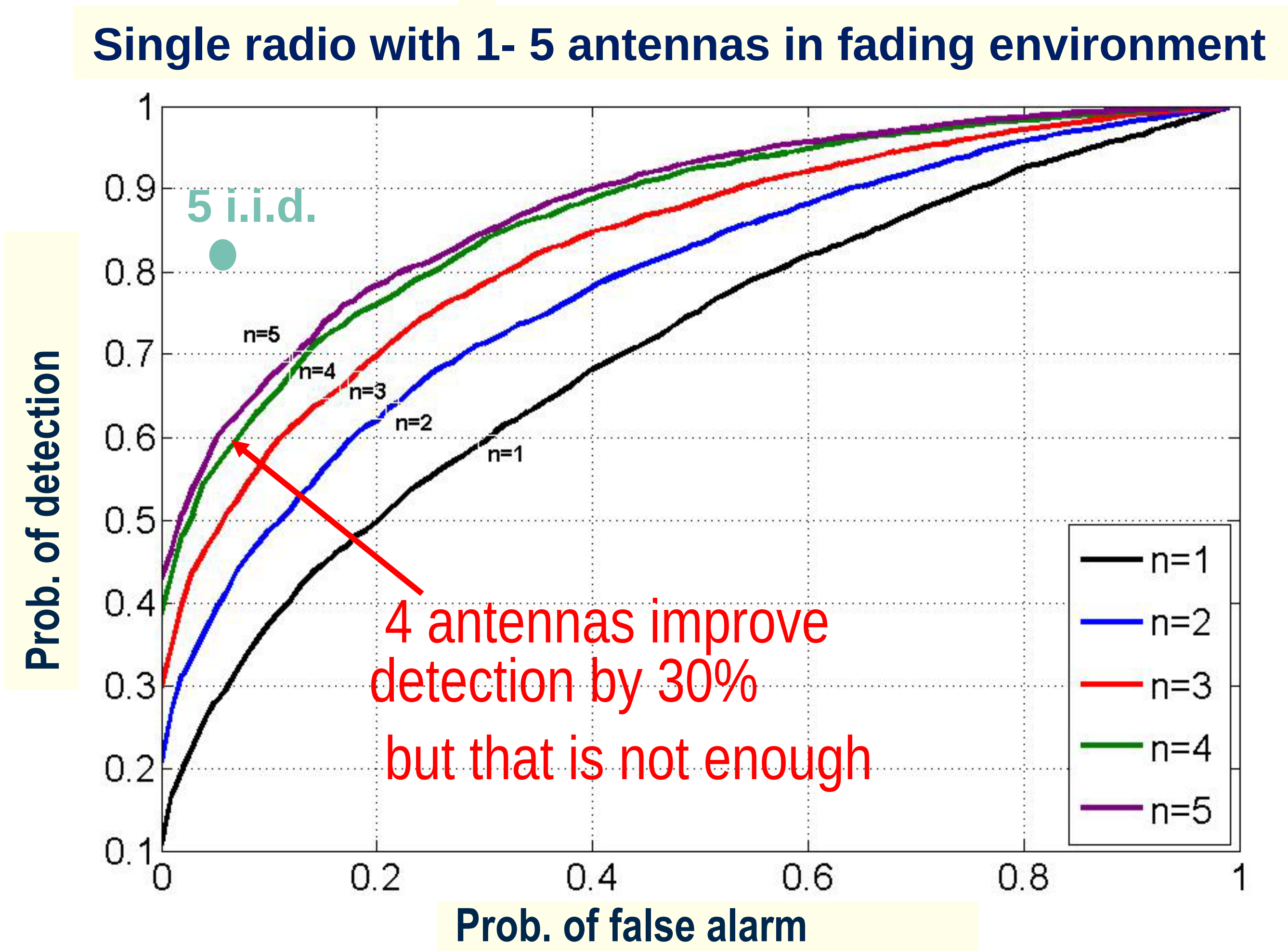


- If radios have independent measurements, detection probability monotonically increases with number of radios N

$$P_{d,\ system}=1-(1-P_{d,\ radio})^N$$

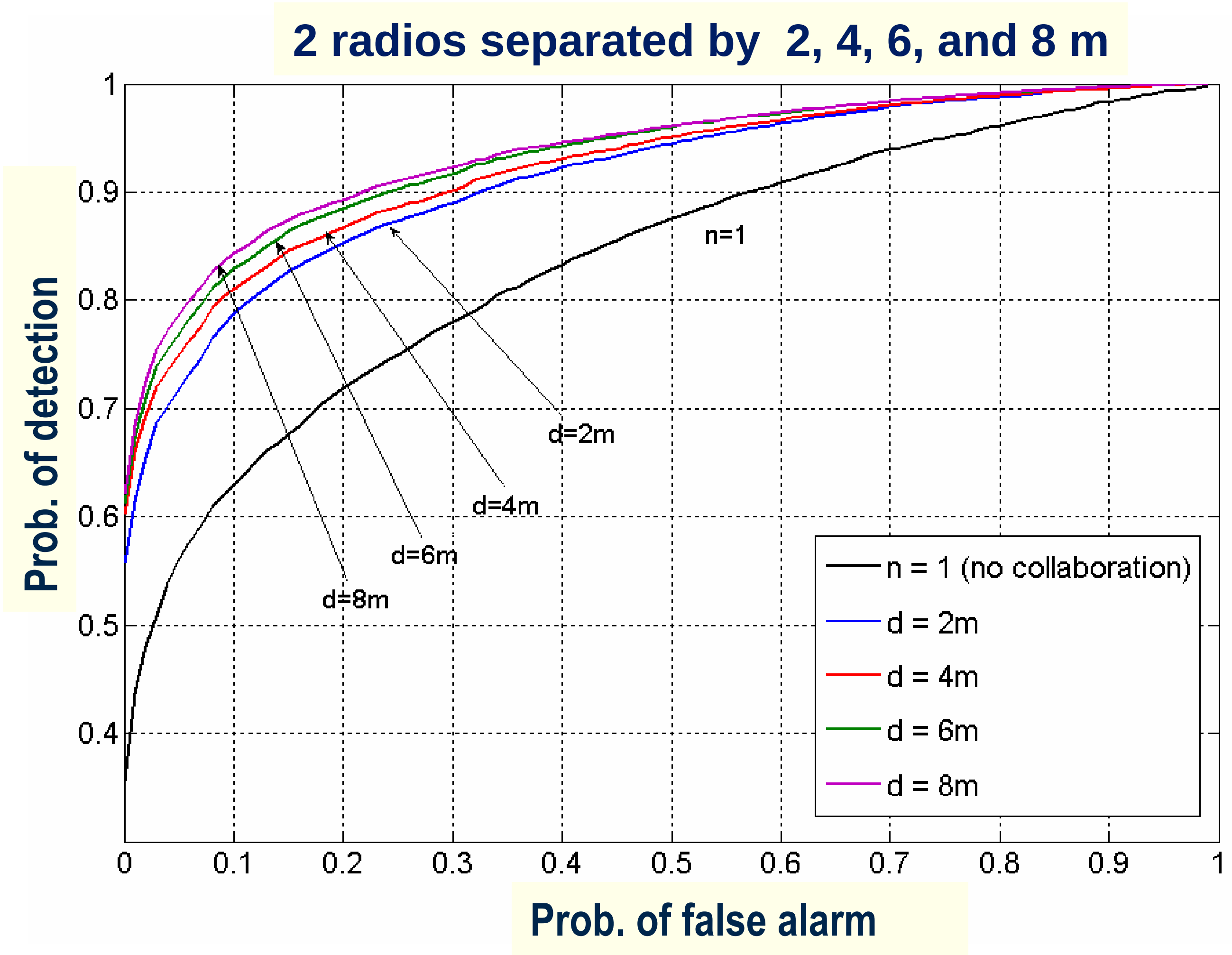
- Do we get this increase in prob. of detection in real wireless environments?
  - Current focus on indoor environments

Multiple Sensors Spaced by λ/2



- Simple equal gain combining with energy detection
- Gain depends on multipath richness, eventually saturates

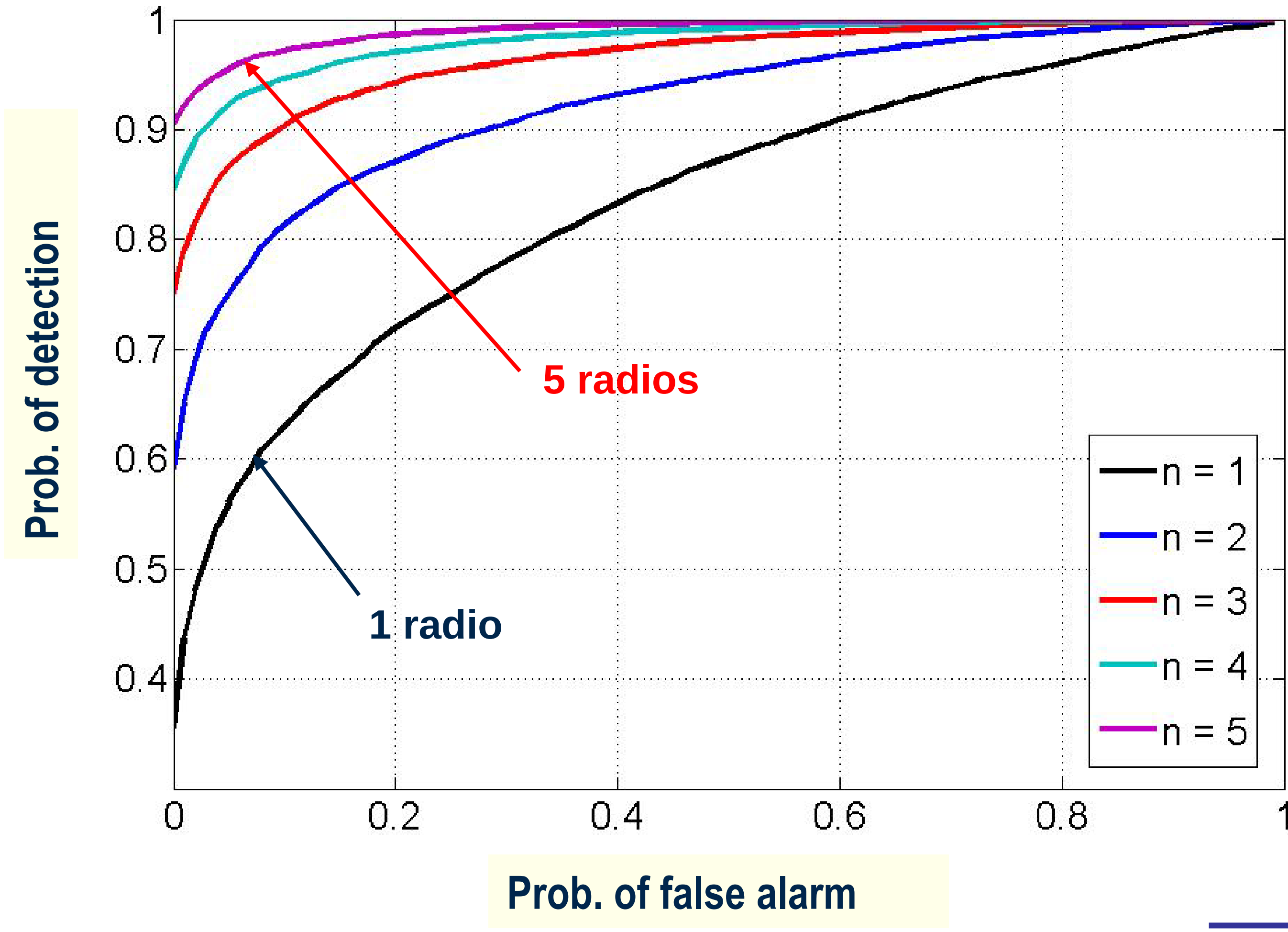
Cooperation Gain Improves with Distance



Measurements at 54 locations on a 2m by 2m grid

Network Cooperation

A few cooperative radios give big improvements



Measurements at 54 locations on a 2m by 2m grid

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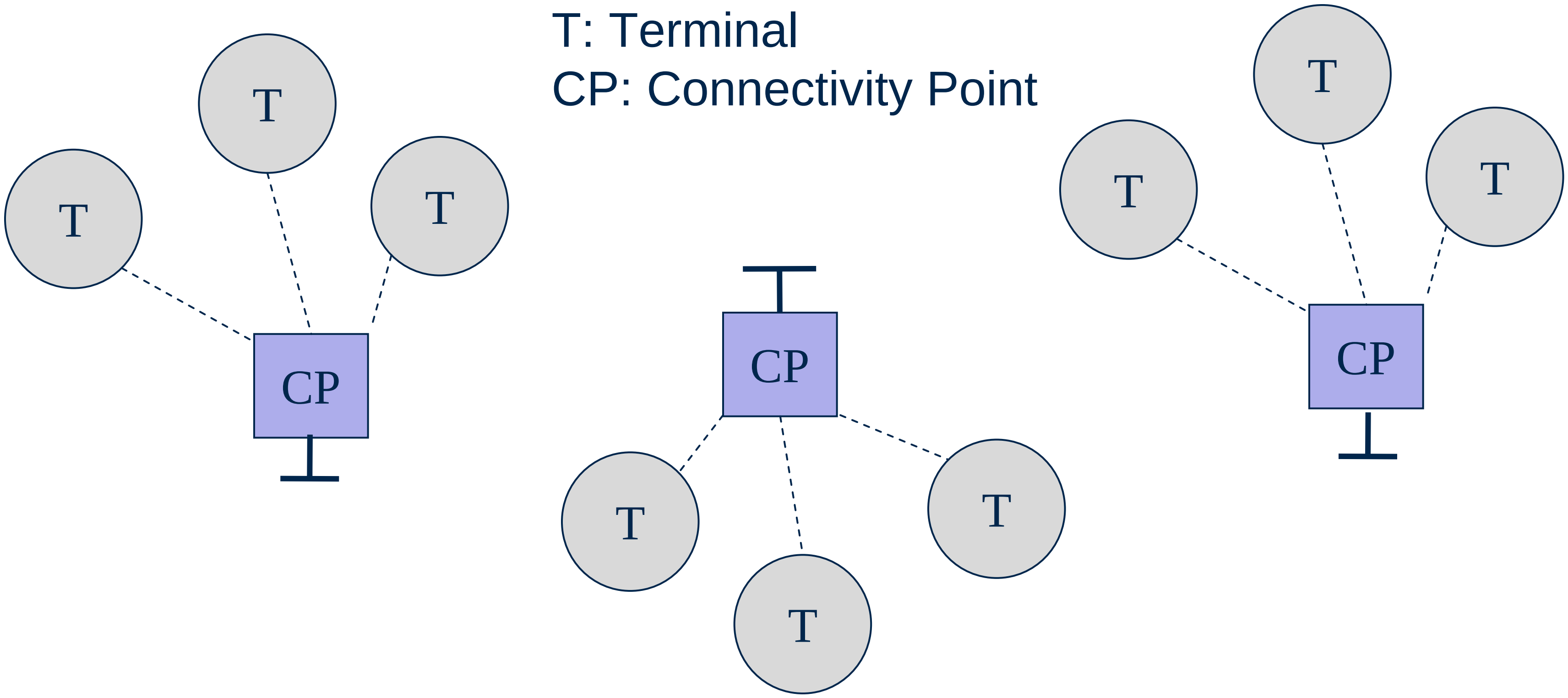
An Abstract Perspective

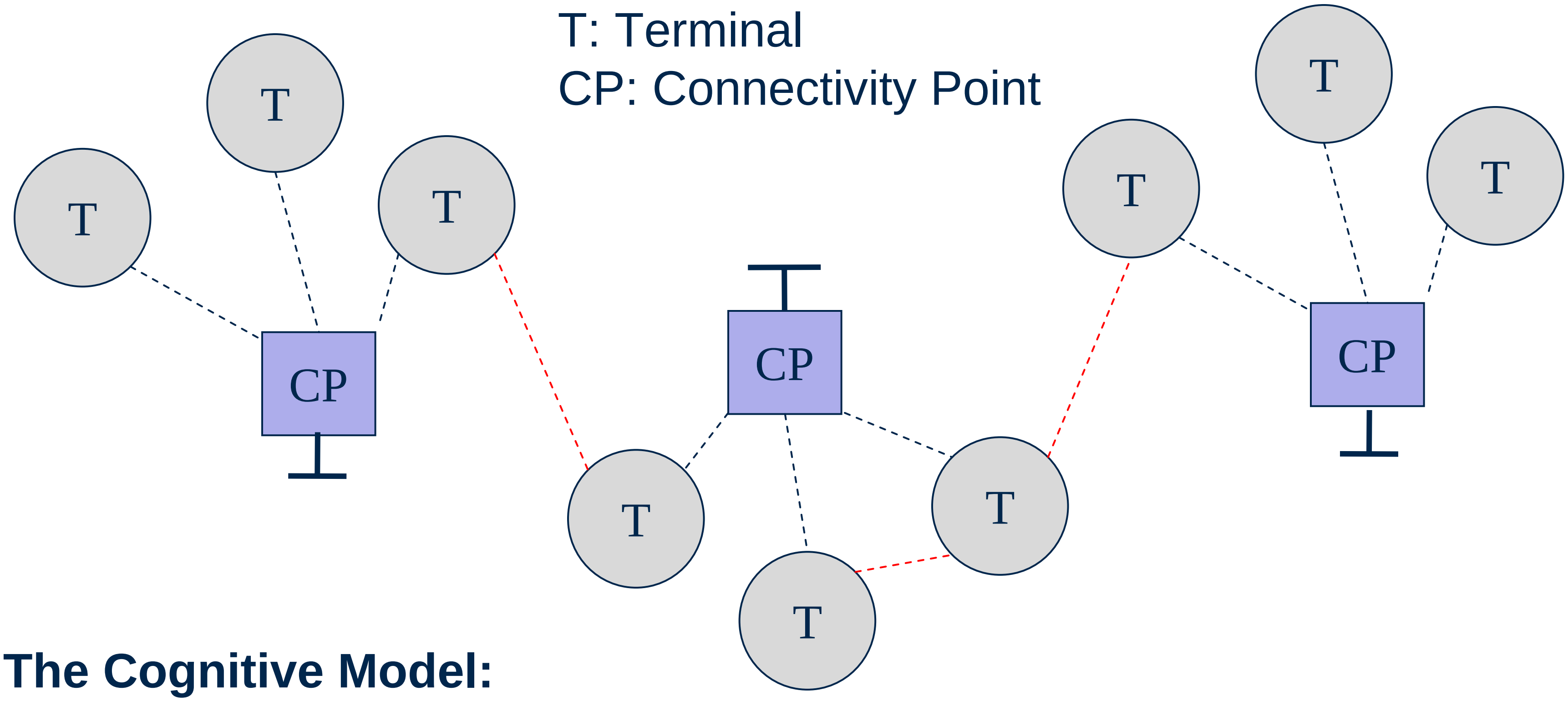
T: Terminal
CP: Connectivity Point



Traditional Model:

- Terminals connected through fixed links to connectivity points (access points, base stations, …)
- Cell only serves homogeneous terminals
- Non-cooperation between heterogeneous networks

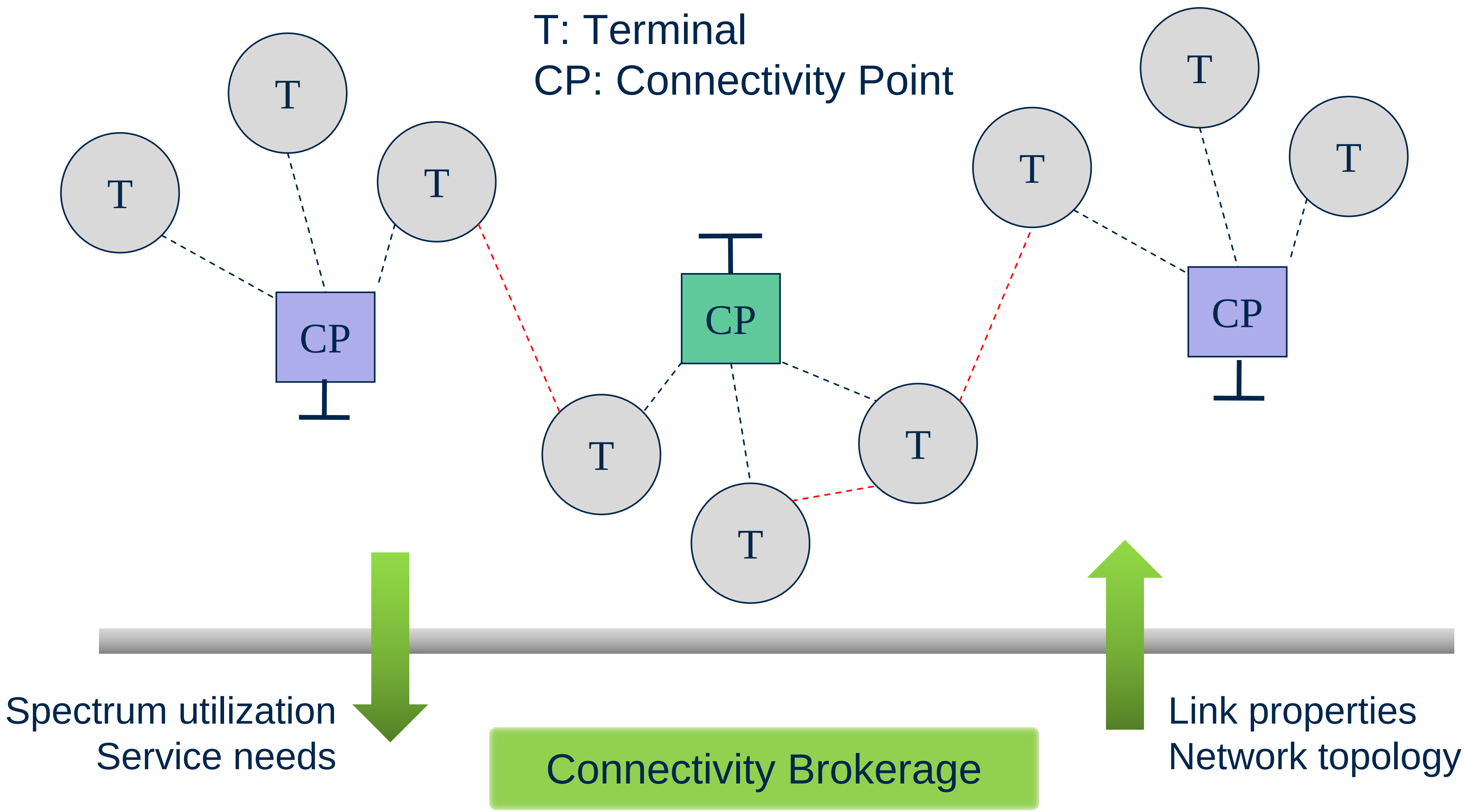
An Abstract Perspective



The Cognitive Model:

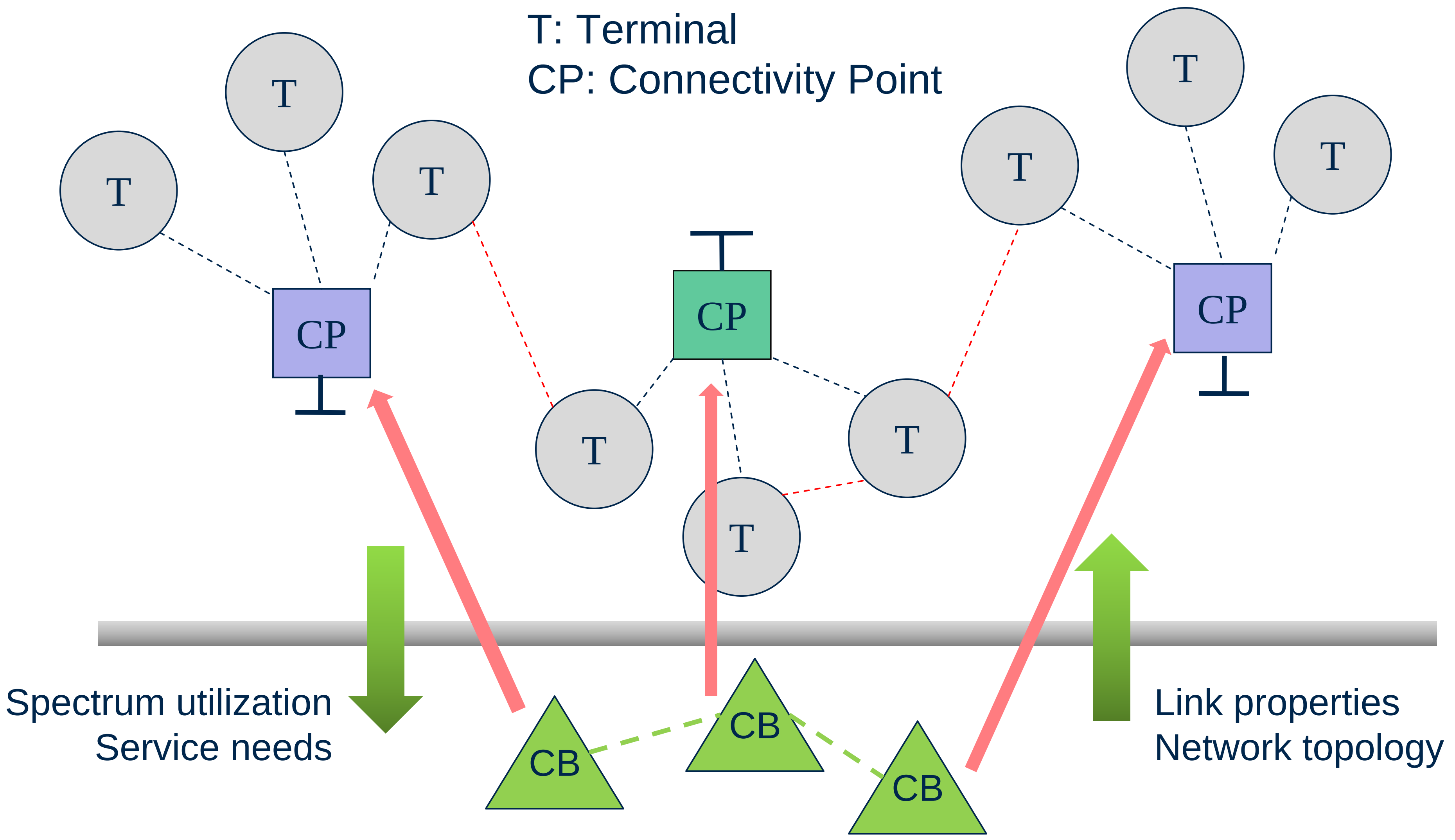
- (Most) terminals are flexible
- Terminals collaborate to optimize spectrum utilization under services requirements

Connectivity Brokerage



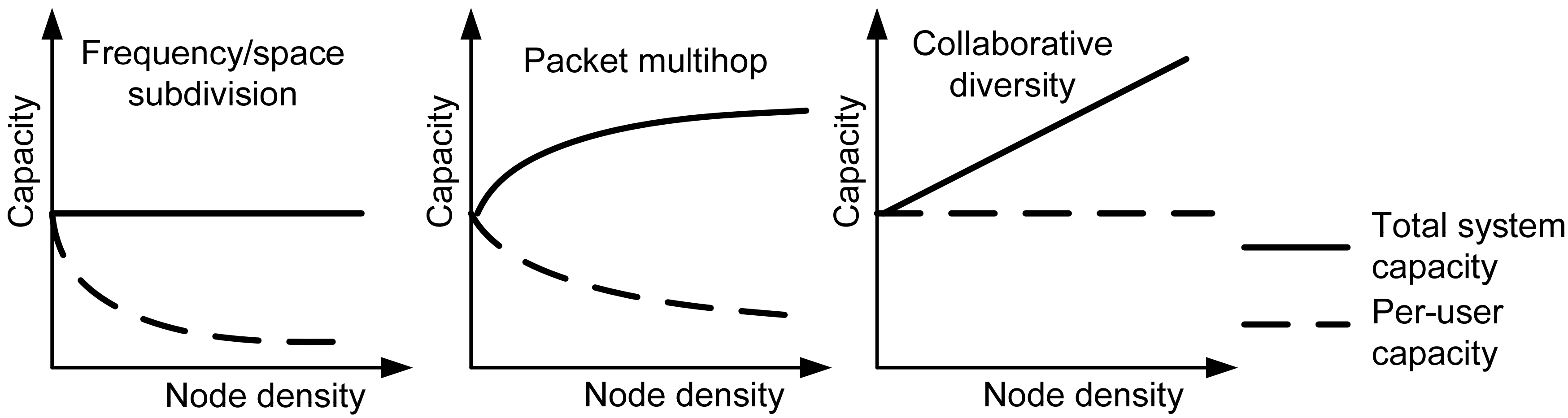
CB term coined by Adam Wolisz, TU Berlin

Connectivity Brokers



Collaborative MIMO

- **System capacity improves linearly!**

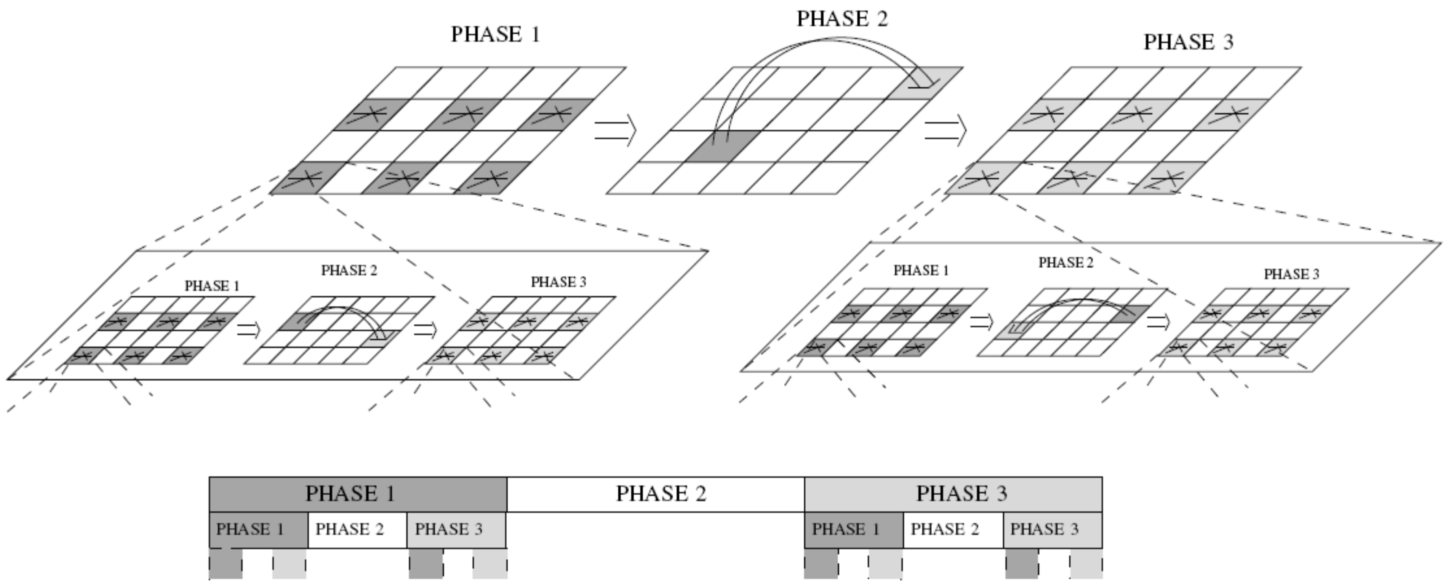


Conventional

Packet multi-hop
Gupta/Kumar'00

Hierarchical collaborative MIMO
Ozgur/Leveque/Tse'07

Collaborative Diversity



- **Scheme:**
  - Distribute symbols across the cluster
  - MIMO transmission from cluster to cluster
  - Distribute information back to nodes

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Conclusion

- **Radios are built on**
  - 100 years of spectrum sharing
  - 80 years of radio architectures
  - 60 years of information theory
  - 50 years of IC technology
- **It takes a lot to change this!**
- **The new spectrum sharing paradigm should be easier to modify in another 100 years**

Contributors

- **Majority of this work is done in Berkeley Wireless Research Center (BWRC)**
  - http://bwrc.eecs.berkeley.edu
- **And Wireless Foundations Center**
  - http://wifo.eecs.berkeley.edu
- **Many of the ideas in this talk hve been provided by Professors Brodersen, Cabric (UCLA), Niknejad, Gray, Rabaey, Tse, Wolisz (TUB)**