CHAPTER 2.
COGNITIVE RADIO

WHAT IS A COGNITIVE RADIO?

A "Cognitive Radio" is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. (Federal Com Commission'05)

FCC (Non-Federal Use of the Spectrum)

WHAT IS A COGNITIVE RADIO?

A radio or system that senses its operational EM environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability and access secondary markets..

NTIA (National Telecom and Info Administration)'05

US Department of Commerce: (NTIA) (FEDERAL USE OF THE SPECTRUM)

SPECTRUM REGULATION

EXAMPLE:

SPECTRUM FROM 322-3,100 MHz:

NTIA regulates 22%

FCC regulates 35%

Shared NTIA/FCC regulates 42%

WHAT IS A COGNITIVE RADIO?

A radio or system that senses and is aware of its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly.

ITU (Wp8A working document)'05

WHAT IS A COGNITIVE RADIO?

A type of radio that can sense and autonomously reason about its environment and adapt accordingly.

This radio could employ knowledge representation, automated reasoning, and machine learning mechanisms in establishing conducting or terminating communication or networking functions with other radios.

CRs can be trained to dynamically and autonomously adjust its operating parameters.

IEEE 1900.1 Group

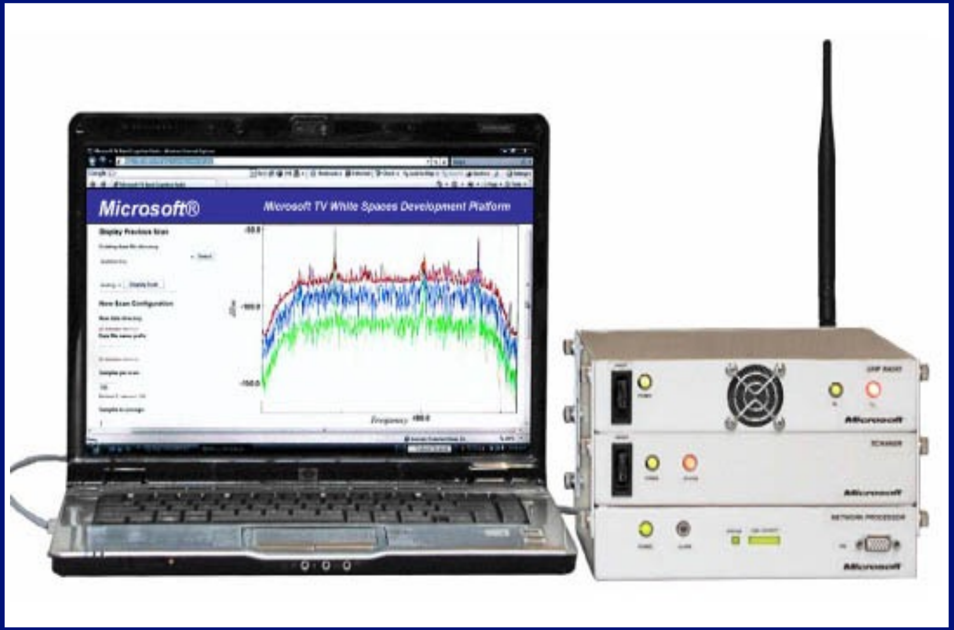
HOW ABOUT???

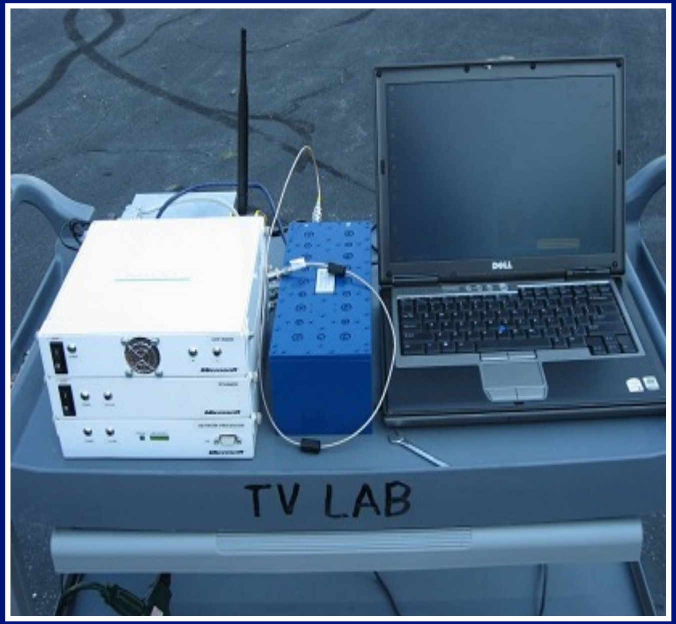
A RADIO THAT IS COGNITIVE !!!!

Microsoft, Google, Dell, HP

KNOWS: Kognitiv Networking Over White Spaces

http://research.microsoft.com/netres/projects/KNOWS/





- Prototypes designed to identify wireless microphone, NTSC and Digital TV signals
- Undergoing testing at FCC

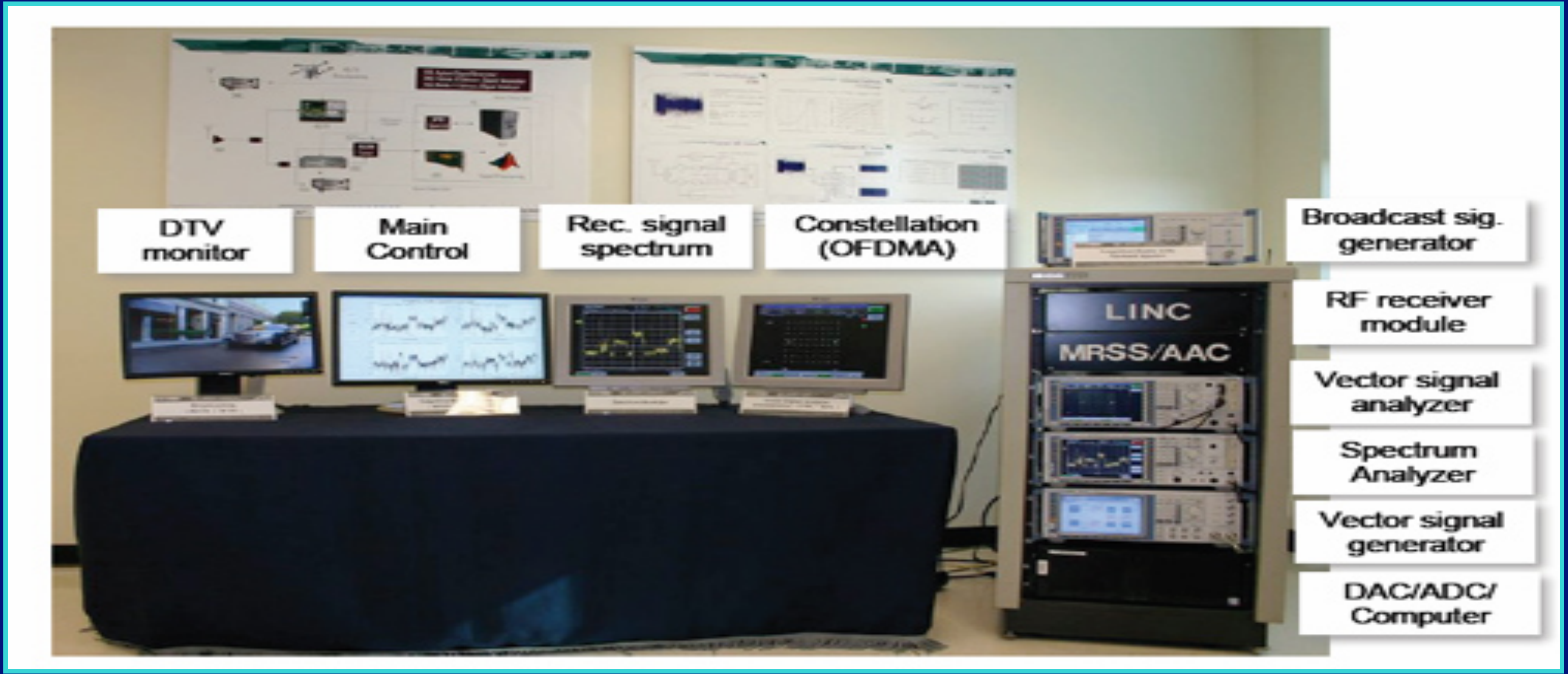
Adaptrum's Testbed

http://www.adaptrum.com/home

- Experiments undertaken in the region of 500 MHz - 700 MHz
- Undergoing testing at FCC

Georgia Tech: OCRA Testbed

http://www.ece.gatech.edu/research/labs/mag/cognitive_radio.htm



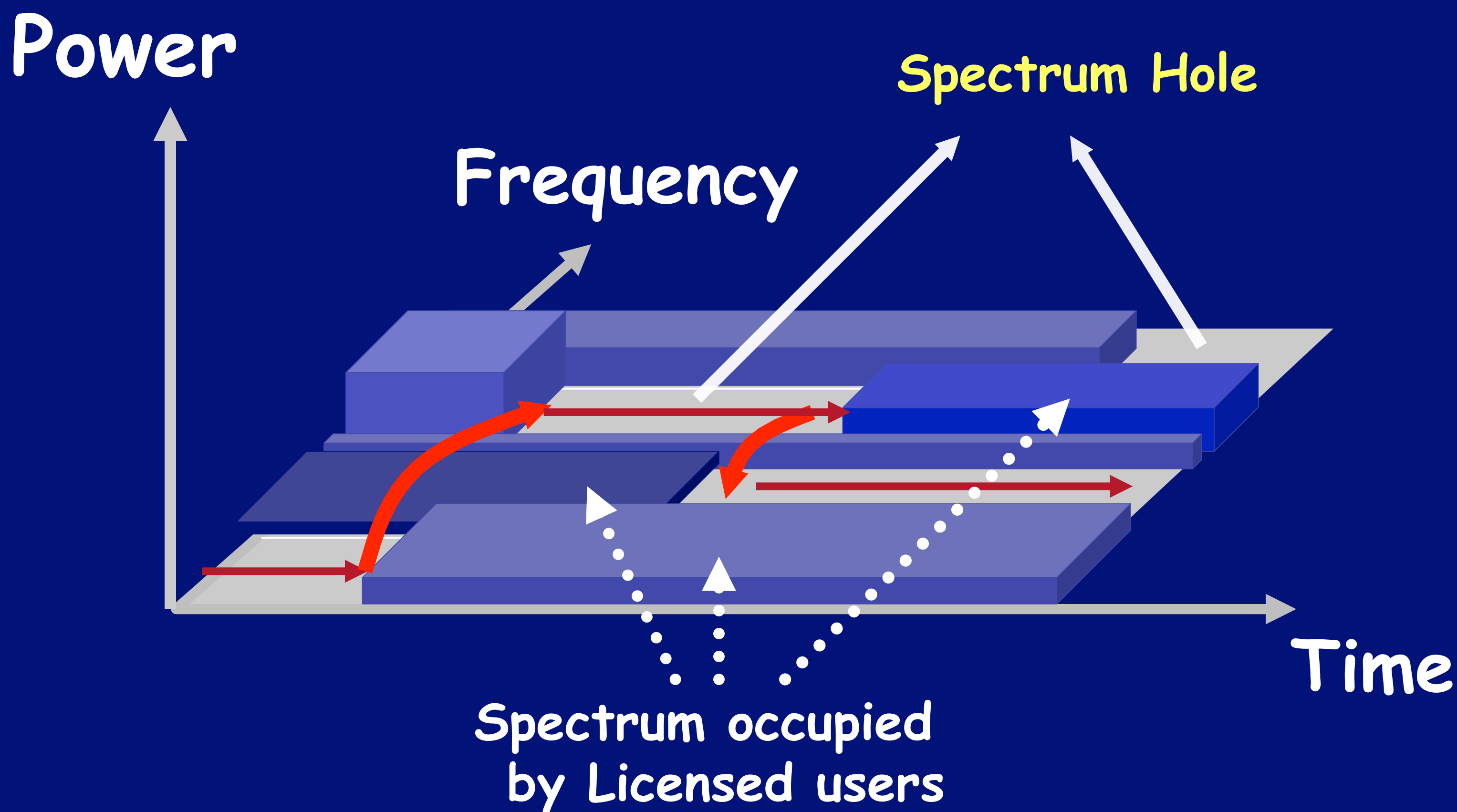
ADVANTAGES OF COGNITIVE RADIO

- Senses RF Environment and modifies frequency, power or modulation
- Allows for Real Time Spectrum Management
- Significantly Increases Spectrum Efficiency

Possible CR Functionalities

- Dynamic Frequency Selection (DFS)
- Adaptive Modulation
- Adaptive Transmit Power Control
- Adjust transmit parameters based on location spectrum sharing between a licensee and a third party
- Other functionalities are being developed as technology progresses

Spectrum Hole Concept



Ultimate Objective of Cognitive Radio

- CR enables the usage of temporally unused spectrum
  → *Spectrum Hole* or *White Space*.

- If this band is further used by a licensed user, CR moves to another spectrum hole or stays in the same band

- Alters its transmission power level or modulation scheme to avoid interference.

MAIN CHARACTERISTICS OF CR

A. Cognitive Capability

B. Reconfigurability (SDR)

Cognitive Capability

SPECTRUM AWARENESS!!

- Capture or sense the information
  (e.g., licensed user's activity) from radio environment

- Capture the temporal and spatial variations in radio environment

- Avoid interference to other users

- Identification of unused spectrum portions at a specific time or location

- Selection of best spectrum and appropriate operating parameters

Reconfigurability
(SDR Functionality)

SDR is a reconfigurable wireless system in which tx parameters (operating frequency band, modulation mode, and protocol) can be controlled dynamically.

The adjustability function is achieved by SW controlled signal processing algorithms

SDR is the key component to implement CRs

Main Functions of Software Defined Radios

Multiband Operation:
Tx over different spectrums
e.g., cellular bands, ISM Band, TV band.

Multistandard Support:
e.g., GSM, WCDMA, cdma2000, WiMAX, WiFi, LTE, LTE-A

Main Functions of Software Defined Radios

Different Air Interfaces within the same Standard:
e.g., IEEE 802.11a, 802.11b, 802.11g, or IEEE802.11n

Multiservice Support (e.g., within WiFi standard)
e.g., cellular systems, Broadband Wireless Internet access

Multichannel Support
(tx and rx on multiple freq. bands simultaneously

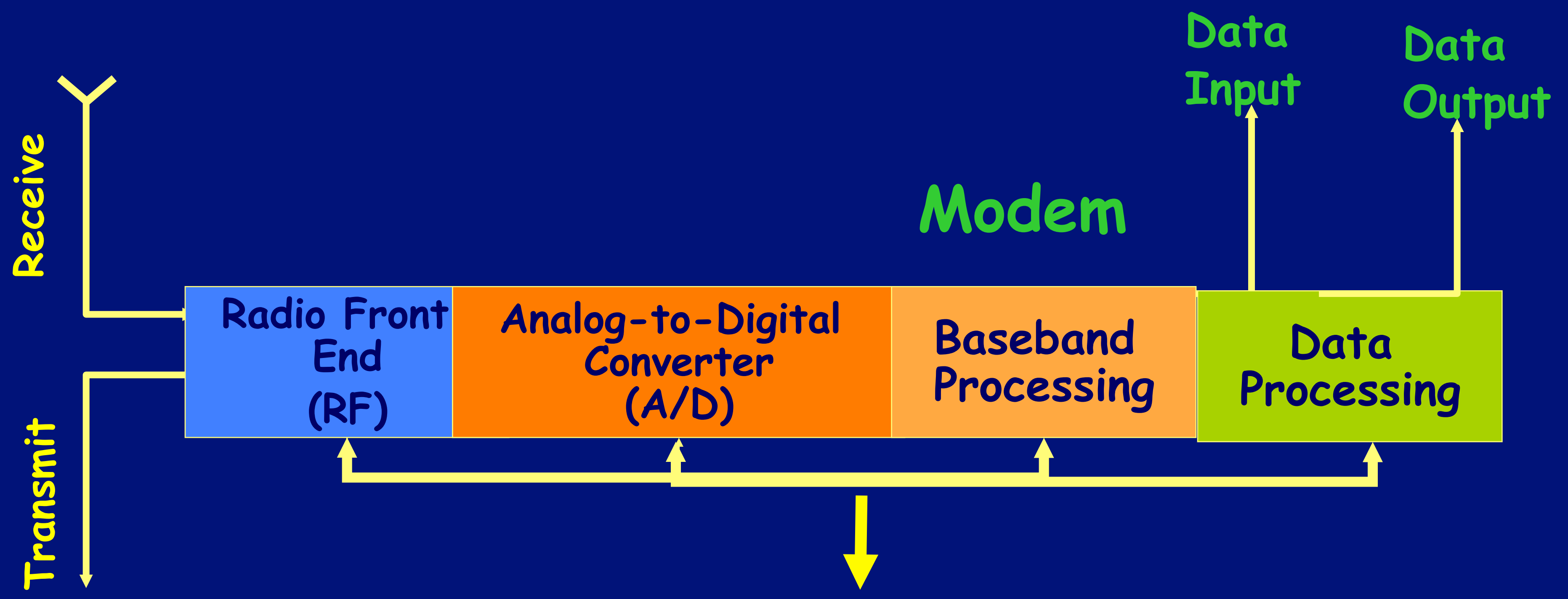
SUMMARY

SDR enables

* to be dynamically programmed to transmit and receive on a variety of frequencies according to the radio environment and

* to use different transmission access technologies supported by its hardware design

Physical Architecture of the Cognitive Radio (Cognitive Radio Transceiver)



Control Signal (Parametrization)
(SDR)
(Reconfiguration)

Cognitive Radio

Most components (data processing, AD converter, baseband processing) are similar to classical transceivers

Difference:

Each component can be controlled from the protocols in the upper layers or can be reconfigured.

Physical Architecture of the Cognitive Radio

* Each component can be reconfigured via a control bus to adapt to the time-varying RF environment.

* Radio front-end receives analog signals from the antenna

* This analog signal is filtered by a bandpass filter to obtain the signal in the desired frequency

Physical Architecture of the Cognitive Radio

* This signal is amplified and processed to generate an in-phase (I) path and a quadrature (Q) path by shifting the phase by {-pi/2}

* Both I and Q path signals are then converted to digital data.

* Sampling rate of A/D must be chosen to satisfy the conditions of Nyquist's sampling theorem.

NOTE:
Sampling rate and parameters of analog and digital filters as well as signal processing algorithms can be reconfigured to the operating frequency band and the wireless air interface technology

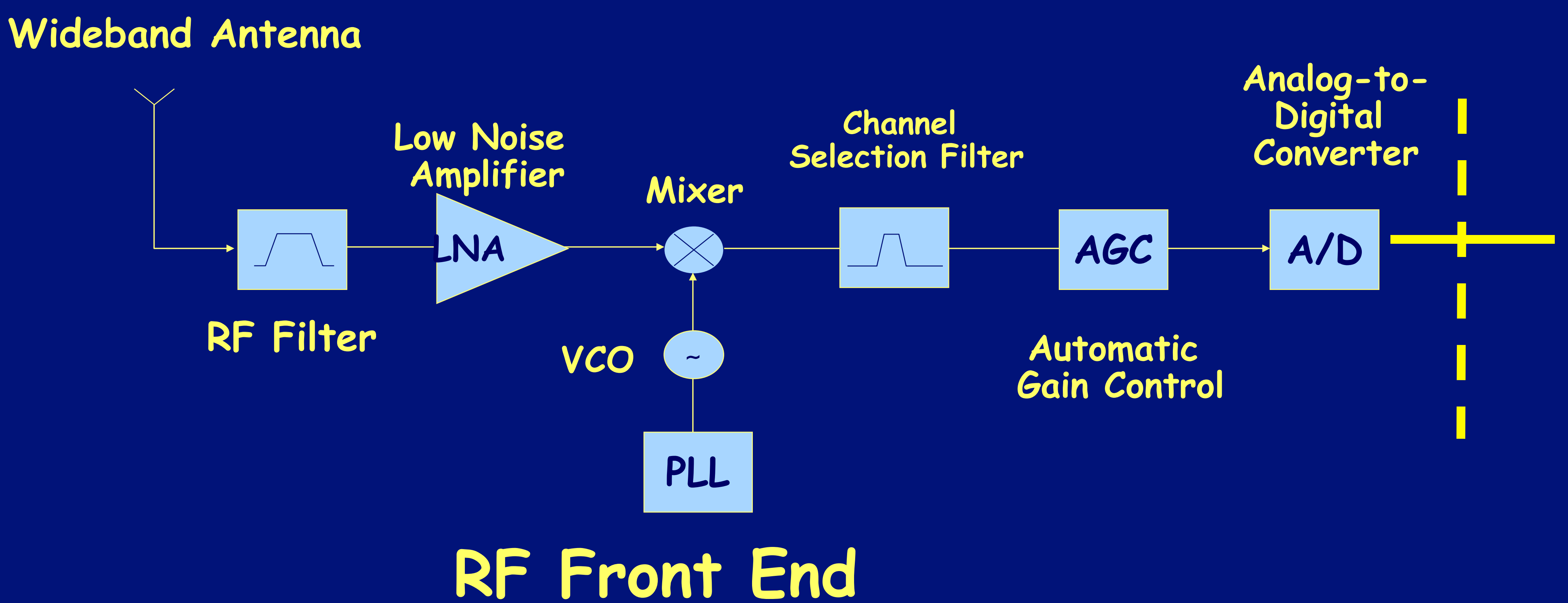
Physical Architecture of the Cognitive Radio

- A "Wideband Sensing Capability" of the RF front-end.

  → mainly related to RF hardware technologies such as wideband antenna, power amplifier, and adaptive filter.

- RF hardware for CR should be capable of tuning to any part of a large range of the frequency spectrum.

Physical Architecture of the Cognitive Radio (Wideband RF/Analog Front-End Architecture)

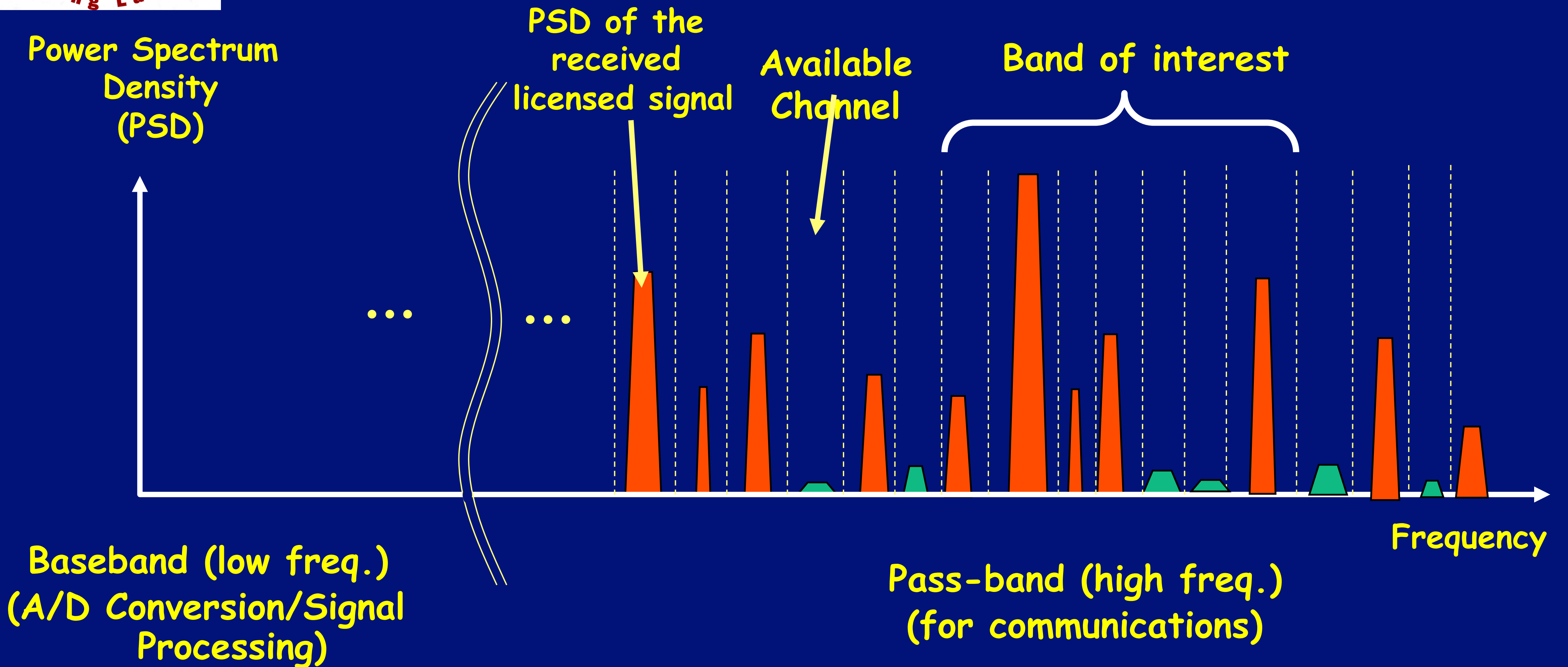


Some Basics

PASSBAND:

Allocated spectrum for each system,
e.g., WiFi → 2.4 GHz; 3G → 2GHz;
2G → 900 & 1800 MHz, etc..

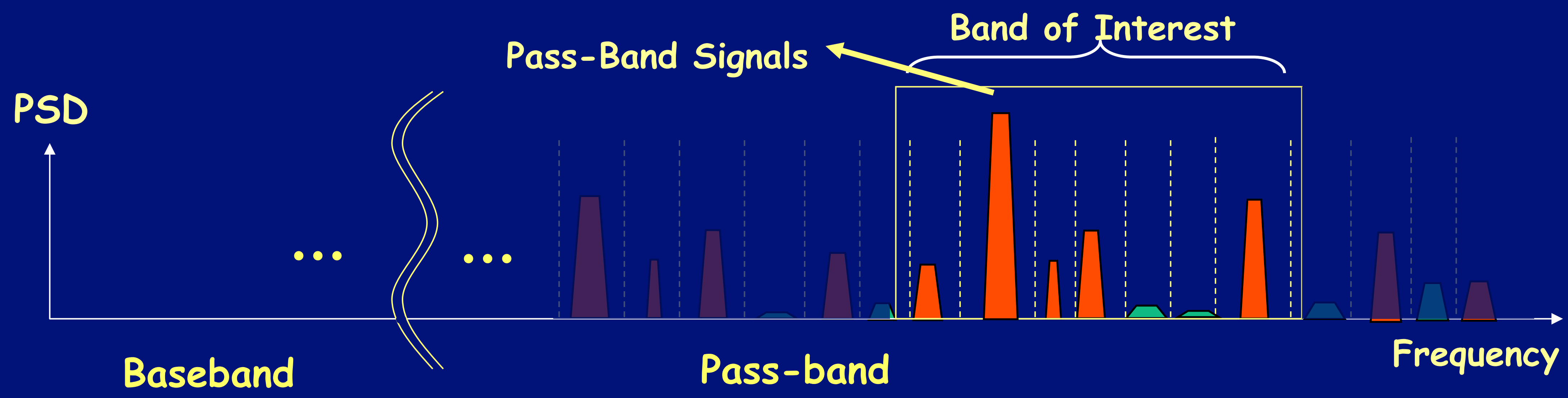
Physical Architecture of the Cognitive Radio (Wideband RF/Analog Front-End Architecture)



Components of a Cognitive Radio RF Front-End

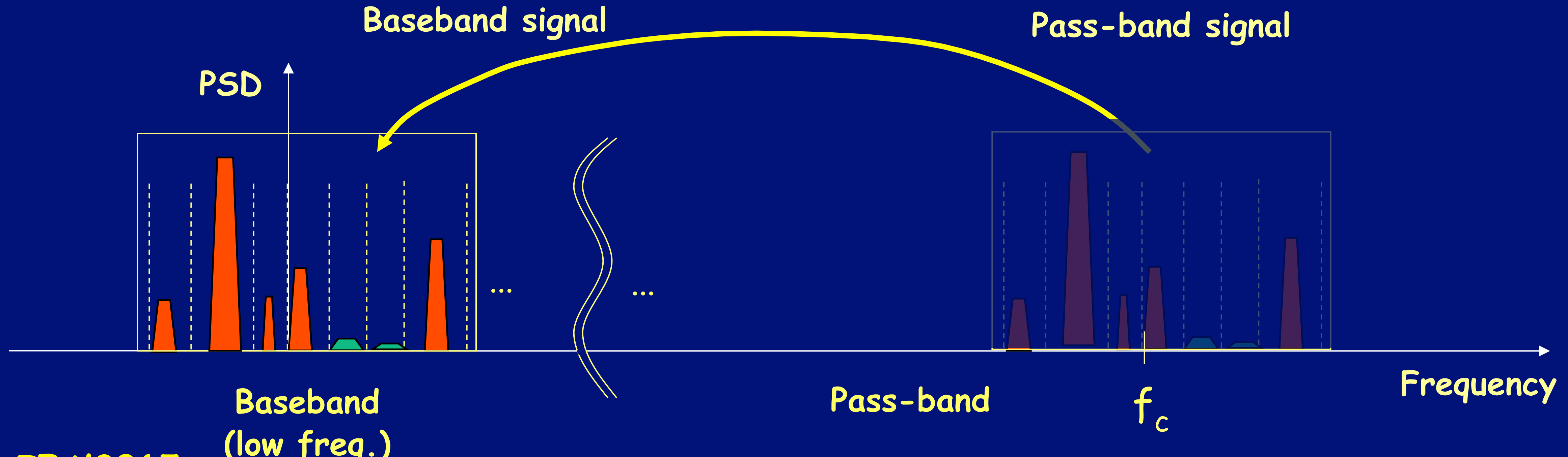
- **RF Filter:**
  selects the desired band by bandpass filtering the received RF signal.

- **Low Noise Amplifier (LNA):**
  amplifies the desired signal while simultaneously minimizing noise component.



Components of a Cognitive Radio RF Front-End

- **Baseband Conversion**
  - Objective: Process and A/D convert the signal easily
  - Needs Mixer, PLL, and VCO

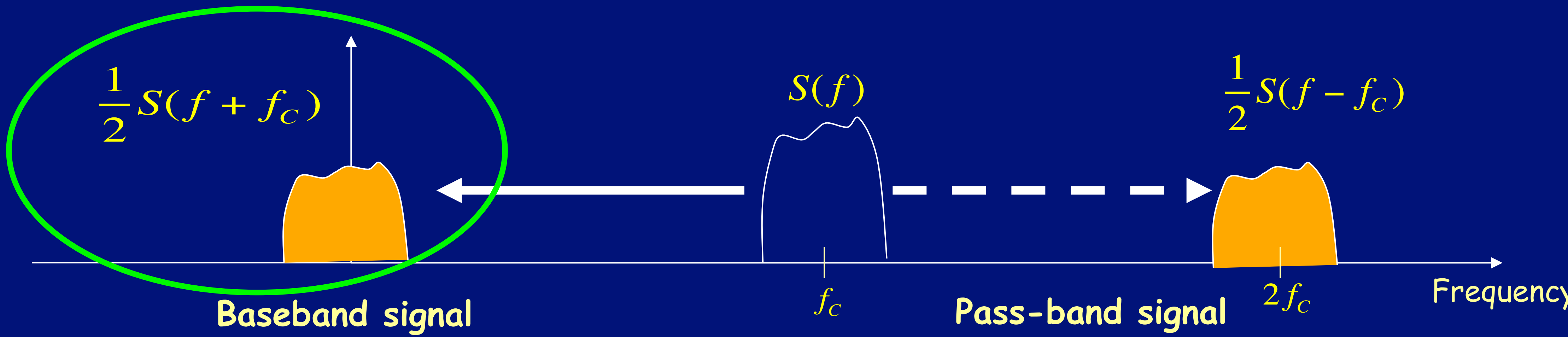


Preliminaries: Baseband Conversion

Time Domain		Frequency Domain
$s(t)$	→	$S(f)$
$s(t)*\cos(2\pi f_C t)$	Fourier Transform →	$\frac{1}{2}\{S(f+f_C)+S(f-f_C)\}$

Passband signal

- Need to generate this signal for the baseband conversion



Components of a Cognitive Radio RF Front-End

- **Mixer**
  - Pass-band signal is mixed (multiplied with s(t)) with a locally generated signal (with frequency f_c) and converted to the baseband

Components of a Cognitive Radio RF Front-End

- **Voltage-Controlled Oscillator (VCO)**
  - Generates a signal at a specific frequency f_c to mix with the pass-band signal. (generates the cosine function)
  - This procedure converts the passband signal to the baseband signal.

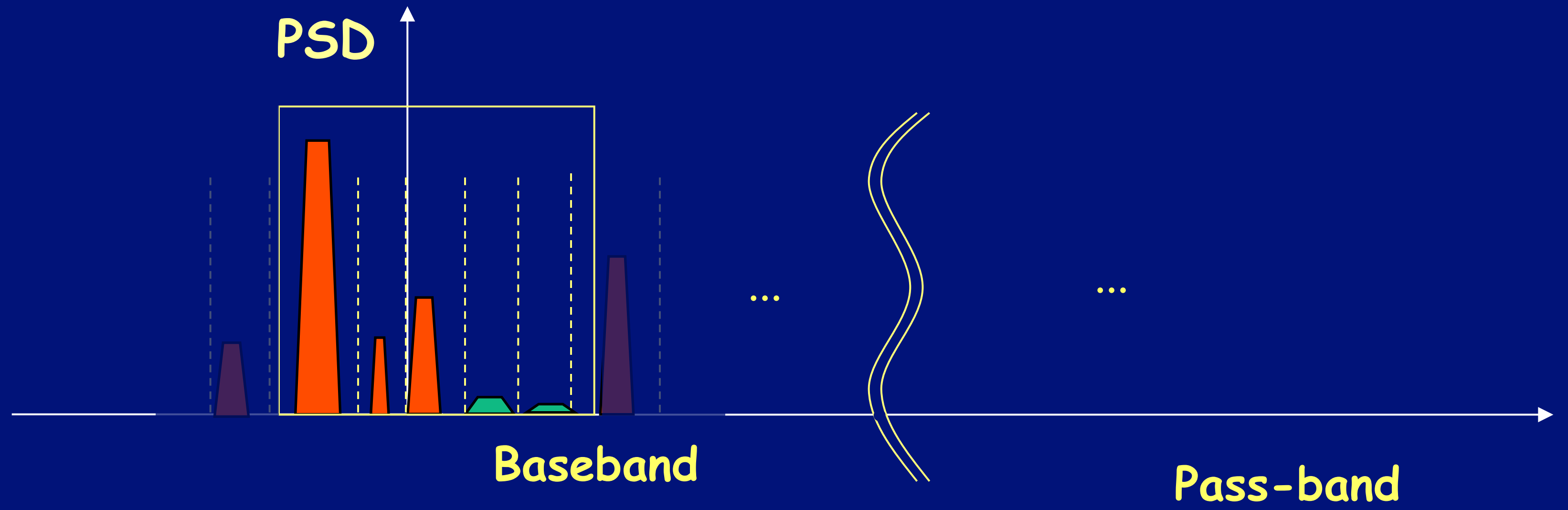
Components of a Cognitive Radio RF Front-End

- Phase Locked Loop (PLL)
  - Ensures that a signal is locked on a specific frequency f_c and can also be used to generate precise frequencies with fine resolution.

Components of a Cognitive Radio RF Front-End

- **Channel Selection Filter:**

  Used to select the desired channels and to reject the adjacent channels.



Components of a Cognitive Radio RF Front-End

- **Automatic Gain Control (AGC):**

  Average output signal level is fed back to adjust the gain to an appropriate level for a range of input signal levels.
  (i.e., maintain the constant gain)

Cognitive Radio RF Front-End Architecture

DATA PROCESSING

→ See SPECTRUM MANAGEMENT FRAMEWORK!!!

Challenges for Development of CR RF Front-End

- Wideband RF antenna receives signals from various transmitters operating at different power levels, bandwidths, and locations.

  → the RF front-end must be able to detect a weak signal in a large dynamic range.

  → Requires a multi GHz speed A/D converter with high resolution → infeasible!!

Possible Solution

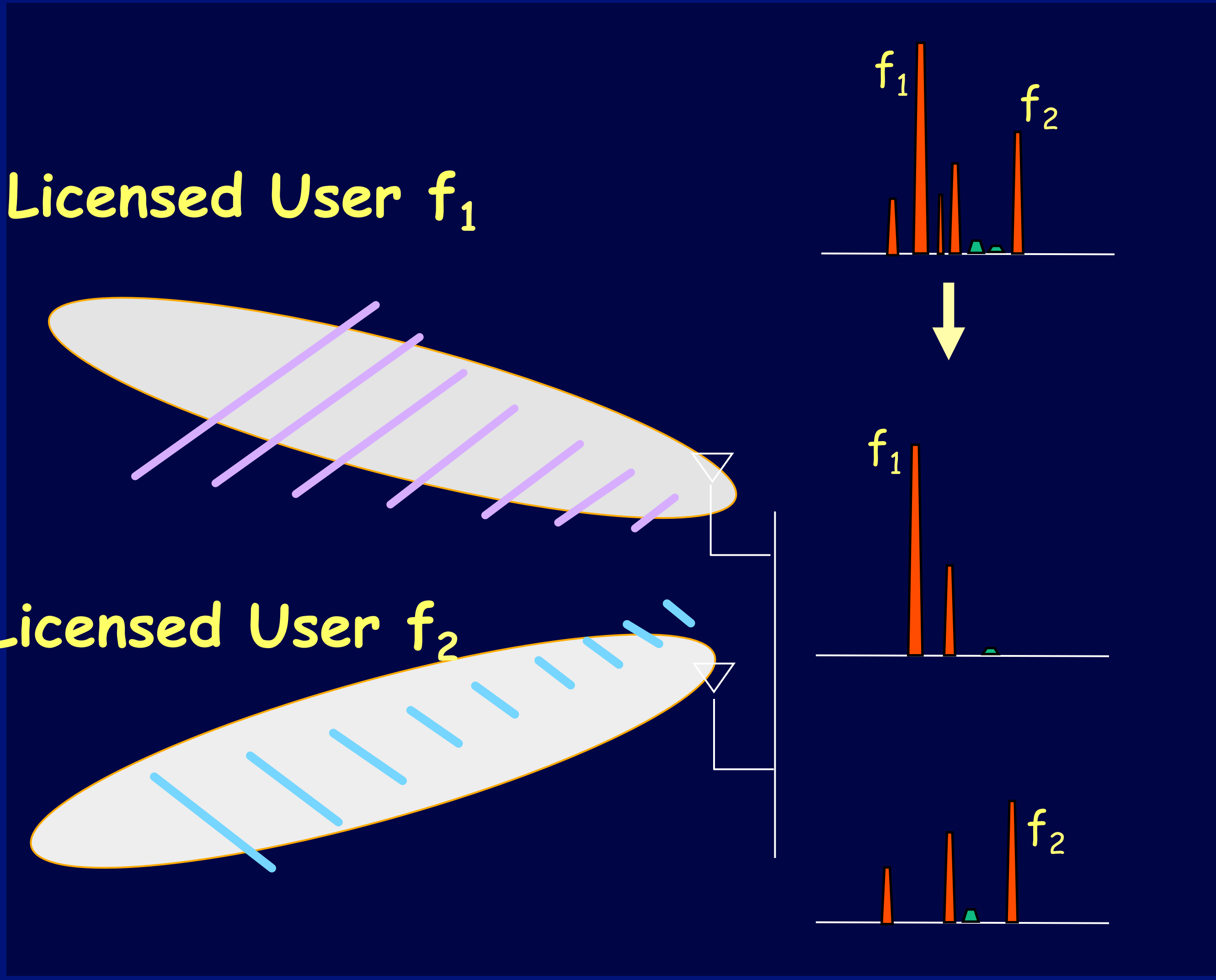
This necessitates the dynamic range of the signal to be reduced before A/D conversion

→ can be achieved by tunable notch filtering of strong signals

Alternative Approach: Directional Antennas

* Use multiple antennas such that signal filtering is performed in the spatial domain rather than in the frequency domain.

- Multiple antennas can receive signals selectively using beam-forming techniques.

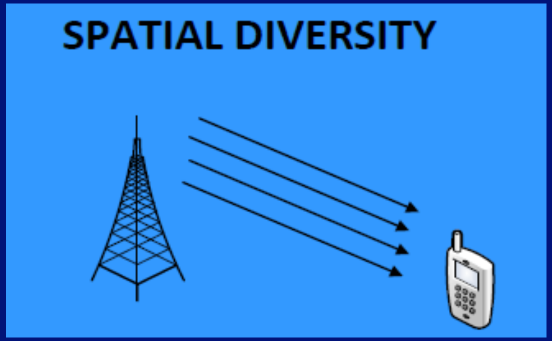


MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) TECHNIQUES

- Higher capacity
- Higher spectral efficiency
- Larger number of users (high throughput)
- Improved coverage
- Tx range without increasing BW demands or tx power

MIMO TECHNIQUES
Basic Modes of Operation

- Single User MIMO (SU-MIMO)



Several Replicas of Same Data Stream

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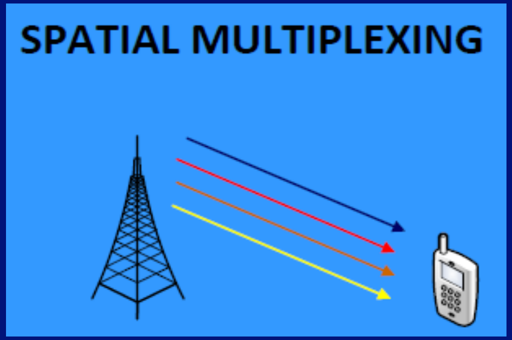
Improved Reliability



Several Data Streams

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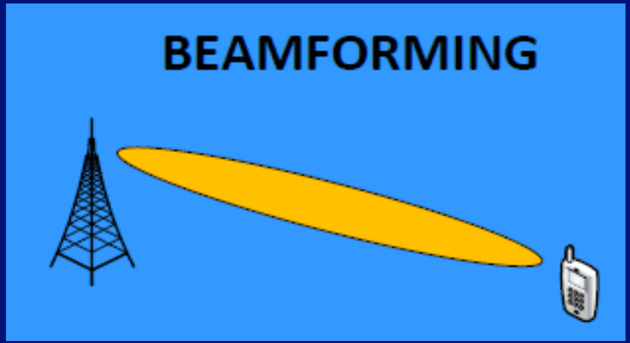
Increased Data Rates



Directional Beam Pattern

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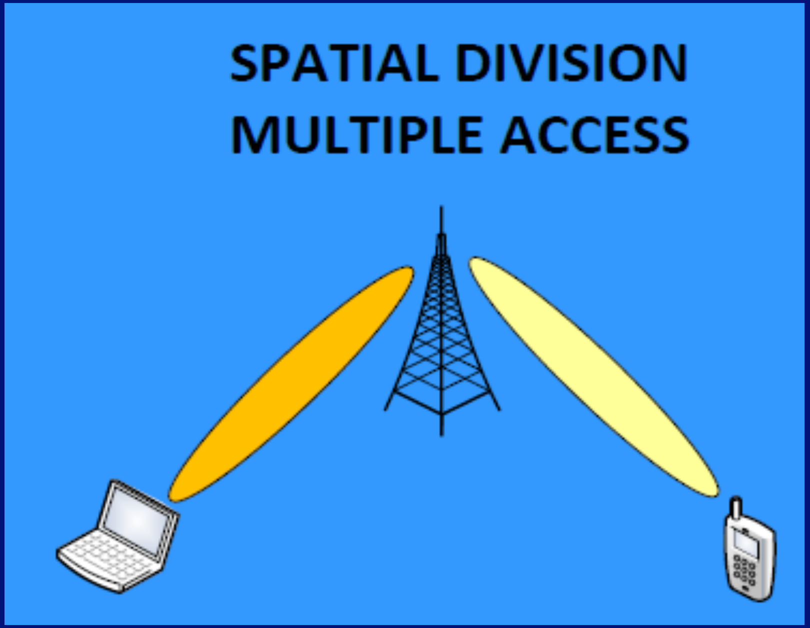
Extended Coverage

MIMO TECHNIQUES
Basic Modes of Operation

- Multiple User MIMO (MU-MIMO)



Multiple users served on the same frequency-time resource

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Increased number of supported users

MIMO for LTE-A
Major Improvements over LTE

- Novel Features:
  - Antenna Configuration
    - 8x8 in DL; 4x4 in UL
  - Dynamic SU/MU-MIMO Switching
    - Fast timescale adaptation transparent to higher layers
  - Advanced beamforming and scheduling techniques
    - Proprietary and implementation-specific
  - Implications on reference signals, feedback design, precoding codebooks, MIMO detector, etc.
    - Very active research is being carried out

MIMO LIMITATIONS

- Improvements by a factor proportional to # antennas at Tx & Rx
- No problem on the BS side but
  handheld devices very limited in size (and also power consumption)
- Placing several antennas in the device with the appropriate antenna spacing may not be feasible.

MIMO FOR LTE-A

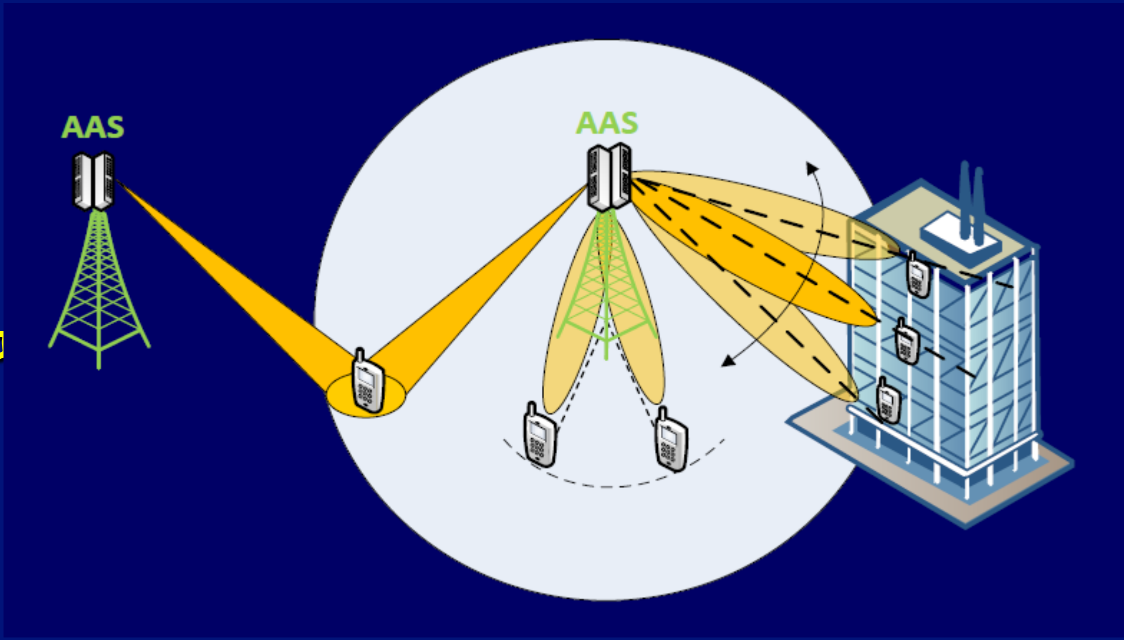
Research Challenges: Massive MIMO

- Potential benefits:
  - Serve large of users
  - Improve cell-edge performance
  - Reduce consumed power and interference
- Challenges:
  - PILOT CONTAMINATION:

    Main performance-limiting factor causing multi-cell channel estimation impairments due to non-orthogonal pilots
  - Detector Complexity
  - Mobility management for very narrow beamforming

MIMO FOR LTE-A
FULL-DIMENSION MIMO

- Main new MIMO technology for (Rel-12)
  - Enables 3D Beamforming (BF)
- Vertical Beamforming based on Active Antenna Systems (AAS)
  - Integration of active and passive components
  - Enables full utilization of spatial domain (Azimuth & elevation)
- New techniques can be enabled
  - Sector-specific/user-specific elevation BF



FD-MIMO allows vertical beam adaptation and well-focused cooperation

MIMO FOR LTE-A

Research Challenges: 3D Channel Modeling (for REL-12)

- Traditional channel model assume paths concentrated in two dimensions
  - Not valid for 2D antenna arrays (needed for physical space limitations)
- Azimuth and elevation directions need to be taken into account in the signa propagation path
  - Need to include 2D multipath fading and large-scale fading correlation with elevation statistics

- **Feedback Enhancements, Reference Signals, Codebook Design**
  - Further optimizations in all three elements
  - Adaptation for future support of FD-MIMO