LONG ISLAND RF/MICROWAVE SYMPOSIUM & EXHIBITS
TRENDS IN MICROWAVES – 2019

"Next Generation Networks: SDR, 5G and IoT, Emerging Trends"

This talk is supported by IEEE Region 1 AP-S & MTT-S

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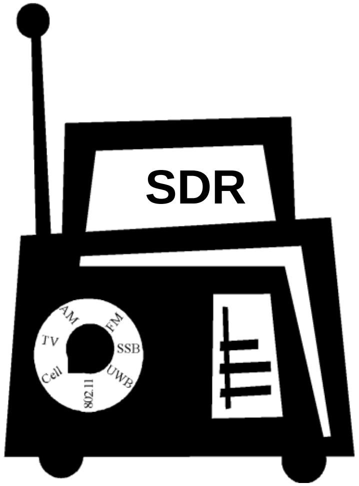
Outline

- SDR (Software Defined Radio) & IoT
- Analog Frond End: Pros & Cons
- High Dynmaic Range Microwave Monitoring Receivers
- Image Rejection Mixer: Eliminate triple conversion
- Important Characteristics of A/D converters
- Important Characteristics of Down Converters
- Characteristics of AGC
- Carrier recovery of Data Communication
- Spectrum Analysis of Communication Receiver
- 5G
- Radio Monitoring Receiver
- Modern Radios-Futuristic Trends & Conclusions

Radio Communication Standard

Problem !

- Myriad of standards exist for terrestrial communications
- Cell phone communication standards change every few years
- Satellite ground station would like to listen to multiple spacecraft, some launched in the 1970s
- Spectrum space is a precious resource
  - Each frequency is “owned”
  - How do we deal with new technologies like ultra wide band (UWB)?



Solution: SDR (Software Defined Radio)

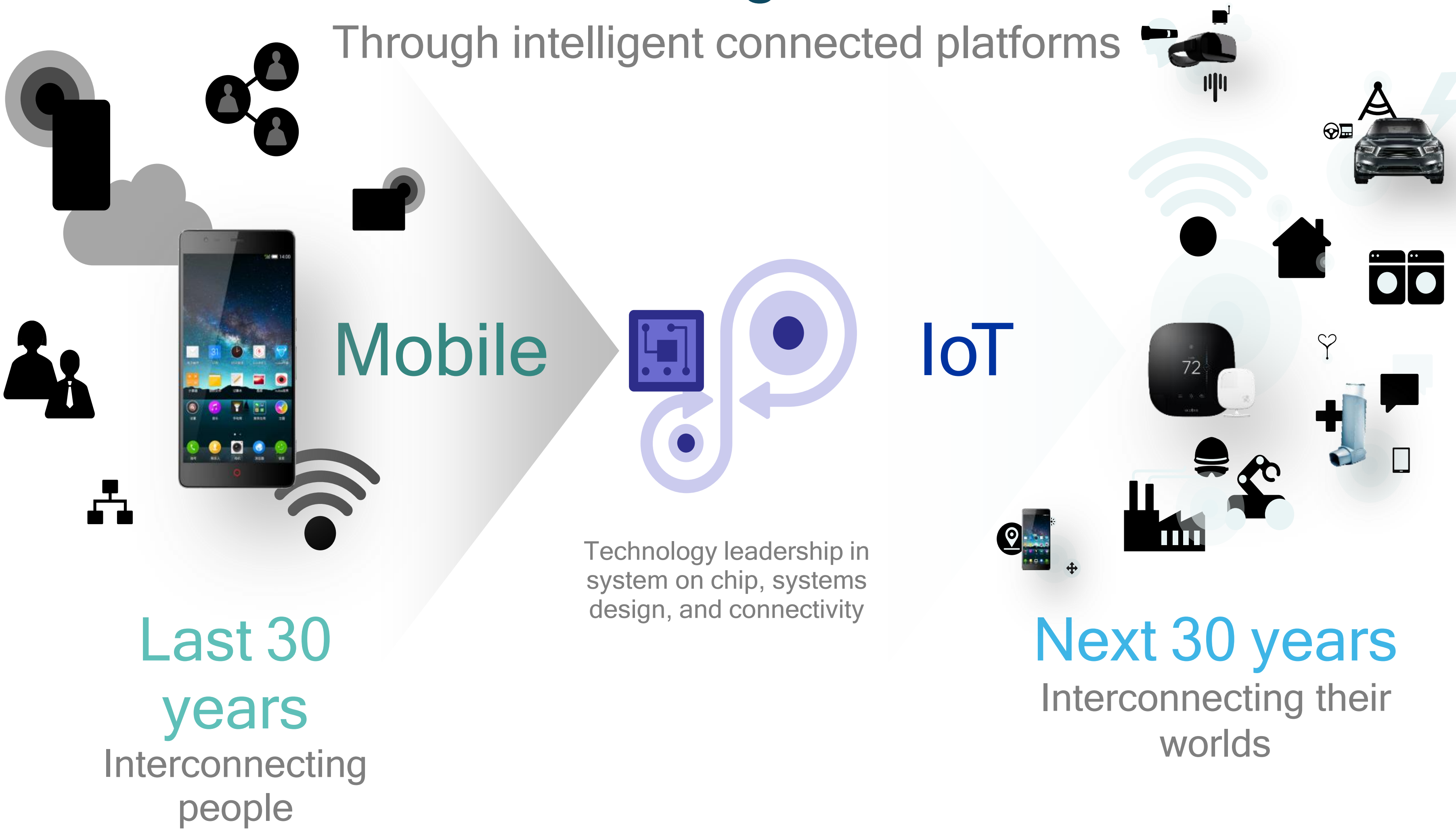
- Flexible radio systems that allow communication standards to migrate
- Flexible methods for reconfiguring a radio in software
- Flexible, intelligent systems that communicate via different protocols at different times

Emerging Trend: Cognitive Radio Solution

SDR & IoT

Transforming our world

Through intelligent connected platforms



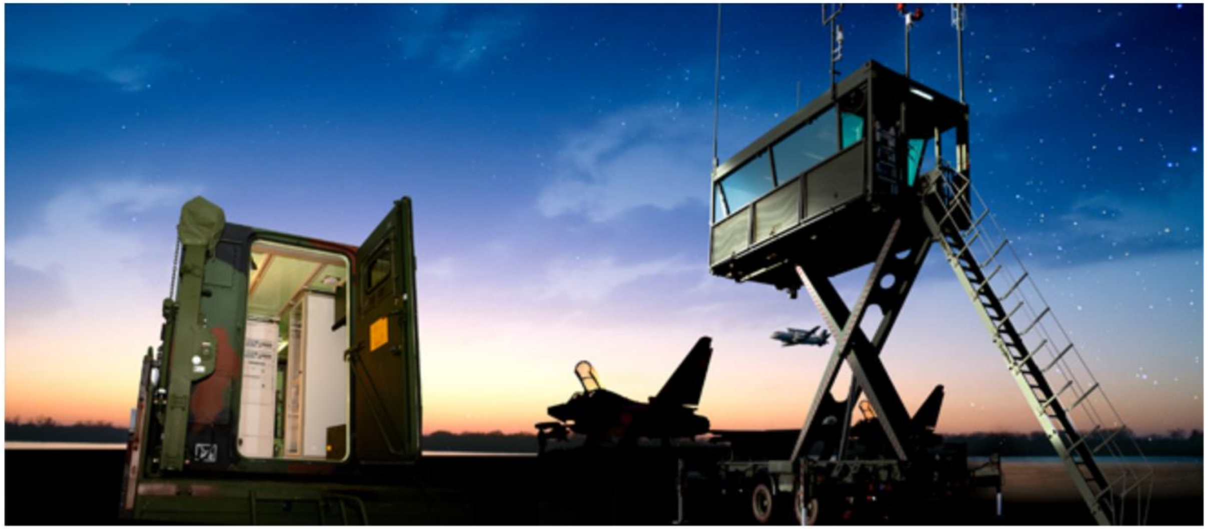
SDR & IoT fundamentally changed how people live, work and stay connected

Courtesy: Qualcomm Technologies

Rohde & Schwarz: Software Defined Radios

Software Defined Radio

Rohde & Schwarz software defined radios (SDR) provide reliable and secure communications.



The Rohde & Schwarz Radiocommunications Systems Division is one of the leading global suppliers of software defined radios (SDR) and systems for use in fixed and mobile ground stations, on board ships and in aircraft.

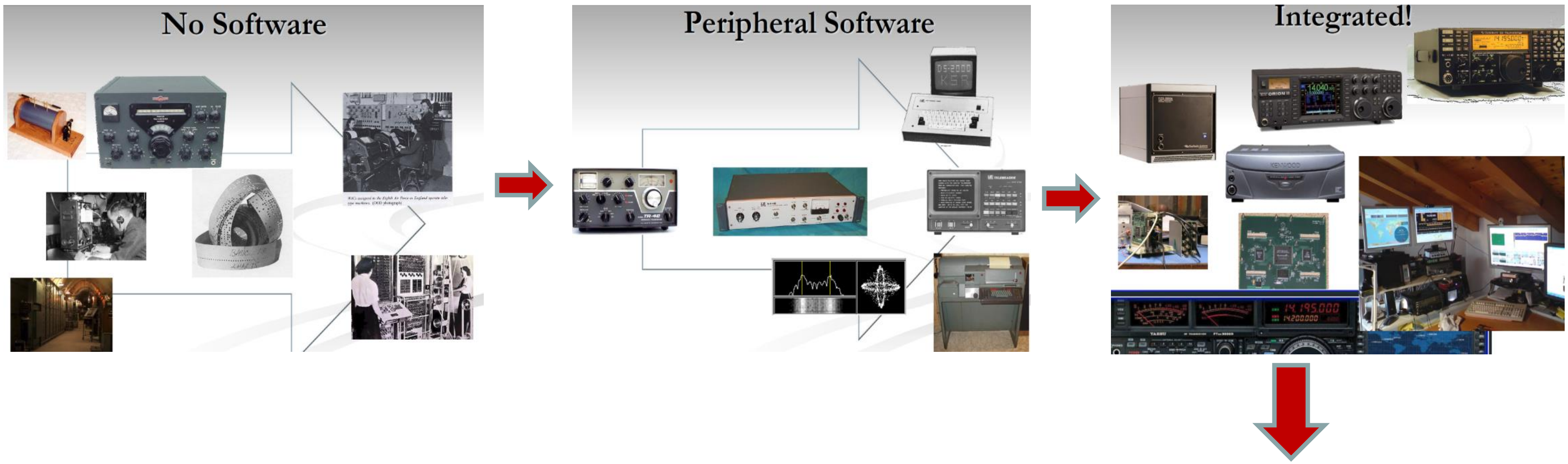
R&S®M3SR Series4100 Software Defined Radios

HF radio family for stationary and shipborne communications

Overview | Models | System Components | Options

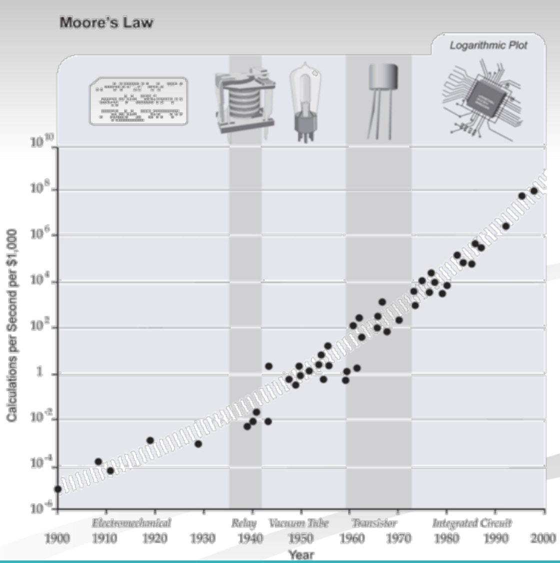
Courtesy: Qualcomm Technologie

Radio Follow Moore's Law

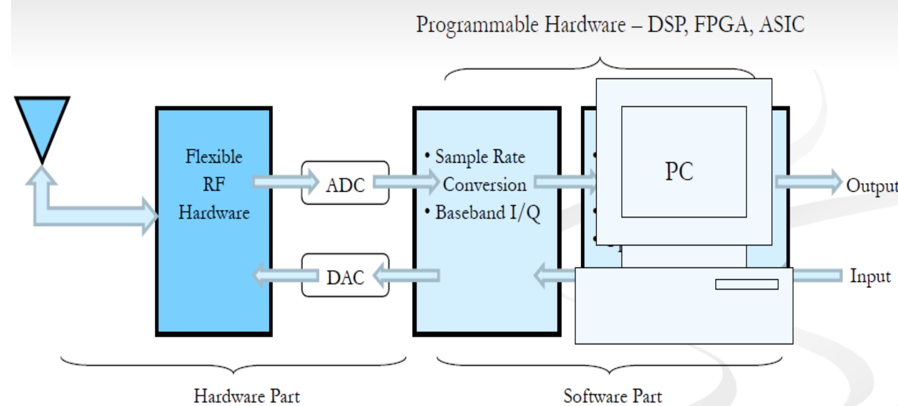


Radio Follows Moore' s Law Too

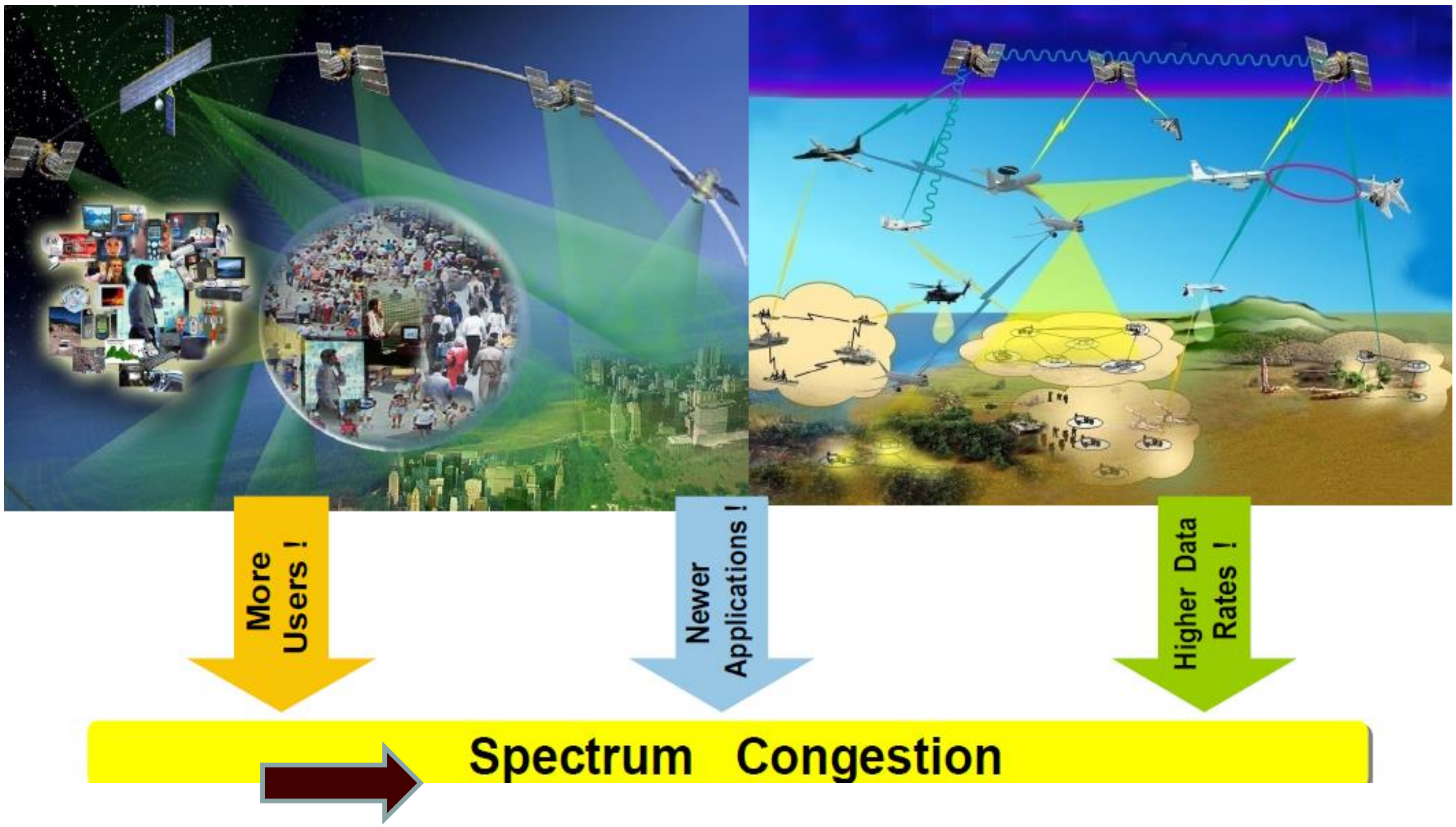
- First 50 Years
  - Electro Mechanical
  - Vacuum Tube
- Second 50
  - Transistor
  - IC
- Next… ?



SDR Architecture



Why SDR ?



High Performance Radio Needed Everywhere !

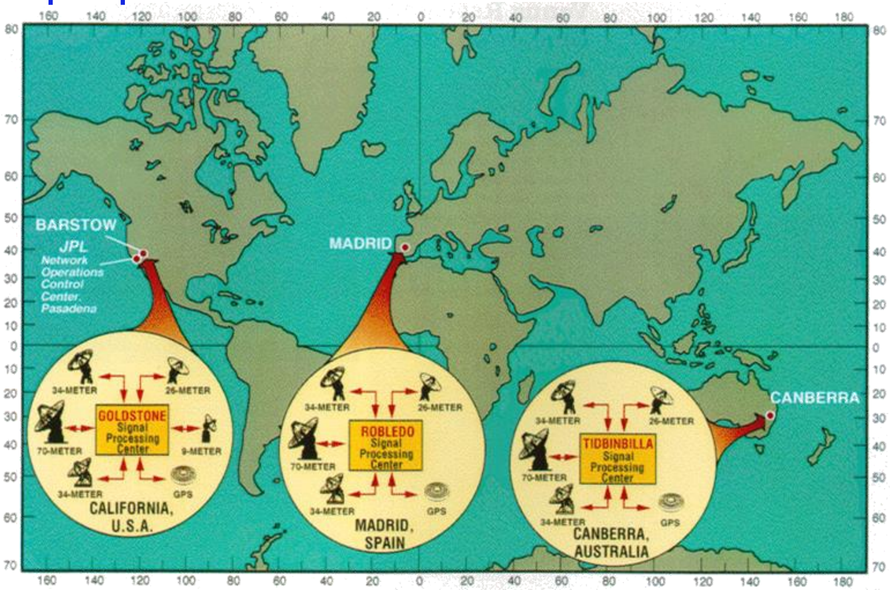
Why SDR ?

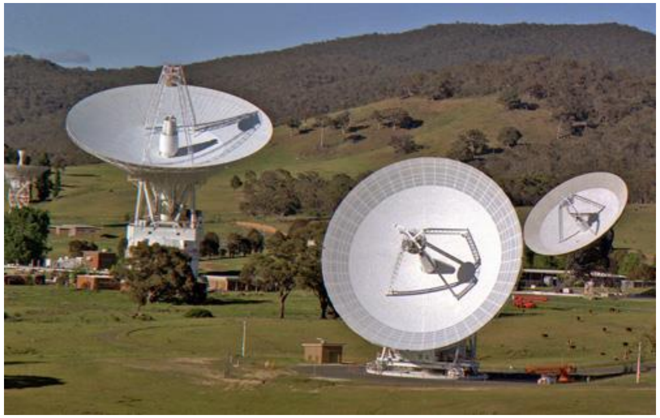
First-Responder Communications Failures

- SDR will facilitate radio interoperability

Why SDR?

Deep Space Communications

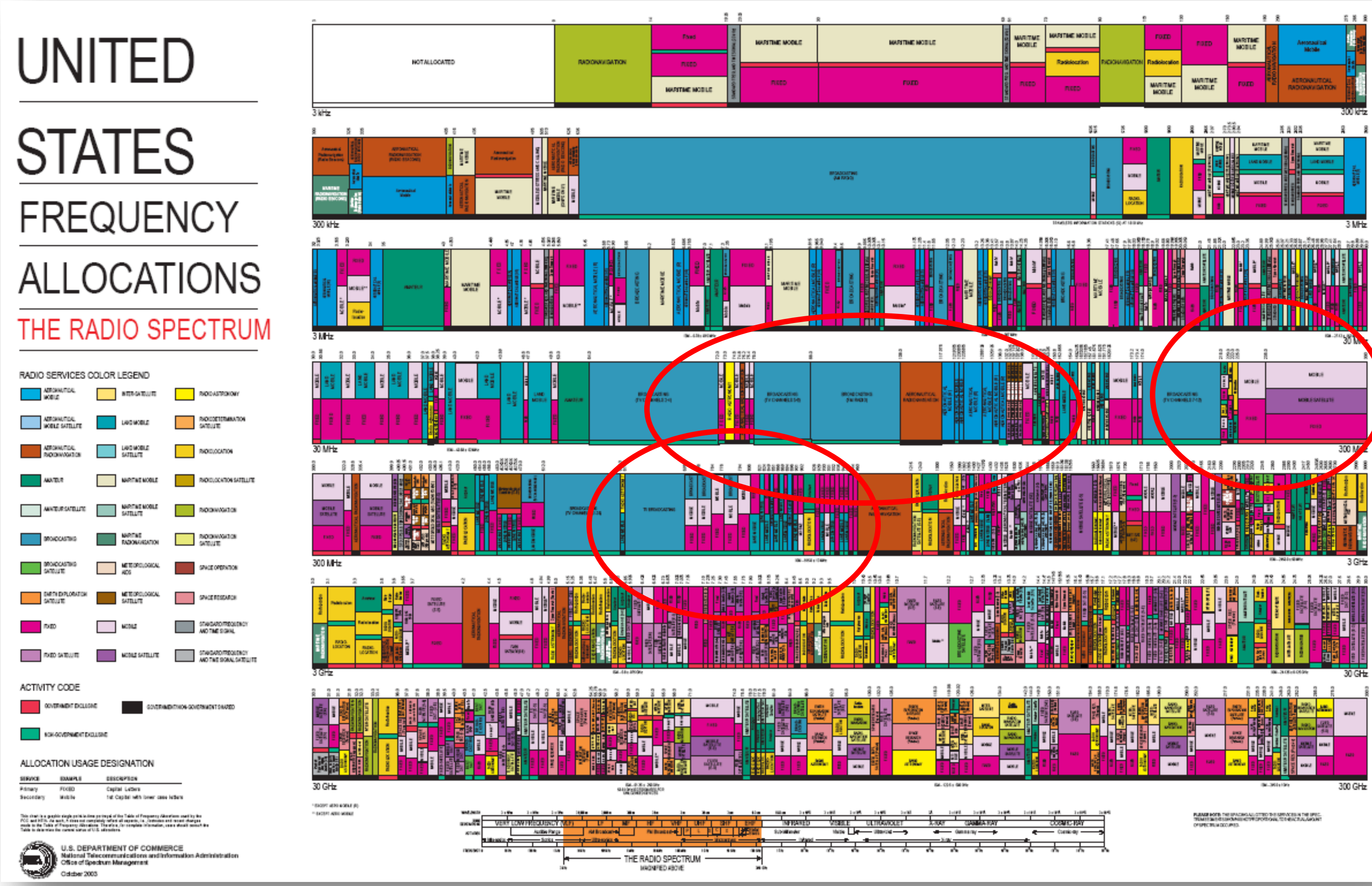




- SDR allows old and new protocols

Why SDR?

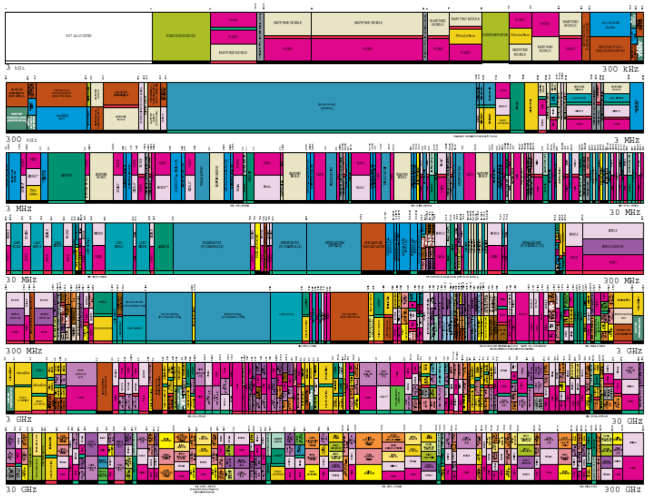
Spectrum space as a scarce resource



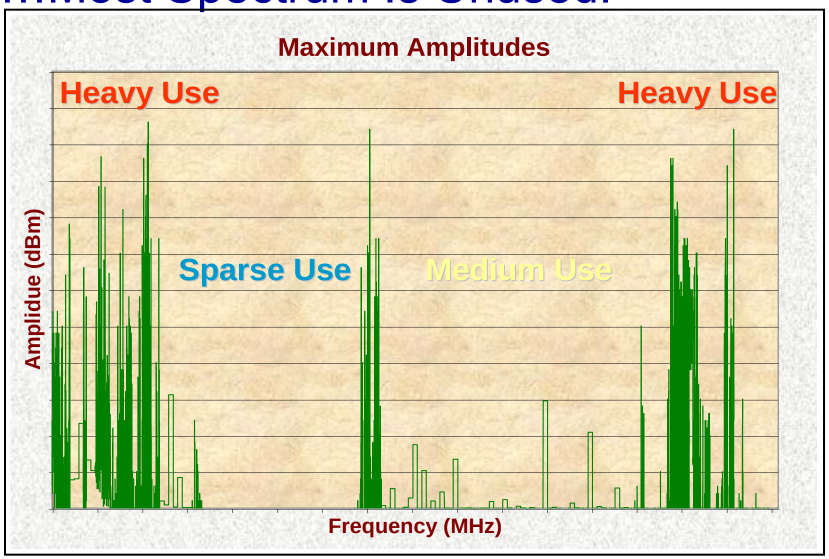
- SDR will enable spectrum reuse

SDR will Dynamically Access Available Spectrum

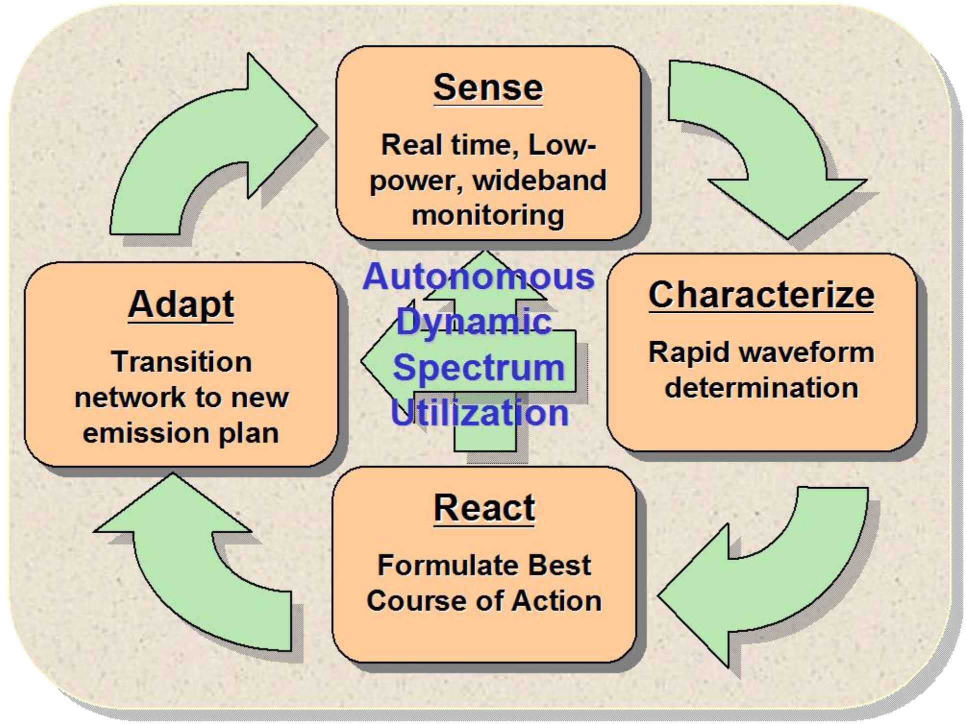
All Spectrum May Be Assigned, But…



…Most Spectrum Is Unused!



Next Generation Radios: Enable Technology and System Concepts for Dynamically Access Available Spectrum



Goal: 10 Folds increase in spectrum access

SDR (Software Defined Radio)

- Definition:

  A Software Defined Radio (SDR) is a communicaton system, where the major part of signal processing components, typically realized in hardware are instead replaced by digital algorithms, written in software (FPGA).

SDR

- Want to make all parameters digitally tunable
  - What Parameters?
    - **RX/TX Frequency**
    - **Bandwidth**
    - **Impedance Match**

- First Reported Publication (February 26-28, 1985):

  Ulrich L. Rohde, Digital HF Radio: "A Sampling of Techniques, presented at the Third International Conference on HF Communication Systems and Techniques", London, England, February 26-28, 1985, Classified Session (U.S Secret).

  http://en.wikipedia.org/wiki/Software-defined_radio

Benefits of Software Defined Radio

- Ease of design
  - Reduces design-cycle time, quicker iterations
- Ease of manufacture
  - Digital hardware reduces costs associated with manufacturing and testing radios
- Multimode operation
  - SR can change modes by loading appropriate software into memory
- Use of advanced signal processing techniques
  - Allows implementation of new receiver structures and signal processing techniques
- Fewer discrete components
  - Digital processors can implement functions such as synchronization, demodulation, error correction, decryption, etc.
- Flexibility to incorporate additional functionality
  - Can be modified in the field to correct problems and to upgrade

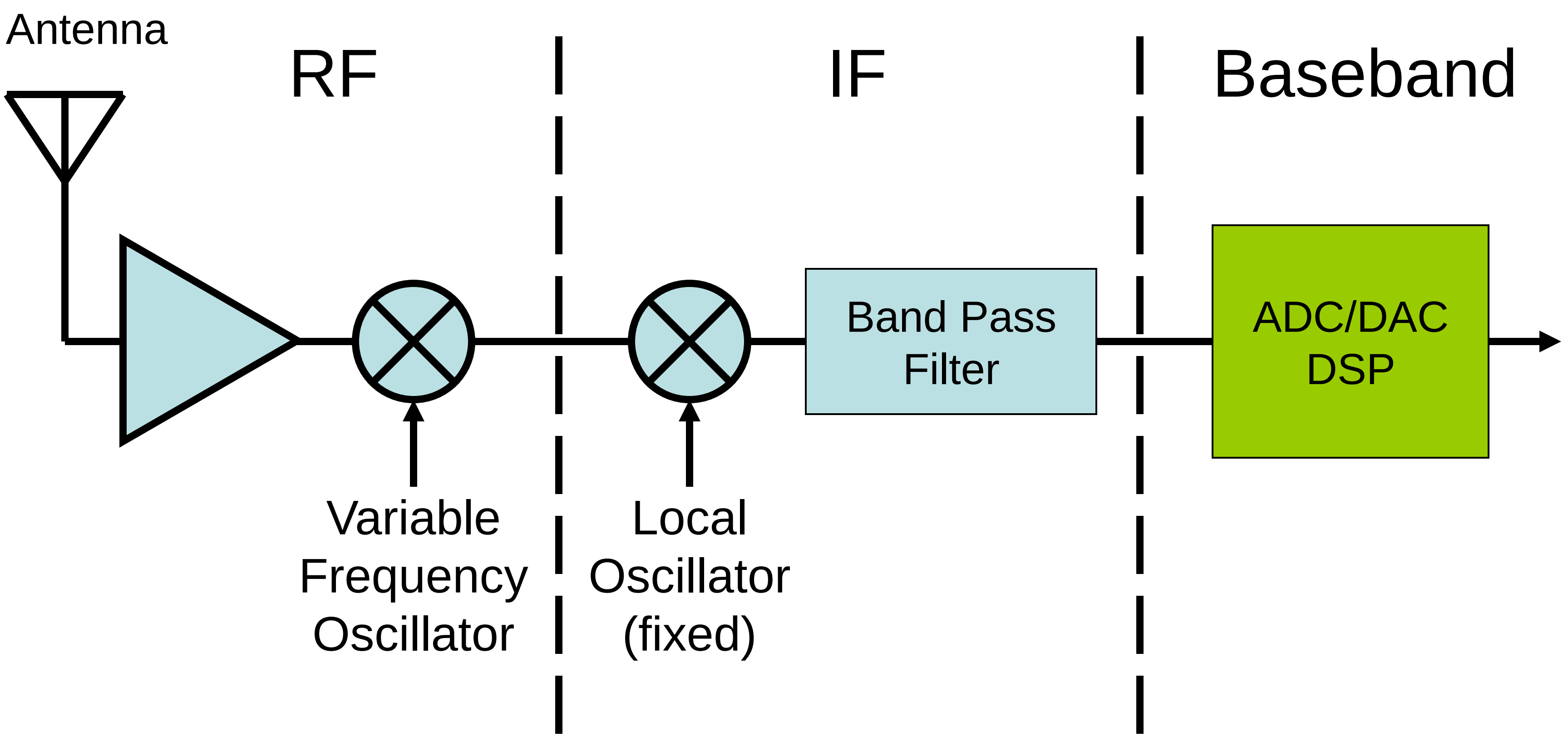
Benefits of SDR, Cont’d.

- Flexible/reconfigurable
  - Reprogrammable units and infrastructure
- Reduced obsolescence
  - Multiband/multimode
- Ubiquitous connectivity
  - Different standards can co-exist
- Enhances/facilitates experimentation
- Brings analog and digital worlds together
  - Full convergence of digital networks and radio science
  - Networkable
  - Simultaneous voice, data, and video

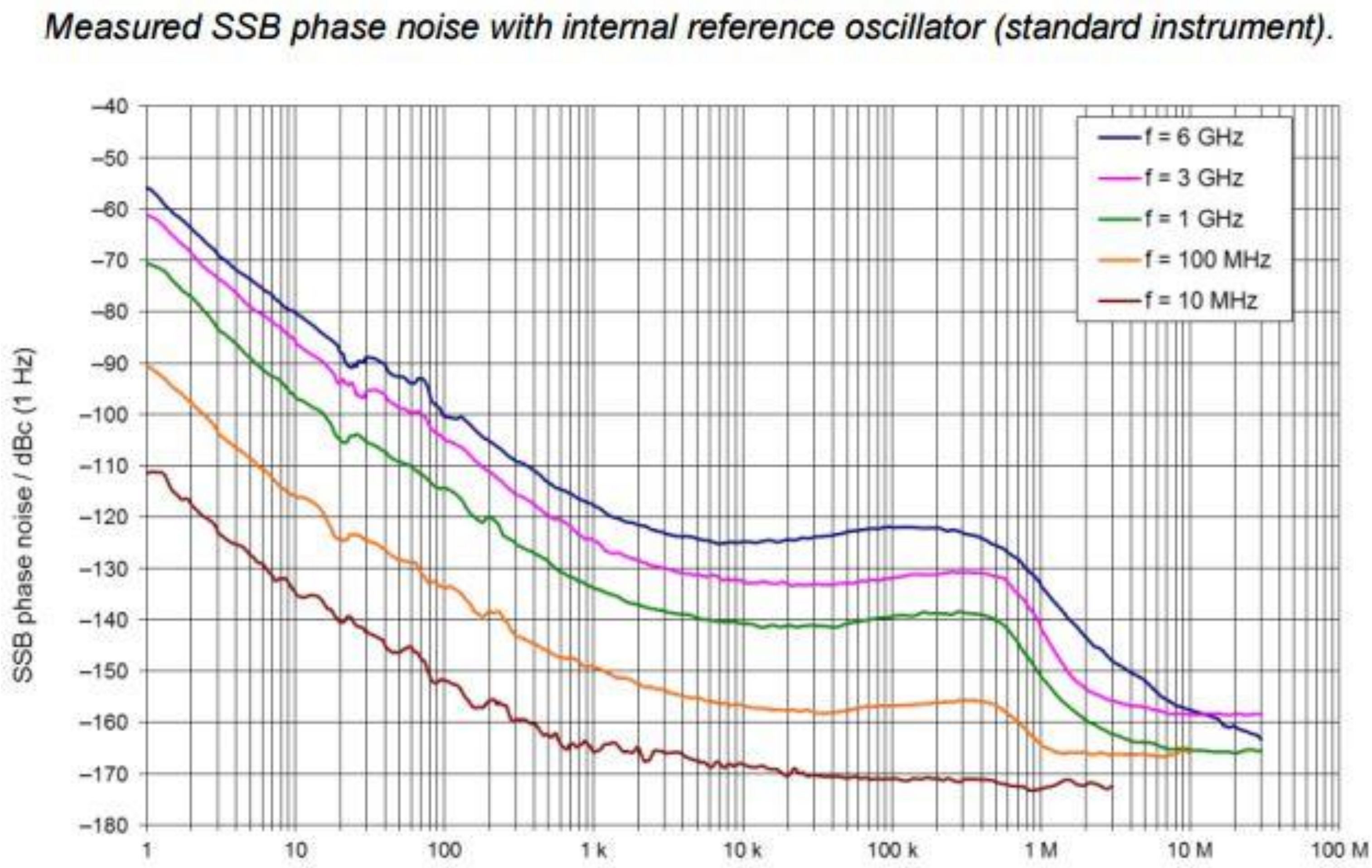
Technologies that enable SDR

- **Antennas**
  - Receive antennas are easier to achieve wide-band performance than transmit ones
  - New fractal & plasma antennas expected in smaller size and wideband capability
- **Waveforms**
  - Management and selection of multiple waveforms
  - Cancellation carriers and pulse shaping techniques
- **Analog-to-digital converters**
  - High ADC sampling speed
  - ADC bandwidth could be digitized instantaneously
- **Digital signal processing/FPGAs**
  - Number of transistors doubles every 18 months
  - More specific purpose DSPs and FPGAs
- **Batteries**
  - More and more power needed (need to focus on more efficient use of power)
  - Fuel cell development for handhelds
- **Terrain databases**
  - Interference prediction, environment awareness
- **Cognitive science**
  - A key aspect will be to understand how multiple CRs work with each other

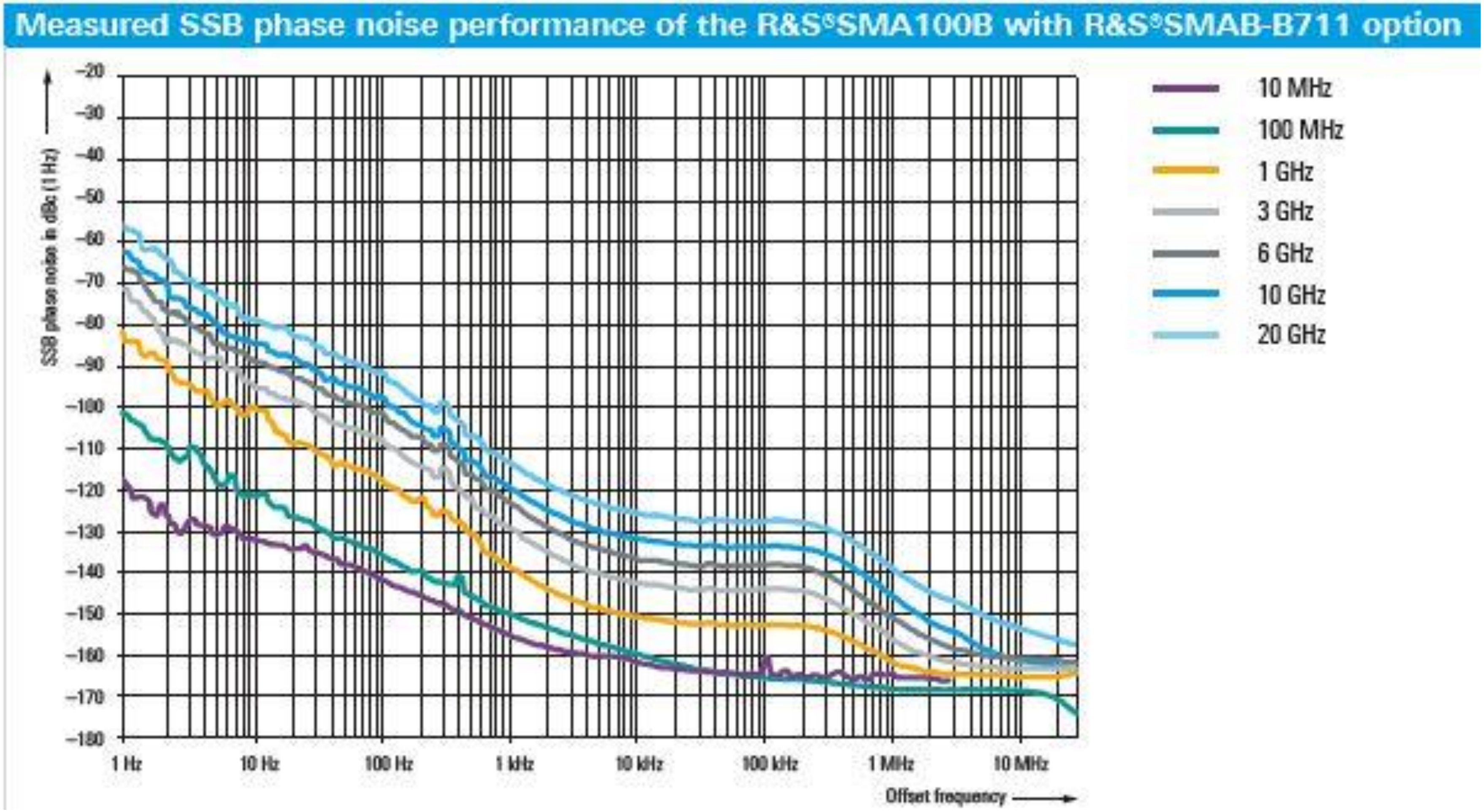
Block Diagram: Software Defined Radio



Oscillator Phase Noise - 1

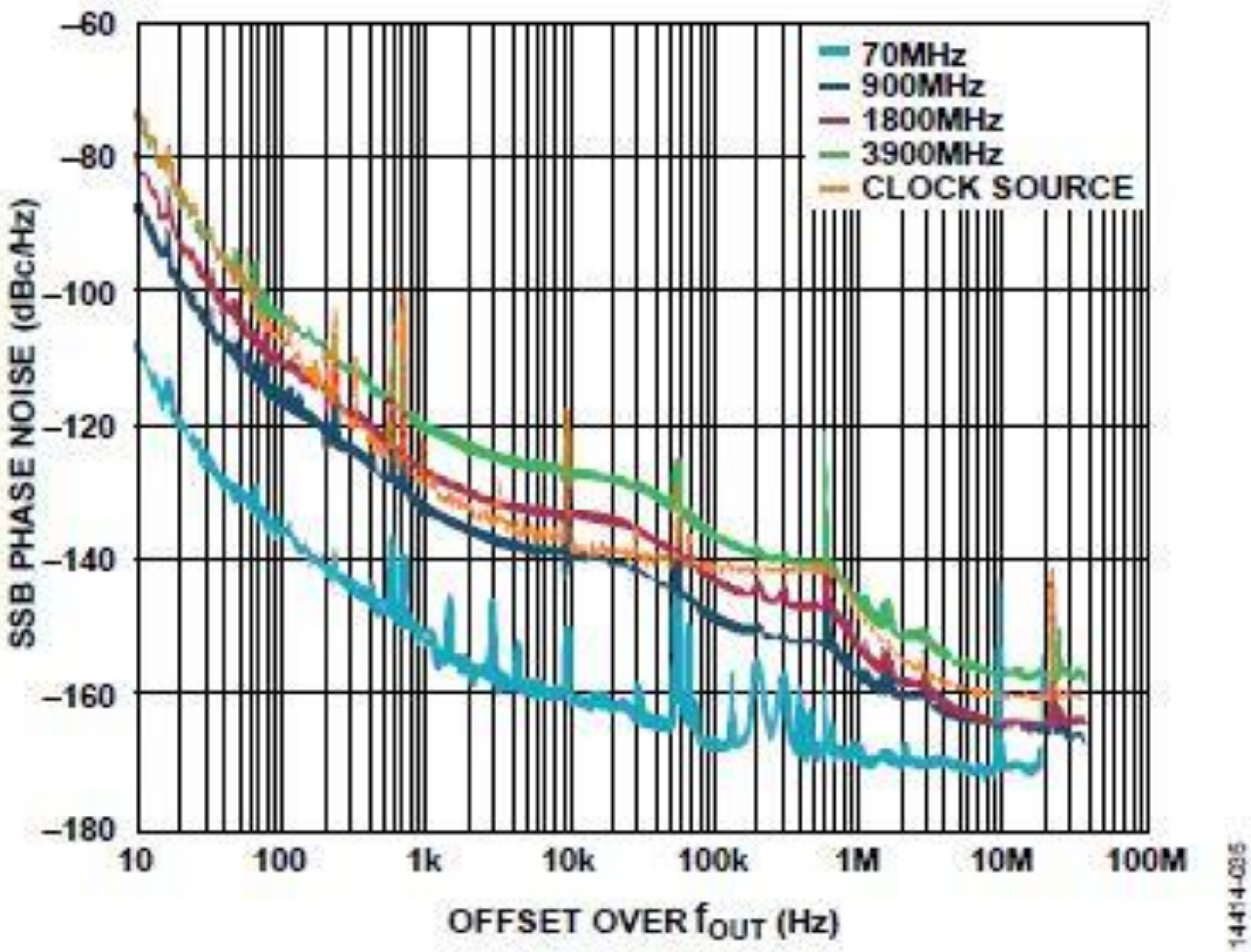


Oscillator Phase Noise - 2

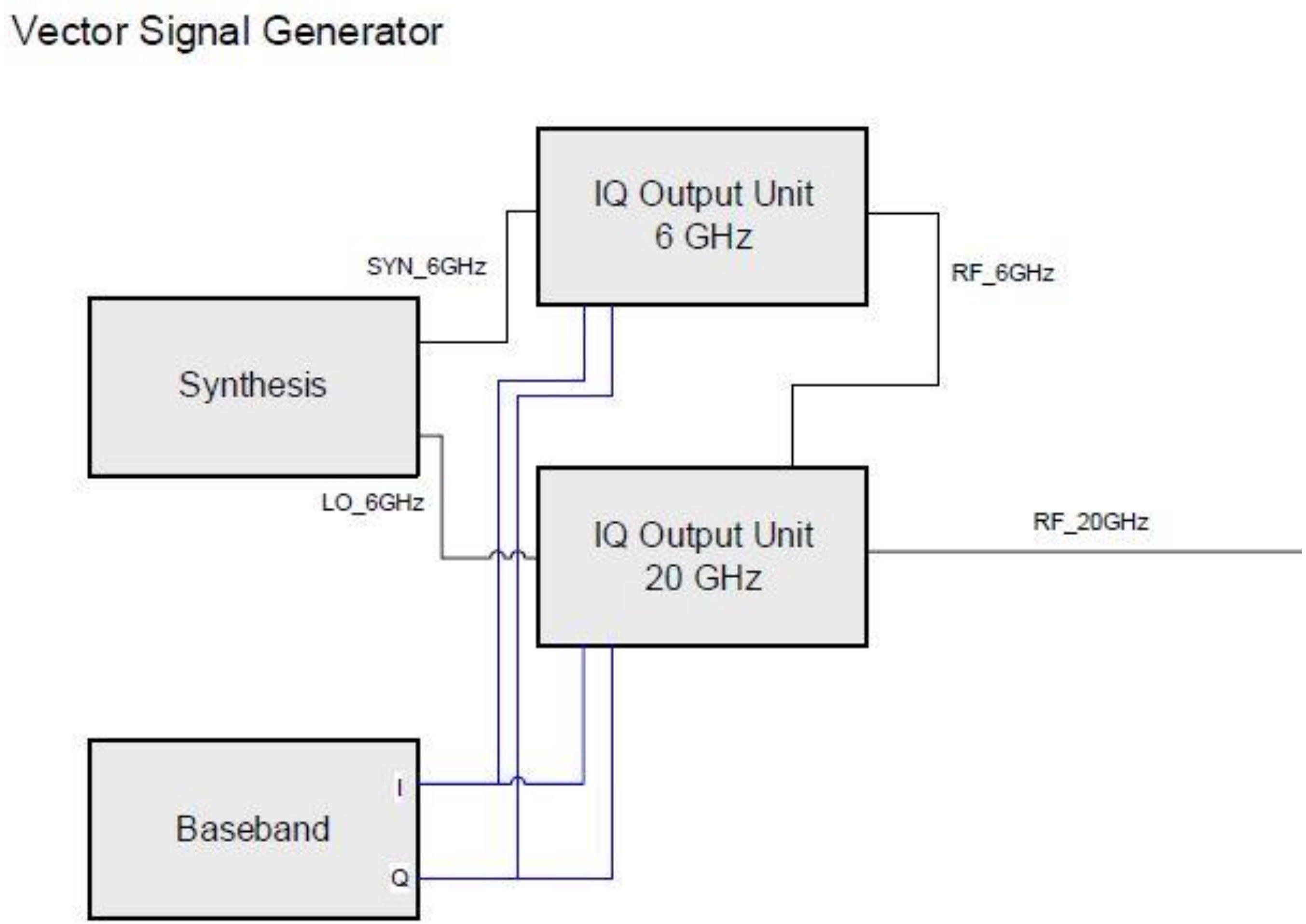


Oscillator Phase Noise – 3

IC -PLL

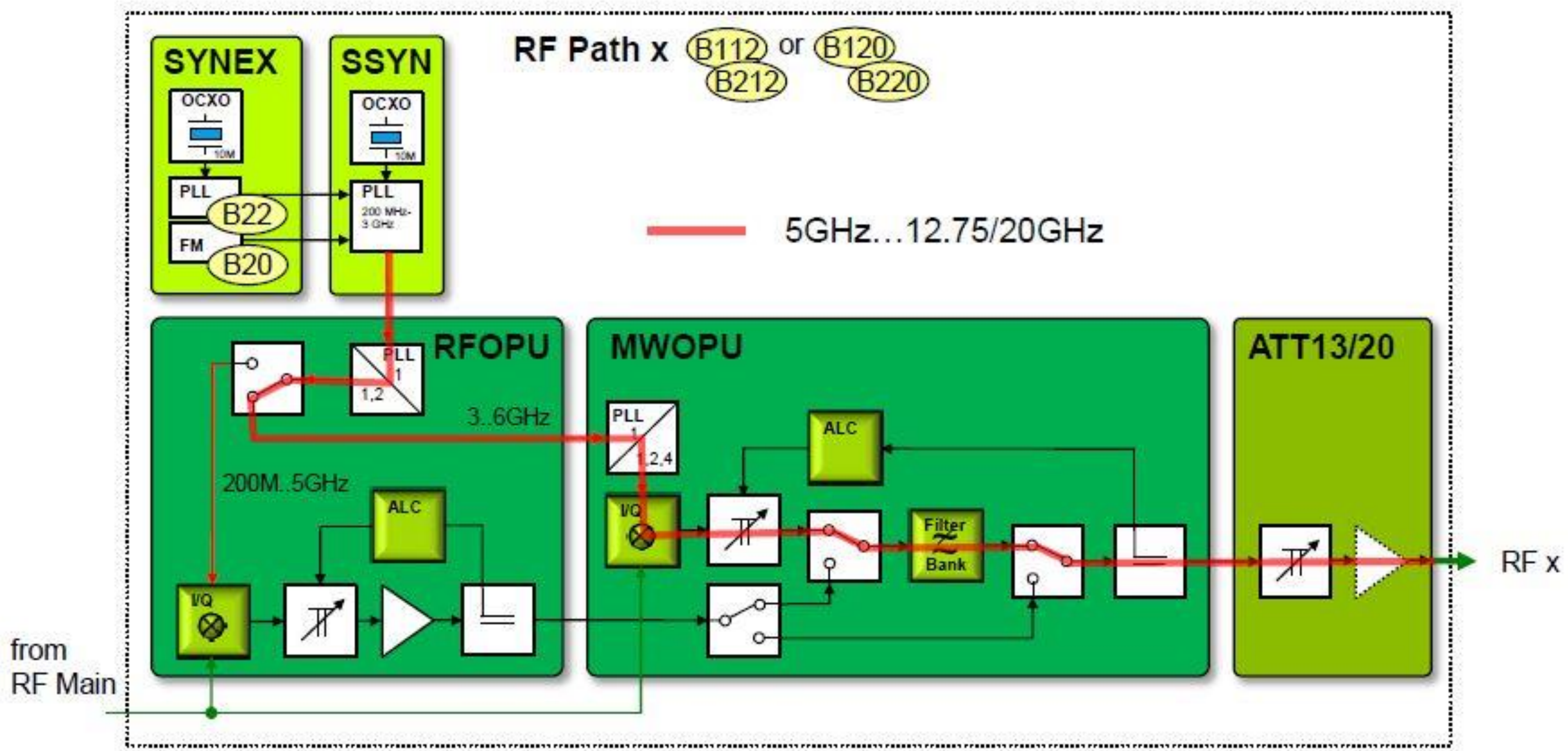


Frequency Generation



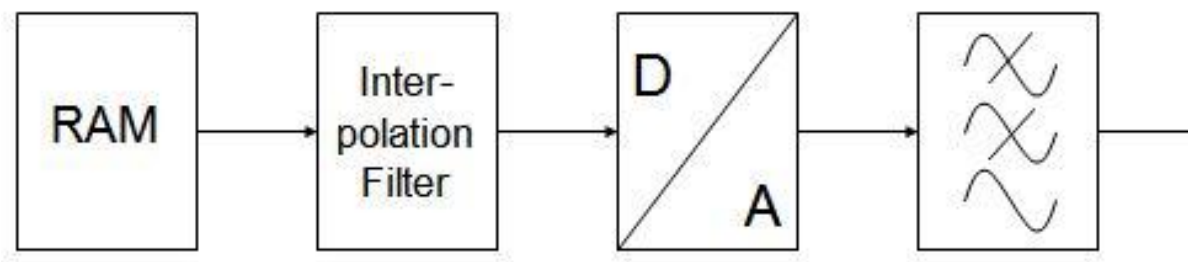
Frequency Generation, cont'd.

RF Block Diagram
Overview (**12.75/20GHz**, IQ)



NCO (Numerically Controlled Oscillator)

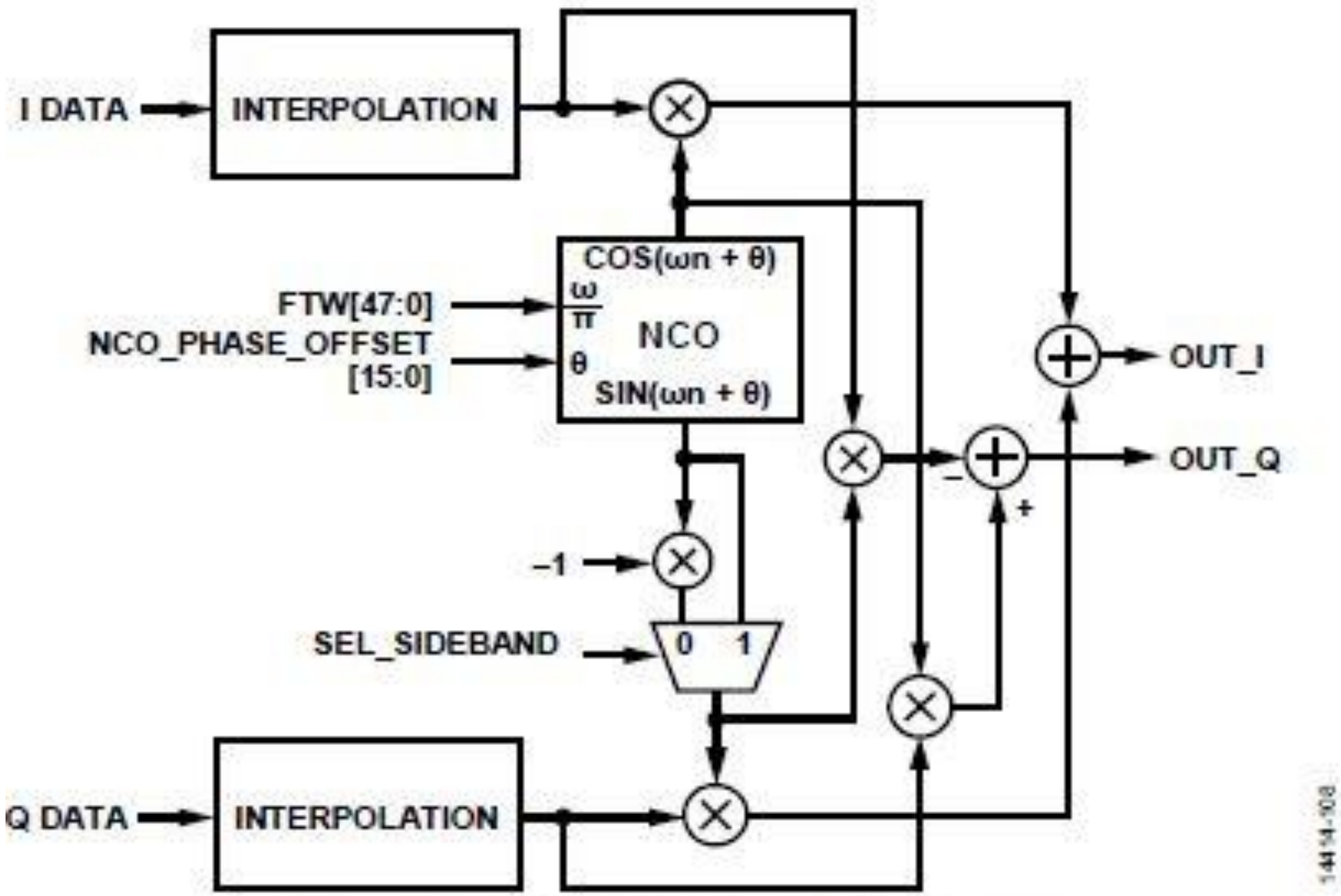
Modern ARB



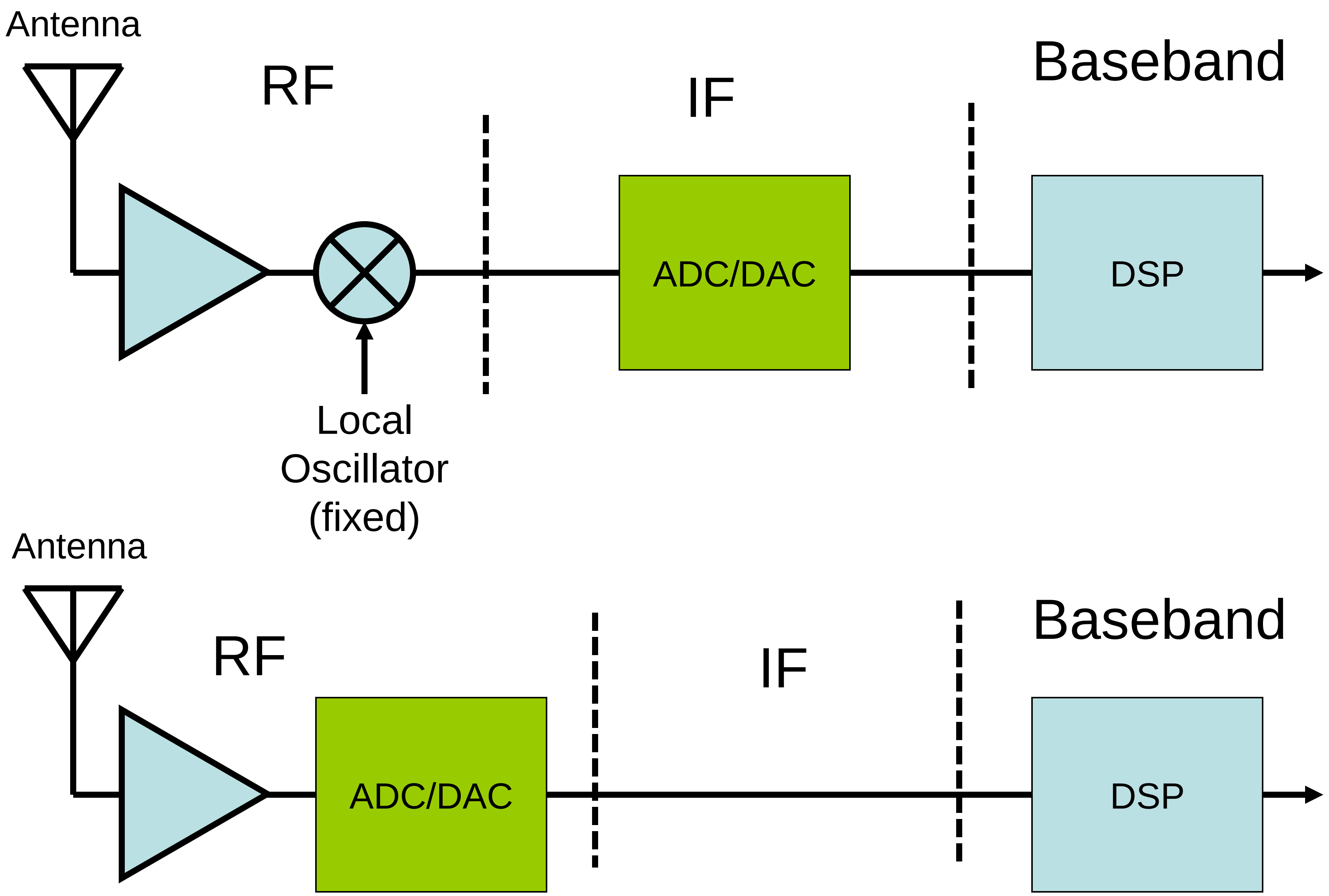
- A modern ARB substantially consists of
  - Output memory
  - **Interpolation filter**
  - D/A-converter
  - Analog low pass filter

NCO Block Diagram

48 Bits Resolution

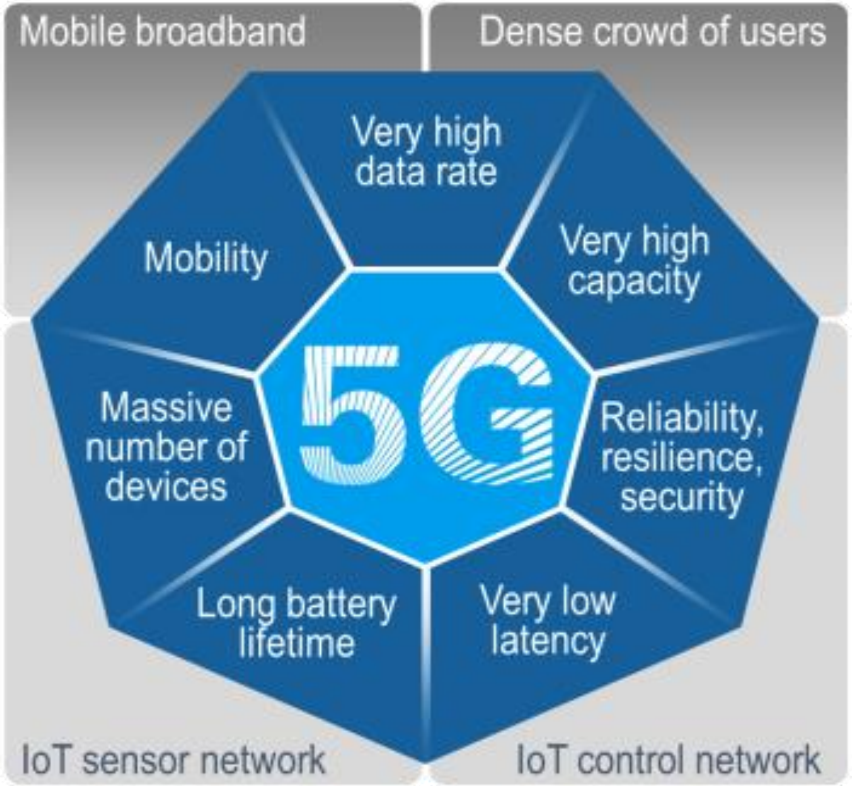


Block Diagram: Software Defined Radio



5G: Emerging Cellular Networks

5G drivers

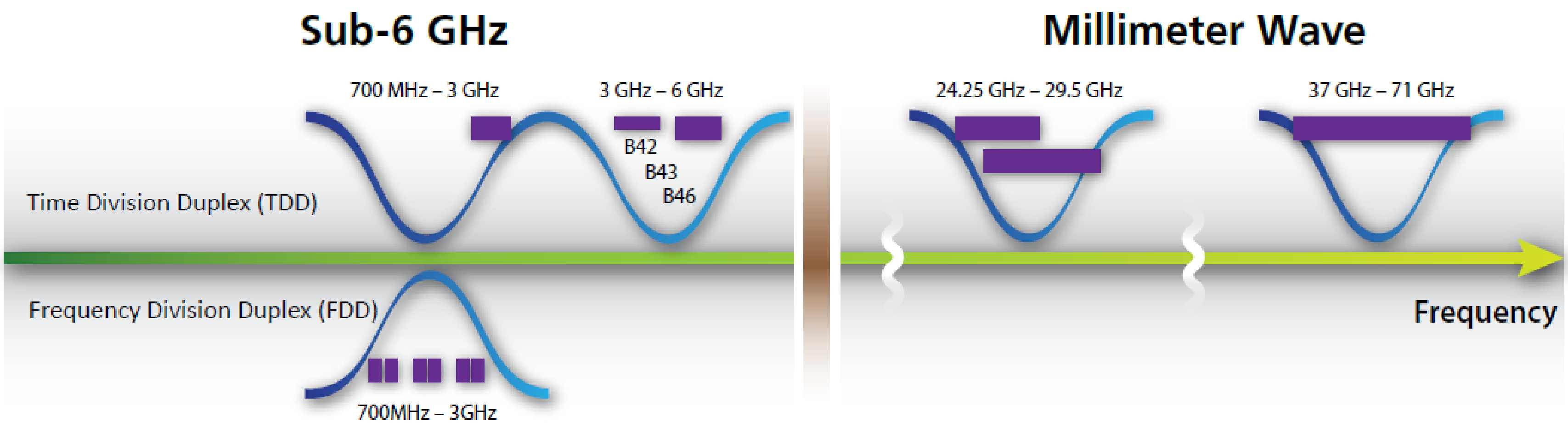


Mobile operators have just commercialized LTE and few of the features that make LTE a true 4G technology have made it into live networks. **So why is industry already discussing 5G?**

- Constant user demands for higher data rates and faster connections require a lot more wireless network capacity, especially in dense areas.
- The industry is expecting demand for 100x higher peak data rate per user and 1000x more capacity, and better cost efficiency defined these as targets for the 5th generation of mobile networks (5G).
- Internet of Things (IoT) provides new challenges to be addressed. It is anticipated that millions of devices will “talk” to each other, including machine to machine (M2M), vehicle-to-vehicle (V2V) or more general x-2-y use cases.

Beyond doubt there is a need to improve the understanding of potential new air interfaces at frequencies above current cellular network technologies, from 6 GHz right up to 100 GHz, as well as advanced antenna technologies such as massive MIMO and beam forming, very long battery lifetimes (years instead of days) and very low response times (latency) call for another “G” in the future !!!

Present Technology and Planned 5G Spectrum



Product Format Example	FEMiD / PAMiD / DRx	FEMiD / PAMiD / DRx	8T / 8R Antenna Complete Front-end	8T / 8R Antenna Complete Front-end
		Technology		
Power Amp	III-V / SiGe / Bulk CMOS	III-V / SiGe / Bulk CMOS	InP / SiGe BiCMOS / Advanced SOI	InP / GaN / SiGe BiCMOS / Advanced SOI
Low Noise Amp	III-V / SiGe / SOI CMOS	III-V / SiGe / SOI CMOS	Advanced SOI / GaN	SiGe BiCMOS / Advanced SOI
RF Switching	SOI CMOS	SOI CMOS	Advanced SOI	Advanced SOI
Filtering	Acoustic / IPD / Ceramic	Acoustic / IPD / Ceramic	IPD / Ceramic	IPD
Antenna Integration	N/A	N/A	Yes	Yes
Signal Generation	N/A	N/A	Advanced SOI / SiGe BiCMOS	Advanced SOI / SiGe BiCMOS

Table represents existing technology and spectrum for SDR frequency spectrum in terms of waveforms

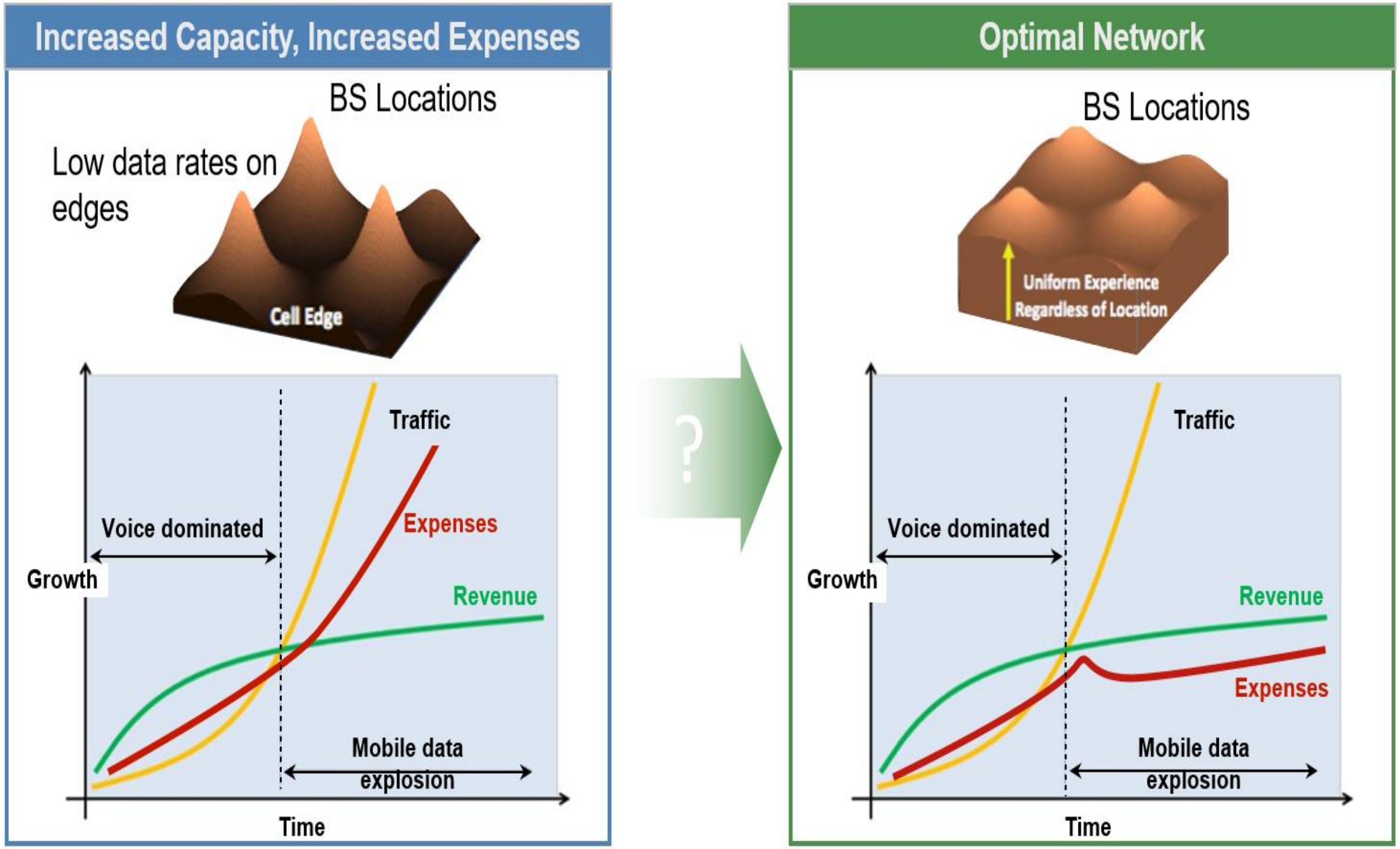
Radios: What is Desired? Capacity or Cost

Spectral Efficiency (Capacity)

Energy Efficiency (Cost)

What is better?
In terms of capacity and cost

5G Business Case



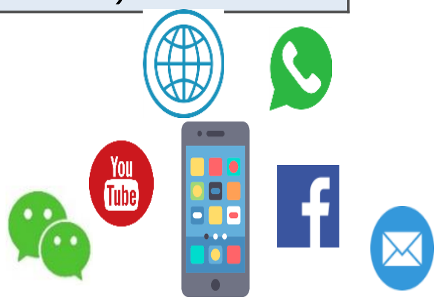
Drive profit by reducing expenses (energy efficiency)

Why 5G? Power Consumption

Cellular Network Energy Consumption (China)

2G GSM
830,000 base stations
80 GWH (96 KWH per BTx)

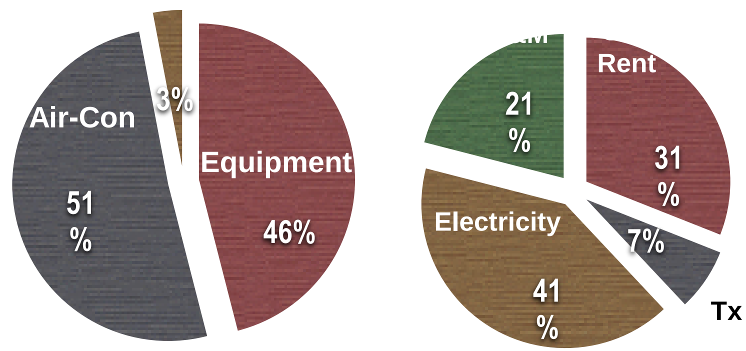
3G TD-SCDMA
350,000 base stations
13 GWH (37 KWH per BTx)



Service Type	Ratio (%)	Packet Size (kB)	Data to Signaling Ratio (DSR)
Text/IM	**60**	1	1 to 3
Voice	35	10	
Photo	4	150	65 to 375
Video	1	1500	

4G TD-LTE
800,000 base stations
16 GWH (20 KWH per BTx)

Radio Access Network Energy Consumption



CAPEX	OPEX

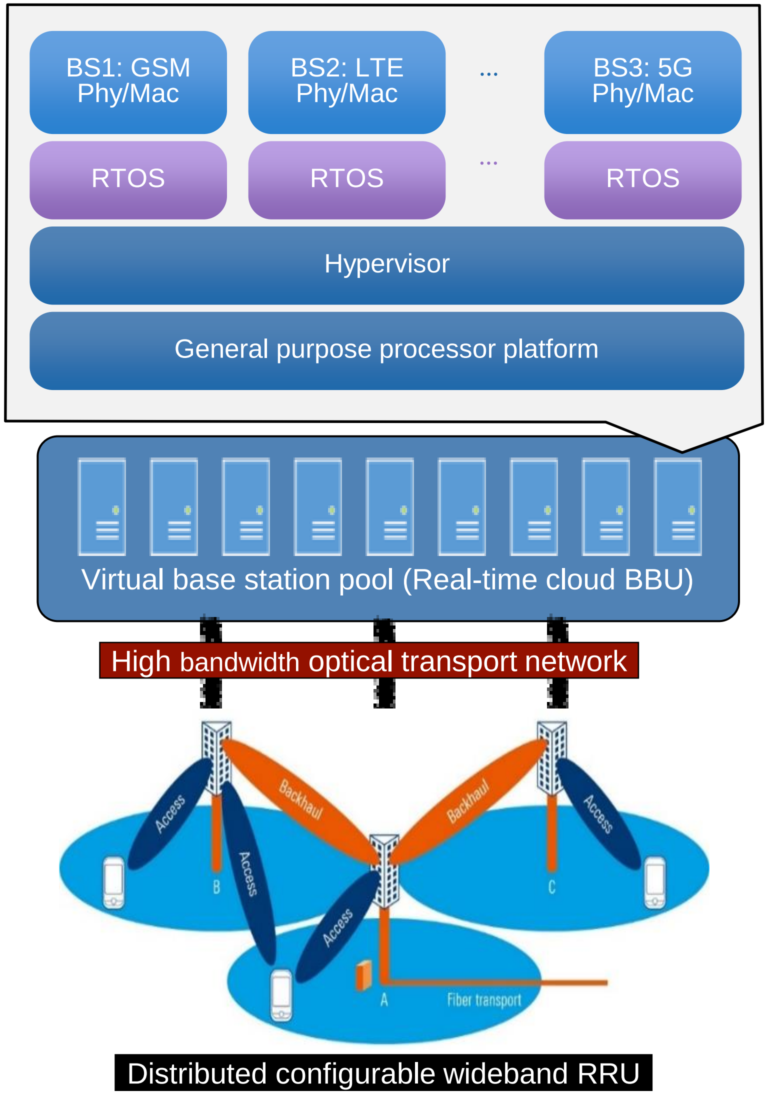
Biggest CAPEX/OPEX Expense is Air Conditioning

CMRI, "C-RAN: The Road Towards Green RAN," Dec. 2013

Example: China Mobile Network in 2013 consumed over 15 Billion KWH

Source: IEEE Communications Magazine, Feb 2014

Energy Efficiency: Centralized Baseband Processing



Centralized Control/Processing
- Centralized processing resource pool that can support 10~1000 cells

Collaborative Radio
- Multi-cell joint scheduling and processing

Real-Time Cloud
- Target to open IT platform
- Consolidate the processing resource into a cloud
- Flexible multi-standard operation and migration

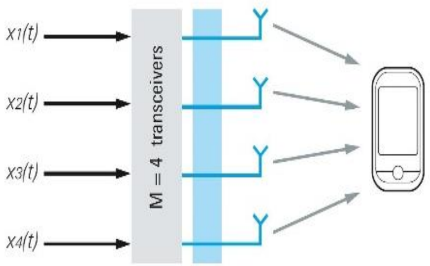
Clean System Target
- Less power consuming
- Lower OPEX
- Fast system roll-out

-15% Capital Costs
-50% Operating Costs
-70% Power Consumption

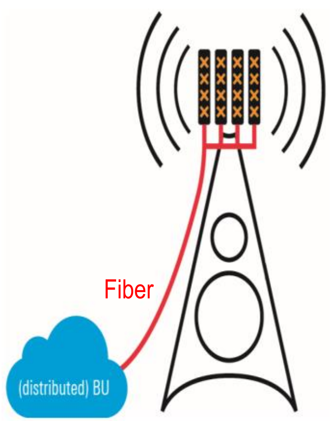
Architecture	Equipment	Air Con	Switching	Battery	Transmission	Total
Traditional	0.65 kW	***2.0 kW***	0.2 kW	0.2 kW	0.2 kW	3.45 kW
Cloud Radio	0.55 kW	***0.01 kW***	0.2 kW	0.1 kW	0.0 kW	0.86 kW

Spectral Efficiency

More channels = MIMO (5G FR1)
Linear increase



Massive MIMO



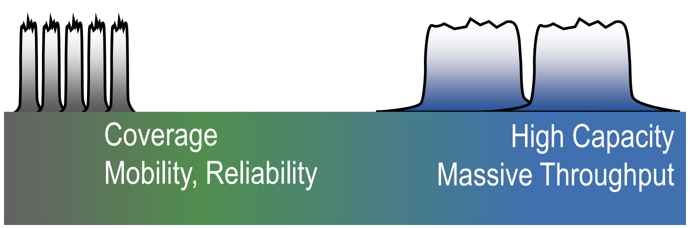
Shannon Channel Information Capacity

Capacity (bits/second)

$$C = W \log_2 (1 + \gamma)$$

Signal BW (Hz) — SNR *(S/N)*

Larger signal BW = mmWave (5G FR2)
Linear increase

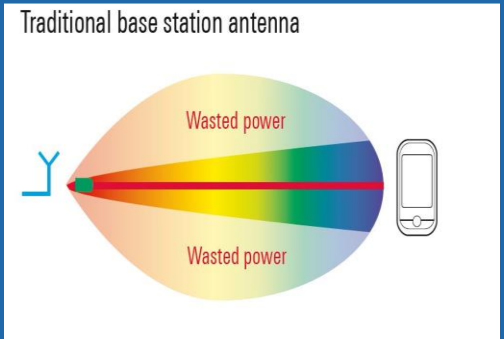


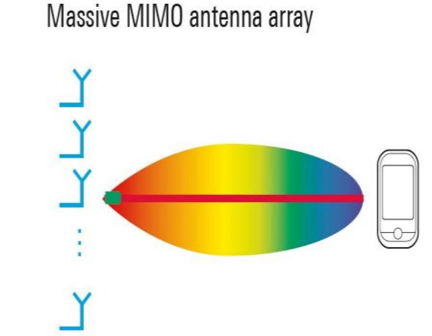
FR1: Sub-6GHz

FR2 mmWave: 24-90 GHz

SNR increase (log2 increase)

Energy Efficiency: Why Massive?





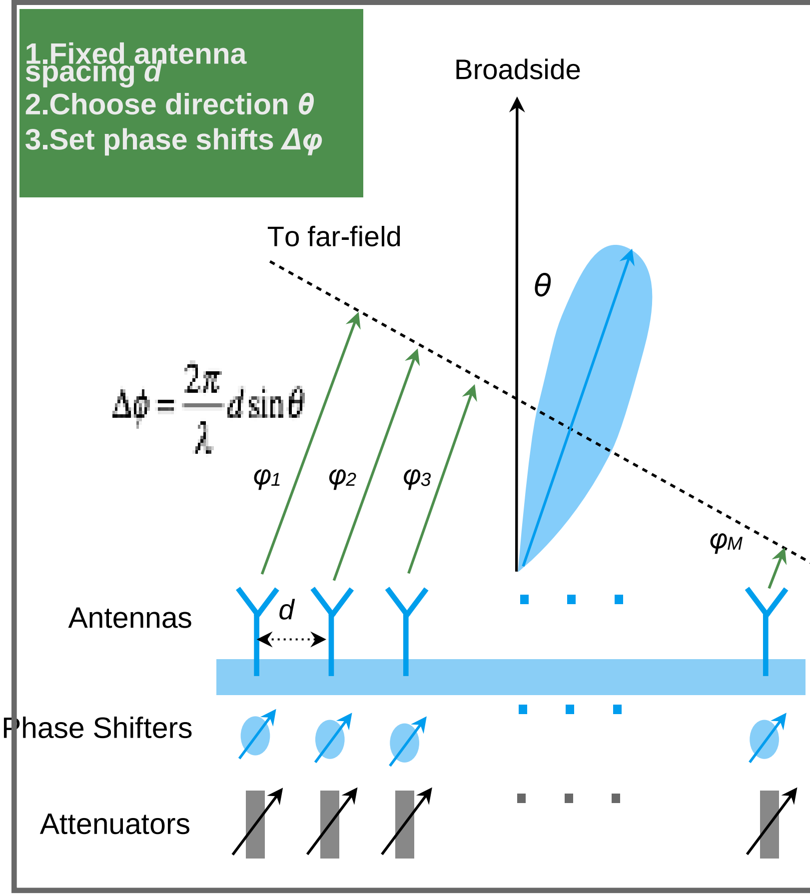
Number of antennas = 1		Number of UEs: 1 120 antennas per UE
Number of BS transmit antennas	1	120
Normalized output power of antennas	$P_{ant} = \frac{1}{M_t} = 1$	$P_{ant} = \frac{1}{P_t^2}$
Normalized output power of base station	$P_{total} = \sum_{i=1}^{M_t} P_{ant}^i = 1$	$P_{total} = \sum_{i=1}^{M_t} P_{ant}^i \sim 1/1000$

Source: IEEE Signal Processing Magazine, Jan 2013

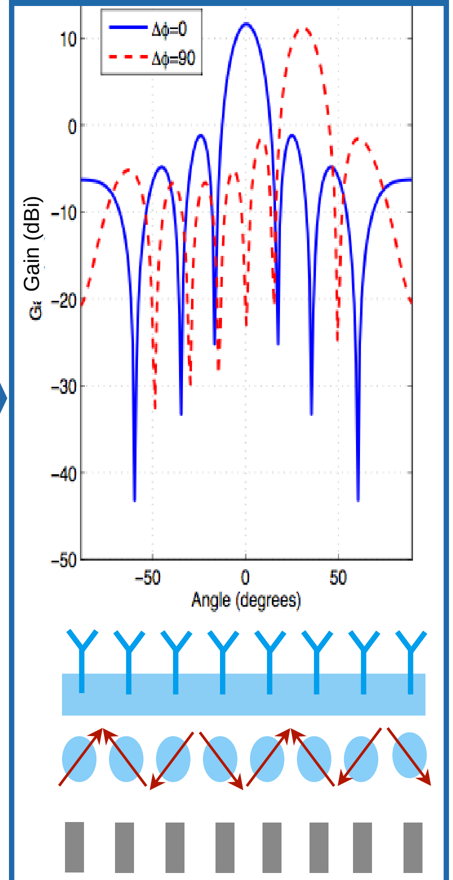
Improve energy efficiency: beamforming

How to Beam form?

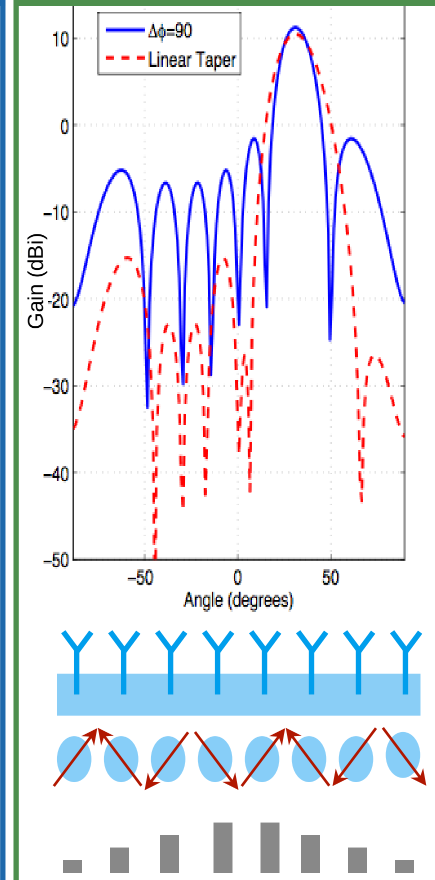
Principle of Beamforming & Beamsteering



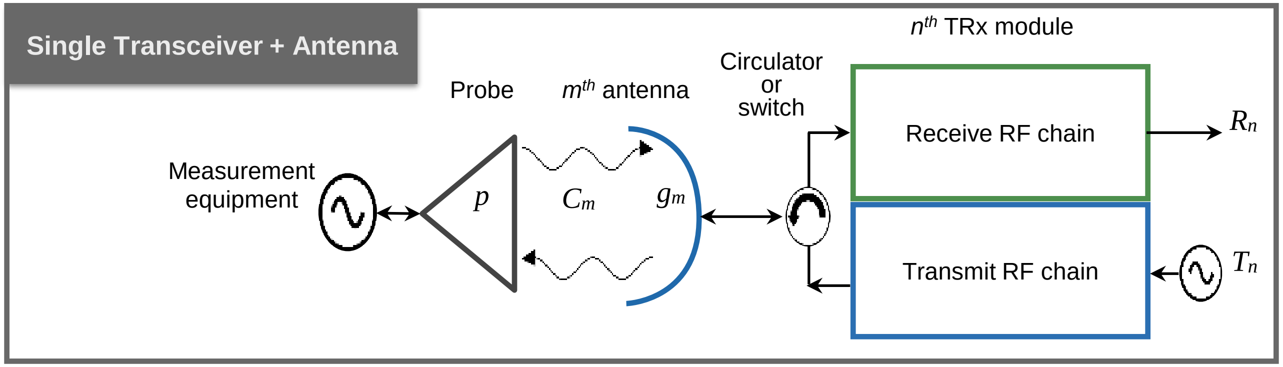
Beamsteering (Phase Shift)



Sidelobe Suppression

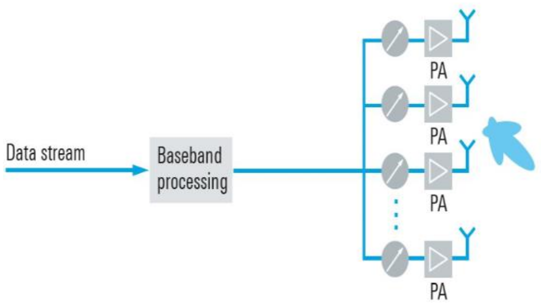


Beamforming Architectures

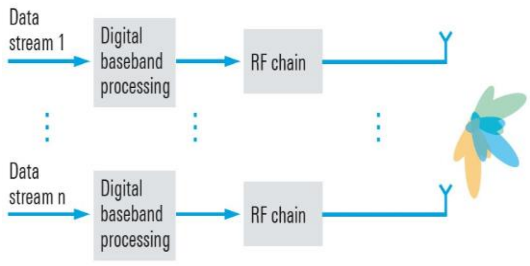


From Analog .... To Digital ... To Hybrid

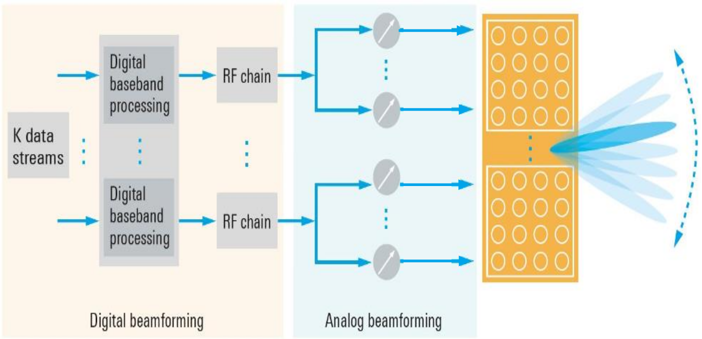
Analog Beamforming (ABF)



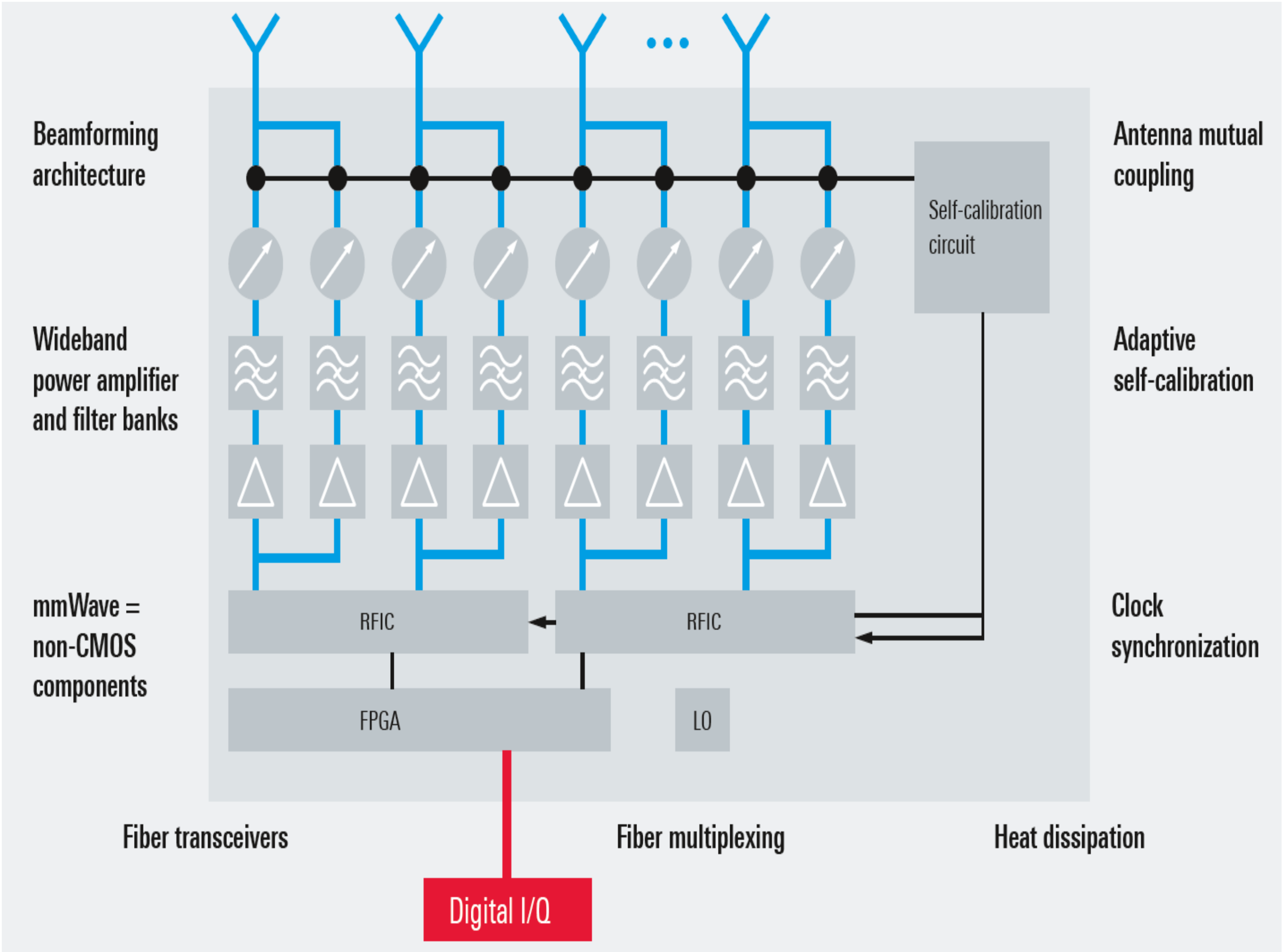
Digital Beamforming (DBF): 5G FR1



Hybrid Beamforming (HBF): 5G FR2

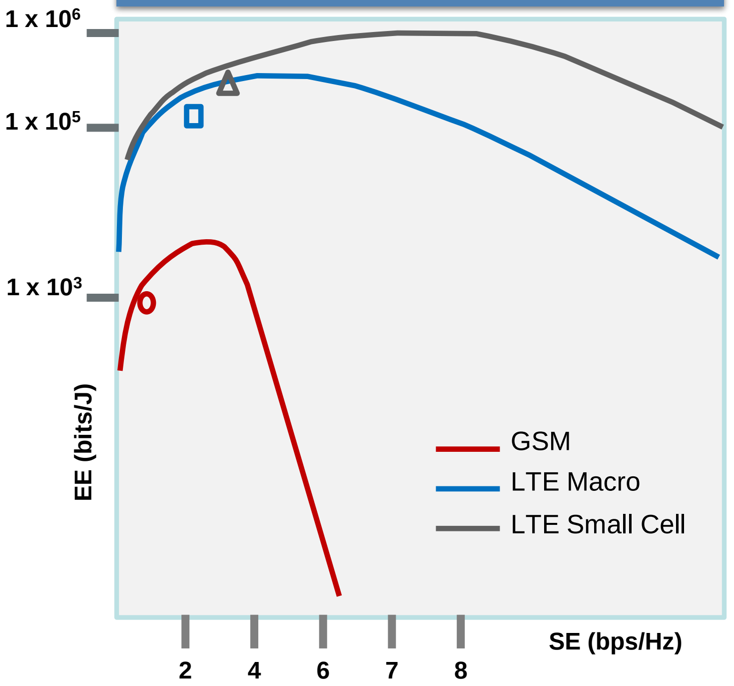


Massive MIMO = Complex Base Stations



Which is the Optimal Network?

2G & 4G Capacity

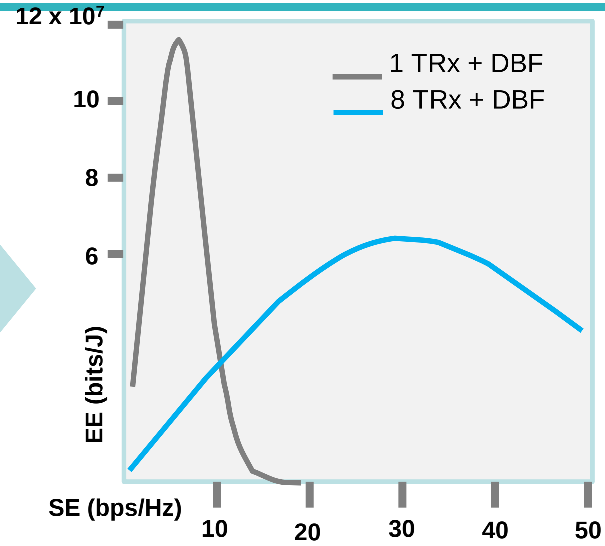


2G Optimal Capacity: 2-4 bps/Hz

4G Optimal Capacity: 8-10 bps/Hz

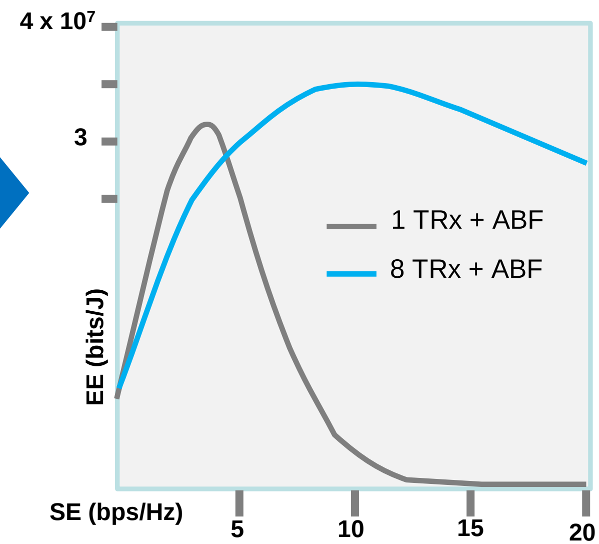
Sources: IEEE Communications Magazine, Feb 2014 & Jan 2015

FR1



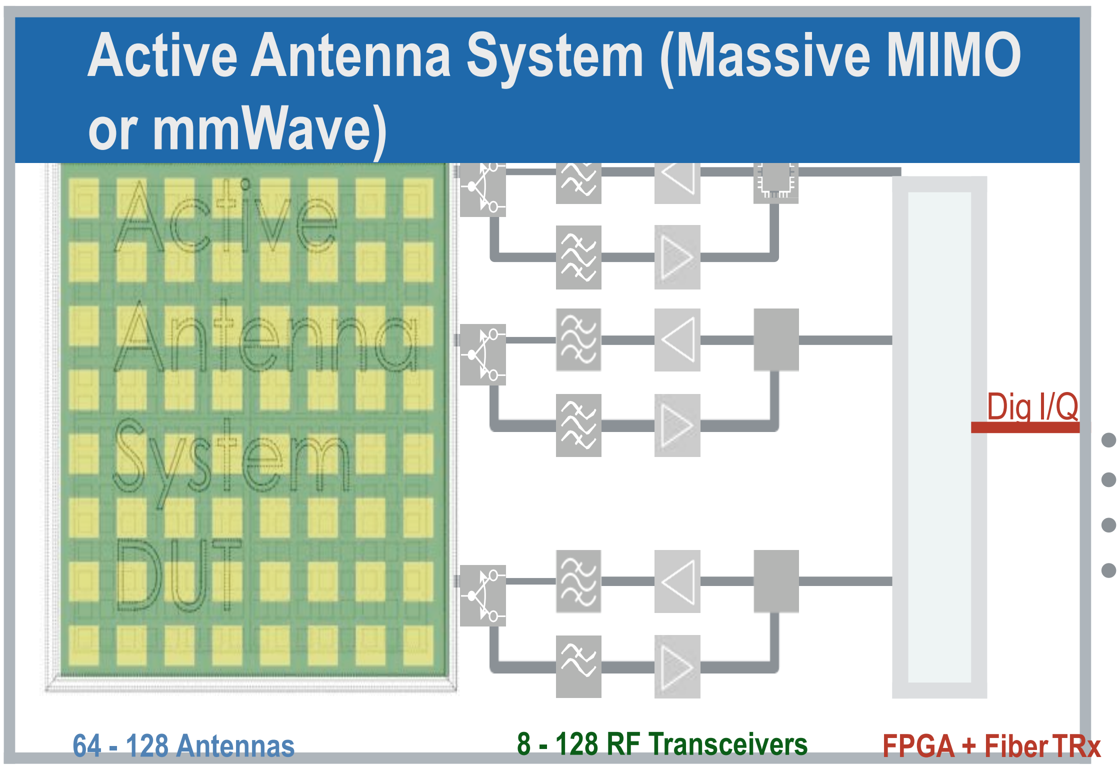
5G optimal capacity for DBF massive MIMO
(8 TRx per user)
SE: 30 bps/Hz
EE: 6 x 10^7 bits/Joule

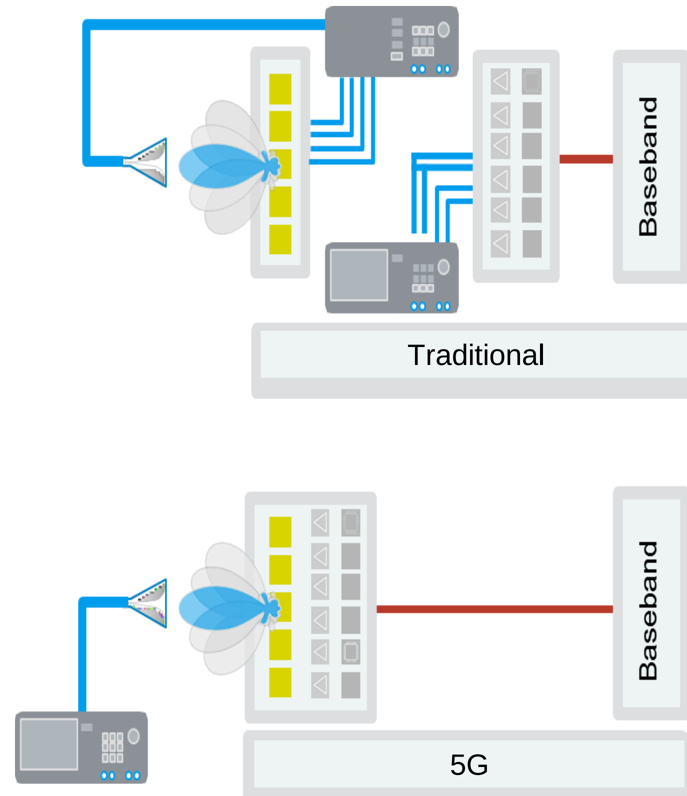
FR2



5G optimal capacity for hybrid beamforming mmWave (50 antennas)
(8 TRx per array)
SE: 10 bps/Hz
EE: 3.5 x 10^7 bits/Joule

5G Devices: New Measurement Paradigms

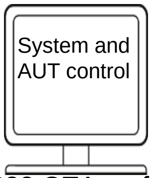




Basic Over-The-Air (OTA) Test Setup

Passive measurements

2D/3D antenna characterization



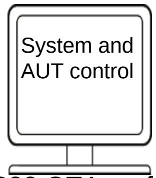
R&S®AMS32 OTA performance measurement software

R&S®CONTEST

R&S®ZNA vector network analyzer

Active measurements

RF transceiver characterization



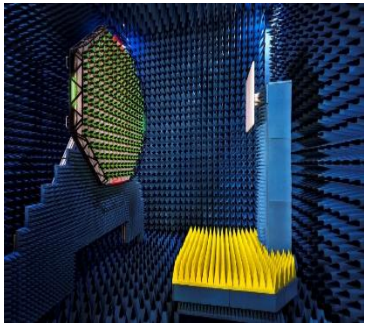
R&S®AMS32 OTA performance measurement software

R&S®CONTEST

R&S®SMW200A vector signal generator

R&S®FSW signal and spectrum analyzer

OTA test solutions



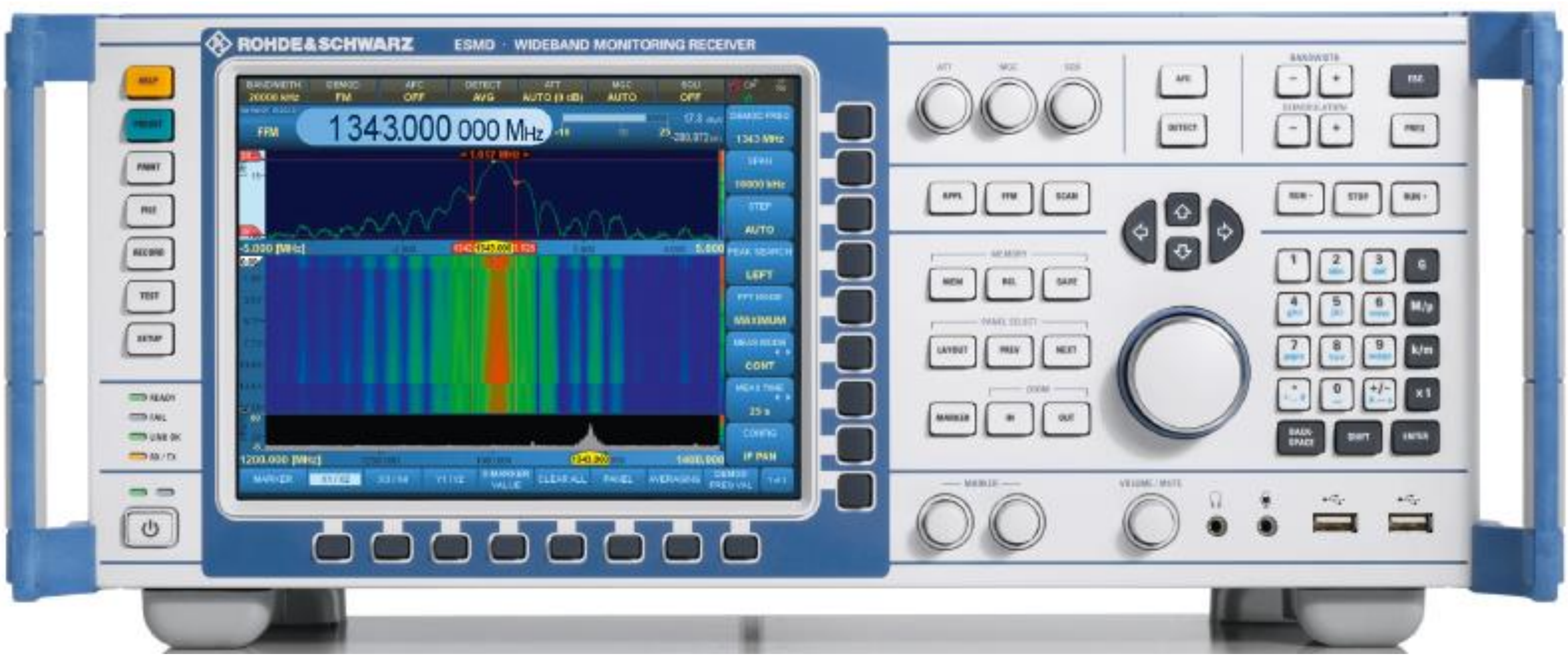
R&S®PWC200 plane wave converter

R&S®ATS800R CATR rack based antenna test system

R&S®ATS1800C CATR conformance chamber system

5G & SDR Inspired Monitoring Receiver

R&S ESMD Wide Band Monitoring Receiver



High Dynamic Range !!!

Monitoring Receivers

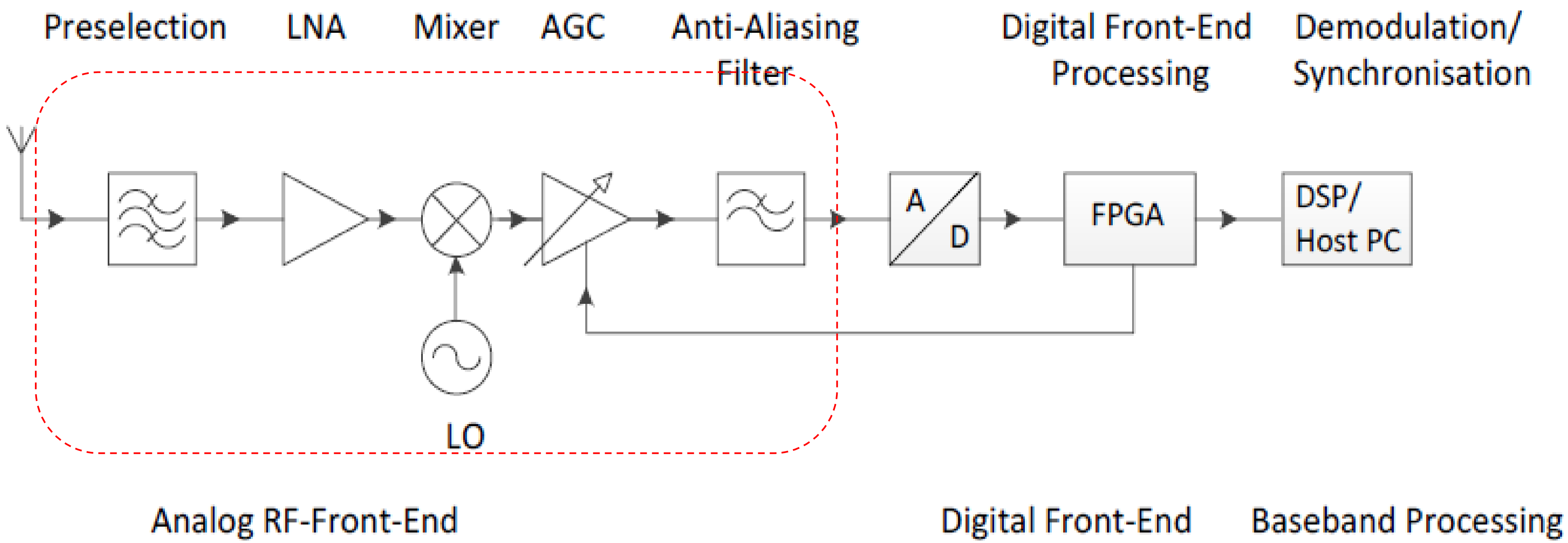
High Dynmaic Range Microwave Monitoring Receivers

- Searching for faults in professional radio networks
- Comprehensive spectrum analysis
- Monitoring of user-specific radio services
- Monitoring on behalf of regulating authorities
- Handoff receivers, i.e. **parallel demodulation** of narrowband signals and simultaneous broadband spectrum scanning=High Dynamic Range
- Critical Parameters: Noise Figure, IP2, IP3, and instantaneous dynamic range

Best solution: → Software Defined Radio

Typical Microwave Receiver

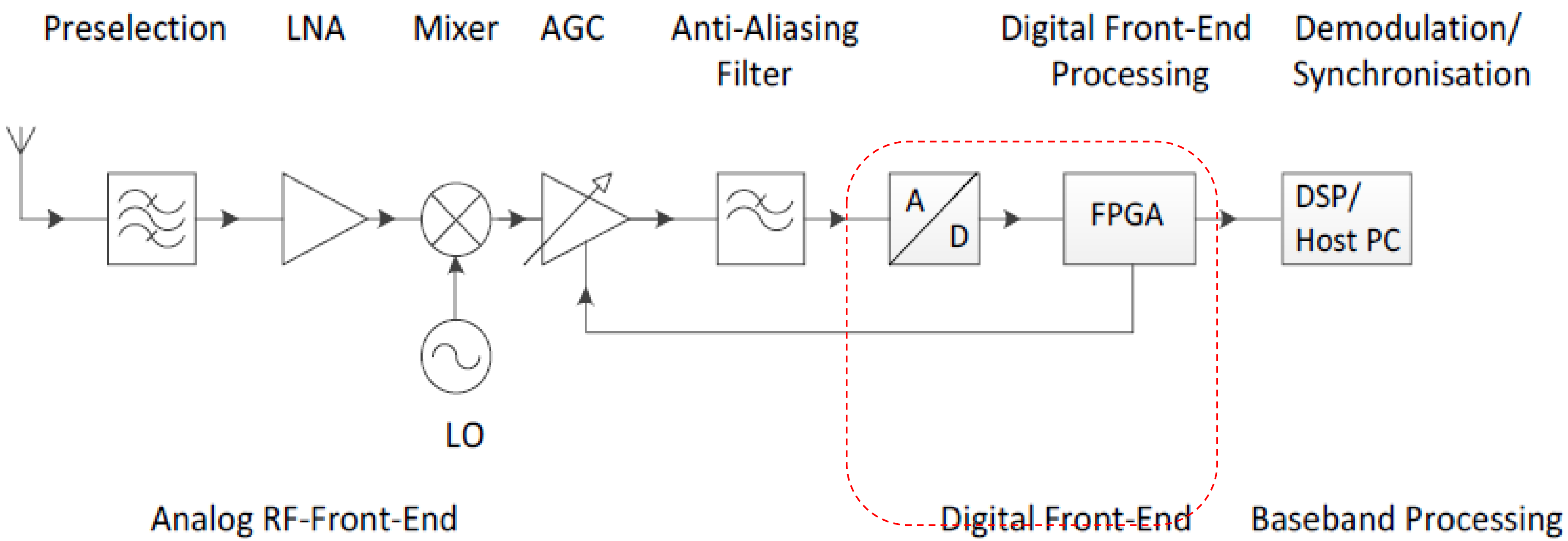
Principal Arrangment for Typical Microwave Receivers



The analog front end is downconverting the RF signals into an IF range <200MHz

Microwave Receiver, Cont'd.

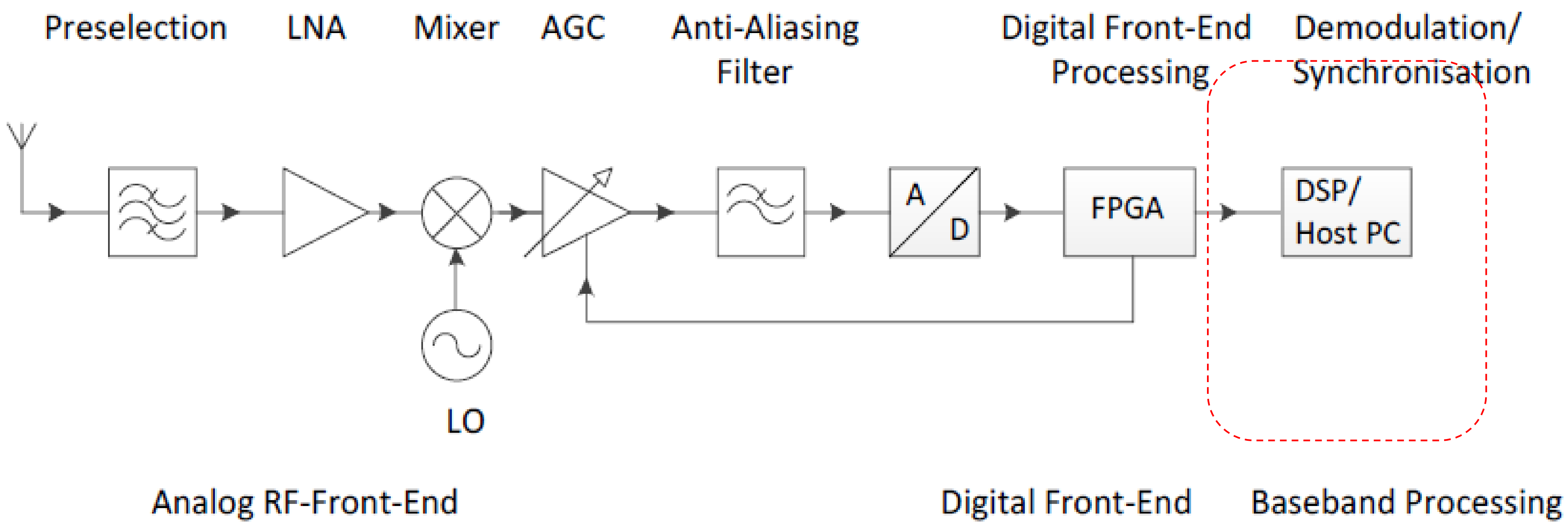
Principal Arrangment for Typical Microwave Receivers



The digital front end consists of an Analog to Digital converter and a digital down- converter to reduce the sample rate down to the bandwidth needed by the application. Sampling rate of AD converters are rising up to 250Msps with resolutions of 14 or 16 bits.

Microwave Receiver, Cont'd.

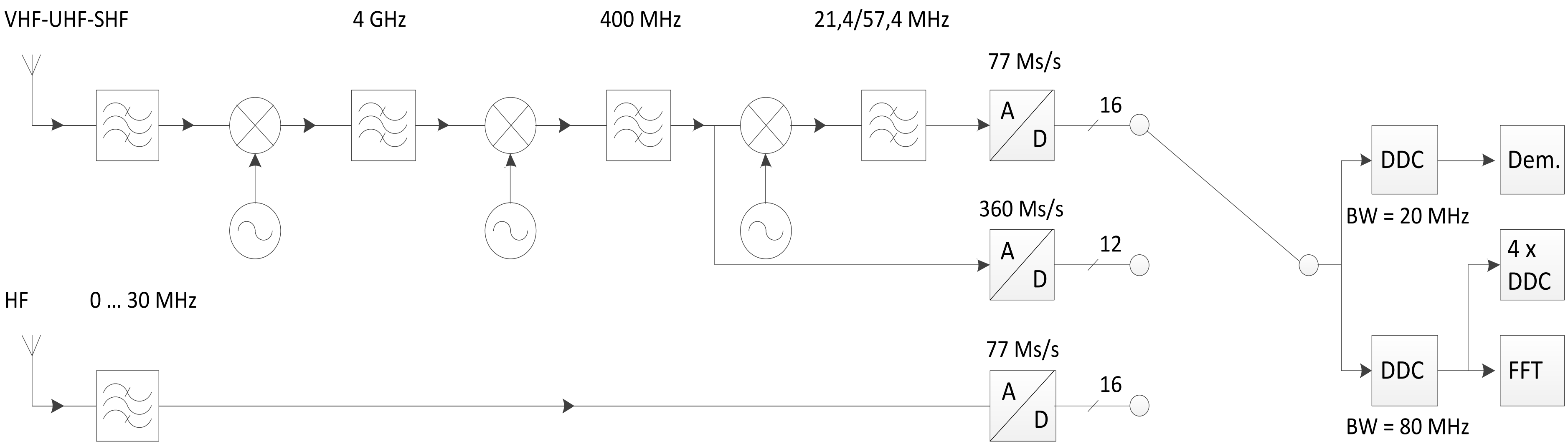
Principal Arrangment for Typical Microwave Receivers



The baseband processing takes over the base band filtering, AGC, demodulation, and the signal regeneration..

Typical Analog Front End

Possible Drawbacks on the Analog Front End



- **Wide band microwave receivers need tripple conversion to prevent image reception**
- **Several expensive and switchable filters are required for pre- and IF-selection**
- **Intermodulation and Oscillator Phase Noise are the main issues**
- **Low noise and high dynamic range are contradictionary**

Image Rejection Mixer

Solution to eliminate tripple Conversion

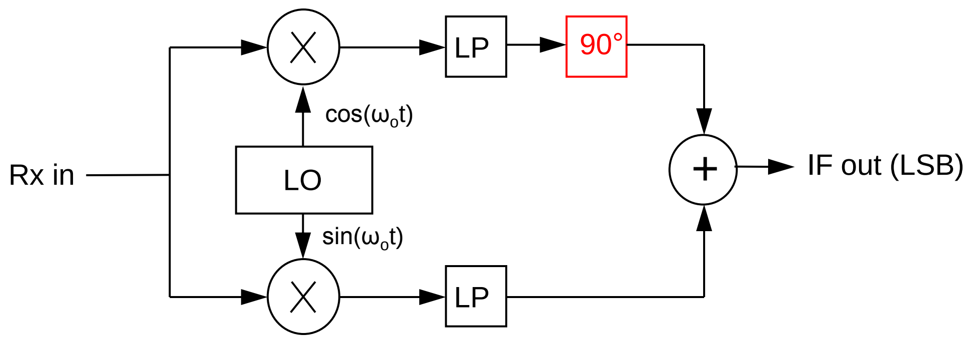
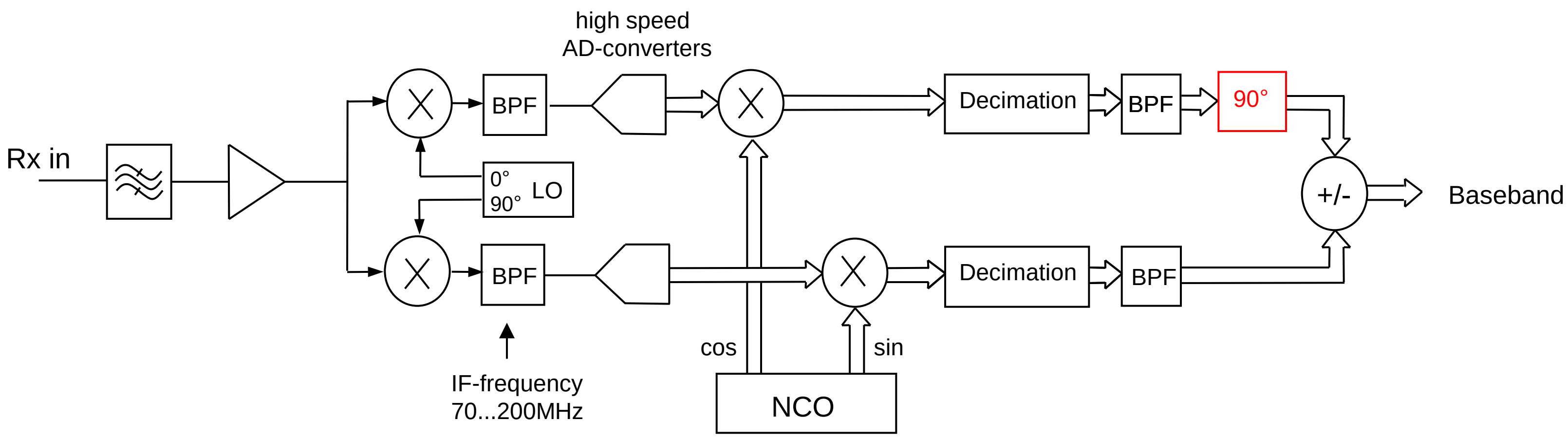


Image Rejection Mixer

- **An analog Image Rejection Mixer is capable to attenuate the Image by 30...40dB**
- **Criterions for the image attenuation are amplitude and phase errors in both branches**
- **The most critical element is the 90° phase shifter, mainly for wide band IF**
- **The SDR technology allows to move the phase shifter from analog into the digital part, where it can be realized nearly ideal by means of a Hilbert Transformer**

Image Rejection Mixer

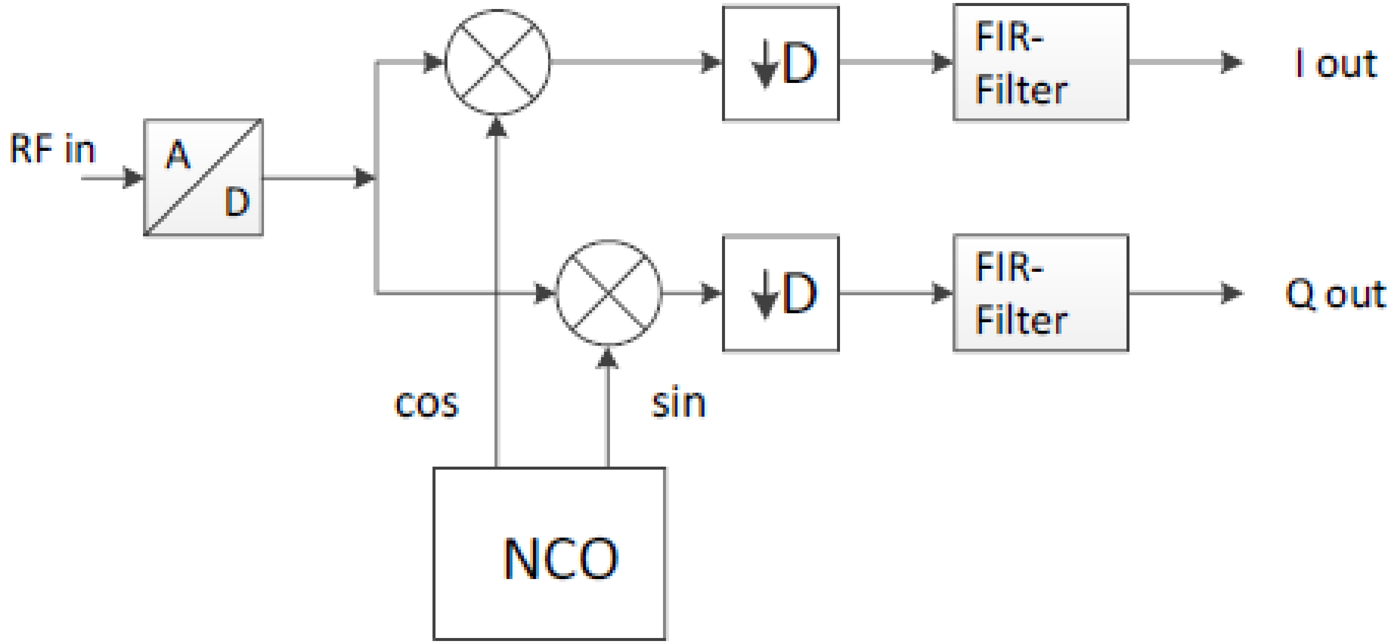
Solution with a distributed Image Rejection Mixer



- **The preselector filters may be wider, as they are no longer used for image rejection**
- **The digital parts, following the AD converter, can be realized in a FPGA**
- **In a wide band receiver, the LO can be tuned in steps from up to 10MHz which is simplifying the PLL loop filter design. The fine tuning will be done by the NCO**
- **The image rejection can be further improved by calibration algorithms in the digital part to values up to 80dB**

Down Converters

Digital Down Converter

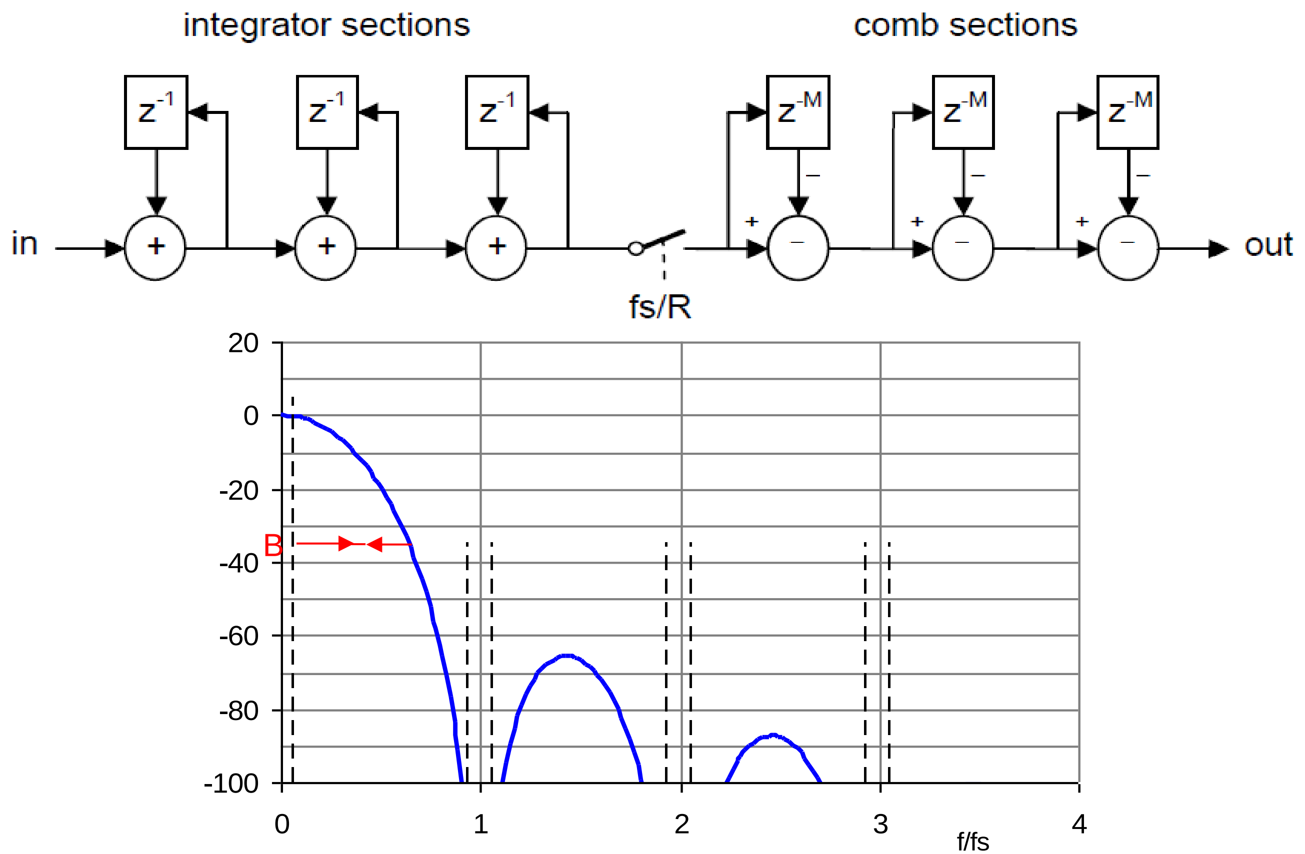


The digital down converter includes:

- a numerically oscillator (NCO)
- a complex IQ-mixer to convert the IF down to approx. 0Hz (zero-IF)
- several decimation filter stages for reducing the sampling rate
- final lowpass FIR-filters (Finite Impulse Response)

Down Converters, Cont'd.

Digital Down Converter



$$|H(f)| = \left|\frac{\sin(\pi \cdot M \cdot f)}{\sin(\pi \cdot f / R)}\right|^N$$

R: decimation factor

N: filter order (sections)

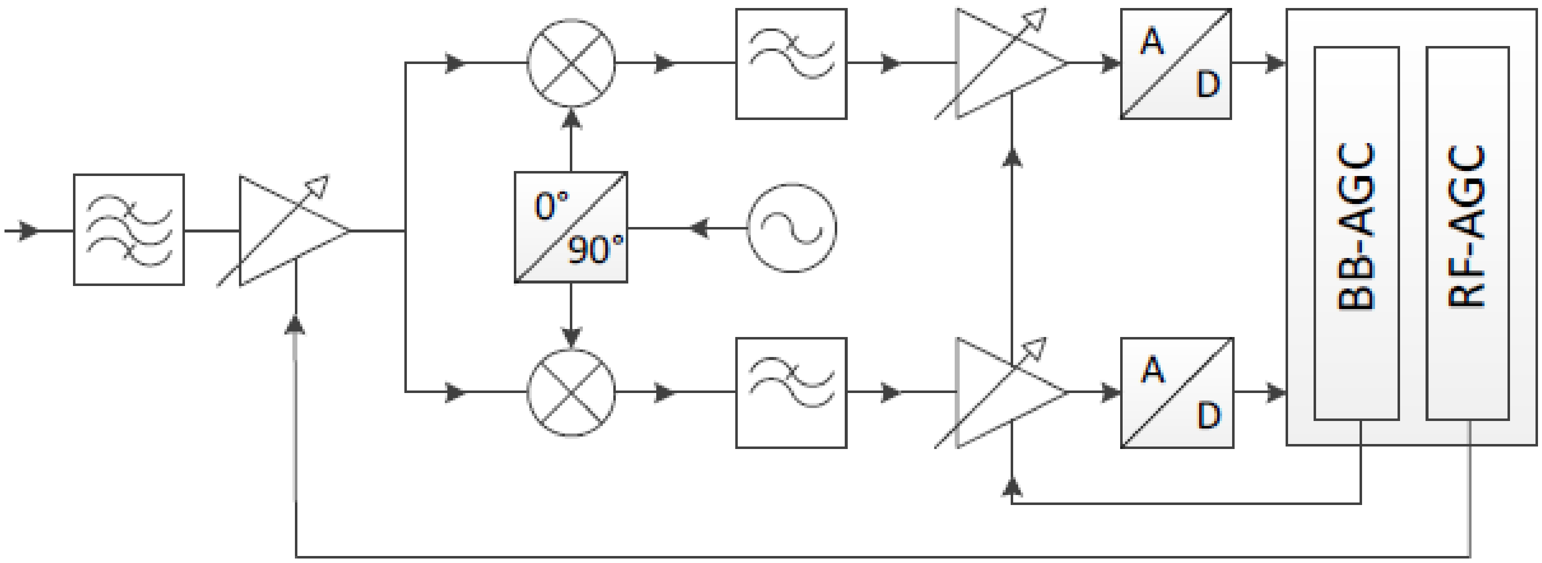
M = 1 or 2

fs: input sample rate

B = fs / R

CIC-Filter with R = 16, N = 5, M = 1 (CIC: Cascaded Integrator Comb)

Automatic Gain Control

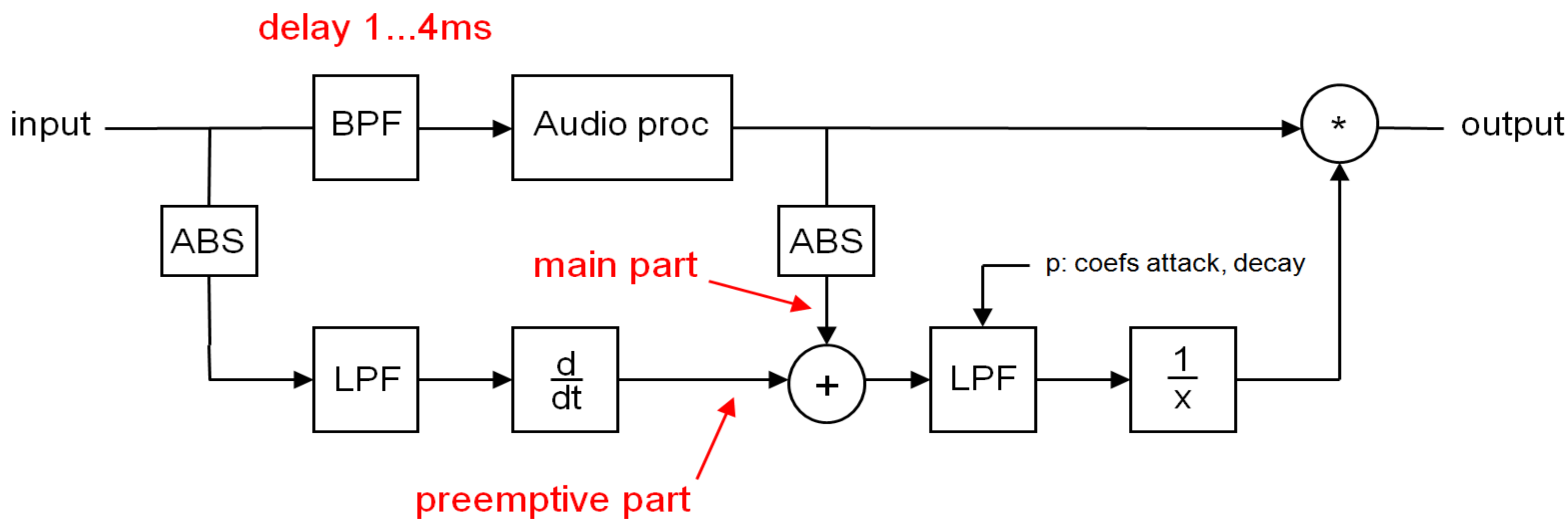


The broadband AGC serves to protect the AD converter from overvoltages. The RF-AGC can be used to set the receiver sensitivity just below the external noise.

The digital processing part is free from distortions, therefore the final AGC can be placed near the analog output.

Automatic Gain Control, Cont'd.

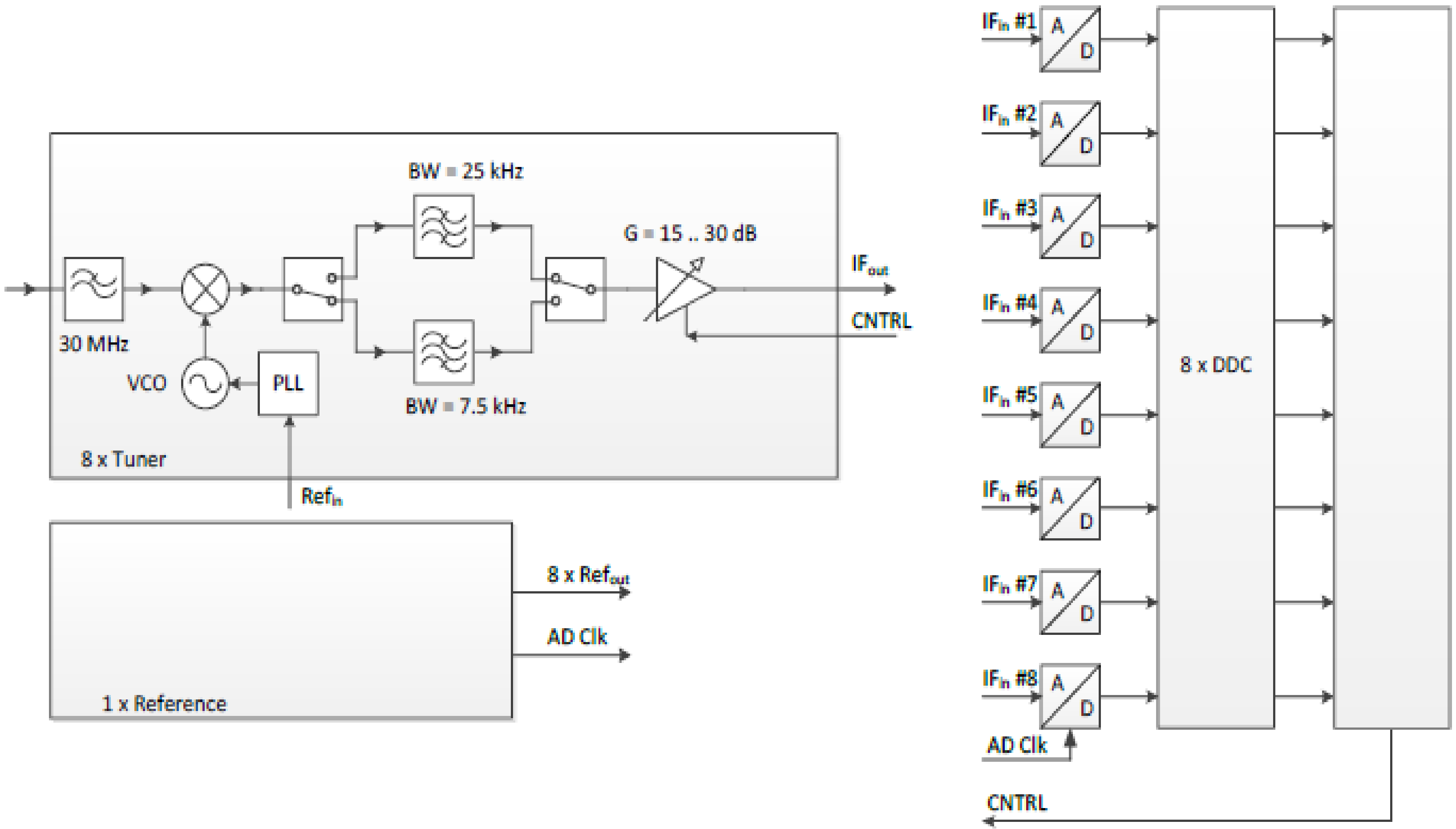
Automatic Gain Control



The main AGC control is realized near the of the signal processing chain as a feed forward control.

Typical Multi-Channel Receiver

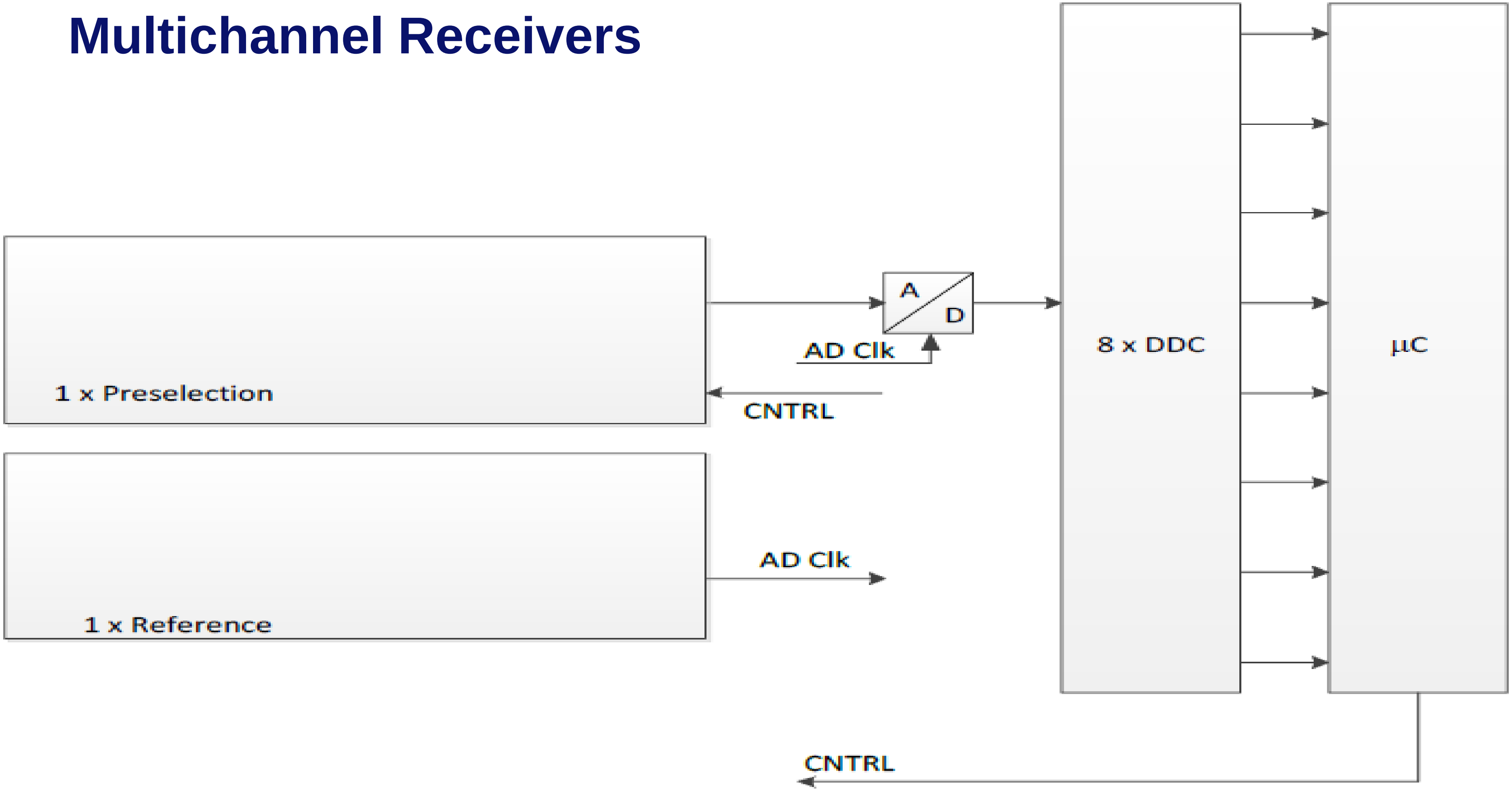
Multichannel Receivers



N - channel Receiver with N analog front ends

Receiver, Cont‘d.

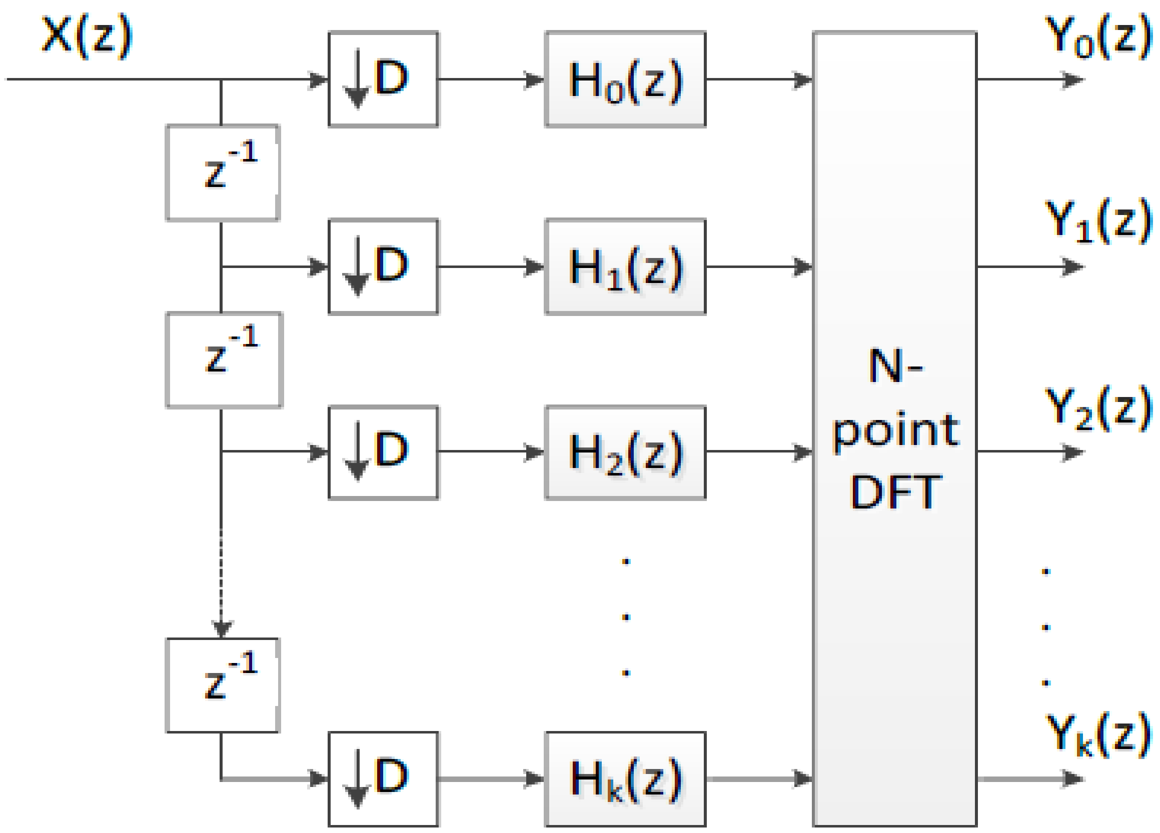
Multichannel Receivers



N - channel Receiver with only one analog front end and N digital down converters. The channel frequencies must be allocated inside the preselector passband.

Receiver, Cont‘d.

Multichannel Receivers



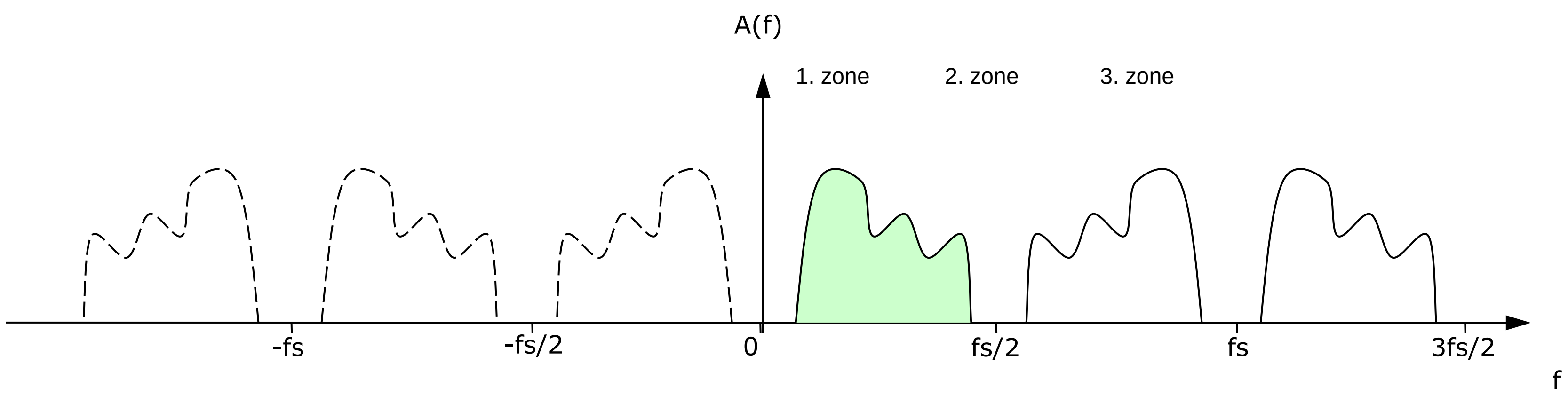
“Polyphase Filters” is often incorrectly taken to mean some special kind of filter… instead, it is merely a special structure that is handy when using filters in multi-rate settings.

Polyphase is a way of doing sampling-rate conversion that leads to very efficient implementations.

If all channels are equally spaced, then a **Polyphase Filter bank** can replace the multiple channels in the downconverter

Typical Characteristics of Sampled Systems

Important Characteristics of sampled Systems



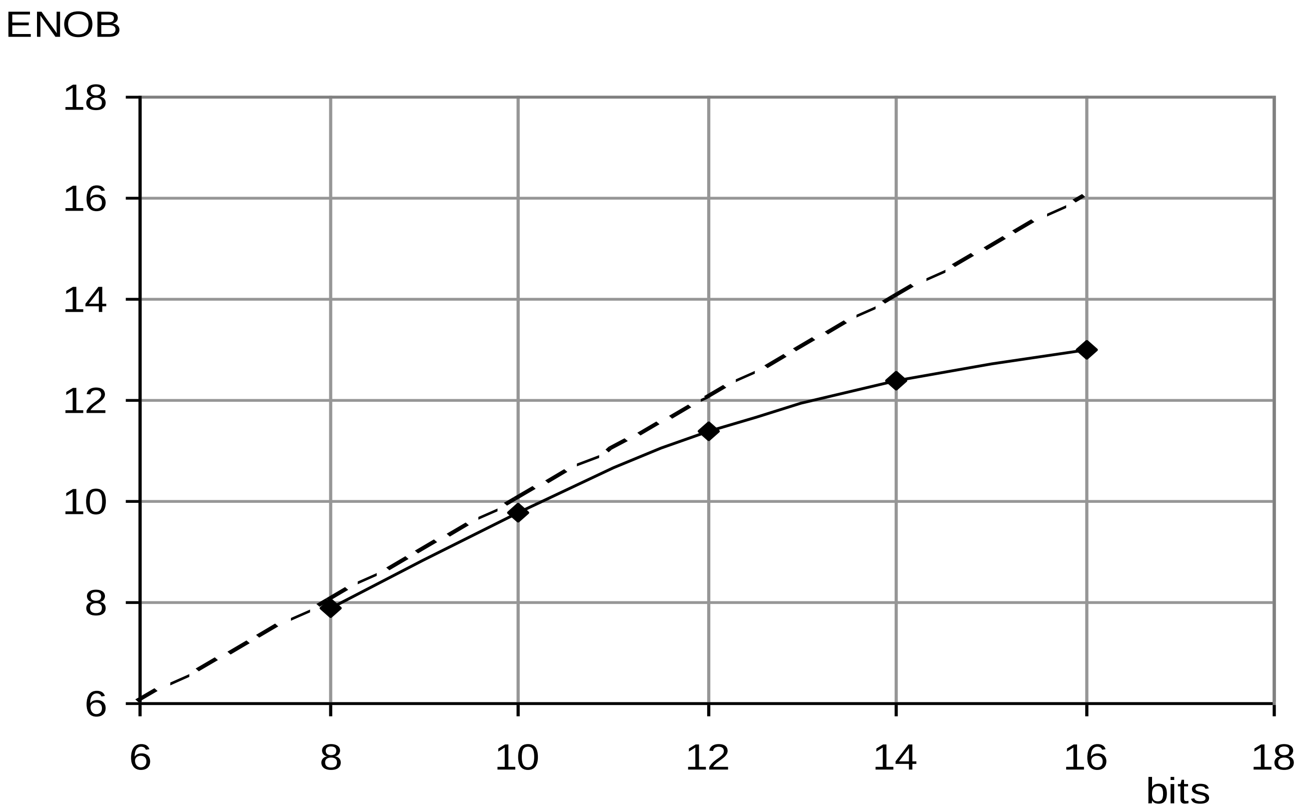
The Sampling Theorem (Nyquist / Shannon)

- **A bandlimited signal can be reconstructed, when B < fs/2**
- **Due to aliasing, replicas in all Nyquist zones will occur**
- **The aliasing effect can be used to sample a bandlimited signal B in a higher Nyquist zone (bandpass- or undersampling)**

B = (n – 1) · fs/2 ... n · fs/2 whereas n is the zone (1,2, …)

Typical Characteristics of AD Converters

Characteristics of AD Converters



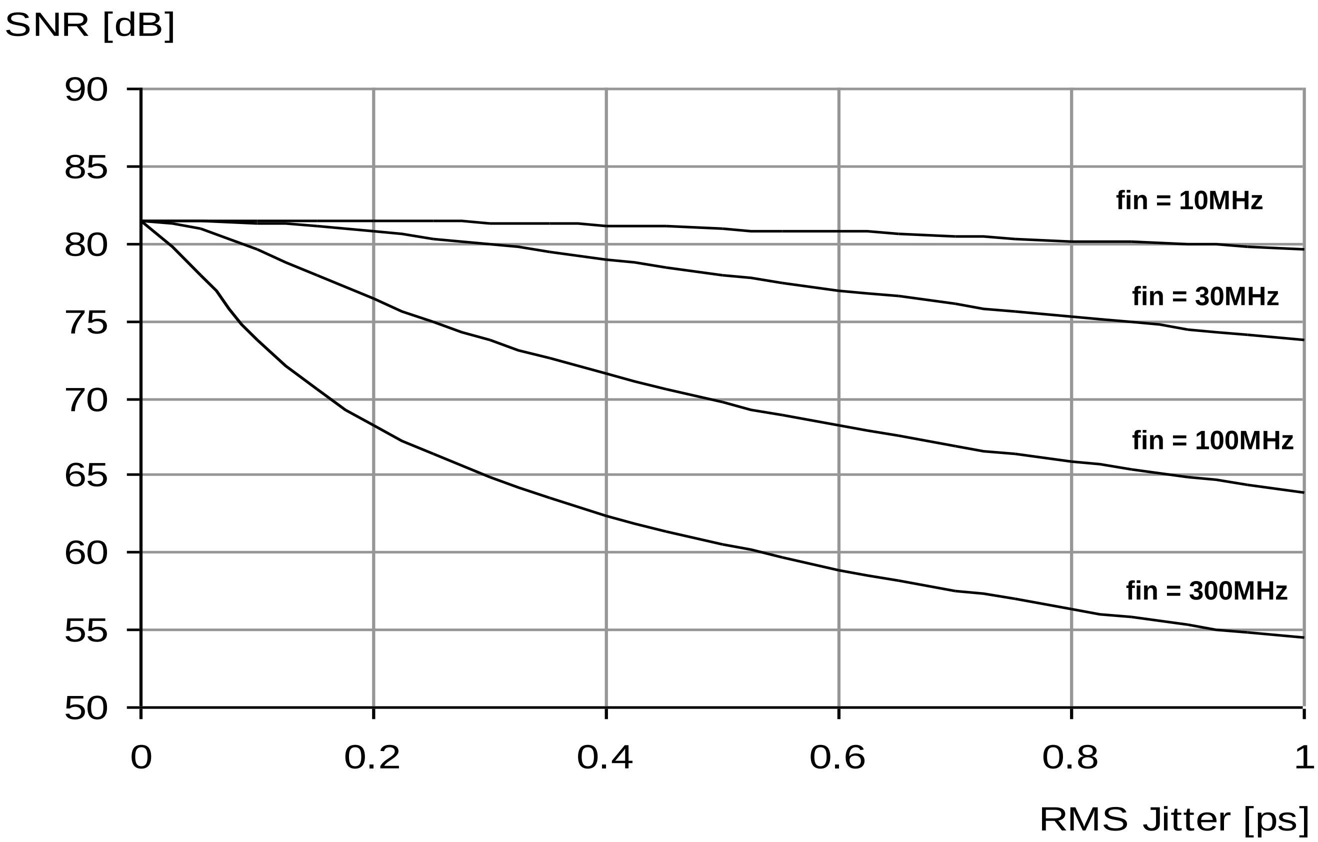
ENOB: the Effective usable Number Of Bits

$$SNR_{eff} = 1.76dB + ENOB \cdot 6.02dB$$

(measured in B = fs/2)

Characteristics of AD Converters, Cont'd.

Characteristics of AD Converters

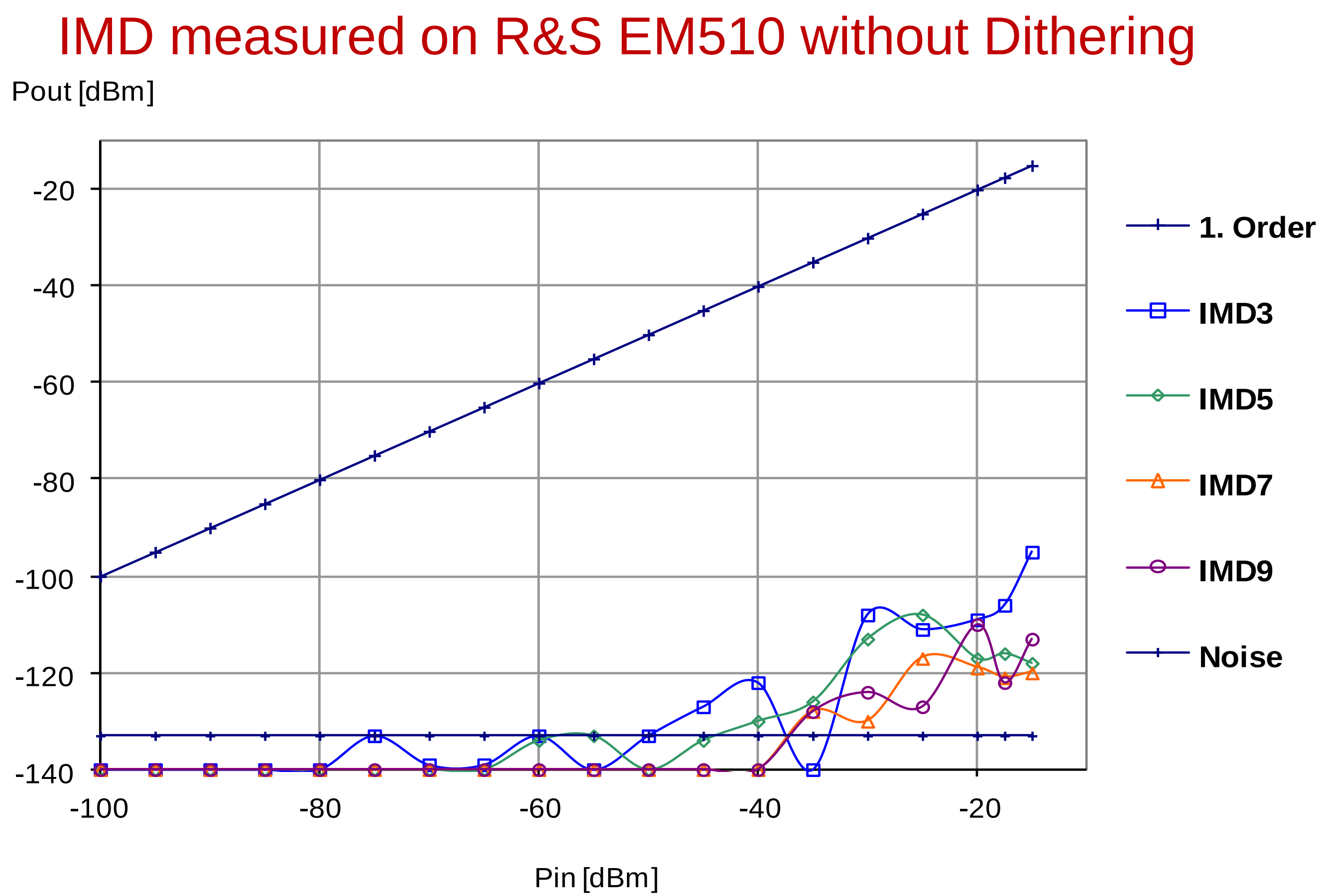


Degradation of SNR by clock jitter

very important when applying undersampling!

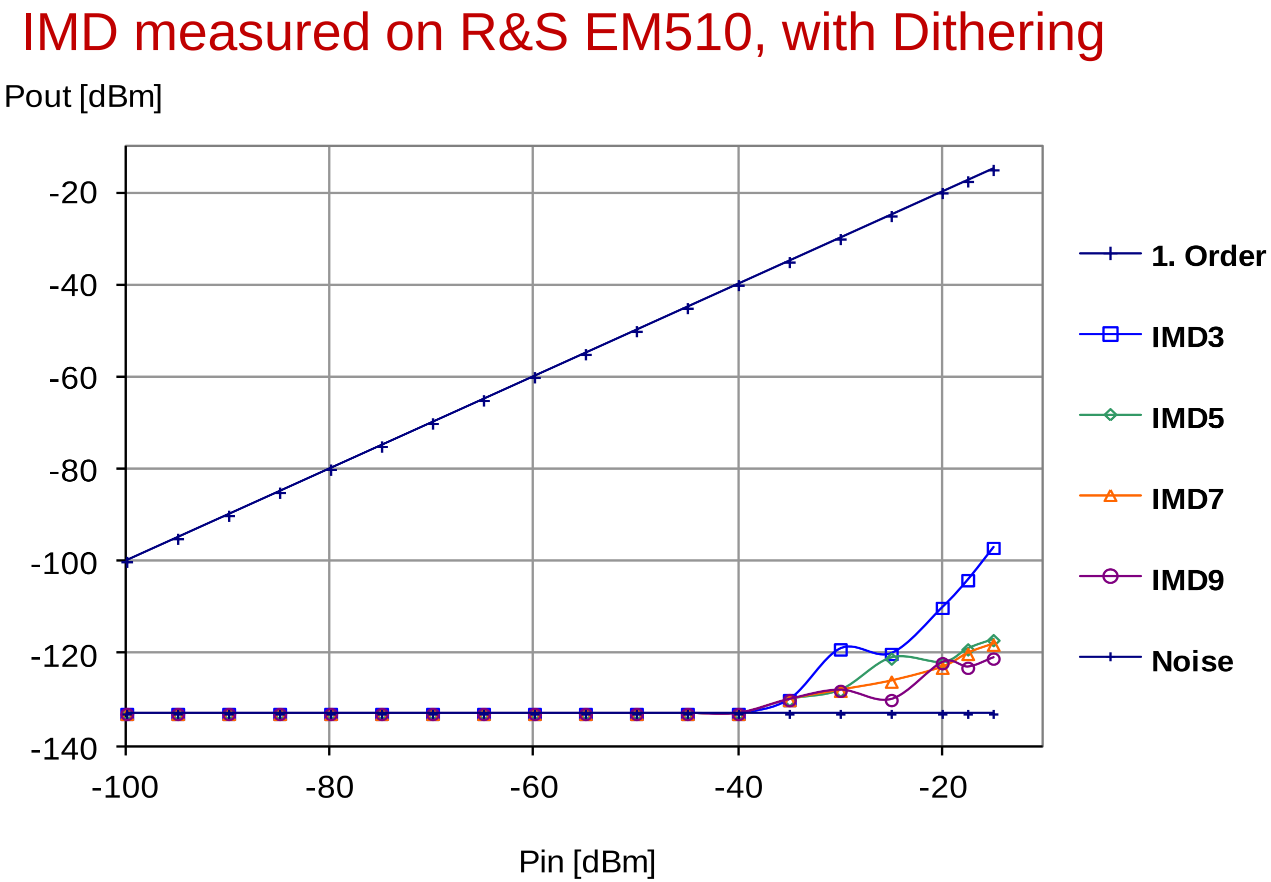
Characteristics of AD Converters

Important Characteristics of AD converters



Higher order intermodulation products as a function of the input signal. The known relationship of n·dB/dB (n = order of IM) can not be applied. Therefore an Intercept point cannot be calculated. In practice, the IM is measured with two tones on -7dBm

Important Characteristics of AD converters



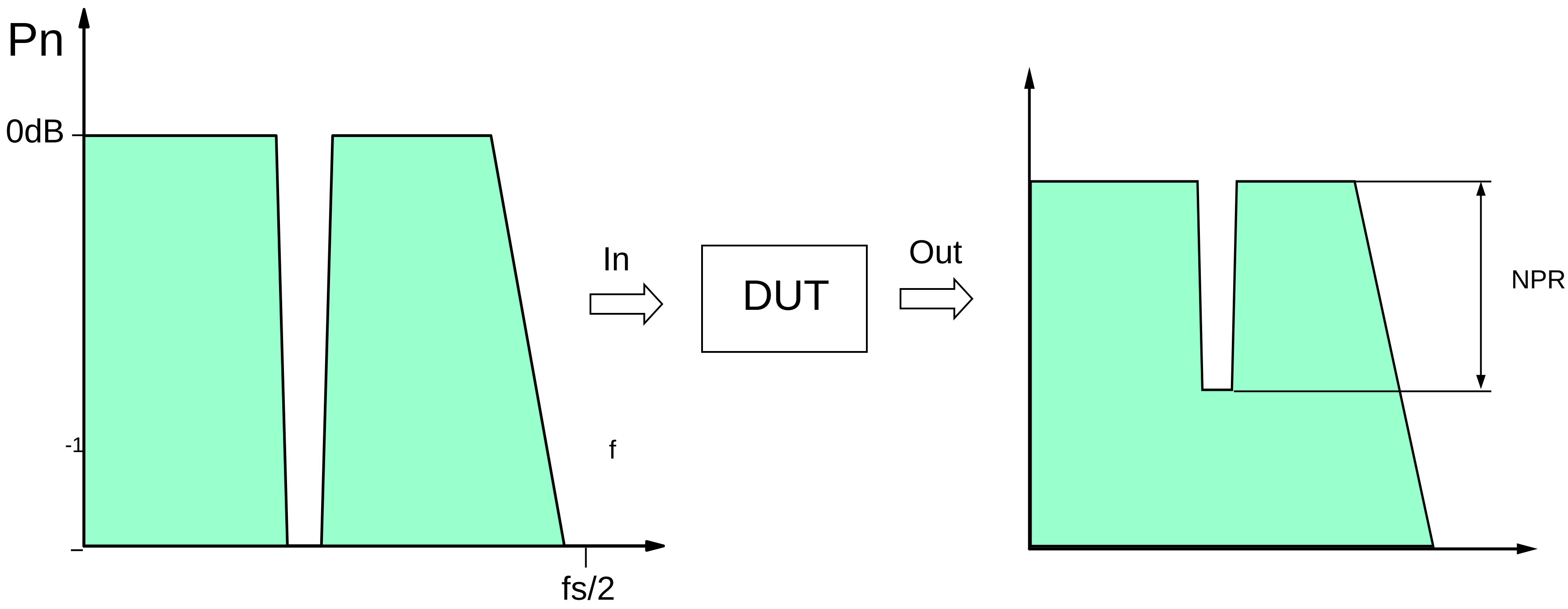
Applying dithering noise has the effect, that the discontinuities are no longer periodic and therefore the spuriies are reduced.

Characteristics of AD Converters

Important Characteristics of AD converters

Altrernative Methode for IM measuring

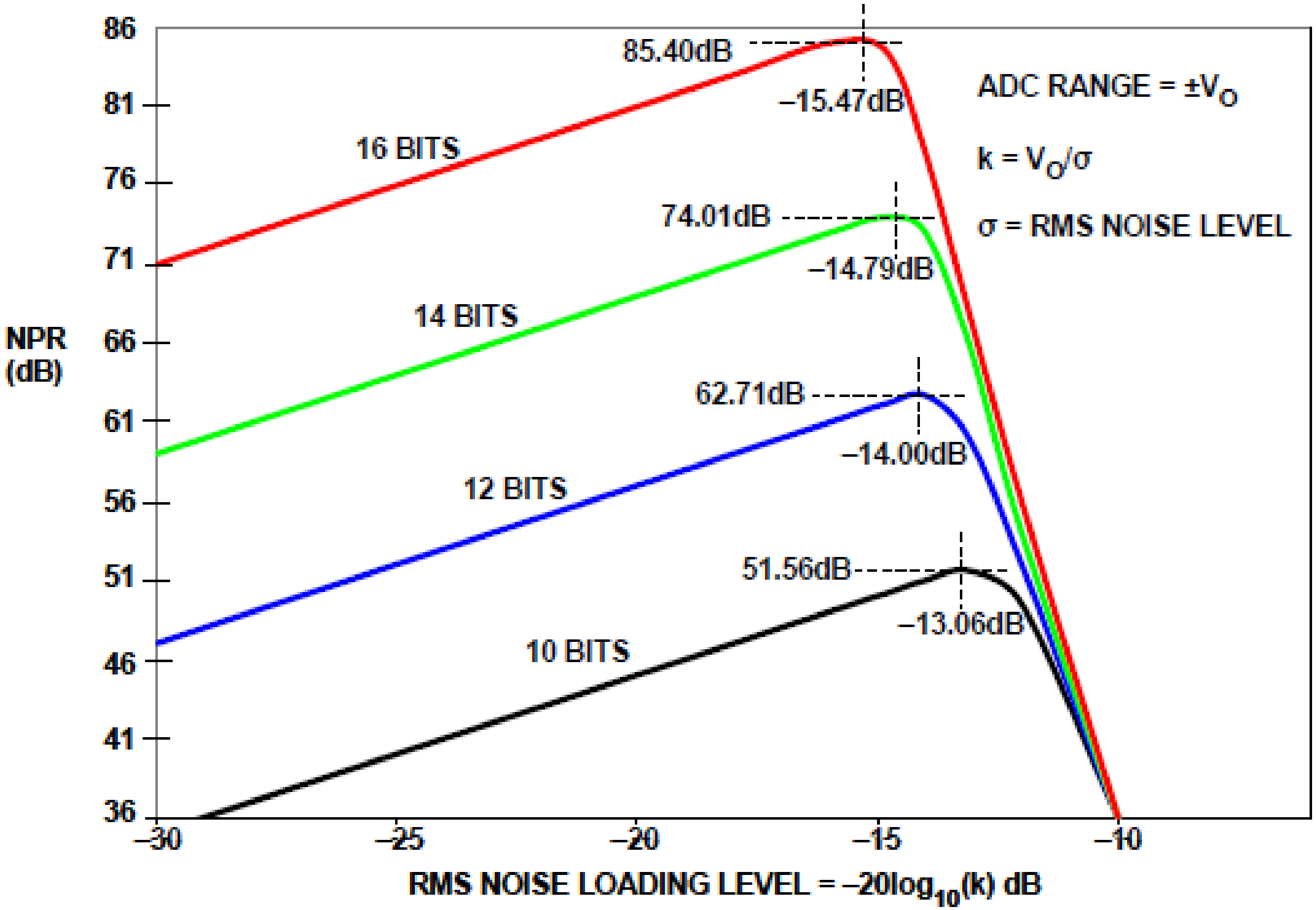
The Noise Power Ratio



The NPR methode reflects the true impact of intermodulation from any order

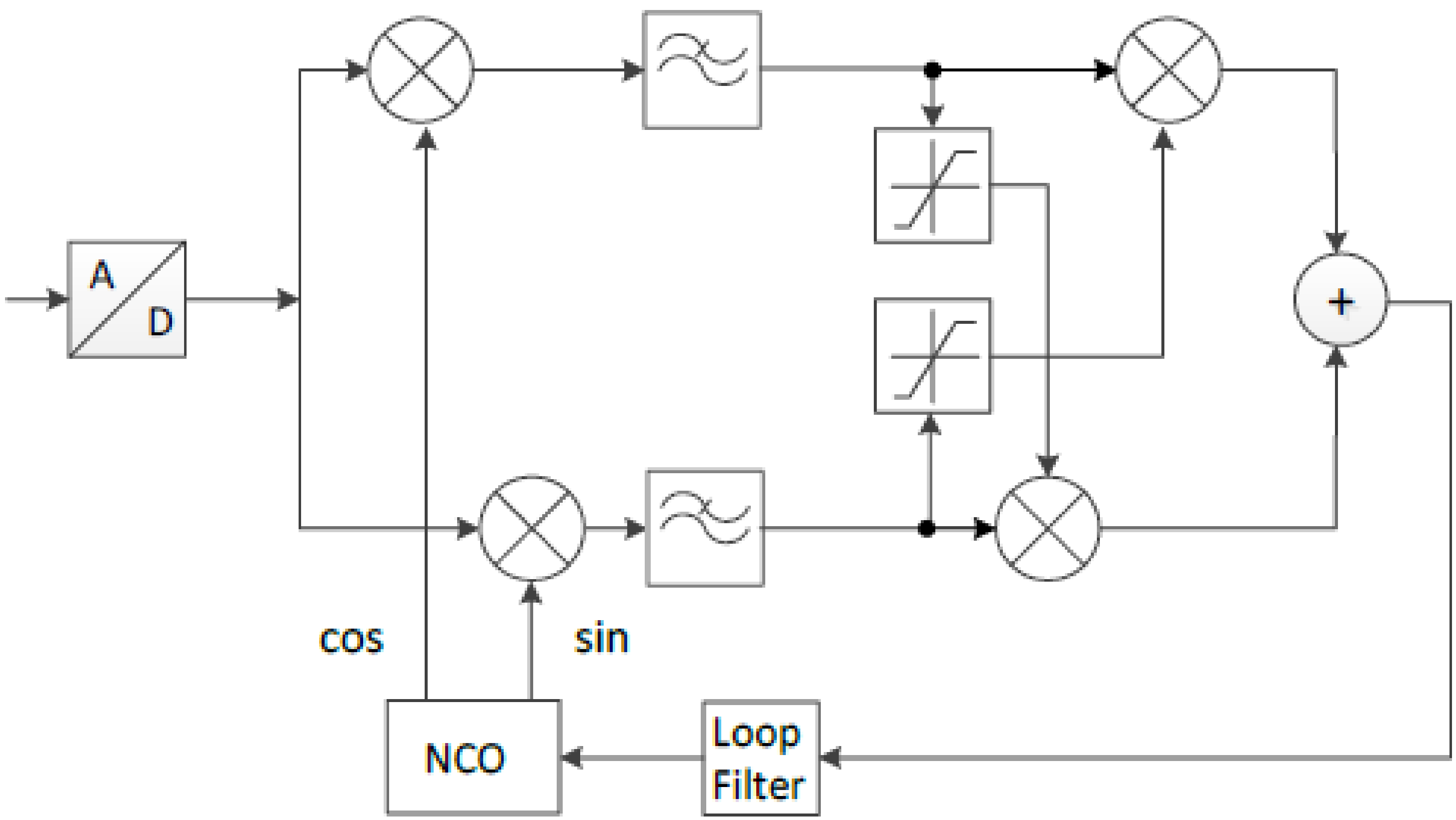
Characteristics of AD Converters

Important Characteristics of AD converters



Theoretical NPR for 10, 12,14 and 16bit AD converter

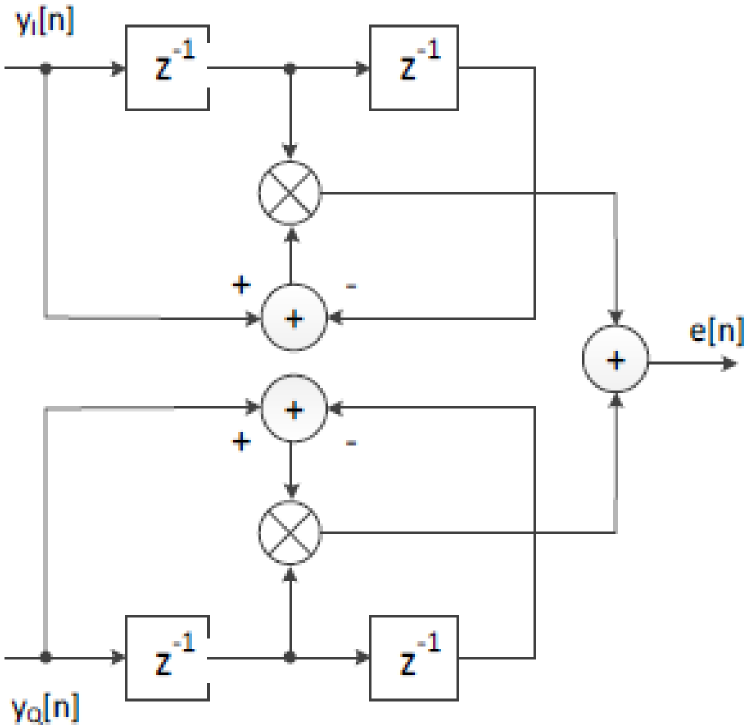
Carrier Recovery for Data Communication

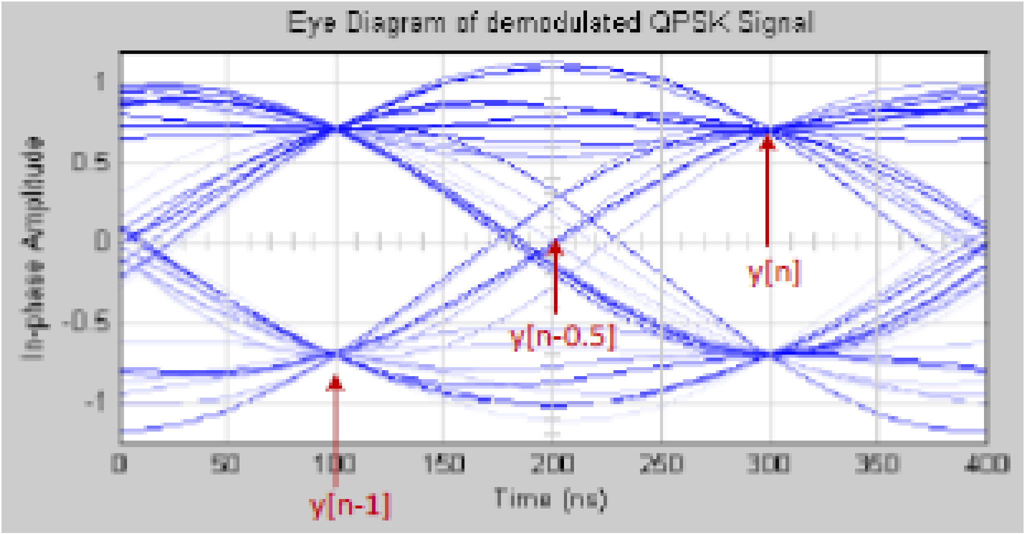


Example for the carrier synchronisation for a QPSK modulated carrier.

Data Clock Extraction

Data clock extraction for Data Communication

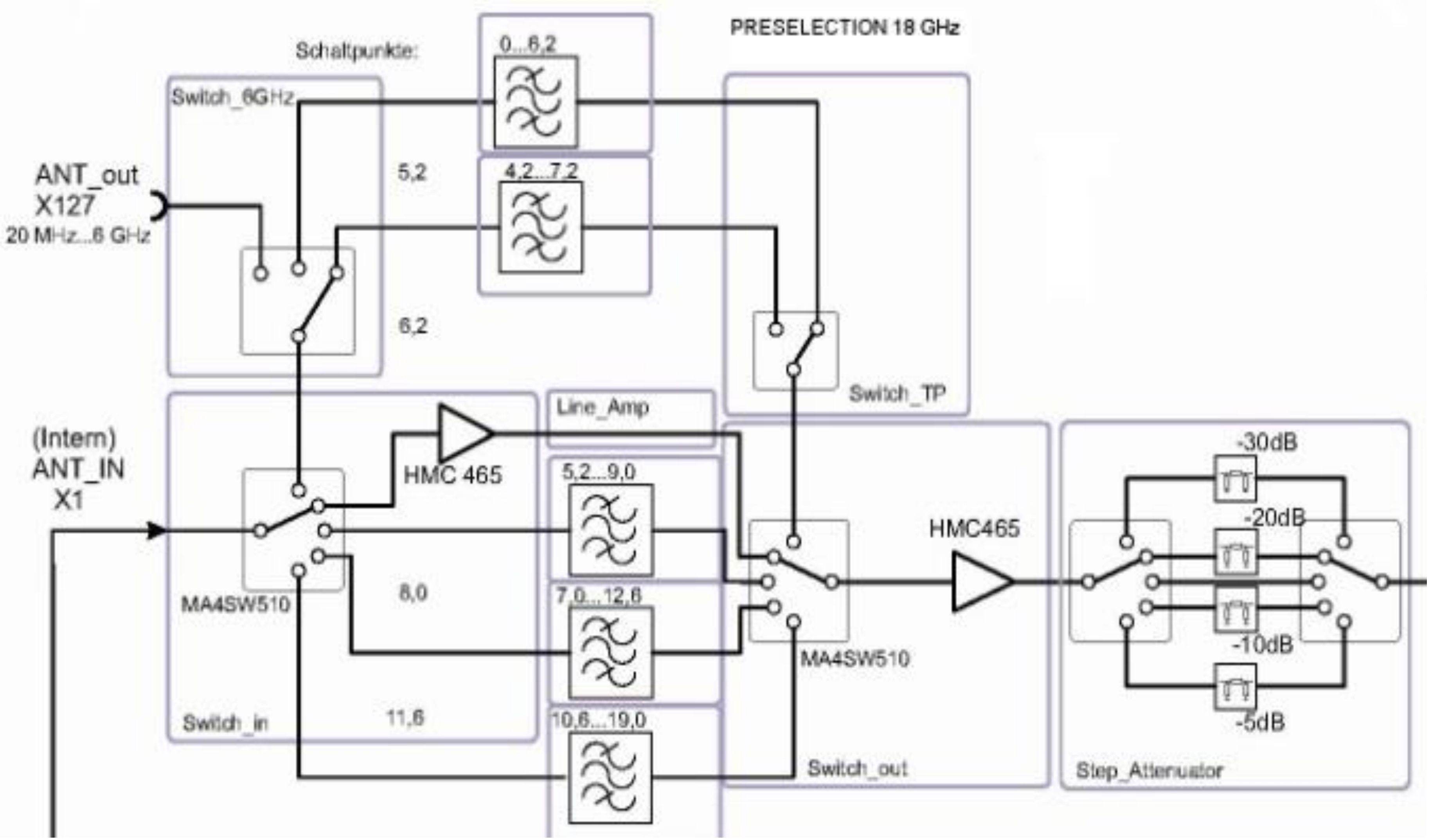




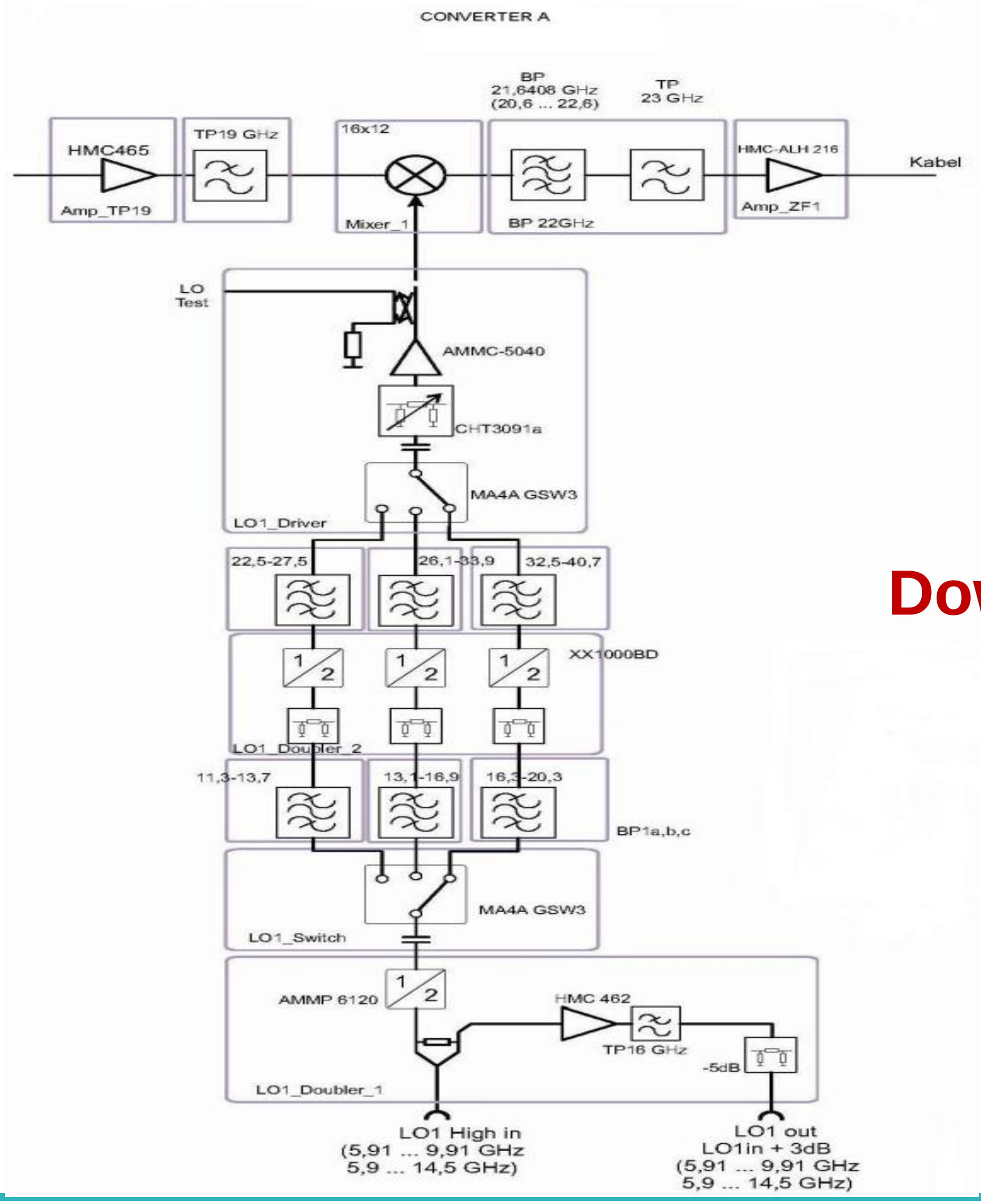
Example for a Timing Error Detector for a QPSK modulated signal according to Gardner.

Typical Architecture of Communication Receiver

Filter portion of the front-end of the receiver

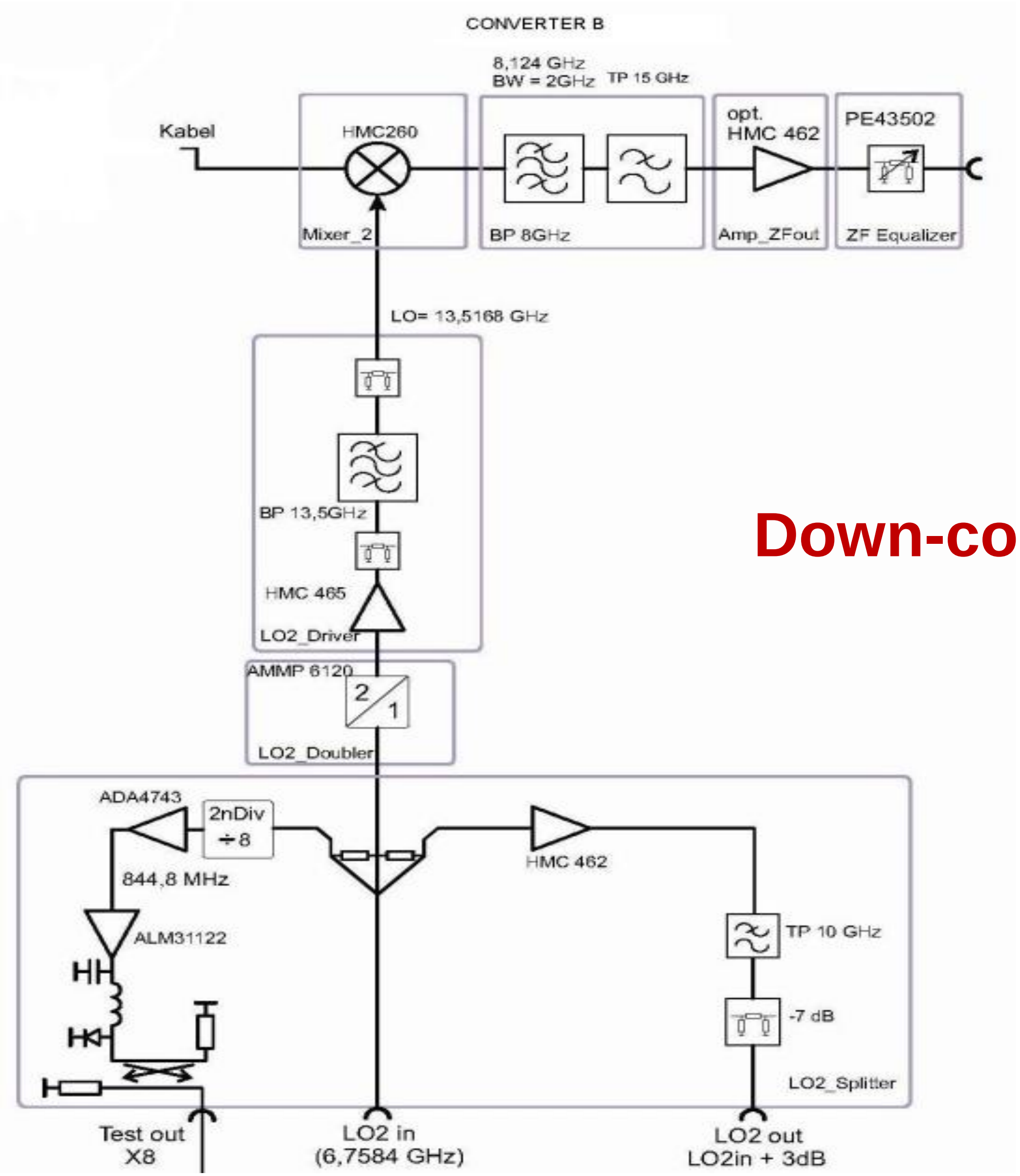


Typical Down-Conversion Architecture



Down-converter of the receiver

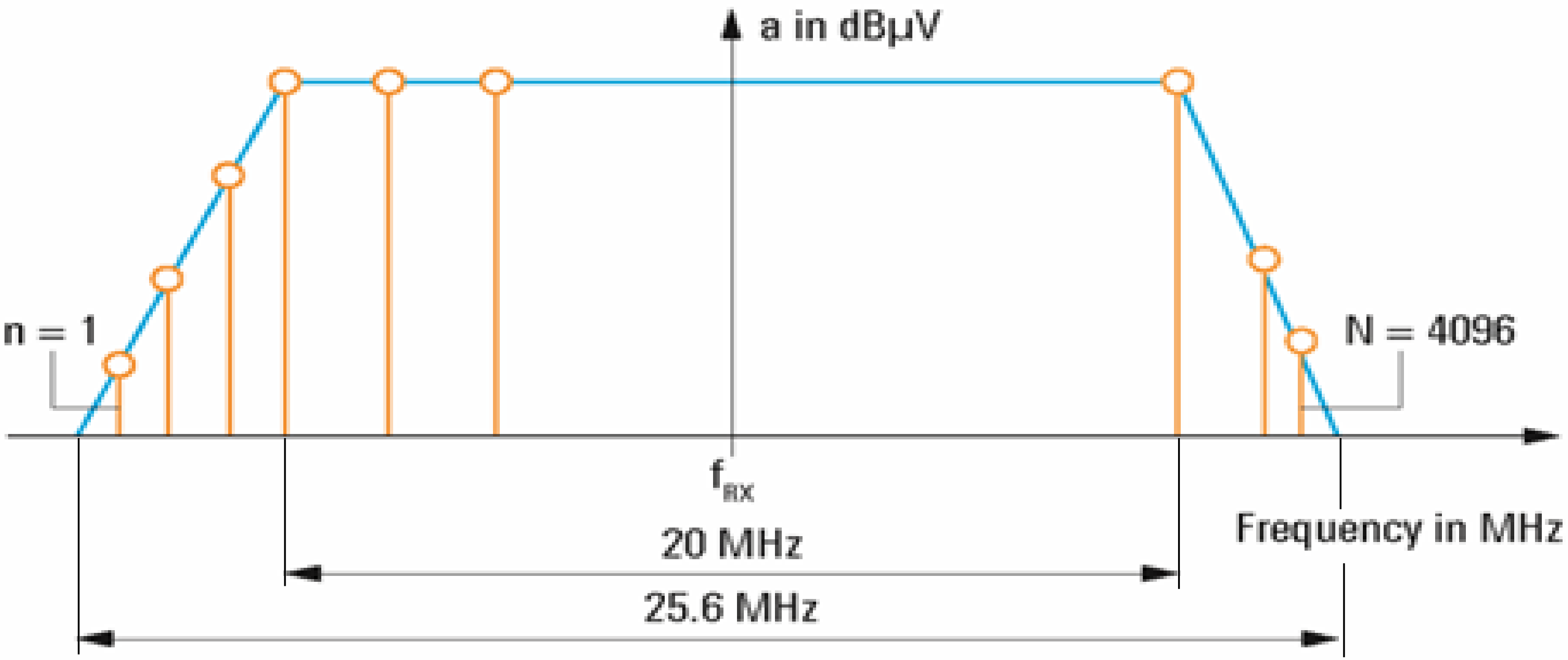
Typical Down-Conversion Architecture



Down-converter of the receiver

Spectrum Analysis in Receiver

Spectrum Analysis in Communication Receivers



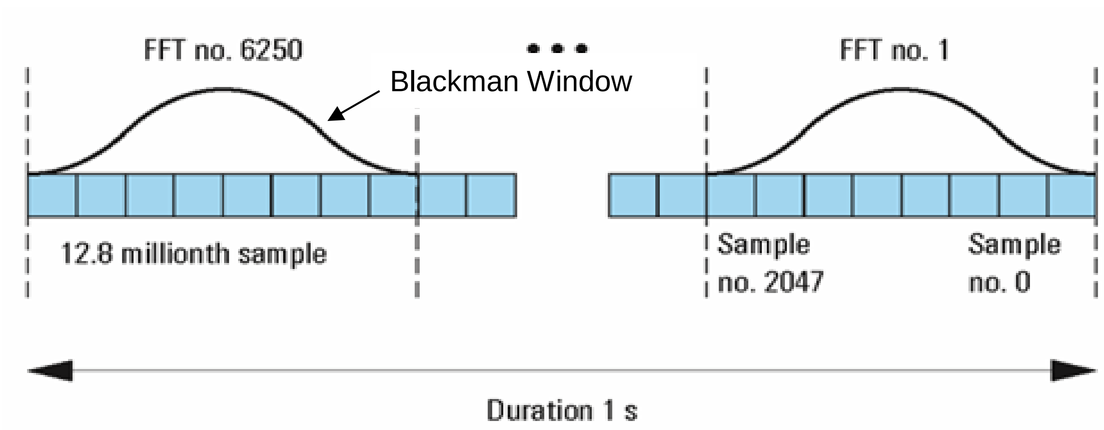
The actual usable bandwidth is reduced by a factor k compared with the sampling rate fs:

$$B_{eff} = fs / k$$

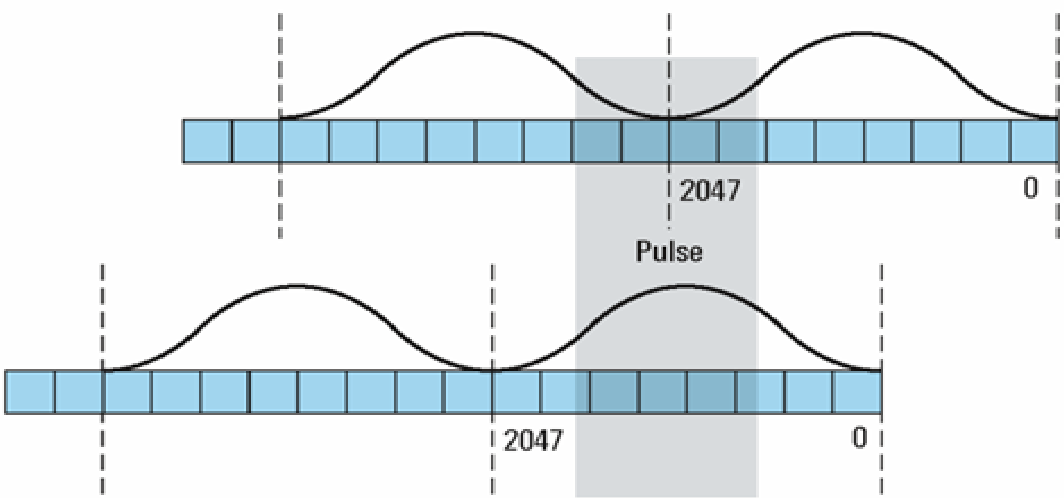
In this exemple k = 1.28

Spectrum Analysis in Receiver, Cont'd.

Spectrum Analysis in Communication Receivers



An fs = 12.8Msps allows to process 6250 FFTs per second



Due to the applied window function, the capability to detect short pulses at both ends of the window is reduced

Solution: overlapping FFTs

Spectrum Analysis in Receiver, Cont‘d.

Spectrum Analysis in Communication Receivers

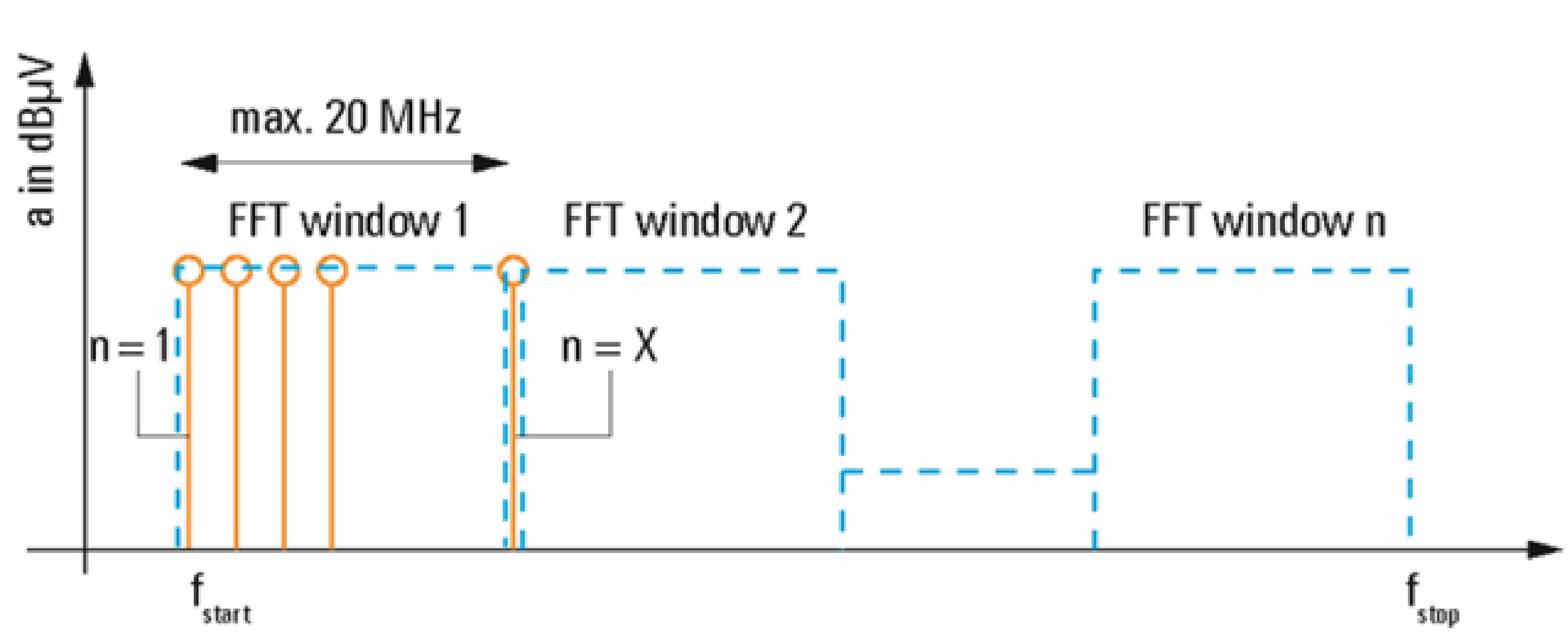
Computing Power for overlapping 2048 bins FFT and fs = 12.8Msps:

≈ 2GFLOPs (Floating Point Operations)

Internal computing power of the R&S®ESMD		
Frequency -resolution in kHz	80 MHz realtime -bandwidth	
	Spectra per second	Time resolution in is
25	25 000	40
50	50 000	20
100	100 000	10
500	500 000	2
2000	2 000 000	0.5

Spectrum Analysis in Receiver, Cont‘d.

Spectrum Analysis in Communication Receivers

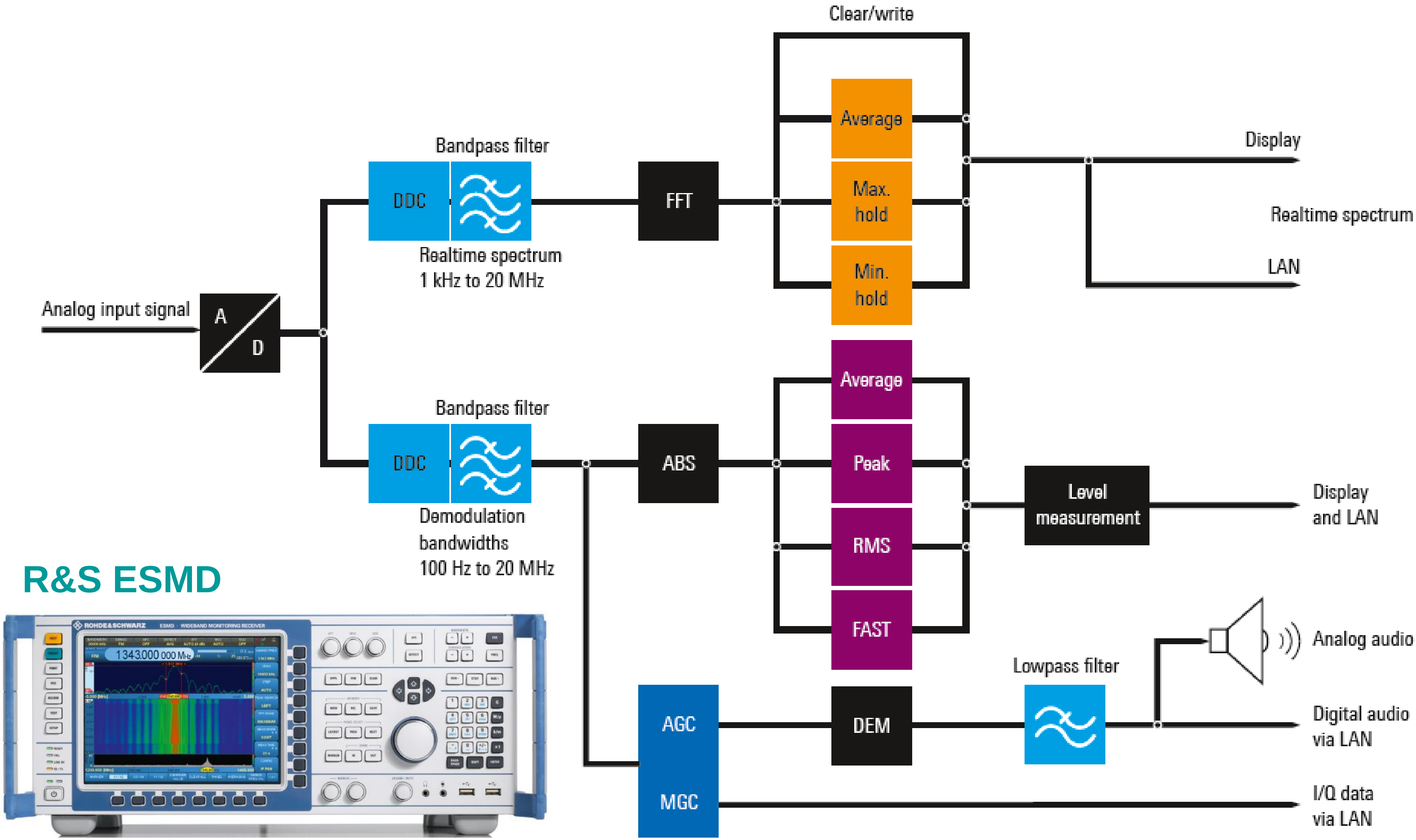


Panorama Function with N consecutive FFT slices

⇨ for any bandwidth, but lacks in time resolution

Widebnad Monitoring Receiver

Figure 1: R&S ESMD Wide Band Monitoring Receiver

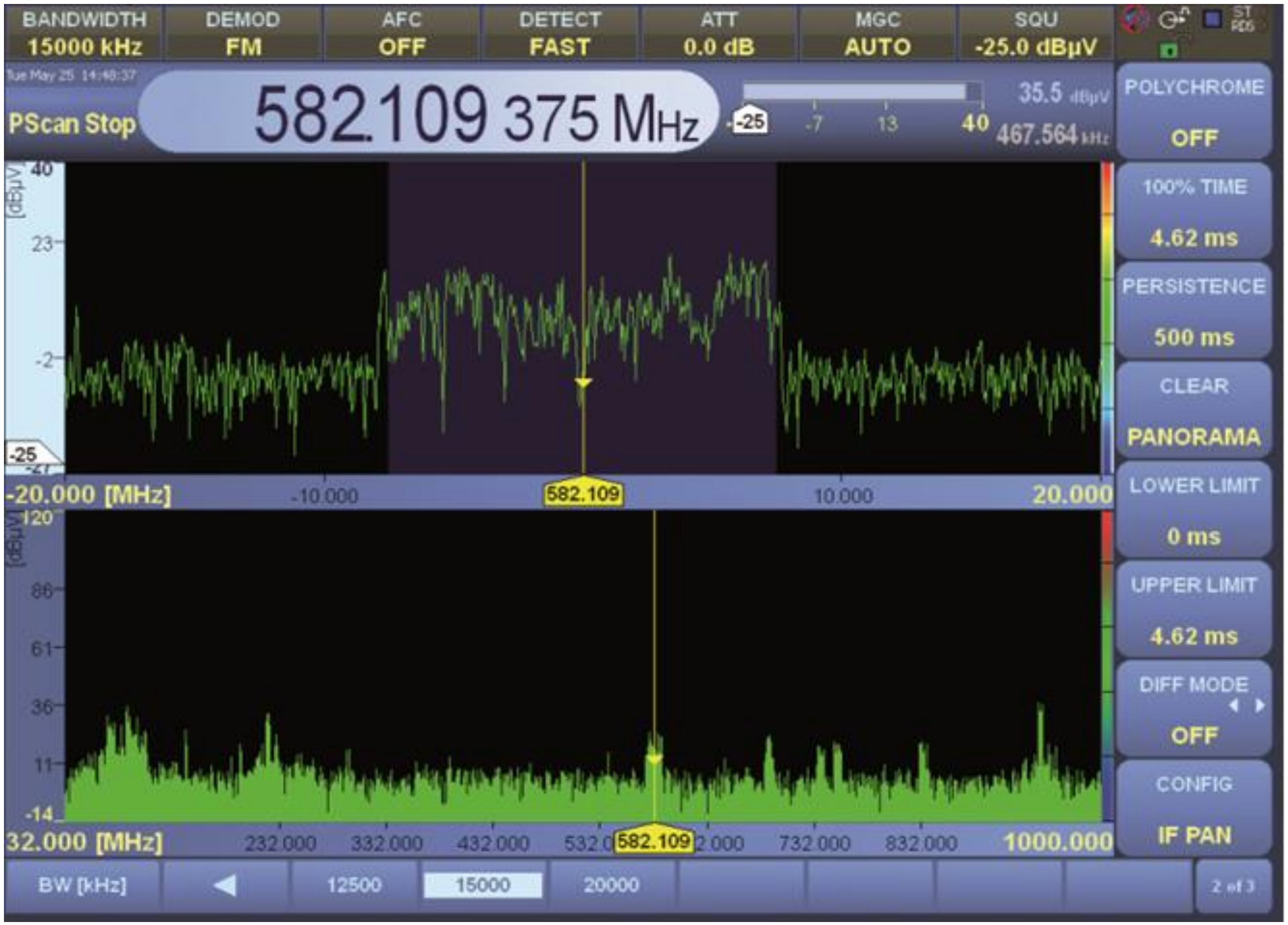


R&S ESMD

High Dynamic Range

Spectrum Analysis in Receiver, Cont‘d.

Spectrum Analysis in Communication Receivers

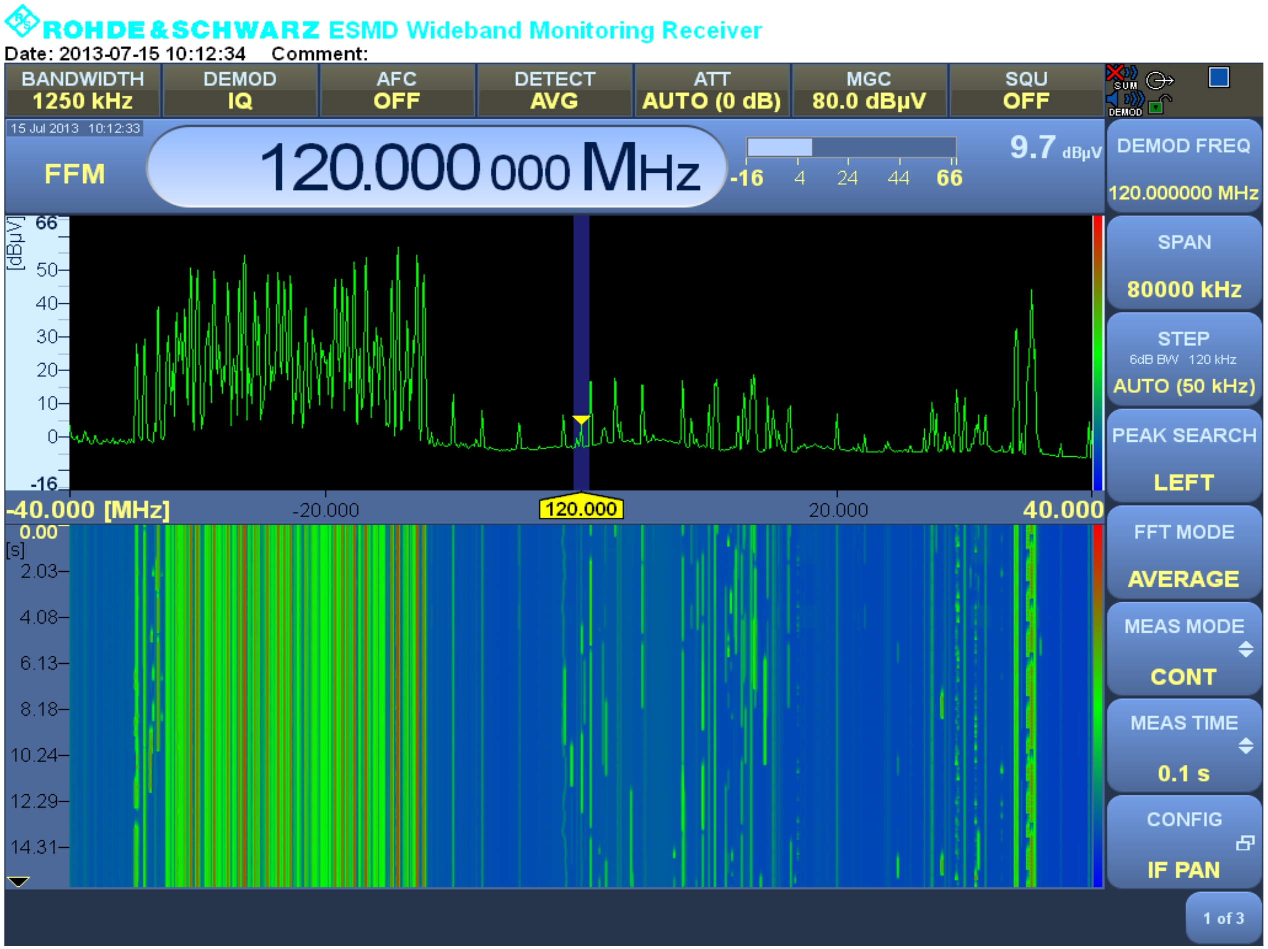


Narrowband Analysis

Wideband Analysis

Spectrum Analysis in Communication Receiver

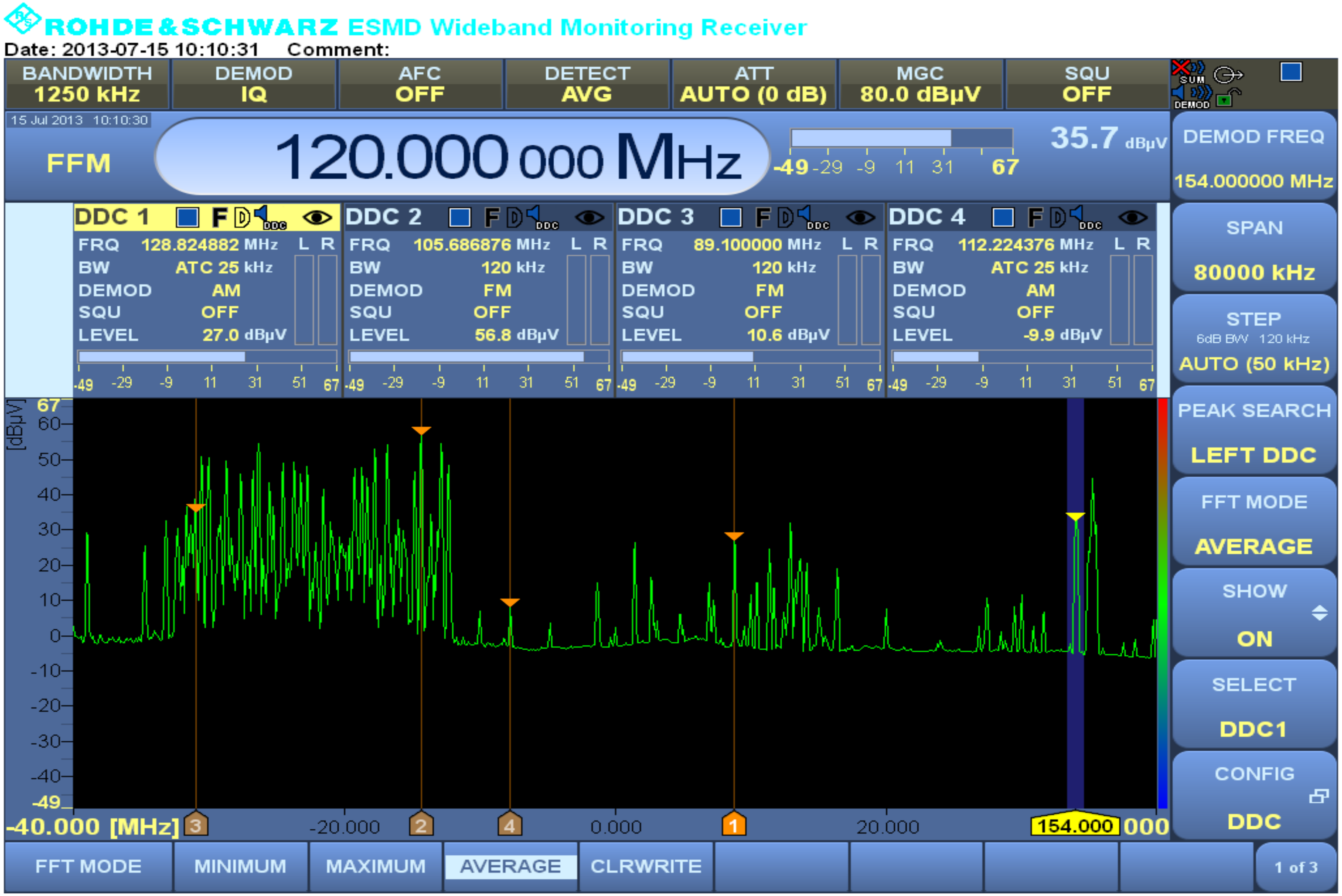
Proof of Available Dynamic Range



Aircraft Radio Communication Receiver can be monitored abd demodulated in the presence of strong FM Radio signal

Spectrum Analysis in Communication Receiver

Multichannel (4) Operation

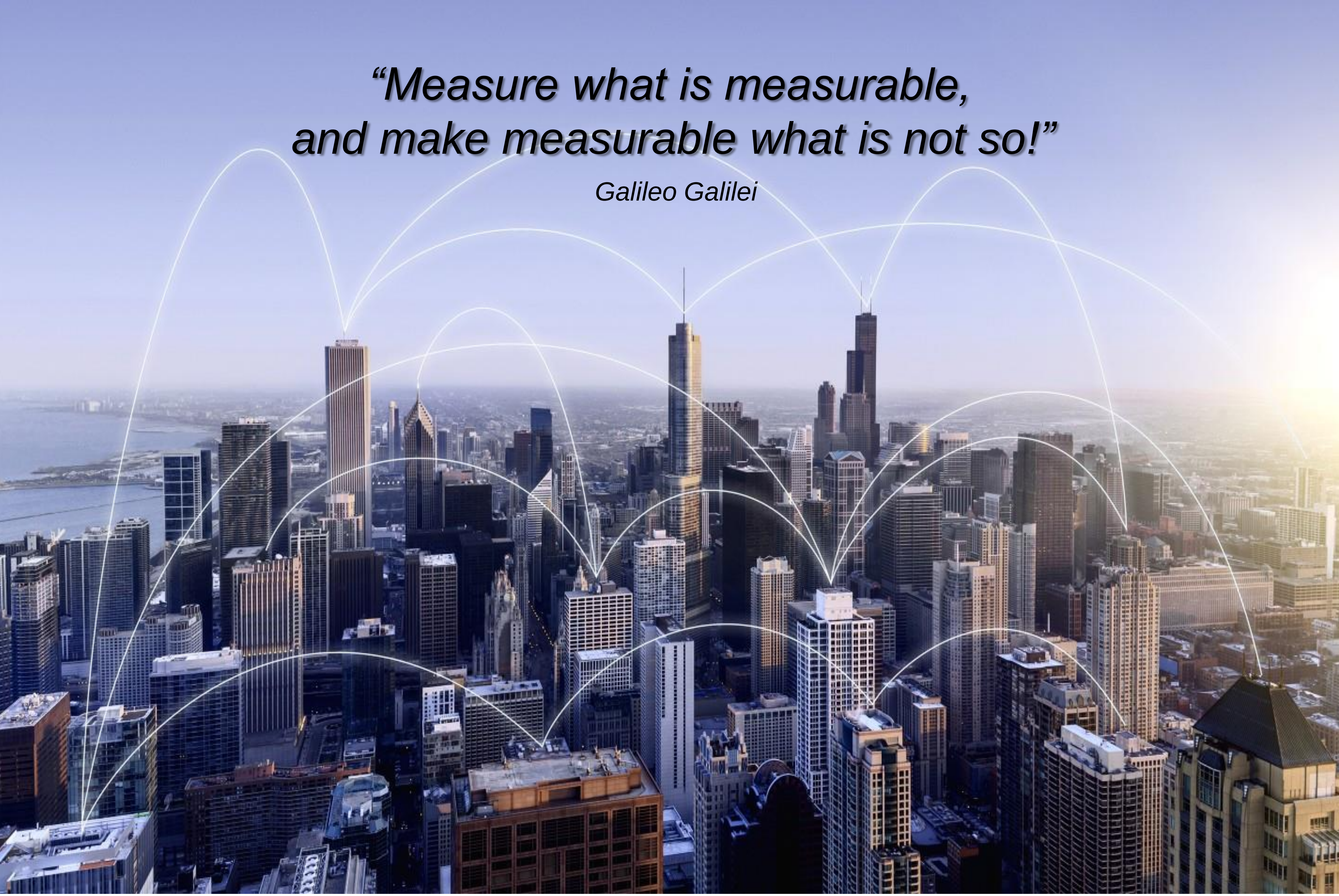


All 4-Channels can be anlayzed

Antenna for Communication Receiver

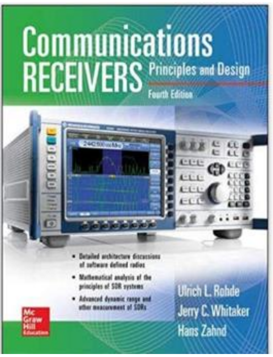
Typical Antennas for high dynmaic range Communications Receivers

Input level up to 0 dBm !


“Measure what is measurable,
and make measurable what is not so!”
Galileo Galilei

References


Ulrich L. Rohde “radio house”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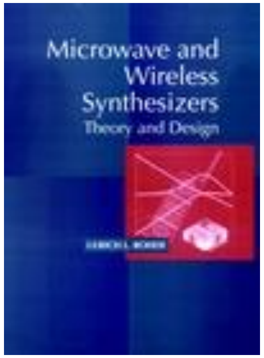
Ulrich L. Rohde
Jerry C. Whitaker
Hans Zahnd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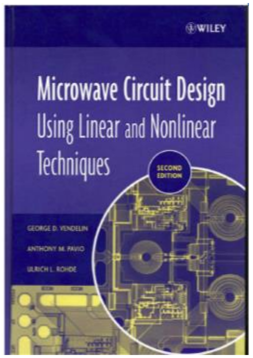
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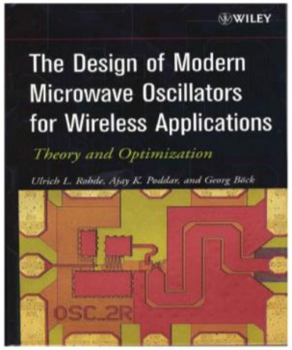
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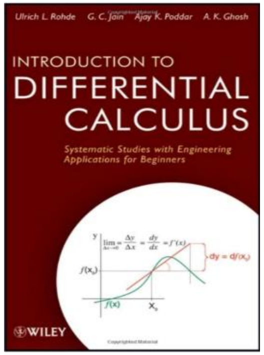
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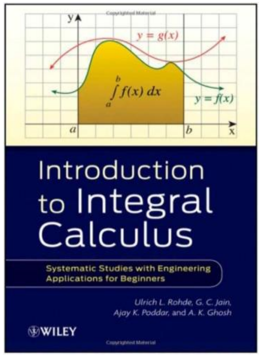
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