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

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

Prof. Dr. Ing. Habil Ulrich L. Rohde
Chairman, Synergy Microwave Corp., NJ, USA
Partner, Rohde & Schwarz, Munich, NJ
Professor, Oradea Univ., Romania
Professor, BTU Cottbus, Germany
Hon. Chair Prof. IIT-Jammu, India
Hon. Professor, IIT-Delhi, India
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
Transforming our world
Through intelligent connected platforms

Mobile
Last 30 years
Interconnecting people

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

IoT
Next 30 years
Interconnecting their worlds

Courtesy: Qualcomm Technologies
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 Series 4100 Software Defined Radios

HF radio family for stationary and shipborne communications
Radio Follows Moore’s Law Too

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

SDR Architecture

Programmable Hardware – DSP, FPGA, ASIC

Flexible RF Hardware

- Sample Rate Conversion
- Baseband I/Q

PC

Hardware Part

Output

Input

DAC

ADC
Why SDR?

High Performance Radio Needed Everywhere!
Why SDR?

First-Responder Communications Failures

- SDR will facilitate radio interoperability

11 September 2001

Hurricane
Why SDR?

Deep Space Communications

- SDR allows old and new protocols
Why SDR?

Spectrum space as a scarce resource

- SDR will enable spectrum reuse
All Spectrum May Be Assigned, But…

Most Spectrum Is Unused!


Goal: 10 Folds increase in spectrum access
SDR (Software Defined Radio)

• Definition:
  A Software Defined Radio (SDR) is a communication 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):

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

Antenna

Variable Frequency Oscillator

Local Oscillator (fixed)

Band Pass Filter

RF

IF

Baseband

ADC/DAC DSP
Oscillator Phase Noise - 1

Measured SSB phase noise with internal reference oscillator (standard instrument).

![Graph showing measured SSB phase noise with internal reference oscillator. The x-axis represents frequency (1 Hz to 100 MHz) and the y-axis represents SSB phase noise (dBc/Hz). Different curves represent different frequencies (6 GHz, 3 GHz, 1 GHz, 100 MHz, and 10 MHz).]
Oscillator Phase Noise - 2
Oscillator Phase Noise – 3

IC - PLL
Frequency Generation

Vector Signal Generator

- Synthesis
- IQ Output Unit 6 GHz
- IQ Output Unit 20 GHz
- Baseband

Connections:
- SYN_6GHz to IQ Output Unit 6 GHz
- RF_6GHz from IQ Output Unit 6 GHz
- LO_6GHz to IQ Output Unit 20 GHz
- RF_20GHz from IQ Output Unit 20 GHz
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

Antenna → RF → Local Oscillator (fixed) → IF → ADC/DAC → DSP → Baseband

Antenna → RF → ADC/DAC → IF → DSP → Baseband
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!!!

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.
## Present Technology and Planned 5G Spectrum

### Sub-6 GHz
- 700 MHz – 3 GHz
- 3 GHz – 6 GHz

### Millimeter Wave
- 24.25 GHz – 29.5 GHz
- 37 GHz – 71 GHz

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

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)

<table>
<thead>
<tr>
<th>2G GSM</th>
<th>3G TD-SCDMA</th>
<th>4G TD-LTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>830,000 base stations</td>
<td>350,000 base stations</td>
<td>800,000 base stations</td>
</tr>
<tr>
<td>80 GWH (96 KWH per BTx)</td>
<td>13 GWH (37 KWH per BTx)</td>
<td>16 GWH (20 KWH per BTx)</td>
</tr>
</tbody>
</table>

### Radio Access Network Energy Consumption

- **Air-Con**: 3%
- **Equipment**: 46%
- **Electricity**: 41%
- **Rent**: 31%
- **Tx**: 7%

Biggest CAPEX/OPEX Expense is Air Conditioning

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

Source: IEEE Communications Magazine, Feb 2014

### Service Type

<table>
<thead>
<tr>
<th>Type</th>
<th>Ratio (%)</th>
<th>Packet Size (kB)</th>
<th>Data to Signaling Ratio (DSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Text/IM</td>
<td>60</td>
<td>1</td>
<td>1 to 3</td>
</tr>
<tr>
<td>Voice</td>
<td>35</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Photo</td>
<td>4</td>
<td>150</td>
<td>65 to 375</td>
</tr>
<tr>
<td>Video</td>
<td>1</td>
<td>1500</td>
<td></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th>Equipment</th>
<th>Air Con</th>
<th>Switching</th>
<th>Battery</th>
<th>Transmission</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>0.65 kW</td>
<td>2.0 kW</td>
<td>0.2 kW</td>
<td>0.2 kW</td>
<td>0.2 kW</td>
<td>3.45 kW</td>
</tr>
<tr>
<td>Cloud Radio</td>
<td>0.55 kW</td>
<td>0.01 kW</td>
<td>0.2 kW</td>
<td>0.1 kW</td>
<td>0.0 kW</td>
<td>0.86 kW</td>
</tr>
</tbody>
</table>

High bandwidth optical transport network

Distributed configurable wideband RRU
Spectral Efficiency

\[ C = W \log_2 \left( 1 + \frac{\gamma}{\text{SNR}} \right) \]

**Shannon Channel Information Capacity**

- Capacity (bits/second)
- Signal BW (Hz)
- SNR (S/N)

**More channels = MIMO (5G FR1)**
- Linear increase

**Massive MIMO**

- M = 4 transmitters

**SNR increase (log2 increase)**

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

**FR1: Sub-6GHz**

**FR2 mmWave: 24-90 GHz**

**Coverage, Mobility, Reliability**

**High Capacity, Massive Throughput**

**Fiber**

(distributed) BU
Energy Efficiency: Why Massive?

Number of antennas = 1

Number of BS transmit antennas | 1
---|---
Normalized output power of antennas | $P_{ant} = \frac{1}{M_t} = 1$
Normalized output power of base station | $P_{total} = \sum_{i=1}^{M_t} P_{ant}^i = 1$

Number of UEs: 1
120 antennas per UE

$P_{ant} = \frac{1}{P_t^2}$

$P_{total} = \sum_{i=1}^{M_t} P_{ant}^i \sim 1/1000$


Improve energy efficiency: beamforming
How to Beam form?

### Principle of Beamforming & Beamsteering

1. Fixed antenna spacing $d$
2. Choose direction $\theta$
3. Set phase shifts $\Delta \phi$

\[ \Delta \phi = \frac{2\pi}{\lambda} d \sin \theta \]

**Antennas**

- $\varphi_1$
- $\varphi_2$
- $\varphi_3$
- $\varphi_M$

**Phase Shifters**

**Attenuators**

To far-field

**Beamsteering (Phase Shift)**

**Sidelobe Suppression**

Gain (dBi)
Beamforming Architectures

**Analog Beamforming (ABF)**

- Data stream
- Baseband processing
- PA

**Digital Beamforming (DBF): 5G FR1**

- Data stream 1
- Digital baseband processing
- RF chain
- ... (repeated for n streams)

**Hybrid Beamforming (HBF): 5G FR2**

- K data streams
- Digital baseband processing
- RF chain
- Analog beamforming
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
Active Antenna System (Massive MIMO or mmWave)

- 64 - 128 Antennas
- 8 - 128 RF Transceivers
- FPGA + Fiber TRx

5G Devices: New Measurement Paradigms
Basic Over-The-Air (OTA) Test Setup

<table>
<thead>
<tr>
<th>Passive measurements</th>
<th>Active measurements</th>
<th>OTA test solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D/3D antenna characterization</td>
<td>RF transceiver characterization</td>
<td>R&amp;S®PWC200 plane wave converter</td>
</tr>
<tr>
<td>System and AUT control</td>
<td>System and AUT control</td>
<td>R&amp;S®ATS800R CATR rack based antenna test system</td>
</tr>
<tr>
<td>R&amp;S®AMS32 OTA performance measurement software</td>
<td>R&amp;S®AMS32 OTA performance measurement software</td>
<td></td>
</tr>
<tr>
<td>R&amp;S®CONTEST</td>
<td>R&amp;S®CONTEST</td>
<td></td>
</tr>
<tr>
<td>R&amp;S®ZNA vector network analyzer</td>
<td>R&amp;S®SMW200A vector signal generator</td>
<td></td>
</tr>
<tr>
<td>R&amp;S®FSW signal and spectrum analyzer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R&amp;S®FSW signal and spectrum analyzer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R&amp;S®ATS1800C CATR conformance chamber system</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5G & SDR Inspired Monitoring Receiver

R&S ESMD Wide Band Monitoring Receiver

High Dynamic Range !!!
Monitoring Receivers

High Dynamic 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 Arrangement for Typical Microwave Receivers

The analog front end is downconverting the RF signals into an IF range <200MHz
Microwave Receiver, Cont’d.

Principal Arrangement 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.

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 triple 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 contradictory
An analog Image Rejection Mixer is capable to attenuate the Image by 30...40dB.

Criteria 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.
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.
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**: \( \frac{fs}{R} \)

CIC-Filter with \( R = 16, N = 5, M = 1 \) (CIC: Cascaded Integrator Comb)
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.
The main AGC control is realized near the end of the signal processing chain as a feed forward control.
Multichannel Receivers

N - channel Receiver with N analog front ends
N-channel Receiver with only one analog front end and N digital down converters. The channel frequencies must be allocated inside the preselector passband.
If all channels are equally spaced, then a Polyphase Filter bank can replace the multiple channels in the downconverter.
Important Characteristics of sampled Systems

The Sampling Theorem (Nyquist / Shannon)

- A bandlimited signal can be reconstructed, when \( B < \frac{fs}{2} \)
- 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)

\[
B = (n - 1) \cdot \frac{fs}{2} \ldots n \cdot \frac{fs}{2}
\]

whereas \( n \) is the zone \((1, 2, \ldots)\)
ENOB: the Effective usable Number Of Bits

\[ \text{SNR}_{\text{eff}} = 1.76\text{dB} + \text{ENOB} \cdot 6.02\text{dB} \]

(measured in \( B = \frac{f_s}{2} \))
Degradation of SNR by clock jitter

very important when applying undersampling!
Higher order intermodulation products as a function of the input signal. The known relationship of $n \cdot \text{dB}/\text{dB}$ ($n =$ order of IM) cannot be applied. Therefore an Intercept point cannot be calculated. In practice, the IM is measured with two tones on -7dBm.
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

Alternative Method for IM measuring

The Noise Power Ratio

The NPR method reflects the true impact of intermodulation from any order
Important Characteristics of AD converters

Theoretical NPR for 10, 12, 14 and 16 bit AD converters
Carrier Recovery

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
Down-converter of the receiver
Typical Down-Conversion Architecture

Down-converter of the receiver
The actual usable bandwidth is reduced by a factor $k$ compared with the sampling rate $f_s$:

$$B_{\text{eff}} = \frac{f_s}{k}$$

In this example $k = 1.28$
Spectrum Analysis in Communication Receivers

An $f_s = 12.8$Msps 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 Communication Receivers

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

\[ \approx 2 \text{GFLOPs} \quad (\text{Floating Point Operations}) \]

<table>
<thead>
<tr>
<th>Internal computing power of the R&amp;S®ESMD</th>
<th>80 MHz realtime -bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency resolution in kHz</td>
<td>Spectra per second</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>25</td>
<td>25 000</td>
</tr>
<tr>
<td>50</td>
<td>50 000</td>
</tr>
<tr>
<td>100</td>
<td>100 000</td>
</tr>
<tr>
<td>500</td>
<td>500 000</td>
</tr>
<tr>
<td>2000</td>
<td>2 000 000</td>
</tr>
</tbody>
</table>
Spectrum Analysis in Communication Receivers

Panorama Function with N consecutive FFT slices

for any bandwidth, but lacks in time resolution
Wideband Monitoring Receiver

Figure 1: R&S ESMD Wide Band Monitoring Receiver

R&S ESMD

High Dynamic Range
Spectrum Analysis in Communication Receivers

Narrowband Analysis

Wideband Analysis
Aircraft Radio Communication Receiver can be monitored and demodulated in the presence of strong FM Radio signal.
Multichannel (4) Operation

All 4-Channels can be analyzed.
Antenna for Communication Receiver

Typical Antennas for high dynamic 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”
Thank You