Software Defined Radio Technologies
--Versatile Transceivers--

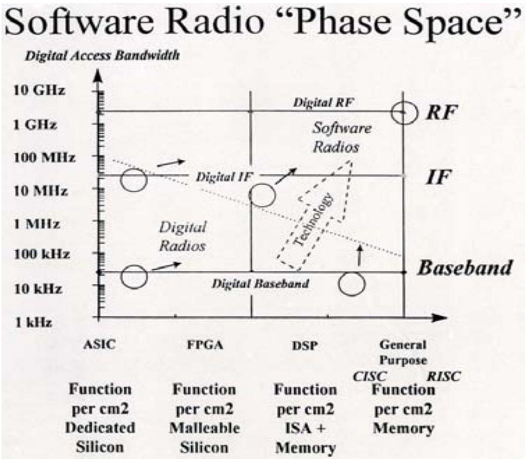
Agenda

- Historical Background
- R & D of SDR
- Basic Concept of SDR
- Technological Issues
- Applications and Market for SDR
- Standardization and Regulation

Historical Background

– Military Communication System :
- In 1970's Smart Antenna
- The End of "Cold War" Regime
- In 1990's Speak Easy, MBMM
- 2—2000MHz
- SE Phase II Programmable Processor
- Voice Bridge : AM to FM

– Commercial :
- In 1996/27/20131 AMPS Base Station
- Multi Mode Base Station to Mini Cell
  – AMPS, N-AMPS, TDMA, CDPD, GSM, CDMA
- Soft Wave, DSP-Based Receiver



SDR Related Projects

- **Glomo (Global Mobile) :Distributed Packet Wireless Network**
- **SORT : Software Radio Technology**
- **SLATS : Software Libraries for Advanced Terminal Solutions**
- **PROMULA : Programmable Multimode Radio for Multimedia Wireless Terminals**
- **MMITS Forum → SDR Forum**

SDR Study Group in Japan

1996 — 1999 ARIB Study Group
Radio Surveillance
1999 — Present IEICE SDR Study Group

2000 — Present TELEC SDR Approval
FCC Collaboration
Electronic Labeling
Tamper-resistant Module

SDR Prototypes in Japan

- ARIB SDR Receiver
- CRL ITS
- NTT SDR Base station
- Toshiba DCR
- Toyo Com. Intelligent Base station
- Hitachi/Kokusai SDR Transceiver
- NEC, Anritsu Radio wave Monitoring

Basic Concept of SDR

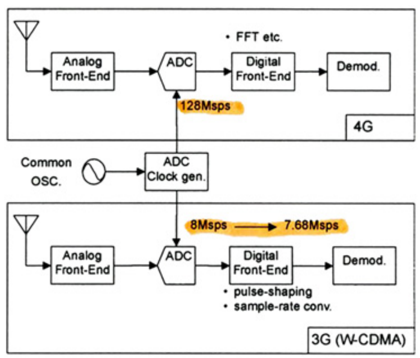
- Analog Radio
- Digital Radio

- Software Defined Radio
- Cognitive Radio ?

- Perfect Programmable Radio
- Programmable Analog Circuit
- RF: Multi band IF: Digital Processing
  BB: Multi mode
- Reconfiguration through Air Interface
- High-level Digital Architecture

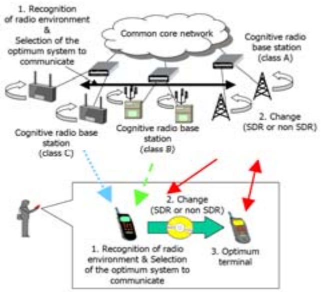
Application (Application Software) Adaptive Equalizer, Position Service, Multimedia Service, etc								
Application (Basic Software) Channel Filter, AFC, AGC, Demodulation, FEC, Voice Codec, etc								
Library								
OS								
Device Driver	Device Driver	Device Driver	Device Driver	Device Driver	Device Driver	Device Driver	Device Driver	
Antenna	RF	Synthesizer	A-D/C	FPGA	DSP		User I/O	CPU

Model of SDR Receivers

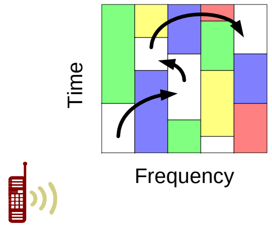


Cognitive radio

A radio that senses its operational environment and can dynamically and autonomously adjust its radio operating parameters



H. Harada, "cognitive radio technology", MWE2005, pp235-240, Nov.2005.



Adaptive use of

Time, Frequency and Space

View Point from System request (1)

Major Issues

- High-speed, Multi media (Voice, Image, Data) Transmission
- High Utilization of Spectrum
- Overcome of Multi path・Fading Problem

Expected Versatile Radio TX／RX

- Free Access
- Frequency Band
- Channel Width
- Modulation Scheme
- Antenna Directivity

View Point from System request (2)

Current Status

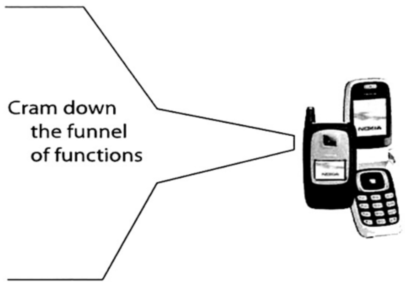
- Many Standards
  (AMPS, GSM, PDC, IS-95, PCS, PHS, CDMA-one, IMT-2000)
- Shortening of TAT (Increase of R&D Cost and Bug Patch)

Desirable Terminal

- Multi mode
- Software Oriented

The Need

Quad-band GSM
GPRS
Wideband CDMA
EDGE
GPS
Bluetooth
802.11b ...



- **Large number of independently developed radio boards, all squeezed into a small mobile device ...**
- **You see one antenna, there are actually 3 or 4 ...**
- **Next month there will be a new wireless application**
- **Where will this end??**

View Point from Device/Circuit Technology

- Small Size → Direct Conversion Receivers
- One-Chip → One-Chip Receivers
- Digital → Digital Receivers
- Software → Software Defined Receivers

Necessary Major Technologies

- Radio System Technology →Smart Radio Architecture
- Antenna → Adaptive Antenna
- Circuit → Circuit Architecture related Device
- Semiconductor Device →

  Optimization of Analog Circuit
- Digital Signal Processing →

  Adaptive & Optimized Algorithm

Feature of SDR Receivers

- Adaptive Modulation
  ～ FSK, GMSK, QPSK, π／4QPSK, 16QAM, etc
- Adaptive Data Rate
  ～ 32kbps, 42kbps, 64kbps, 270kbps, 384kbps, 2Mbps, etc
- Adaptive Access Scheme
  ～ TDMA, FDMA, CDMA, SDMA, TDD, FDD, etc

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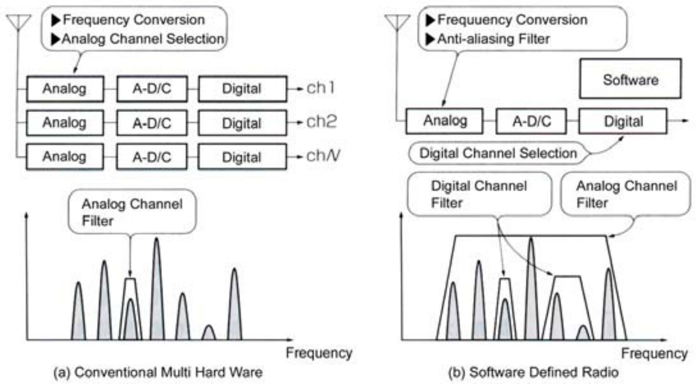
What is a benefit and killer application ?

- World Wide Terminal
  ～ USA, EU, Aus, Japan, Taiwan, China, India, etc



Single Hardware Receivers

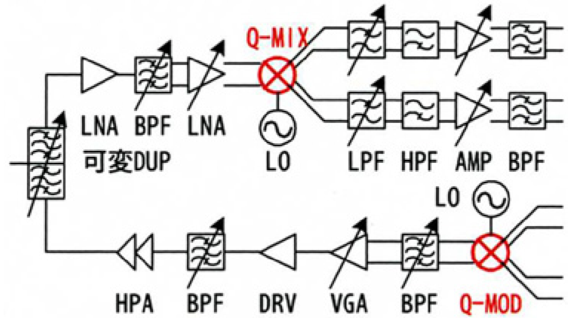
Technical Issues in SDR

- Antenna＋RF Circuit
- Sampling Technology
- Signal Processing

TDD or FDD

- Requirements for Duplexer, RF Filter are quite different for TDD or FDD
- Bandwidth variable Duplexer

Direct Conversion Transceivers

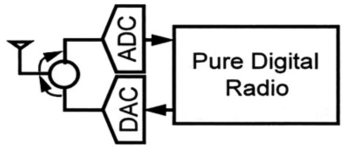


Antenna+RF Circuit

- Adaptation to Environment
- MIMO Technology
- DOA, Spatial Processing
- Broad Band, Multi Band Characteristics
- MEMS Switch

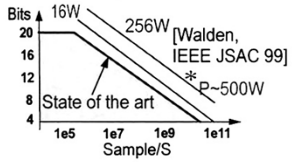
The Software Defined Radio

Mitola 1995



- **Ultimate in flexibility!**

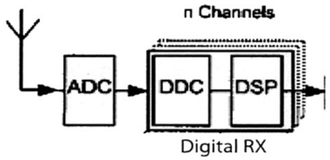
- **Needs 12b, 10 GS/s A/D Converter (ADC)**



- **Low power solution not in sight, Moore's law doesn't help**

What's wrong with this concept?

- **Mitola's SDR can receive every band and channel concurrently!**
- **May be important for military, not necessary for civilian uses**



Standard	Modulation Scheme	Channel BW (MHz)
GSM	GMSK	0.200
EDGE	8PSK	0.200
Bluetooth	GFSK	1
CDMA IS95	QPSK CDMA	1.25
WCDMA/ CDMA2000	QPSK/16QAM CDMA	1.25-5
802.11a/g	OFDM	20
802.11n	OFDM	10-20-40

Modified SDR

① **Good enough to receive one channel at a time, but from any band, with any channel bandwidth, and any modulation**

② **Tunes channel of interest to zero IF**

③ **Wideband receiver (no RF preselect)**

How to make the RF/analog flexible?

- **Push as much to digital as possible**
  - **- With ADCs that dissipate milliwatts!**
- **Model the RF/analog signal processing on digital receiver**

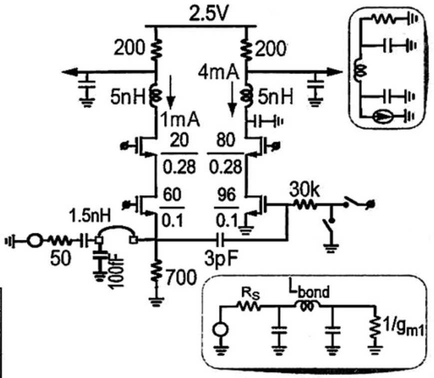
- **Let's design an A/D centric RX, and work upstream towards the antenna**
- **Budget 10mW for A/D–today this gets us:**

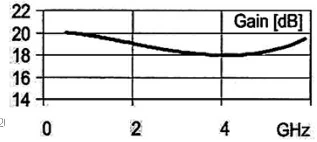
  8b, 40 MHz Nyquist ADC, or
  14b, 10 MHz Delta-Sigma ADC with 200 kHz bandwidth

- **Choose best ADC for channel bandwidth and blocker profile**
- **Develop RX for GSM (200 kHz) and 802.11g (20 MHz)**

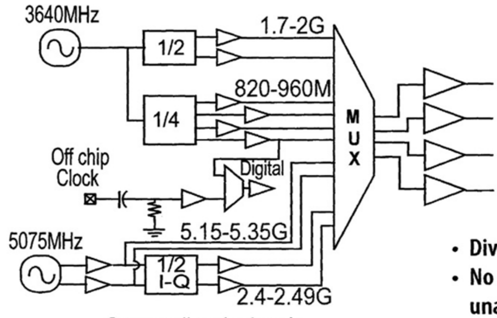
Ultimate challenge: Wideband LNA

- **Departs from conventional narrowband RF practices**
- CG provides input match
- CS to provide extra gain & single to differential
- Input matching forms a 3rd order maximally-flat ladder filter, embedding bondwire
- 3rd order maximally-flat LC ladder filter as wideband load
- Measured: 18-20dB gain and S11<-10dB over 800M-5GHz



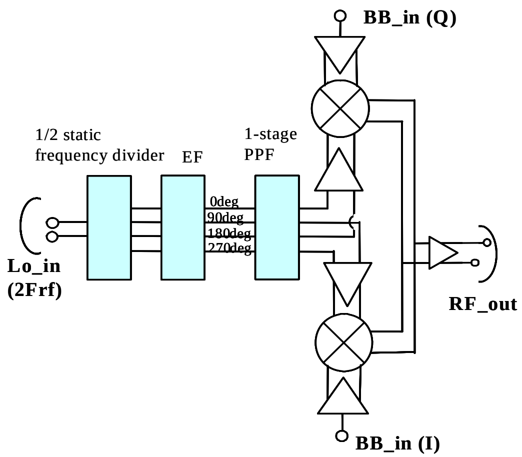


Wideband Frequency Tuning



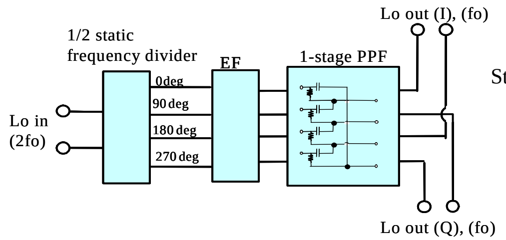
- **Divide & mux only**
- **No SSB mixers—unacceptable spurious tones**
- Covers all major bands
- 2 VCO, only one is active at a time
- 21-33 mA dissipation for different bands
- **3 VCOs can give continuous frequency coverage**

Block Diagram of Q-MOD

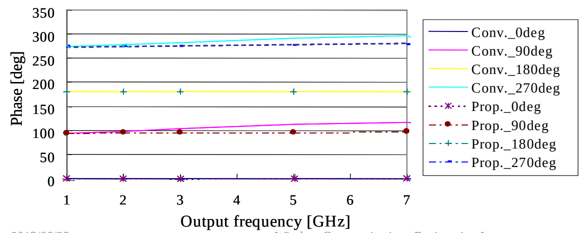


Combination of PPF+Freq. Div.

PPF: Poly phase filter



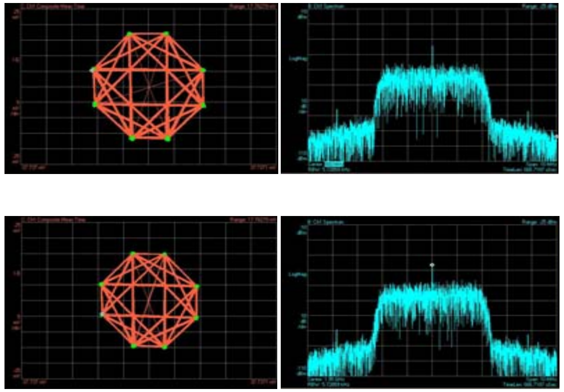
Static Divider + PPF

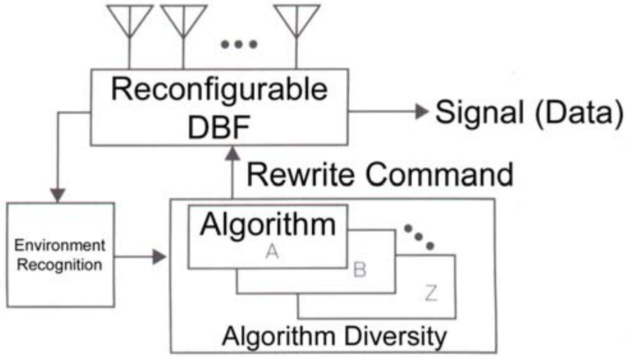


Measured Results (W-CDMA)

RF Frequency
800MHz
EVM 4.0%rms

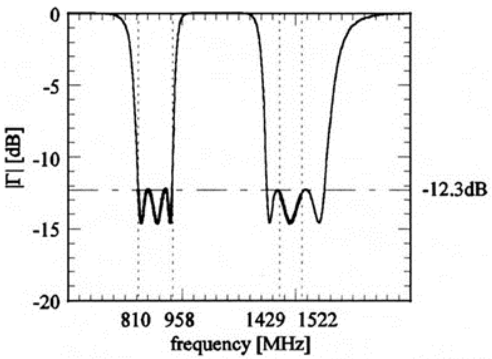
RF Frequency
1.95GHz
EVM 3.1%rms

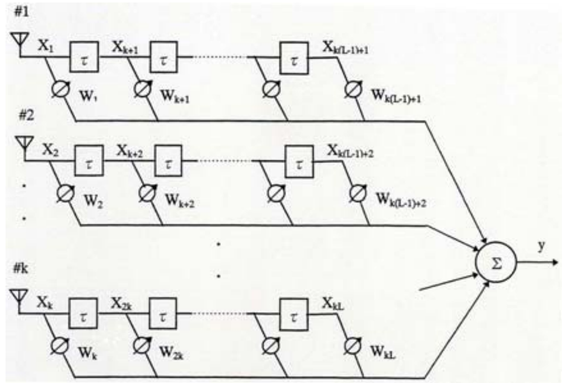




Software Antenna

Multi-band Antenna



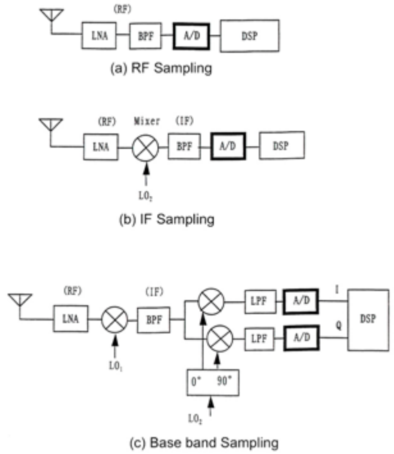


X: Input Y: Output W: Weight τ: Delay Time

Adaptive Tapped Delay Line Array Antenna

Sampling Technologies

- Sampling Scheme
- Image Rejection
- Channel Selection
- Dynamic Range and AGC
- Trend in ADC and High speed
- Optimum Sampling Scheme

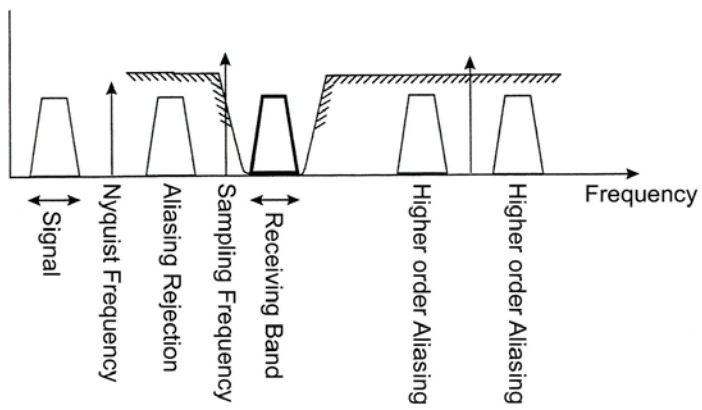


Sampling Scheme

- RF／IF／BB -Sampling

⇐ Harder for ADC , Harder for Analog Circuit ⇒

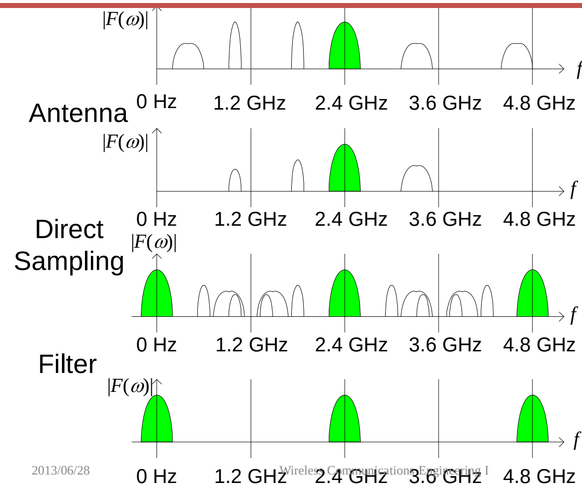
- Nyquist／Over／Under -Sampling
  - Nyquist :
    - Sharp Analog LPF
  - Over :
    - Short Sampling Interval
    - Quantum Noise Reduction
  - Under :
    - Anti-aliasing BPF



Sampling in Time Domain (Interval : Ts)

Copying of Spectrum in Frequency Domain (Interval : Fs=1/Ts)

Direct Sampling



Poisson Summation & SamplingTheorem

$$\sum_{k=-\infty}^{\infty} \exp(j2\pi t k / T)/T = \sum_{n=-\infty}^{\infty} \delta(t - Tn)$$

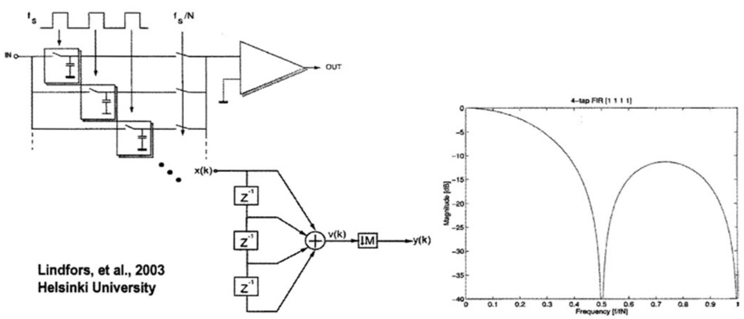
$$\sum_{n=-\infty}^{\infty} s(Tn)\delta(t - Tn) = s(t) \sum_{n=-\infty}^{\infty} \delta(t - Tn)$$

Where to sample the wideband input?

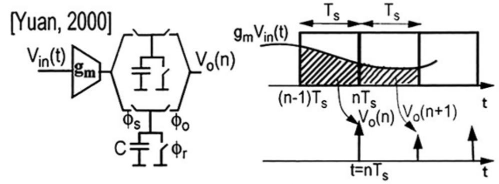
- As soon as the signal of interest is at zero IF ...
- Clock-driven discrete-time analog signal processing gives greatest flexibility
- With 5 GHz-wide input band, what should be the sampling frequency?
  - Only the channel at zero IF is of interest
  - Everything else is unwanted
  - But we'll need an anti-alias filter with 100:1 range in cutoff if we sample 200 kHz to 20 MHz wide channels—impractical

Bring Down the Sample Rate (in Analog)

- Initial sample rate may be very high, to protect the wanted channel
- A/D conversion at this rate wastes power, as wanted signal band is much lower
- Analog decimation filter? Yes ...



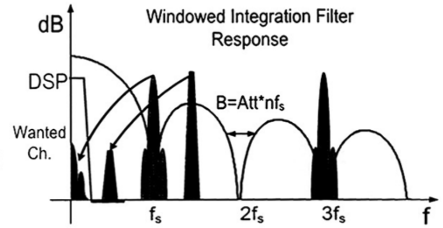
Lowpass Sampler w/ Internal Anti-Alias



$$|H(f)| = \frac{g_m T_s}{C}\left|\frac{\sin(\pi T_s f)}{\pi T_s f}\right|$$

Rectangular Window Integration

- Main-lobe passes wanted signal at DC
- Side-lobes roll off with 20 dB/decade
- Notches @ nf_s for anti-aliasing
- Wider stop-band with higher f_s



RF Circuit for Direct Conversion

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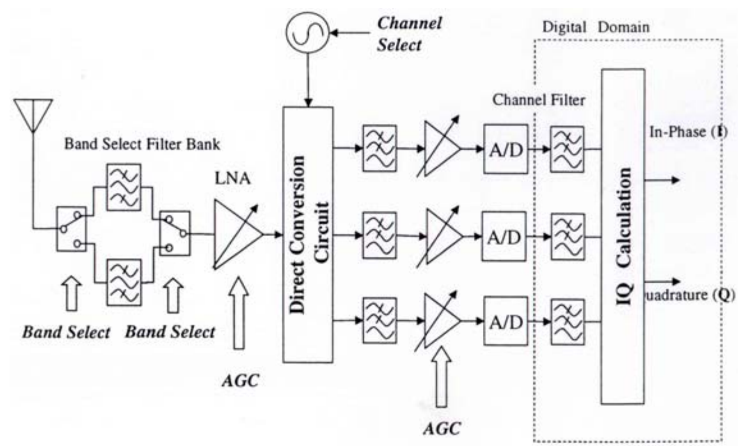
6-port Circuit
(Mixer-free Network Analyzer in Millimeter Wave)



3 Amplitudes→1 Complex value

- Cross point of 3 Circles
- A,B,C : known Complex number
- r, r’ ,r’’ : known Real number
- Z=I+jQ : unknown Complex number

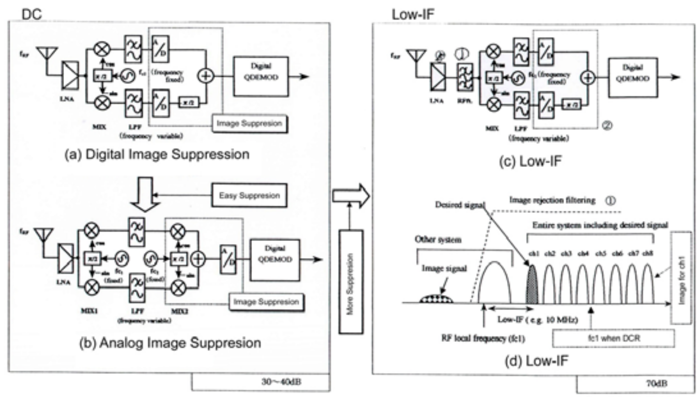
$$|Z-A|=r$$
$$|Z-B|=r'$$
$$|Z-C|=r''$$

Channel Selection

- PLL Frequency Synthesizer
  - Analog Signal Processing
  - Not Suitable for SDR
- Digital Down Converter
  - Programmable
  - Limit of Device Processing Speed
- Software Processing
  - Big Freedom
  - Limit of DSP Processing Speed

Fast Realization of SDR Receivers

- Reduce Sampling Speed : Under Sampling
- Reduce Resolution : Gain Switch
- Reduce Sampling Accuracy : Low-IF Scheme



An example of development scenario of a software defined radio

Circuit and Signal Processing for Wireless Communication (1)

- Oscillation, Frequency Synthesizer, PLL
- Amplification (Low Noise, High Power, Broad Band)
- Distortion Suppression
- Filtering (Analog, Digital), Spectrum Shaping
- Frequency Conversion, Mixing
- ADC, DAC
- Modulation & Demodulation : Analog, Digital
- Synchronization／Timing／Carrier Recovery

Circuit and Signal Processing for Wireless Communication (2)

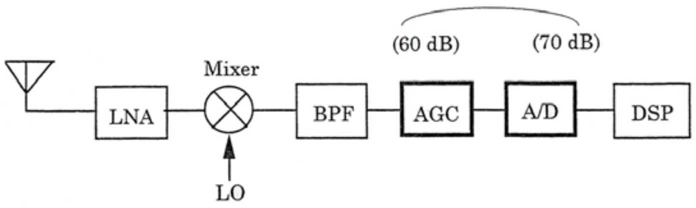
- Interference Canceller, Multi-User Detection
- Equalizing, TOA
- Diversity
- Beam Forming, Null Shaping
- AGC, AFC
- Error Control: ARQ, FEC
- Scramble, Encryption, Authentication
- Data Compression

Requirements for Signal Processing

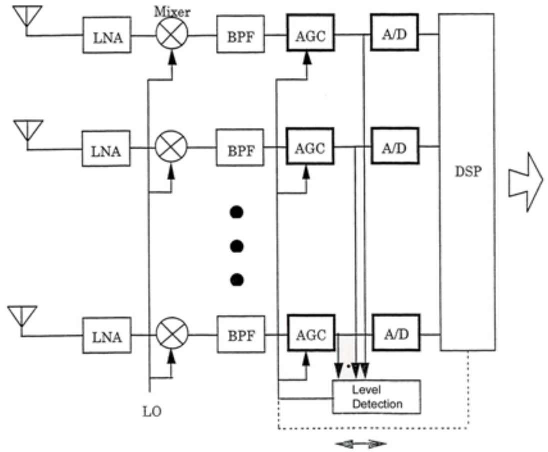
- Hardware
  - Selection of Clock Signal
    → Power Saving
  - Accuracy
  - Processing Unit Configuration
- Software Function
  - Channel Filtering
  - AFC, AGC, Offset Control
  - Demodulation/Modulation
  - Software Download

Dynamic Range & AGC

- Assignment of DR
  - Enlargement of DR by AGC
- Array Antenna
  - N-element Array Antenna :
    Enlargement of DR, 10 log N (dB)

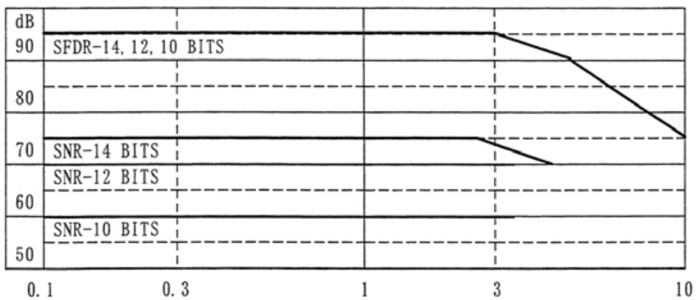


Enlargement of DR by AGC (IF Sampling)



DR Widening and High-Speeding of ADC

- Relation between No. of Bit, SFDR, SNR
- Anti-aliasing Filter
  - ⇒ Reduction of Noise Drivers
- Randomization of Quantum Noise
- Dithering Circuit
- LUT (Look Up Table)
  - ⇒ Widening of DR



Analog Input Frequency MHz

Signal Processing Technology

- Specific Function SDR
- Implementation of Application Program
- Forecast of Programmable Device Trend
- Download Software

Target of Signal Processing in SDR

- Free Space

(Equalization, Interference Suppression, Diversity Combining)

- RF Circuit

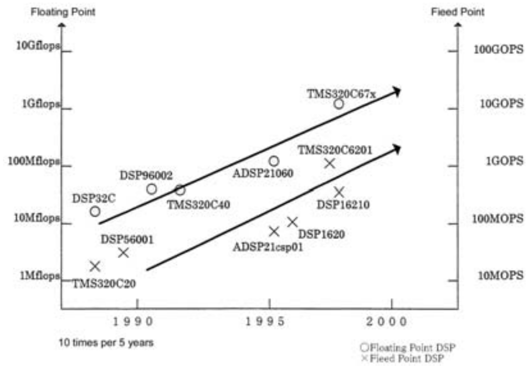
(Distortion Compensation, DC Offset Compensation, Orthogonality Compensation)

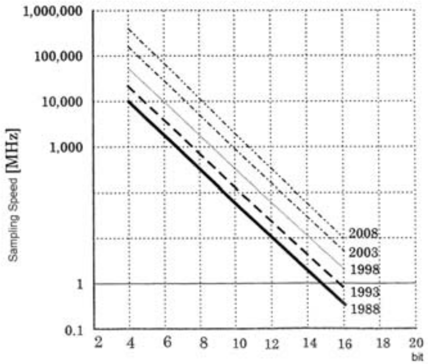
⇒ Digital Assist Technology

Programmable Device

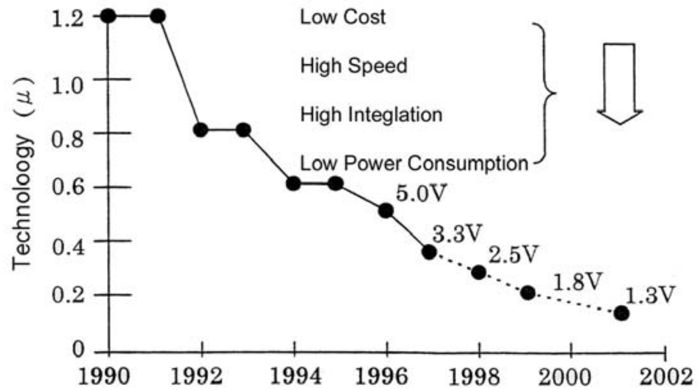
- DSP (Digital Signal Processor)
  - RISC Type Architecture
- ASSP (Application Specific Standard Products)
  - FFT Processor
- ASIC (Application Specific IC)
  - User Design
- FPGA (Field Programmable Gate Array)
  - Reconfigurable
- PLD (Programmable Logic Device)
  - Different Internal Structure
- MP (Micro Processor)
  - General Purpose Processor

DSP Trend





AD／C Performance



Process Technology and Power Supply Voltage

Direct Sampling Mixer

- RF-Front-End
- Sampling + Filtering + Mixing
- Suitable for SDR

Paradigm shift by CMOS Technology

Deep-submicron CMOS process

Disadvantage

- Very limited voltage headroom
- Considerable switching noise

Advantage

- Rise and fall times on the order of picoseconds
- Precise control of capacitance ratio

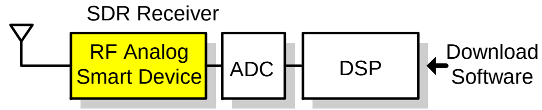
Voltage-domain → Time-domain

Analog → Digital Replacement

- Phase comparator → TDC (Time to Digital Converter)
- VCO → DCO (Digitally Controlled Oscillator)
- PLL → ADPLL (All Digital Phase Locked Loop)
- AGC → DPA (Digitally Controlled RF Power Amplifier)
- Heterodyne → Direct sampling

RF Front-end for SDR

Software Defined Radio

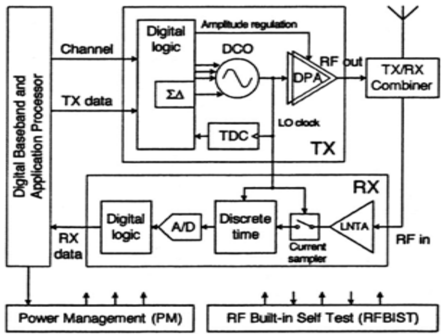


	Amplitude	Time
Analog	Continuous	Continuous
Sample	Continuous	Discrete
Digital	Discrete	Discrete

→ Discrete time receiver

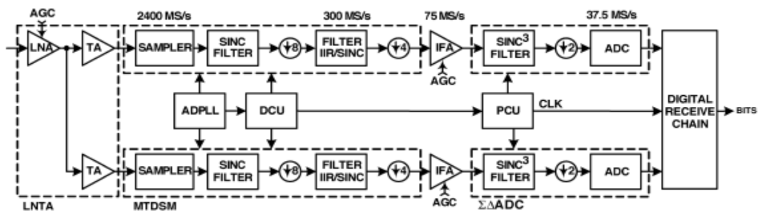
→ DSM (Direct Sampling Mixer)

TI Bluetooth Transceiver



Discrete-Time Receiver

R.B.Stazewski et al., "All-Digital TX Frequency Synthesizer and Discrete-Time Receiver for Bluetooth Radio in 130-nm CMOS," IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 39, NO. 12, DECEMBER 2004



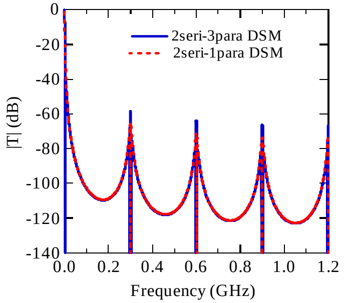
Amplitude Analog
Time Analog

Analog
Digital

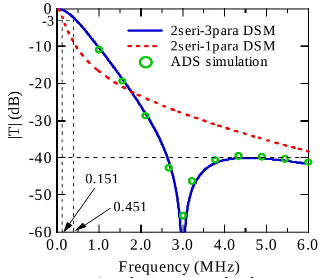
Digital
Digital

Frequency characteristic of 2seri-3para DSM

f_{LO}=2.4GHz, f_{N1}=2MHz, M=8 , g_m=10mS, ω_k=$k\omega_1$ (k=1~3) , f_1=0.61MHz
C_{R1}=0.2584pF, C_{R2}=0.28566pF, C_{R3}=0.11277pF, C_H=C_{B2}=20C_{R1}
C_{B11}=156.55C_{R1} , C_{B12}= 78.273C_{R2}, C_{B13}=52.182C_{R3}



Wideband characteristic

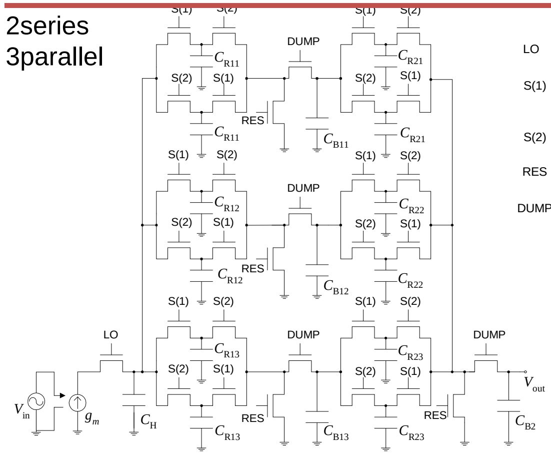


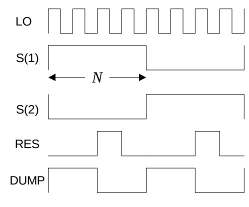
Near DC characteristic

- Perfect attenuation pole is realized
- Simulation results agree with calculation results

Series-Parallel connection of DSM

2series
3parallel





Timing chart

- Only One LNTA parallel architecture is realized

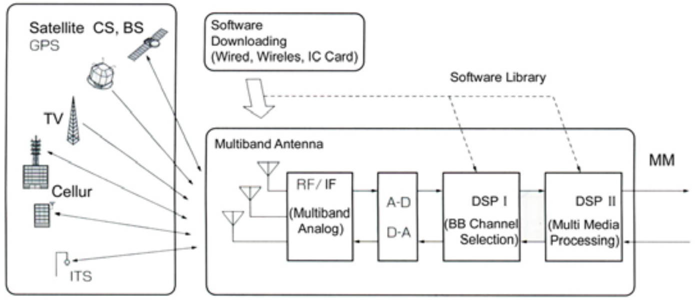
Series-Parallel connection for DSM

Software Download

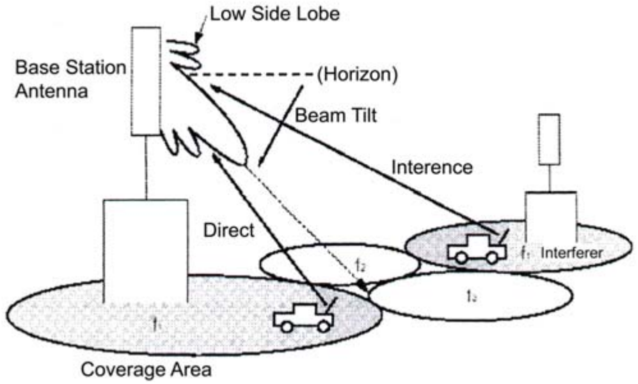
- Insertion of Media
- Fixed Telephone Line ＋ Modem
- Provision of CD-ROM, FD
- Internet
- Service-Center
- Wireless Interface

SDR Market

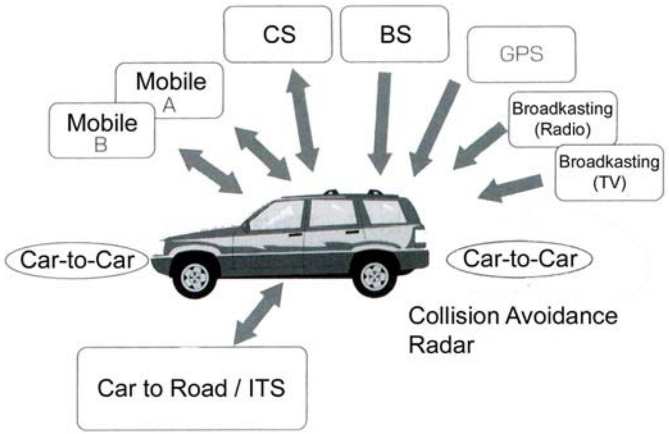
- Satellite Mobile Communication
- Mobile Communication
- In-building PCS
- Pocket Wireless

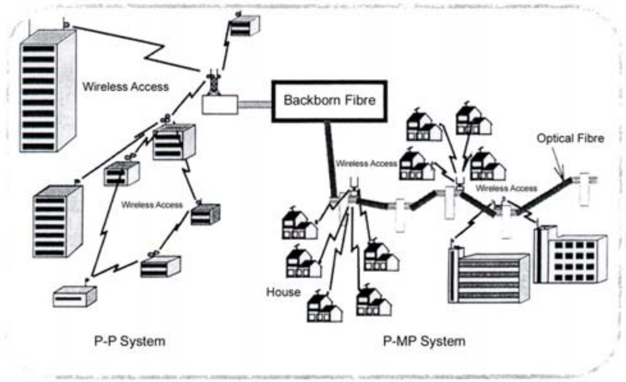


Multi Media Universal Terminal



Base Station Antenna





FWA System

Standardization

- MMITS Forum → SDR Forum
  - Modular Multifunctional Information Transfer System
- de facto Standard
- Software Defined Radio Workshop
- Standardization(Mobile,Base Station,Handheld) is under way
- Approval & Electronic Label

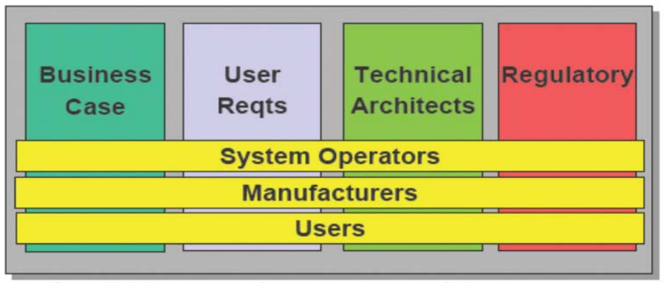
Markets

What is the SDR Forum?

- **World's largest Forum for:**
  - Software (Defined) Radio
  - Cognitive (Smart) Radio
  - Military, public safety, commercial/consumer, avionics, space, academic domains
  - Technical, regulatory and market views
- **Around 120+ international members**
  - Manufacturers
  - Service providers & networks
  - Government agencies & regulators
  - Users
- **Standards development organization (SDO)**
  - Develops voluntary standards, recommendations and reference implementations
- **Non-profit organization**

Markets

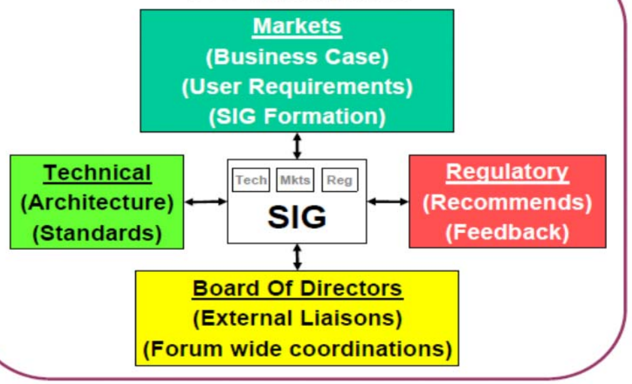
What are Special Interest Groups ?



- *Cross-disciplinary groups of users, operators, manufacturers*
- *Single market domain (e.g. Public Safety, Avionics, Networks…)*
- *Spans technical, regulatory, business case and user aspect*

Markets

SIG Interactions



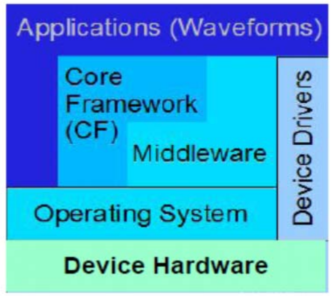
What is a Software Defined Radio?

What is a Software Defined Radio (SDR)?

A radio is considered to be a software defined radio (SDR) if:

- **Some or all of the baseband or RF signal processing is accomplished through the use of software**
- **The signal processing can be modified post manufacture**

(Definition based on draft being developed jointly by the SDR Forum and IEEE P1900.1)



SDR: FCC Definition

A radio that includes a transmitter in which the operating parameters of frequency range, modulation type or maximum output power (either radiated or conducted), or the circumstances under which the transmitter operates in accordance with Commission rules, can be altered by making a change in software without making any changes to hardware components that affect the radio frequency emissions.

SDR: ITU Definition

- **A radio in which RF operating parameters including but not limited to frequency range, modulation type, or output power can be set or altered by software, and/or the technique by which this is achieved.**
- **NOTE 1 – Excludes changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard.**
- **NOTE 2 – SDR is an implementation technique applicable to many radio technologies and standards.**
- **NOTE 3 – Within the mobile service, SDR techniques are applicable to both transmitters and receivers.**

SDR forum — Markets

What is a Cognitive Radio?

SDR forum — Markets

Cognitive Radio (Smart Radio)

- **A radio or system that utilizes a cognitive control mechanism that can sense and autonomously reason about the surrounding radio environment and adapt to it accordingly.**
- **For example, a cognitive radio should be able to detect other radio transmissions and automatically select unused frequency bands in order to increase effectiveness in the usage of the spectrum.**
- **The term radio is used broadly to include cognitive radio systems.**
- **Cognitive radio systems could include components such as sensors and network management systems that are external to the radio but are accessible via a network.**
- **In such a system, individual radio sets might rely on these external elements for much of their cognitive capability.**

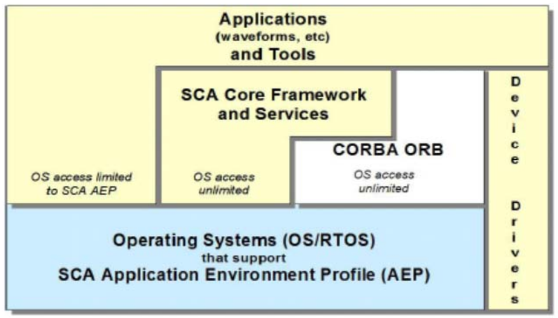
(Definition is based on draft v0.17 document being developed jointly by the SDR Forum and IEEE P1900.1)

SDR forum — Markets

What is the Software Communications Architecture (SCA)?

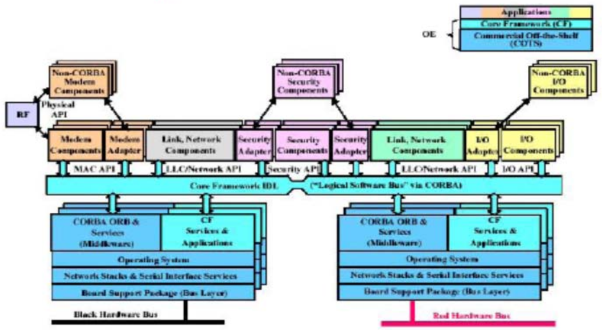
SDR forum — Markets

Software Communications Architecture (SCA) (part of a US DoD procurement specification)



Markets

SCA Diagram: Secure Tactical Radio



Source: US Department of Defense, Joint Tactical Radio System

Markets

SDRF Networking Waveform Protocol Stack Reference Model