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
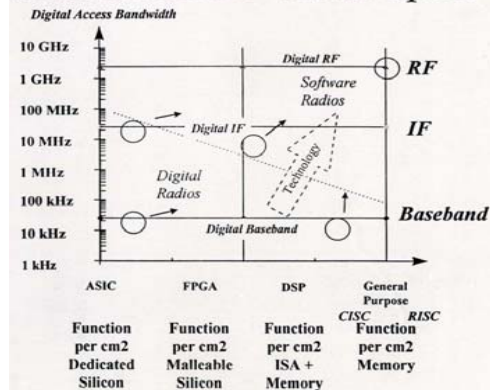 - Voice Bridge：AM to FM

- Commercial :
  - In 1996/14/20121 AMPS Base Station
  - Multi Mode Base Station to Mini Cell
    - AMPS, N-AMPS, TDMA, CDPD, GSM, CDMA
  - Soft Wave, DSP-Based Receiver

1

Software Radio "Phase Space"

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

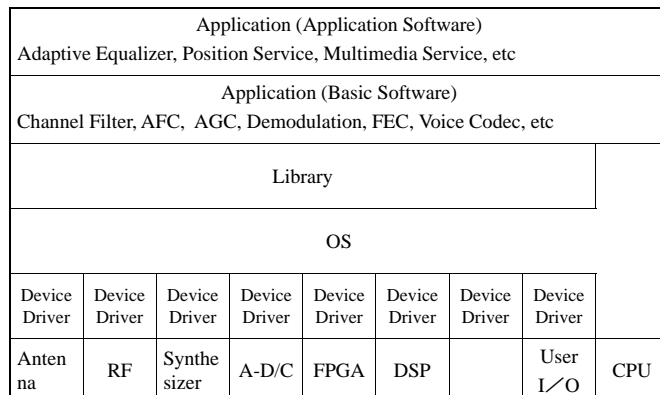⬇

– 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

3

Slide 12
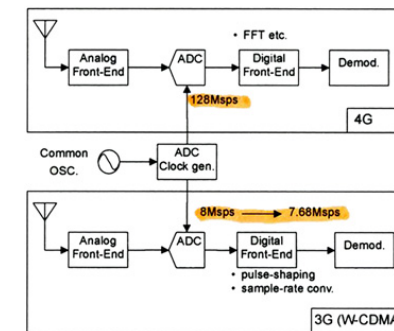
Cognitive radio

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.
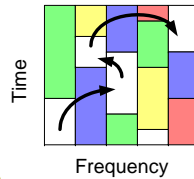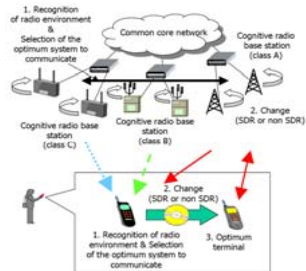
Adaptive use of
Time, Frequency and Space

Communications Engineering I   12

Slide 13

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

2012/06/15   Wireless Communications Engineering I   13

Slide 14

Expected Versatile Radio TX／RX

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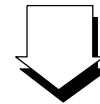- Modulation Scheme
- Antenna Directivity

2012/06/15   Wireless Communications Engineering I   14

Slide 15

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

2012/06/15   Wireless Communications Engineering I   15

4

The Need

Quad-band GSM
GPRS
Wideband CDMA Cram down
EDGE the funnel
GPS of functions
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
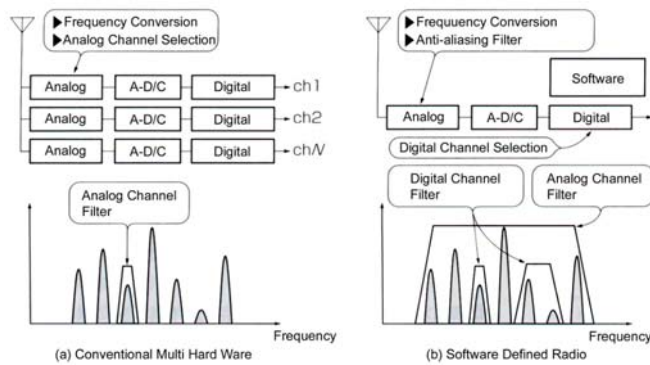- Adaptive Access Scheme
  - ～ TDMA, FDMA, CDMA, SDMA, TDD, FDD, etc

          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
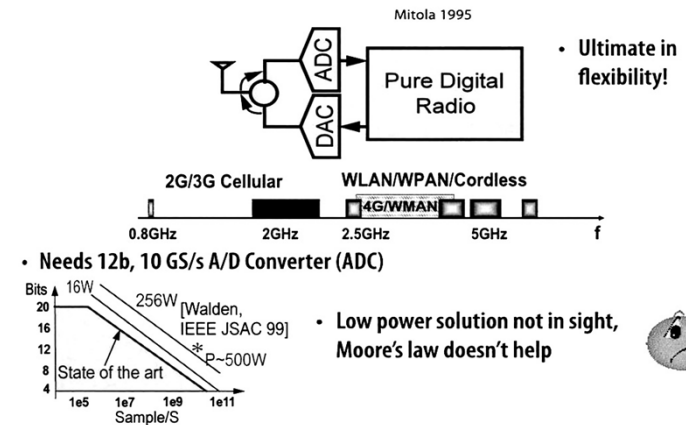
Direct Conversion Transceivers

6
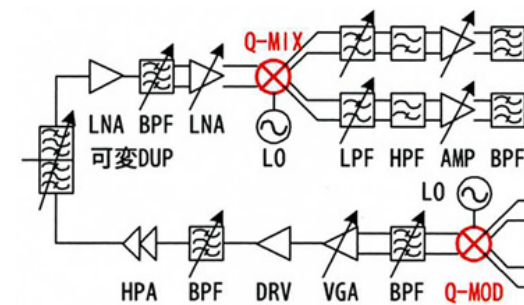
Antenna+RF Circuit

- Adaptation to Environment

- MIMO Technology

- DOA, Spatial Processing

- Broad Band, Multi Band Characteristics

- MEMS Switch

The Software Defined Radio

Mitola 1995

- **Ultimate in flexibility!**

2G/3G Cellular   WLAN/WPAN/Cordless

4G/WMAN

0.8GHz   2GHz   2.5GHz   5GHz   f

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

Bits   16W   256W [Walden, IEEE JSAC 99]   *P~500W
20
16
12
8   State of the art
4
1e5   1e7   1e9   1e11
Sample/S

- **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

n Channels

ADC → DDC → DSP

Digital RX
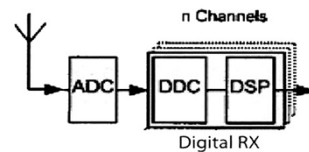
Modified SDR

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)

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

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
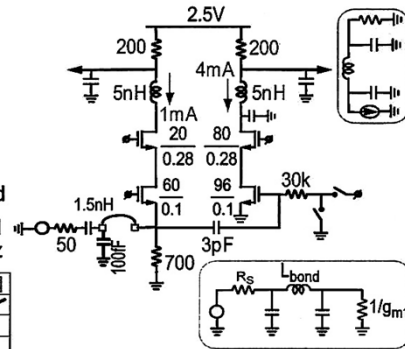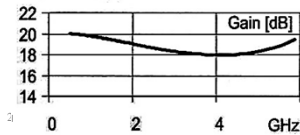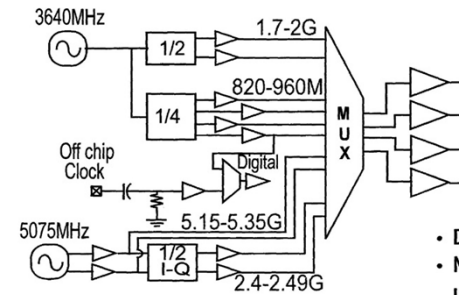 - Develop RX for GSM (200 kHz) and 802.11g (20 MHz)

7

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

2.5V
200 200
4mA
5nH 5nH
1mA
20 80
0.28 0.28
60 96
0.1 0.1
30k
1.5nH
50 100fF 700 3pF
R_S L_{bond} $1/g_{m1}$

Gain [dB]
22 20 18 16 14
0 2 4 GHz

Wideband Frequency Tuning

3640MHz
1/2 → 1.7-2G
1/4 → 820-960M
Off chip Clock
Digital
5.15-5.35G
5075MHz
1/2 I-Q → 2.4-2.49G
M U X

- **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

BB_in (Q)

1/2 static frequency divider   EF   1-stage PPF

0deg
90deg
180deg
270deg

Lo_in (2Frf)

RF_out

BB_in (I)
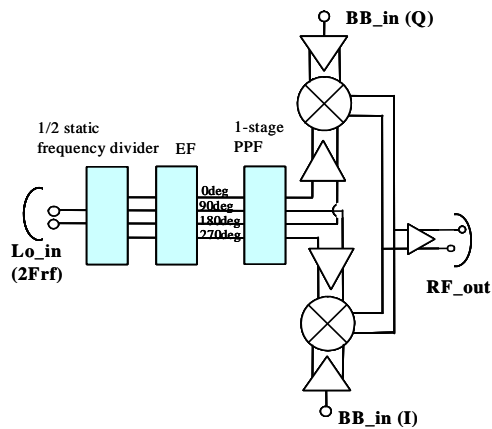
Combination of PPF+Freq. Div.

PPF: Poly phase filter

Lo out (I), (fo)

1/2 static frequency divider   EF   1-stage PPF

0deg
90deg
180deg
270deg

Lo in (2fo)

Static Divider + PPF

Lo out (Q), (fo)

350
300
250
200
150
100
50
0

Phase [deg]

1 2 3 4 5 6 7
Output frequency [GHz]

Conv._0deg
Conv._90deg
Conv._180deg
Conv._270deg
Prop._0deg
Prop._90deg
Prop._180deg
Prop._270deg

8
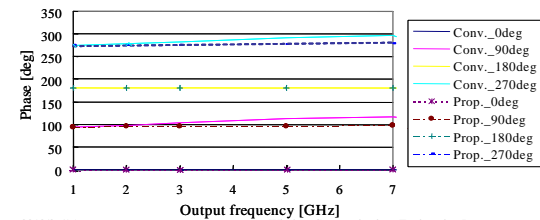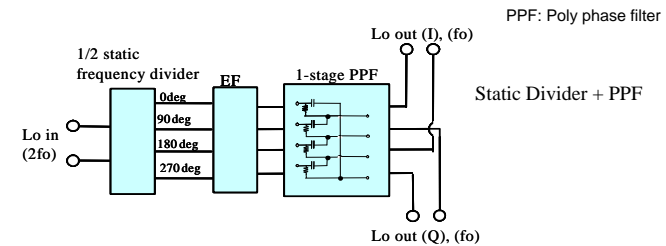
Measured Results (W-CDMA)

RF Frequency
800MHz
EVM 4.0%rms
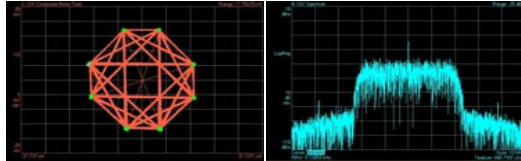
RF Frequency
1.95GHz
EVM 3.1%rms
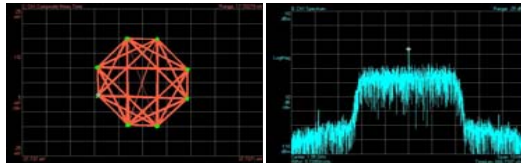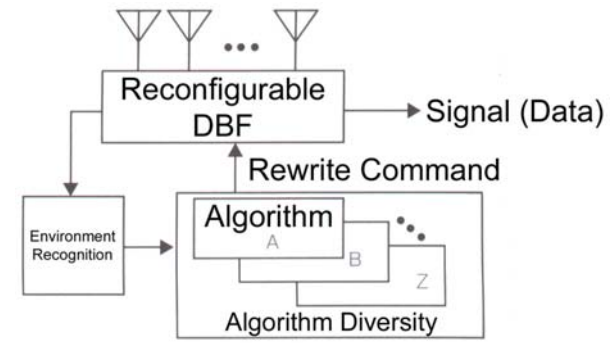
2012/06/15   Wireless Communications Engineering I   32
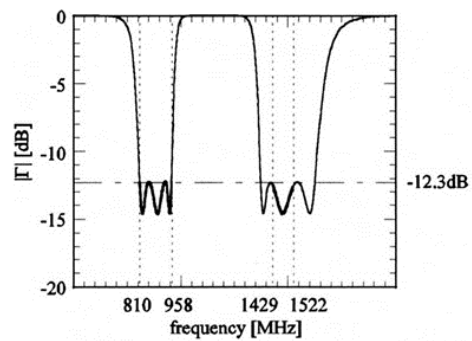

Software Antenna

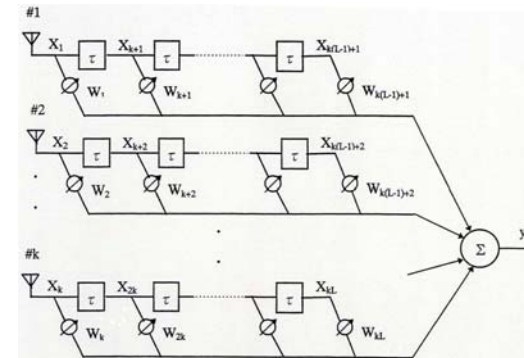2012/06/15   Wireless Communications Engineering I   33

Multi-band Antenna

2012/06/15   Wireless Communications Engineering I   34

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

Adaptive Tapped Delay Line Array Antenna
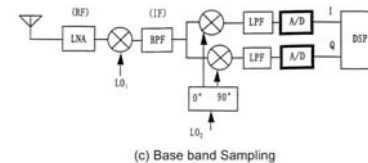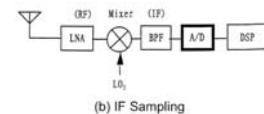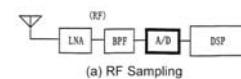
2012/06/15   Wireless Communications Engineering I   35

9

Sampling Technologies

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

(a) RF Sampling
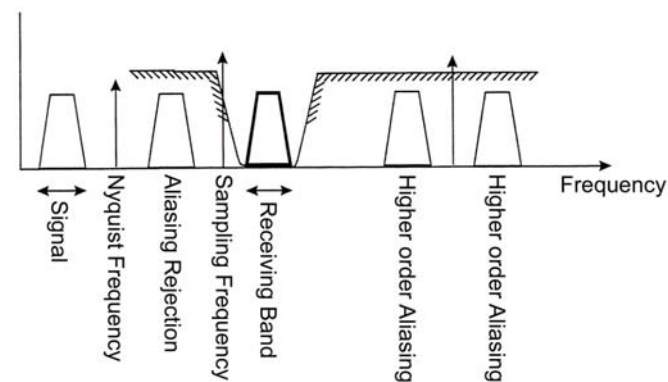
(b) IF Sampling

(c) Base band Sampling

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

Slide 40

Sampling in Time Domain
(Interval : Ts)

⬇

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

Slide 41

Direct Sampling

Antenna

Direct Sampling

Filter

0 Hz   1.2 GHz   2.4 GHz   3.6 GHz   4.8 GHz

Slide 42
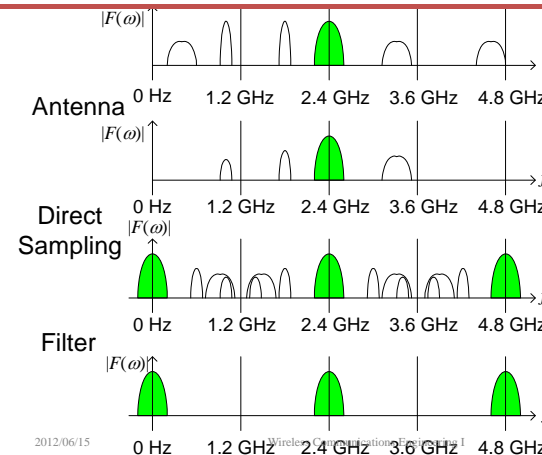
Poisson Summation & SamplingTheorem

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

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

Slide 43

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
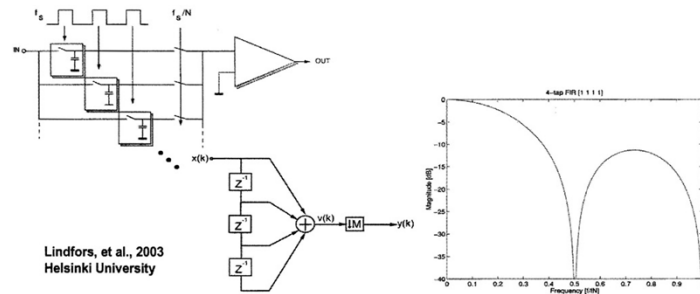
Bring Down the Sample Rate (in Analog)

- 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
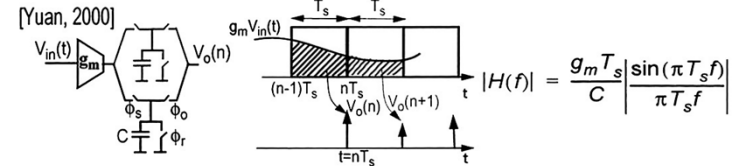- Analog decimation filter? Yes ...

Lindfors, et al., 2003
Helsinki University

Lowpass Sampler w/ Internal Anti-Alias

[Yuan, 2000]

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

Rectangular Window Integration

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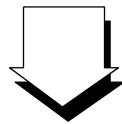- Notches @ nf_s for anti-aliasing
- Wider stop-band with higher f_s

Windowed Integration Filter Response

B=Att*nf_s
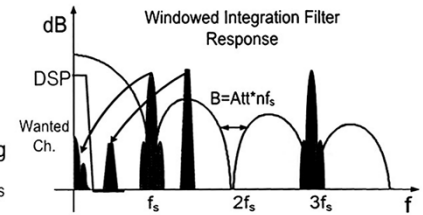
RF Circuit for Direct Conversion

⬇

6-port Circuit
(Mixer-free Network Analyzer in Millimeter Wave)
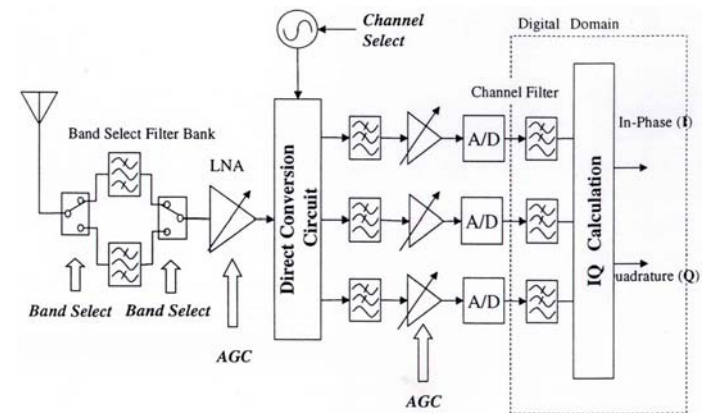
3 Amplitudes→1 Complex value

- 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
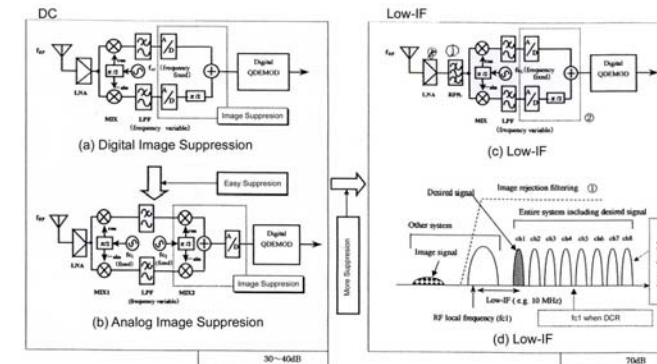
An example of development scenario of a software defined radio

13

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
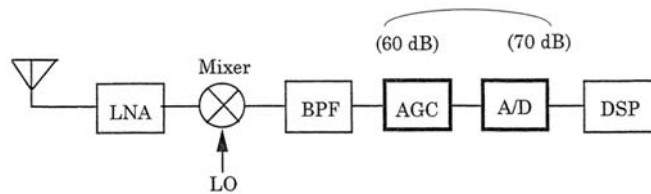 - Demodulation/Modulation
  - Software Download

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)

(60 dB)   (70 dB)

LNA — Mixer (LO) — BPF — AGC — A/D — DSP
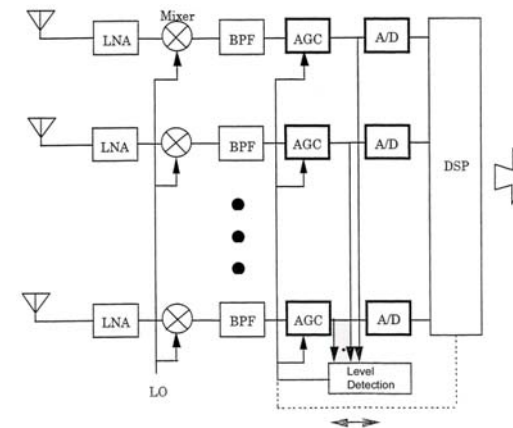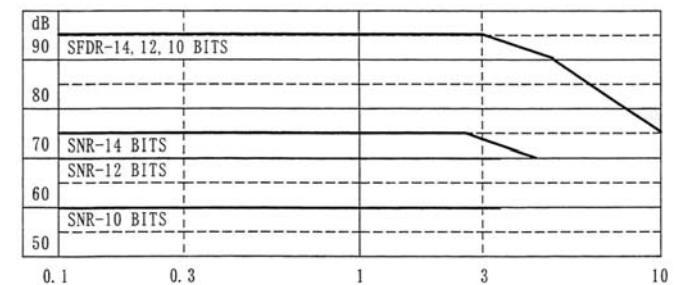
DR Widening and High-Speeding of ADC

- 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

15

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
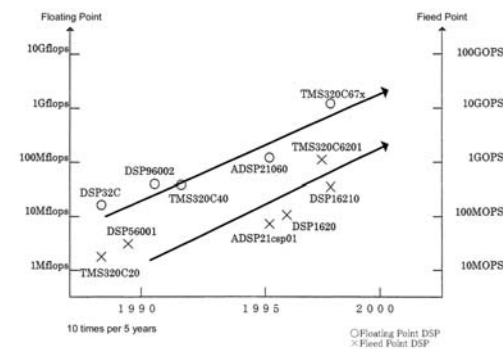
DSP Trend

AD／C Performance

Process Technology and Power Supply Voltage
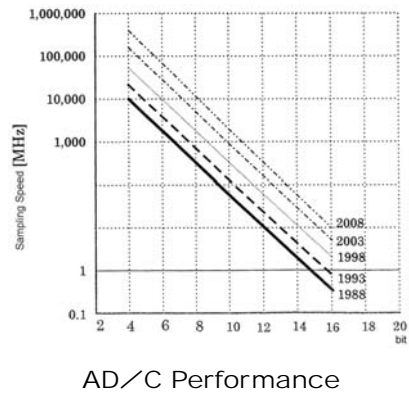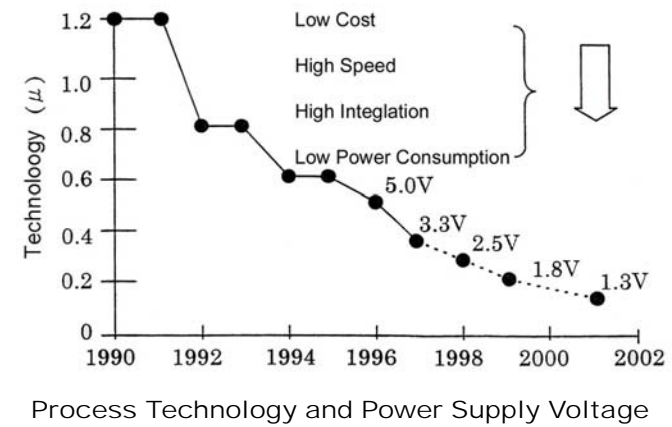
Direct Sampling Mixer

- RF-Front-End

- Sampling + Filtering + Mixing

-Suitable for SDR

Paradigm shift by CMOS Technology

Deep-submicron CMOS process

Disadvantage	Advantage
・Very limited voltage headroom	・Rise and fall times on the order of picoseconds
・Considerable switching noise	・Precise control of capacitance ratio

Voltage-domain ➡ Time-domain

17

Analog → Digital Replacement

・Phase comparator → TDC（Time to Digital Converter）

・VCO → DCO（Digitally Controlled Oscillator）

・PLL → ADPLL（All Digital Phase Locked Loop）

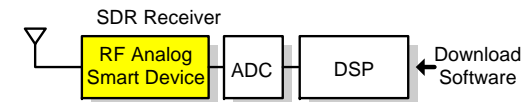・AGC → DPA （Digitally Controlled RF Power Amplifier ）

・Heterodyne → Direct sampling

RF Front-end for SDR

Software Defined Radio

SDR Receiver

RF Analog Smart Device — ADC — DSP ← Download Software

	Amplitude	Time
Analog	Continuous	Continuous
Sample	Continuous	Discrete
Digital	Discrete	Discrete

→ Discrete time receiver

→ DSM (Direct Sampling Mixer)

TI Bluetooth Transceiver
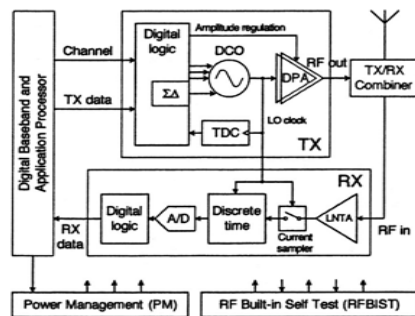
Discrete-Time Receiver

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
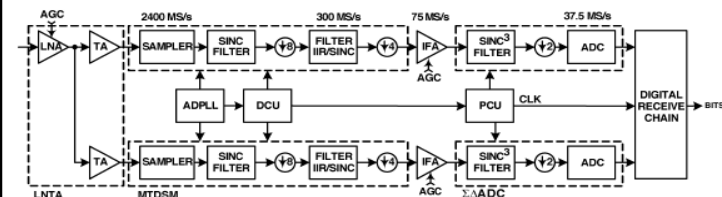
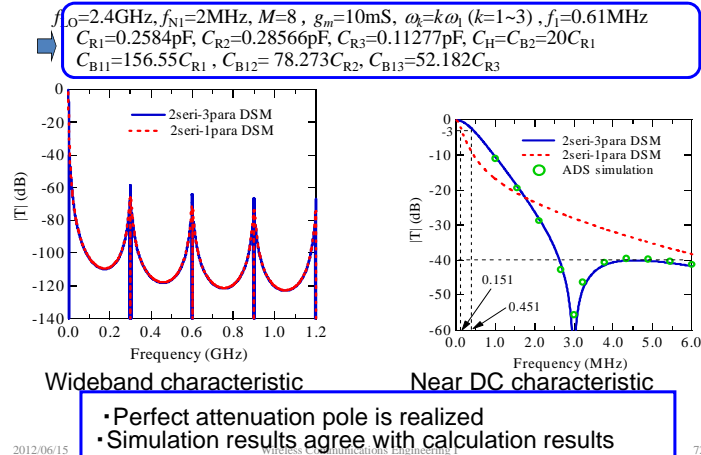Amplitude
Analog

Time
Analog

Analog

Digital

Digital

Digital

18

Frequency characteristic of 2seri-3para DSM

f_{LO}=2.4GHz, f_{N1}=2MHz, M=8 , g_m=10mS, $\omega_k=k\omega_1$ (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
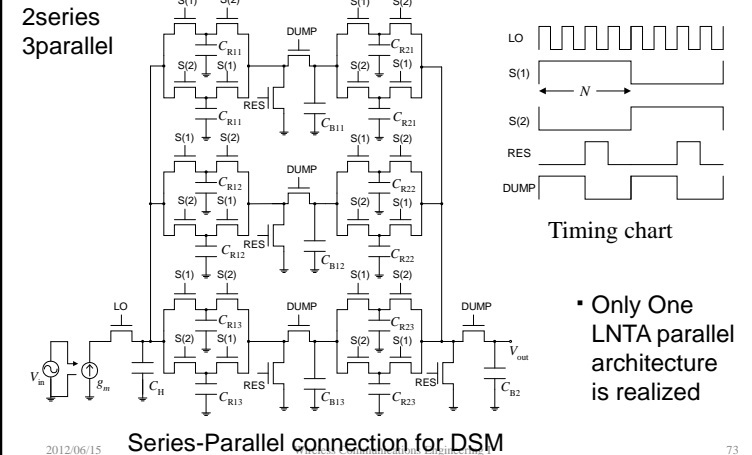
Software Download

- 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
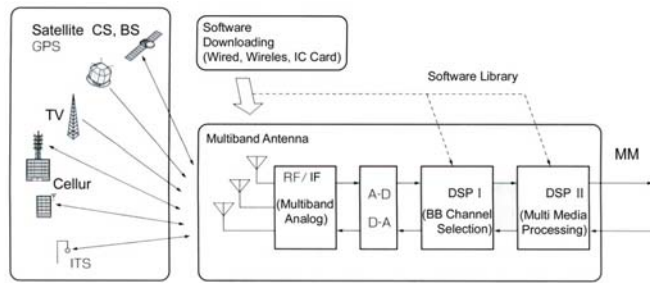
Multi Media Universal Terminal
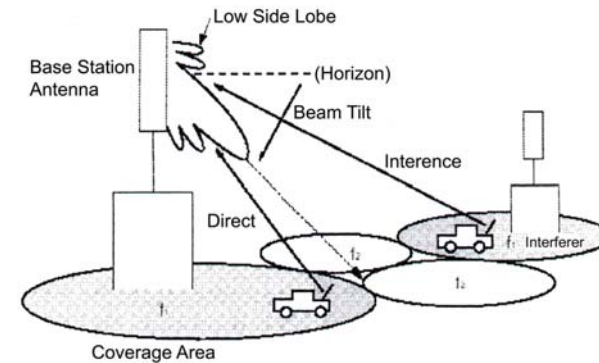
Base Station Antenna
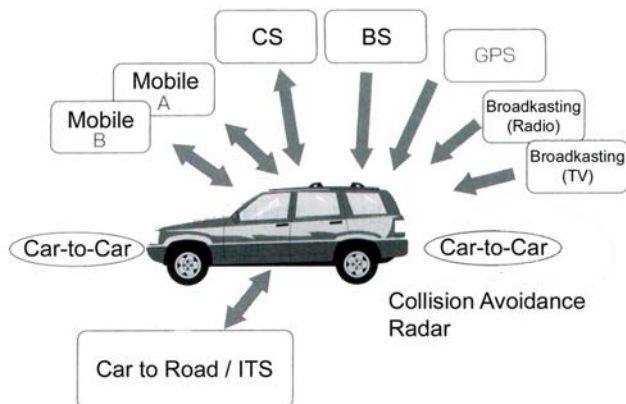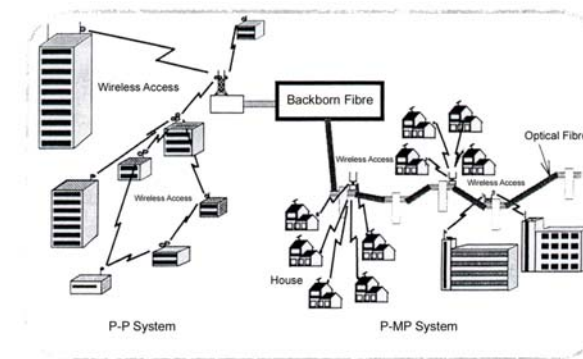
FWA System

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 a Software Defined Radio?
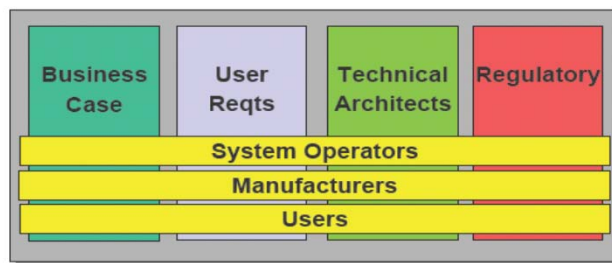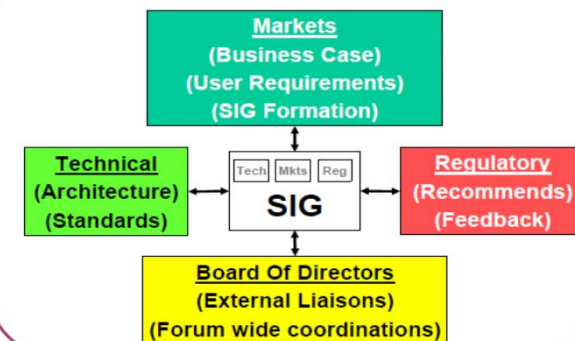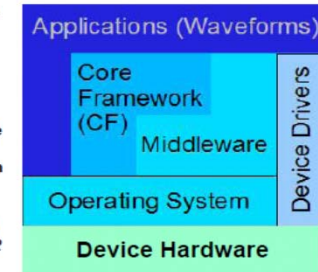

Markets

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)

Applications (Waveforms)
Core Framework (CF) — Middleware
Device Drivers
Operating System
Device Hardware

Markets

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.

Markets

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.

Markets

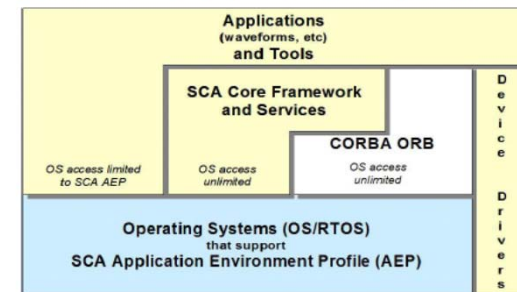## What is a Cognitive Radio?

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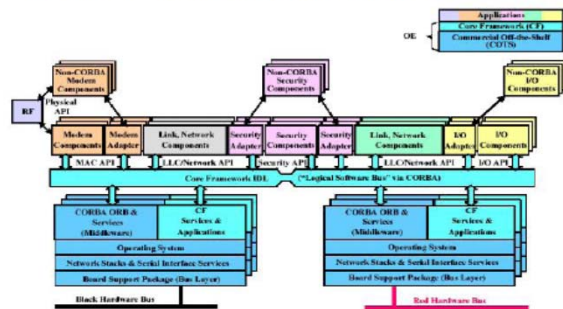
(Definition is based on draft v0.17 document being developed jointly by the SDR Forum and IEEE P1900.1)

Markets

What is the Software Communications Architecture (SCA)?

Markets

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

Applications (waveforms, etc) and Tools

SCA Core Framework and Services

CORBA ORB

Device Drivers

OS access limited to SCA AEP | OS access unlimited | OS access unlimited

Operating Systems (OS/RTOS) that support SCA Application Environment Profile (AEP)

SCA Diagram: Secure Tactical Radio

Source: US Department of Defense, Joint Tactical Radio System

2012/06/15   Wireless Communications Engineering I   92

SDRF Networking Waveform Protocol Stack Reference Model

2012/06/15   Wireless Communications Engineering I   93