Switched MIMO Transceivers Design

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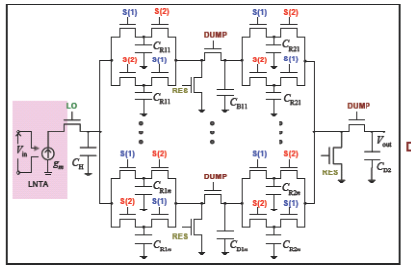
Agenda

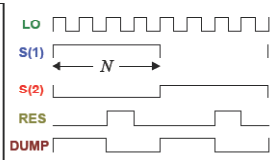
- MIMO Technology for Wireless Communications
- MIMO Channel Modeling
- “Information-Theoretic” Matching Problem
- Load Controlled Parasitic Antenna
- Digital RF Circuits Design
- Switching for Multiplexing and Frequency Conversion
- A New Type of 1-chip MIMO Transceiver

My Research Topics

- RF Circuit Design(Circuit Invariance of Circulator/Directional Coupler) and EM Field Analysis(Hankel-Transform Method)
- Coding Theory(Fast Decoding Algorithm based on Generalized Minimum Distance) and Cryptography(SSSA Algorithm, IEEE1363)
- SDR, Mobile Communication and Array Signal Processing(Complex Angle MUSIC)
- Digital RF and CMOS LSI Design, Cross Layer Co-Design
- Each Research Period is nearly 12 years
- Recently, A New Type of Digital 1-seg Tuner LSI (#MN88448) has been commercialized by Panasonic

Serial-Parallel connection of DSM





$$T = \frac{V_{out}}{V_{in}} = \frac{1}{N} \cdot \frac{1-z^{-N}}{1-z^{-1}} \cdot T_{se} \cdot T_p$$

$$T_{se} = \frac{z^{-N}\sum_{k=1}^{n} C_{R1k}}{\left(\sum_{k=1}^{n} C_{R1k}\right) + C_{B1}\left(1-z^{-N}\right)} \cdot \frac{z^{-N}\sum_{k=1}^{n} C_{R2k}}{\left(\sum_{k=1}^{n} C_{R2k}\right) + C_{B2}\left(1-z^{-N}\right)}$$

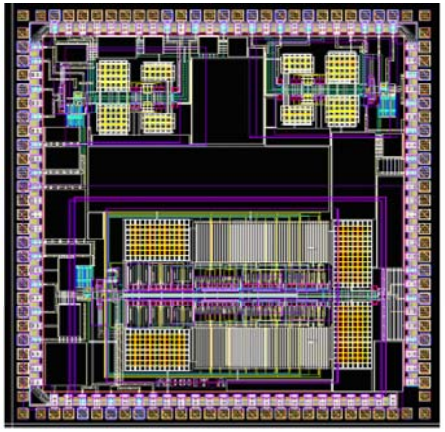
$$T_p = \frac{N g_m T_{LO}}{\pi \sum_{k=1}^{n} C_{R1k} \sum_{k=1}^{n} C_{R2k}} \cdot \sum_{k=1}^{n} \frac{C_{R1k} C_{R2k}}{C_{R1k} + C_{R2k} + C_{B1k}\left(1-z^{-N}\right)}$$

- By arranging the serial–parallel connection, the parallel connection of DSM can be realized with single-LNTA

TSMC
0.18 μ m-process

- Charge sampling DSM
- Voltage-charge sampling DSM
- 2-seri 3-para DSM

Power consumption:
376 μ W



Application to ISDB-T(1segment) receiver

f_{LO}=473MHz , N=4 , C_{R1}=0.256pF, C_{R2}=1.66C_{R1} , C_{R3}=0.901C_{R1}
C_{B11}=22.1C_{R1} , C_{B12}=18.4C_{R1} , C_{B13}=6.65C_{R1} , C_{H}=C_{B2}=55C_{R1}

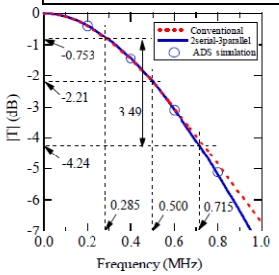


Fig. Near desired signal characteristic

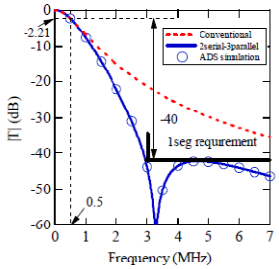


Fig. Near undesired signal characteristic

- The requirement of one-segment receiver is satisfied
- Simulation results in time domain agree well with the calculation results of the transfer function

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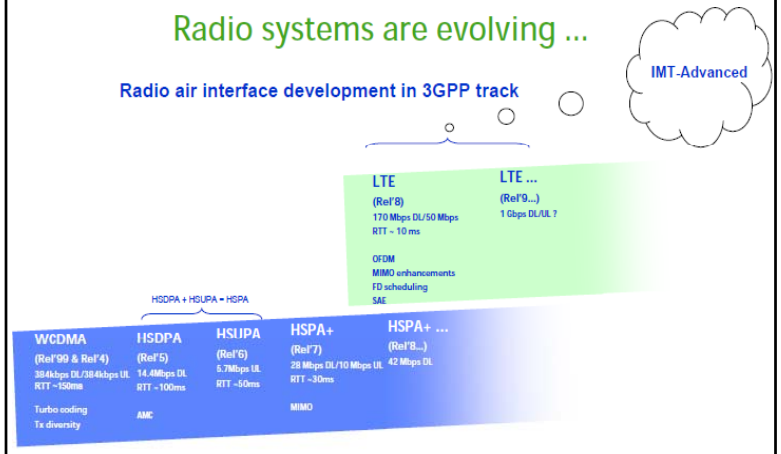
MIMO transmission

- Combination of Antenna/RF Technology and Signal Processing for designing wireless channel
- Orthogonalization is an effective way for increase of channel capacity
- Orthogonal Resource in Communication:
  Time(TDMA), Frequency(OFDM)
  ⇒ Space(MIMO)

Channel Capacity vs.Orthogonality

- For Orthogonal Case C∝B
- For Non-orthogonal Case C∝log(1+S/N)
  Shannon Channel Capacity : C=Blog(1+S/N)
  B:Bandwidth （Frequency is an orthogonal resource）
  S/N : SNR （Amplitude is not an orthogonal resource）
  QPSK（2bit）→ 32QAM（5bit）
  20 times higher Power is required
- MIMO : Orthogonalized Space resource

Radio systems are evolving ...



Main Issues in MIMO System

- Large Size
- High Cost
- Calibration
- CSI Feedback
- Controllability of MIMO Channel
- Optimum Design of MIMO Array Antenna

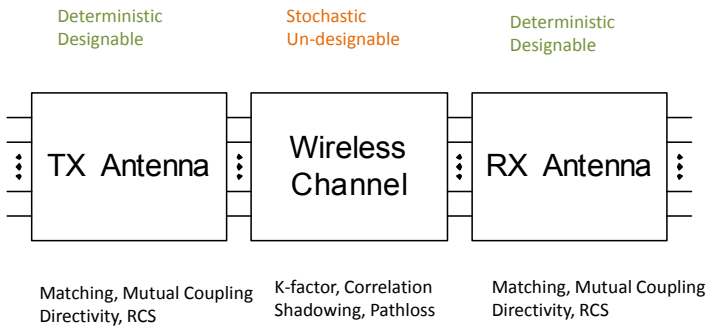
MIMO Channel Modeling

- Classical Friis Formula :

  Gt(λ/4πd)^2Gr

  where channel is fixed, No scattering, No reflection, No mutual coupling

  ⇒ Generalization of Friis Formula is required
- TX (array) antenna : Deterministic and Designable
- Wireless Channel : Stochastic and Un-designable
- RX (array) antenna : Deterministic and Designable
- De-embedding of MIMO Channel should be done

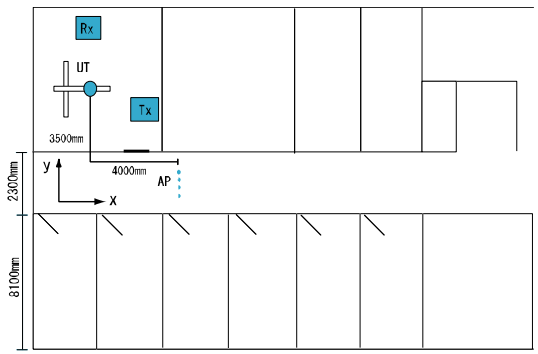


MIMO Channel Modeling

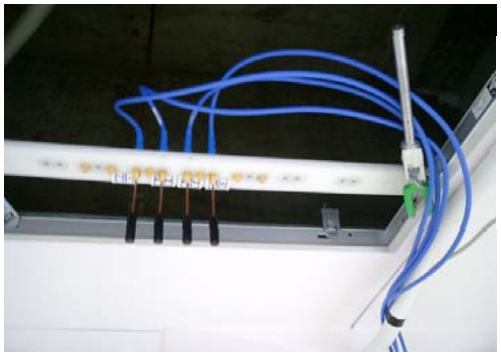
De-embedding of MIMO Channel

- We have to use Antenna for Measurement of MIMO Channel/Propagation Characteristics
- But, if Antenna is replaced with another one, then MIMO Channel will be changed
- We want to know the "intrinsic" MIMO Channel Characteristics
- Thus we need also the "intrinsic" Antenna Characteristics for De-embedding and Calibration

Measured Indoor Environment



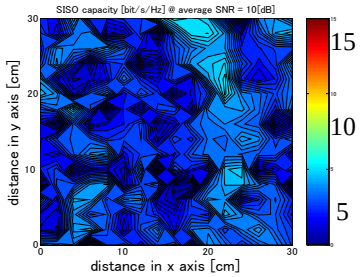
TX Array Antenna



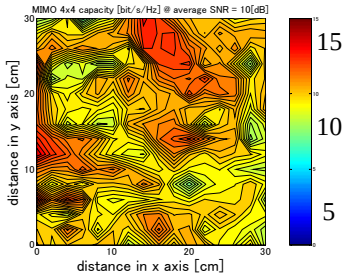
RX Array Antenna

Channel Capacity Analysis

SISO Channel Capacity Distribution



MIMO Channel Capacity Distribution

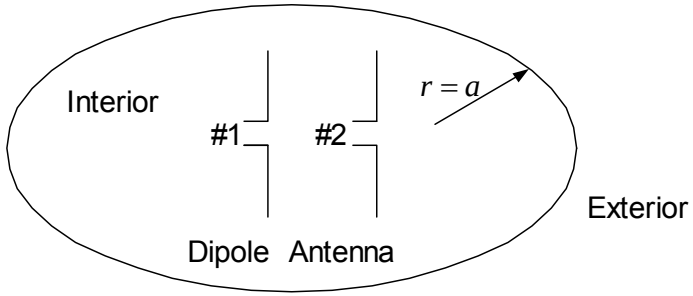


Hierarchy in EM Analysis/Simulation

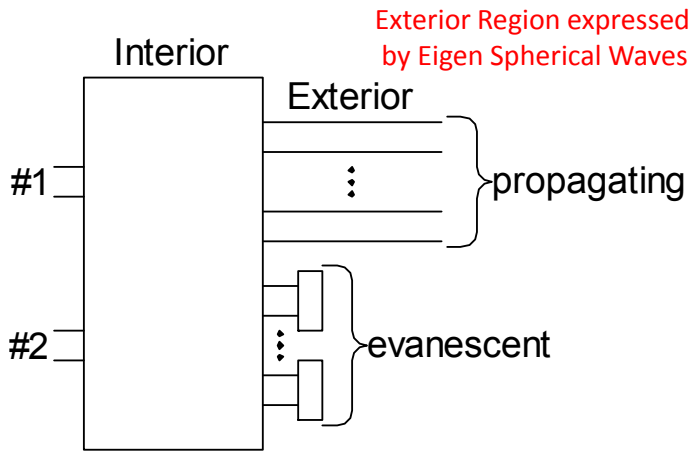
- Time Domain Analysis : FDTD
  Imhomogeneous (Hyperbolic Type) Differential Equation
  Initial Value Problem
  ↓
- Frequency Domain Analysis : FEM, MOM
  Imhomogeneous (Elliptic Type) Differential Equation
  Boundary Value Problem
  ↓
- Equivalent Circuit Analysis : ECA
  Homogenous (Elliptic Type) Differential Equation
  Eigen Value Problem
  3D Structure ⇔ Circuit Parameters

Equivalent Circuit Representation for Antenna

- Interior region : Dyadic Green Function
  → Eigen Mode Functions for PEC
  → Parallel(Series) Connection of Series(Parallel) Resonant Circuits
- Exterior region : Spherical Mode Functions
  → Non-uniform transmission lines



Interior Region includes Array Antenna



EM Field Expansion by Eigen Modes

- Solutions of Maxwell's Eq. with Electric Wall Boundary Condition are not complete
- We need another type of eigen-value problem for EM field expansion. These eigen functions are complete orthonormal.
- From this expansion, equivalent circuit representation can be obtained

Another Type of Eigen Value
Problem for Interior Region(V)

$$\nabla \times \nabla \times \mathbf{E} - \nabla\nabla \cdot \mathbf{E} - k^2 \mathbf{E} = 0 \quad (\text{in } V)$$
$$\mathbf{n} \times \mathbf{E} = 0, \quad \nabla \cdot \mathbf{E} = 0 \quad (\text{on } S)$$

Orthonormality
for Vector Eigen Functions

$$\int \mathbf{E}_n \cdot \mathbf{E}_m \, dv = 0 \quad (n \neq m)$$
$$\int \mathbf{E}_n \cdot \mathbf{E}_m \, dv = 1 \quad (n = m)$$

Grouping

Ⅱ : Resonant Mode
Ⅰ, Ⅲ : Static Mode

$$\text{I.} \quad \nabla \times \mathbf{E}_n = 0, \quad \nabla \cdot \mathbf{E}_n = 0$$
$$\text{II.} \quad \nabla \times \mathbf{E}_n \neq 0, \quad \nabla \cdot \mathbf{E}_n = 0$$
$$\text{III.} \quad \nabla \times \mathbf{E}_n = 0, \quad \nabla \cdot \mathbf{E}_n \neq 0$$

Adjoint Eigen Value Problem

$$\nabla \times \nabla \times \mathbf{H} - \nabla\nabla \cdot \mathbf{H} - k^2 \mathbf{H} = 0 \quad (\text{in } V)$$

$$\mathbf{n} \cdot \mathbf{H} = 0, \quad \mathbf{n} \times \nabla \times \mathbf{H} = 0 \quad (\text{on } S)$$

Group Ⅲ Eigen-Mode Pair : Resonant Mode

$$\nabla \times \mathbf{E}_a = k_a \mathbf{H}_a$$

$$\nabla \times \mathbf{H}_a = k_a \mathbf{E}_a$$

ka : eigen-value for “a-th” mode

Group Ⅰ, Ⅲ : Static Field

$$\nabla \times \mathbf{E}_\nu = 0$$

$$\nabla \times \mathbf{H}_\lambda = 0$$

EM Field Expansion by Eigen Functions

$$\mathbf{E} = \sum_a \mathbf{E}_a \int \mathbf{E} \cdot \mathbf{E}_a \, dv + \sum_\nu \mathbf{E}_\nu \int \mathbf{E} \cdot \mathbf{E}_\nu \, dv$$

$$\mathbf{H} = \sum_a \mathbf{H}_a \int \mathbf{H} \cdot \mathbf{H}_a \, dv + \sum_\lambda \mathbf{H}_\lambda \int \mathbf{H} \cdot \mathbf{H}_\lambda \, dv$$

$$\nabla \times \mathbf{E} = \sum_a \mathbf{H}_a \left(k_a \int \mathbf{E} \cdot \mathbf{E}_a \, dv + \int \mathbf{n} \times \mathbf{E} \cdot \mathbf{H}_a \, dS \right)$$

$$+ \sum_\lambda \mathbf{H}_\lambda \int \mathbf{n} \times \mathbf{E} \cdot \mathbf{H}_\lambda \, dS$$

$$\nabla \times \mathbf{H} = \sum_a \mathbf{E}_a k_a \int \mathbf{H} \cdot \mathbf{H}_a \, dv$$

Expanded Form of Maxwell’s Equation

$$k_a \int \mathbf{E} \cdot \mathbf{E}_a \, dv + \int \mathbf{n} \times \mathbf{E} \cdot \mathbf{H}_a \, dS = -j\omega\mu \int \mathbf{H} \cdot \mathbf{H}_a \, dv$$

$$\int \mathbf{n} \times \mathbf{E} \cdot \mathbf{H}_\lambda \, dS = -j\omega\mu \int \mathbf{H} \cdot \mathbf{H}_\lambda \, dv$$

$$k_a \int \mathbf{H} \cdot \mathbf{H}_a \, dv = (\sigma + j\omega\varepsilon) \int \mathbf{E} \cdot \mathbf{E}_a \, dv$$

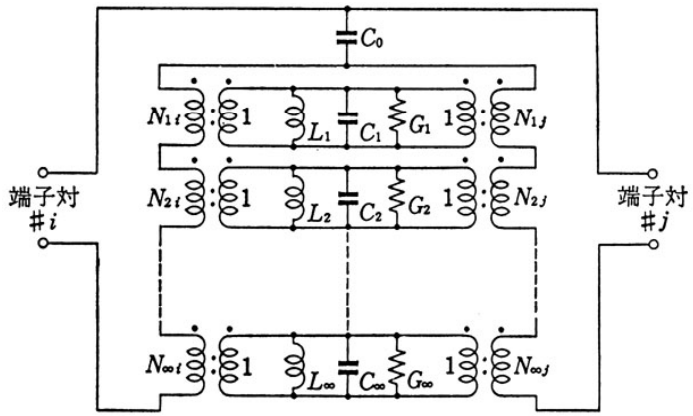
$$\int \mathbf{E} \cdot \mathbf{E}_\nu \, dv = 0$$

$\therefore$

$$\left\{ j\omega\mu + k_a^2 / (\sigma + j\omega\varepsilon) \right\} \int \mathbf{H} \cdot \mathbf{H}_a \, dv = -\int \mathbf{n} \times \mathbf{E} \cdot \mathbf{H}_a \, dS$$

Equivalent Circuit for Antenna

- On S (r=a) n × E（Tangential Electric Field) is given
  S : Interface between Interior and Exterior Region
- Then all coefficients of ∫H ・Hadv and ∫H・Hλdv are solved by the previous equations
- Thus n × H(Tangential Magnetic Field) on S is provided
  n × H=∑n × Ha ∫H ・Hadv +∑n × Hλ ∫H・Hλdv
- n × E（Voltage）⇒ n × H（Current） on S
- [Admittance Matrix] of Interior Region is obtained



Equivalent Circuit Representation

Spherical Wave Functions

- Complete Orthogonal Functions for Wave-Equations derived by Maxwell's Eq.
- Each Spherical wave function corresponds to non-uniform transmission line
- Characteristic impedance changes with position of r

Spherical wave function for Exterior Region

$$\vec{F}^{(c)}_{1mn}(r,\theta,\phi)=\frac{1}{\sqrt{2\pi}}\frac{1}{\sqrt{n(n+1)}}\left(-\frac{m}{|m|}\right)^m\left\{z_n^{(c)}(kr)\frac{im\overline{P}_n^{|m|}(\cos\theta)}{\sin\theta}e^{im\phi}\hat{\theta}-z_n^{(c)}(kr)\frac{d\overline{P}_n^{|m|}(\cos\theta)}{d\theta}e^{im\phi}\hat{\phi}\right\}$$

The normalized associated Legendre function

$$\vec{F}^{(c)}_{2mn}(r,\theta,\phi)=\frac{1}{\sqrt{2\pi}}\frac{1}{\sqrt{n(n+1)}}\left(-\frac{m}{|m|}\right)^m\left\{\frac{n(n+1)}{kr}z_n^{(c)}(kr)\overline{P}_n^{|m|}(\cos\theta)e^{im\phi}\hat{r}\right.$$
$$+\frac{1}{kr}\frac{d}{d(kr)}\left[krz_n^{(c)}(kr)\right]\frac{d\overline{P}_n^{|m|}(\cos\theta)}{d\theta}e^{im\phi}\hat{\theta}$$
$$\left.+\frac{1}{kr}\frac{d}{d(kr)}\left[krz_n^{(c)}(kr)\right]\frac{im\overline{P}_n^{|m|}(\cos\theta)}{\sin\theta}e^{im\phi}\hat{\phi}\right\}$$

$k=\frac{2\pi}{\lambda}$
$n=1,2,3,\cdots$
$m=0,\pm1,\pm2,\cdots,\pm n$

m: order
n : degree

$z_n^{(1)}=j_n(kr)$ (Spherical Bessel function; The standing wave, finite origin)
$z_n^{(2)}=n_n(kr)$ (Spherical Neumann function; The standing wave, infinite origin)
$z_n^{(3)}=h_n^{(1)}(kr)=j_n(kr)+in_n(kr)$ (Spherical Hankel function; The radial outgoing wave)
$z_n^{(4)}=h_n^{(2)}(kr)=j_n(kr)-in_n(kr)$ (Spherical Hankel function; The radial incoming wave)

Spherical Wave Function

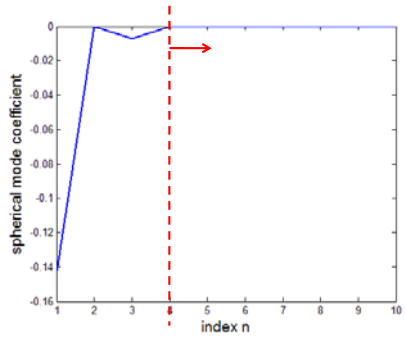
- Non-uniform Transmission Line
- For kr → 0 evanescent mode
- For kr → ∞ propagating mode
- k: wave number k=ω√(εμ)
- Effective number of propagating mode

  N ≧[ka]

  a: Minimum Radius of Interior Region
- [ka]: Effective Dimension of Antenna

Example: Half-wave dipole

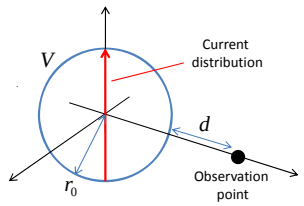
About index 'n': Spherical mode coefficient Q



The radius of the minimum sphere

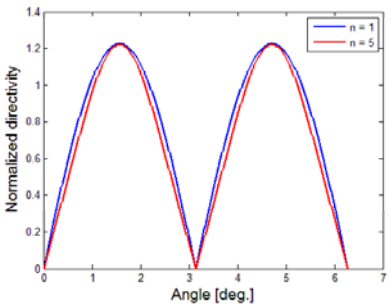
$N \geq [kr_0] + n_1$ (k is wave number.)

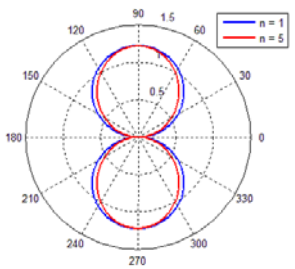
n_1 depends on kd and truncation error.



Example: Half-wave dipole

About index 'n': Directivity

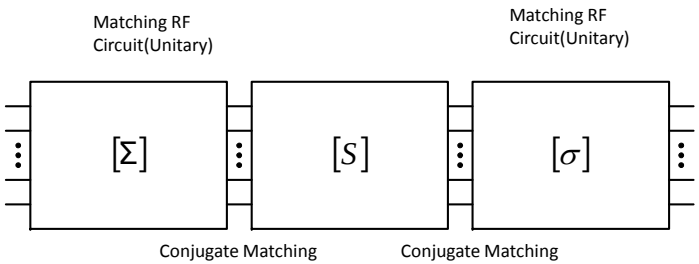




"Information-Theoretic" Matching Problem in MIMO Systems

- MIMO Channel Capacity

  C=log{det[I+ρHH†]} (bps/Hz)
- det[]:Determinant
- I : M × M Unit Matrix
- ρ : SNR
- H:M × N Channel Matrix
- † : Complex Conjugate and Transpose
- M:# of receiving antenna
- N : # of transmitting antenna



Tandem Connection of
MIMO Channel and RF Matching Circuits

Overall MIMO Channel Matrix

- (M+N) × (M+N) Scattering Matrix [S]

  | S11 S12|
  | S21 S22|

  1 : TX 2 : RX
- S11:TX Antenna's M × M Scattering Matrix
- S12:RX→TX M × N Transfer Matrix(UL)
- S21:TX→RX N × M Transfer Matrix ⇒ MIMO Channel H (DL)
- S22:RX Antenna's N × N Scattering Matrix

SVD-MIMO

- All-Pass Circuits (U,V) at TX and RX
- Scattering Matrix of All-Pass Circuit:

  |0 U|

  |U^† O| where U: Unitary
- Tandem Connection:

  S11 → U^†S11U S22 → V^†S22V

  S12 → V^†S12U S21 → U^†S21V

SFG vs. Circuit

- SFG(Signal Flow Graph): Pure Algorithmic Processing (Algebraic Operation)
- (RF) Circuit: Similar Algorithmic but a little bit different
- In the circuit, 2 different variables (voltage/ current or incident/reflected waves) should be treated simultaneously
- Thus, if reflected waves are neglected, then (RF) circuit gives the same performance as SFG

SVD and Channel Capacity

- Channel Capacity is expressed by Singular values of H（λ1,λ2,…,λr）

  r：rank of H

C=log(1+ρλ1)+ log(1+ρλ2)+…+log(1+ρλr)

Matching Problem in Power Amplifiers

- What is MAG(Maximum Available Gain) in PA?
- Tandem Connection：[S]=[Σ]◎[s]◎[σ]
- [Σ]：Input Matching 2-port Circuit→ Unitary Matrix
- [s]:PA's 2-port Scattering Matrix
- [σ]： Output Matching 2-port Circuit→ Unitary Matrix
- ◎：Tandem Connection≠Matrix Multiplication

Simultaneous Matching

- Target：｜S21｜ → Maximize
- [Σ],[σ]：adjustable parameters under Unitary condition
- When |S21| is maximized
- Then Σ22=s'11* σ11=s''22*
- Where [s']=[s]◎[σ] [s"]=[Σ]◎[s]
- ｜S21|max＝MAG

Maximization of SISO channel capacity

- For M=N=1⇒ SISO
- r=1 ∴ C=log(1+ρλ1)：Maximization

  ⇒ λ1： Maximization

  ⇒ |S21|：Maximization

∴ SISO Channel Maximization ⇔ MAG of 2port

For SISO

"(Circuit Theoretic) Matching Problem"

="(Information Theoretic) Matching Problem"

Open Problem

- Maximization of C in MIMO is related to a maximization of SV(λ1,λ2,…,λr), but this should be done
  under the constraint unitary condition.

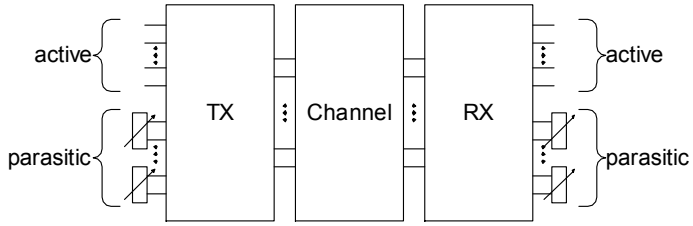
"Information-Theoretic" Matching Problem
= "Circuit-Theoretic" Matching Problem ?
in MIMO

Variable RF Front-end for Adaptive MIMO

- Conventionally, MIMO technology is based on Digital Signal Processing at BB
  ⇒ Spatial Multiplexing (Pre-coding at TX Post-coding at RX)
- Analog Signal Processing at RF
  ⇒ Maximization of Channel Matrix's SV
- Furthermore, Digital/Analog Signal Processing at BB/RF ⇒ "Adaptive MIMO"

Adaptive MIMO

- Cross layer design between RF and BB
- Parasitic Antenna ＋ Active antenna
- Control of "Re-radiation" from parasitic antenna using a reactance load



Adaptive MIMO Channel

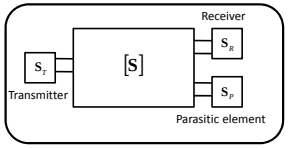
Single Input Single Output(SISO)システム

Shannon Channel Capacity

$$C = \log_2(1+|S_{RT}|^2 \frac{S}{N})\,[\text{bps/Hz}]$$

S_{RT} : Channel Response

With Parasitic Element



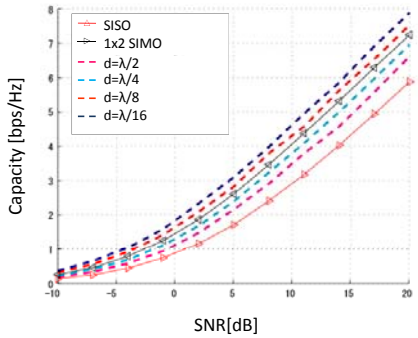
$$S_{RT} \Longrightarrow S'_{RT}$$

$$|\tilde{S}_{RT}|_{MAX} = \left|S_{RT} + \frac{S^*_{PP} S_{RP} S_{PT}}{1-|S_{PP}|^2}\right|^2 + \left|\frac{|S_{RP} S_{PT}|}{1-|S_{PP}|^2}\right|$$

Impedance Matrix to Scattering Matrix

$$\mathbf{S} = (\mathbf{Z}+\mathbf{Z}_0)^{-1}(\mathbf{Z}-\mathbf{Z}_0)$$

Simulation Result



Improvement
- Channel capacity is more than that of SISO

For small antenna separation
◎ Channel Capacity becomes large especially when d>λ/8 larger than that of SIMO

Average Channel Capacity

Digital RF Transceivers

- CMOS sub-micron technology
- Paradigm Shift in RF Transceiver Design
- Digitally Assisted Analog/RF Circuits
- Role of Clock Signal

Design Strategy for Transceivers

- System Level Design

↓ ↑

- Circuit Level Design

↓ ↑

- Device Level Design

Vertical Integration is important

CMOS Submicron Technology brings

- Low Voltage Operation
- Reduction of Headroom
- High Speed Operation
- Integration of RF and BB
- Sophisticate DSP : Digital Assist Technology

  ⇒ "Digital RF"

What is a paradigm shift in Analog CMOS Circuit ?

- Amplitude Domain ⇒ Time Domain
- CMOS Sub-micron Technology→Low Voltage Operation, Short Delay
- Analog Control ⇒Digital Control
- Integration of 3 different Systems

  Analog Amplitude・Continuous Time System⇔

  Analog Amplitude・Discrete Time System⇔

  Discrete Amplitude・Discrete Time System

Examples of Digital RF Circuits

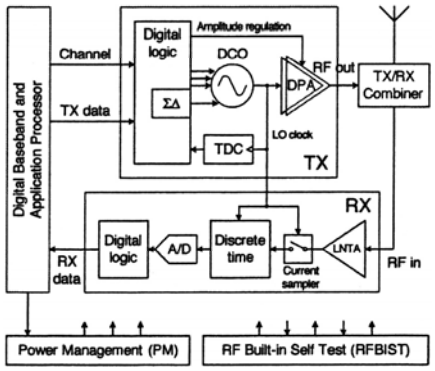
- Oscillation : VCO→DCO PLL→ADPLL
- Frequency Conversion :

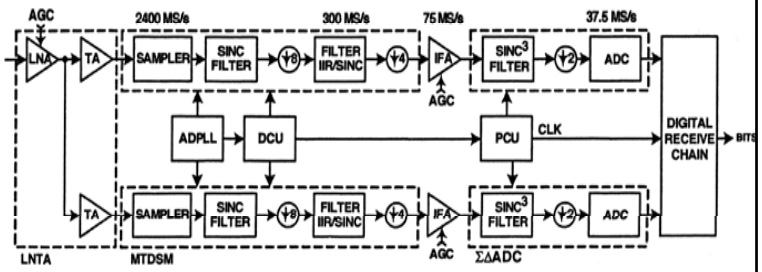
  Mixer→Sampling Mixer

  Multiplication ON/OFF
- Modulation :

  IQ Modulation→Polar Modulation
- Variable Gain : AGC→AA (Array Amplifier)

TI Bluetooth Transceiver





Circuit Characteristics

- Clock Frequency and Capacitance Ratio
- Digital (ON/OFF) Control of Capacitance Array
- Controllability by Changing Clock Frequency and/or Capacitance Ratio
- Reconfigurable RF Circuits（SDR)
- Especially Clock signal is very important for design/control of RF Circuit

Variety of Clock Signal

- Multi-phase
- Multi-Duty
- Multi-Rate
- Design Example :

  Harmonic Rejection Mixer

  Complex Pole (Digital) Filter

HRM

- Harmonic Rejection Mixer is important circuit for both transmitter and receivers
- High efficiency of Switching Mixer and Wide Band SDR

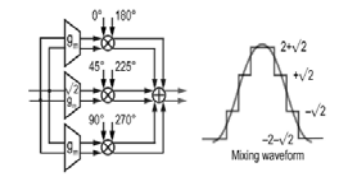
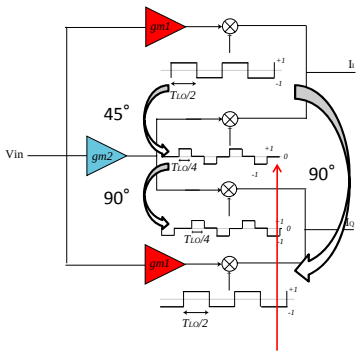


Fig. 11. Harmonic-suppressing mixer block diagram and its sinusoidal approximated mixing waveform.

An 800-MHz–6-GHz Software-Defined Wireless Receiver in 90-nm CMOS

- For IQ Modulation System, Homodyne Receiver needs 3 × 2=6 Mixers
- Wasting time period occurs
- Imbalance in 3 amplifiers becomes serious
- 3 spurious capacitances in architecture are drawback

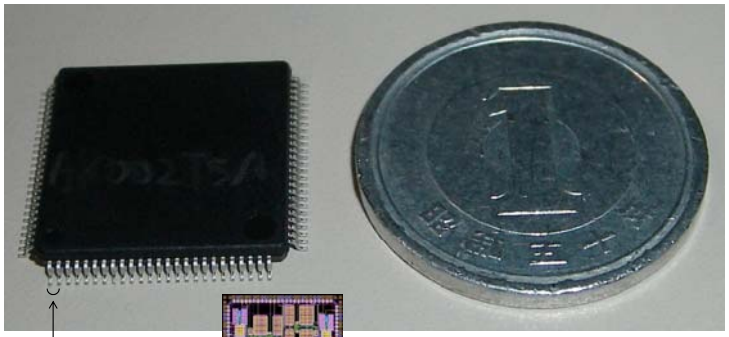
New Type of HRM



In this period reverse pass is connected

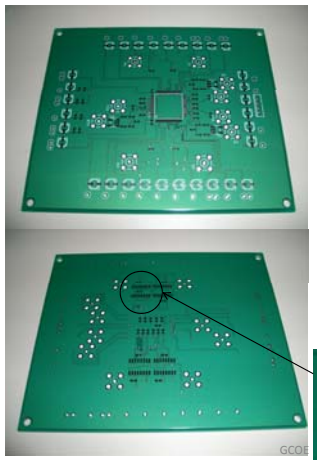
- ¼ Duty Pulse
- For I-Pass,Q-Pass gm1
- For I-Q Common Pass gm2(gm2=√2gm1)
- No Wasted Power
- Differential Mode

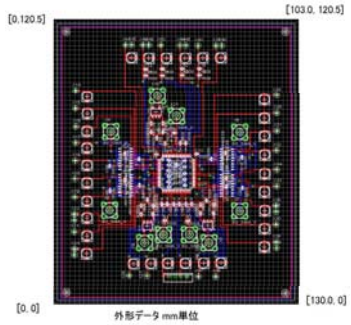
Prototype LSI Photo



0.5mm Pitch
25 Terminals

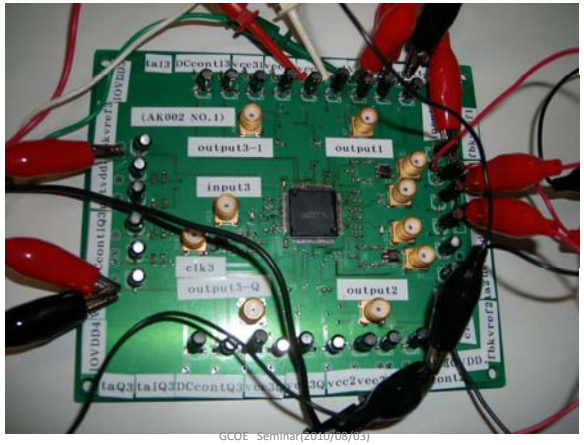
TEG for Measurement





Misdesign

Testing



Measurement

	Basic	1/3Duty	Harmonic Rejected I	Harmonic Rejected Q
Gain[dB]@473MHz	15.5	18.4	-2	2
Gain[dB]@946MHz	-16	-17.3	-30	-14
Gain[dB]@1419MHz	-2	-10.6	-32	-25
Gain[dB]@1892MHz	-29	-22.2	-37	-32
Gain[dB]@2365MHz	-20	-10.5	-37	-31
3rd HRR	17.5	29	30	27
5th HRR	35.5	28.9	35	33
IP1dB[dBm]@473.2MHz	-2	-2	-2	-9
OP1dB[dBm]@473.2MHz	9.7	12.2	-19.3	-26.4

To suppress DC Noise, 10kHz offset measurement

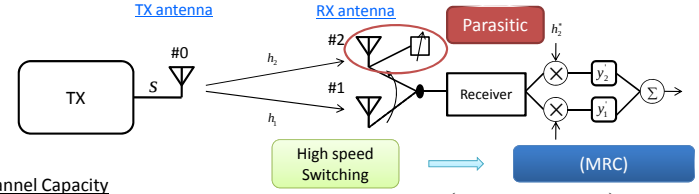
Unreliable data

Switched Parasitic MIMO

- Time Multiplexing → One Transceiver
- For Non-active antenna, reactance load termination for "positive" re-radiation
- SISO＜Selection Diversity＜MRC＜Switched Parasitic-MIMO

Switched MIMO

Switched Array Antenna



Channel Capacity

$$C = \log_2\left(1 + \frac{P}{\sigma^2}|h|^2\right) \text{ [bps/Hz]}$$

$$C = \log_2\left(1 + \frac{P}{\sigma^2}\left(\frac{|h_1|^2 + |h_2|^2}{2}\right)\right) \text{ [bps/Hz]}$$

$$|h_1|^2 \Rightarrow |h_1'|^2$$

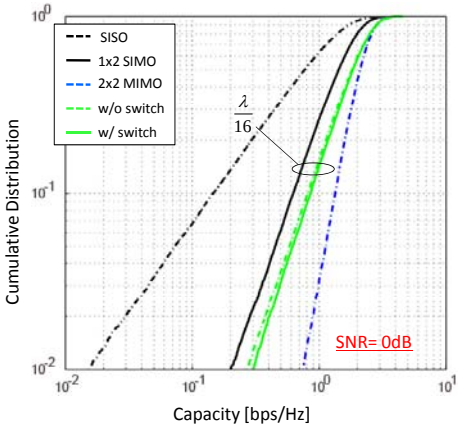
$$|h_2|^2 \Rightarrow |h_2'|^2$$

$$\Rightarrow \frac{|h_1|^2 + |h_2|^2}{2}$$

Control of Parasitic Load ⇔ MRC by Switching

$$\frac{|h_1'|^2 + |h_2'|^2}{2}$$

Simulation Result



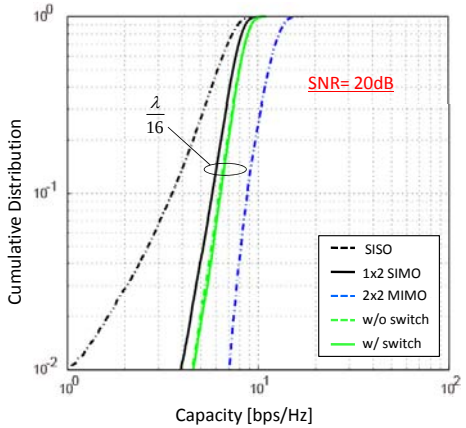
CDF of Channel Capacity

Improvement
- Channel Capacity is larger than that of SISO
- Moreover Diversity Effect is obtained by Switching

For small antenna separation
◎ Channel Capacity becomes large
△Switching effect decreases

Optimum Antenna Separation

Simulation Result



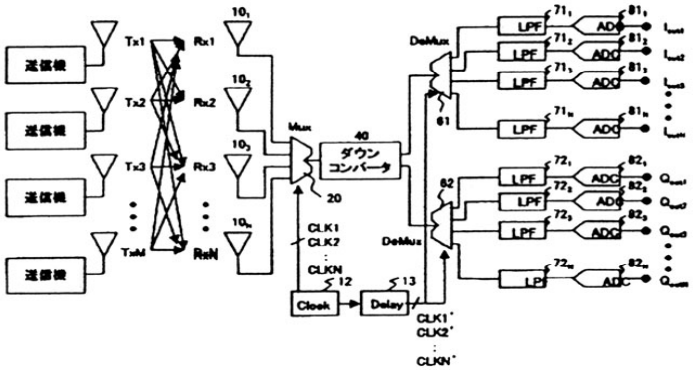
CDF of Channel Capacity

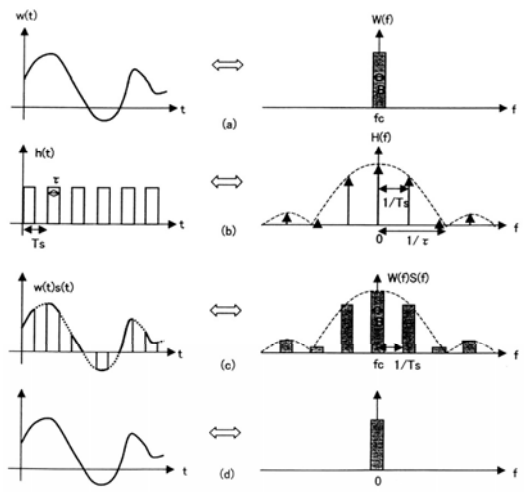
Improvement
◎ **For High** SNR, S-P effect becomes significant
△Compared with low SNR, Switching Effect is relatively small

Multiplexed Receivers

- N Branch Receiver：⇒N:1 Multiplexer＋One Receiver
- SNR decreases 1/N
- No imbalance between N different receivers
- Switching Speed should be higher than Modulated Bandwidth ←Shannon Sampling Theorem

Switched MIMO Receivers

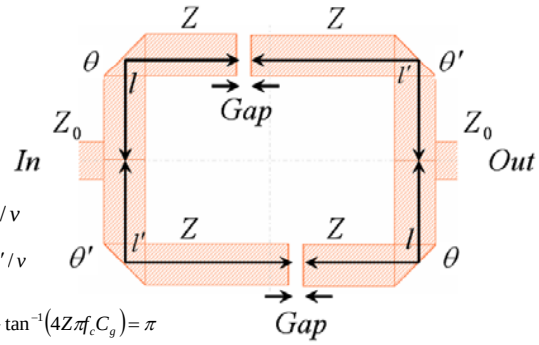




Anti-Aliasing

- Using Sharp BPF, Aliasing Spectrum due to switching can not be transmitted and received
- Analog Signal Processing: BPF and Reactance Load Control

Microstrip Gap-coupling Bandpass Filter:



$\theta = 2\pi f l / v$

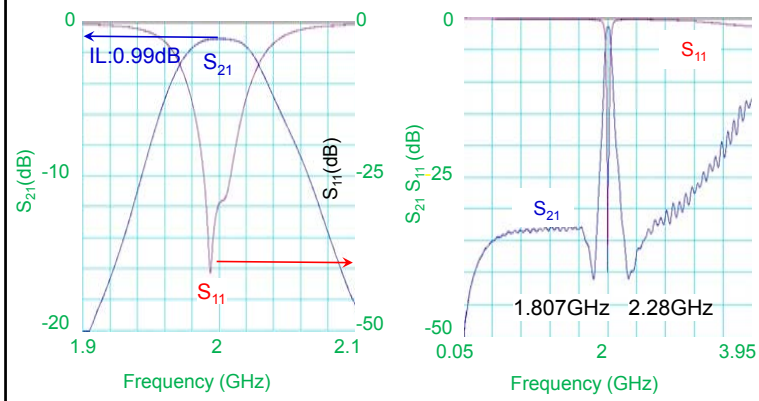
$\theta' = 2\pi f l' / v$

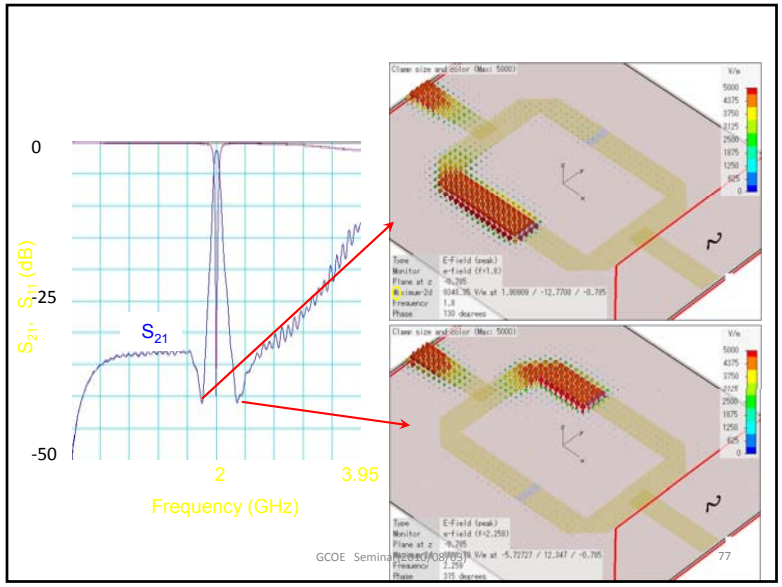
$\theta + \theta' + \tan^{-1}(4Z\pi f_c C_g) = \pi$

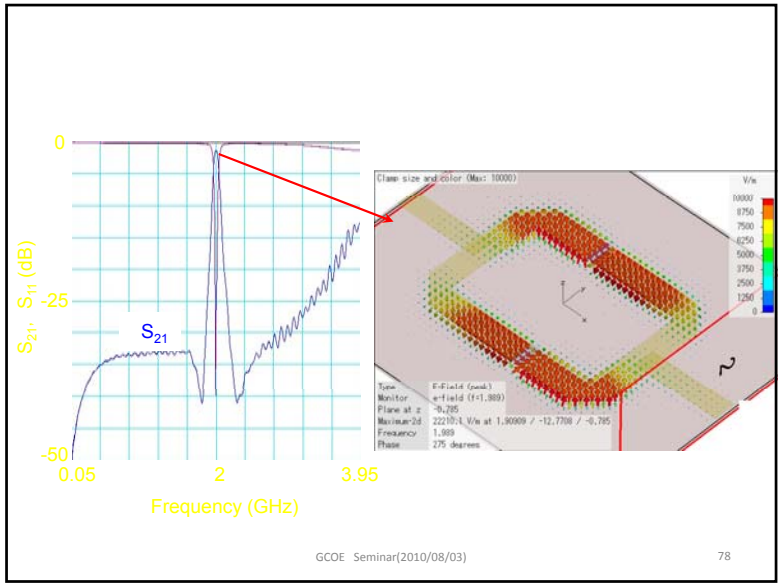
C_g: Gap Capacitance

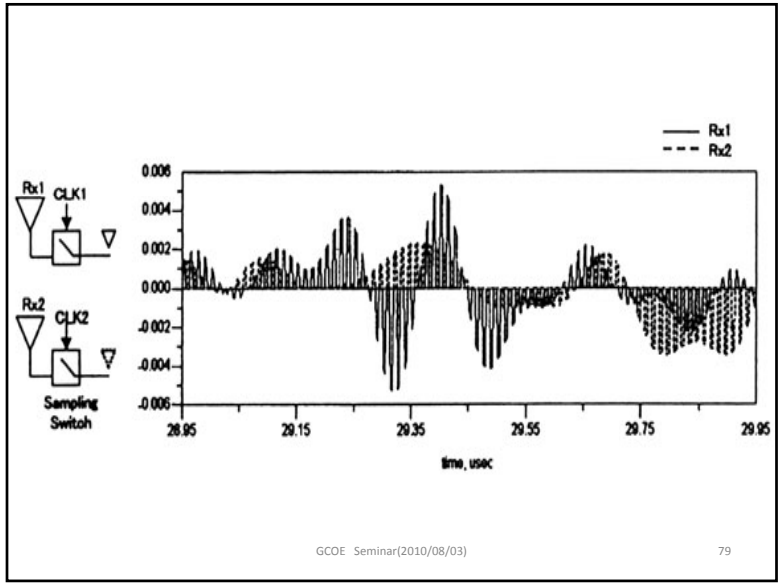
v :TEM Wave Velocity

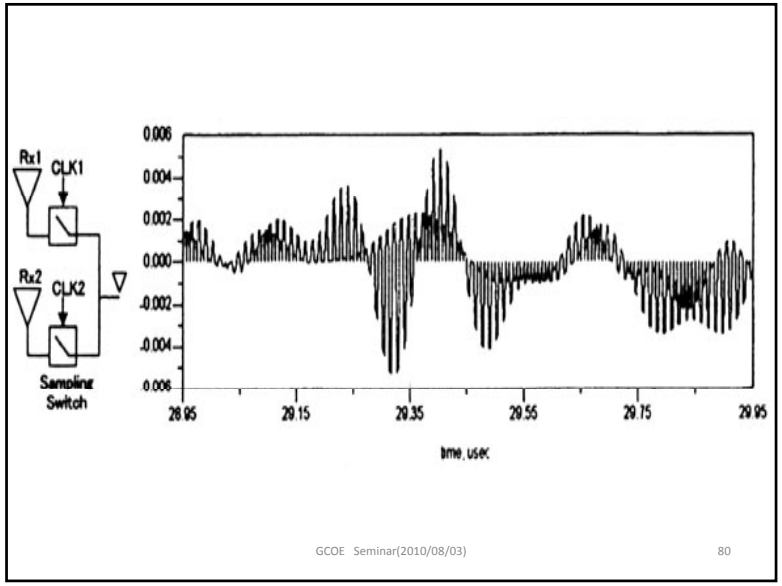
f_c :Center Frequency

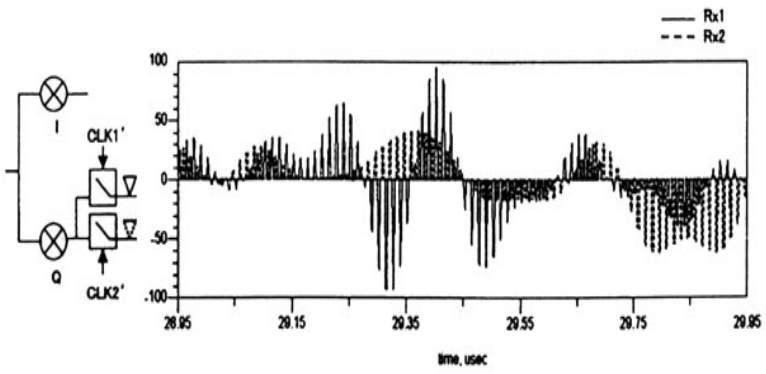


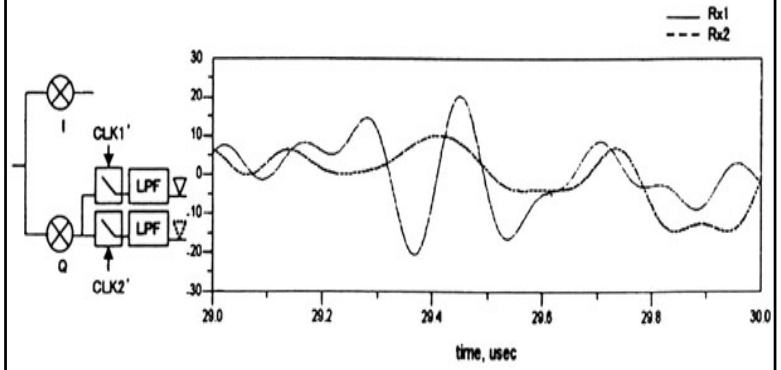

0
-25
-50
S_{21}, S_{11} (dB)
S_{21}
2
3.95
Frequency (GHz)
GCOE Seminar(2010/08/03)
77

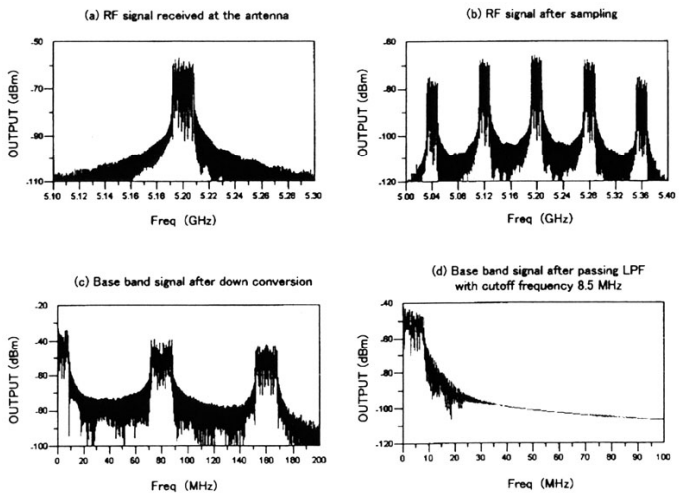

0
-25
-50
S_{21}, S_{11} (dB)
S_{21}
0.05
2
3.95
Frequency (GHz)
GCOE Seminar(2010/08/03)
78


Rx1
Rx2
CLK1
CLK2
Sampling Switch
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
28.95
29.15
29.35
29.55
29.75
29.95
time, usec
GCOE Seminar(2010/08/03)
79


Rx1
Rx2
CLK1
CLK2
Sampling Switch
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
28.95
29.15
29.35
29.55
29.75
29.95
time, usec
GCOE Seminar(2010/08/03)
80







DSM and SP-MIMO

- Switching in DSM : Frequency Conversion
- Switching in (De)Multiplexers : Reduction of RF Circuits

  ⇒ Integration of Frequency Conversion＋(De)Multiplexing
- Higher Level Integration of CT/DT Mixed system⇒ Future 1 Chip Transceiver !?

Conclusion

- MIMO Channel Modeling
- Information-Theoretic Matching Problem
- Antenna Equivalent Circuit
- Parasitic Antenna for Adaptive MIMO
- Digital RF Circuit Design
- Multiplexed MIMO and RF Front-end BPF
- Adaptive Switched 1-chip MIMO Transceivers

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