Antenna Design Strategy and Demonstration for SDR

Taeyoung Yang, William A. Davis, Warren L. Stutzman,
S.M. Shajedul Hasan, Randall Nealy, Carl B. Dietrich, Jeff H. Reed

{mindlink, wadavis, stutzman, hasan, rnealy, cdietric, reedjh} @ vt.edu

Prepared for SDR'10
December 3rd, 2010, Session 7B: RF, IF, ADC, *Regency D*,
08:30 "Antenna Design Strategy and Demonstration for Software-Defined Radio" (Best of R&D Track)

Wireless @ Virginia Tech (http://wireless.vt.edu)
Bradley Department of Electrical and Computer Engineering
Blacksburg, VA

Outline

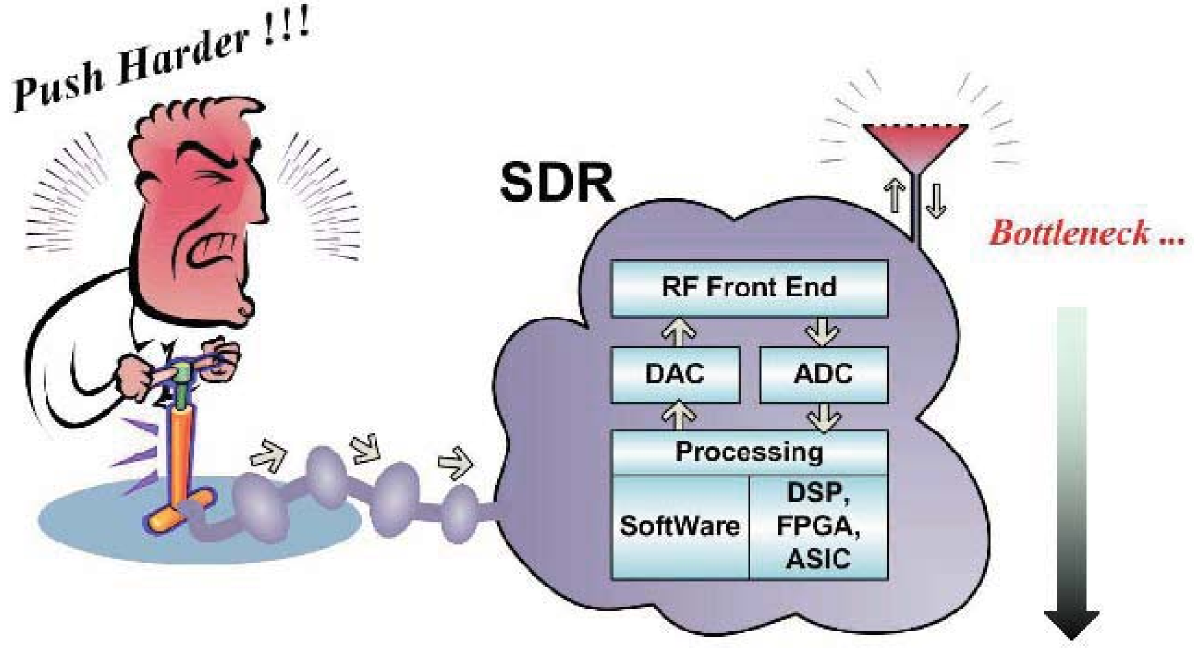
1. Motivation

2. Ant. Design Challenges
   - Radiation Physics
   - Fundamental Limit on Size & Performance
   - Size Miniaturization Techniques

3. Ant. Design Strategy for SDR

4. Demonstration

Motivation



Limited by radiation physics principles, not technology

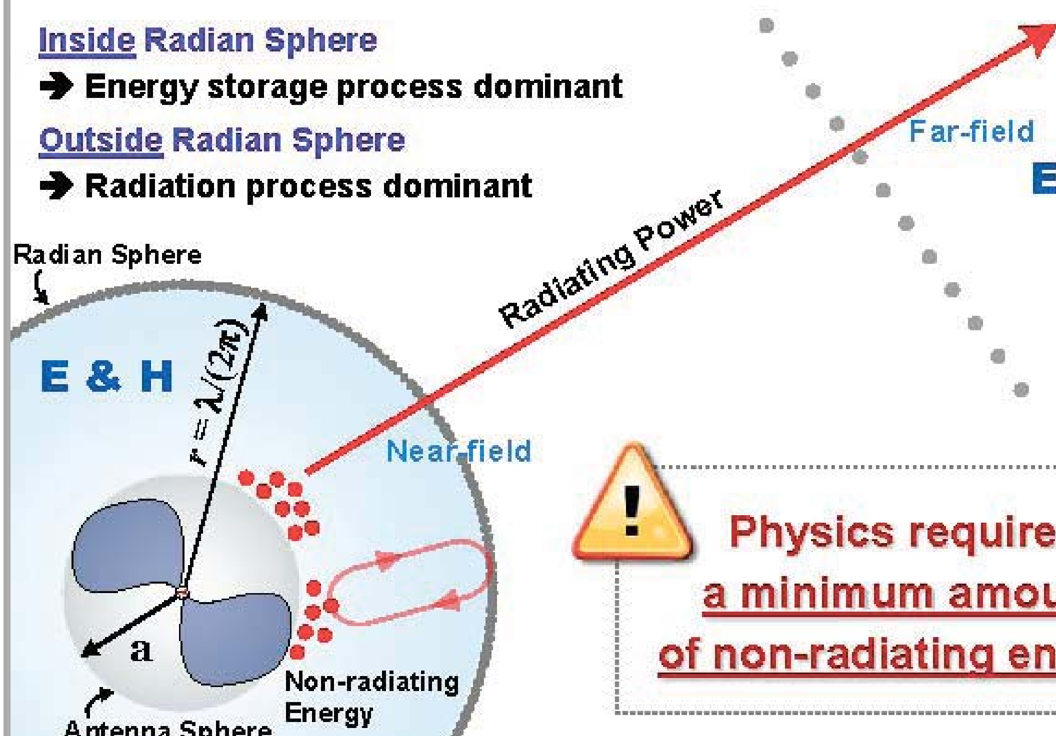
Antenna Radiation Physics

<u>Inside</u> Radian Sphere

➔ **Energy storage process dominant**

<u>Outside</u> Radian Sphere

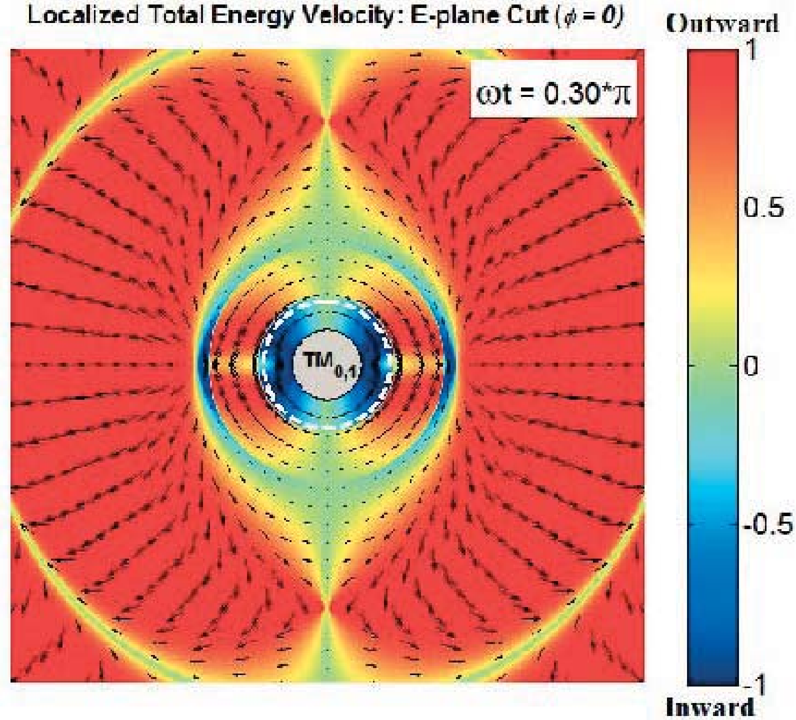
➔ **Radiation process dominant**



Physics requires
<u>a minimum amount</u>
<u>of non-radiating energy</u>

VIRGINIA TECH VTAG ANTENNA GROUP — Wireless @ Virginia Tech

Antenna Radiation Physics - II

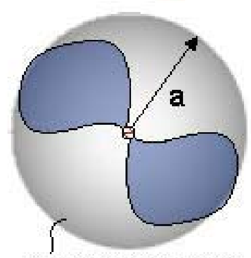


VIRGINIA TECH VTAG ANTENNA GROUP — Wireless @ Virginia Tech

Fundamental-Limit Theory

❑ Frontiers

- H.A. Wheeler, 1947
- L.J. Chu, 1948



❑ Basic Assumptions

- Passive LTI system
- Antenna is enclosed in minimum sphere (*antenna sphere*)
- Antenna structure has all-pass-filter characteristics
- Spherical-mode excitation

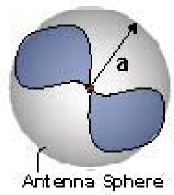
❑ Radiation *Q*

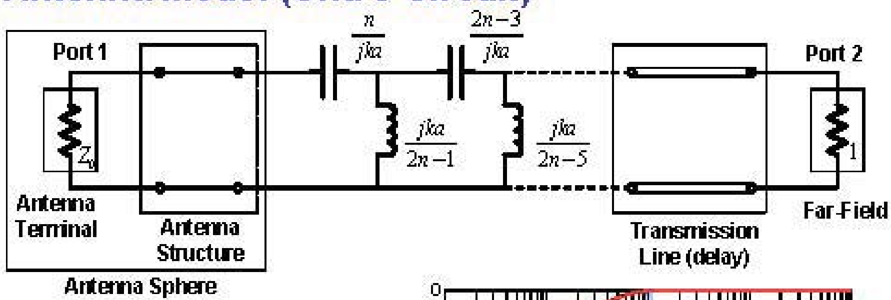
Connect to Impedance-Matching Limit

$$Q_{rad} = e_r \frac{\left[W_{non-rad}\right]_{peak}}{\langle P_{rad} \rangle / \omega} \approx \boxed{\frac{f_c}{BW_{3dB}}} \text{ for single-resonant antenna}$$

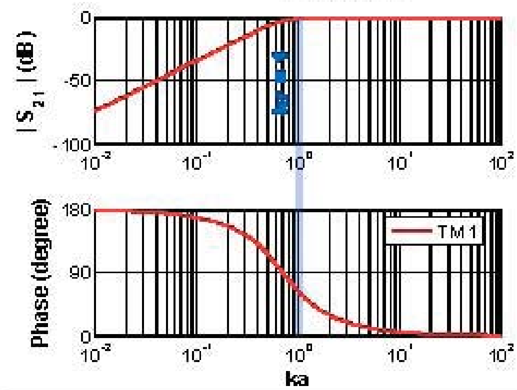
Fundamental-Limit Theory: Ideal Antenna ➔ Minimum Q_{rad}

- Two-Port Ideal Antenna Model (Chu's Circuit)

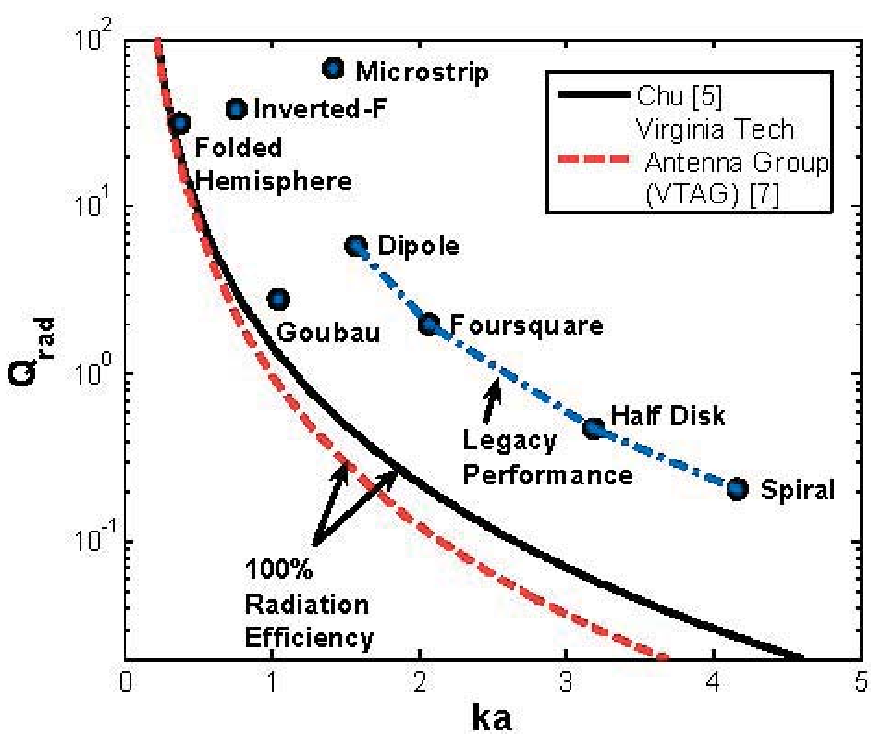




- High-Pass Filter Characteristic
- Relatively Constant Gain above Cut-off frequency
- For example, TM_1 Fundamental Mode ➔

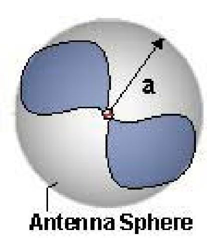


Theoretical-Limit versus Reality



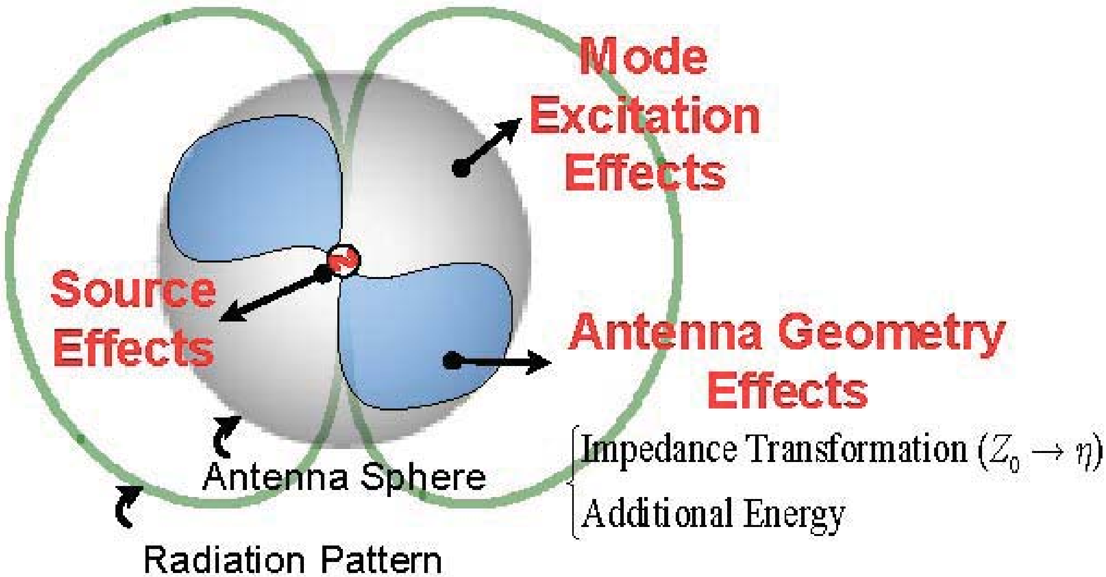
$$Q_{rad,\ Chu}^{min} = e_r \frac{(1+2k^2a^2)}{(k^3a^3)(1+k^2a^2)}$$

$$Q_{rad,\ VTAG}^{min} = e_r \frac{1}{k^3a^3}$$



$$k = \frac{2\pi}{\lambda}$$

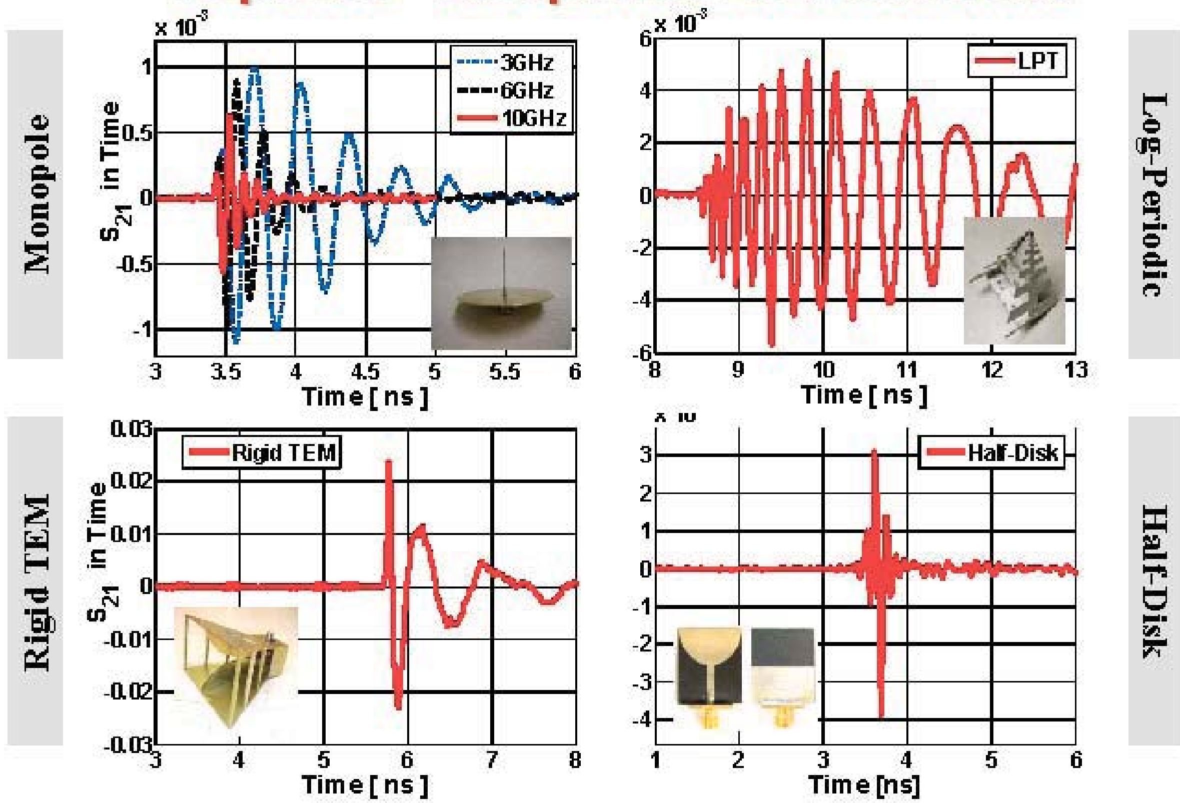
Real Antenna Problem



Antennas for SDR

- **Resonant**
  - ✓ Smallest form factor ➔ Best for handheld devices
  - ✓ To resolve impedance-matching / Narrow BW issues
    - ➔ Resistive loading ($e_r \downarrow$)
    - ➔ Reconfigurable (Switching speed? ; power consumption ↑)
    - ➔ Multi-band (complexity ↑)
  - ✓ To resolve varying radiation-pattern issue over operational freq.
    - ➔ Traps
- **Frequency-independent**
  - ✓ Wide bandwidth, but not instantaneous (dispersive)
    - ➔ Best for 'fixed'-channel radio
  - ✓ Directional patterns (high directivity)
- **Ultra-wideband**
  - ✓ Wide instantaneous bandwidth
    - ➔ Best for dynamic freq. agile functions
  - ✓ Directional or omni-directional patterns
  - ✓ Size issues ➔ Tradeoffs

"Impulse" Response of Antennas



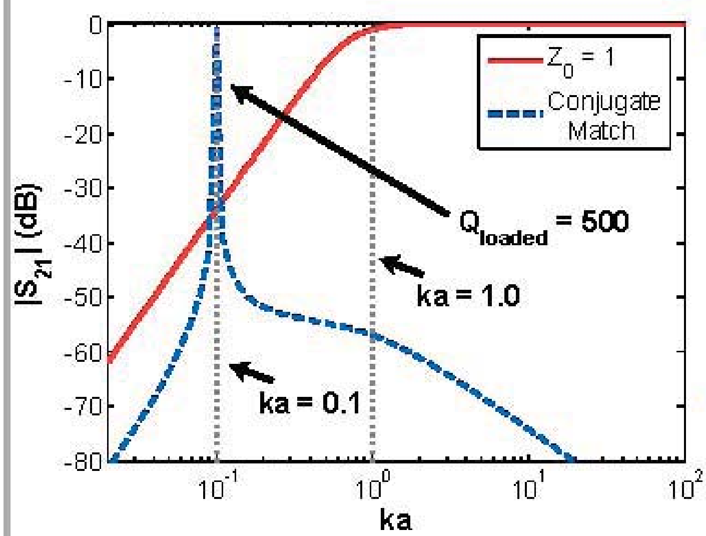
SDR Antenna Design Challenges

Antenna Design ⇄ Limits ⇄ How Antenna Works?

- Size
- Performance
- Function
- Cost

Tradeoffs !

Antenna Design Strategy Based on Fundamental-Limit Theory

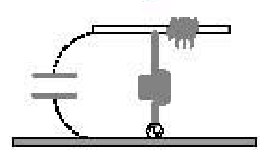


- If $ka \geq 1$,
  - → Set $Z_0 = Z_{wave}$ for maximum BW
  - → Otherwise, need impedance trans.
  - → Best for freq.-agile functions
- If $ka < 1$ (electrically small),
  - → Tune antenna for maximum gain
  - → Add loss for wide BW

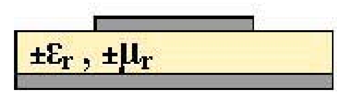
➔ Antenna Size & function need to be defined <u>at initial stage of system design</u>

Ant. Miniaturization Techniques

- Impedance Loading
  - BW limitations



- Material Loading
  - Just ε_r ↑ or μ_r ↑ ➔ Size ↓ & BW ↓
  - Both ε_r ↑ & μ_r ↑ ➔ Size ↓ with same BW
    - ➔ Usually, heavy and lossy
    - ➔ Not available at high freq.

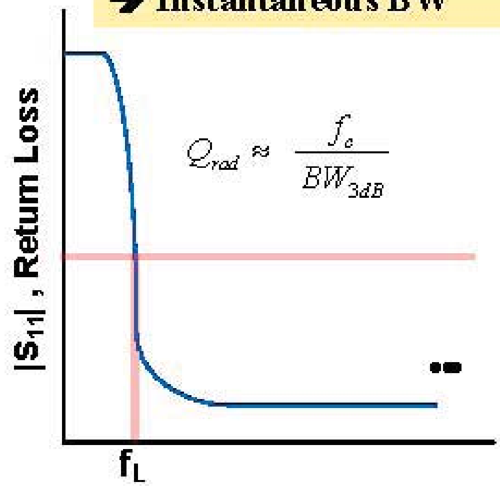


- Slow-wave Structural Patterns
  - Usually drops gain
  - Easy to get smaller size & maintain BW

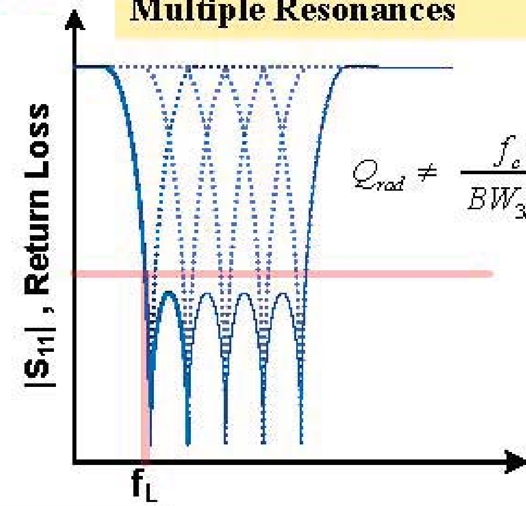
- Negative Impedance Converter (NIC) ➔ Stability issues
- Engineered/Meta Materials ➔ Narrow BW & efficiency issues

Antenna Design Strategy to Get Around Fundamental-Limit Theory

Fundamental-Limit Theory
➔ Instantaneous BW

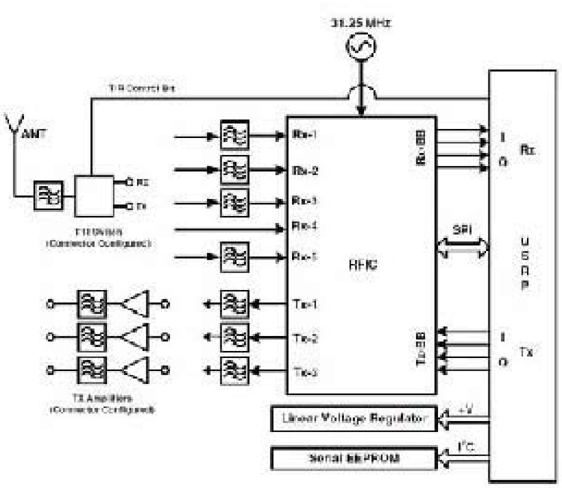


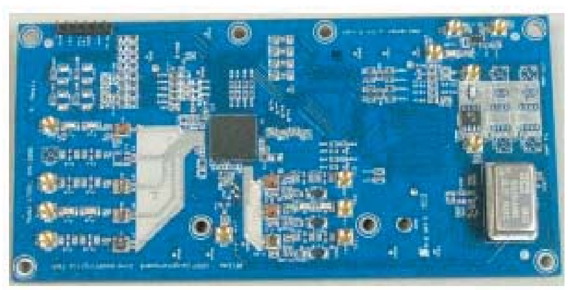
Continuous Wide BW with Multiple Resonances



$$\boxed{Q_{r,INS} \leq Q_{r,MR}}$$

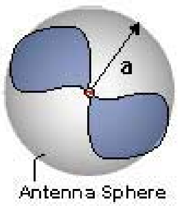
The Targeted SDR Platform

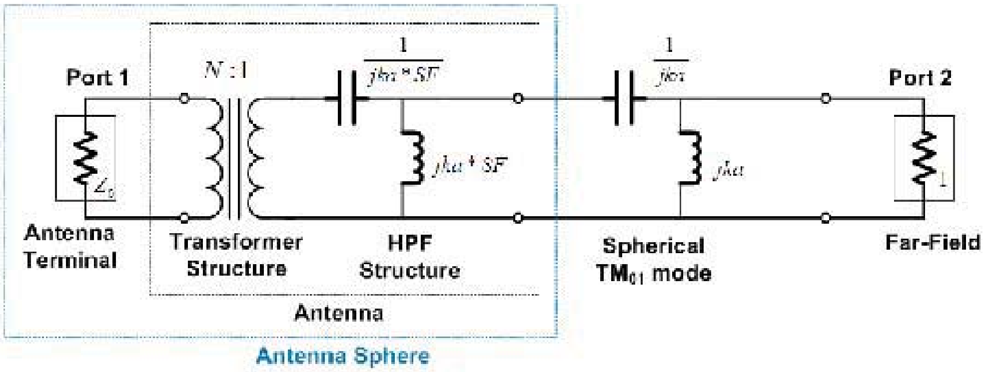




- ✓ Developed in Wireless@VT
- ✓ Direct conversion radio using Motorola RFIC
- ✓ 100 MHz - 4 GHz operational frequency range with a 9 kHz to 20 MHz channel bandwidth

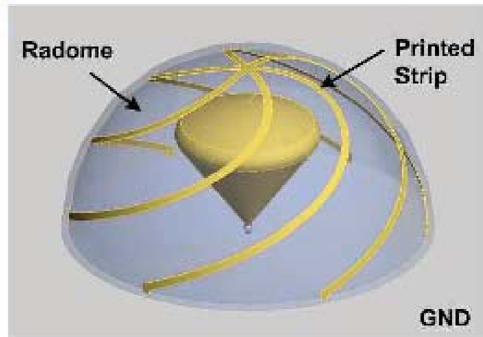
Compact UWB Antenna for SDR – I





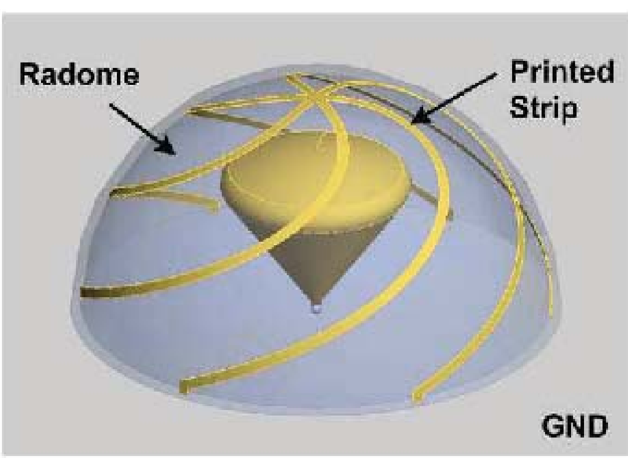
❑ Preliminary Specifications

- Size: 3" High
- Instantaneous BW: 450 MHz – 6 GHz
- Realized Gain: 5 dBi
- Form Factor: Hemispherical



Compact UWB Antenna for SDR – II

✓ Measured radome material characteristics: ε_r = 2.53, tanδ = 0.01
✓ Silver paint

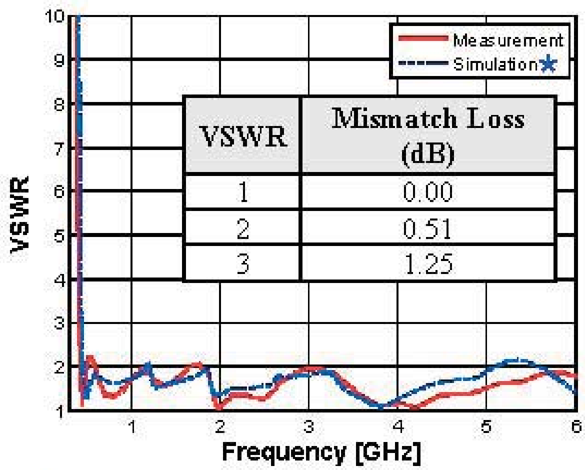


Initial Design

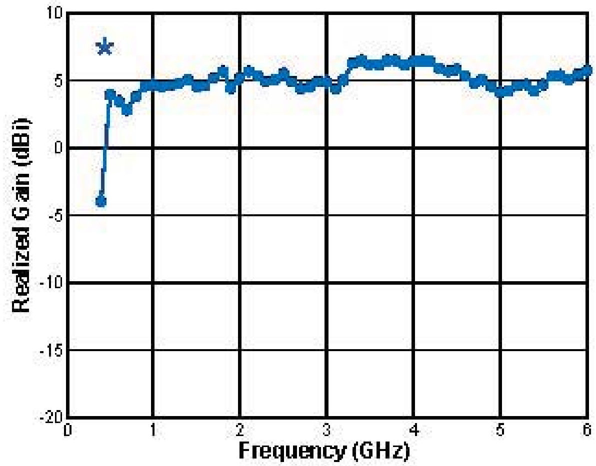
2nd Prototype

Compact UWB Antenna for SDR - III

- ✓ Instantaneous BW: From 433 MHz to ???
- ✓ Electrical Size: 0.11 λ @ 433 MHz
- ✓ Radiation Pattern: Omni-directional in azimuth with LP

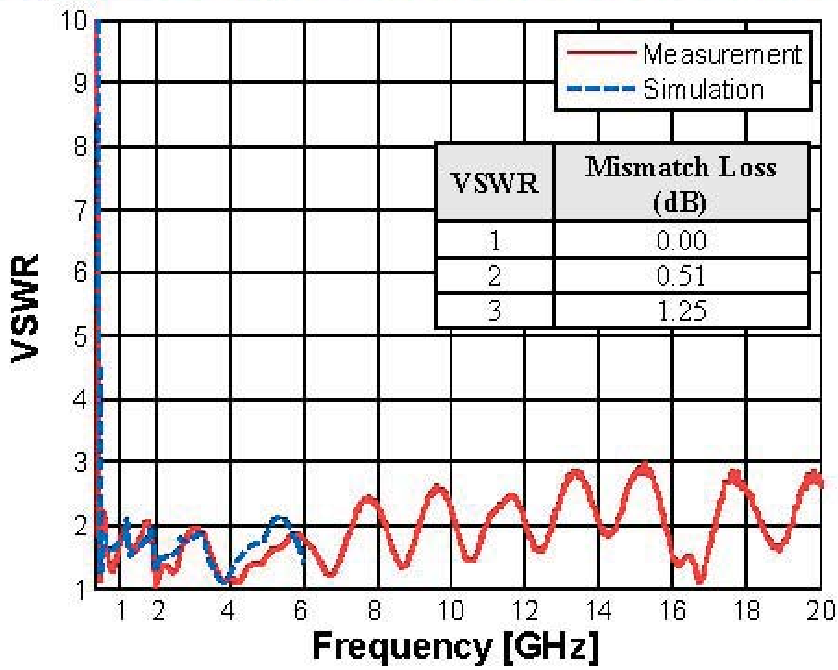


VSWR	Mismatch Loss (dB)
1	0.00
2	0.51
3	1.25



* Commercial Hybrid Code (FEM + MoM): FEKO Suite v5.5 (http://www.feko.info)

Compact UWB Antenna for SDR - IV

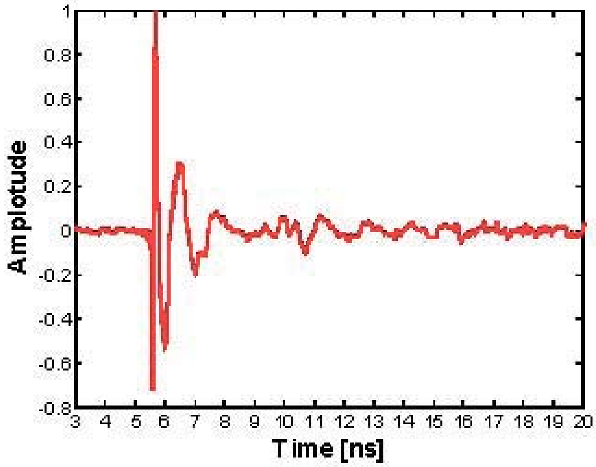


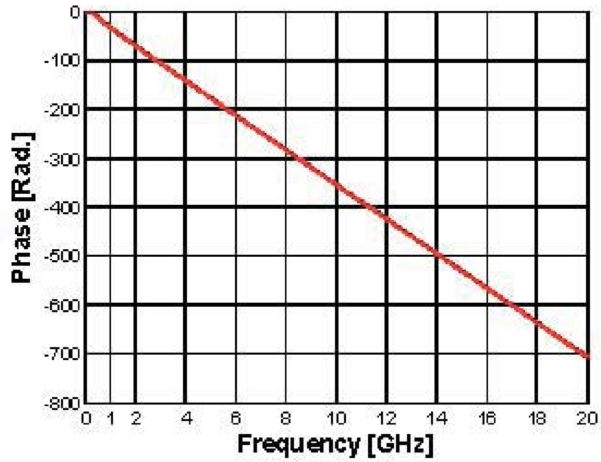
VSWR	Mismatch Loss (dB)
1	0.00
2	0.51
3	1.25

- ✓ Instantaneous BW: From 433 MHz to 20 GHz (46:1 BW)

Compact UWB Antenna for SDR - V

- ❑ **Measured Impulse Response for 50-ps Gaussian input pulse**





- ✓ **Extremely narrow pulse radiation**
- ✓ **Linear Phase over entire band ➔ Instantaneous BW !**

Prototype Antenna In DEMO Session

OSSIE/GNU Radio Generic Component Demonstration

- Duyun Chen (University of Pennsylvania)
- Garrett Vanhoy (University of Arizona)
- Marypat Beaufait (University of Michigan)
- Carl B. Dietrich (Virginia Tech)

Conclusion

- Ant. Design Challenges
  - ✓ Antenna Radiation Physics
    → Minimum non-radiating energy
  - ✓ Limitations on Size and Performance → Tradeoffs
  - ✓ Miniaturization Techniques → Loading
- Ant. Design Strategy for SDR
  - ✓ Beyond the Classic Fundamental Limit ← Concept
  - ✓ Size Criteria to Choose Antenna Type
  - ✓ Resonant (smallest), Frequency-independent (directivity), Ultra-wideband (instantaneous) antennas
- Demonstration – Compact UWB antenna

Next Step

- Add Reconfigurable functions
  - ✓ Both instantaneous BW (above Cut-off Freq.)
    + tunable BW (below Cut-off Freq.)
    with the Same Form Factor
  - ✓ Radiation Pattern Reconfigurability:
    Omni or Directional Pattern
  - ✓ Polarization Reconfigurability:
    Linear or Circular Polarization
  - ✓ Receiving Near Vertical Incident Signal (NVIS)