Pulse-Based Ultra-Wideband Transmitters for Digital Communication

Ph.D. Thesis Defense

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Thesis Committee:

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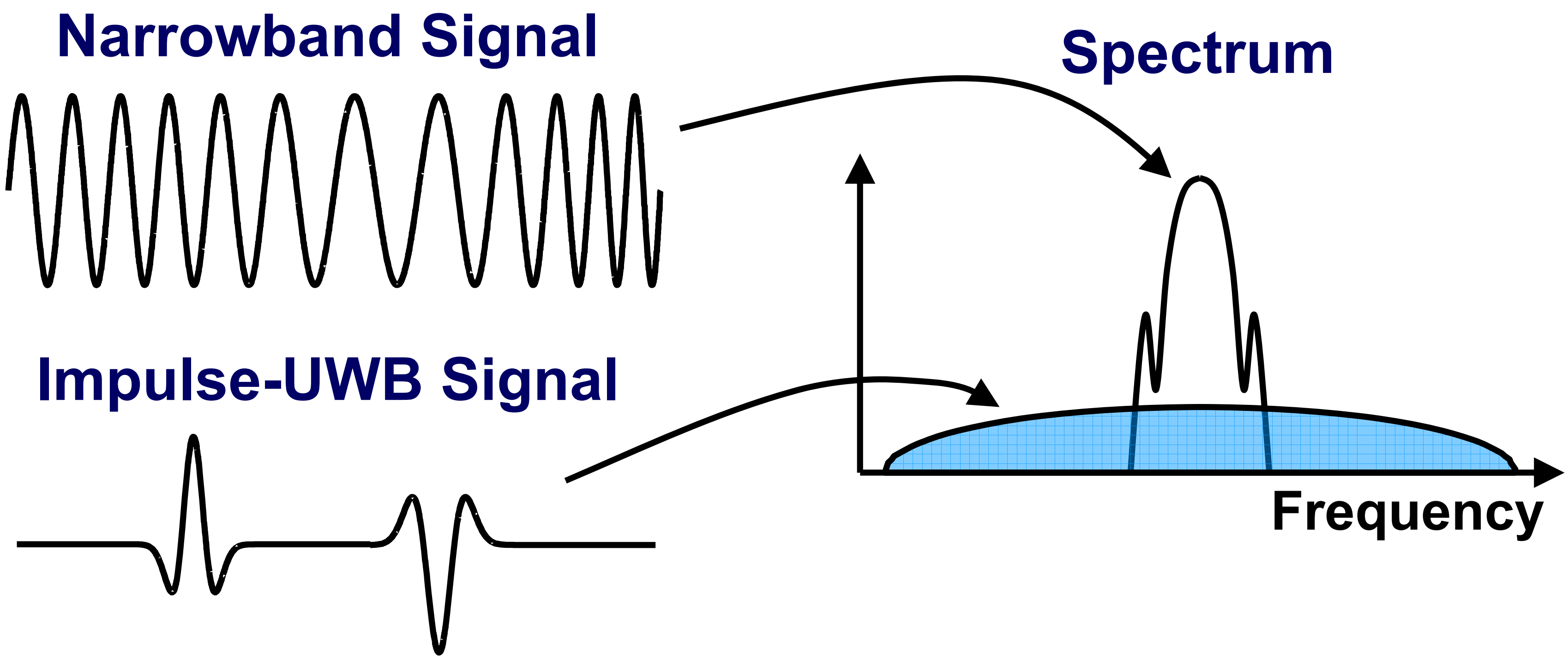
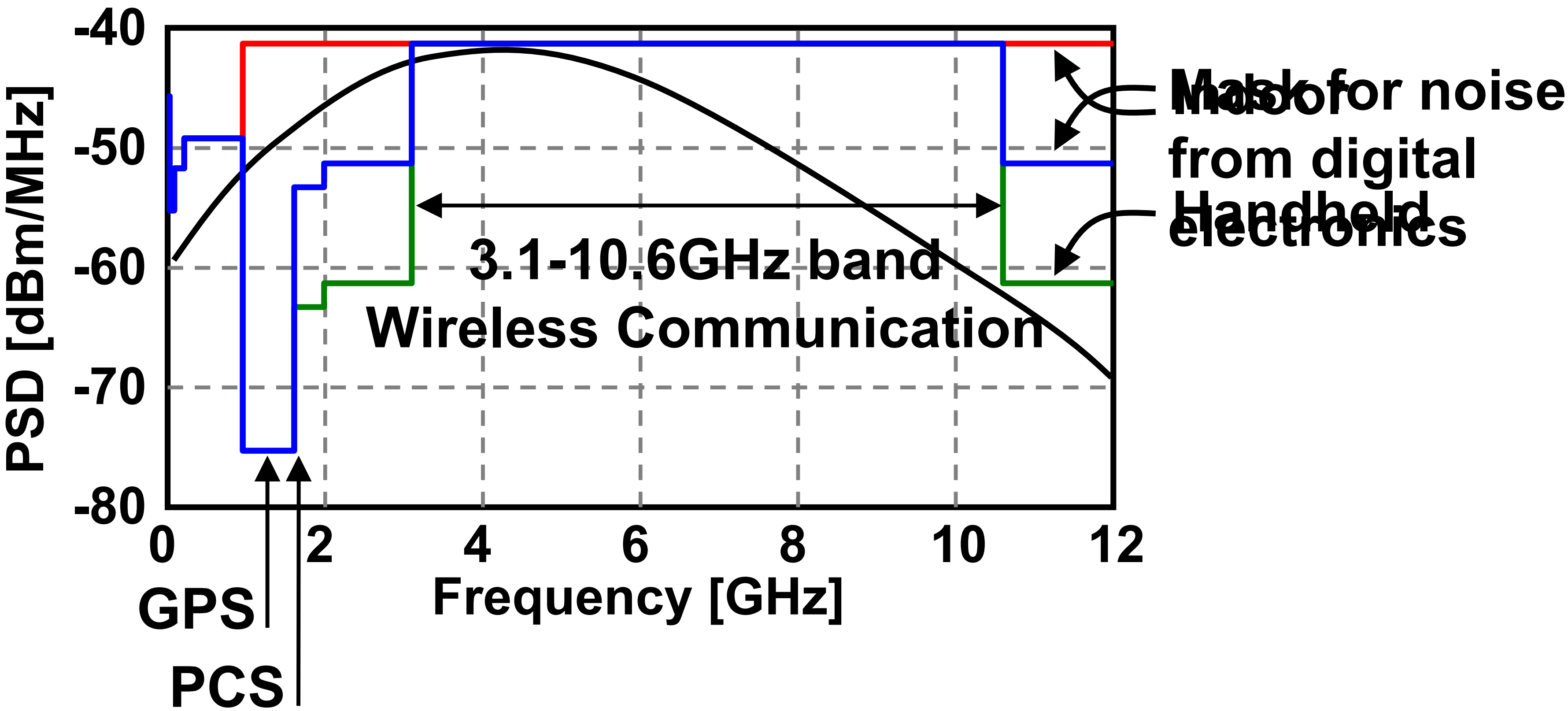
Ultra-Wideband (UWB) Signaling



- FCC defines UWB as bandwidth >500MHz

UWB signals are narrow in time
Energy spread over wide bandwidth

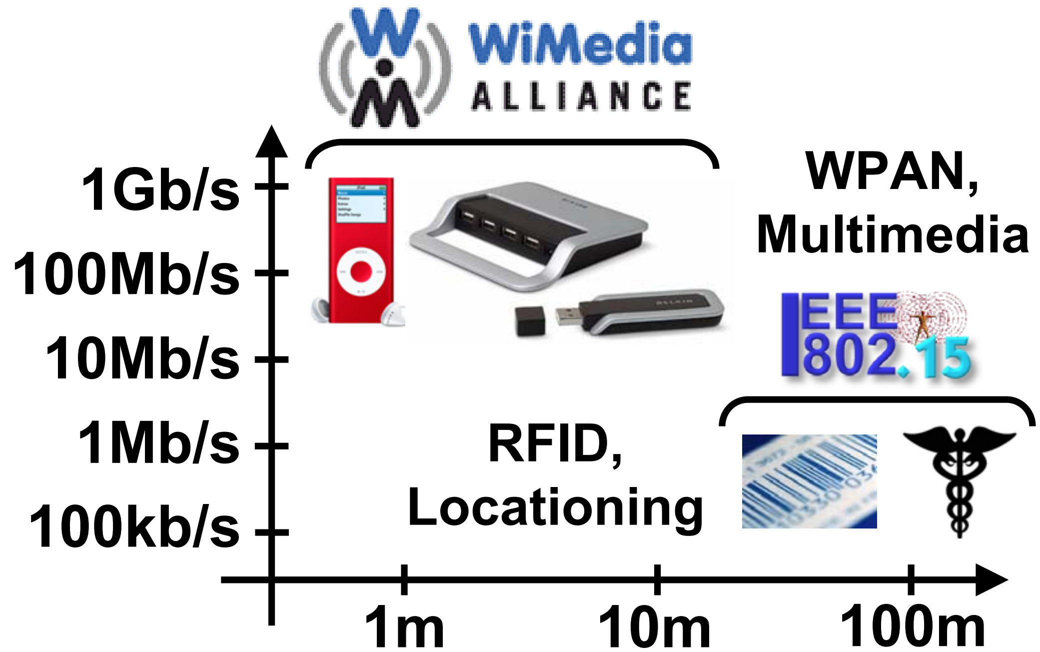
UWB Regulations



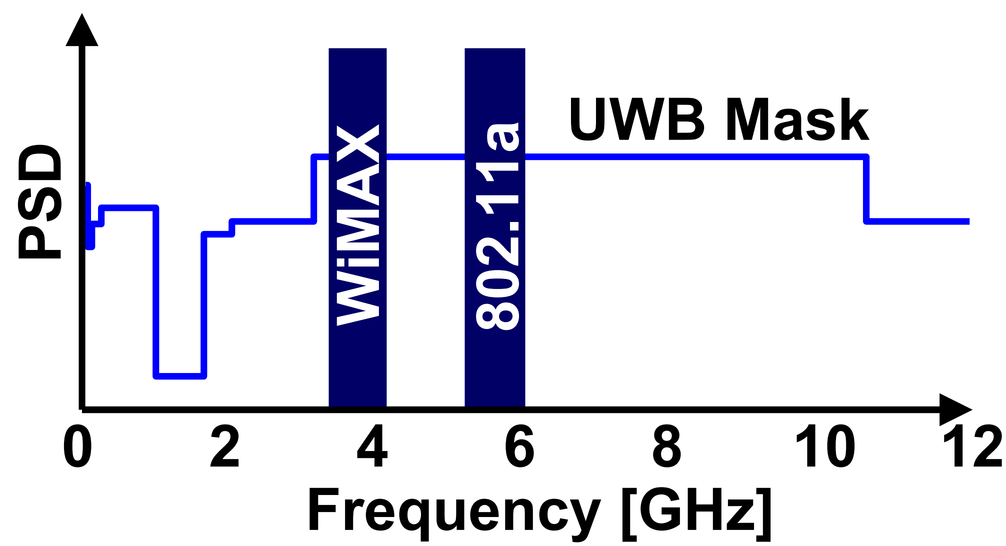
- FCC issues notice of inquiry in 1998
- First report and order in 2002 opening 3.1-10.6GHz band for wireless communication

Advantages and Challenges

- ✓ High data rate
- ✓ Precise locationing
- ✓ Low interference and probability of interception



- ✗ Interference
- ✗ Multipath
- ✗ Wide bandwidth circuits



Outline

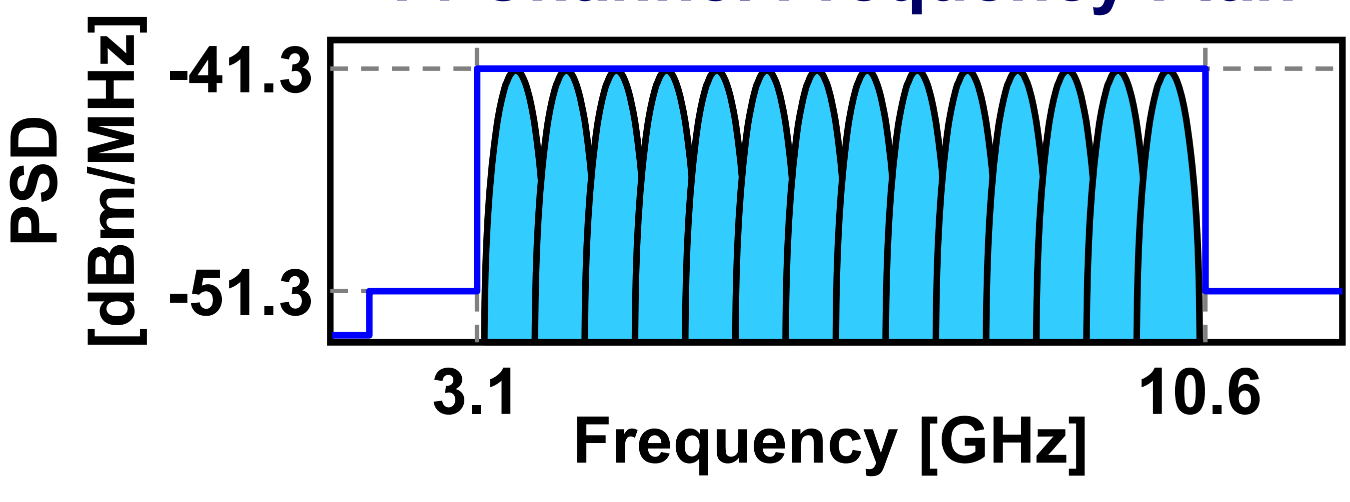
- High data rate transmitter
  - Gaussian pulse shaping
- Variable low data rate transmitter
  - All-digital architecture
- Conclusions and future directions

High Data Rate System

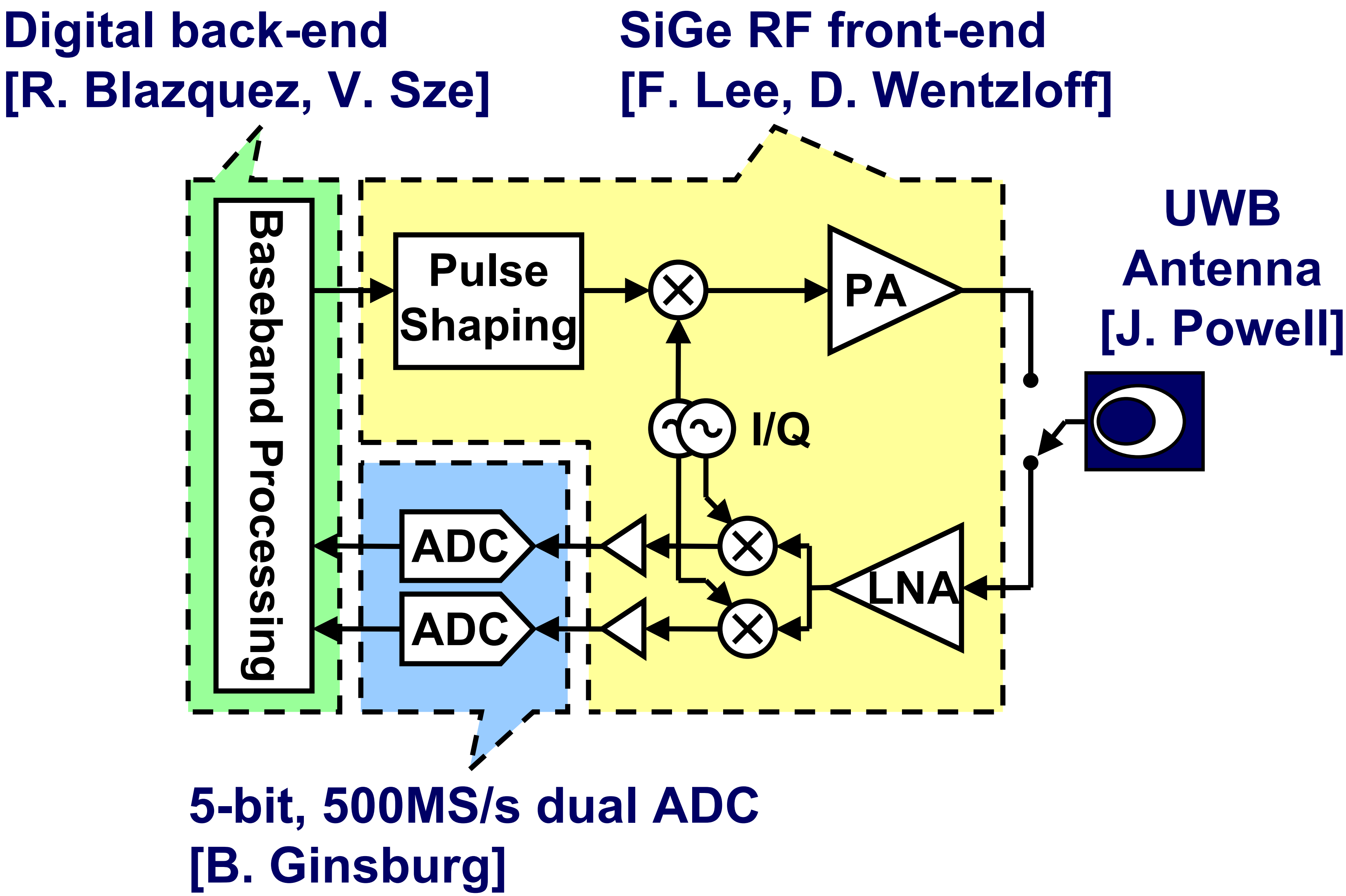
- 100Mb/s at 10m in dense multipath
- Minimize acquisition time, energy/bit
- Sub-banded frequency plan

Application	Data Rate
HD Video	19.2Mb/s
Dolby 5.1	13.8Mb/s
PC Monitor	63-1000Mb/s
MPEG2	75-150Mb/s

14 Channel Frequency Plan

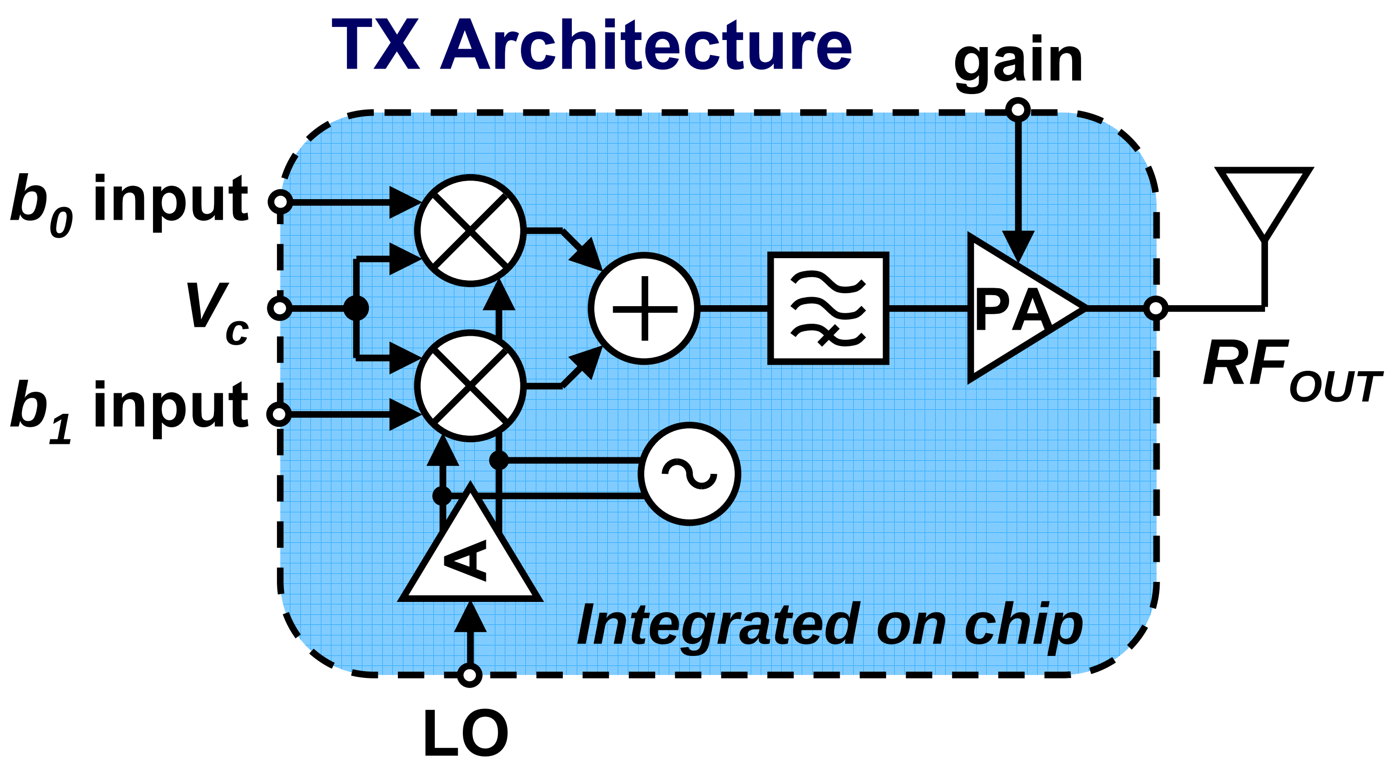


Transceiver Architecture



Gaussian Pulse Generator

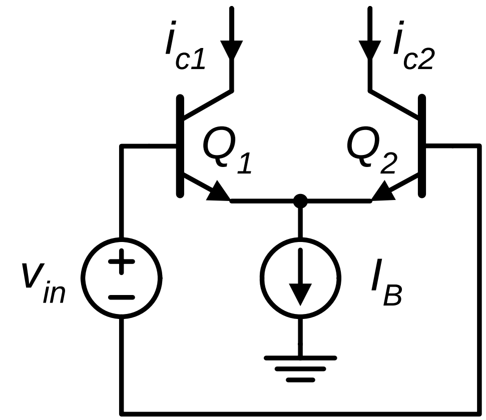
- Generate Gaussian pulse shape
- Tunable from 3.1-10.6GHz (14 channels)
- Matched BPSK pulses



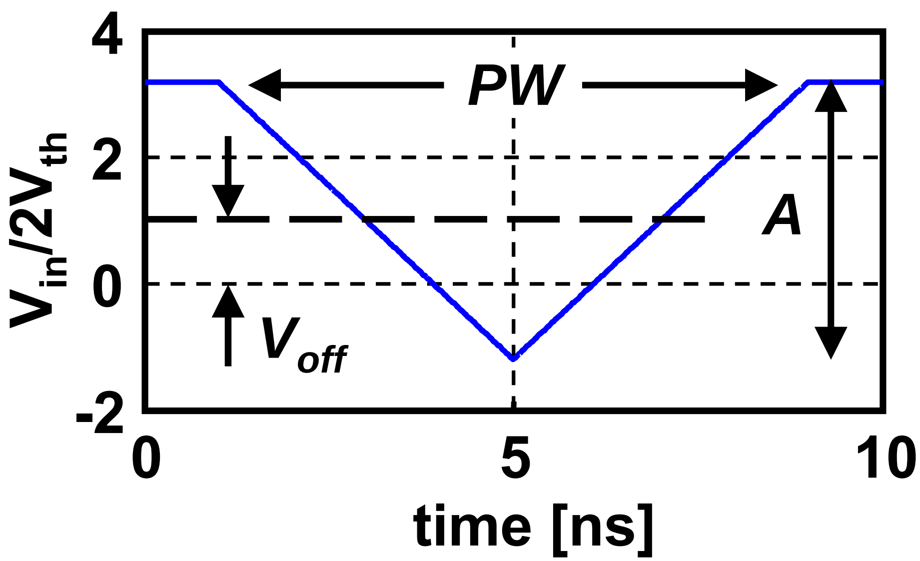
Tanh Approximation

- Exploit exponential BJT
- Apply empirically optimized triangle signal
- Output current approximates Gaussian pulse

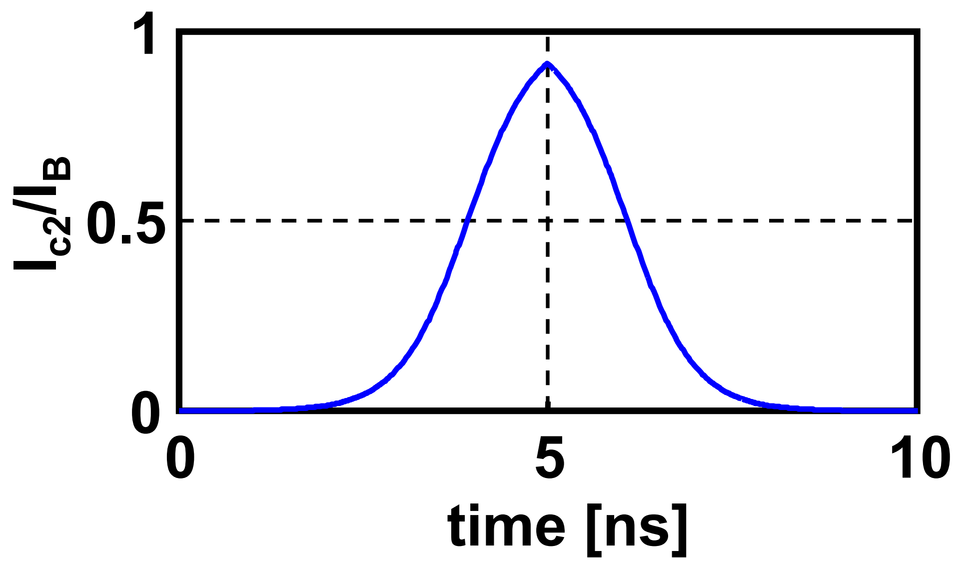
Core Circuit



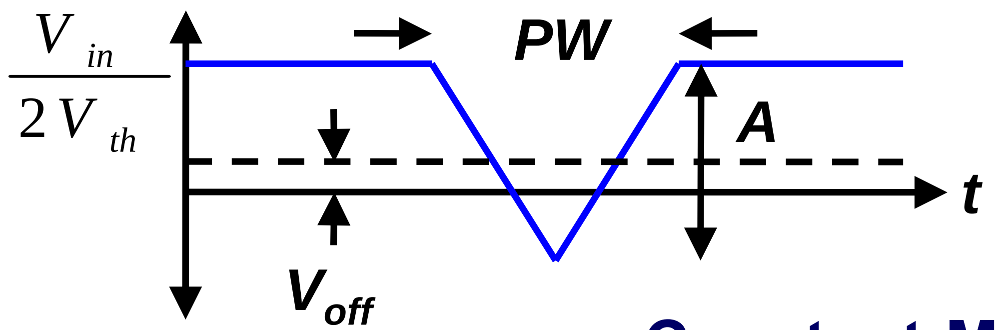
Differential Input Signal

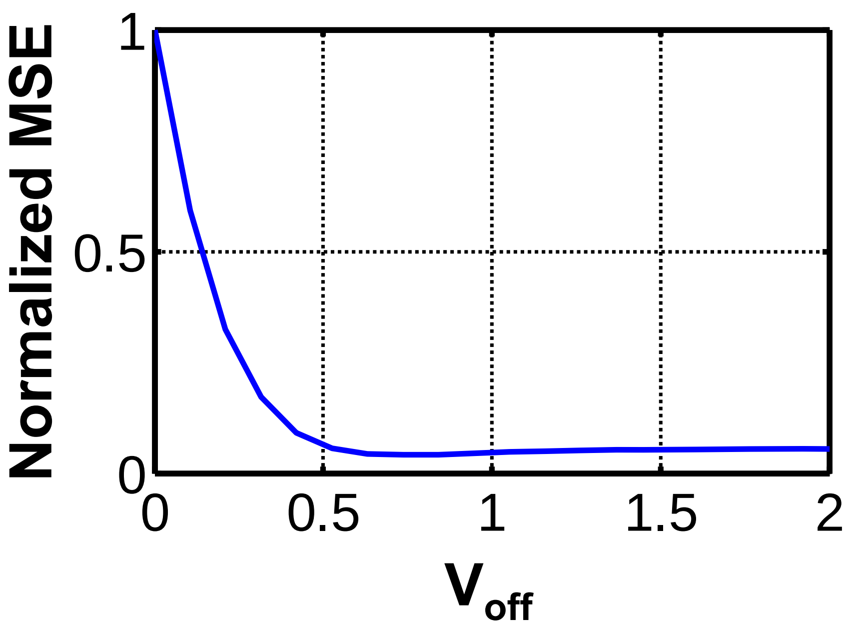


Single-Ended Output Current

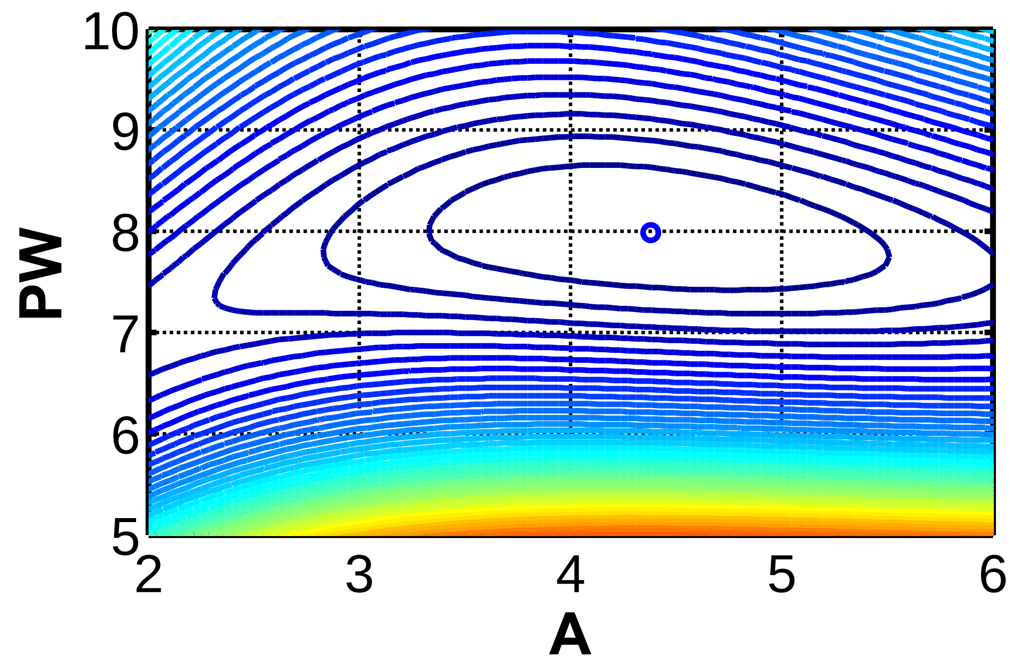


Optimization Results



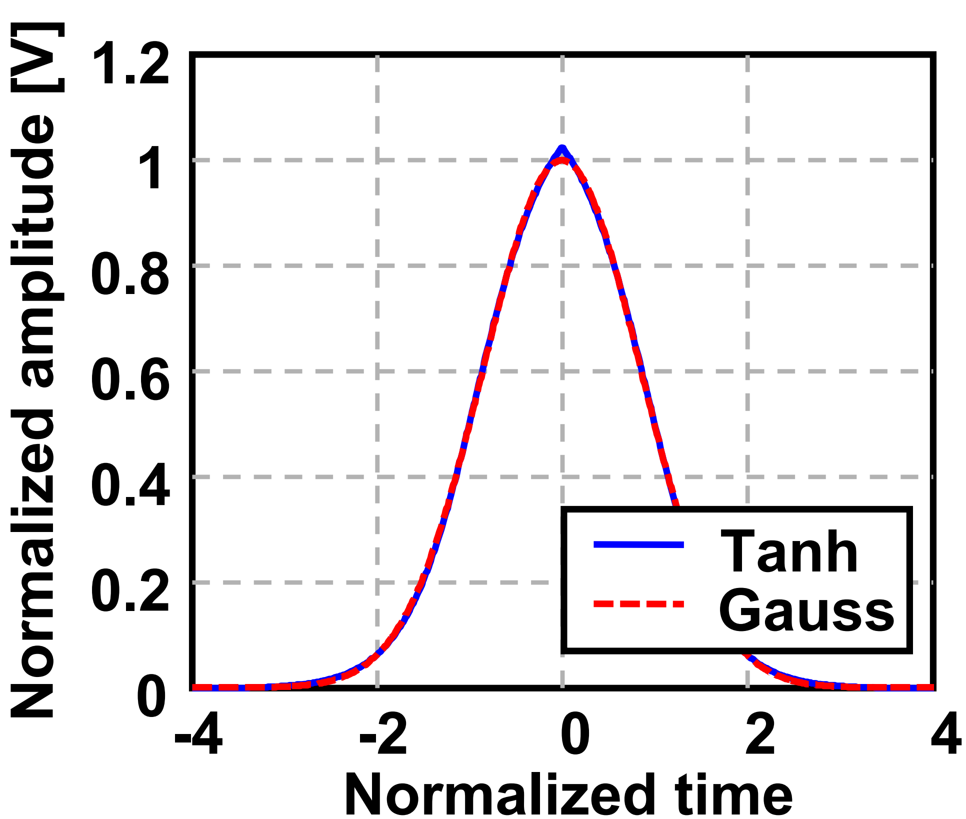


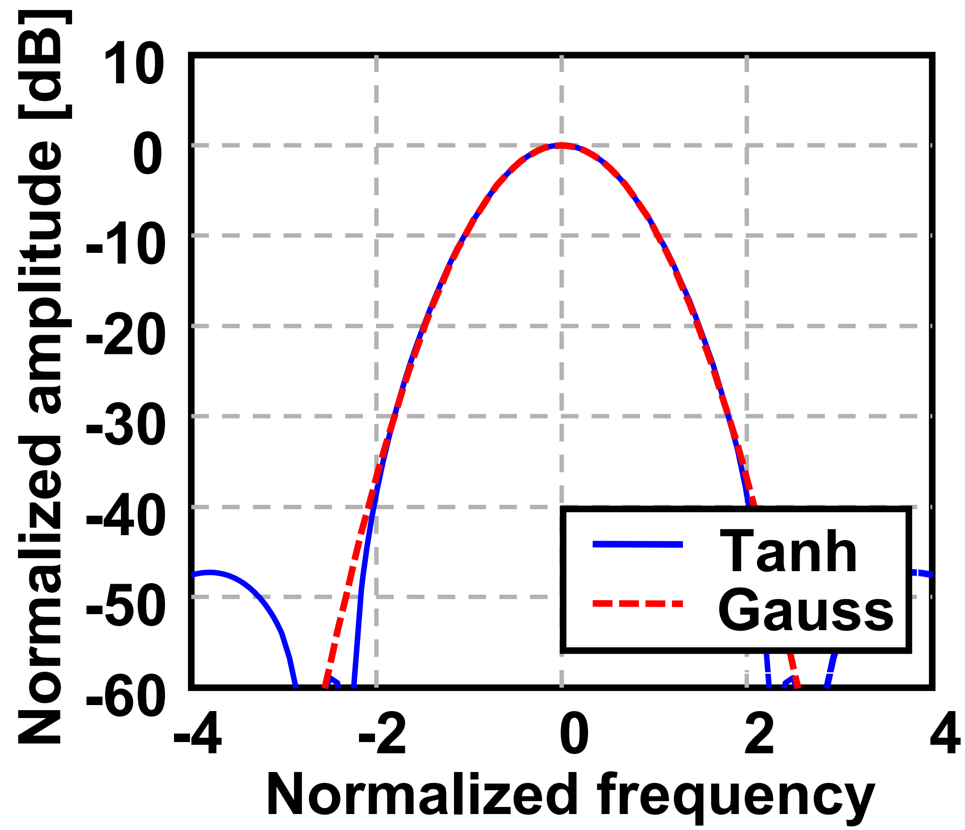
Constant-MSE Contours



Minimum MSE is broad

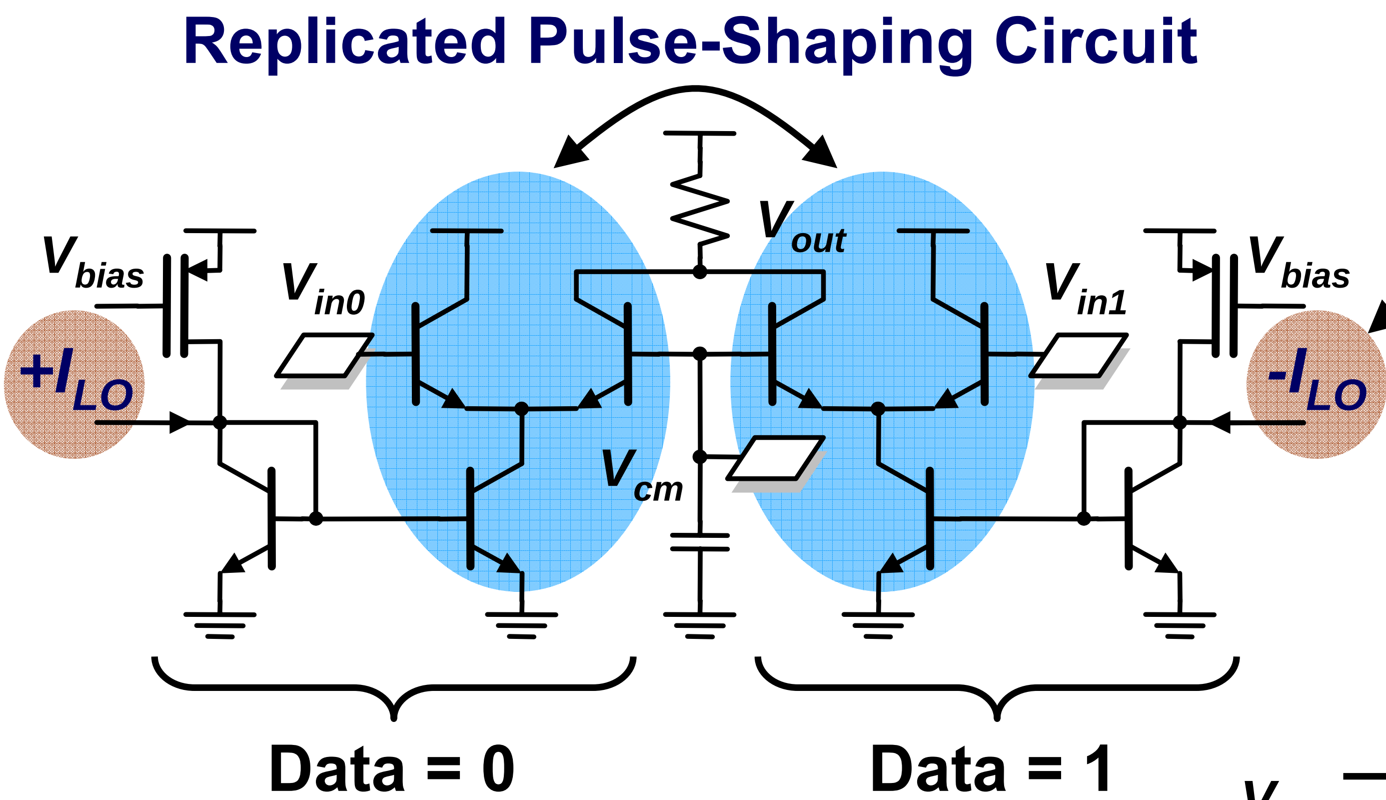
Optimized Pulse



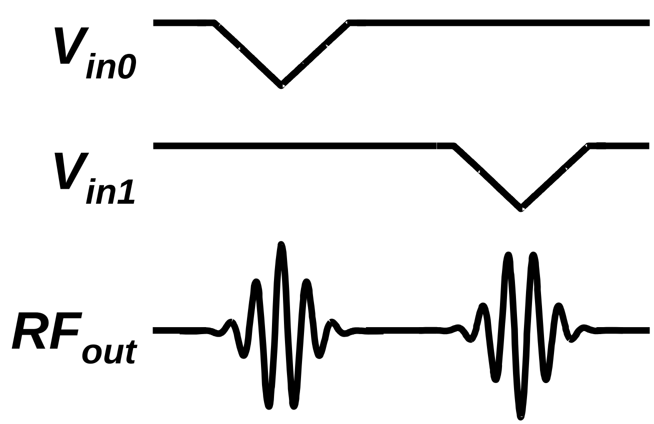


1.7% maximum in-band error between Tanh and Gaussian pulse

Pulse-Shaping Mixers

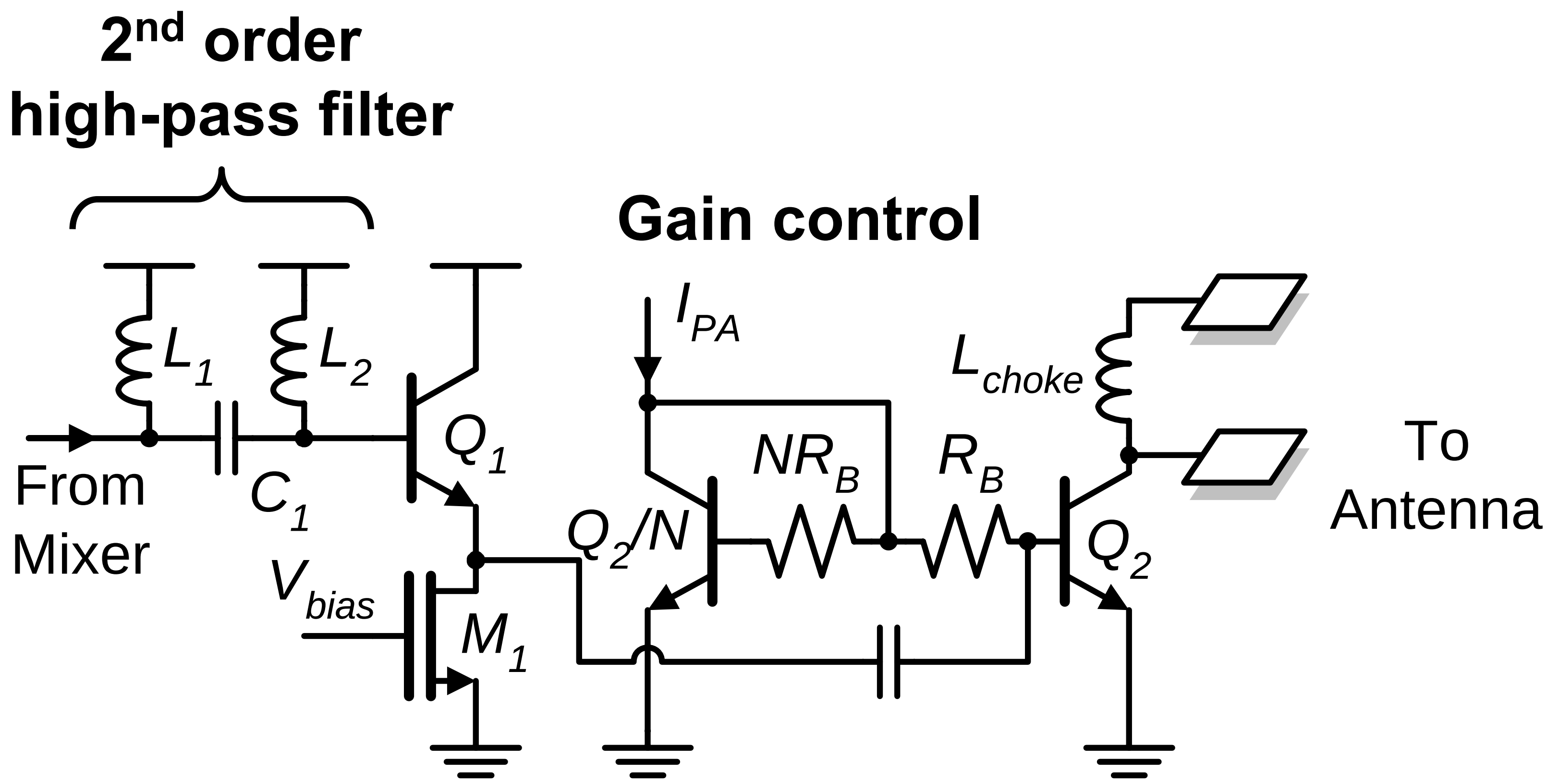


BPSK from opposite LO phases to each side



- BPSK by pulsing one of two mixers
- Expandable to QPSK

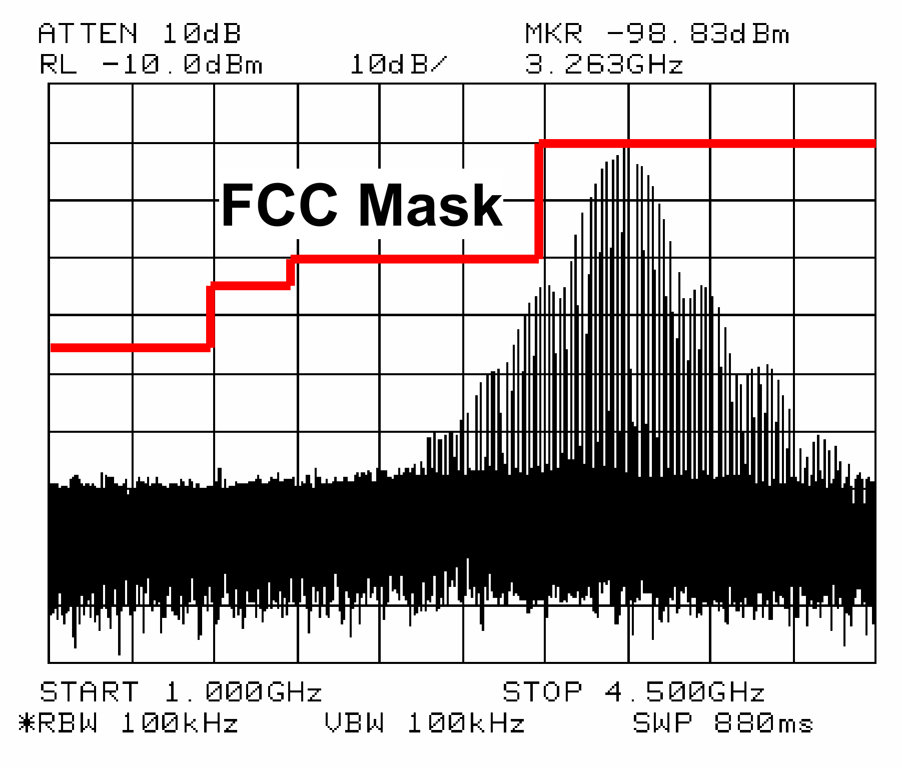
RF Amplifier



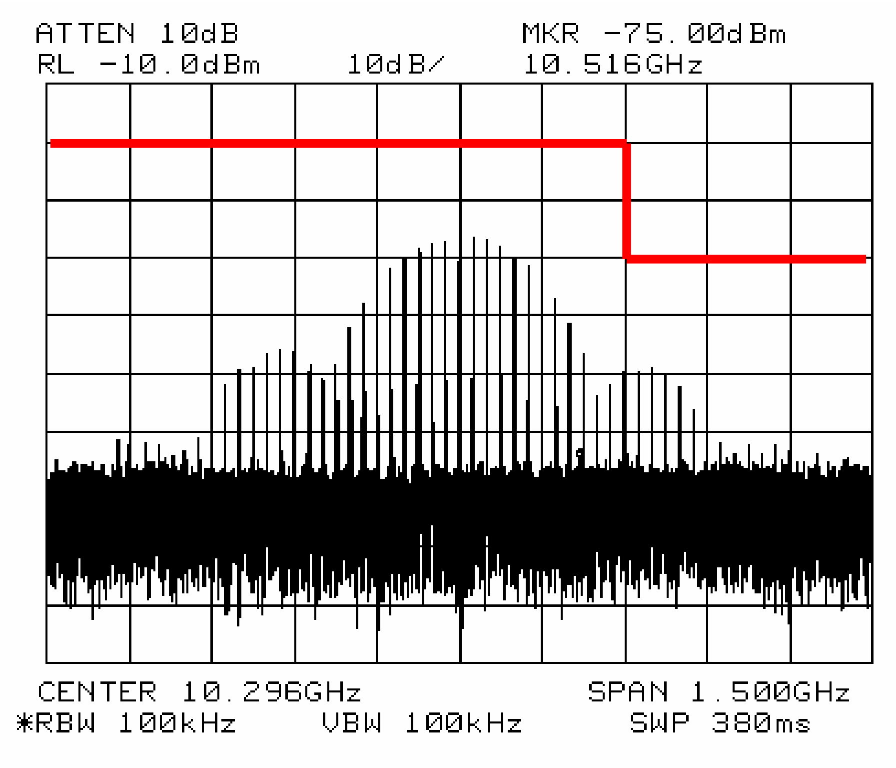
Class A amplifier directly drives UWB antenna

Measured Spectrum

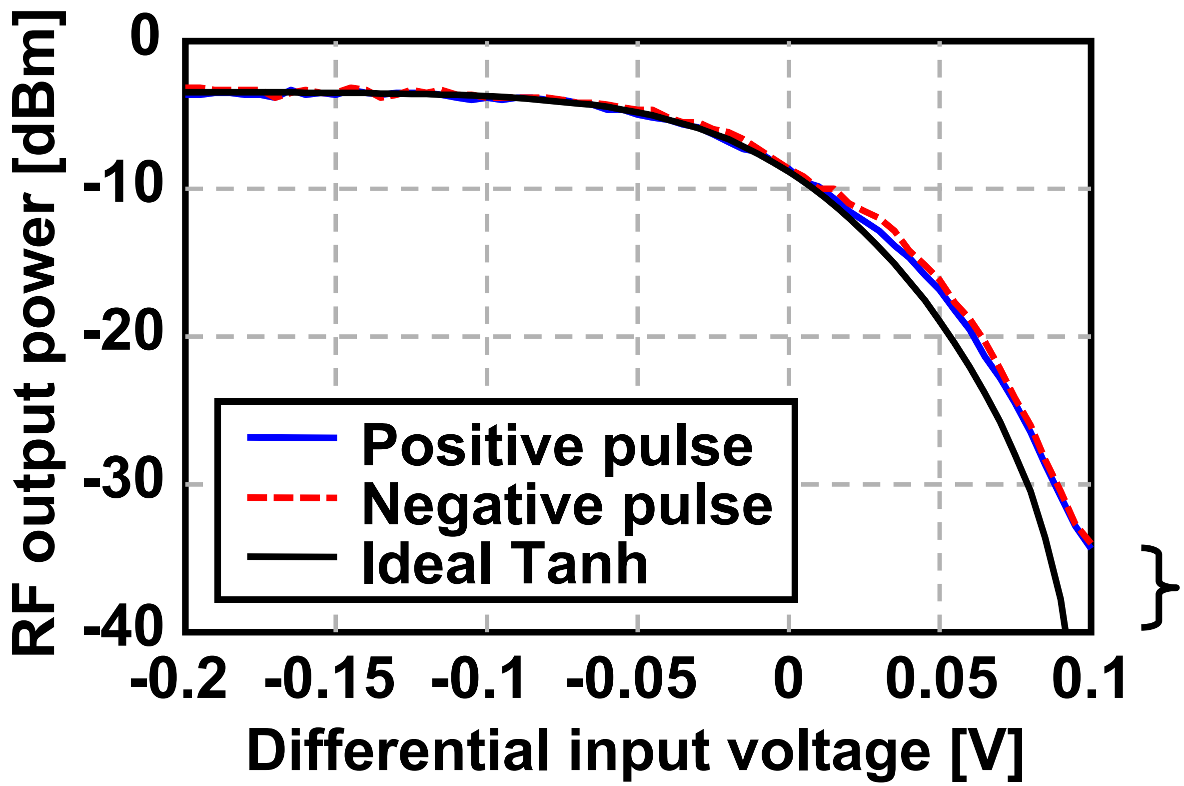
Channel 1

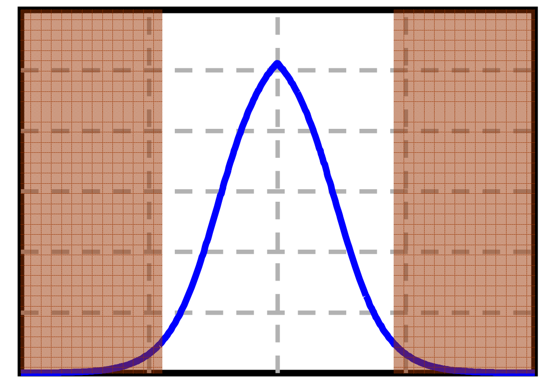


Channel 14



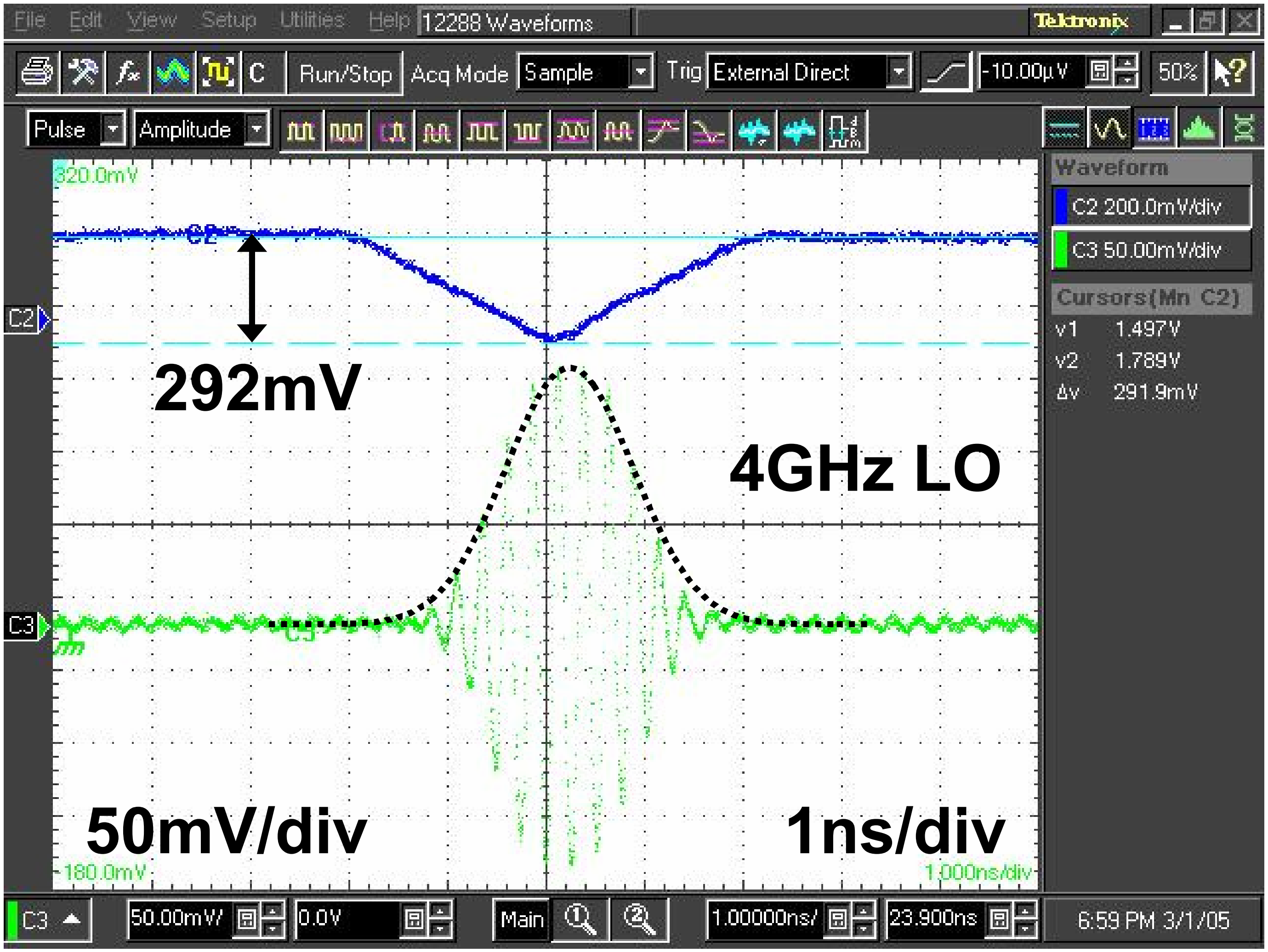
BPSK Matching





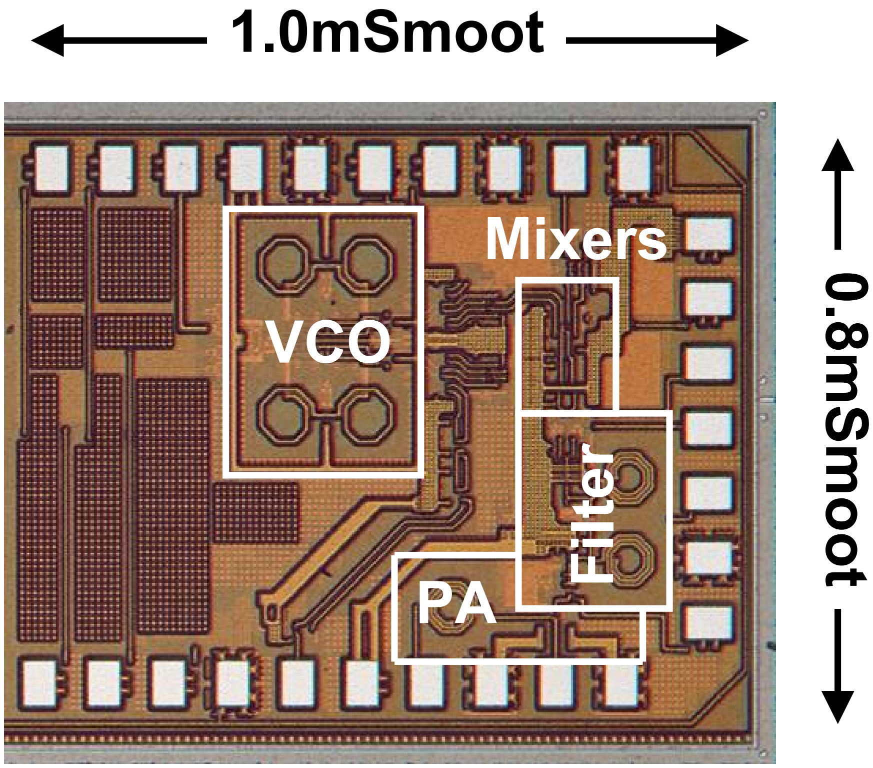
- Measured matching using on-chip VCO
- Comparison to ideal Tanh response

Measured Pulse



Performance Summary

Process	0.18µm SiGe BiCMOS
Modulation	BPSK
Pulse shape	Gaussian
Pulse width	1.7-3.3ns
Supply voltage	1.8V
Total power	31.3mW



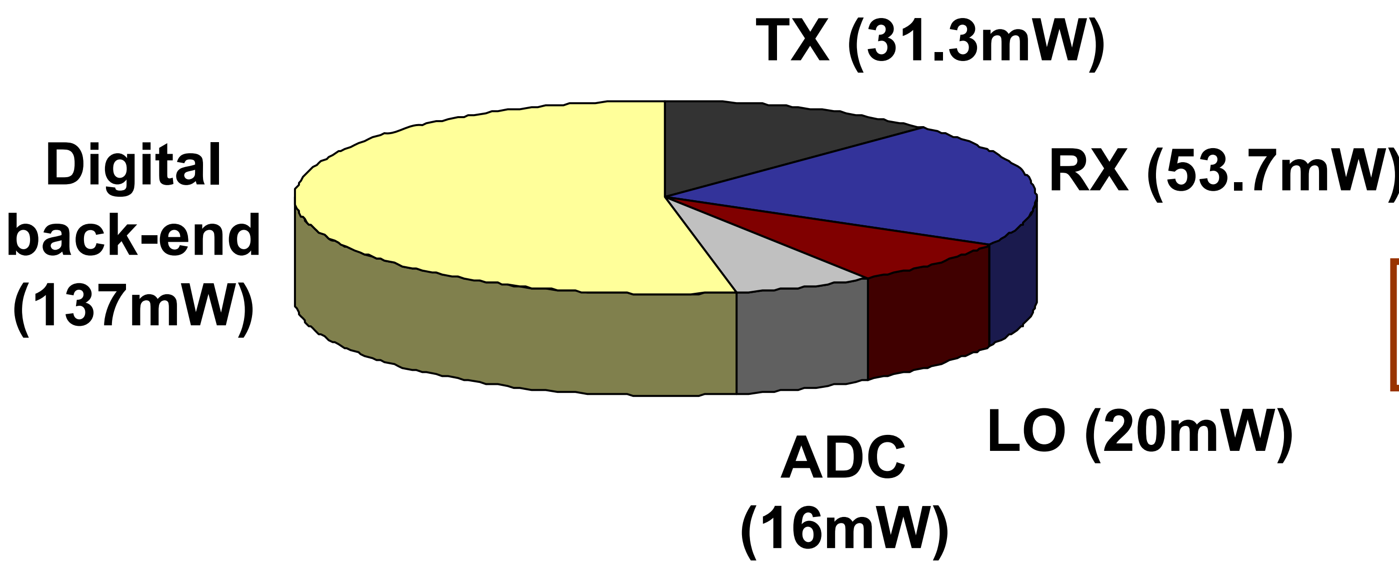
[VCO by B. Ginsburg]

- Pulse-shaping and up-conversion in one circuit
- BPSK inversion in RF for improved matching

High-Rate System Summary

- Custom chipset and antenna solution
- Pulse-based, 14 channel, CDMA architecture

- Total power at 100Mb/s
  - Receive mode: 227mW
  - Transmit mode: 51mW



2.6nJ/bit

Outline

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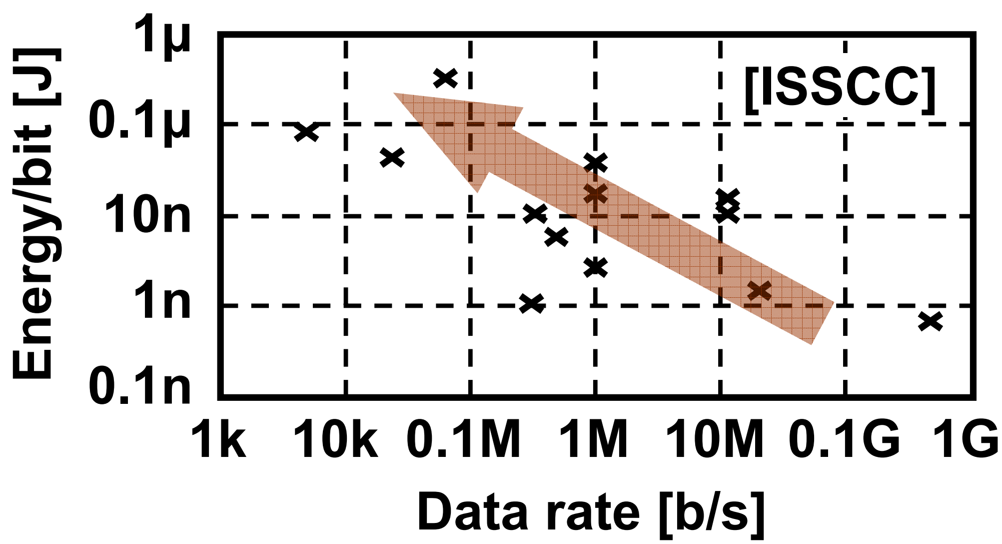
Motivation

- Low data rate, energy-constrained apps.

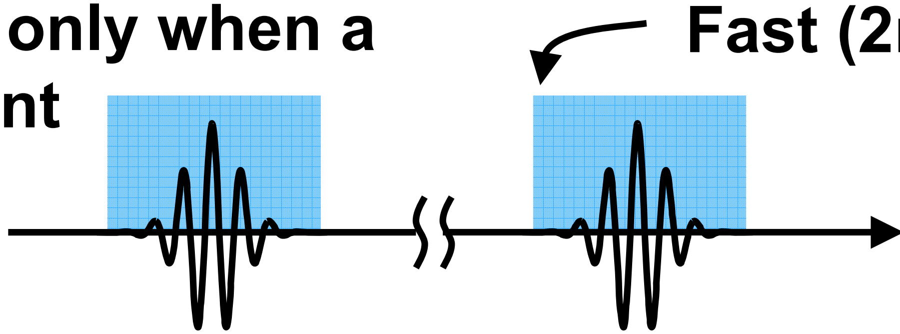


Trend:
Data rate ▼
Energy/bit ▲

- Impulse-UWB signaling inherently duty-cycled

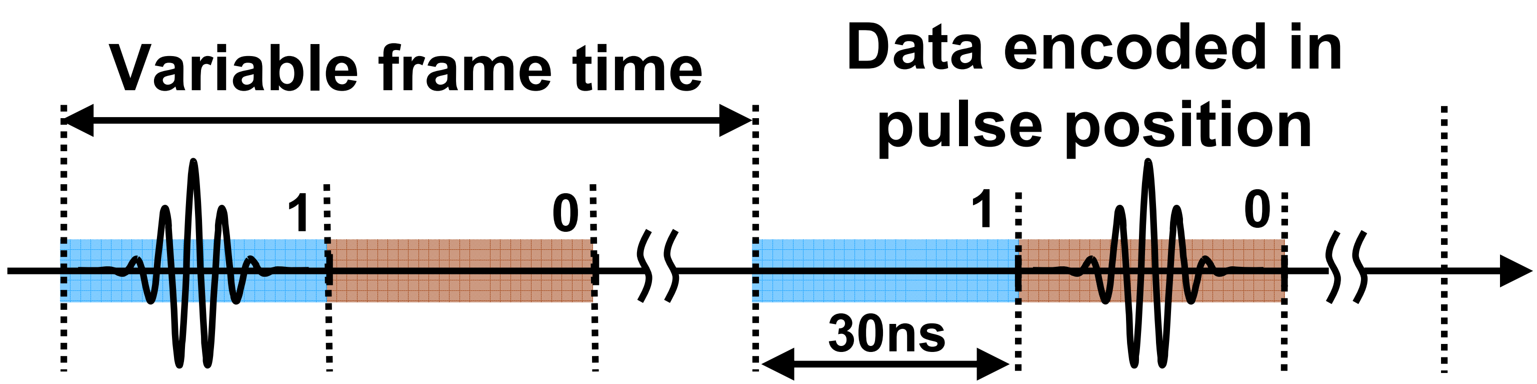
TX and RX on only when a pulse is present

Fast (2ns) turn-on time

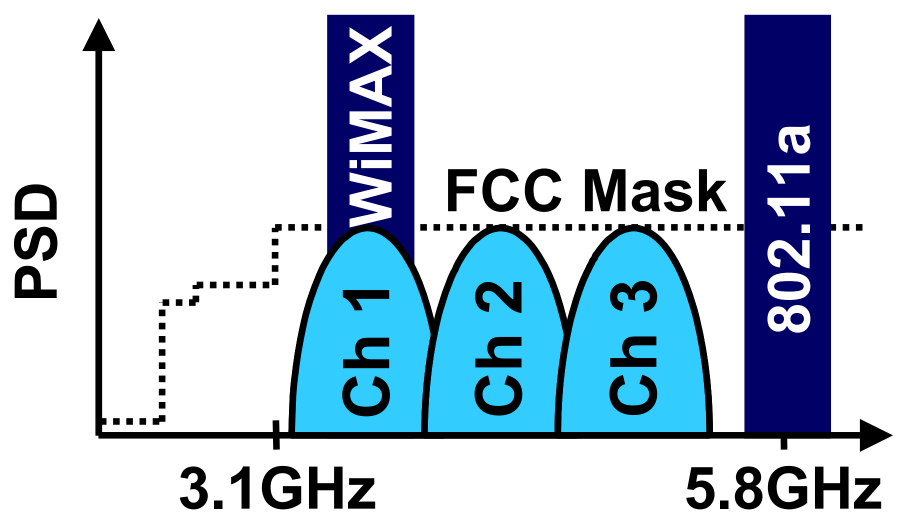


System Specifications

- PPM signaling with non-coherent receiver



- Three channel frequency plan



Center frequency: 6000ppm

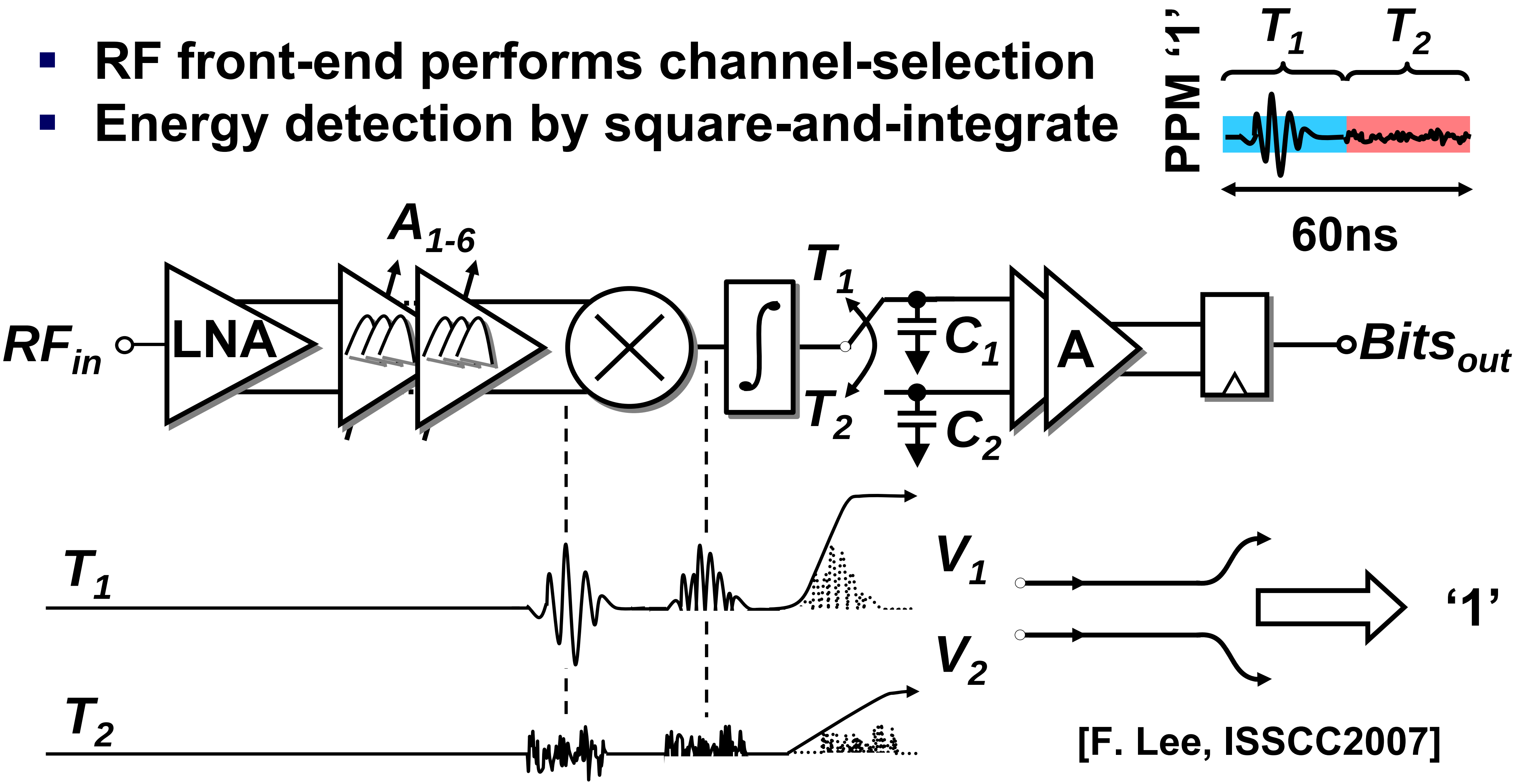
Relaxed RF tolerance

↓

All-Digital Transmitter

Energy-Detection Receiver

- RF front-end performs channel-selection
- Energy detection by square-and-integrate

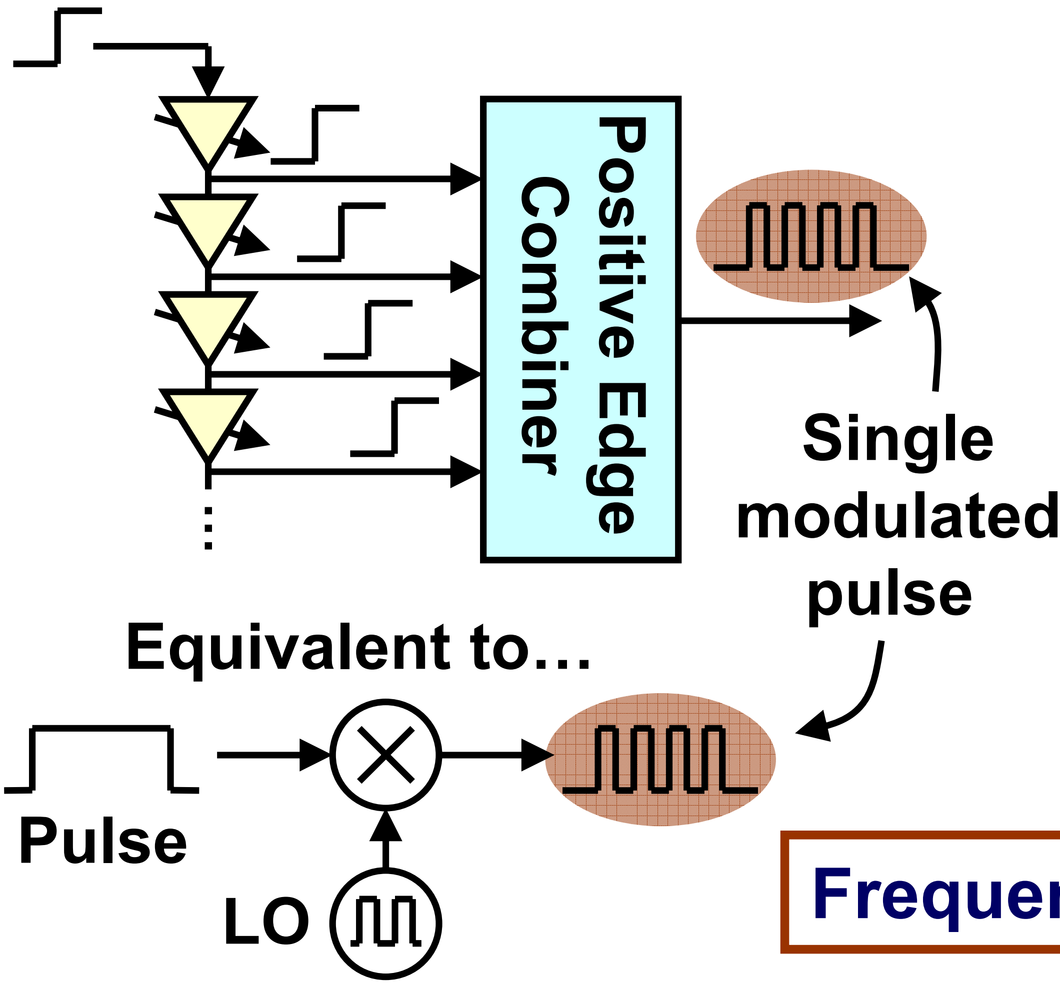


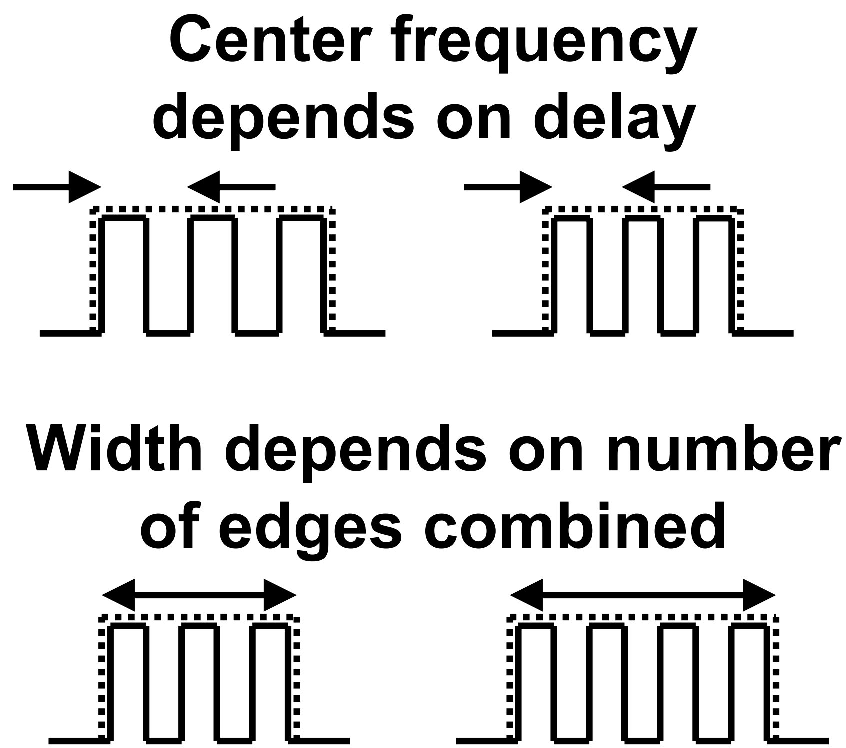
[F. Lee, ISSCC2007]

No RF oscillator required

Pulse Generation Principle

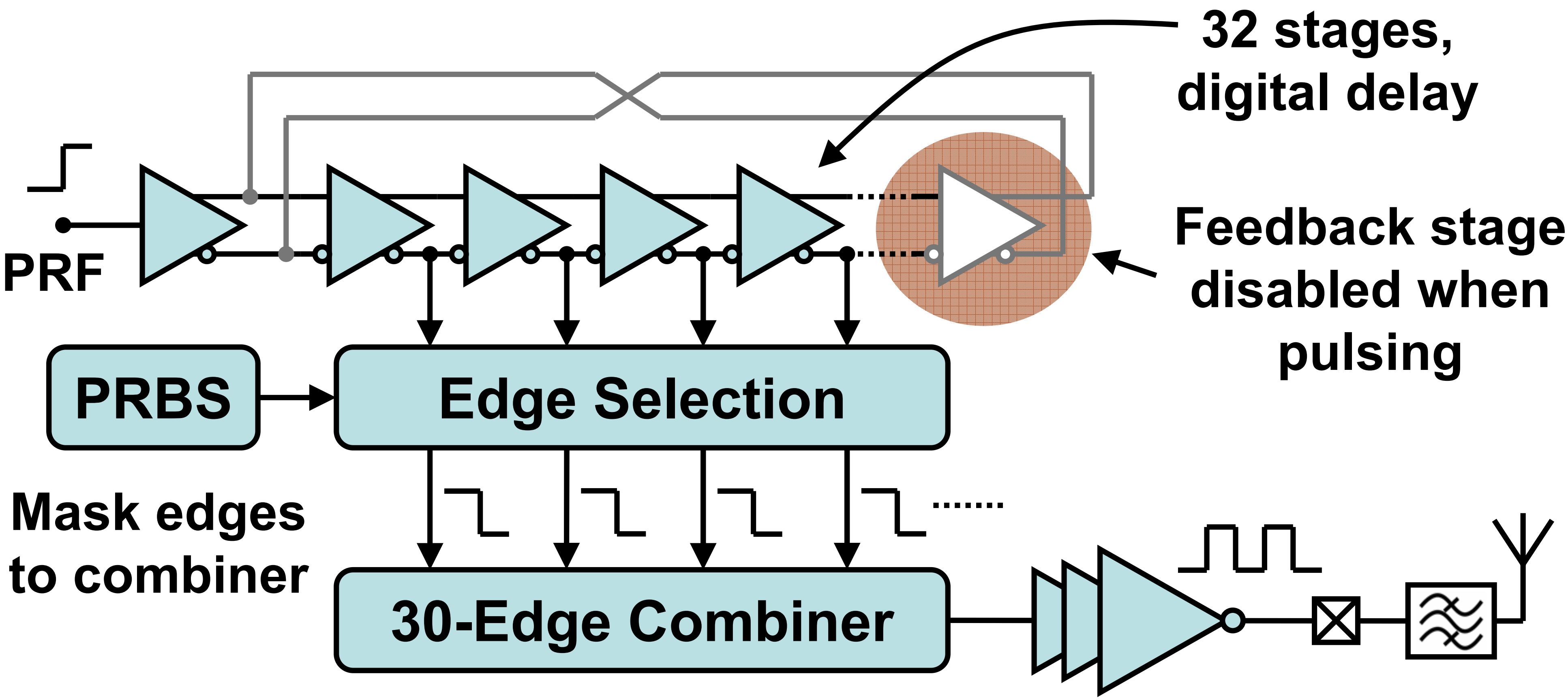
- Use a tapped variable delay line and edge combiner to synthesize a pulse





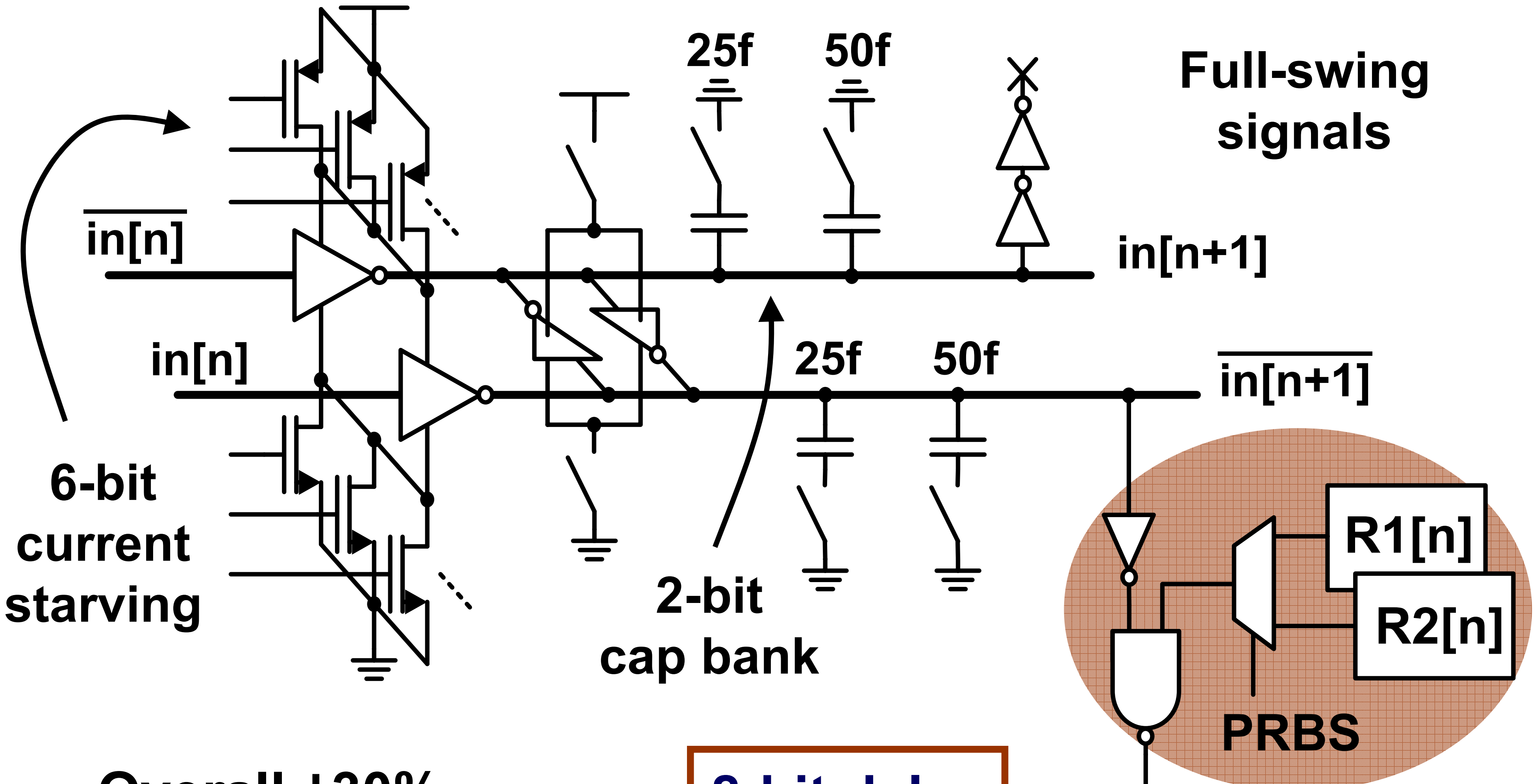
Frequency selectivity without LO

Transmitter Block Diagram



All full-swing static CMOS circuits

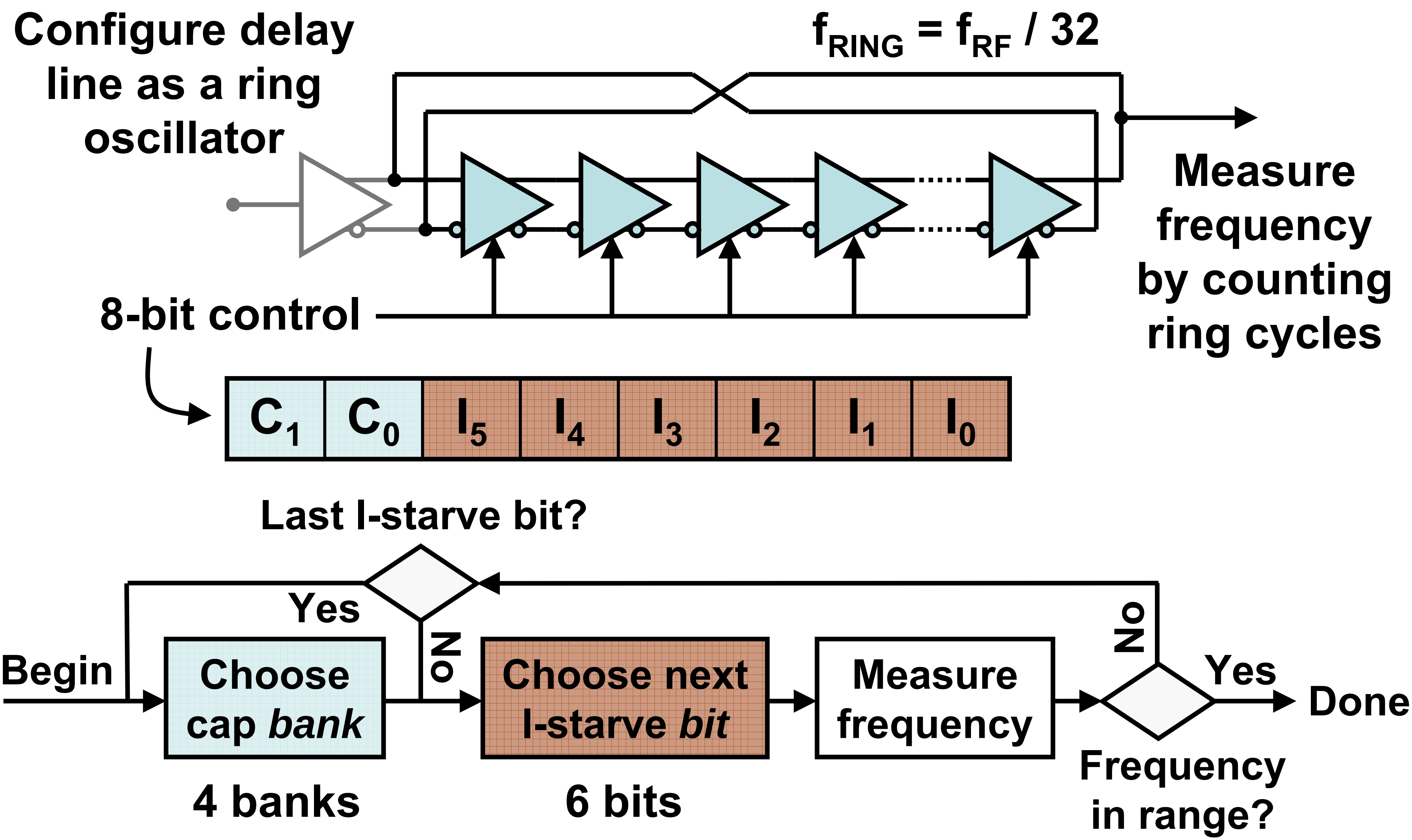
Digital Delay Stage



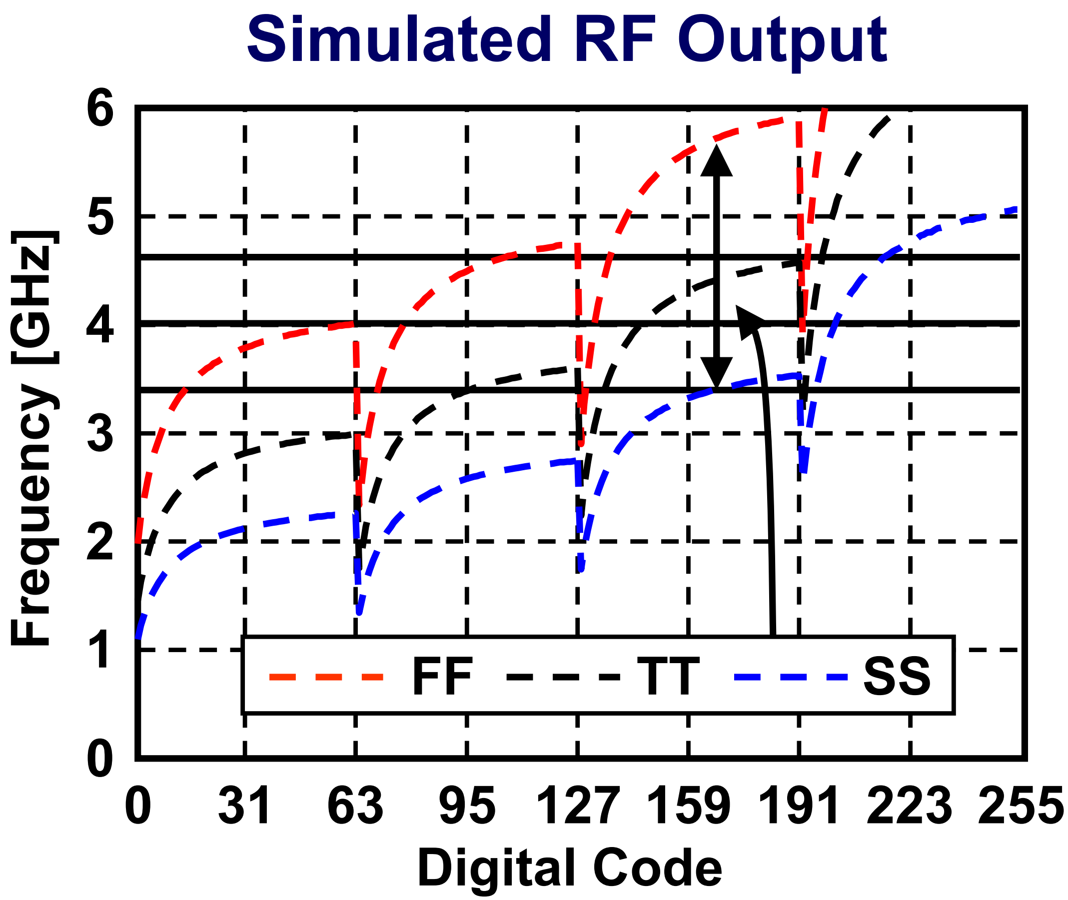
Overall ±30% variation in delay → **8-bit delay control**

Only selected edges are combined

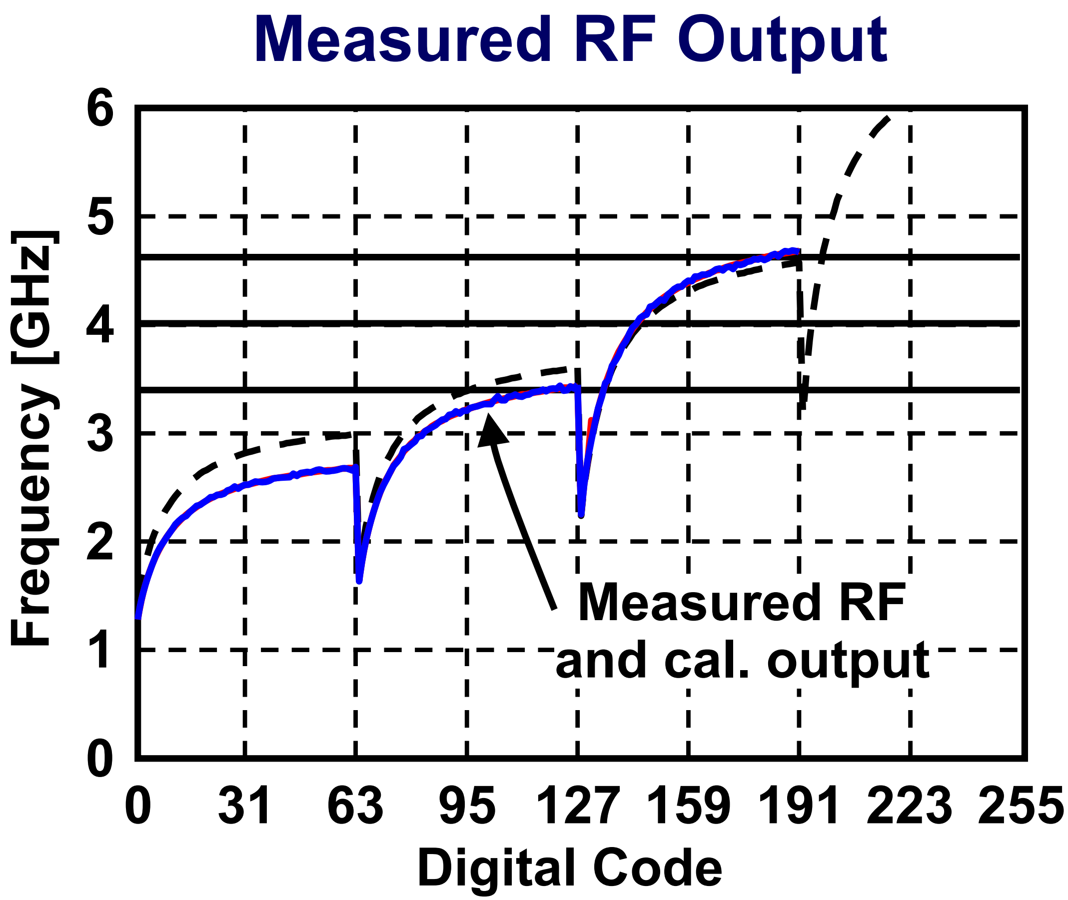
Delay Line Calibration

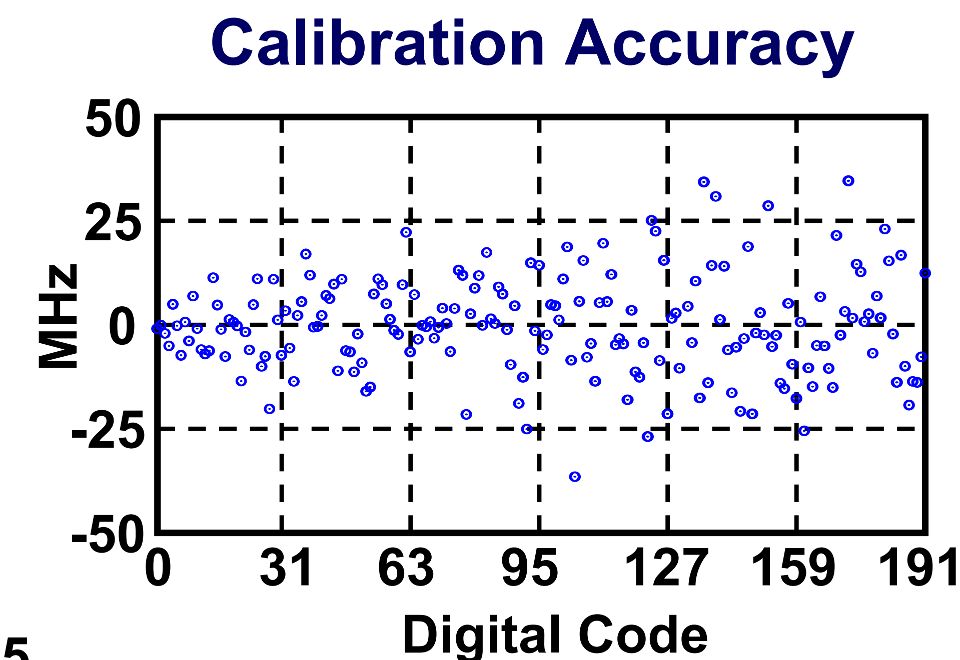


Delay Range and Accuracy



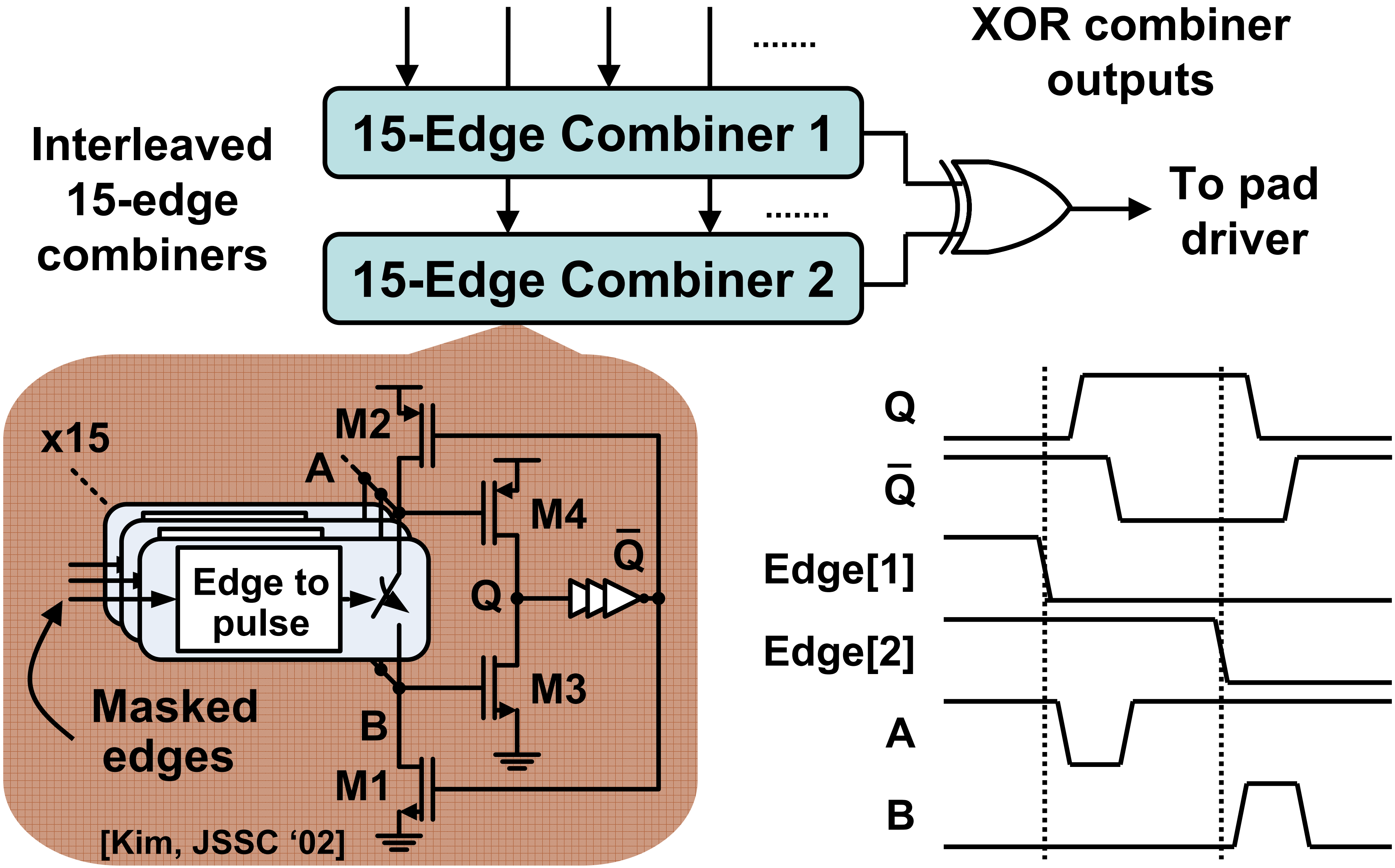
Delay Range and Accuracy



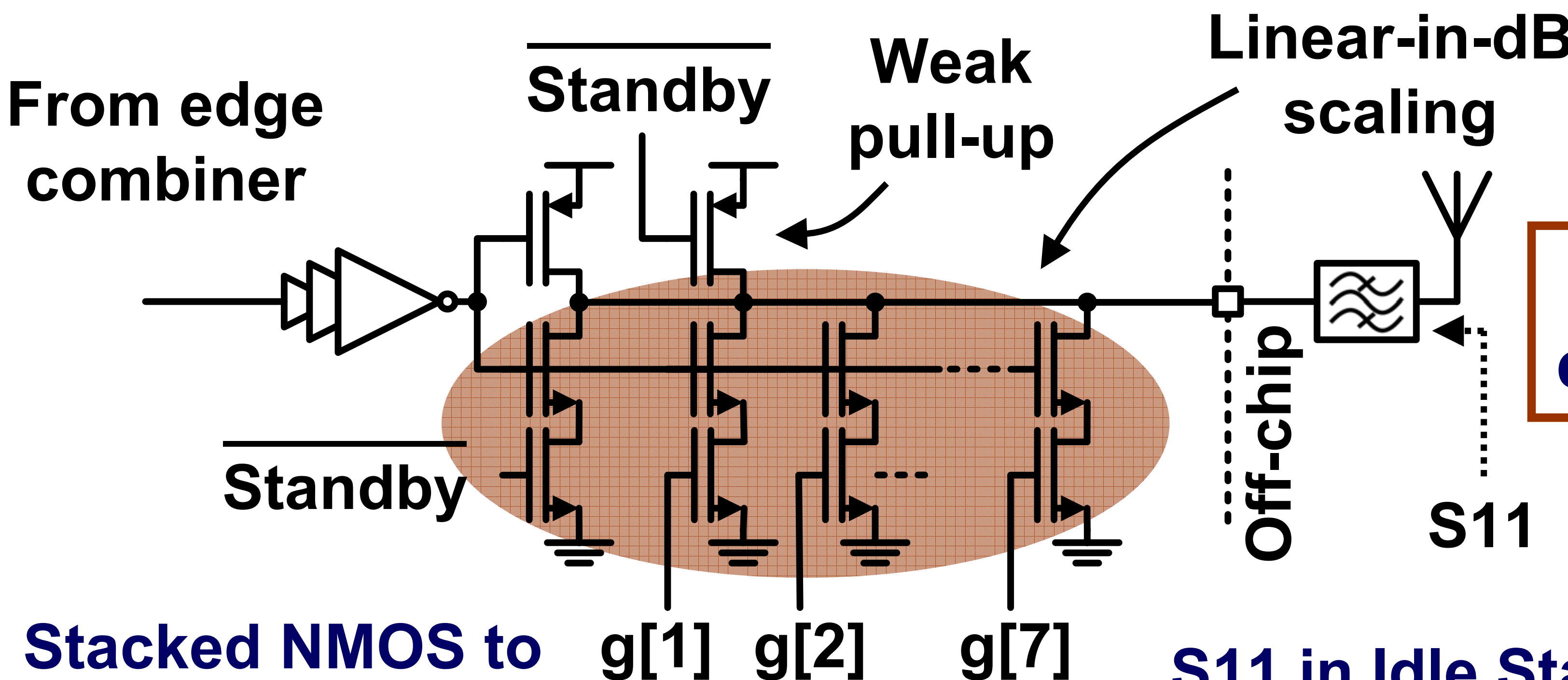


Ring output is an accurate measure of pulse center frequency

30-Edge Combiner

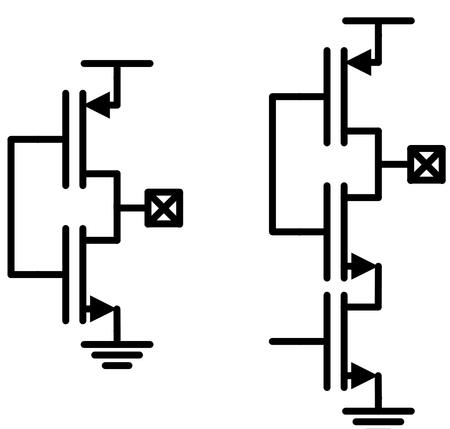


RF Pad Driver

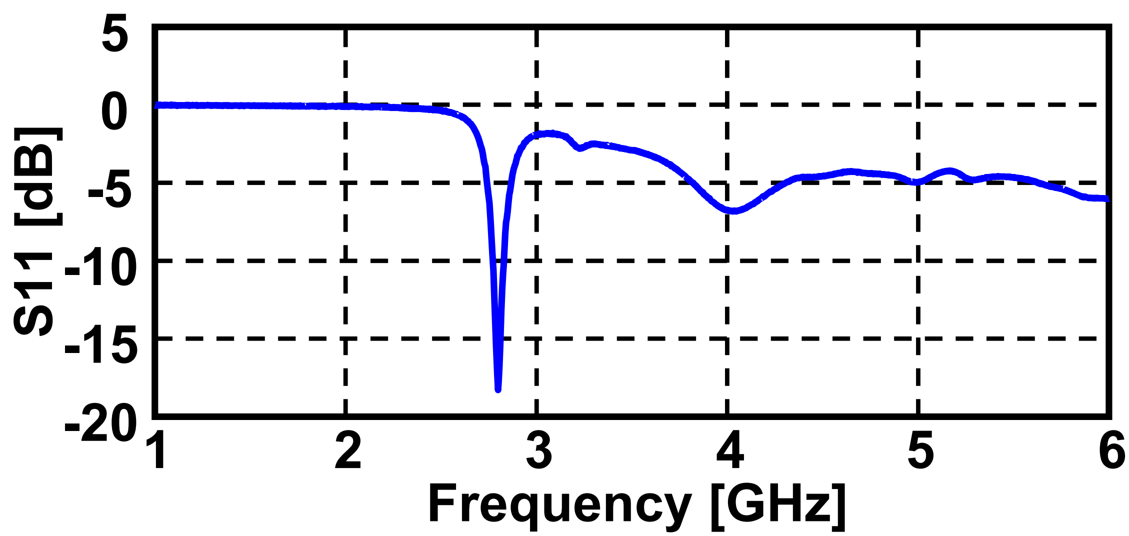


27% efficiency

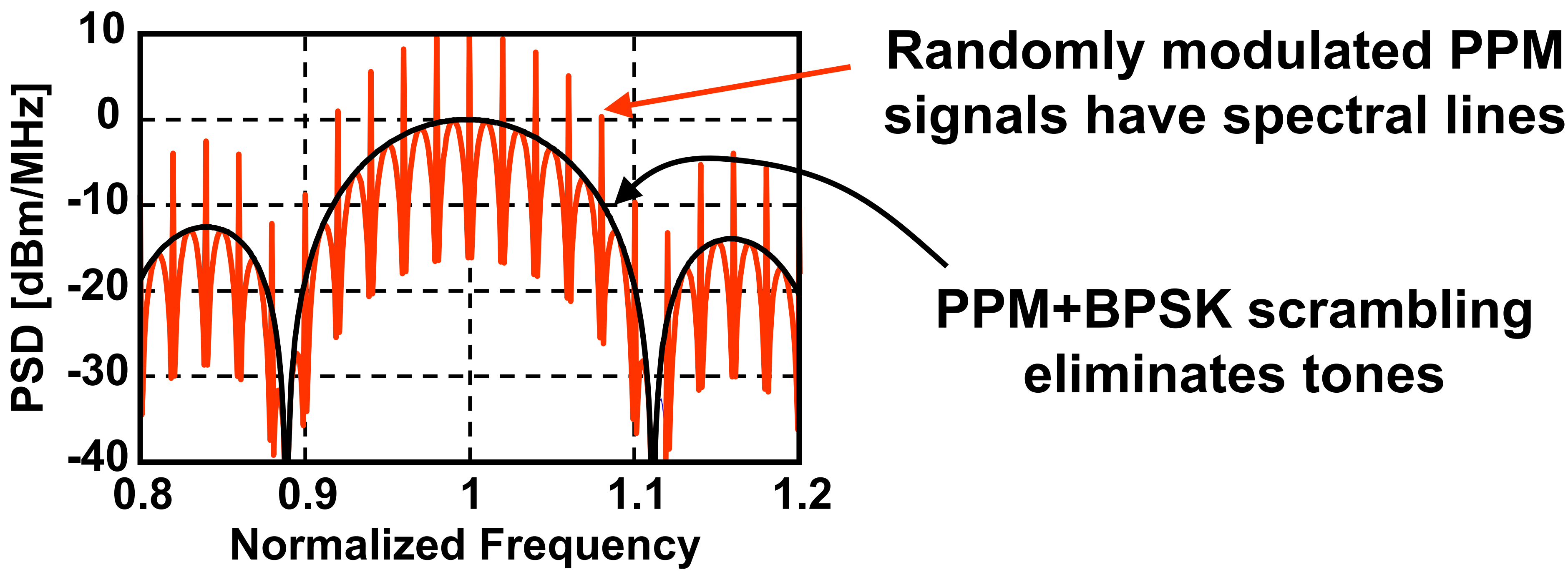
Stacked NMOS to reduce leakage

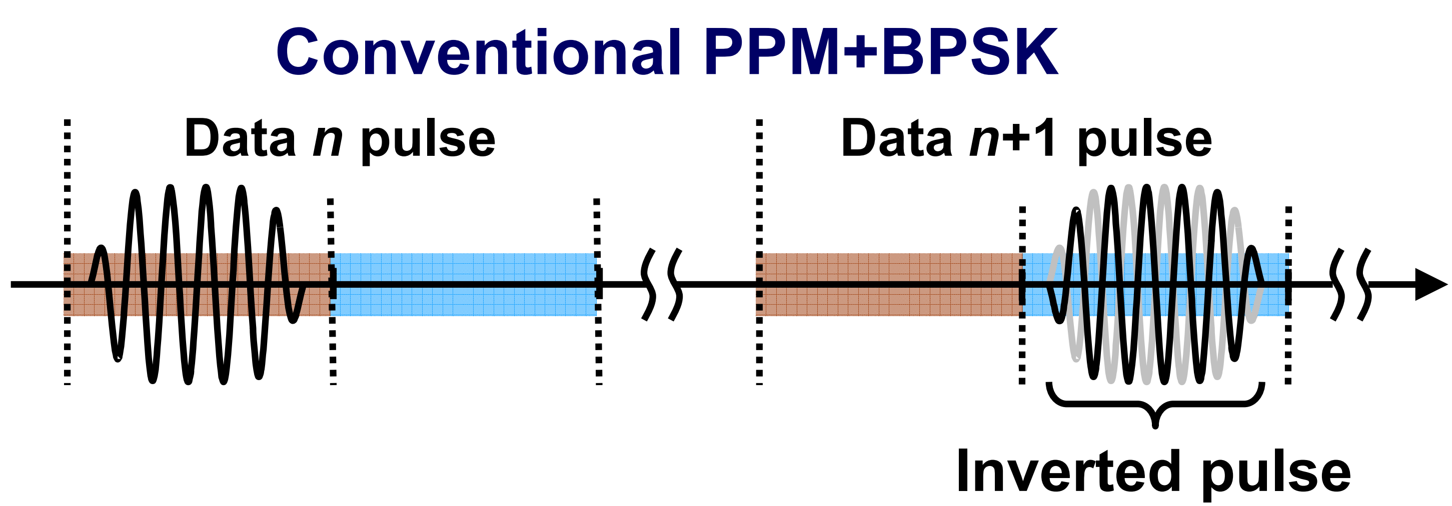


S11 in Idle State

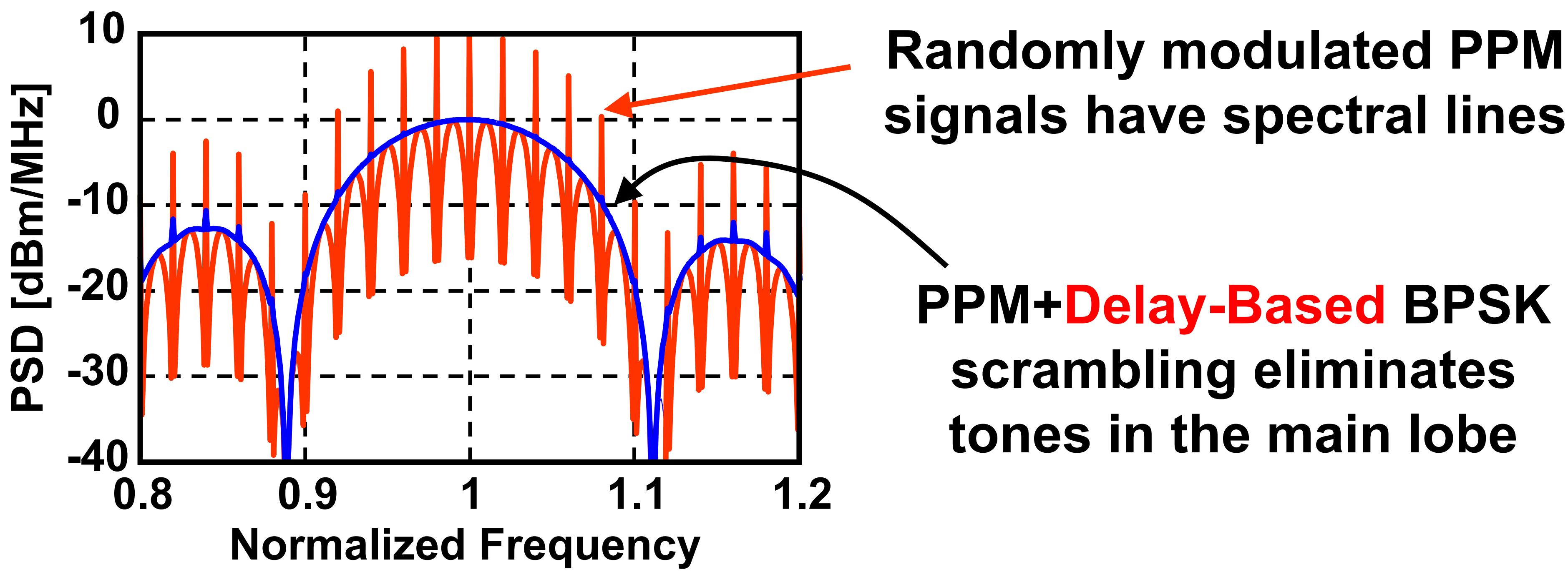


Spectrum Scrambling

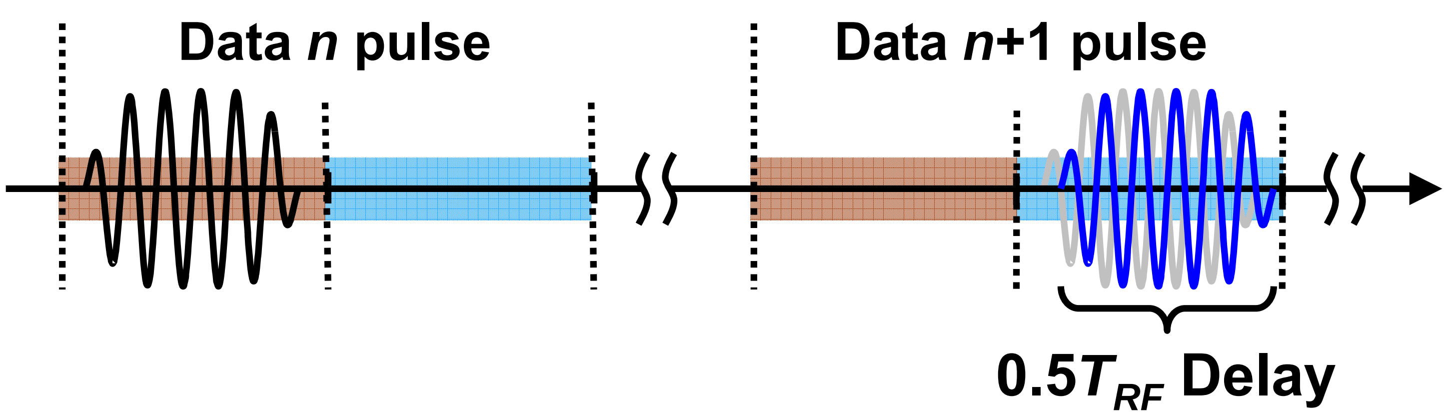




Spectrum Scrambling



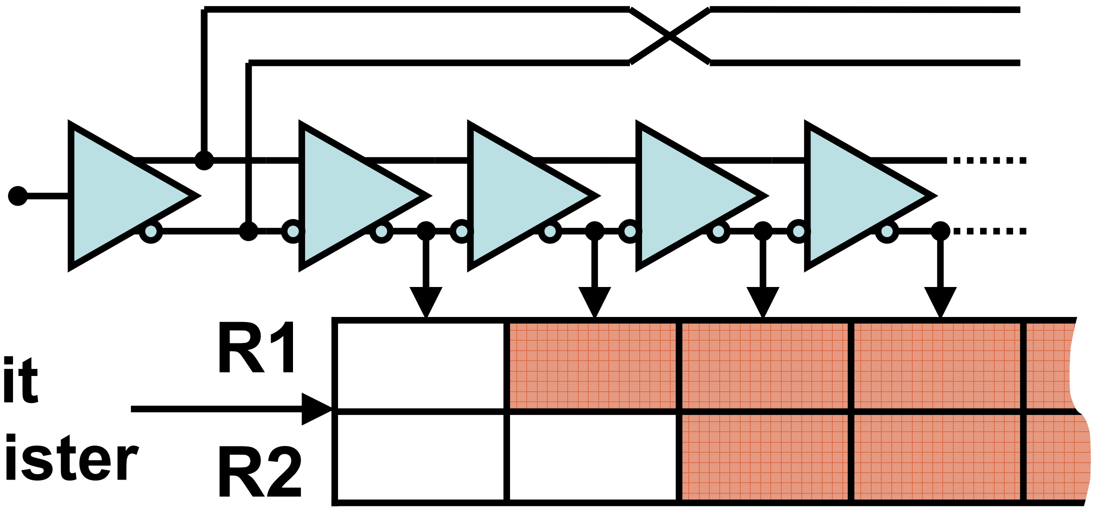
Proposed PPM+DB-BPSK



DB-BPSK: Minimal Overhead

DB-BPSK Implementation

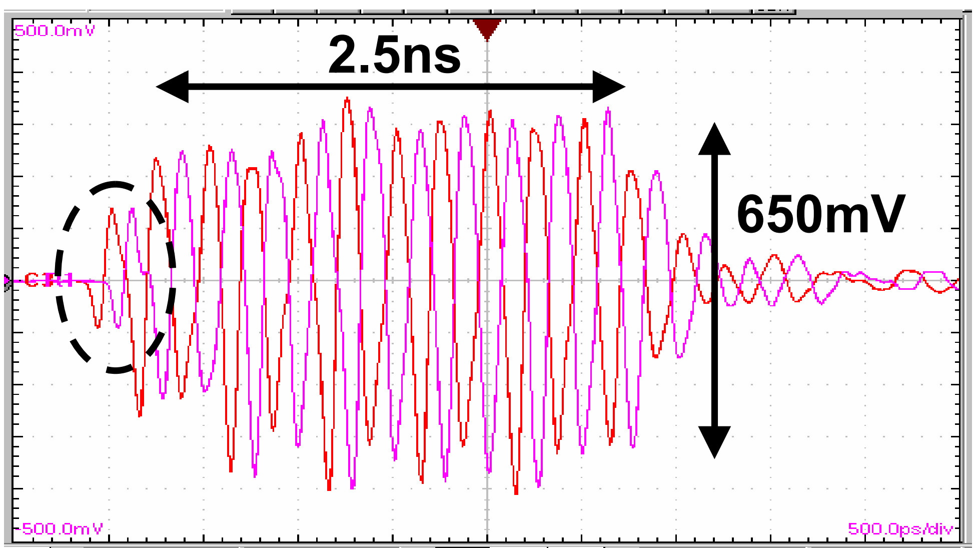
Per-stage delay is ½ RF period



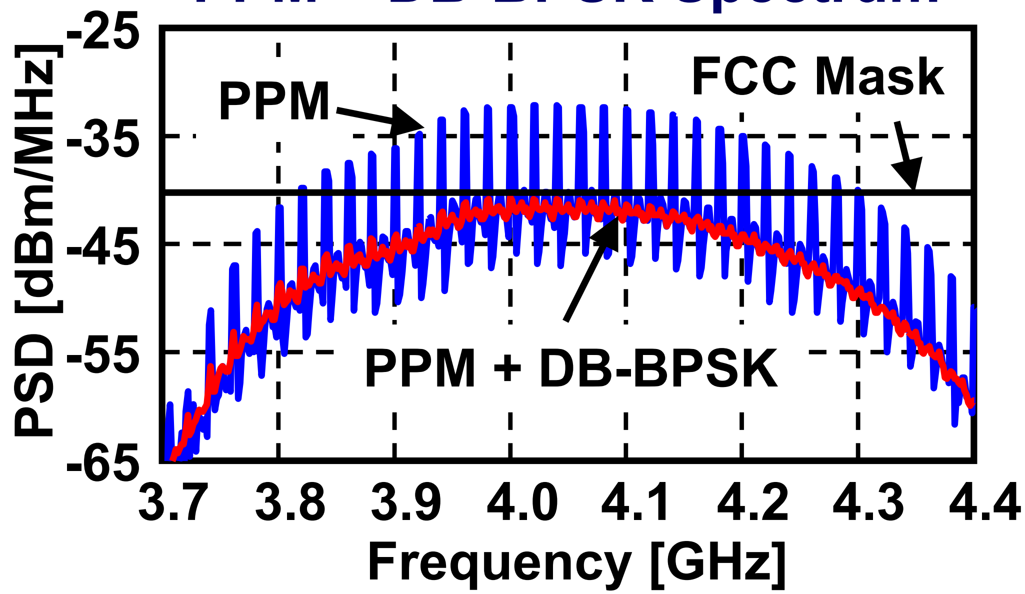
PRBS bit selects register

Mask values offset by 1 bit

DB-BPSK Pulses

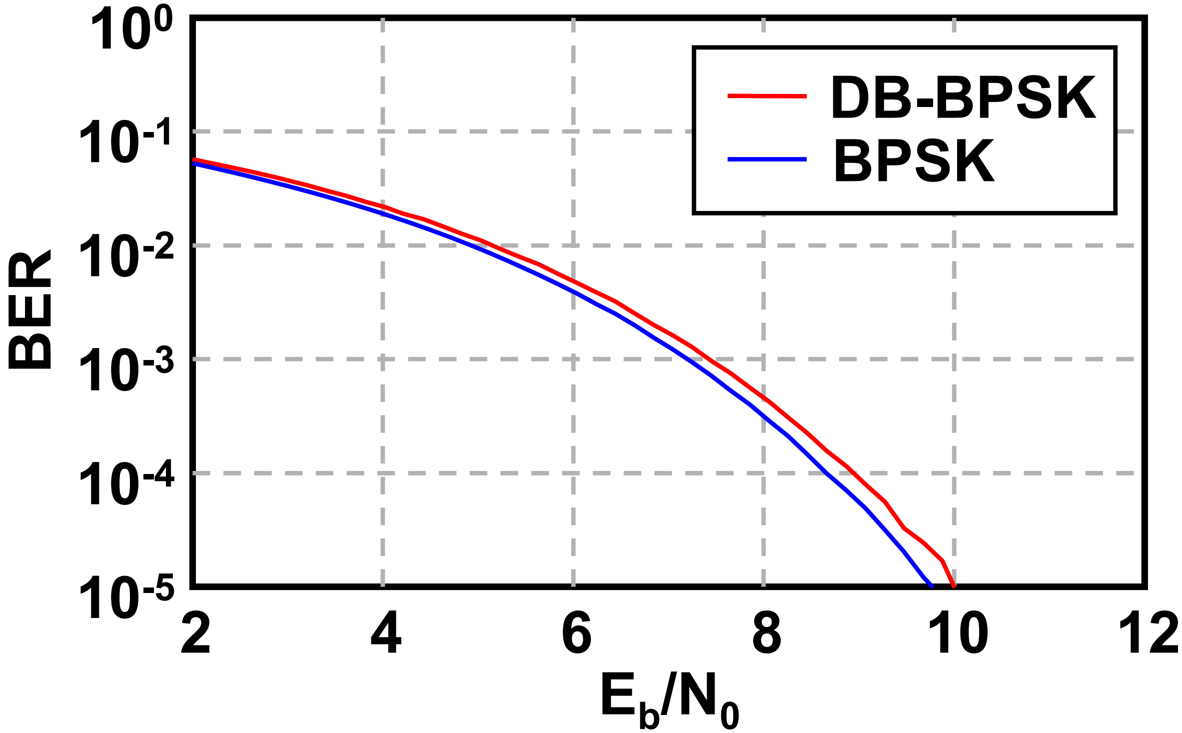


PPM + DB-BPSK Spectrum



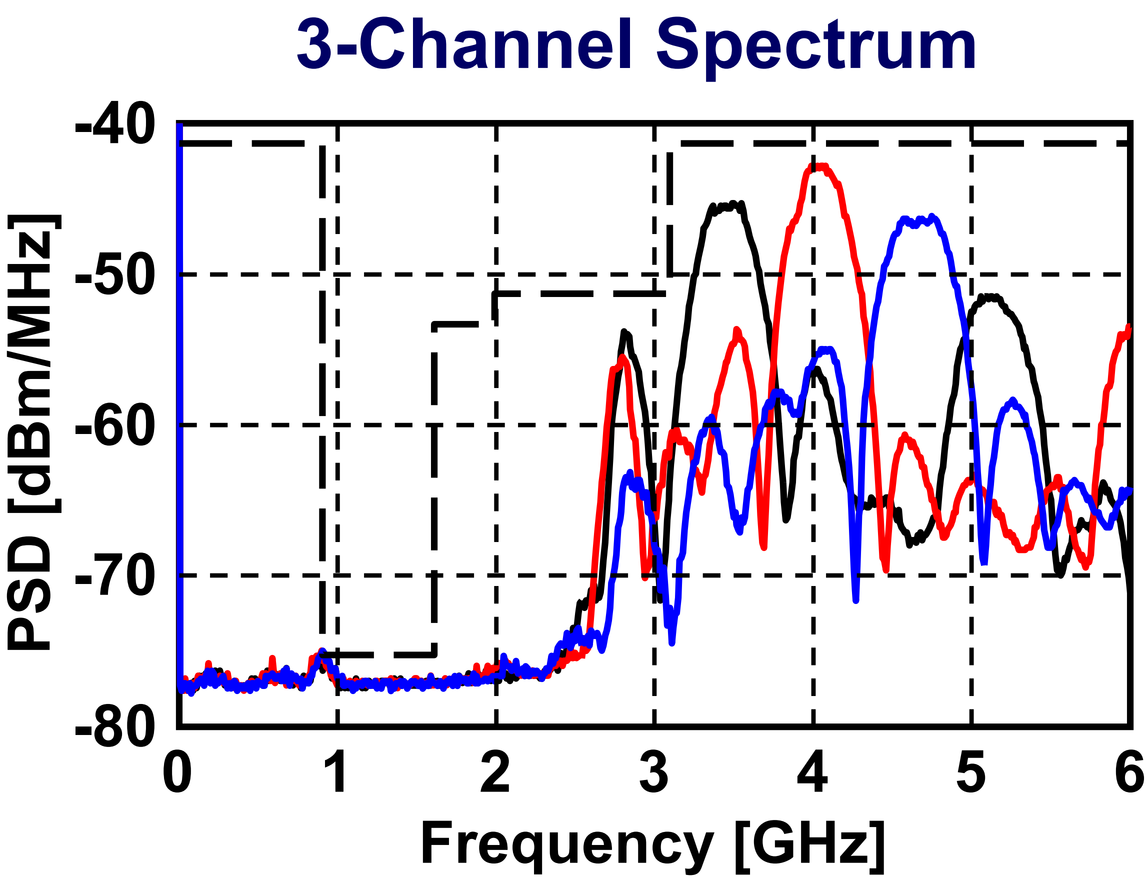
DB-BPSK Modulation

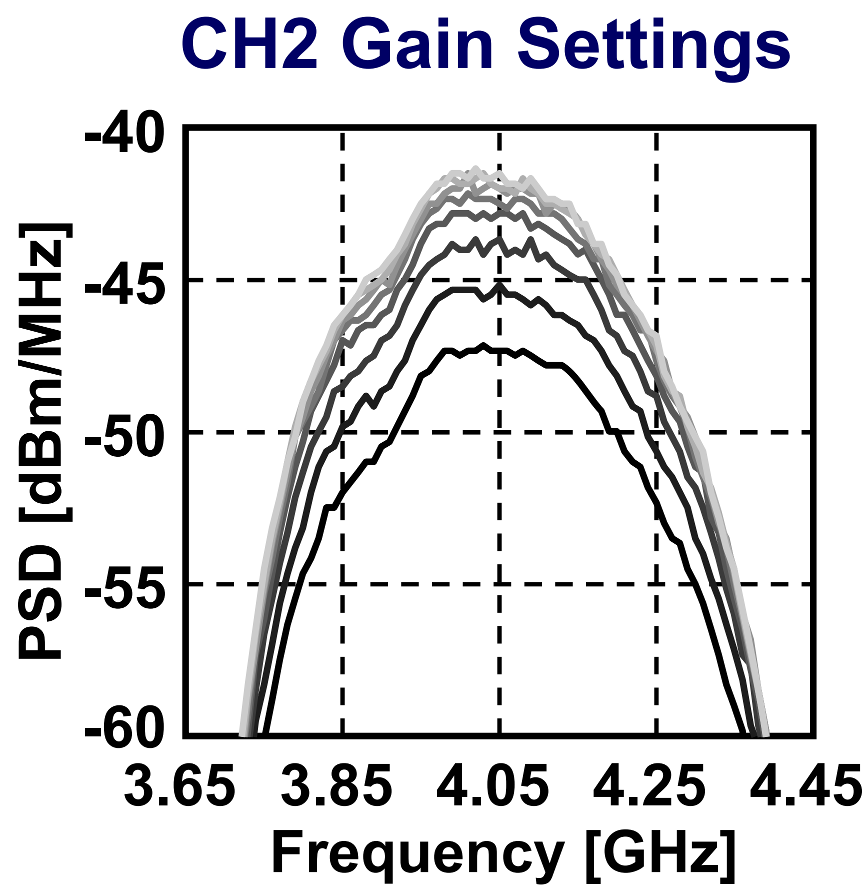
Coherent Receiver Simulations



DB-BPSK can replace BPSK in a coherent receiver with 0.2dB loss

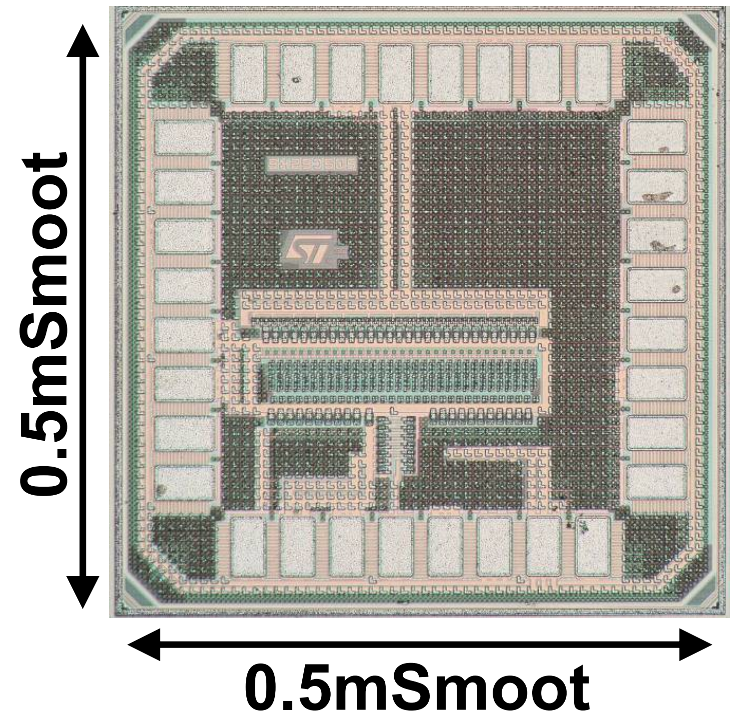
Measured Spectrum





Transmitter Summary

Technology	90nm CMOS
Active Area	0.11x0.22mSmoot^2
Modulation	PPM
Scrambling	DB-BPSK
Supply	1V
Leakage Power	96µW
Active E/pulse	37pJ/pulse
PRF Range	10kHz to 16.7MHz
Total E/bit	9.6nJ/bit to 43pJ/bit



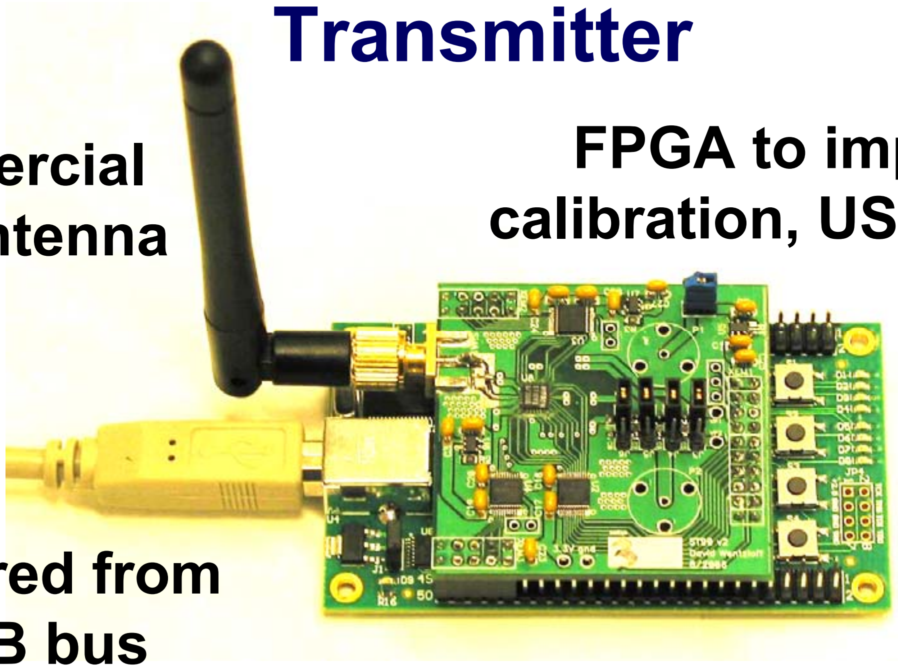
- Energy consumed in sub-V_t leakage and CV^2
- Digital architecture practical for non-coherent RX

Low-Rate System Demo

Transmitter

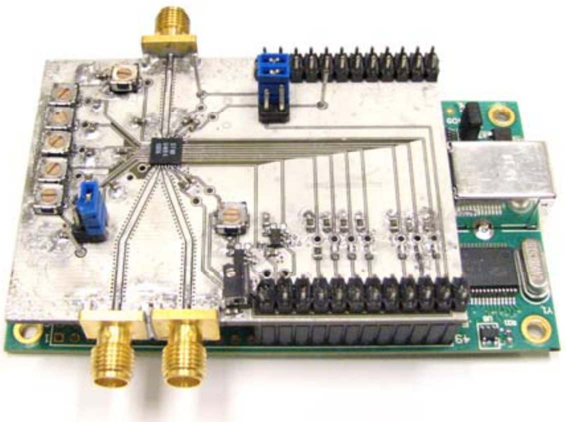
Commercial UWB antenna

FPGA to implement calibration, USB interface



Powered from USB bus

Receiver



Acquisition and timing implemented on FPGA

Demonstrated wireless link at 16.7Mb/s, 1kb packets

Outline

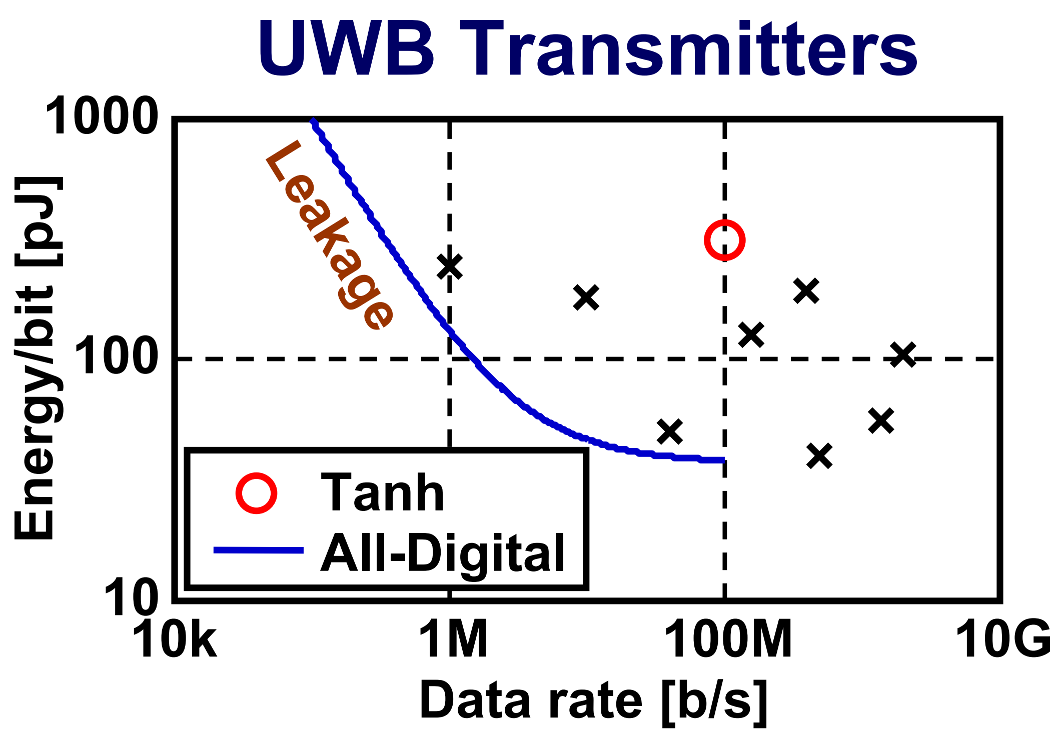
- High data rate transmitter
  - Gaussian pulse shaping
- Variable low data rate transmitter
  - All-digital architecture
- Conclusions and future directions

Summary of Contributions

- **Gaussian pulse approximation**
  - Spectrally efficient for dense networks
- **All-digital pulse generation**
  - Relax spectral efficiency requirement
  - Digitally programmable pulse spectrum
  - Ultra-low power
- **Proposed DB-BPSK modulation**
  - Suitable for scrambling PPM, BPSK replacement

Conclusions

- Exploit available bandwidth to reduce power in electronics
- UWB systems are receiver power dominated
- Energy/bit compares favorably to other work
  - Dominated by leakage currents at low data rates



Future Directions

- UWB suitable for high and low data rates

- Narrowband relies on fine-tuning
- UWB signaling enables relaxed frequency tolerance ►CMOS integration

- Highly digital radios
  – Use standard digital design flow
  – Benefit from process scaling
  – Ultra-low power and area

Synthesizable transmitter for UWB

Acknowledgements

- Anantha Chandrakasan
- Joel Dawson and Charlie Sodini
- Margaret Flaherty
- Friends@MIT and family
- MARCO/DARPA Focus Center for Circuits and Systems Solutions (C2S2), National Science Foundation (NSF), HP/MIT Alliance
- STMicroelectronics for chip fabrication

- Thank YOU for your attention