A 0.55V 16Mb/s 1.6mW Non-Coherent IR-UWB Digital Baseband with ±1ns Synchronization Accuracy

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Motivation

Asset Management

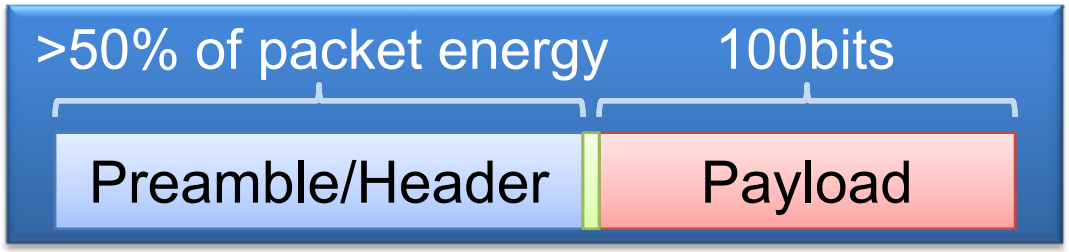
Medical Monitoring & Telehealth

Emergency Telemetry

Common attributes:

- Short-range wireless
- Low data rates
- Small payloads

Example ZigBee/Bluetooth packet:

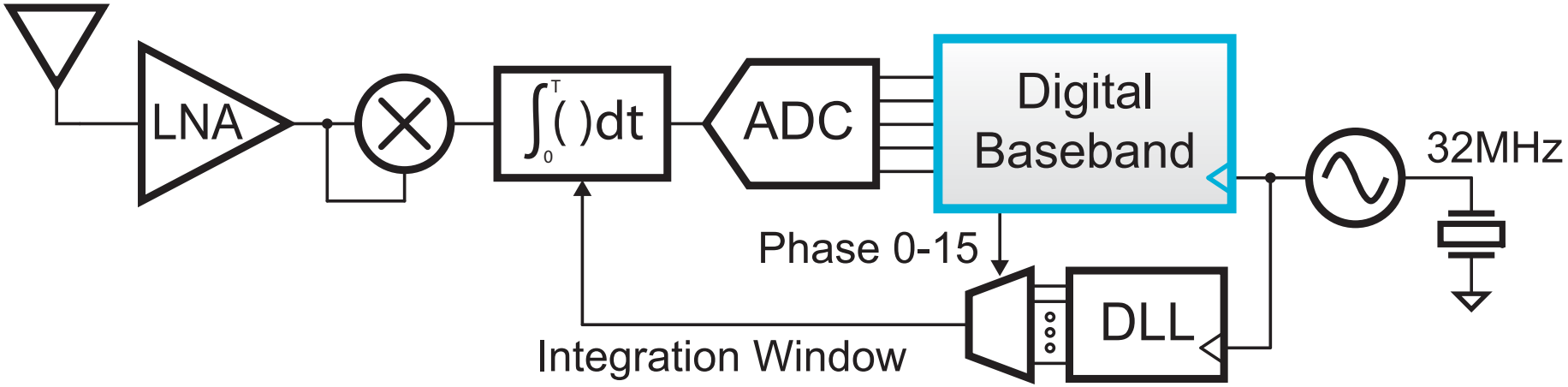


Goal: Minimize synchronization time and power

↳ minimizes energy per *useful* bit (EPUB)

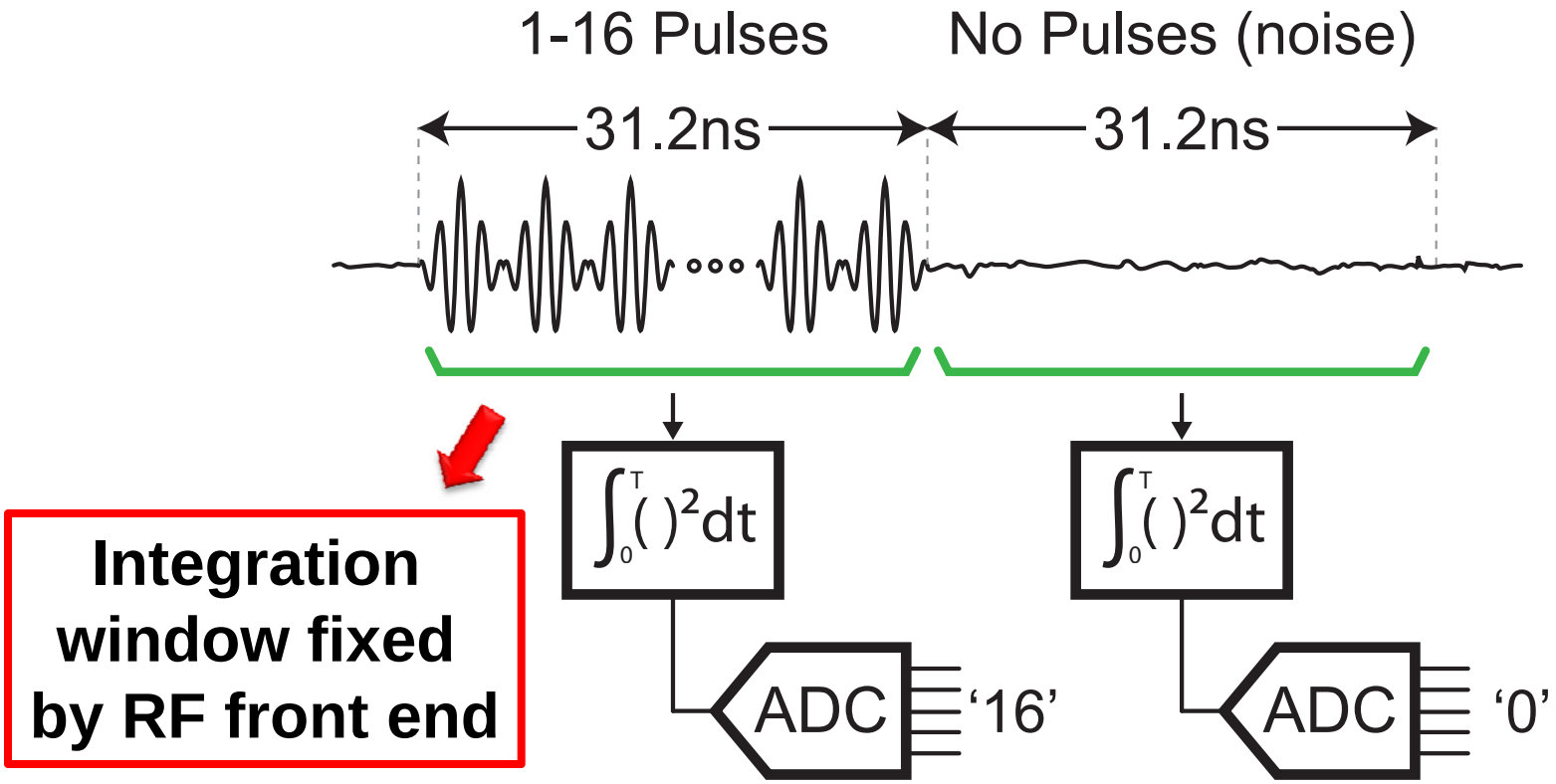
Non-Coherent IR-UWB Receiver

- **RF front end is a square-and-integrate energy detector with 500MHz BW @ 3.5, 4.0, or 4.5 GHz**
- **Fastest system clock is at baseband (32MHz)**



- **High synchronization accuracy with slow clock**
- **Integration window phase changed only once**
- **No clock synthesis required (e.g. PLL)**

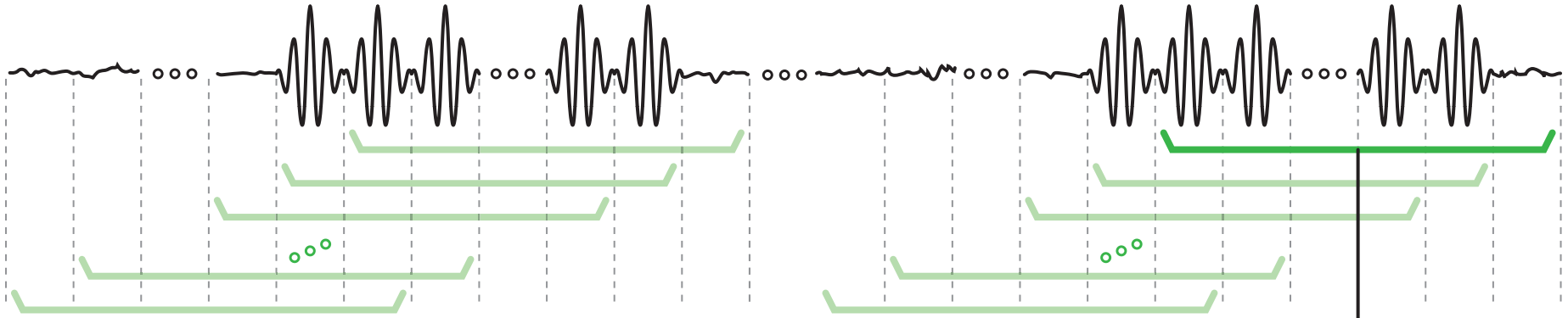
Non-Coherent UWB Signaling

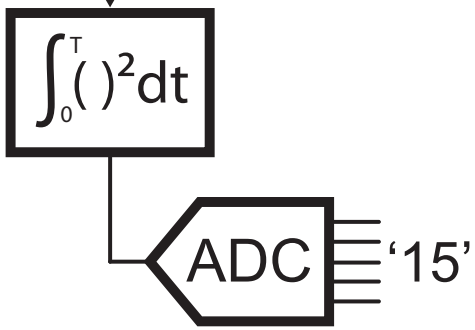


- **Up to sixteen 1.95ns pulses per window**
  - **OOK modulation in <u>preamble</u> (32Mb/s max)**
  - **PPM modulation in <u>payload</u> (16Mb/s max)**

Previous Synchronization Approach: Repetition Codes

- **Goal: align integration window with payload**
- **Approach: slide window phase**



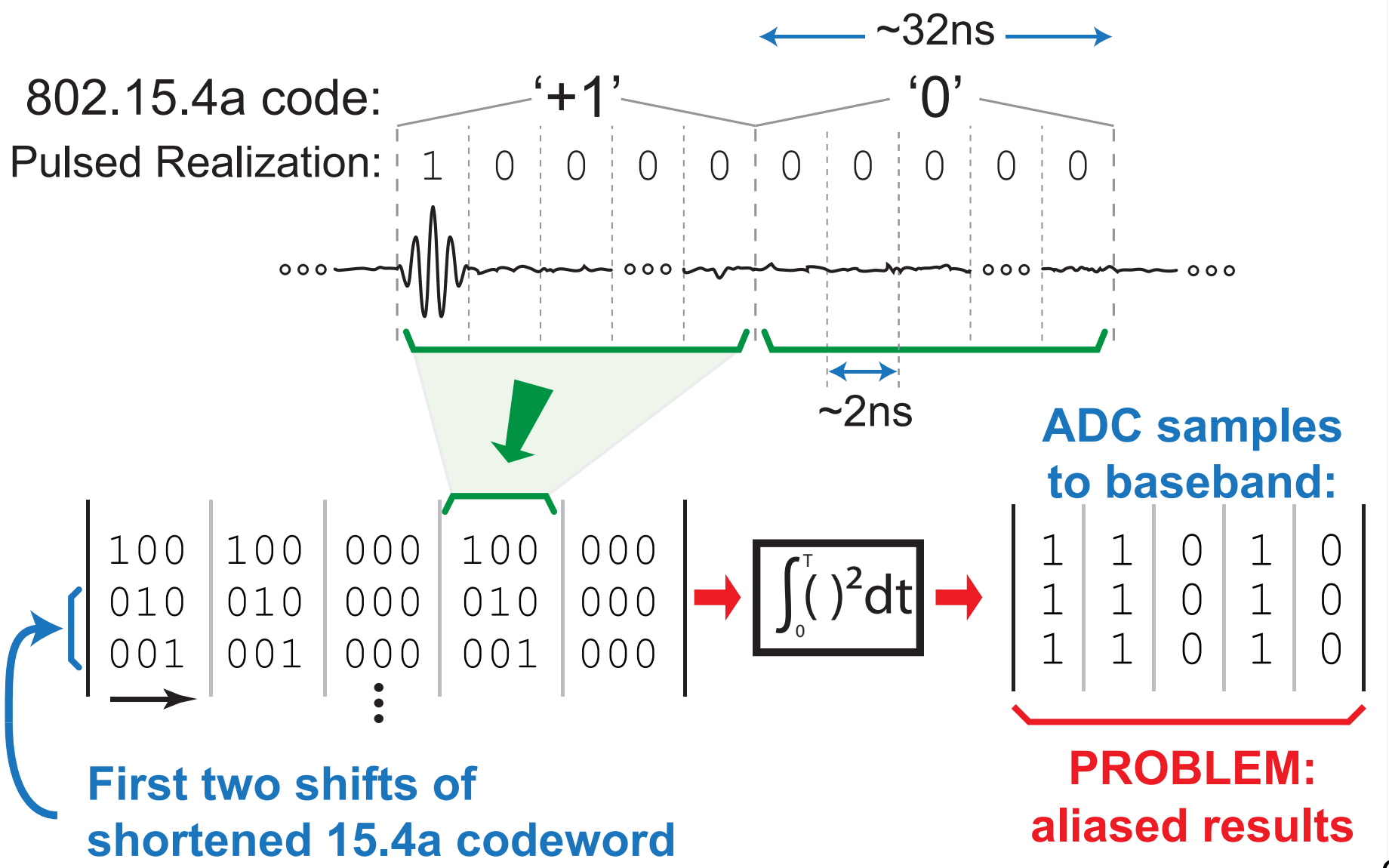


MAX

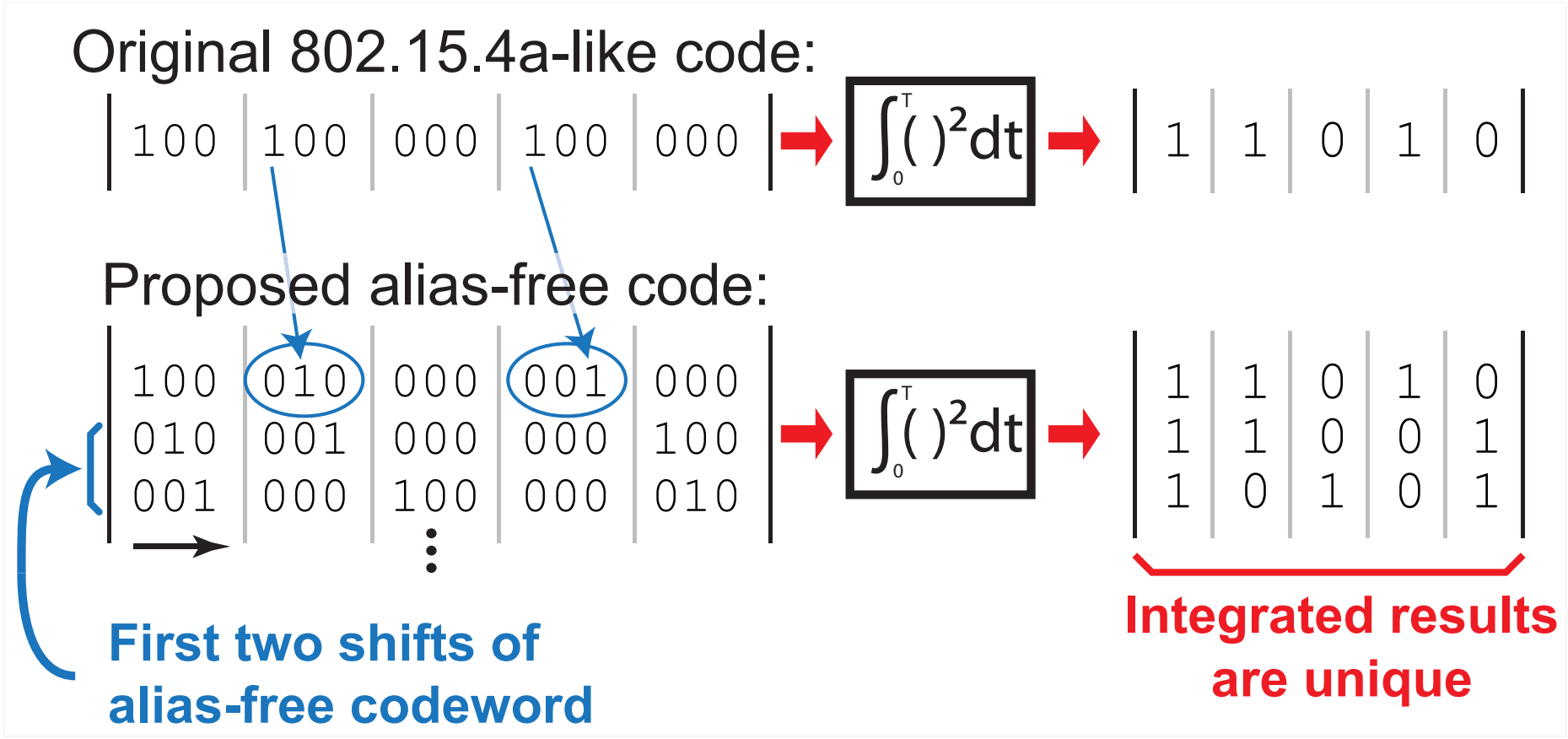
Window	Integration
0	'2' + '2' = '4'
1	'3' + '3' = '6'
⋮	⋮
14	'15' + '15' = '30'
15	'16' + '16' = '32'
16	'15' + '15' = '30'

- Simple implementation
- Low processing gain
  - → **Long preambles**
  - → **High EPUB**

Non-Coherent Synchronization Using 802.15.4a Codes



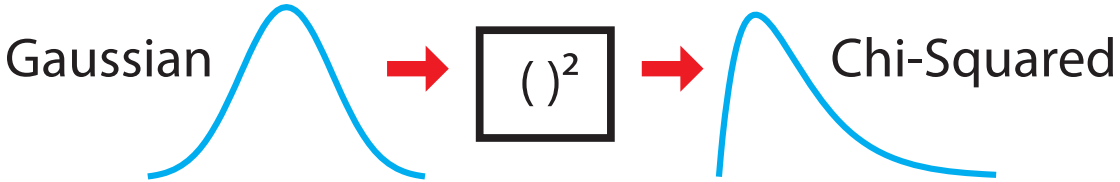
Proposed Alias-free Synchronization Code



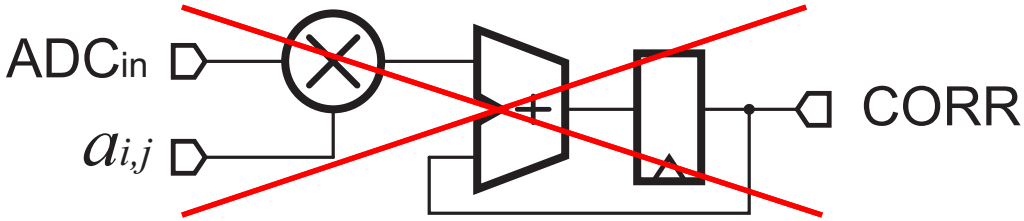
Alias-free codes allow accurate non-coherent synchronization with a slow clock

Synchronization: Non-Coherent Correlation

- **Squaring element in RF changes receiver statistics**

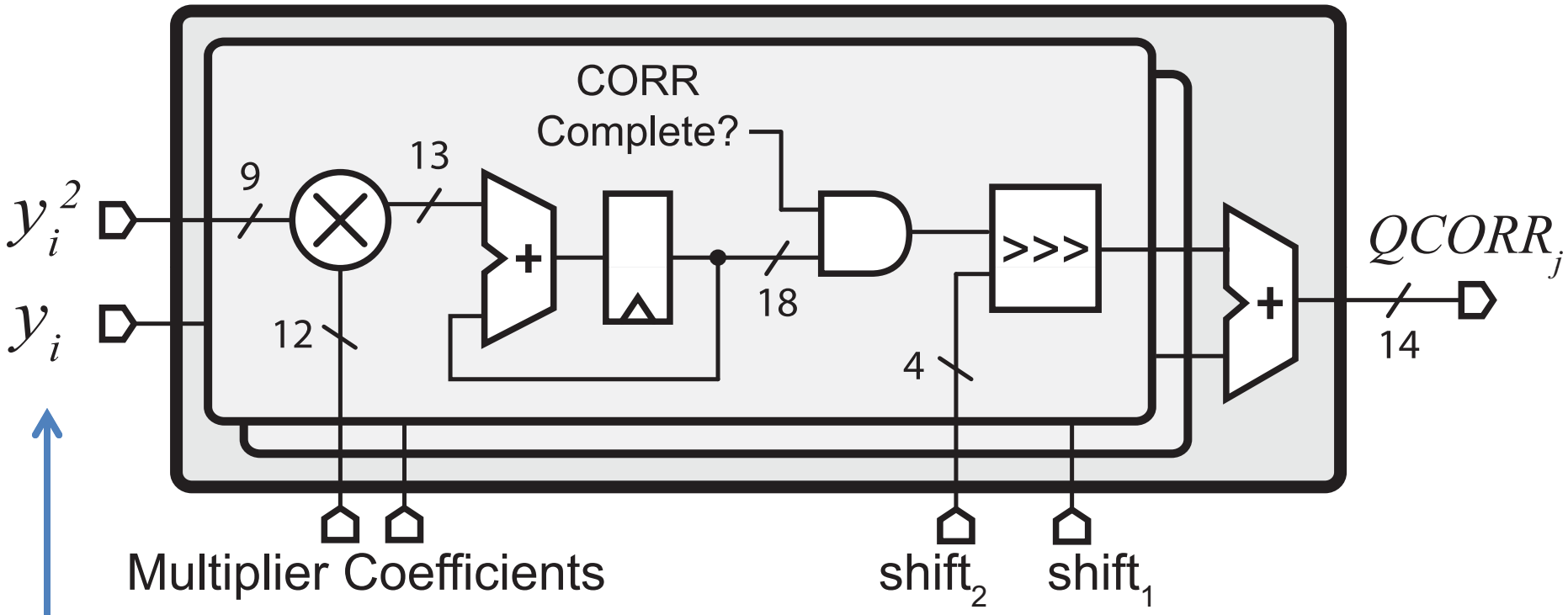


- **Matched-filters (MFs) are not necessarily optimal**



- **Maximum-likelihood (ML) implementation must calculate Bessel-functions**
  - Increasing SNR involves averaging correlator outputs, not input samples → **large energy overhead**

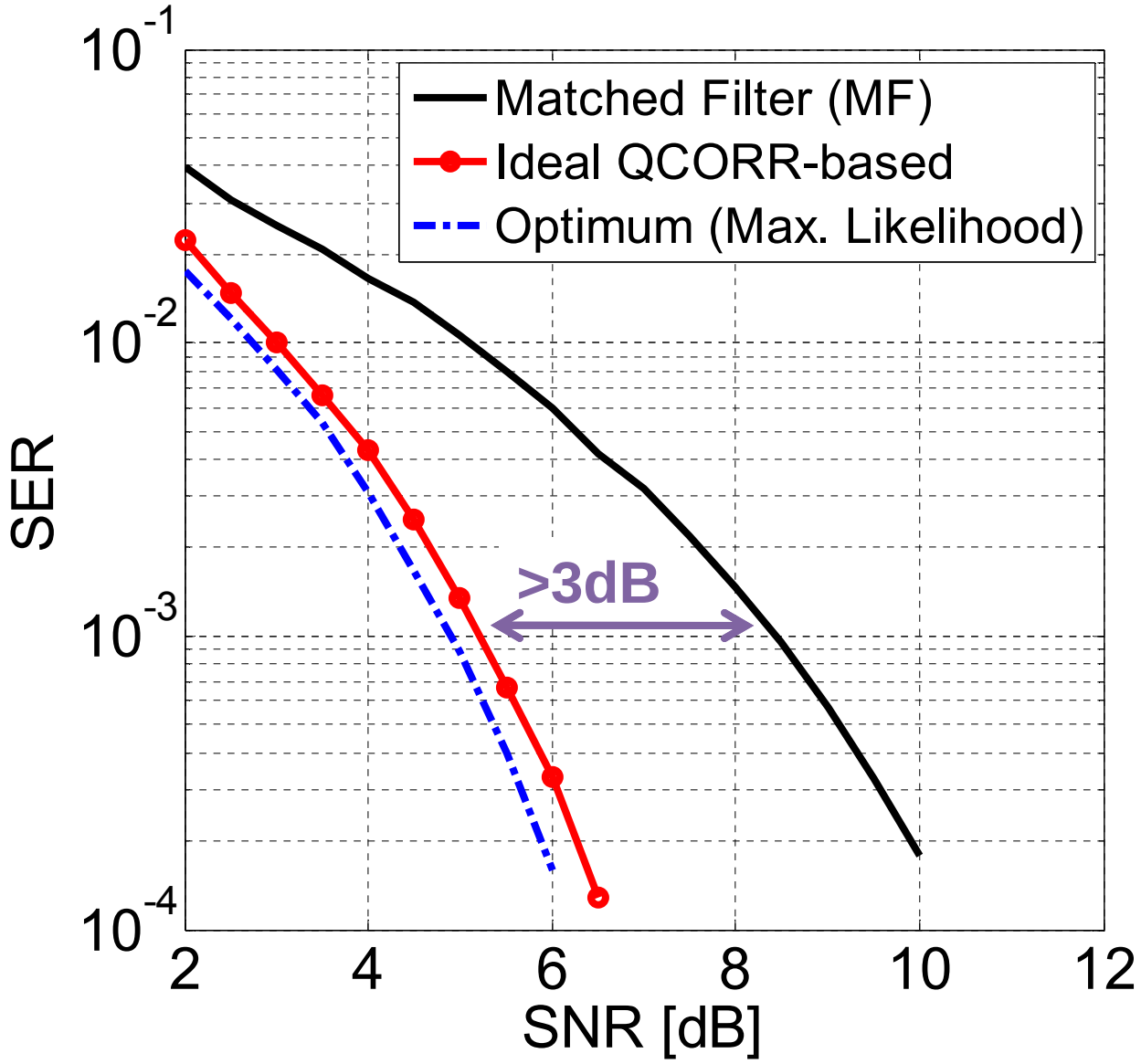
Proposed Solution: Quadratic Correlator (QCORR)



Dual MFs with linear and squared inputs @ 32MHz

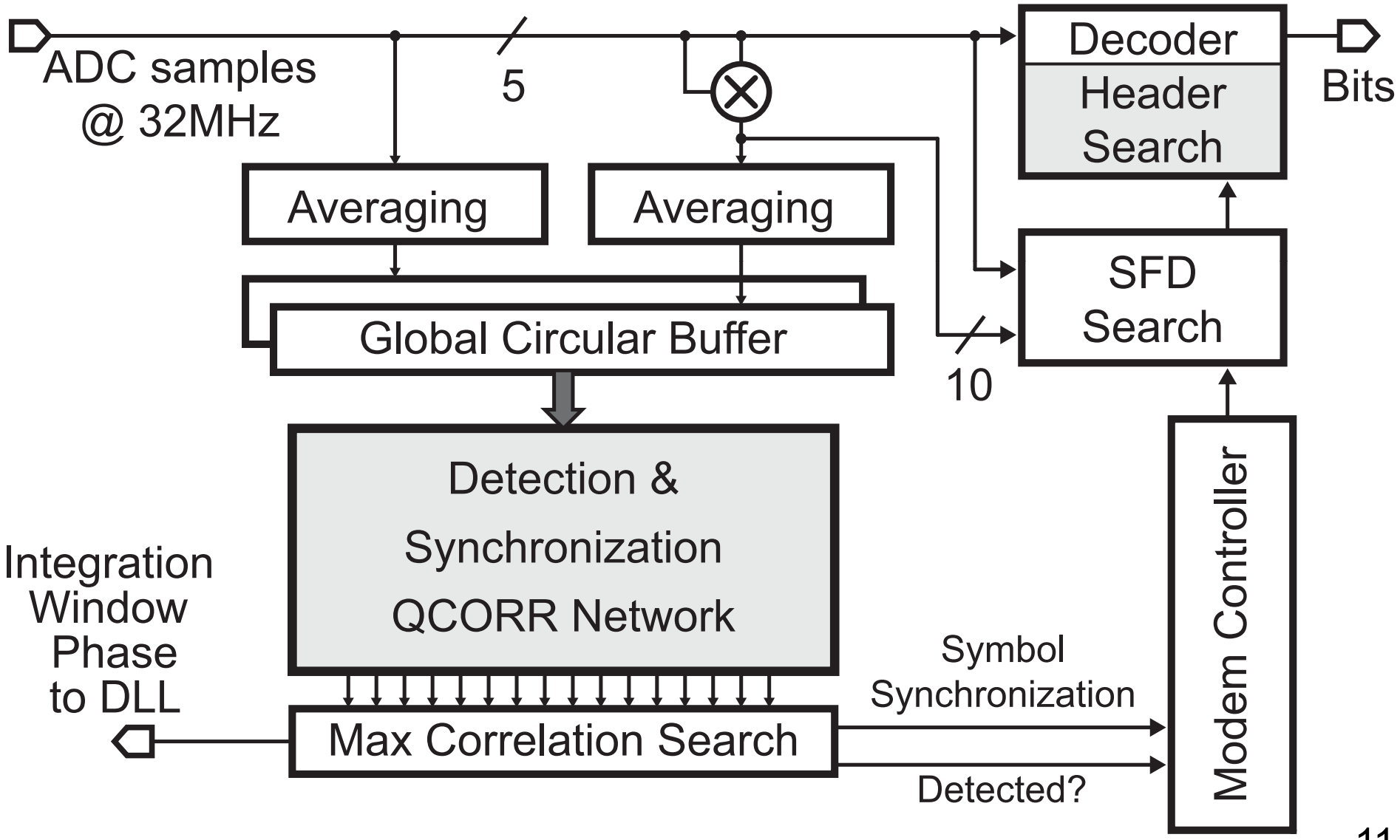
Input codewords can be averaged → linear energy savings with code repetitions

Theoretical QCORR Results



- QCORR within 0.3dB of optimum ML receiver
- QCORR requires 3dB lower SNR than MF

IR-UWB Baseband Architecture



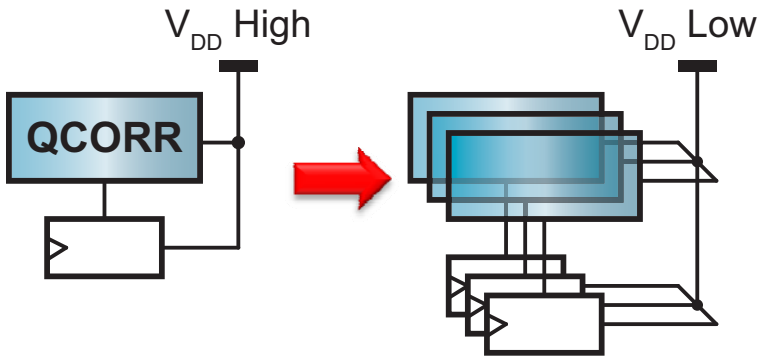
Power Reduction Techniques

- **Algorithmic transforms**
  - Reduced computational complexity

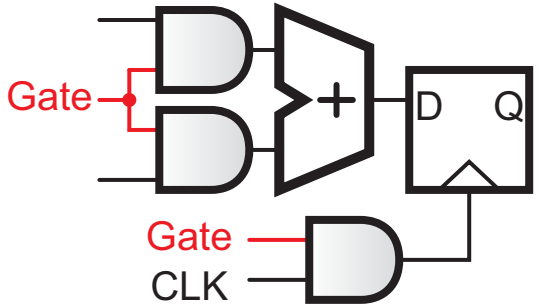
$$\left(\sum_{k=0}^{q-1}\frac{(y_k - \mathrm{E}[y_k \mid t_k])^2}{\mathrm{var}[y_k \mid t_k]}\right) + c$$

$$\left(\sum_{k=0}^{q-1} y_k^2 a_{2,k} + y_k a_{a,k}\right) + c_0$$

- **Architectural transforms**
  - Low voltage & parallelism
  - Scheduling to reduce complexity



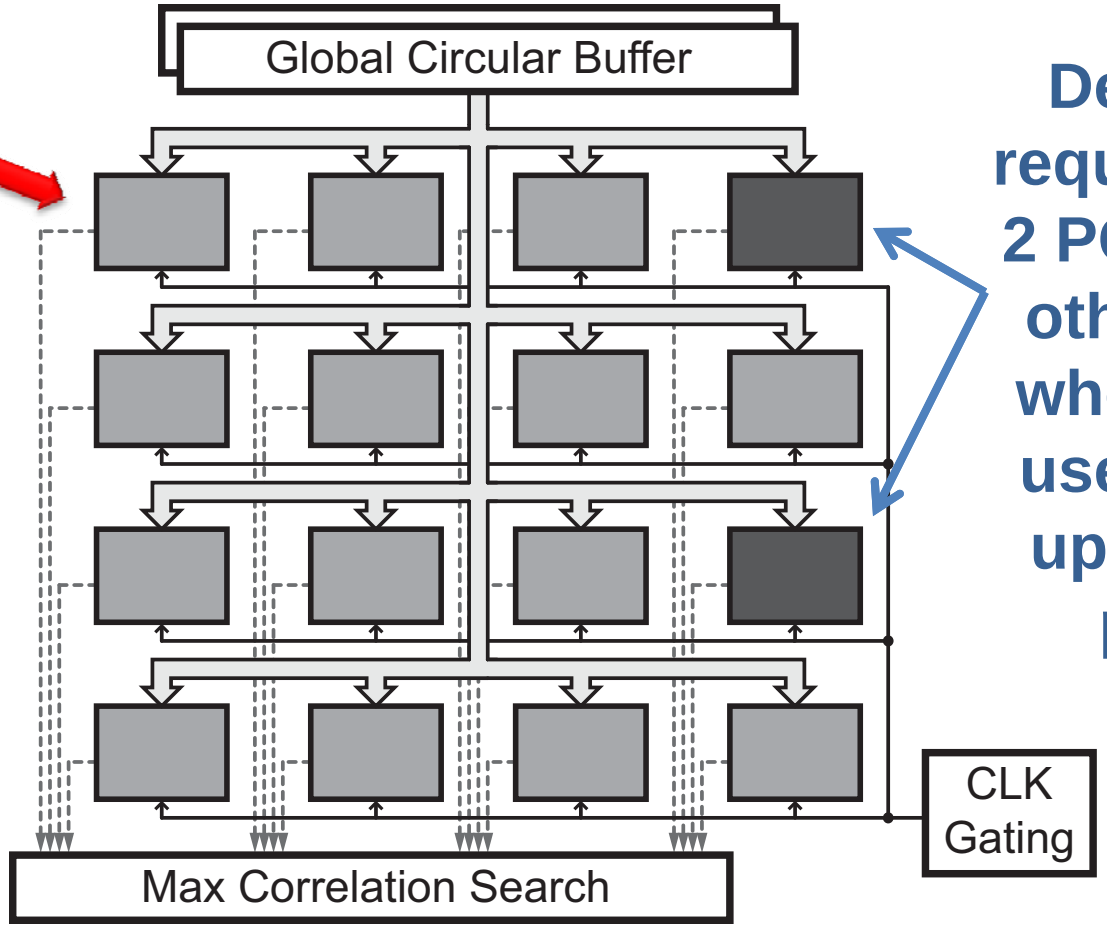
- **Data and clock gating**
  - Reduced circuit activity factors



Detection/Synchronization Network

of correlations for synchronization
= (PN code length) x (integration window phases)
= 32 x 16 = **512 quadratic correlations**

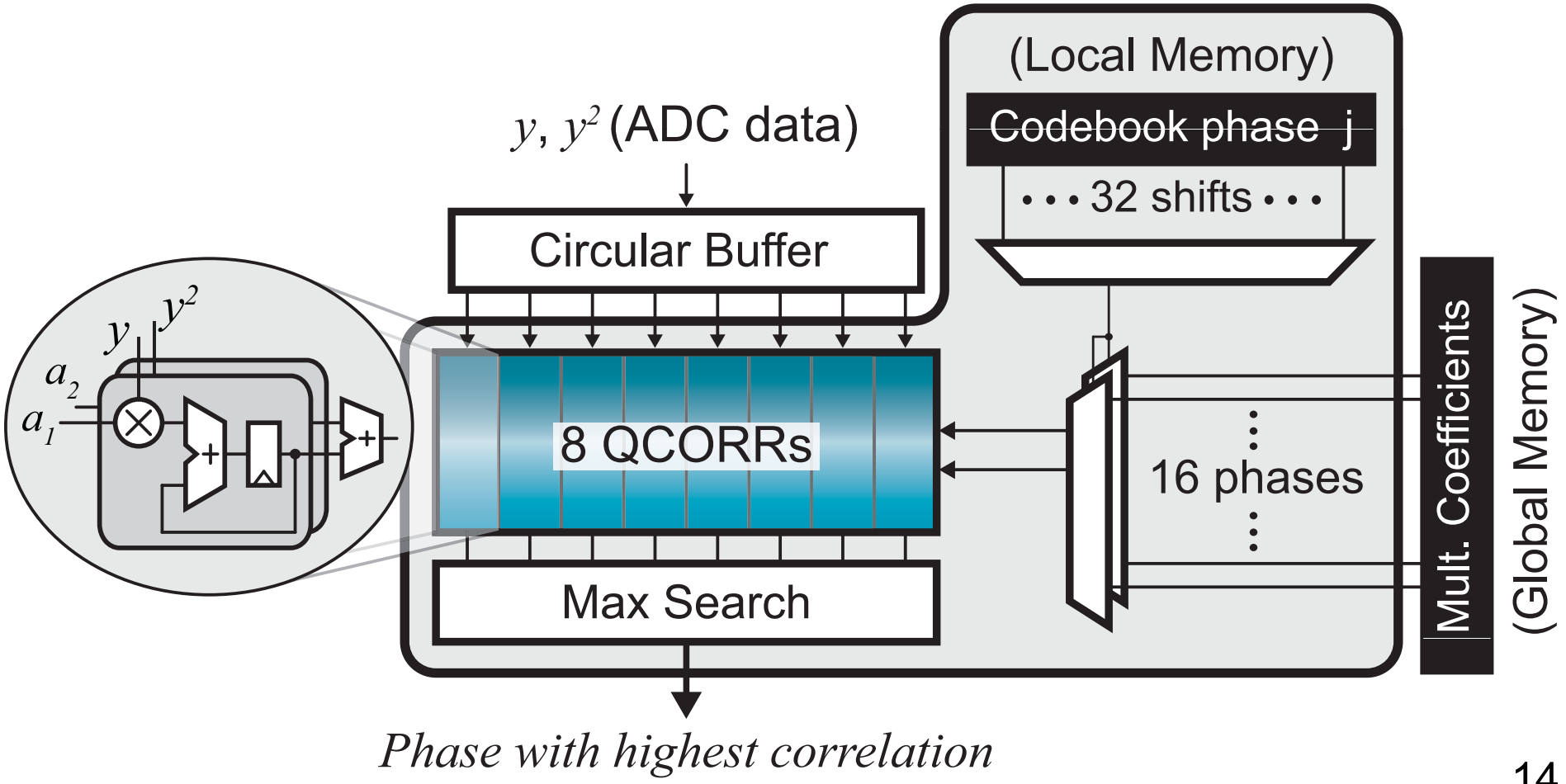
Distribute over 16 parallel *phase-correlation tiles* (PCTs)



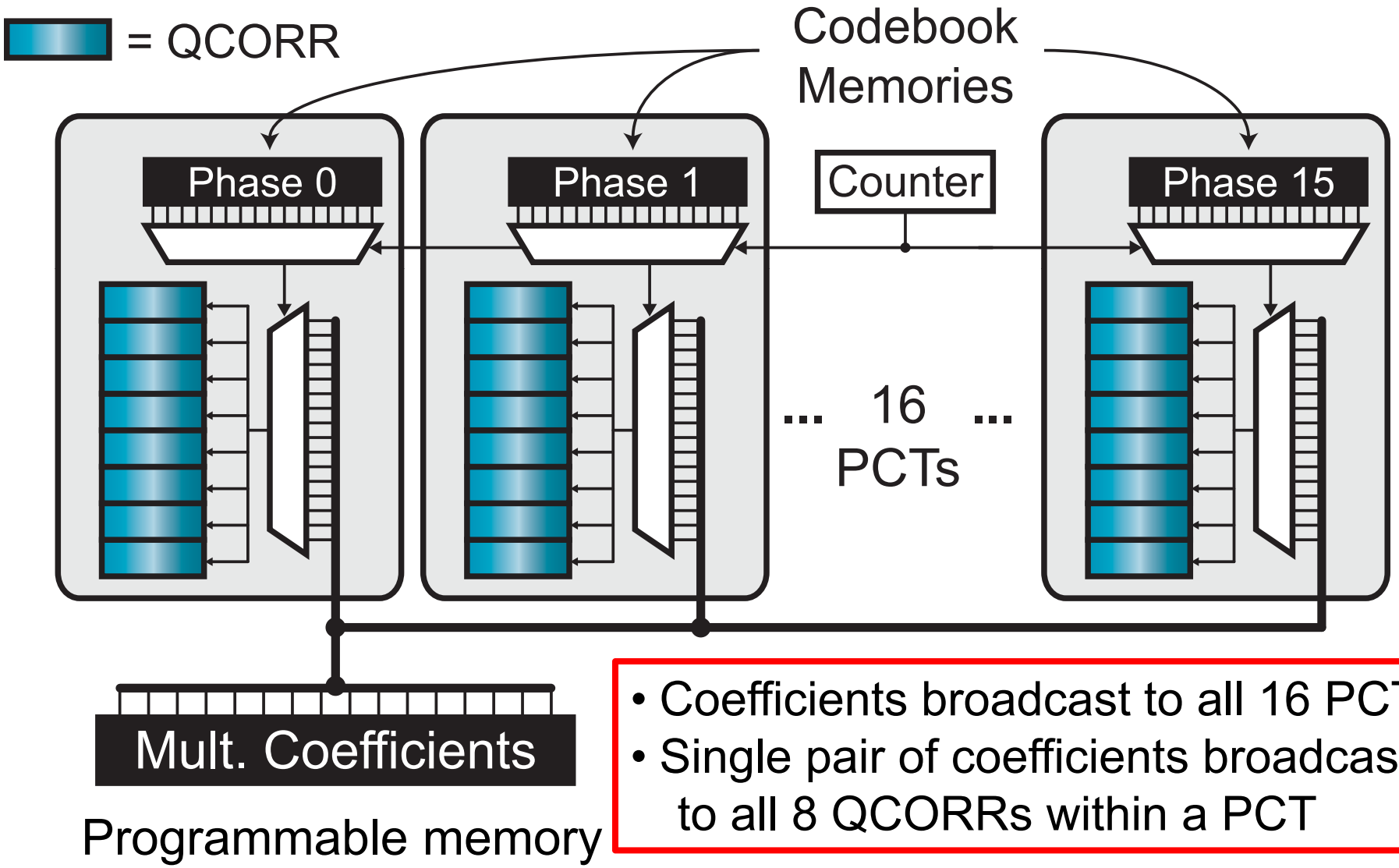
Detection requires only 2 PCTs; gate other PCTs when not in use, saving up to 4X in power

Phase-Correlation Tile (PCT)

- **8 parallel QCORRs perform 4 sets each, for a total of 32 correlations per PCT**

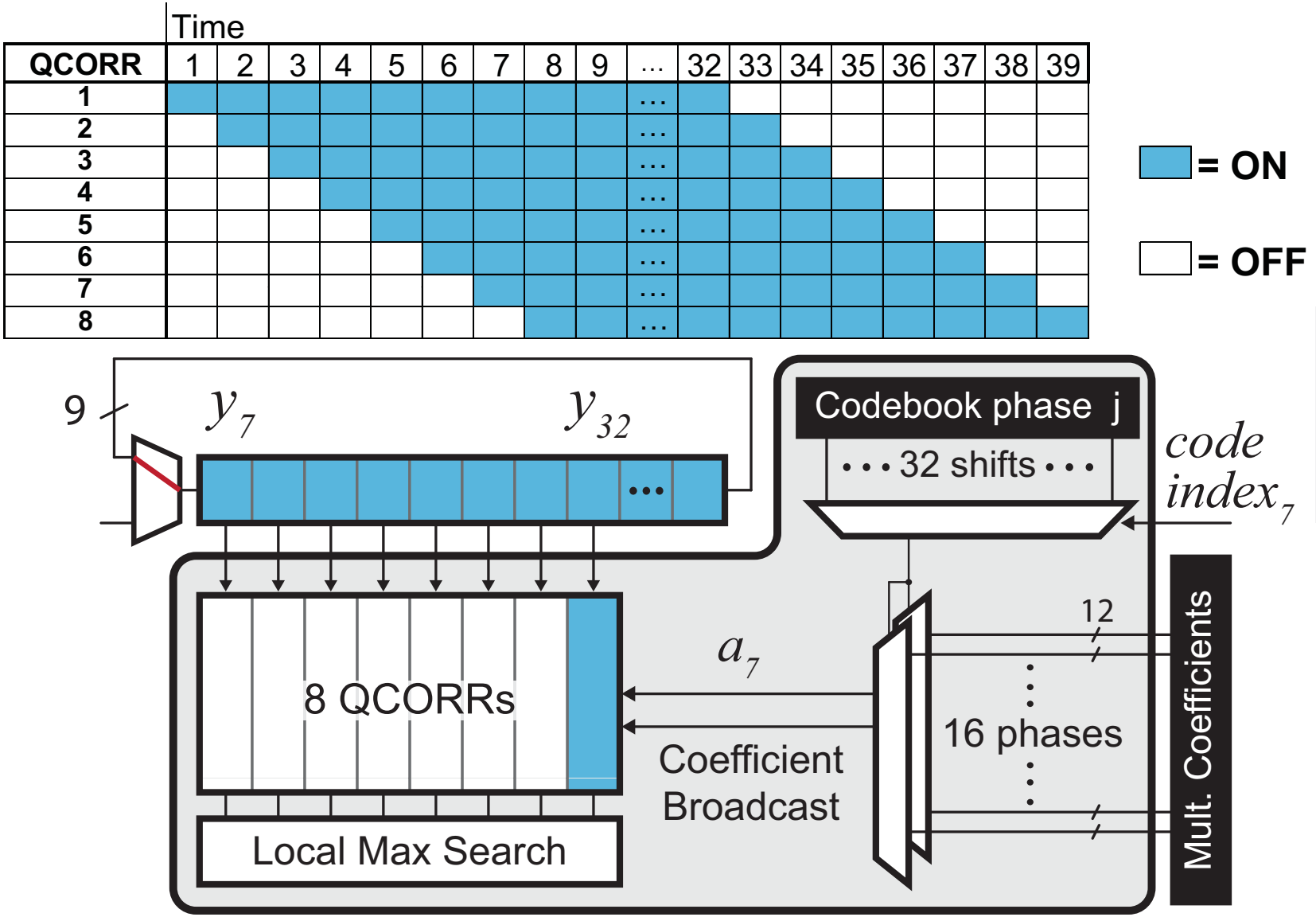


Simplified PCT Coefficient Distribution

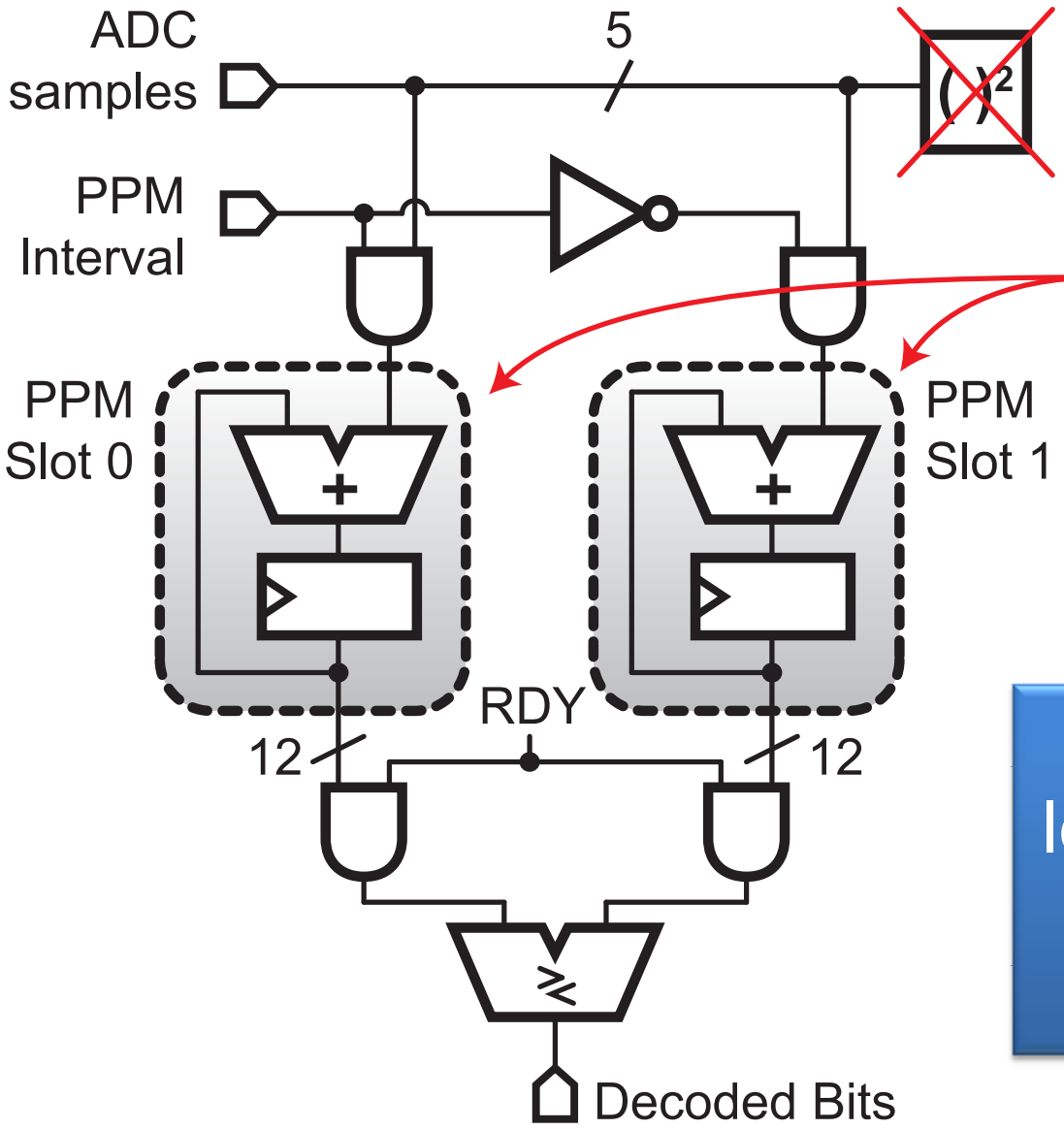


- Coefficients broadcast to all 16 PCTs
- Single pair of coefficients broadcast to all 8 QCORRs within a PCT

PCT Schedule with Circular Buffer



Payload Decoder



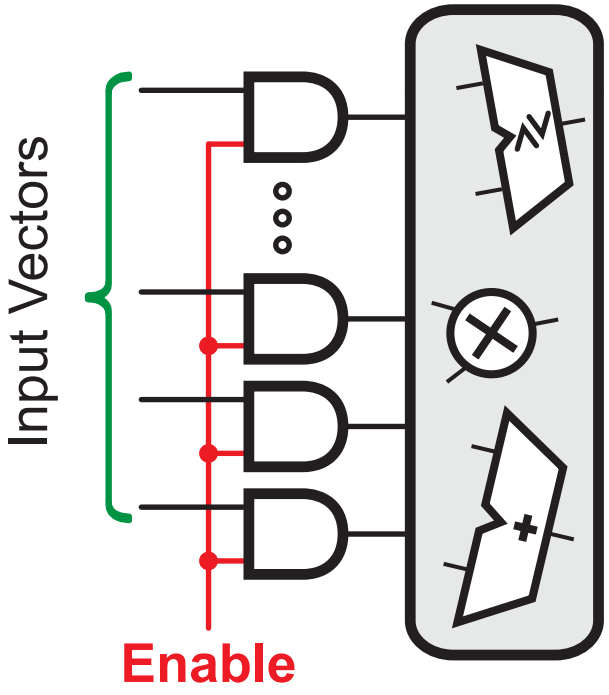
Quadratic samples not required

Dual accumulators prevent throughput loss or buffering

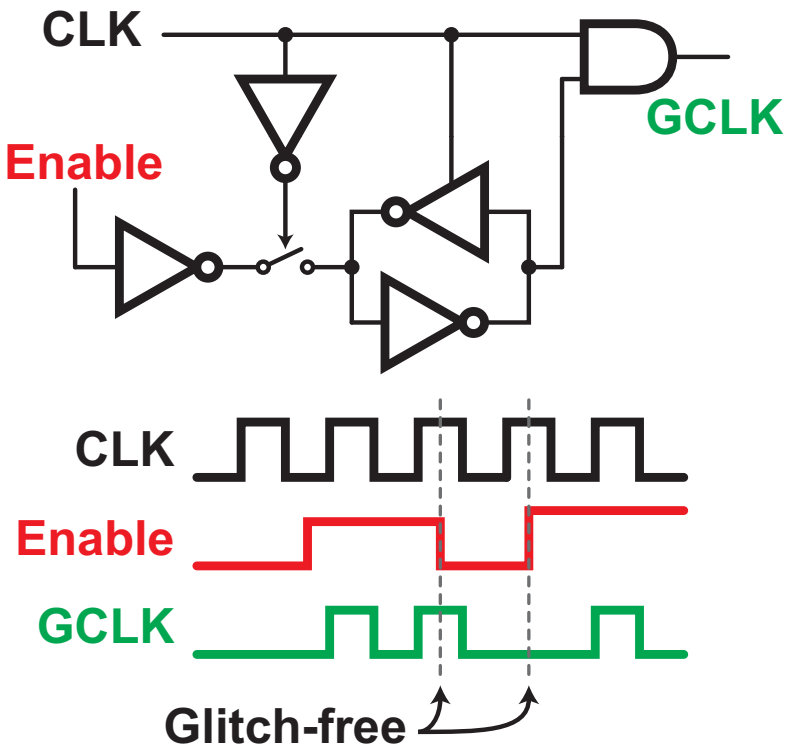
Decodes variable-length PPM data with PPM intervals from 31.2ns to 3993.6ns

Fine-Grained Circuit Gating Techniques for Power Reduction

Activity reduction of unused combinational logic by forcing zero inputs



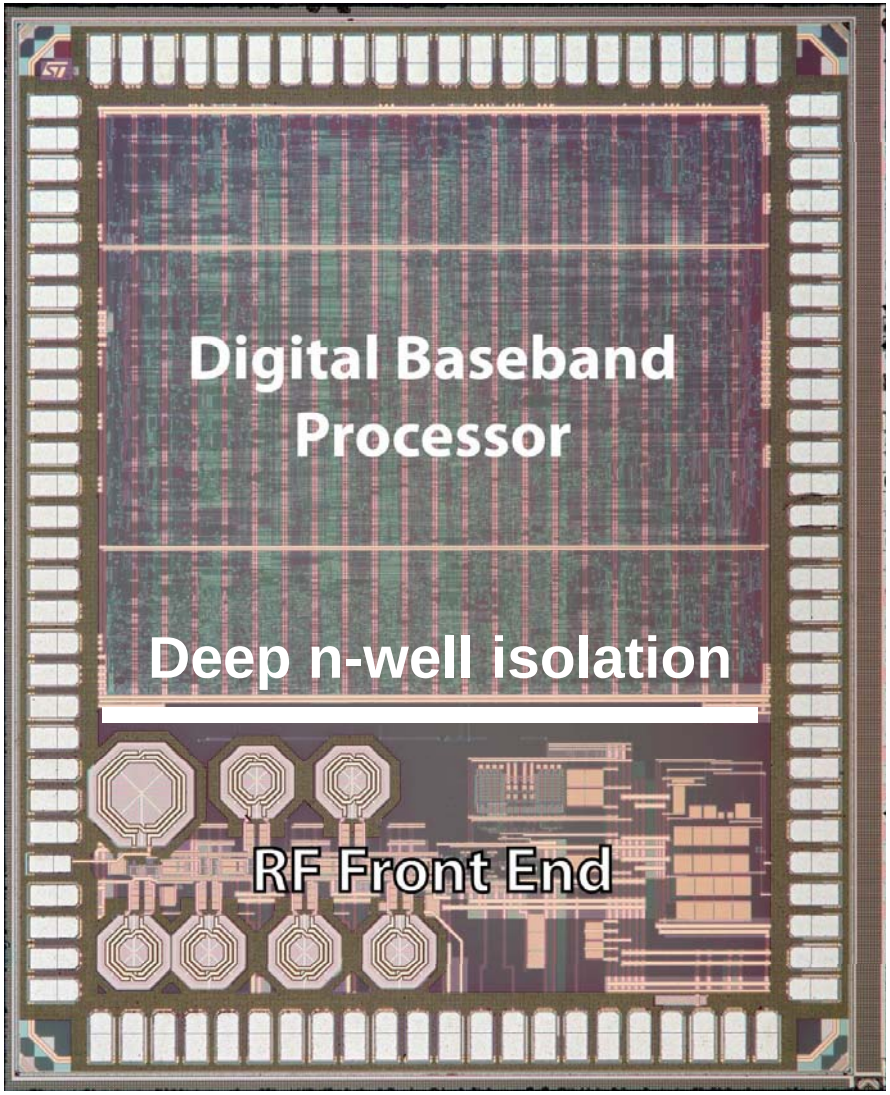
Clock gating unused blocks using a level sensitive latch



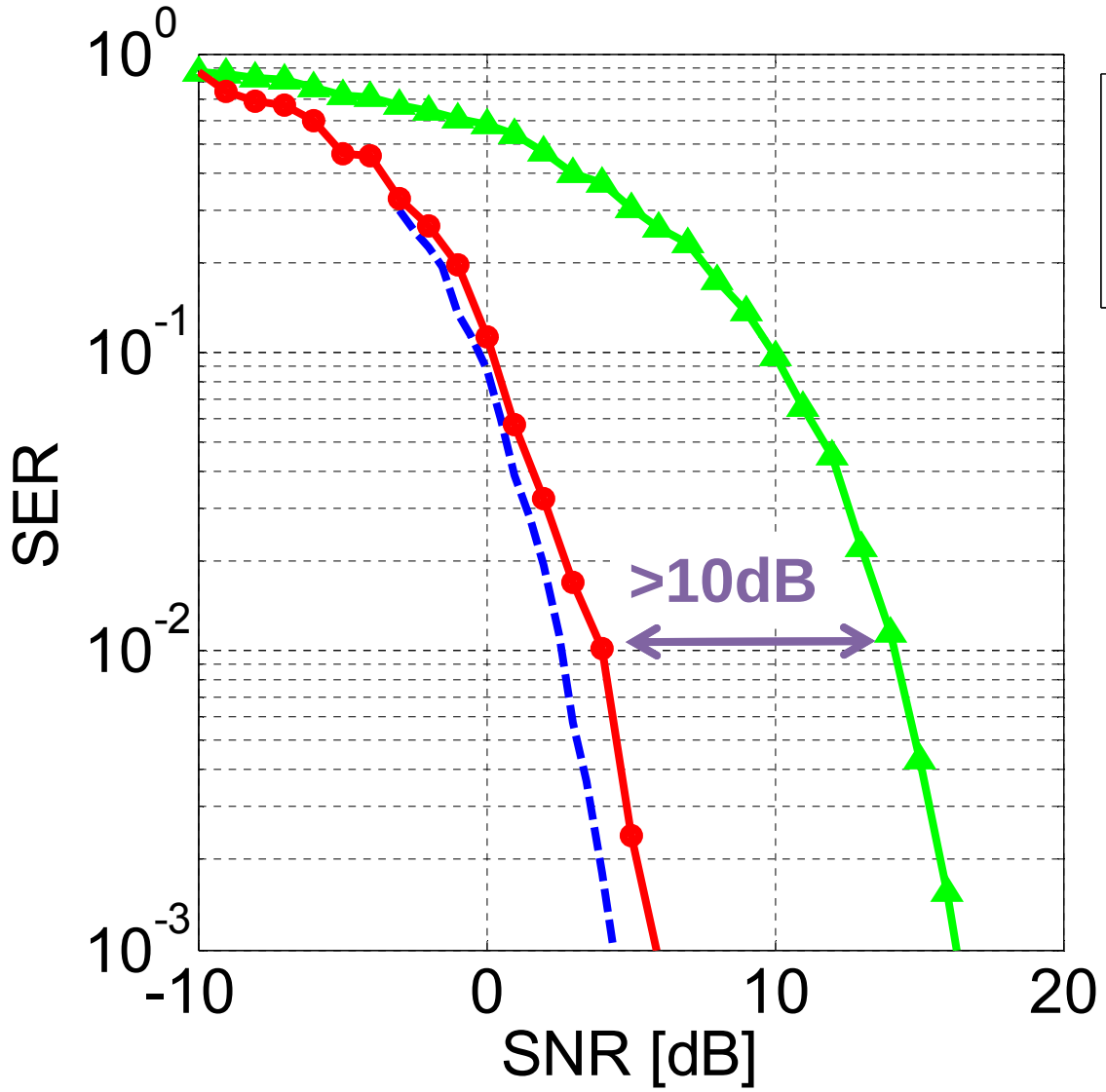
Saves 2.7X power in idle mode, up to 22X in active mode

Die Photo & Table of Resuts

Chip Summary	
Technology	90nm CMOS
Voltage supply (core, I/O)	0.55V, 1.2V
Core size	1.5x1.7mm^2
Clock frequency	32MHz
Max. data rate	16Mbps
Power & Energy	
Idle-mode power	129µW
Preamble lengths	14-to-79µs
Preamble energy	34-to-55nJ
Preamble power	0.7-to-2.4mW



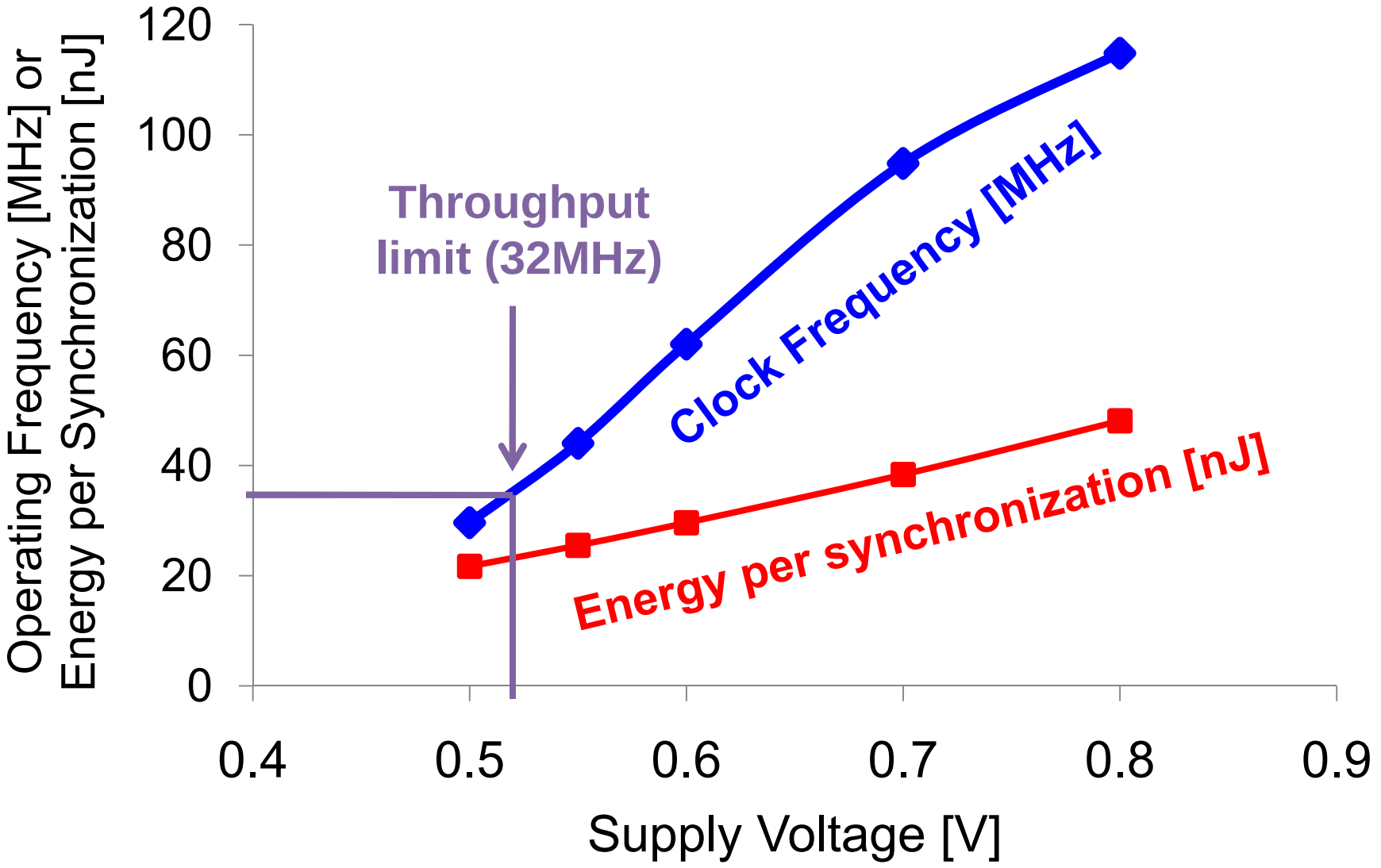
Measured Synchronization Error Rate (SER) for +/-1ns Synch. Accuracy



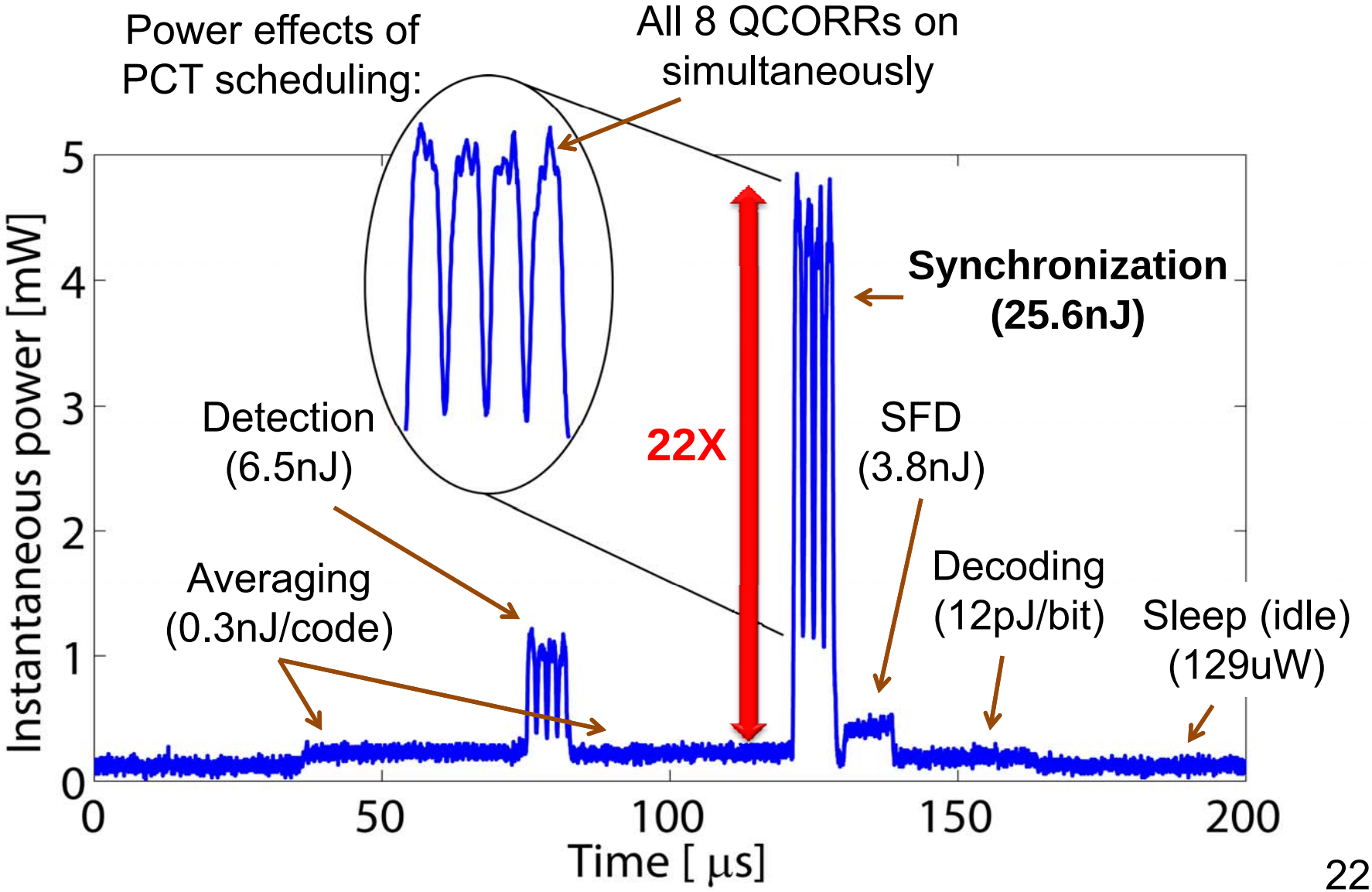
Repetition (simulated)
Optimum (simulated)
This work (measured)

- Less than **1.5dB** implementation loss over optimum ML receiver
- **11X** shorter synchronization than repetition-based receiver

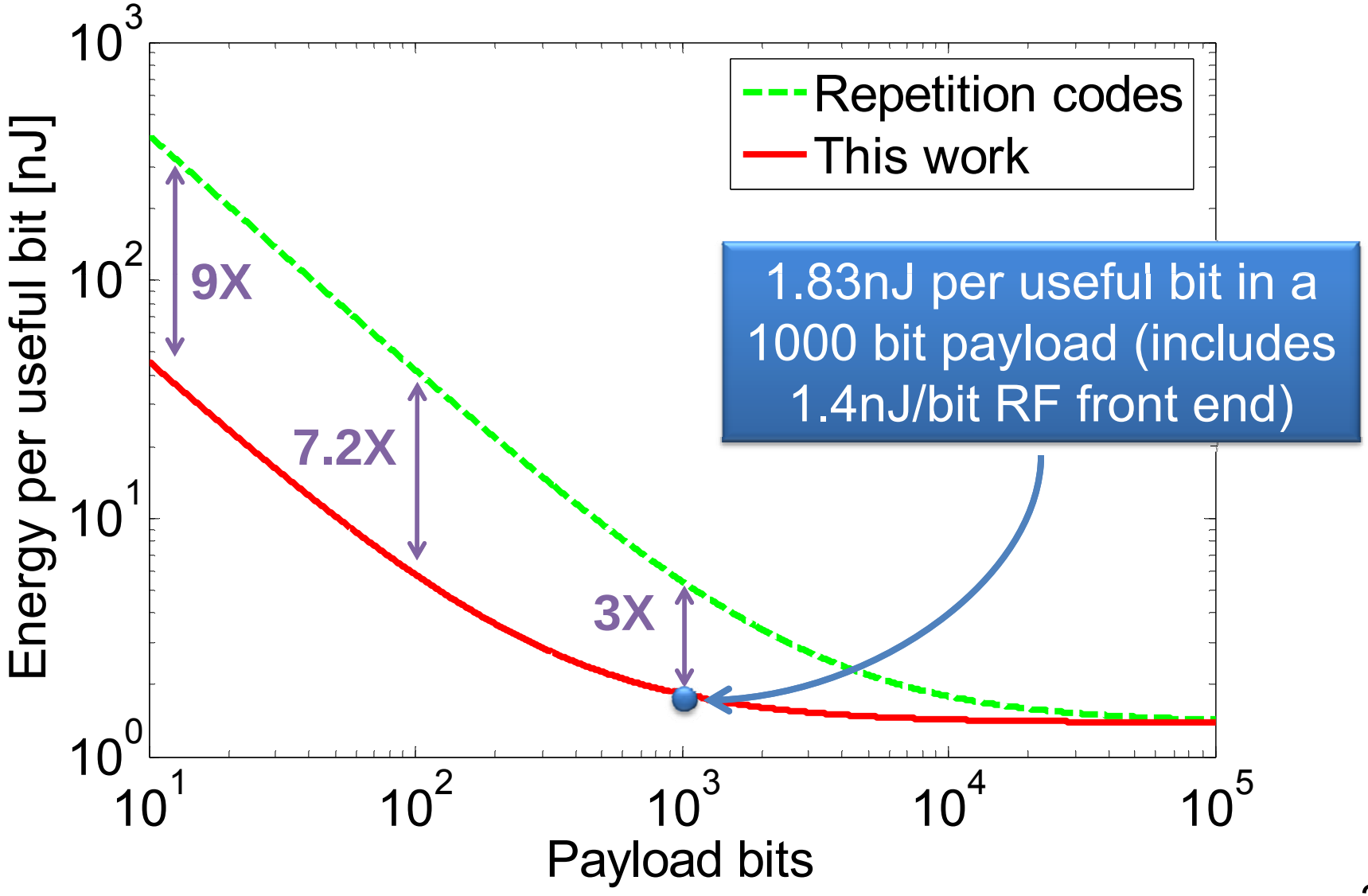
Voltage Scaling



Measured Power Management Results (V_{DD} = 0.55V)



Energy Per Useful Bit (EPUB)



Previous IR-UWB Basebands

	Yang, ISSCC 05	Blazquez, JSSC 06	Sze, ISLPED 07	Verhelst, JSSC 08	This work
Technology	0.18µm	0.18µm	90nm	0.13µm	**90nm**
V_{DD}	1.2V	1.8V	0.4V	0.95V	**0.55V**
Area	1.0mm^2	12mm^2	8.4mm^2	2.0mm^2	**2.6mm^2**
Data Rate	62.5Mb/s	193kb/s	100Mb/s	40Mb/s	**16Mb/s**
Decoding Type	Nyquist coherent MF	Nyquist coherent MF approx.	Nyquist coherent MF	Analog-correlation	**Energy-detecting QCORR**
ADC Resolution	1bit	4bits	5bits	4bits	**5bits**
Preamble Power (scaled)*	6.7mW (3.4mW)	75mW (38mW)	7mW	3.5mW (2.4mW)	**1.6mW**

* First order W/L scaling rules, normalized to 90nm CMOS

Conclusions

- **Alias-free codes enable high-accuracy non-coherent synchronization (±1ns) with a slow clock (32MHz)**
- **Quadratic correlation (QCORR) improves performance with non-linear receiver statistics**
- **Parallelism, scheduling, and power management techniques shorten synchronization time & power**
  - **Decrease system energy per useful bit**

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IC fabrication provided by ST Microelectronics