# SIPHER: Scalable Implementation of Primitives for Homomorphic EncRyption

## FPGA implementation using Simulink

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**Dave Cousins,**
**Kurt Rohloff, Rick Schantz: BBN**
{dcousins, krohloff, schantz,}@bbn.com
**Chris Peikert: Georgia Tech**
cpeikert@cc.gatech.edu

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# Outline

- Motivation for Fully Homomorphic Encryption
- Our encryption scheme and primitives
- Why use an FPGA, and why Simulink?
- Examples
- Where do we go next?

# What is Fully Homomorphic Encryption?

- DoD is excited about Cloud Computing, but needs *guaranteed* security!
  - Requirement: Send high-value data to an un-trusted second party for ***processing, not just storage***.
  - *No decryption of data allowed at any point!*
- Example:
  - Need to deconflict airspace for multiple missions, but cannot share the mission tracks due to security requirements (different countries involved).
- Theoretical breakthrough by Craig Gentry (IBM) 2009*
  - Presented the first Fully Homomorphic Encryption (FHE) scheme that allows "computation" on encrypted variables without intermediate decryption.
  - Computation means multiple individual operations (and/or) on encrypted data → we are very far from full "programs"
  - Led to a rapid development of improved techniques.

*C. Gentry. Fully Homomorphic Encryption Using Ideal Lattices. STOC, 2009.

# FHE comes with great cost!

- FHE schemes allow “unlimited” computation on encrypted data.
- Based on “computationally hard” stochastic lattice theory problems.
  - Stochastics introduce noise term that grows with the number of operations applied to the encrypted data.
    - Too much noise → can no longer decrypt the data.
    - Requires a recrypt ( “decryption/encryption”) operation built out of FHE operations to “clean” the intermediate results of noise.
  - Leads to a HUGE computational burden
    - Current benchmarks on workstation PC → 30 sec / gate.

# Our goal: Build an FHE co-processor

- Reduce the time necessary for FHE computation by
  - Using more efficient algorithms
  - Hardware implementation of FHE primitives using FPGA
- Our approach:
  - Define a “Somewhat” HE scheme
  - Specify a maximum number of operations on the data before noise growth makes decryption impossible.
  - No need for recrypt → Much less burdensome
  - Uses all the same primitives as FHE
- Do this in a flexible and scalable way so we can keep up with the theory

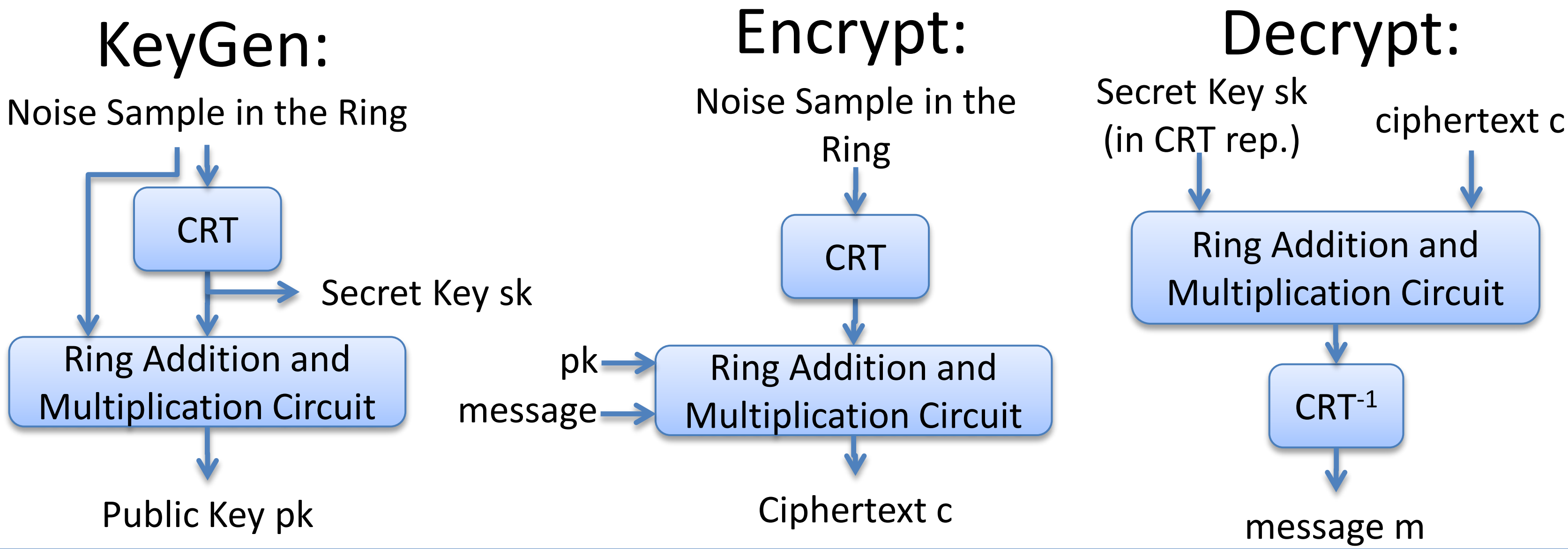
# Our chosen SHE scheme

- Based on “Learning with Errors over Rings”*
  - also stochastic lattice based
- Uses Chinese Remainder Transform (CRT) to simplify structure of “add” and “multiply” operations
  - Analogous to Fourier Transform pair: convolution ⇔ multiplication
- Formulation can encode and manipulate arrays of small integers or bits
  - Remainder of talk focuses on arrays of bits
  - Addition in the ring →XOR
  - Multiplication in the ring →AND
  - Can support unlimited # XOR, limited # AND operations

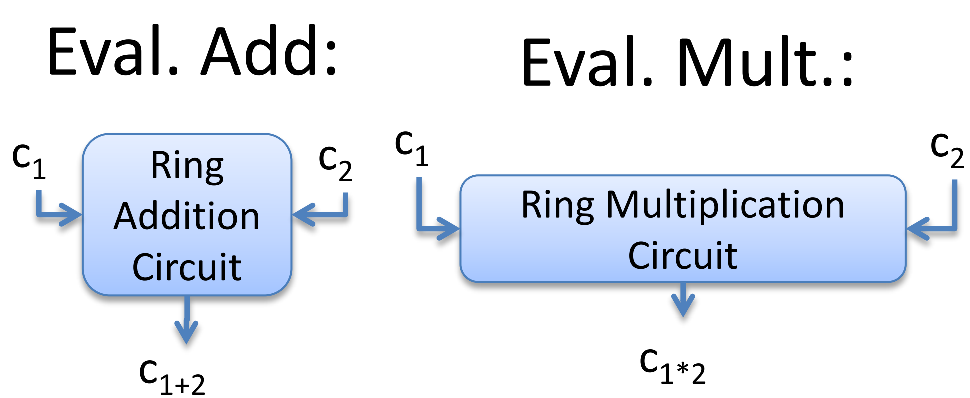
*V. Lyubashevsky, C. Peikert, and O. Regev. "On ideal lattices and learning with errors over rings". In Henri Gilbert, editor, Advances in Cryptology - EUROCRYPT 2010, V 6110 of Lecture Notes in Computer Science, Ch 1, PP 1-23. Springer Berlin / Heidelberg, Berlin.

# Baseline SHE Primitives

**Primitives that are done once**




**Primitives that are done multiple times**



# Why FPGA? Efficiency in computation!

- All primitives are computed on arrays modulo a large prime q
  - One selects the degree parameter (number of EvalMul operations supported) and a security parameter $\delta$ (encryption "hardness")
  - Generates parameters n (size of the plaintext vectors) and q.
- One bit encrypted into 2*width.q bits.
- Large bit-width modulo arithmetic is inefficient on a CPU

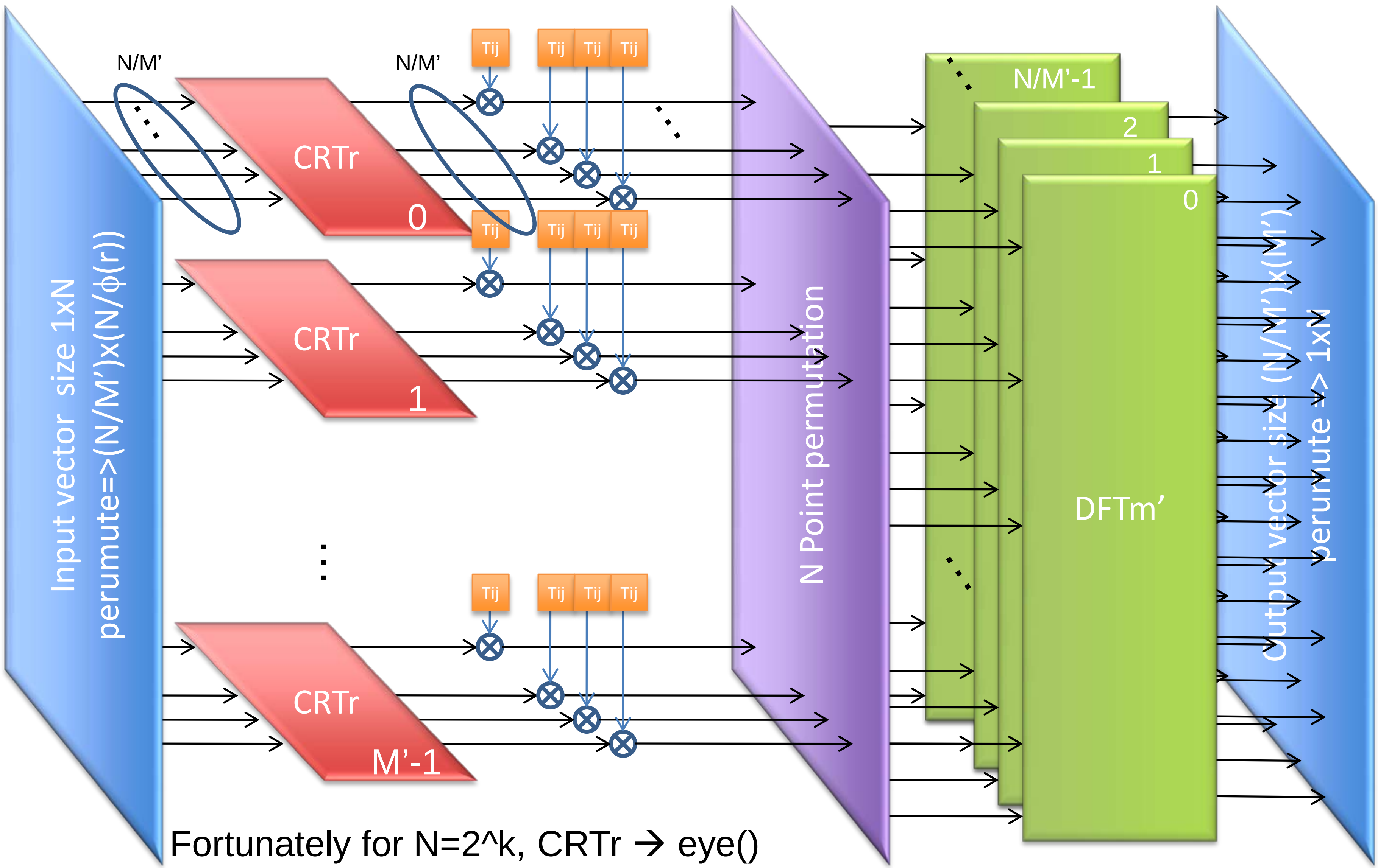
| Degree | Fair Encryption (SSN) | | Good Encryption (Credit Card) | |
|---|---|---|---|---|
| | n | q # bits | n | q # bits |
| 4 | 128 | 31 | 1024 | 37 |
| 5 | 256 | 41 | 1024 | 46 |
| 6 | 256 | 50 | 2048 | 59 |
| 7 | 256 | 58 | 2048 | 68 |
| 8 | 256 | 66 | 2048 | 78 |
| 9 | 512 | 79 | 2048 | 88 |

# Why Matlab/Simulink?

- Matlab fixed point library allows us to quickly code our SHE benchmarks in a high level language.
  - LWE uses "signal processing" constructs:
    - CRT for $n=2^k$ is based on FFT(x)%q
    - Noise selection uses discretized Gaussian random number pool
  - Theory is constantly being improved upon!
    - Our code life is about 3-4 months before new innovations require rewrite
- Simulink HDL coder lets us code our primitives directly in a data flow diagram, in parameterized form.
  - One diagram for all combinations of n and q
- Co-verification of the primitives in Matlab, Simulink and VHDL is easy!

# Example of Similarity with Signal Processing: CRT

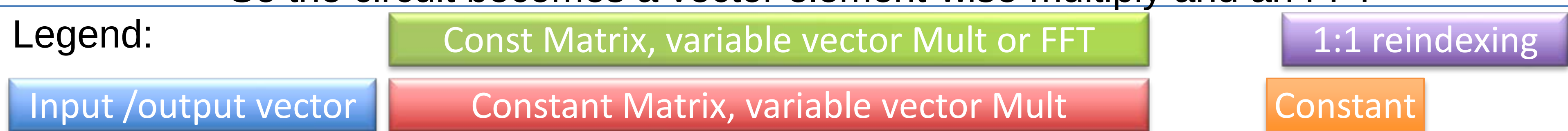




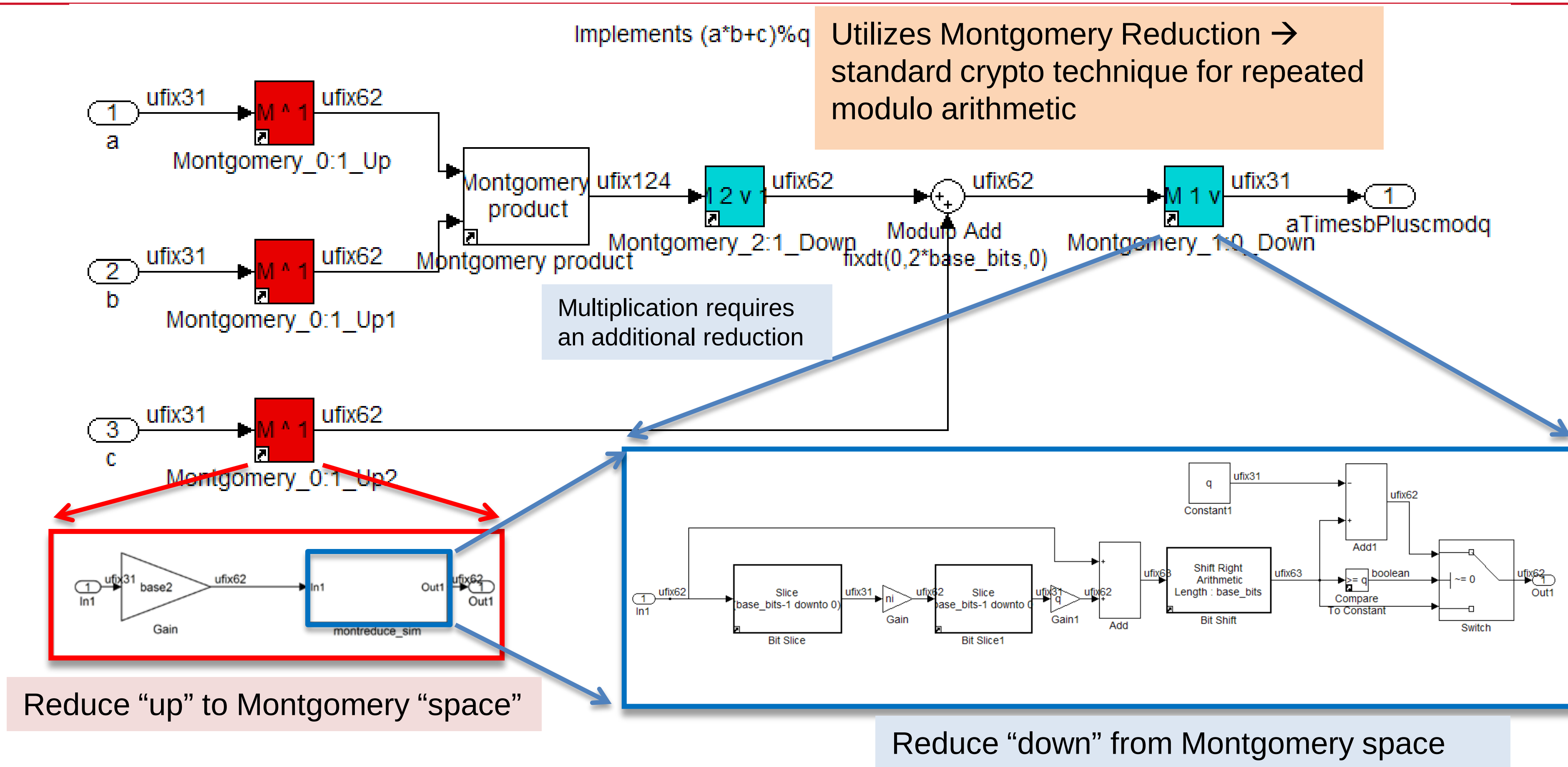

Fortunately for N=2^k, CRTr → eye()

So the circuit becomes a vector element-wise multiply and an FFT

Legend:



# Example: Simulink RingMultiplyAdd (a.*b+c)%q




- Montgomery reduction doubles required bit-width…
  …but now Product and Add are Simulink primitives with rounding set to "wrap" → no trial division needed for modulo
- Model is serialized, iterated for n values.

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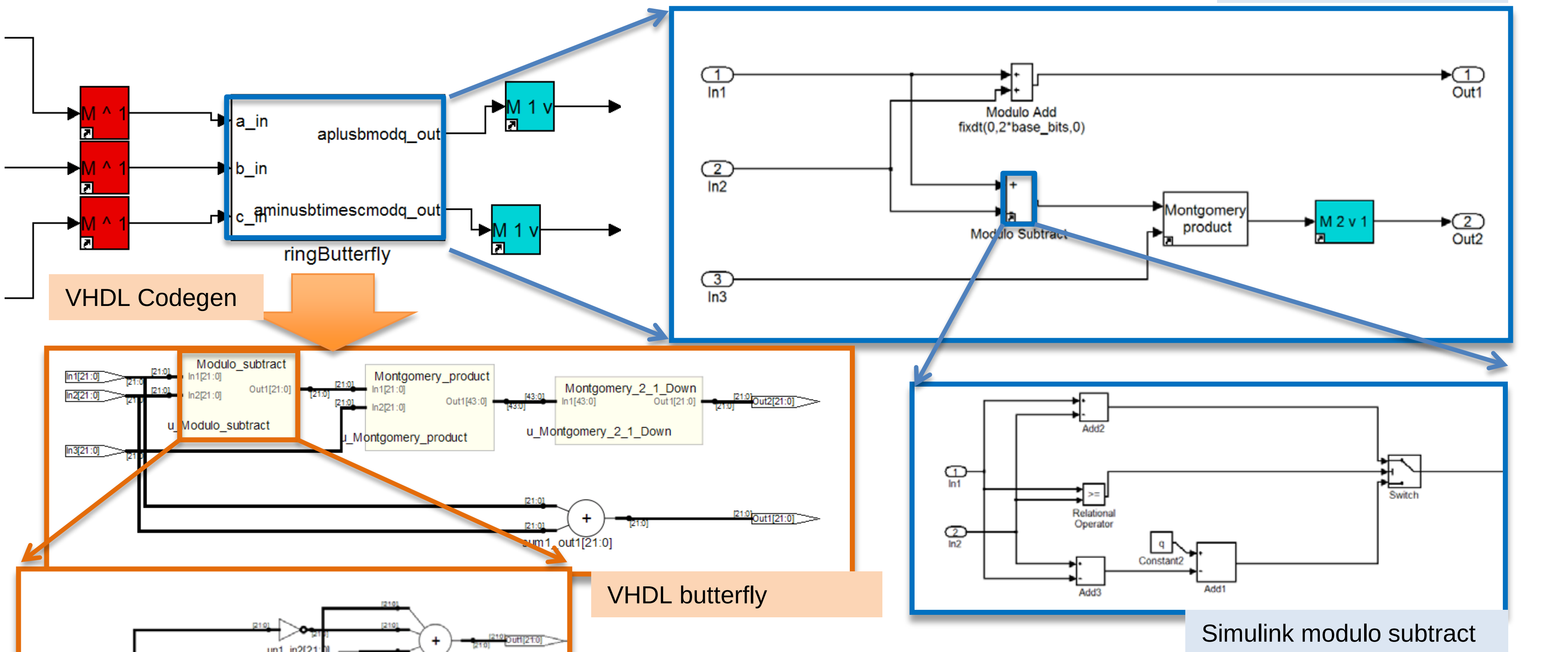
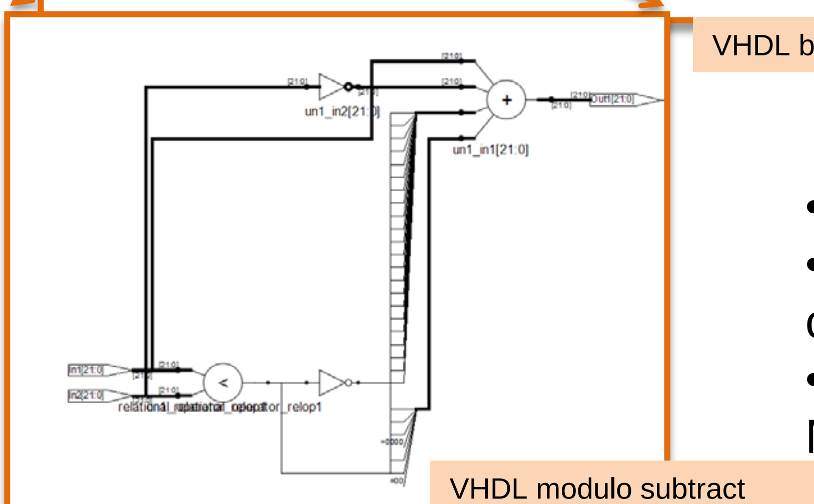
# Example: RingButterfly VHDL generation




- Butterfly is *the* core component of CRT (FFT)
- Simulink tools generated VHDL code that compiled in ACTEL tool chain unedited!
- Simulink generated test benches that ran in Modelsim unedited !

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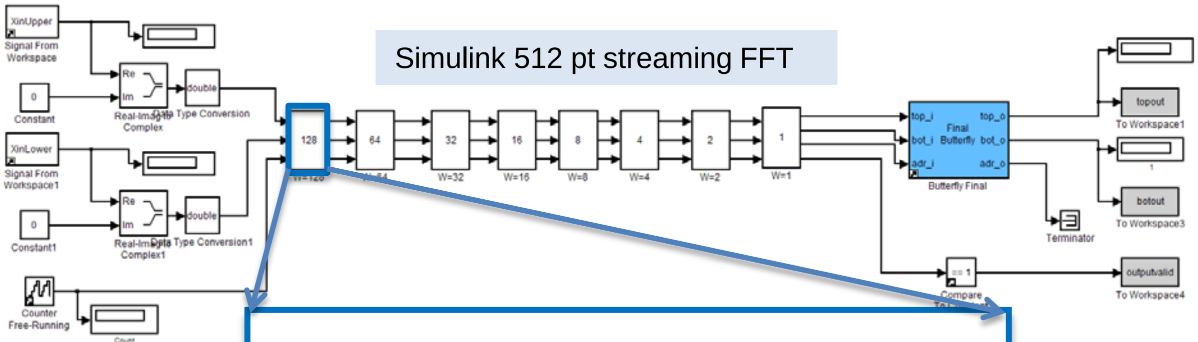
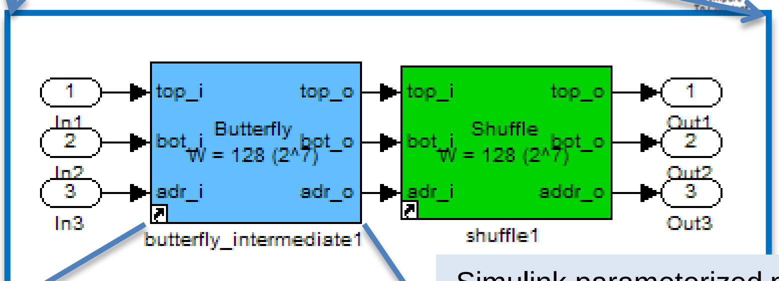
# Example: Pipelined FFT structure

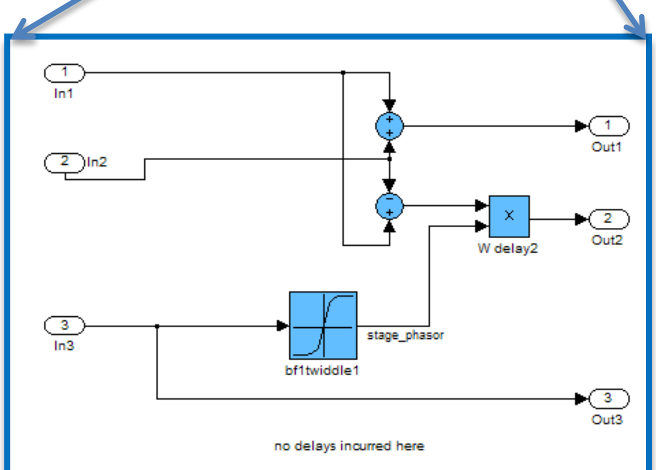
- Scalable radix 2 FFT is the basis for CRT
- Data streams in 2 points per clock cycle
- Can cascade stages for larger FFTs
- Each stage uses same library model with a different parameter



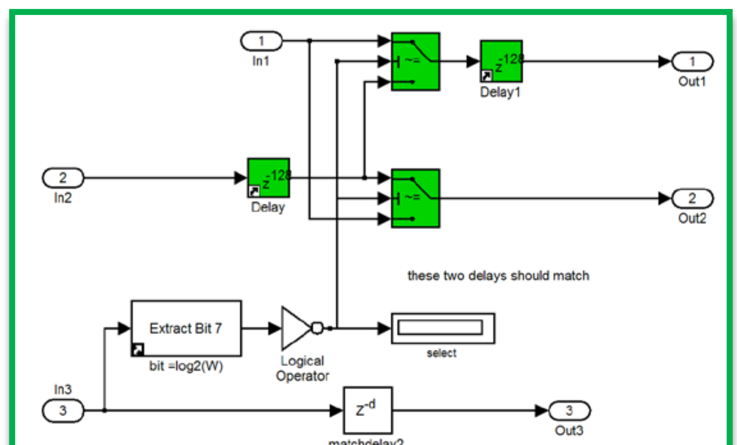

Simulink 512 pt streaming FFT




Simulink parameterized processing stage

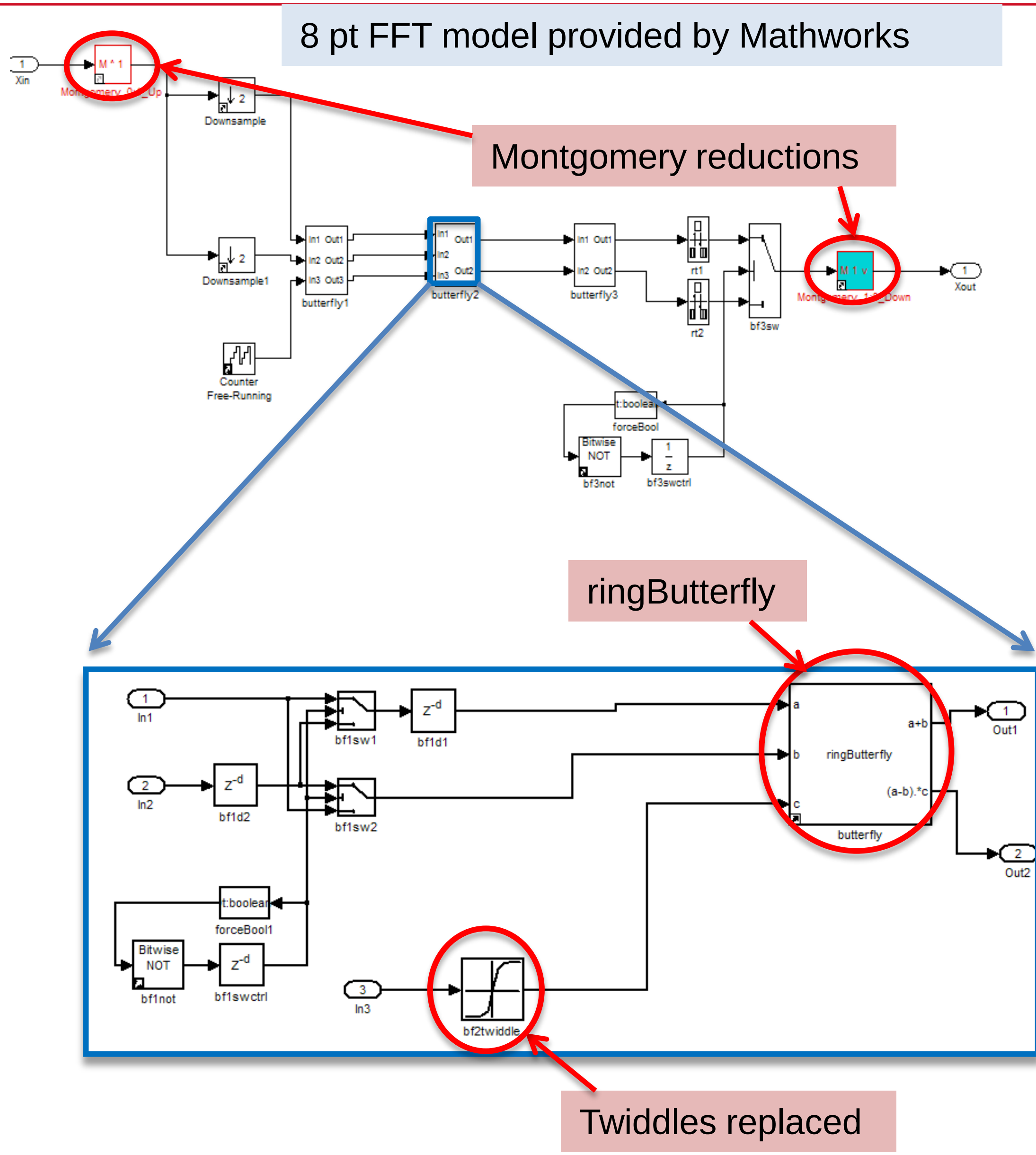



Simulink complex butterfly stage




Simulink shuffle stage

# Conversion from complex to ring arithmetic




- No major changes!!
  - Replace input variable with fixed point integers mod q
  - Twiddle factors replaced with modulo versions and stored in Montgomery form
  - Add Montgomery blocks to input and output
  - Complex butterfly block replaced with ringButterfly block
- Equivalent to mod(fft(x),q)

# Where do we go next?

- Go faster
  - Current primitives have no pipelining, so they are slow (e.g. butterfly has 88 ns cycle time on ACTEL A3PE)
    - typical of first cut code → get it to work right, then get it to work fast
  - Can use Simulink tools for adding pipelining
- Go bigger
  - Simulink is limited to 128 bit word widths.
    - Impacts multipliers in Montgomery Stages when q larger than 32 bits
    - Investigating Montgomery Multiplier (pipelined modulo multiply) and breaking multiplies into smaller chunks
  - Build full CRT and $CRT^{-1}$ models and register architecture
- Build in more functionality
  - Next year's goal is to build complete SHE processing unit on Xlinx FPGA
    - Registers, and simple ALU-like instruction set
  - Move towards FHE
    - Algorithms are constantly improving, reducing required computational load

# Special Thanks to the Mathworks Team

- Jeff Miller, Brian Ogilvie, Jared Schuler
- Mathworks second pilot program with BBN
  - First pilot program focused on Matlab to Blackfin code generation
- Taught us how to become “power users”
  - Provided sample code for Montgomery Methods using fixed point toolbox
  - Provided sample models for HDL friendly serialized Ring Ops and basic streaming FFT
  - (Bi)Weekly webconferences really bootstrapped our program