

VLSI Implementation of a Pipelined 128 points 4-Parallel radix-2³ FFT Architecture via Folding Transformation

James J. W. Kunst `jjwk89@gmail.com`

Kevin H. Viglianco `kevinviglianco@gmail.com`

Daniel R. Garcia `dani6rg@gmail.com`

July 22, 2020



Outline - Table of Contents

- 1 Introduction
- 2 The Radix-2³ FFT Algorithm
- 3 Design of FFT architecture via folding transformation
 - Parallel radix-2³ 16-Points
- 4 Implementation
 - Parallel radix-2³ 16-Points

Section 1

Introduction

Introduction

Introduction:

Objetives

- Design and implement a 4-parallel pipelined architecture for the Complex Fast Fourier Transform (CFFT) based on the radix-2³ algorithm with 128 points using folding transformation and register minimization techniques based on
- Frequency of implementation: 500MHz.
- Optimization with CSD^a multipliers.
- Test the design with a mixture of two sinusoids using MATLAB.
- Generate power-area-timing report with different optimizations.

^aCanonic Signed Digit

Introduction

Introduction:

Workflow

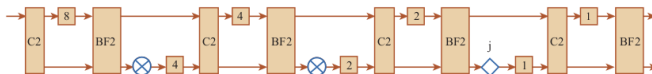
- 1 Obtain the equations that correspond to Butterfly structure of radix-2³ FFT for 8 points.
- 2 Apply this idea to design a 2-parallel pipelined architecture radix-2³ 16-points FFT via folding transformation.
- 3 Translate this to a 128-points model.
- 4 Elaborate a float-point simulator in Matlab of the 128-points.
- 5 Elaborate a synthesizable verilog code HDL and verify the DFT functionality.
- 6 Generates power-area-timing report with different optimizations.

Introduction

Introduction:

Types of pipelined Radix-2 FFT architectures

- 1 Feedforward Multi-Path Delay Commutator (MDC).
 - 2 Single-Path Delay Feedback architectures (SDF).
- Both butterflies and multipliers are in 50% utilization
 - The SDF use registers more efficiently.
 - We will focus on the feedforward MDC architecture.



(1) . R2MDC(N-16)



(2) . R2SDF(N-16)

Section 2

The Radix-2³ FFT Algorithm

The Radix-2³ FFT Algorithm

The Radix-2³ FFT Algorithm:

N-point DFT of an input sequence $x[n]$

$$X[k] = \sum_{n=0}^{N-1} x[n] \cdot W_N^{nk}, \quad k = 0, 1, \dots, N-1 \quad (1)$$

where $W_N^{nk} = e^{-j\frac{2\pi}{N}nk}$.

- Direct computation of the DFT is inefficient because it does not exploit the properties of:
 - ① Symmetry: $W_N^{k+N/2} = -W_N^k$
 - ② Periodicity: $W_N^{k+N} = W_N^k$
- The FFT based on Cooley-Tukey algorithm reduce the number of operations from $O(N^2)$ for the DFT to $O(N \log_2 N)$ for the FFT.

The Radix-2³ FFT Algorithm

The Radix-2³ FFT Algorithm:

Divide and Conquer approach

- We can calculate the DFT in series of $s = \log_{\rho} N$ stages, where ρ is the base of the *radix*.
- This is based on the decomposition of an N point DFT into successively smaller DFTs.
- In our case, the number of stages is:

$$s = \log_2(128) = 7 \quad (2)$$

Methods to design FFT algorithms

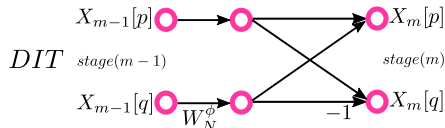
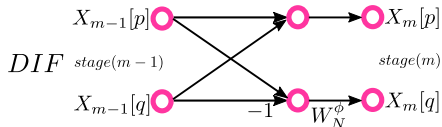
- 1 **Decimation In Time (DIT):** Splitting successively data sequence $x[n]$ by a factor of 2.
- 2 **Decimation In Frequency (DIF):** Splitting successively the data sequence $X[k]$ by a factor of 2.

The Radix-2³ FFT Algorithm

The Radix-2³ FFT Algorithm:

DIT and DIF Butterflies

The difference is the instant in which the multiplication by W_N^ϕ is accomplished.

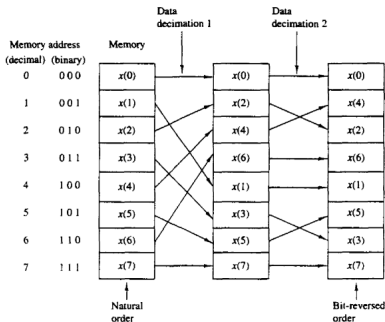


The Radix-2³ FFT Algorithm

The Radix-2³ FFT Algorithm:

Order of samples in DIT and DIF

- The input samples in FFT algorithms DIF are organized in natural order but its output has not in order.
- The opposite is for DIT.



Order of inputs and outputs for DIF FFT.

The Radix-2³ FFT Algorithm

The Radix-2³ FFT Algorithm:

Mathematic expression of radix-8 butterfly element

$$C_{8k+0} = \sum_{n=0}^{N/8-1} \left\{ [(x_n + x_{n+\frac{N}{2}}) + (x_{n+\frac{N}{4}} + x_{n+\frac{3N}{4}})] + [(x_{n+\frac{N}{8}} + x_{n+\frac{5N}{8}}) + (x_{n+\frac{3N}{8}} + x_{n+\frac{7N}{8}})] \right\} W_N^{0n} W_{N/8}^{nk}$$

$$C_{8k+4} = \sum_{n=0}^{N/8-1} \left\{ [(x_n + x_{n+\frac{N}{2}}) + (x_{n+\frac{N}{4}} + x_{n+\frac{3N}{4}})] - [(x_{n+\frac{N}{8}} + x_{n+\frac{5N}{8}}) + (x_{n+\frac{3N}{8}} + x_{n+\frac{7N}{8}})] \right\} W_N^{4n} W_{N/8}^{nk}$$

$$C_{8k+2} = \sum_{n=0}^{N/8-1} \left\{ [(x_n + x_{n+\frac{N}{2}}) - (x_{n+\frac{N}{4}} + x_{n+\frac{3N}{4}})] - j[(x_{n+\frac{N}{8}} + x_{n+\frac{5N}{8}}) - (x_{n+\frac{3N}{8}} + x_{n+\frac{7N}{8}})] \right\} W_N^{2n} W_{N/8}^{nk}$$

$$C_{8k+6} = \sum_{n=0}^{N/8-1} \left\{ [(x_n + x_{n+\frac{N}{2}}) - (x_{n+\frac{N}{4}} + x_{n+\frac{3N}{4}})] + j[(x_{n+\frac{N}{8}} + x_{n+\frac{5N}{8}}) - (x_{n+\frac{3N}{8}} + x_{n+\frac{7N}{8}})] \right\} W_N^{6n} W_{N/8}^{nk}$$

$$C_{8k+1} = \sum_{n=0}^{N/8-1} \left\{ [(x_n - x_{n+\frac{N}{2}}) - j(x_{n+\frac{N}{4}} - x_{n+\frac{3N}{4}})] + W_N^{N/8} [(x_{n+\frac{N}{8}} - x_{n+\frac{5N}{8}}) - j(x_{n+\frac{3N}{8}} - x_{n+\frac{7N}{8}})] \right\} W_N^n W_{N/8}^{nk}$$

$$C_{8k+5} = \sum_{n=0}^{N/8-1} \left\{ [(x_n - x_{n+\frac{N}{2}}) - j(x_{n+\frac{N}{4}} - x_{n+\frac{3N}{4}})] - W_N^{N/8} [(x_{n+\frac{N}{8}} - x_{n+\frac{5N}{8}}) - j(x_{n+\frac{3N}{8}} - x_{n+\frac{7N}{8}})] \right\} W_N^{5n} W_{N/8}^{nk}$$

$$C_{8k+3} = \sum_{n=0}^{N/8-1} \left\{ [(x_n - x_{n+\frac{N}{2}}) + j(x_{n+\frac{N}{4}} - x_{n+\frac{3N}{4}})] + W_N^{3N/8} [(x_{n+\frac{N}{8}} - x_{n+\frac{5N}{8}}) + j(x_{n+\frac{3N}{8}} - x_{n+\frac{7N}{8}})] \right\} W_N^{3n} W_{N/8}^{nk}$$

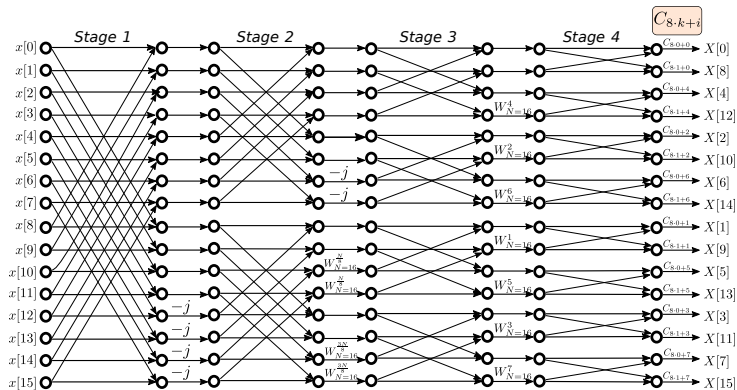
$$C_{8k+7} = \sum_{n=0}^{N/8-1} \left\{ [(x_n - x_{n+\frac{N}{2}}) + j(x_{n+\frac{N}{4}} - x_{n+\frac{3N}{4}})] - W_N^{3N/8} [(x_{n+\frac{N}{8}} - x_{n+\frac{5N}{8}}) + j(x_{n+\frac{3N}{8}} - x_{n+\frac{7N}{8}})] \right\} W_N^{7n} W_{N/8}^{nk}$$

The Radix-2³ FFT Algorithm

The Radix-2³ FFT Algorithm:

Radix-2^k Implementation

The quantity of rotators of an architecture radix-2^k (with $k > 1$) is less than the radix-2.



Flow graph of a radix-2³ 16-point DIF DFT.

The Radix-2³ FFT Algorithm

The Radix-2³ FFT Algorithm:

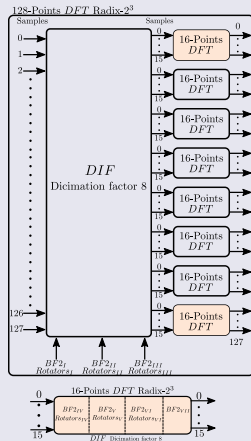
The Radix-2³ FFT Algorithm

- Applying (12) for the 128 point DFT and calculating each coefficient for $k = 0, 1, \dots, (128/8) - 1$:

$$C_{8k+i} = \sum_{n=0}^{128/8-1} \{ \cdot \}$$

We get a sequence in chain of butterflies with its corresponding rotation factor.

- The 128 point DFT goes through a processes that involve tree stages of butterflies to arrive finally to a set of eight DFT where each of one is a 16 point DFT.



Section 3

Design of FFT architecture via folding transformation

Design of FFT architecture via folding transformation

Design of FFT architecture via folding transformation: Parallel radix-2³ 16-Points

Folding Set

- Is an ordered set of operations executed by the same functional unit.
- Each folding set contains K entries, where K is called the folding factor.
- The operation in the j th position (where goes from 0 to $K-1$) is called the folding order.

Folding Equations

- Consider an edge e connecting the nodes U and V with $w(e)$ delays.
- The executions of the l th iteration of U and V are scheduled at the time units $Kl + u$ and $Kl + v$ respectively, where u and v are the folding orders of the nodes U and V .
- The folding equation for the edge e is:

$$D_F(U \rightarrow V) = Kw(e) - P_U + v - u \quad (3)$$

where P_U is the number of pipeline stages in the node U .

Design of FFT architecture via folding transformation

Design of FFT architecture via folding transformation: Parallel radix-2³ 16-Points

Folding equations without retiming/pipeline

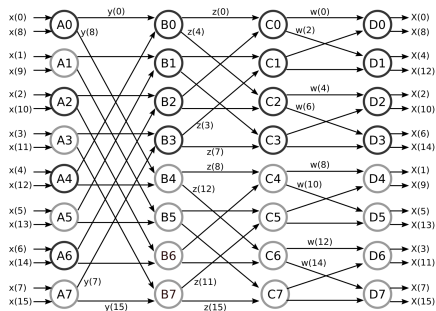
- Consider the folding sets:

$$\begin{aligned} A &= \{A_0, A_2, A_4, A_6\} & A' &= \{A_1, A_3, A_5, A_7\} \\ B &= \{B_1, B_3, B_5, B_7\} & B' &= \{B_0, B_2, B_4, B_6\} \\ C &= \{C_2, C_1, C_3, C_0\} & C' &= \{C_6, C_5, C_7, C_4\} \\ D &= \{D_3, D_0, D_2, D_1\} & D' &= \{D_7, D_4, D_6, D_5\} \end{aligned}$$

- For example:

$$\begin{aligned} D_F(D_3 \rightarrow B_3) &= v - u \\ &= 0 - 1 \\ &= -1 \end{aligned}$$

- The folding equations can be derived for all edges.



DFG of a radix-2³ 16-point DIF DFT.

Design of FFT architecture via folding transformation

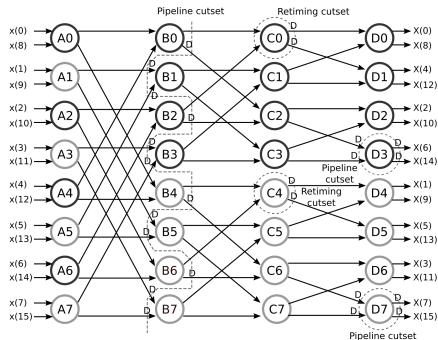
Design of FFT architecture via folding transformation: Parallel radix-2³ 16-Points

Folding equations with retiming/pipeline

- For the folded system to be realizable, $D_F(U \rightarrow V) \geq 0$ must hold for all the edges.
- For example:

$$\begin{aligned} D_F(D3 \rightarrow B3) &= Kw(e) + v - u \\ &= 4(1) + 0 - 1 \\ &= 3 \end{aligned}$$

- This result $D_F(U \rightarrow V) \geq 0$ for all the edges.
- Applying the folding equations for all the edges, the number of registers required is 80.



DFG of a radix-2³ 16-point DIF DFT applying pipeline and retiming.

Design of FFT architecture via folding transformation

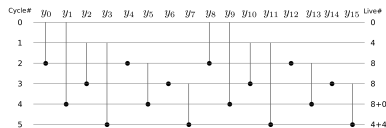
Design of FFT architecture via folding transformation: Parallel radix-2³ 16-Points

Lifetime analysis

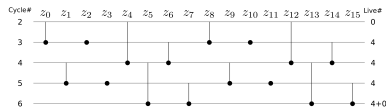
- Is a procedure used to compute the minimum number of registers.
- For example, the variable y_1 be live during time units $n \in \{1, 2, 3, 4\}$.
- The number of live variables y_i during the time units $\{1, 2, 3, 4, 5\}$ is $\{4, 8, 8, 8, 4\}$. So the number of register for this stage is:

$$\max\{4, 8, 8, 8, 4\} = 8$$

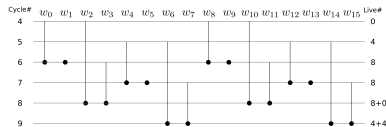
- The total number of registers is reduced from 80 to 20.



Lifetime chart for stage 1.



Lifetime chart for stage 2.



Lifetime chart for stage 3.

Design of FFT architecture via folding transformation

Design of FFT architecture via folding transformation: Parallel radix-2³ 16-Points

Forward Register Allocation

- This dictates how the variables are assigned to the minimum numbers of registers.
- If R_i holds a variable in the current cycle, then R_{i+1} hold the same variable on the next cycle.

	I/P	R1	R2	R3	R4	R5	R6	R7	R8
0	y0,y8,y1,y9								
1	y2,y10,y3,y11	y1		y0		y9		y8	
2	(y4)y12,y5,y13	y3	y1	y2	(y0)	y11	y9	y10	(y8)
3	(y6)y14,y7,y15	y5	y3	y1	(y2)	y13	y11	y9	(y10)
4		y7	(y5)	y3	(y1)	y15	y13	y11	(y9)
5			(y7)		(y3)	(y15)		(y11)	

Allocation table for stage 1.

	I/P	R1	R2	R3	R4
2	z0,z4,z8,z12				
3	(z2)z6,(z10)z14	z4	(z0)	z12	(z8)
4	z1,z5,z9,z13	(z6)	(z4)	(z14)	(z12)
5	(z3)z7,(z11)z15	z5	(z1)	z13	(z9)
6		(z7)	(z5)	(z15)	(z13)

Allocation table for stage 2.

	I/P	R1	R2	R3	R4	R5	R6	R7	R8
4	w0,w2,w8,w10								
5	w4,w6,w12,w14	w2		w0		w10		w8	
6	(w1)w3,(w9)w11	w6	w2	w4	(w0)	w14	w10	w12	(w8)
7	(w5)w7,(w13)w15	w3	w6	w2	(w4)	w11	w14	w10	(w12)
8		w7	(w3)	w6	(w2)	w15	(w11)	w14	(w10)
9			(w7)		(w6)		(w15)		(w14)

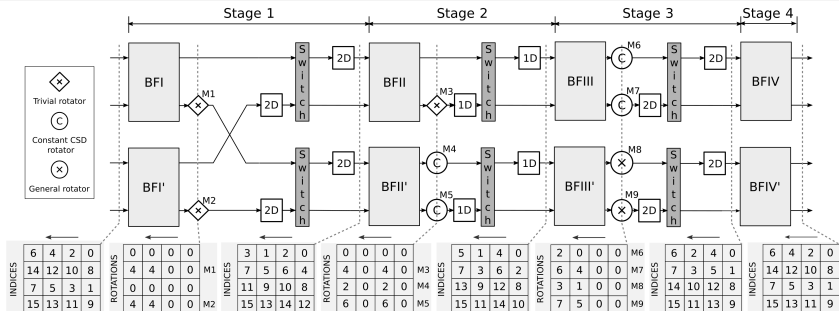
Allocation table for stage 3.

Design of FFT architecture via folding transformation

Design of FFT architecture via folding transformation: Parallel radix-2³ 16-Points

Folding architecture for radix-2³ 16 points FFT

- The values in the same column are data that flow in parallel and values in the same row flow through the same path in consecutive clock cycles.
- For the rotator matrix, each number k of the matrix represent a multiplication by W_N^k .

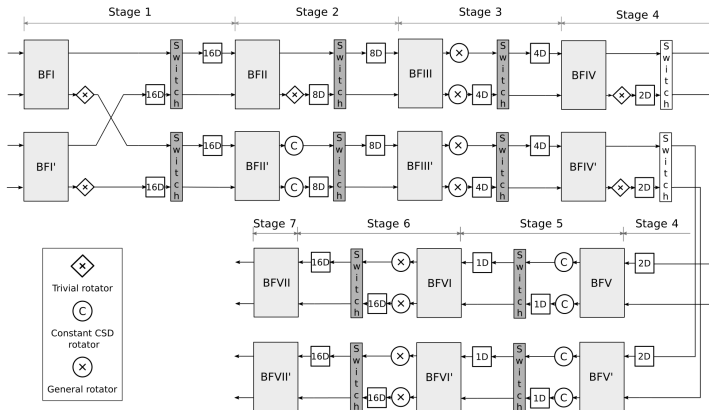


Folding architecture for radix-2³ 16 points FFT.

Design of FFT architecture via folding transformation

Design of FFT architecture via folding transformation: Parallel radix-2³ 16-Points

We can deduce the folding architecture for 128 points radix-2³ following the same method.



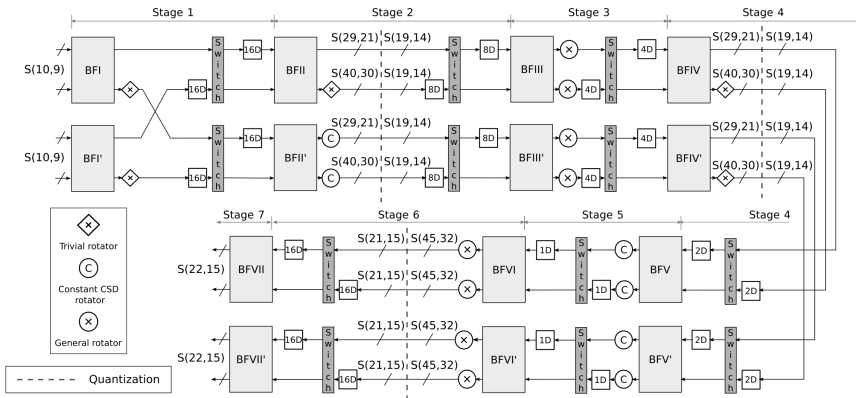
Folding architecture for radix-2³ 128 points FFT.

Section 4

Implementation

Design of FFT architecture via folding transformation

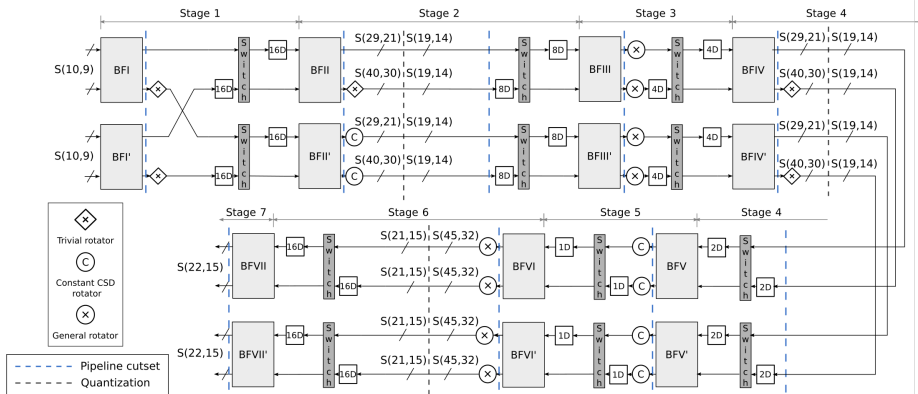
Implementation: Parallel radix-2³ 16-Points



Folding architecture for radix-2³ 128 points FFT with quantization.

Design of FFT architecture via folding transformation

Implementation: Parallel radix- 2^3 16-Points



Folding architecture for radix- 2^3 128 points FFT with quantization and pipeline.

Thanks!