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Evaluating the Impact of Interconnections in Quantum-dot Cellular Automata (QCA)

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Outline



- Motivation
- Design Automation
- Analysis Environment
- Results
- Conclusions

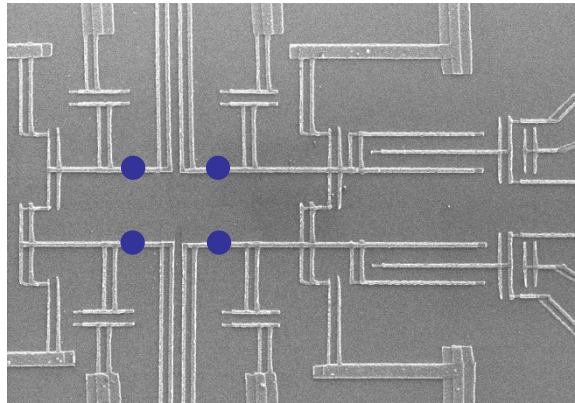


Motivation

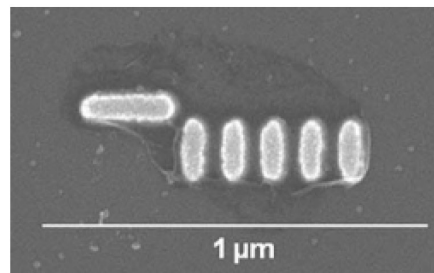


Quantum-dot Cellular Automata (QCA)

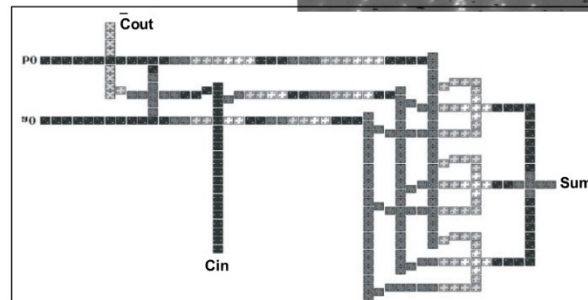
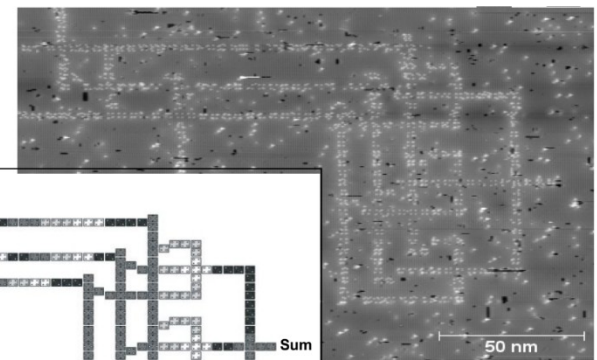
- Promising nanotechnology based on **quantum dots**
- Remarkable **low energy** dissipation
- Several (experimental) **physical realizations** based on different concepts (Metal islands, nanomagnets, dangling bonds, ...)



Metal islands



Nanomagnets



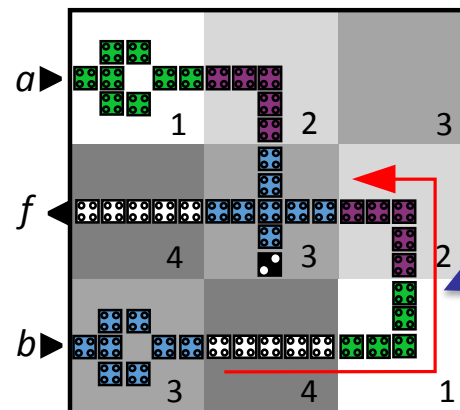
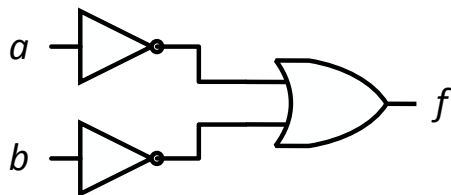
Dangling bonds

Motivation



Interconnections

- Challenging routing in QCA
 - QCA is (nearly) **planar technology**
 - Current state: 1 layer for logic & routing, 1 layer for crossings
 - Outlook: low amount of layers
 - Data flow must follow **clocking constraint** (clock 1 \rightarrow clock 2 \rightarrow clock 3 \rightarrow ...)
 - Only **orthogonal** routing
- Simple example:



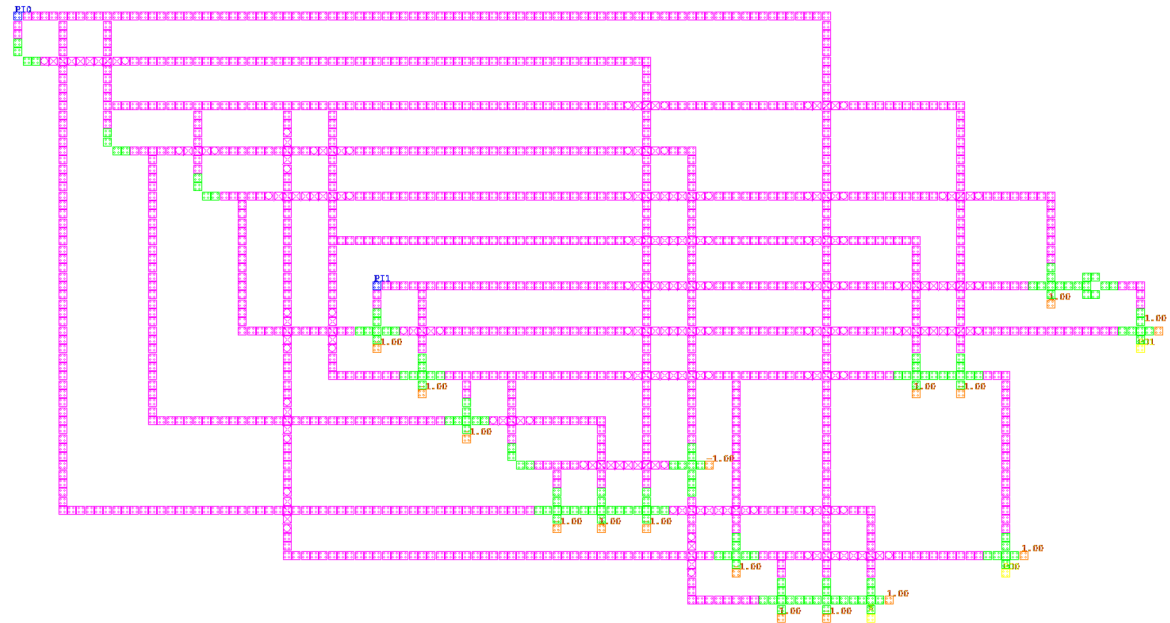
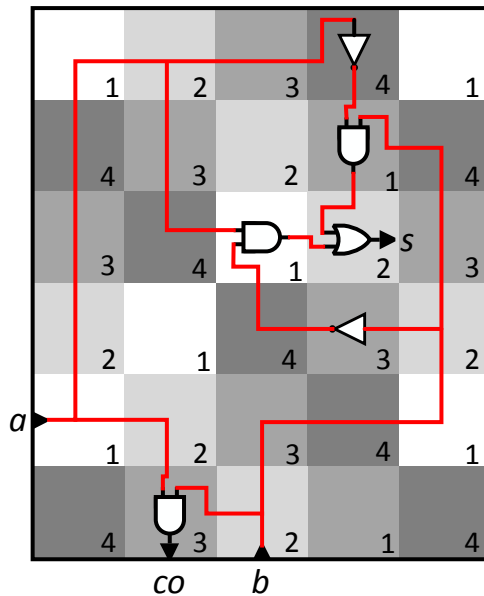
Routing overhead

Motivation



Interconnections cont'd

- More complex design

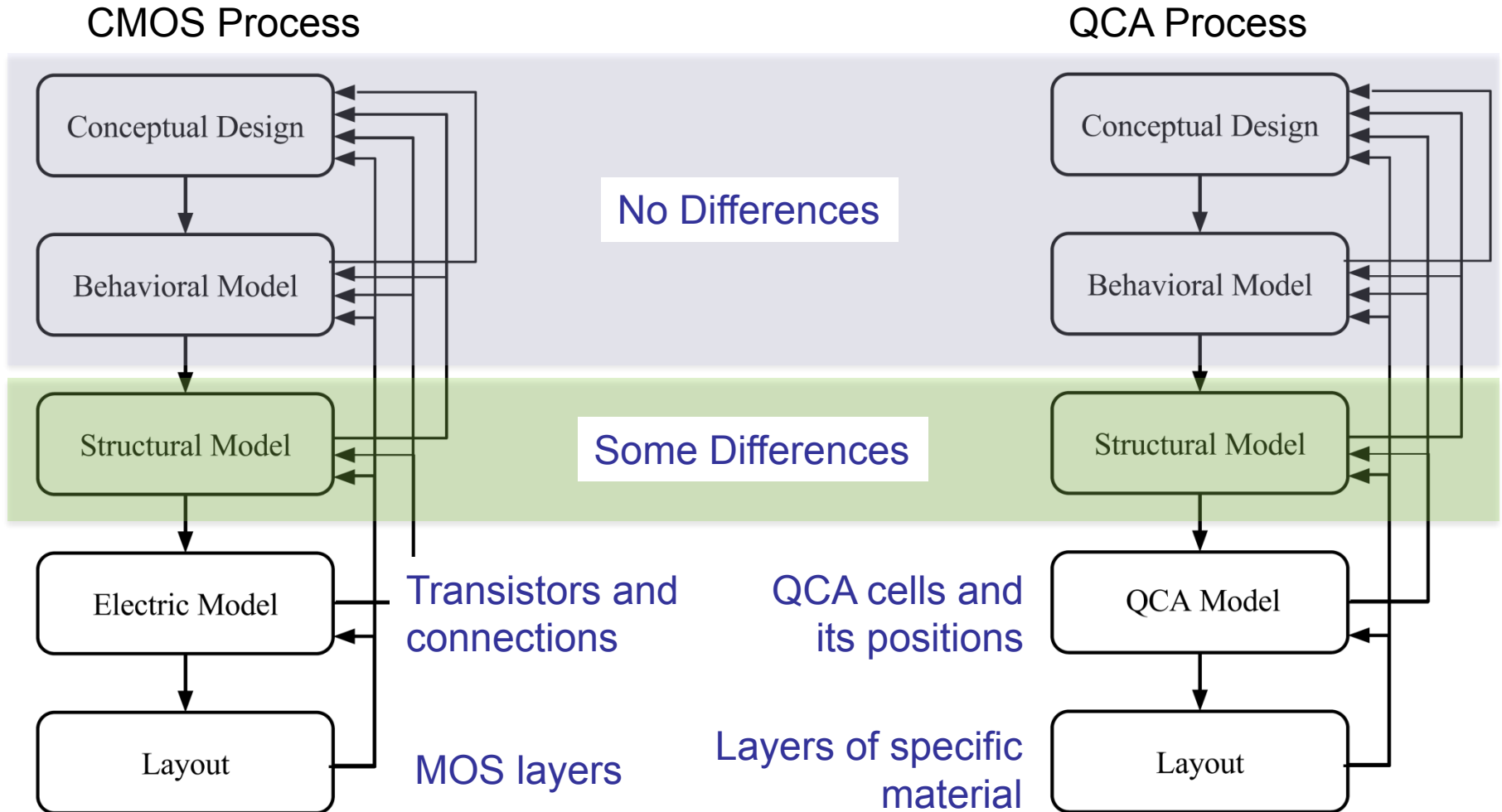


- Interconnections with notable impact on Area, Delay, Energy increase
- Question: **What is the actual impact?**

Design Automation



Comparison



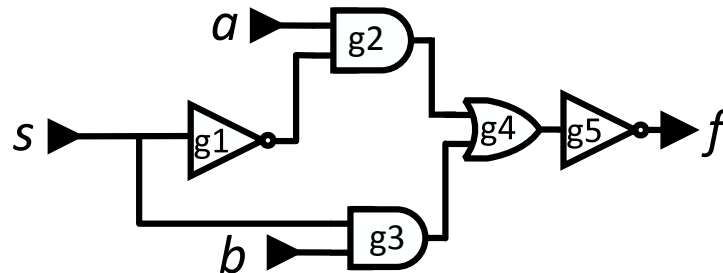
Design Automation



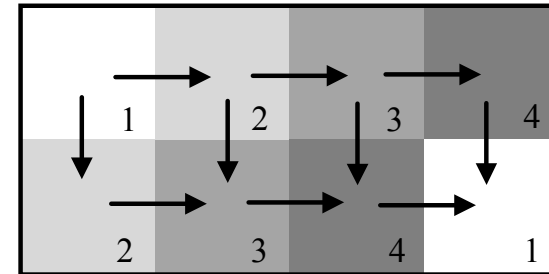
Principal Flow

```
if a > 0 then
  ergebnis := (a + b/2);
else
  ergebnis := -(a + b/2);
end if;
```

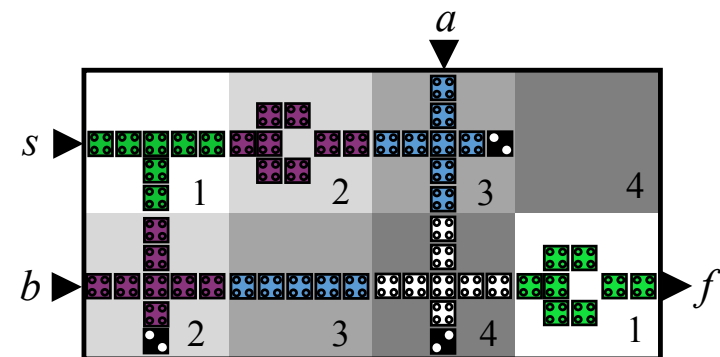
HDL Description



Netlist



Tile (clock zone) grid



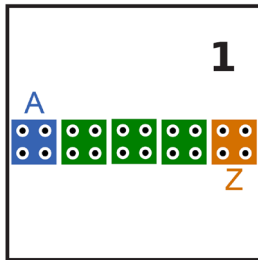
Layout

Design Automation

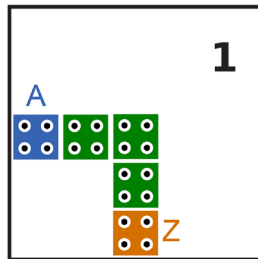


Gate Library

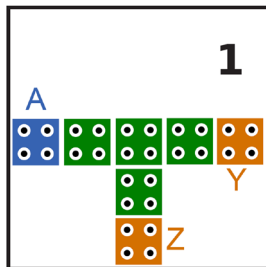
Routing Elements



Wire

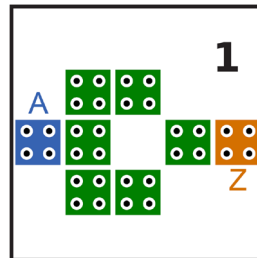


Bent wire

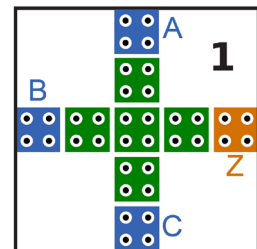


Fanout

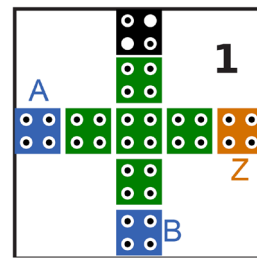
Simple Gates



Inverter

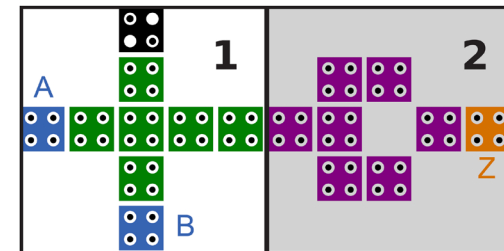


Majority

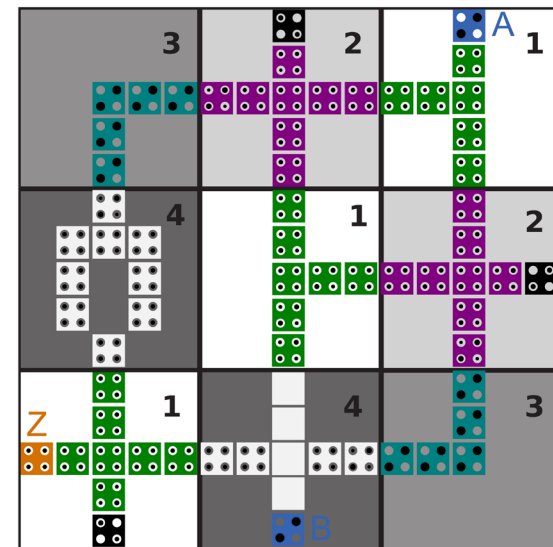


OR

Complex Gates



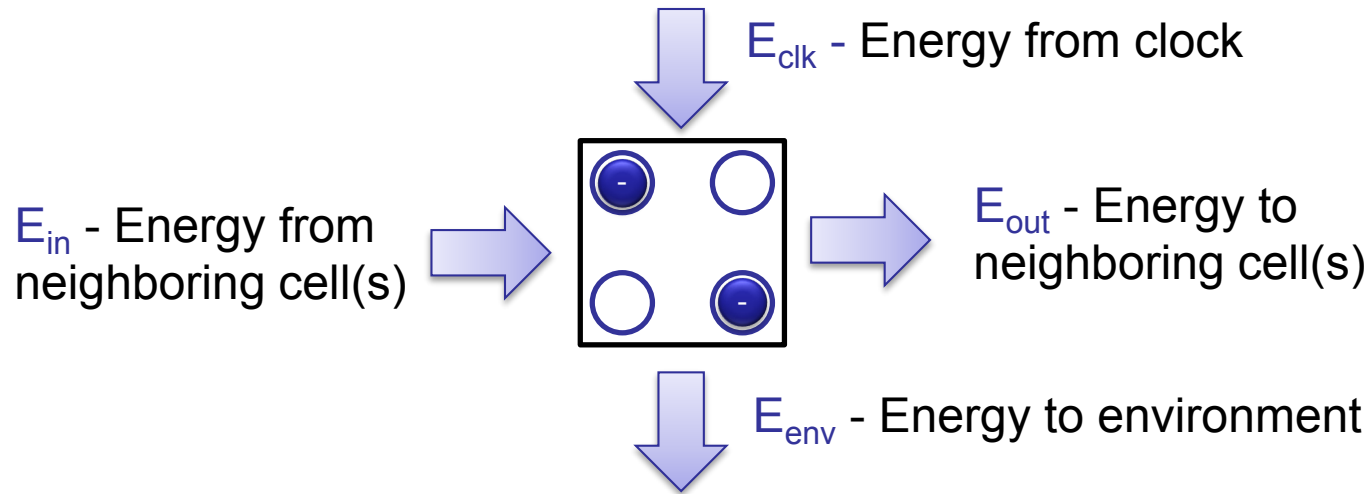
NOR



XOR

Energy Model

- Components of energy dissipation of QCA:



- Dissipated energy: $E_{env} = E_{clk} + E_{in} - E_{out}$

$$E_{env} = \frac{\hbar}{2} \int \left(\vec{\Gamma} \cdot \vec{\lambda} + |\vec{\Gamma}| \tanh \eta_{th} \right) dt'$$

- QCADesigner-E - Physics simulator including determination of energy dissipation of QCA (<https://github.com/FSillIT/QCADesigner-E>)

Design Automation



Characterized Gate library

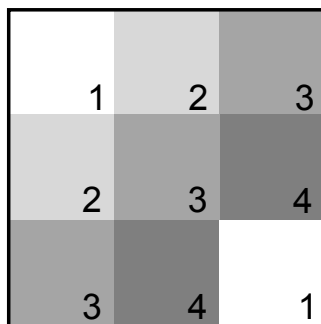
		Area [μm^2]	Delay [tiles]	Energy Dissipation [meV]					
				Regl. Mode (25 GHz)			Fast mode (100 GHz)		
				000	...	111	000	...	111
Routing Elements	Wire	0.01	1	0.09	...	-	0.82	...	-
	Bent-wire	0.01	1	0.10	...	-	0.84	...	-
	Fanout	0.01	1	0.12	...	-	1.15	...	-
Logic Gates	Inverter	0.01	1	0.13	...	-	1.19	...	-
	Majority	0.01	1	0.15	...	0.15	1.41	...	1.41
	OR	0.01	1	0.18	...	-	1.30	...	-
	NOR	0.02	2	0.31	...	-	2.49	...	-

Analysis Environment

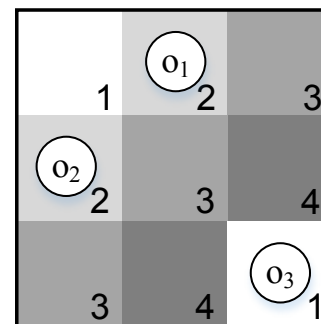


P&R Algorithm

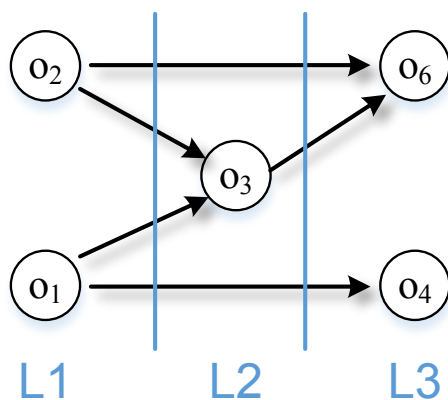
1. Diagonal arrangement of clocking



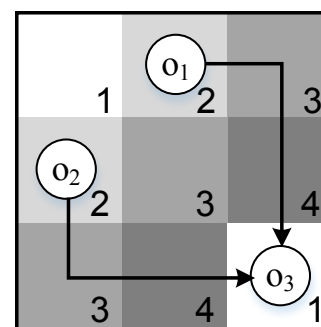
3. Diagonal placement of each level



2. Levelizing of netlist graph



4. Routing



Analysis Environment



Flow

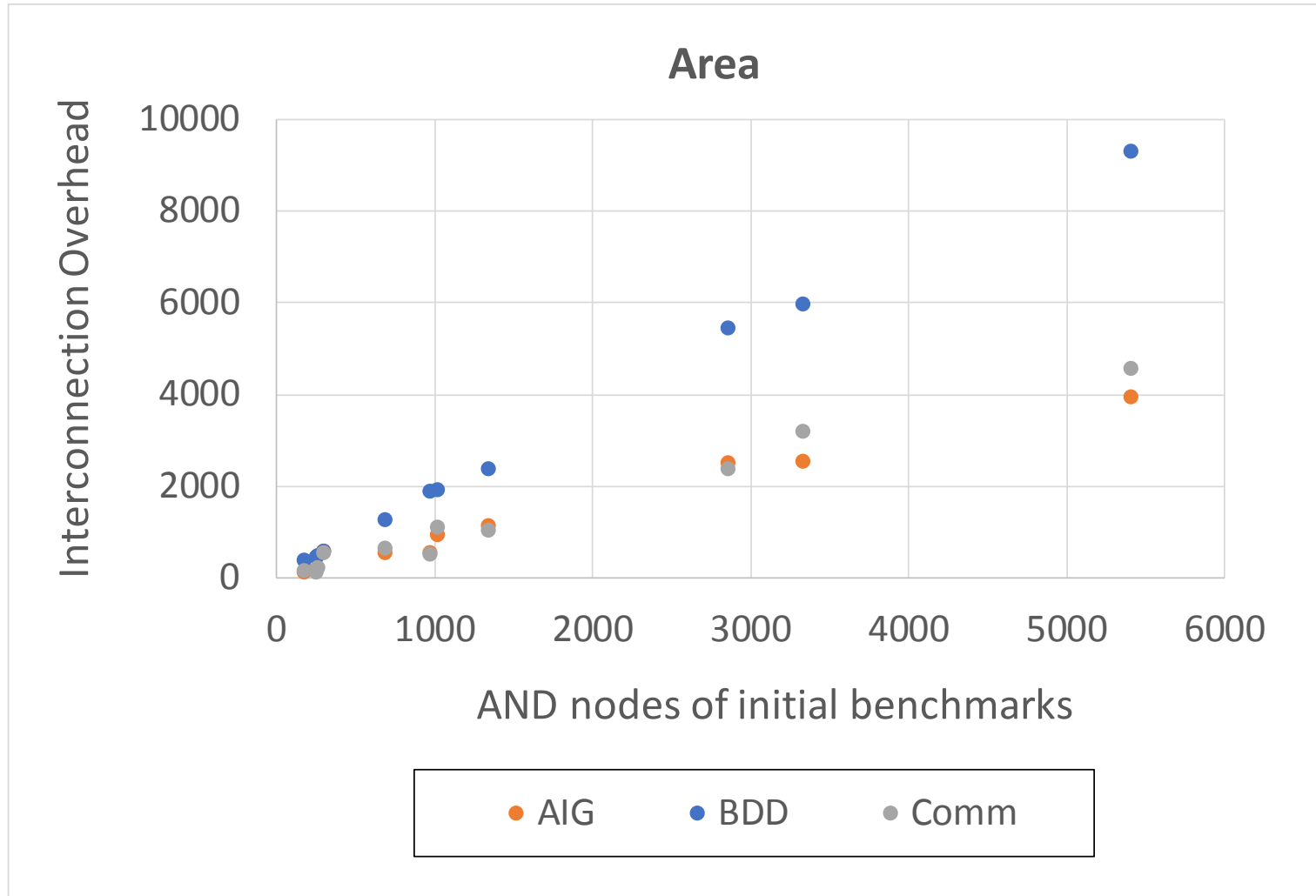
- **Synthesis:**
 - Synthesis library (*.lib) for QCA gate library
 - Synopsys **Design Compiler**
 - **ABC** (AIG, BDD)
- **EFPL Benchmarks**

Benchmark name	Inputs	Outputs	AND nodes
Adder (adder)	256	129	1020
Barrel shifter (barrel)	135	128	3336
Max (max)	512	130	2865
Sine (sin)	24	25	5416
...

Results



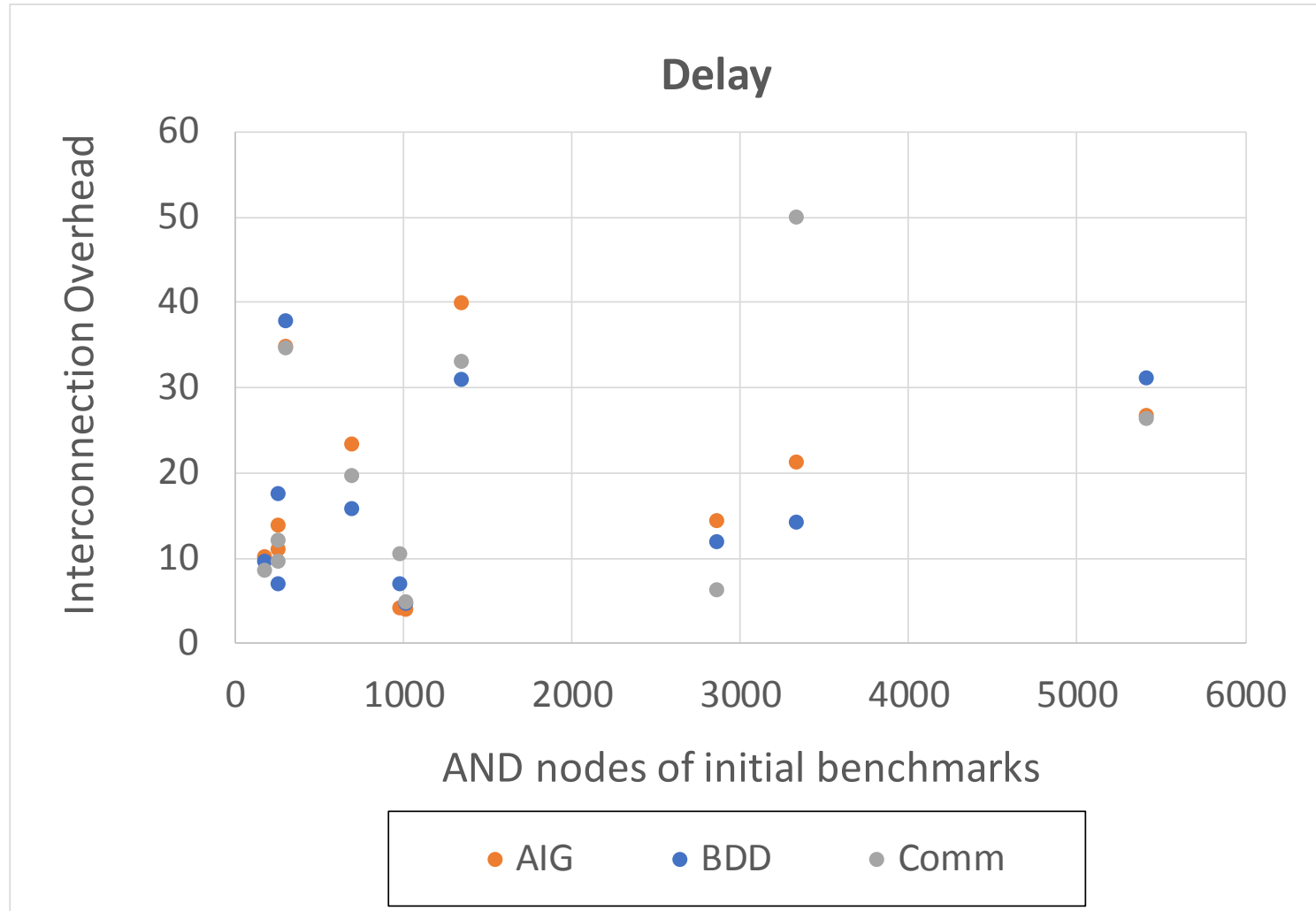
Area



Results



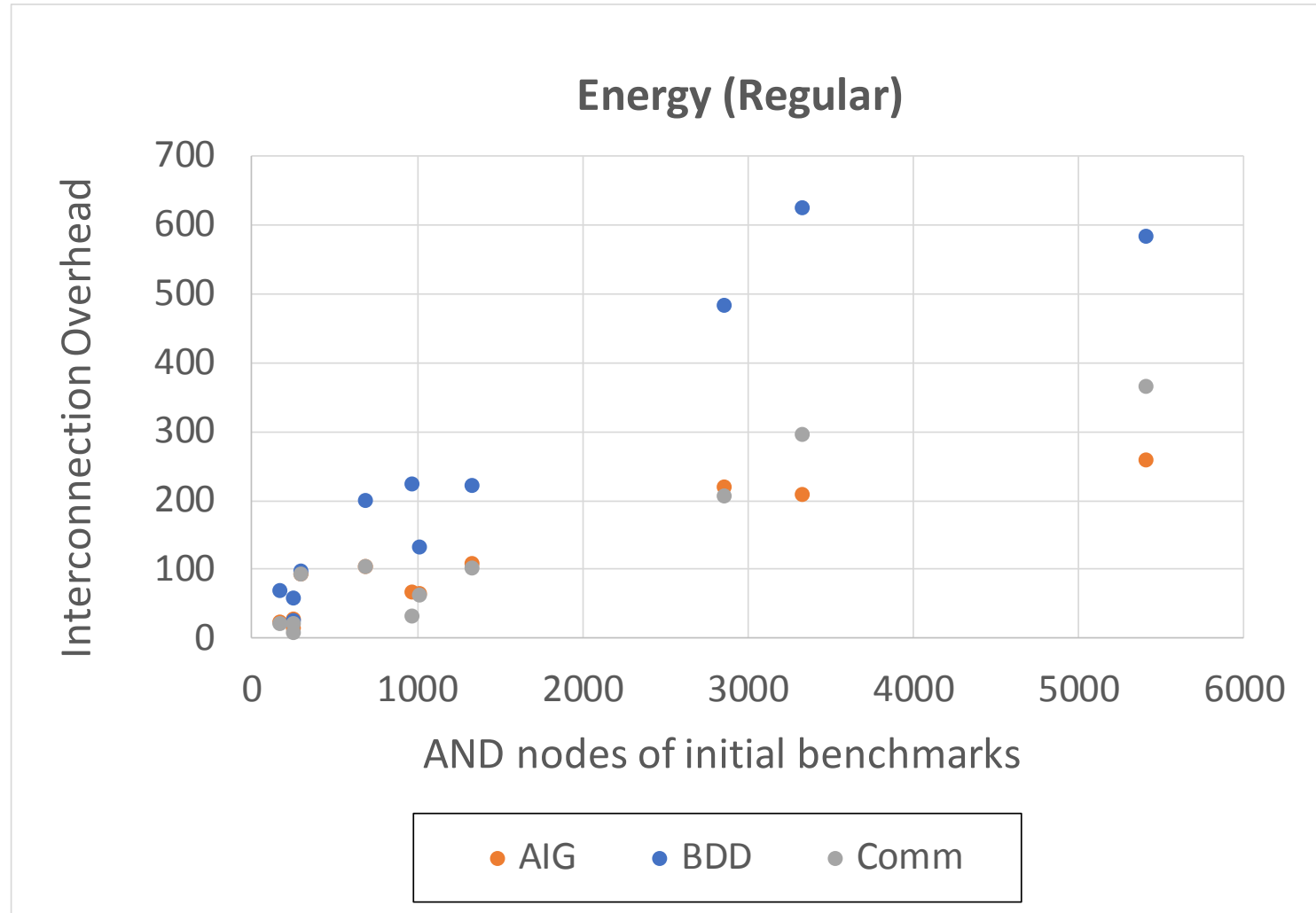
Delay



Results



Energy Dissipation





- QCA is a promising nanotechnology for low energy applications
- Specific characteristics of QCA design require **notable** amount of **interconnections**
- Here: Evaluation of this impact
- Results indicate high impact of Interconnections with **consequences** on **area, delay, energy**
- Requirements for **future research**:
 - Comprehensive synthesis **cost model** for interconnections
 - **New synthesis strategies** with emphasis on reduction of interconnections
 - Exploration of **new concepts** (systolic arrays, logic duplication, ...)

Thank you!

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