High-Level Time-Accurate Model for the Design of Self-timed Ring Oscillators

ASYNC 2008 - Newcastle

Jérémie Hamon[1,2], Laurent Fesquet[1], Benoît Miscopein[2] and Marc Renaudin[3]

[1]TIMA Laboratory - [2]Orange Labs - [3]TIEMPO SAS
Grenoble, FRANCE

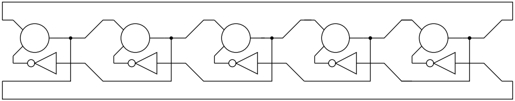
April 2008

Context of the Study

- On-chip digital oscillators are very useful in a great variety of communication systems:
  - Radio Frequency systems
  - Intra-chip communication systems
  - ...
- A lot of advantages:
  - Standard CMOS design flow
  - Frequency range
  - Configurability
  - ...
- And a major constraint: robustness to PVT
- Self-timed rings should be a promising solution for such digital oscillators...

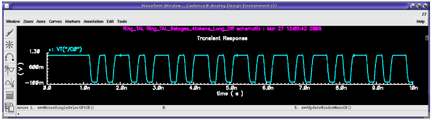
State of the Art

- Structure of a self-timed ring:

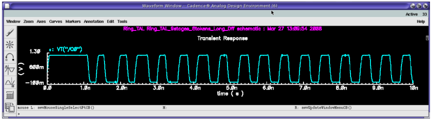


5-stage self-timed ring

- It exists different stable propagation modes:



Example of a burst propagation



Example of an evenly-spaced propagation

- Previous works have been focused on the stage timing properties to analyse or control these propagation modes.

Contributions

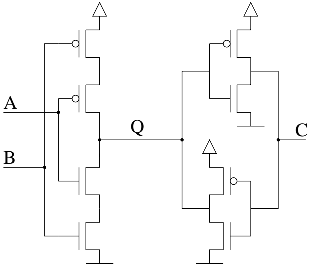
- A model based on the combination of two different abstraction level models:
  - The 3D Charlie Model: timing properties of a ring stage
  - A behavioural model: ring structure and initialisation
- A high-level time-accurate model for self-timed rings:
  - Evenly-spaced or burst propagation modes
  - Oscillating period and phases analytical expression
  - Robustness to the process variability
- Validated by electrical simulations on CMOS 65nm STMicroelectronics technology.

1. **3D Charlie Model**
2. **Timed Behavioural Model**
3. **Numerical Simulations**
4. **Electrical Simulations**
5. **Conclusions and Prospects**

1. **3D Charlie Model**
   - The Charlie and the Drafting Effects
   - The Analytical 3D Charlie Model
2. **Timed Behavioural Model**
3. **Numerical Simulations**
4. **Electrical Simulations**
5. **Conclusions and Prospects**

The Charlie and the Drafting Effects

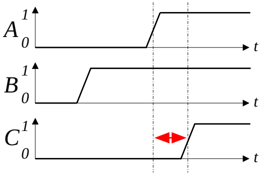
- The Charlie effect: the closer the input events, the longer the propagation delay
- The Drafting effect: the shorter the time between two successive output commutations, the shorter the propagation delay

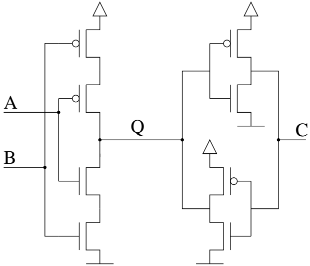


A possible Muller gate implementation

The Charlie and the Drafting Effects

- The Charlie effect: the closer the input events, the longer the propagation delay
- The Drafting effect: the shorter the time between two successive output commutations, the shorter the propagation delay

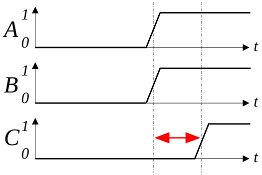


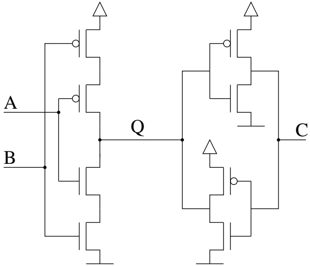


A possible Muller gate implementation

The Charlie and the Drafting Effects

- The Charlie effect: the closer the input events, the longer the propagation delay
- The Drafting effect: the shorter the time between two successive output commutations, the shorter the propagation delay

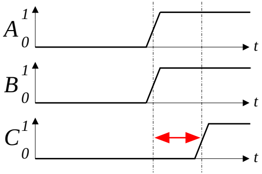


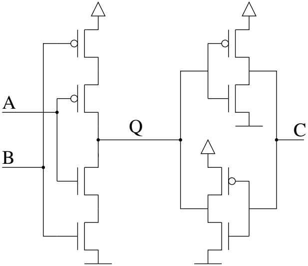


A possible Muller gate implementation

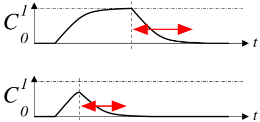
The Charlie and the Drafting Effects

- The Charlie effect: the closer the input events, the longer the propagation delay
- The Drafting effect: the shorter the time between two successive output commutations, the shorter the propagation delay

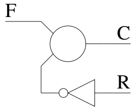




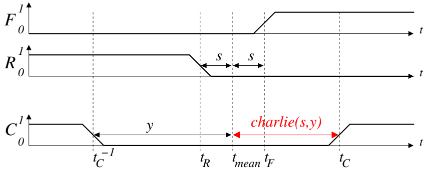
A possible Muller gate implementation



The Analytical 3D Charlie Model



Ring stage structure



Timing diagram of a stage

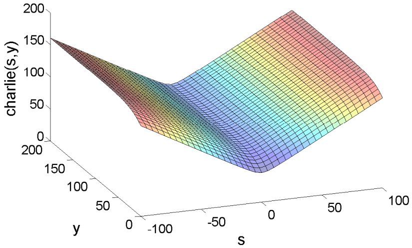
- Output commutation instant:

$$t_C = \frac{t_F + t_R}{2} + charlie(s,y)$$

- Analytical 3D Charlie Model:

$$charlie(s,y) = D_{mean} + \sqrt{D_{charlie}^2 + (s - s_{min})^2} - Be^{-\frac{y}{A}}$$

With: $D_{mean} = \frac{D_{rr}+D_{ff}}{2}$ and $s_{min} = \frac{D_{rr}-D_{ff}}{2}$



3D Charlie Model diagram

1. 3D Charlie Model

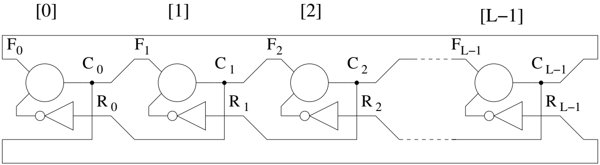
2. **Timed Behavioural Model**
   - Notations and Definitions
   - Behavioural Model
   - Time Annotation
   - Propagation Modes
   - Period and Phases

3. Numerical Simulations

4. Electrical Simulations

5. Conclusions and Prospects

Notations and Definitions



Structure of an L-stage asynchronous ring

- Definitions:
  - L the number of stages
  - i the stage index
  - N_T the number of tokens
  - N_B the number of bubbles
- Ring structure:

$$C_i = F_{(i+1)\%L} = R_{(i-1)\%L}$$

- Tokens and bubbles:

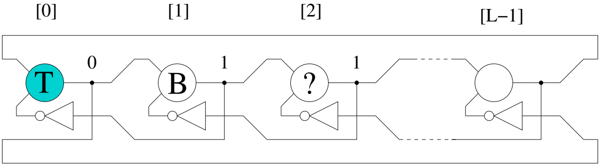
$$stage_i \subset token \Leftrightarrow C_i \neq C_{i+1}$$

$$stage_i \not\subset token \Leftrightarrow C_i = C_{i+1}$$

- Propagation rules:

$$C_{i-1} \neq C_i = C_{i+1}$$

Notations and Definitions



Structure of an L-stage asynchronous ring

- Definitions:
  - L the number of stages
  - i the stage index
  - N_T the number of tokens
  - N_B the number of bubbles

- Ring structure:

$$C_i = F_{(i+1)\%L} = R_{(i-1)\%L}$$

- Tokens and bubbles:

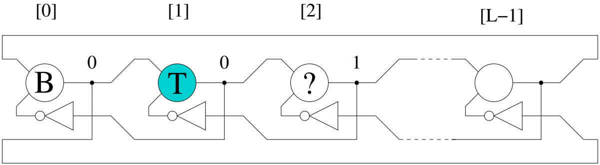
$$stage_i \subset token \Leftrightarrow C_i \neq C_{i+1}$$

$$stage_i \not\subset token \Leftrightarrow C_i = C_{i+1}$$

- Propagation rules:

$$C_{i-1} \neq C_i = C_{i+1}$$

Notations and Definitions



Structure of an L-stage asynchronous ring

- Definitions:
  - L the number of stages
  - i the stage index
  - N_T the number of tokens
  - N_B the number of bubbles

- Ring structure:

$$C_i = F_{(i+1)\%L} = R_{(i-1)\%L}$$

- Tokens and bubbles:

$$stage_i \subset token \Leftrightarrow C_i \neq C_{i+1}$$

$$stage_i \not\subset token \Leftrightarrow C_i = C_{i+1}$$

- Propagation rules:

$$C_{i-1} \neq C_i = C_{i+1}$$

Behavioural Model

Example of 5-stage ring with 2 tokens

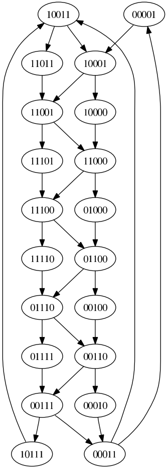
- Ring state representation:
  - At logical abstraction level:

    $$C = \{C_0, C_1, C_2, ..., C_{L-1}\} \quad C_i \in \{0, 1\}$$

  - At token/bubble abstraction level:

    $$X = \{X_0, X_1, X_2, ..., X_{L-1}\} \quad X_i \in \{T, B\}$$

- State graph model:
  - A node represents a possible state of the ring.
  - An edge represents a possible transition from one state to another.
  - Without any temporal assumption on the propagation delays of the stages.



State graph of a 5-stage ring with 2 tokens

Behavioural Model

Example of 5-stage ring with 2 tokens

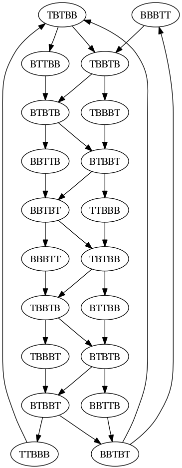
- Ring state representation:
  - At logical abstraction level:

    $$C = \{C_0, C_1, C_2, ..., C_{L-1}\} \quad C_i \in \{0, 1\}$$

  - At token/bubble abstraction level:

    $$X = \{X_0, X_1, X_2, ..., X_{L-1}\} \quad X_i \in \{T, B\}$$

- State graph model:
  - A node represents a possible state of the ring.
  - An edge represents a possible transition from one state to another.
  - Without any temporal assumption on the propagation delays of the stages.



State graph of a 5-stage ring with 2 tokens

Time Annotation

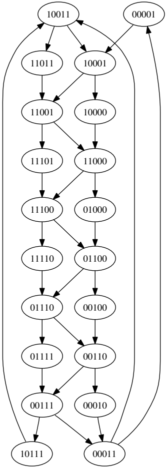
Example of a 5-stage ring with 2 token

- On the vector C state graph
- Vector t of the last commutation instants of each stage

$$t = \{t_0, t_1, t_2, ..., t_{L-1}\}$$

- t_i computed with respect to the 3D Charlie Model:

$$t_i = \frac{t_{i-1} + t_{i+1}}{2} + charlie(s, y)$$



Timed state graph of a 5-stage ring with 2 tokens

Time Annotation

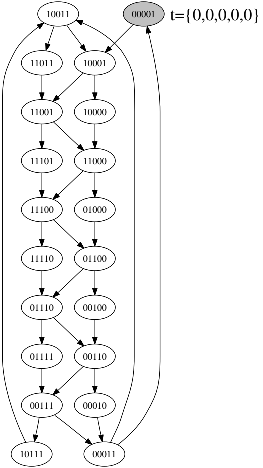
Example of a 5-stage ring with 2 token

- On the vector C state graph
- Vector t of the last commutation instants of each stage

$$t = \{t_0, t_1, t_2, ..., t_{L-1}\}$$

- t_i computed with respect to the 3D Charlie Model:

$$t_i = \frac{t_{i-1} + t_{i+1}}{2} + charlie(s, y)$$



Timed state graph of a 5-stage ring with 2 tokens

Time Annotation

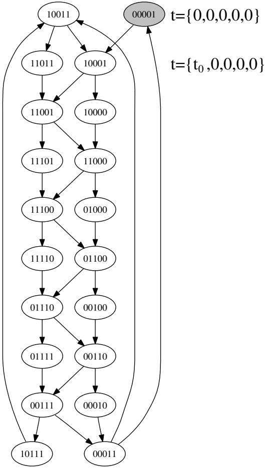
Example of a 5-stage ring with 2 token

- On the vector C state graph
- Vector t of the last commutation instants of each stage

$$t = \{t_0, t_1, t_2, ..., t_{L-1}\}$$

- t_i computed with respect to the 3D Charlie Model:

$$t_i = \frac{t_{i-1} + t_{i+1}}{2} + charlie(s, y)$$



Timed state graph of a 5-stage ring with 2 tokens

Time Annotation

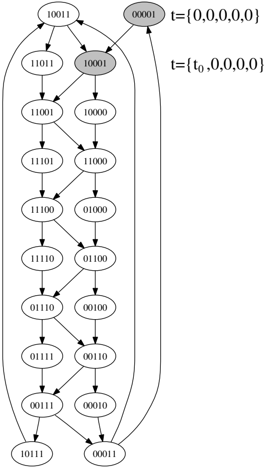
Example of a 5-stage ring with 2 token

- On the vector C state graph
- Vector t of the last commutation instants of each stage

$$t = \{t_0, t_1, t_2, ..., t_{L-1}\}$$

- t_i computed with respect to the 3D Charlie Model:

$$t_i = \frac{t_{i-1} + t_{i+1}}{2} + charlie(s, y)$$



Timed state graph of a 5-stage ring with 2 tokens

Time Annotation

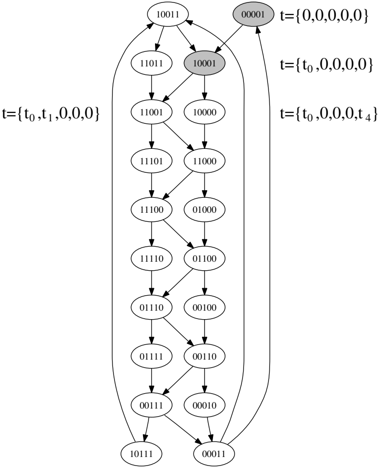
Example of a 5-stage ring with 2 token

- On the vector *C* state graph
- Vector *t* of the last commutation instants of each stage

$$t = \{t_0, t_1, t_2, ..., t_{L-1}\}$$

- t_i computed with respect to the 3D Charlie Model:

$$t_i = \frac{t_{i-1} + t_{i+1}}{2} + charlie(s, y)$$



Timed state graph of a 5-stage ring with 2 tokens

Time Annotation

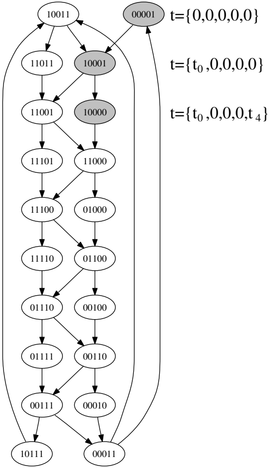
Example of a 5-stage ring with 2 token

- On the vector *C* state graph
- Vector *t* of the last commutation instants of each stage

$$t = \{t_0, t_1, t_2, ..., t_{L-1}\}$$

- t_i computed with respect to the 3D Charlie Model:

$$t_i = \frac{t_{i-1} + t_{i+1}}{2} + charlie(s, y)$$

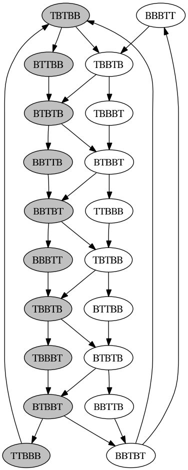


Timed state graph of a 5-stage ring with 2 tokens

Propagation Modes

Example of 5-stage ring with 2 tokens

- On the vector *X* state graph
- Characterisation of the propagation modes at token/bubble abstraction level:
  - Burst : the tokens get together to form a cluster
  - Evenly-spaced: the tokens spread all-around the ring
- Criterion based on the numbers of bubbles that separate two tokens

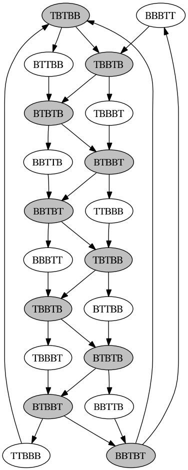


Burst path of a 5-stage ring with 2 tokens

Propagation Modes

Example of 5-stage ring with 2 tokens

- On the vector *X* state graph
- Characterisation of the propagation modes at token/bubble abstraction level:
  - Burst : the tokens get together to form a cluster
  - Evenly-spaced: the tokens spread all-around the ring
- Criterion based on the numbers of bubbles that separate two tokens



Evenly-spaced path of a 5-stage ring with 2 tokens

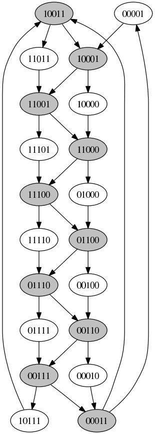
Period and Phase expressions

Example of 5-stage ring with 2 tokens

- Expression of the oscillating period and phases based on:
  - the evenly-spaced propagation assumption
  - time annotation of the evenly-spaced path on the state graph
- Example of a 5-stage ring with 2 tokens:

$$T = 4 \times charlie\left(\frac{T}{20}, \frac{T}{4}\right)$$

- Expression of the period with respect to :
  - the timings parameters of the stage
  - the numbers of tokens and bubbles



Evenly-spaced path of a 5-stage ring with 2 tokens

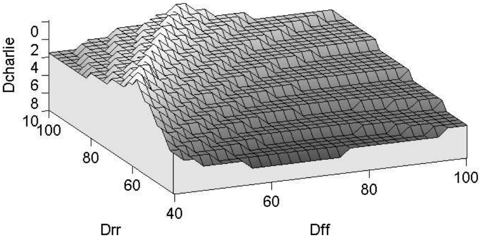
Evenly-spaced Volume

Example of 5-stage ring with 2 tokens

- Set constant the ring initialisation (2 tokens and 3 bubbles)
- Tune all the parameters all the 3D Charlie Model

Medium Drafting effect

$A = B = 25$



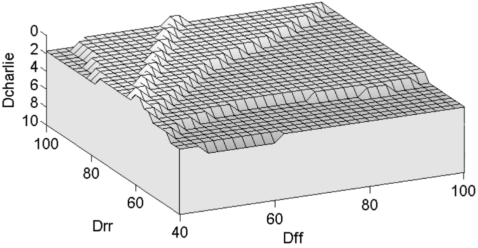
Evenly-spaced Volume

Example of 5-stage ring with 2 tokens

- Set constant the ring initialisation (2 tokens and 3 bubbles)
- Tune all the parameters all the 3D Charlie Model

Low Drafting effect

$A = B = 15$



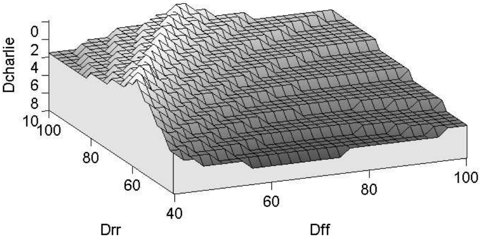
Evenly-spaced Volume

Example of 5-stage ring with 2 tokens

- Set constant the ring initialisation (2 tokens and 3 bubbles)
- Tune all the parameters all the 3D Charlie Model

Medium Drafting effect

$A = B = 25$



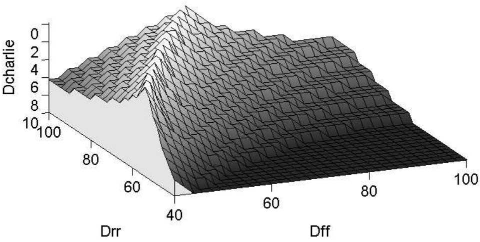
Evenly-spaced Volume

Example of 5-stage ring with 2 tokens

- Set constant the ring initialisation (2 tokens and 3 bubbles)
- Tune all the parameters all the 3D Charlie Model

High Drafting effect

$A = B = 35$



Evenly-spaced Volume

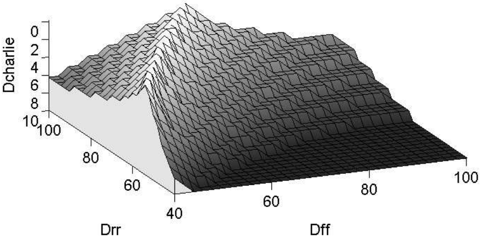
Example of 5-stage ring with 2 tokens

- Set constant the ring initialisation (2 tokens and 3 bubbles)
- Tune all the parameters all the 3D Charlie Model
- Specific static delays ratio that ensures an evenly-spaced propagation:

$$\frac{D_{ff}}{D_{rr}} = \frac{2}{3} = \frac{N_T}{N_B}$$

High Drafting effect

$$A = B = 35$$



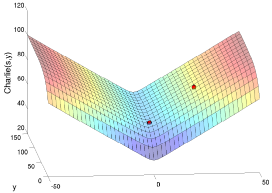
Operating Points

- Representation of the ring evolution by a succession of points:

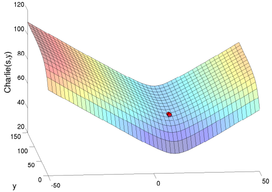
$$\{s, y, charlie(s, y)\}$$

- Burst propagation: two attractors
- Evenly-spaced propagation: unique attractor
- Location of the attractor controlled by the tokens/bubbles ratio
- In the "valley" of the diagram:

$$\frac{N_T}{N_B} = \frac{D_{ff}}{D_{rr}}$$



Operating points - burst propagation



Operating points - specific ratio of static delays

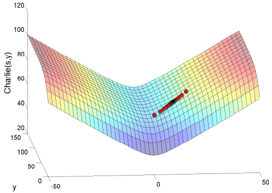
Operating Points

- Representation of the ring evolution by a succession of points:

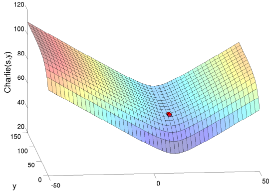
$$\{s, y, charlie(s, y)\}$$

- Burst propagation: two attractors
- Evenly-spaced propagation: unique attractor
- Location of the attractor controlled by the tokens/bubbles ratio
- In the "valley" of the diagram:

$$\frac{N_T}{N_B} = \frac{D_{ff}}{D_{rr}}$$



Operating points - evenly-spaced propagation



Operating points - specific ratio of static delays

Sensitivity to process variability

Example of 5-stage ring with 2 tokens

- Modelling the process variability:
  - Each parameter of the 3D Charlie model is substituted with a Gaussian random variables:

$$\begin{cases} D_{rr}(x) = \dfrac{1}{\sigma_{Drr}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-m_{Drr}}{\sigma_{Drr}}\right)^2} \\ D_{ff}(x) = \dfrac{1}{\sigma_{Dff}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-m_{Dff}}{\sigma_{Dff}}\right)^2} \\ D_{charlie}(x) = \dfrac{1}{\sigma_{D_{charlie}}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-m_{D_{charlie}}}{\sigma_{D_{charlie}}}\right)^2} \\ A(x) = \dfrac{1}{\sigma_{A}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-m_{A}}{\sigma_{A}}\right)^2} \\ B(x) = \dfrac{1}{\sigma_{B}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-m_{B}}{\sigma_{B}}\right)^2} \end{cases}$$

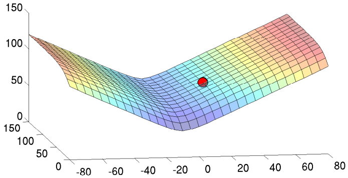
  - Period and Phases dispersions are measured by numerical simulations:
    - Standard deviations set to 5% of the mean value of each parameters
    - 1000 runs

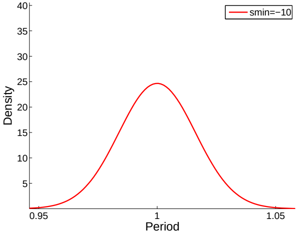
Sensitivity to process variability

Example of 5-stage ring with 2 tokens

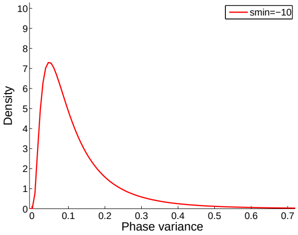
- Influence of the static delay ratio on the process variability:
- N_T and N_B are set constant.
- Variation of the static delay ratio:

$$\frac{D_{ff}}{D_{rr}} = \frac{60}{40} \gg \frac{N_T}{N_B} \Leftrightarrow s_{min} = -10$$





Normalised period distribution

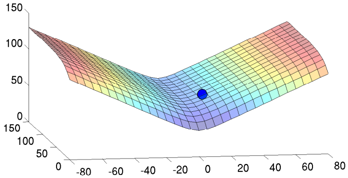


Normalised phase variance distribution

Sensitivity to process variability

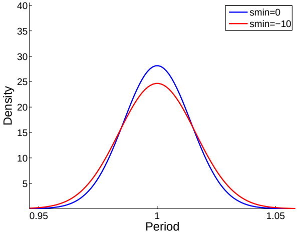
Example of 5-stage ring with 2 tokens

- Influence of the static delay ratio on the process variability:

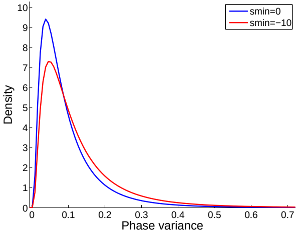


- N_T and N_B are set constant.
- Variation of the static delay ratio:

$$\frac{D_{ff}}{D_{rr}} = \frac{50}{50} > \frac{N_T}{N_B} \Leftrightarrow s_{min} = 0$$



Normalised period distribution



Normalised phase variance distribution

Sensitivity to process variability

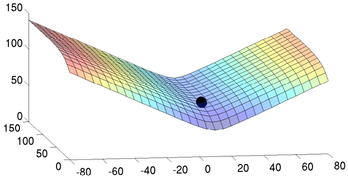
Example of 5-stage ring with 2 tokens

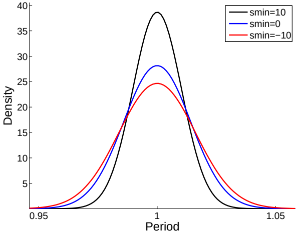
- Influence of the static delay ratio on the process variability:

- N_T and N_B are set constant.

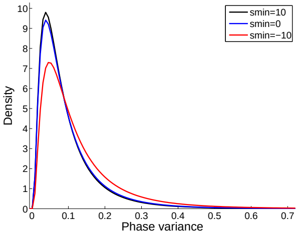
- Variation of the static delay ratio:

$$\frac{D_{ff}}{D_{rr}} = \frac{40}{60} = \frac{N_T}{N_B} \Leftrightarrow s_{min} = 10$$





Normalised period distribution



Normalised phase variance distribution

Sensitivity to process variability

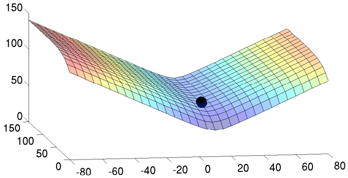
Example of 5-stage ring with 2 tokens

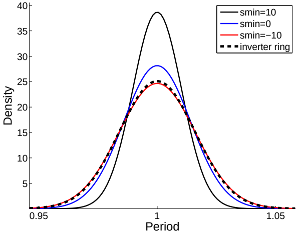
- Influence of the static delay ratio on the process variability:

- N_T and N_B are set constant.

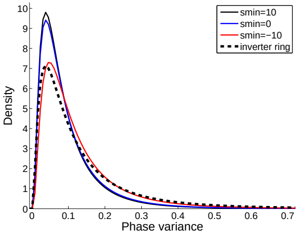
- Variation of the static delay ratio:

$$\frac{D_{ff}}{D_{rr}} = \frac{40}{60} = \frac{N_T}{N_B} \Leftrightarrow s_{min} = 10$$





Normalised period distribution



Normalised phase variance distribution

1. 3D Charlie Model

2. Timed Behavioural Model

3. Numerical Simulations

4. **Electrical Simulations**
   - Stage Characterisation
   - Self-timed Rings Simulations
   - Monte Carlo Simulations

5. Conclusions and Prospects

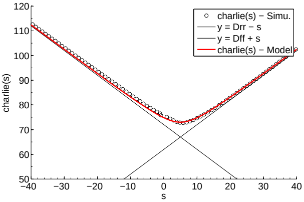
Stage Characterisation

- Standard cells of the TAL (Tima Asynchronous Library) in CMOS 65 nm STMicroelectronics technology
- Simulated with *Cadence Spectre* analog simulator

Parameters of the 3D Charlie Model of a stage
TAL Library - 65 nm STMicroelectronics

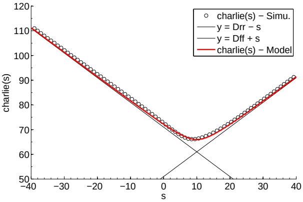
	Rising	Falling	Mean
Drr	71 ps	73 ps	72 ps
Dff	51 ps	62 ps	56.5 ps
$D_{Charlie}$	5 ps	5 ps	5 ps
A	22 ps	16 ps	19 ps
B	10 ps	10 ps	10 ps

Falling transition characterisation



charlie(s) for constant $y \gg 0$

Rising transition characterisation



charlie(s) for constant $y \gg 0$

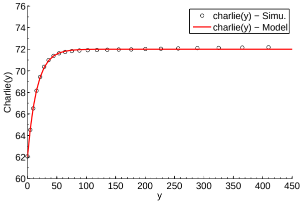
Stage Characterisation

- Standard cells of the TAL (Tima Asynchronous Library) in CMOS 65 nm STMicroelectronics technology
- Simulated with *Cadence Spectre* analog simulator

Parameters of the 3D Charlie Model of a stage
TAL Library - 65 nm STMicroelectronics

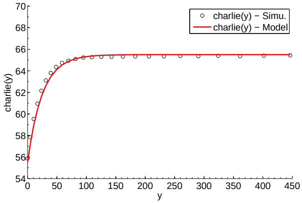
	Rising	Falling	Mean
Drr	71 ps	73 ps	72 ps
Dff	51 ps	62 ps	56.5 ps
$D_{Charlie}$	5 ps	5 ps	5 ps
A	22 ps	16 ps	19 ps
B	10 ps	10 ps	10 ps

Falling transition characterisation



$charlie(y)$ for $s = s_{min}$

Rising transition characterisation



$charlie(y)$ for $s = s_{min}$

Self-timed Rings Electrical Simulations

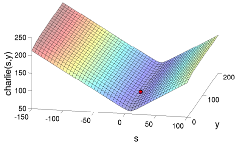
- 9-stage ring with 4 tokens and 5 bubbles:

$$\frac{N_T}{N_B} = 0.8 \simeq \frac{D_{ff}}{D_{rr}} = 0.784$$

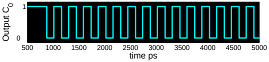
  - Analytical oscillation period:

$$T = 4 \times charlie\left(\frac{T}{36}, \frac{T}{4}\right) = 276\ ps$$

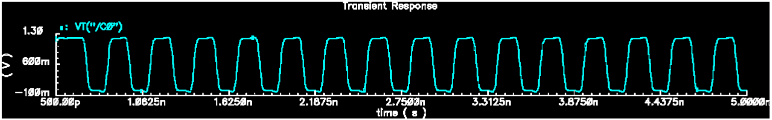
  - Measured period: 281 ps
  - Estimation error less than 2%



Operating points



Numerical simulation diagram



Electrical simulation diagram of a 9-stage ring with 4 tokens and 5 bubbles

Self-timed Rings Electrical Simulations

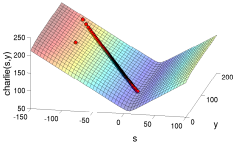
- 9-stage ring with 6 tokens and 3 bubbles:

$$\frac{D_{ff}}{D_{rr}} = 0.784 \ll 2 = \frac{N_T}{N_B}$$

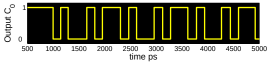
  - Analytical oscillation period:

$$T = 4 \times charlie\left(-\frac{T}{12}, \frac{T}{4}\right) = 433\ ps$$

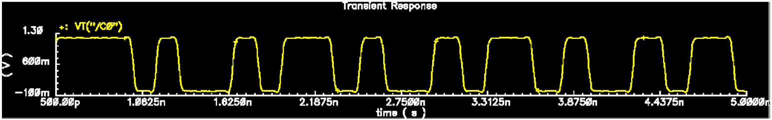
  - Measured period: 438 ps
  - Estimation error less than 2%



Operating points



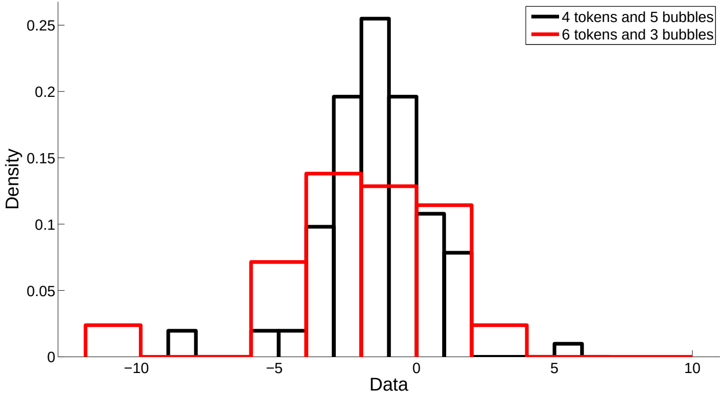
Numerical simulation diagram



Electrical simulation diagram of a 9-stage ring with 6 tokens and 3 bubbles

Monte Carlo Simulations

- "Process and Mismatch" variation for 100 sweeps:



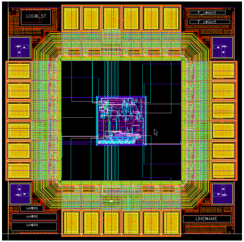
Centred period distributions of asynchronous rings from 100 Monte Carlo sweeps

Conclusions

- A high-level time-accurate model for asynchronous rings
- The analytical expression of the oscillation period and phases with respect to the parameters of the 3D Charlie Model and to the ring size and configuration
- A simple design rule to avoid burst oscillating mode and minimise the effect of the process variability

Prospects

- Enhance the model by adding the differences of rising and falling propagation delays
- Study the possibility to dynamically tune the oscillation period by injecting or removing tokens at run time
- Adapt and use the model to study more complex structures built out of asynchronous ring combinations
- Validate on silicon the method by experimentation on a test chip (currently under production process)



Asynchronous Rings Test chip

HCMOS9 - 130nm STMicroelectronics

Thank you for your attention!