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

ASYNC 2008 - Newcastle

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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](image)

- It exists different stable propagation modes:

![Example of a burst propagation](image)  
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

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A possible Muller gate implementation
The Analytical 3D Charlie Model

- 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

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

Numerical Simulations

Electrical Simulations

Conclusions and Prospects
**Notations and Definitions**

![Structure of an L-stage asynchronous ring](image)

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

- **Tokens and bubbles:**
  - $stage_i \subset token \Leftrightarrow C_i \neq C_{i+1}$
  - $stage_i \not\subset token \Leftrightarrow C_i = C_{i+1}$

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

- **Propagation rules:**
  - $C_{i-1} \neq C_i = C_{i+1}$
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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

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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

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

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

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

\[ T = 4 \times \text{charlie} \left( \frac{T}{20}, \frac{T}{4} \right) \]

- 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
3D Charlie Model
Timed Behaviour Model
Numerical Simulations
Evenly-spaced Volume
Operating Points
Sensitivity to process variability
Electrical Simulations
Conclusions and Prospects
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)
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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

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  \]
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:

\[
\begin{align*}
D_{rr}(x) &= \frac{1}{\sigma_{Drr} \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x-m_{Drr}}{\sigma_{Drr}} \right)^2} \\
D_{ff}(x) &= \frac{1}{\sigma_{Dff} \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x-m_{Dff}}{\sigma_{Dff}} \right)^2} \\
D_{\text{charlie}}(x) &= \frac{1}{\sigma_{D_{\text{charlie}}} \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x-m_{D_{\text{charlie}}}}{\sigma_{D_{\text{charlie}}}} \right)^2} \\
A(x) &= \frac{1}{\sigma_A \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x-m_A}{\sigma_A} \right)^2} \\
B(x) &= \frac{1}{\sigma_B \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x-m_B}{\sigma_B} \right)^2}
\end{align*}
\]

- 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:

\[
\frac{D_{ff}}{D_{rr}} = \frac{60}{40} \gg \frac{N_T}{N_B} \iff s_{\text{min}} = -10
\]
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:
    
    \[
    \frac{D_{ff}}{D_{rr}} = \frac{50}{50} > \frac{N_T}{N_B} \iff s_{min} = 0
    \]

![Normalised period distribution](image1)
![Normalised phase variance distribution](image2)

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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:

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

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

![Graph showing normalised period distribution and normalised phase variance distribution](attachment:image.png)
3D Charlie Model

Timed Behavioural Model

Numerical Simulations

Electrical Simulations

Conclusions and Prospects

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

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<tr>
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<th>Falling</th>
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<tr>
<td>$D_{rr}$</td>
<td>71 ps</td>
<td>73 ps</td>
<td>72 ps</td>
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<tr>
<td>$D_{ff}$</td>
<td>51 ps</td>
<td>62 ps</td>
<td>56.5 ps</td>
</tr>
<tr>
<td>$D_{charlie}$</td>
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</tr>
<tr>
<td>$A$</td>
<td>22 ps</td>
<td>16 ps</td>
<td>19 ps</td>
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<tr>
<td>$B$</td>
<td>10 ps</td>
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### 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
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Parameters of the 3D Charlie Model of a stage TAL Library - 65 nm STMicroelectronics

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Falling transition characterisation

Rising transition characterisation

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

$charlie(y)$ for $s = s_{min}$
Self-timed Rings Electrical Simulations

- 9-stage ring with 4 tokens and 5 bubbles:
  \[ \frac{N_T}{N_B} = 0.8 \approx \frac{D_{ff}}{D_{rr}} = 0.784 \]

- Analytical oscillation period:
  \[ T = 4 \times charlie \left( \frac{T}{36}, \frac{T}{4} \right) = 276 \text{ ps} \]

- Measured period: 281 ps

- Estimation error less than 2%

![Numerical simulation diagram](image)

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:

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

- Measured period: 438 ps

- Estimation error less than 2%

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
1. 3D Charlie Model
2. Timed Behavioural Model
3. Numerical Simulations
4. Electrical Simulations
5. Conclusions and Prospects
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)
Thank you for your attention!