Investigation of the Package Crosstalk Noise to DDR4-IF Signal by IBIS [Define Package Model]

Akiko Tsukada
tsukada.akiko@jp.fujitsu.com

Masaki Kirinaka
mkirinaka@jp.fujitsu.com

FUJITSU INTERCONNECT TECHNOLOGIES LIMITED

Asian IBIS Summit
Tokyo, JAPAN
November 17, 2017
Agenda

- Background
- Package Modeling Method
- Crosstalk Noise by Package
- Crosstalk Noise by Package and Board
- Conclusions
Background
[Define Package Model]

FBGA-1000
FICT
FICT
1000 pin BGA package
2
A1 | 1  DQ0
B1 | 2  DQ1
Banded_matrix
0
A1 | R11
1.000 | R11
0.950 | R22
Sparse_matrix
A1 | L11
5.000e-009 | L11
0.999e-010 | L12
B1 | L12
5.500e-009 | L22
Sparse_matrix
A1 | C11
1.500e-012 | C11
-5.000e-013 | C12
B1 | C12
1.400e-012 | C22
C11’(=C11+C12)
C22’(=C22+C12)
Background

Coupled parameters of package are rarely used in the SI simulation.

- Because the board design period is short, own SI simulation is the first priority.
- Because Simulator does not support coupled parameter (C12, L12) modeling.

The board design rule became severe with DDR3, DDR4.

ex. 《Skew Constraints》 Data to DQS: ±5ps

Therefore the crosstalk noise of the board is designed to become small.

However, the influence of the crosstalk noise of package is unknown. So investigated it by [Define Package model].
Package Modeling Method
Package Modeling Method

Package Substrate (4-2-4 Buildup) Model

Two parallel line in Layer3
L=15mm, W=40um, Gap=45um

C4 pad 180um pitch
Laser Via
Two parallel line in Layer3

S-parameter

Lumped Circuit Model

R, Ls, Cs, Lm, Cm

W-element RLGC Model (Distributed Circuit Model)

(Coupled Transmission Line model in IBIS ISS Specification.)
Choose W-element for package modeling.
How to make of the Coupled Package Model

1Byte Data Signal Coupled Package Model

IBIS [Define Package Model]

- Resistance Matrix
  - Banded_matrix
  - [Bandwidth] 0
  - [Row] AC1 0.69
  - [Row] AC2 0.55

- Inductance Matrix
  - Sparse_matrix
  - [Row] AC1 5.64e-009
  - AC1 0.97e-009
  - AC2 4.92e-009

- Capacitance Matrix
  - Sparse_matrix
  - [Row] AC1 2.68e-012
  - AC1 -3.59e-013
  - AC2 2.47e-012

W-element description by IBIS-ISS

W_controller
+ AC1_die AC2_die ............... 0
+ AC1_bga AC2_bga ............... 0
+ RLGCMODEL=rlgc_controller N=11 L=1

.MODEL rlgc_controller W
+ MODELTYPE=RLGC N=11
+ L0=
$ AC2 AC1 ............... $ AC2
+ 4.92E-09 5.64E-09 $ AC1
+ C0=
$ AC2 AC1 ............... $ AC2
+ 2.47E-12 2.68E-12 $ AC1
+ R0=
$ AC2 AC1 ............... $ AC2
+ 0.55 $ AC2
+ 0 0.69 $ AC1
How to make of the Coupled Package Model

1Byte Data Signal Coupled Package Model

Subckt description by IBIS-ISS

```
.subckt Controller_PKG
+ AC2_die AC1_die ⋅⋅⋅ AC2_bga AC1_bga ⋅⋅⋅

W_controller
+ AC1_die AC2_die ⋅⋅⋅ ⋅⋅⋅ 0
+ AC1_bga AC2_bga ⋅⋅⋅ ⋅⋅⋅ 0
+RLGC.MODEL=rlgc_controller N=11 L=1

.MODEL rlgc_controller W
+ MODELTYPE=RLGC N=11
+ L0=
$ AC2 AC1 ⋅⋅⋅ ⋅⋅⋅ ⋅⋅⋅ $ AC2
+ 4.92E-09 $ AC2
+ C0=
$ AC2 AC1 ⋅⋅⋅ ⋅⋅⋅ ⋅⋅⋅ $ AC2
+ 2.47E-12 $ AC2
+ R0=
$ AC2 AC1 ⋅⋅⋅ ⋅⋅⋅ ⋅⋅⋅ $ AC2
+ 0.55 $ AC2

.ends Controller_PKG
```

Symbol of Simulator to use SUBCKT
Crosstalk Noise by Package
Crosstalk Noise Level only with a Package

Topology

Coupled PKG Model or Uncoupled PKG Model

Aggressor

Victim

Controller
- DDR4-2666
- DDR3-1600

Board trace
Uncoupled Model
- Single-end: 40Ω
- Differential: 80Ω

Aggressor

Crosstalk Noise

DDDR3/DDR4

Static Low
## Crosstalk Noise Level only with a Package

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR4 Controller PKG Model</th>
<th>DDR4 PKG Model</th>
<th>Crosstalk Noise Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>23.1mV</td>
</tr>
<tr>
<td>2</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>32.0mV</td>
</tr>
</tbody>
</table>

**Case1: Controller PKG Crosstalk Noise**

![Graph of Case 1](image1)

- 20.8mV
- 23.1mV

**Case2: DDR4 PKG Crosstalk Noise**

![Graph of Case 2](image2)

- 32.0mV
- 31.7mV
Crosstalk Noise Level only with a Package

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR3 Controller PKG Model</th>
<th>DDR3 PKG Model</th>
<th>Crosstalk Noise Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>47.4mV</td>
</tr>
<tr>
<td>4</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>37.6mV</td>
</tr>
</tbody>
</table>

**Case3: Controller PKG Crosstalk Noise**

- 41.4mV
- 47.4mV

**Case4: DDR3 PKG Crosstalk Noise**

- 37.6mV
- 35.8mV
Skew only by a Package Crosstalk Noise

Topology

Coupled PKG Model or Uncoupled PKG Model

Aggressor

Victim

Controller
- DDR4-2666
- DDR3-1600

Aggressor

Board Trace
- Uncoupled Model
  - Single-end: 40Ω
  - Differential: 80Ω

DDR3/DDR4

Skew Measurement

Switching
### Skew only by a Package Crosstalk Noise

<table>
<thead>
<tr>
<th>DDR4 -2666</th>
<th>Case</th>
<th>DDR4 Controller PKG Model</th>
<th>DDR4 PKG Model</th>
<th>Switching Pattern(*)</th>
<th>Skew</th>
<th>Skew Variation (Difference with case 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>Even mode</td>
<td>139.6ps</td>
<td>-7.9ps</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>Odd mode</td>
<td>150.8ps</td>
<td>3.3ps</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Even mode</td>
<td>137.5ps</td>
<td>-10ps</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Odd mode</td>
<td>153.7ps</td>
<td>6.2ps</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Uncoupled</td>
<td>Uncoupled</td>
<td>Even mode</td>
<td>147.5ps</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

*Switching Pattern

- **Even mode**: Victim
- **Odd mode**: Victim

---

Case 1

![Case 1](image1)

**Case 1**

- DQS
- Victim DQ
- Aggressor DQ

Case 1: 139.6ps

Case 2

![Case 2](image2)

**Case 2**

- DQS
- Victim DQ
- Aggressor DQ

Case 2: 150.8ps

Case 5

![Case 5](image3)

**Case 5**

- DQS
- Victim DQ
- Aggressor DQ

Case 5: 147.5ps
## Skew only by a Package Crosstalk Noise

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR3 Controller PKG Model</th>
<th>DDR3 PKG Model</th>
<th>Switching Pattern</th>
<th>Skew</th>
<th>Skew Variation (Difference with case 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>Even mode</td>
<td>274.8ps</td>
<td>-18.3ps</td>
</tr>
<tr>
<td>2</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>Odd mode</td>
<td>292.0ps</td>
<td>-1.1ps</td>
</tr>
<tr>
<td>3</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Even mode</td>
<td>277.8ps</td>
<td>-15.3ps</td>
</tr>
<tr>
<td>4</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Odd mode</td>
<td>296.4ps</td>
<td>3.3ps</td>
</tr>
<tr>
<td>5</td>
<td>Uncoupled</td>
<td>Uncoupled</td>
<td>Even mode</td>
<td>293.1ps</td>
<td>---</td>
</tr>
</tbody>
</table>

**Case 1**

**Case 2**

**Case 5**

---

**Notes:**
- **Case 1:** Skew: 274.8ps, Skew Variation: -18.3ps
- **Case 2:** Skew: 292.0ps, Skew Variation: -1.1ps
- **Case 5:** Skew: 293.1ps, Skew Variation: ---
Crosstalk Noise by Package and Board
Crosstalk Noise Level only with a Board

Topologies

- **Aggressor**
  - DQ0
  - DQ1
  - DQ2
  - DQ3
  - DQ4
  - DQ5
  - DQ6
  - DQ7
  - DM0
- **Victim**
  - DQSp/DQSn

**Controller**
- DDR4-2666
- DDR3-1600

**Board Model**
- S-param

**DDRR3/DDR4**

**Probe**
- Static Low

**Crosstalk Noise**
- Gap $\geq 3\, \text{W} (\text{Se to Se})$
- Gap $\geq 6\, \text{W} (\text{Se to Diff})$

**Single-end: 40Ω**

**Differential: 80Ω**
Crosstalk Noise Level only with a Board

### Board Crosstalk Noise Level

<table>
<thead>
<tr>
<th>Case</th>
<th>Controller PKG Model</th>
<th>Board Model</th>
<th>Memory PKG Model</th>
<th>Crosstalk Noise Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DDR4 Cont. wo PKG</td>
<td>Coupled</td>
<td>DDR4 Mem. wo PKG</td>
<td>0.4mV</td>
</tr>
<tr>
<td>2</td>
<td>DDR3 Cont. wo PKG</td>
<td>Coupled</td>
<td>DDR3 Mem. wo PKG</td>
<td>0.2mV</td>
</tr>
</tbody>
</table>

**Case1: Board Crosstalk Noise by DDR4-2666**

**Case2: Board Crosstalk Noise by DDR3-1600**
Skew only by a Board Crosstalk Noise

Topology

Aggressor

Victim

Aggressor

Controller

Board Model

S-param

DDR3/DDR4

Skew Measurement

Controller

Controller

Single-end: 40Ω
Differential: 80Ω
Gap ≥ 3W (Se to Se)
Gap ≥ 6W (Se to Diff)

· DDR4-2666
· DDR3-1600

· DDR4-2666
· DDR3-1600
## Skew only by a Board Crosstalk Noise

### DDR4-2666

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR4 Cont. PKG Model</th>
<th>Board Model</th>
<th>DDR4 PKG Model</th>
<th>Switching Pattern</th>
<th>Skew</th>
<th>Skew Variation (Difference of case 1 and 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nothing</td>
<td>Coupled</td>
<td>Nothing</td>
<td>Even mode</td>
<td>110.0ps</td>
<td>0.1ps</td>
</tr>
<tr>
<td>2</td>
<td>Nothing</td>
<td>Coupled</td>
<td>Nothing</td>
<td>Odd mode</td>
<td>109.9ps</td>
<td></td>
</tr>
</tbody>
</table>

![Graphs showing skews for Case 1 and Case 2](image-url)
## Skew only by a Board Crosstalk Noise

### DDR3-1600

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR3 Cont. PKG Model</th>
<th>Board Model</th>
<th>DDR3 PKG Model</th>
<th>Switching Pattern</th>
<th>Skew</th>
<th>Skew Variation (Difference of case 3 and 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Nothing</td>
<td>Coupled</td>
<td>Nothing</td>
<td>Even mode</td>
<td>282.7ps</td>
<td>4.8ps</td>
</tr>
<tr>
<td>4</td>
<td>Nothing</td>
<td>Coupled</td>
<td>Nothing</td>
<td>Odd mode</td>
<td>277.9ps</td>
<td></td>
</tr>
</tbody>
</table>

**Case3**

- **282.7ps**

**Case4**

- **277.9ps**

---

- **DQS**
- **Victim DQ**
- **Aggressor DQ**
Crosstalk Noise Level with Package and Board

Topology

Coupled PKG Model or Uncoupled PKG Model

Board Model S-param

Coupled PKG Model or Uncoupled PKG Model

Aggressor

Victim

Controller
- DDR4-2666
- DDR3-1600

Crosstalk Noise Probe

Single-end: 40Ω Gap ≥ 3W (Se to Se)
Differential: 80Ω Gap ≥ 6W (Se to Diff)

Aggressor

Controller

DDR3/DDR4
# Crosstalk Noise Level with Package and Board

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR4 Controller PKG Model</th>
<th>Board Model</th>
<th>DDR4 PKG Model</th>
<th>Crosstalk Noise Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Coupled</td>
<td>54.4mV</td>
</tr>
<tr>
<td>2</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>0.9mV</td>
</tr>
</tbody>
</table>

Case 1: Coupled Controller & DDR4 PKG Model

![Graph](image1.png)

Case 2: Uncoupled Controller & DDR4 PKG Model

![Graph](image2.png)
# Crosstalk Noise Level with Package and Board

## DDR3-1600

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR3 Controller PKG Model</th>
<th>Board Model</th>
<th>DDR3 PKG Model</th>
<th>Crosstalk Noise Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Coupled</td>
<td>75.9mV</td>
</tr>
<tr>
<td>4</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>0.7mV</td>
</tr>
</tbody>
</table>

**Case3: Coupled Controller & DDR3 PKG Model**

- Crosstalk Noise Level: 73.5mV
- Crosstalk Noise Level: 75.9mV

**Case4: Uncoupled Controller & DDR3 PKG Model**

- Crosstalk Noise Level: 0.5mV
- Crosstalk Noise Level: 0.7mV
Skew by Package and Board Crosstalk Noise

Topology

Coupled PKG Model or Uncoupled PKG Model

Board Model S-param

Coupled PKG Model or Uncoupled PKG Model

Controller

- DDR4-2666
- DDR3-1600

Single-end: 40Ω Gap ≥ 3W (Se to Se)
Differential: 80Ω Gap ≥ 6W (Se to Diff)

Aggressor

Victim

Switching

Skew Measurement

DDR3/DDR4

Controller

DDR3/DDR4
# Skew by Package and Board Crosstalk Noise

## DDR4-2666

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR4 Controller PKG Model</th>
<th>Board Model</th>
<th>DDR4 PKG Model</th>
<th>Switching Pattern</th>
<th>Skew</th>
<th>Skew Variation (Difference with case 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Even mode</td>
<td>110.2ps</td>
<td>-17.6ps</td>
</tr>
<tr>
<td>2</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Odd mode</td>
<td>135.8ps</td>
<td>8ps</td>
</tr>
<tr>
<td>3</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>Even/Odd mode</td>
<td>127.8ps</td>
<td>---</td>
</tr>
</tbody>
</table>

**Graphs:**

- **Case 1:**
  - Skew: 110.2ps
  - Diagram showing Aggressor DQ, Victim DQ, and DQS

- **Case 2:**
  - Skew: 135.8ps
  - Diagram showing Aggressor DQ, Victim DQ, and DQS

- **Case 3 (Even):**
  - Skew: 128.1ps
  - Diagram showing Aggressor DQ, Victim DQ, and DQS

- **Case 3 (Odd):**
  - Skew: 127.5ps
  - Diagram showing Aggressor DQ, Victim DQ, and DQS
## Skew by Package and Board Crosstalk Noise

### DDR3-1600

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR3 Controller PKG Model</th>
<th>Board Model</th>
<th>DDR3 PKG Model</th>
<th>Switching Pattern</th>
<th>Skew</th>
<th>Skew Variation (Difference with case 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Even mode</td>
<td>251.0ps</td>
<td>-25.9ps</td>
</tr>
<tr>
<td>5</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Odd mode</td>
<td>280.3ps</td>
<td>3.4ps</td>
</tr>
<tr>
<td>6</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td>Even/Odd mode Average</td>
<td>276.9ps</td>
<td>---</td>
</tr>
</tbody>
</table>

**Diagram:**

- **Case 4:**
  - 251.0ps skews are marked with arrows on the diagrams showing DQS, Victim DQ, and Aggressor DQ.
- **Case 5:**
  - 280.3ps skews are similarly marked.
- **Case 6 (Even):**
  - 274.9ps skews are marked.
- **Case 6 (Odd):**
  - 278.8ps skews are marked.
Eye Diagram by Package and Board Crosstalk Noise

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR4 Controller PKG Model</th>
<th>Board Model</th>
<th>DDR4 PKG Model</th>
<th>Random Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Coupled</td>
<td>PRBS2^7-1</td>
</tr>
<tr>
<td>2</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td></td>
</tr>
</tbody>
</table>

![Eye Diagram](image)

- **Case1**
- **Case2**

**DDR4-2666**
Eye Diagram by Package and Board Crosstalk Noise

<table>
<thead>
<tr>
<th>Case</th>
<th>DDR3 Controller PKG Model</th>
<th>Board Model</th>
<th>DDR3 PKG Model</th>
<th>Random Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Coupled</td>
<td>Coupled</td>
<td>Coupled</td>
<td>PRBS2^7-1</td>
</tr>
<tr>
<td>4</td>
<td>Uncoupled</td>
<td>Coupled</td>
<td>Uncoupled</td>
<td></td>
</tr>
</tbody>
</table>

Case3

Case4
Conclusions
Conclusions

- The crosstalk noise of the package of controller and DDR3/4 is 20~50mV each.
- The skew variation by the crosstalk noise of the package of controller and DDR3/4 is 20ps each.
- These are bigger than noise level (0mV) and the skew variation (<5ps) of the DDR4-IF board which we used in this investigation.
- The crosstalk noise when we connected the coupled model of controller, board and DDR3/4 became almost the value that added the noise level of each model. (DDR4: 54.4mV≒23.1mV+0.4mV+32.0mV=55.5mV, DDR3: 75.9mV≒47.4mV+0.2mV+37.6mV=85.2mV)
- The skew variation when we connected the coupled model of controller, board and DDR3/4 became almost the value that added the skew of each model. (DDR4: 25.6ps≒11.2ps+16.2ps=27.4ps, DDR3: 29.3ps≒17.2ps+18.6ps=35.8ps)
- The Eye Diagram when we connected the coupled model of controller, board and DDR3/4, had little influence by the crosstalk noise. This is because all bits did not change at the same time and in the same direction for a random pattern.
Conclusions

- The above skew exceeds the rule of the board design guide of the IC vendor.
- The crosstalk noise of the package cannot control the IC user.
- Therefore it is thought that the IC vendor decides the rule of the board design guide of DDR-IF in consideration of the skew variation by package crosstalk noise. In addition, it is supposed that the skew adjustment function of the controller IC coordinates the skew by the package crosstalk noise more than rules.
- In the case of DDR3, DDR4, there is not a rule to judge the good or bad even if we simulate a skew variation by the package crosstalk noise.
- In the case of former PCI-IF, SDR-SDRAM, DDR-SDRAM, a user calculated a timing margin using the AC specifications of the IC and decided a board design rule. Therefore the coupled package model was necessary to consider the skew variation of package.
- But in the case of DDR3, DDR4, we think that it does not have to do simulation including coupled package model, because rule of skew and pitch between signals of the board are given from the IC vendor.
References

  http://www.ibis.org/ver6.1/  for ibis 6.1

- “IBIS Interconnect SPICE Subcircuit (IBIS-ISS) Specification Version 1.0”, IBIS Open Forum 2011
  http://www.ibis.org/ibis-iss_ver1.0/  for ibis-iss
shaping tomorrow with you