# Network-on-Chip benchmarks

## A summary of Network-on-Chip benchmarks

Khanh N. Dang

The University of Aizu

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Contact: khanh@u-aizu.ac.jp
https://u-aizu.ac.jp/~khanh/

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# Introduction

Why do we select these benchmarks? Because these benchmarks can exploit the characteristics of NoC: parallelism and scalability.
Why not the realistic benchmarks? Because we aim the study the network only, not the system performance, therefore, selecting these benchmarks is enough for evaluating.

- Selecting and using benchmark are important for evaluating any system.
- Using benchmarks helps designer understand the performance of their own system and compare with others.
- This presentation aims to explain in details of the benchmarks which are used in OASIS.
    - Transpose
    - Uniform
    - Matrix-multiplication
    - Hotspot 10%
    - Realistic Traffic Pattern

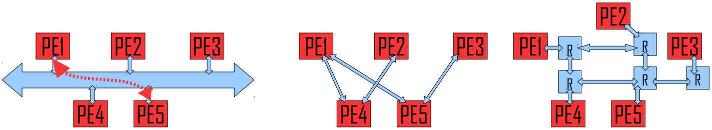
# Network-on-Chip

## Traditional on-chip communication methods

**Bus**: a shared connection between PE (Processing Elements). In a clock cycle, only one communication is performed.
**Point-to-Point**: direct connection between two PEs.

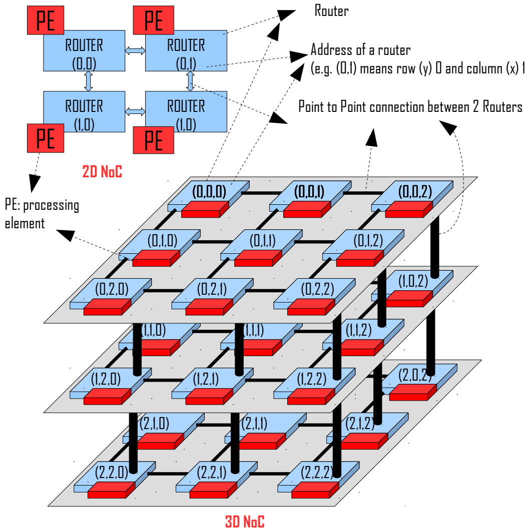
## Network-on-Chip idea

PEs are attached to routers. A communication is done by routing the packets from the source node to the destination node.




Bus Point-to-Point Network-on-Chip

# NoC Annotation



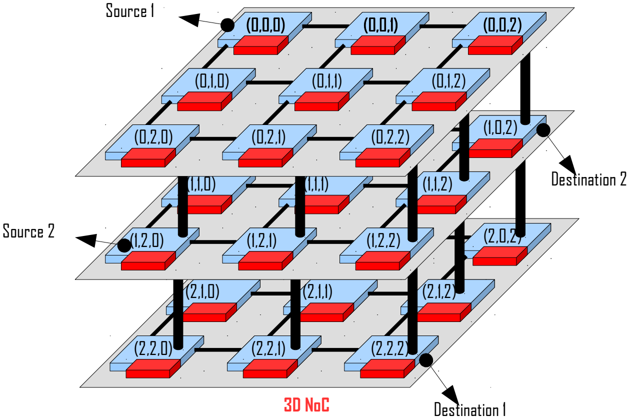
# Detail of Benchmark

| Benchmark | Description | Citation |
|---|---|---|
| Transpose | Each node (a,b,c) in a network with (X,Y,Z) sends packets to node (X-a, Y-b, Z-c) | [1] |
| Uniform | Each node in a network sends packets to all nodes | [2] |
| Matrix-multiplication | Performs C=A*B. Matrix A is stored in layer-1, is sent to layer-2 which has matrix B. The final values are accumulated in layer-3 as matrix C. | [3, 4] |
| Hotspot 10% | Each node in a network sends packets to all nodes. X (X=1 or 2 or more) nodes have additional 10% amount of traffic. | [5] |
| Realistic Traffic Pattern | Generate from task graphs which provide the connections (e.g: node A→B) and the traffic (e.g: 100 packets). | [6, 7] |

⇒ The following slides will explain these benchmarks in details.

# Transpose

**Transpose** is a communication pattern which is based on tranposed matrix. Each nodes sends messages to a reversed dimension index node. A network with size (X,Y,Z). Node (a,b,c) in this network will send to node (X-a-1, Y-b-1, Z-c-1).



# Transpose (cnt)

**Why not (X-a,X-b,Z-c)?** Consider a network with size (3,3,3). The lowest index is 0 and the highest index is 2. If we use (X-a, Y-b, Z-c), router with index 0 will send to router with index 3 (the correct index is 2).
**What if the index start from 1 instead 0?** Consider a network with size (3,3,3). The lowest index is 1 and the highest index is 3. If we use (X-a, Y-b, Z-c), router with index 1 will send to router with index 2 (the correct index is 3). ⇒ In this case, the correct index is (X+1-a, Y+1-b, Z+1-c).
Characteristic:

- Consists of long and short communication hops. For example: A network of $3 \times 3 \times 3$ has 7 hopes connections (e.g (0,0,0) → (2,2,2)) and 1 hopes connections (e.g (1,1,1) → (1,1,1)). ▸ Matlab code
- Bottle-neck: the vertical connection is shared between several connections. A network of $X \times Y \times Z$ has $floor(Z/2)$ pairs of node share a vertical communication. For example: (X=6,Y=6,Z=6), vertical connection between (0,0,2) → (0,0,3) is shared between 3 pairs: (0,0,2) → (0,0,3),(0,0,1) → (0,0,4) and (0,0,0) → (0,0,5).

# Transpose: Communication Length Distribution

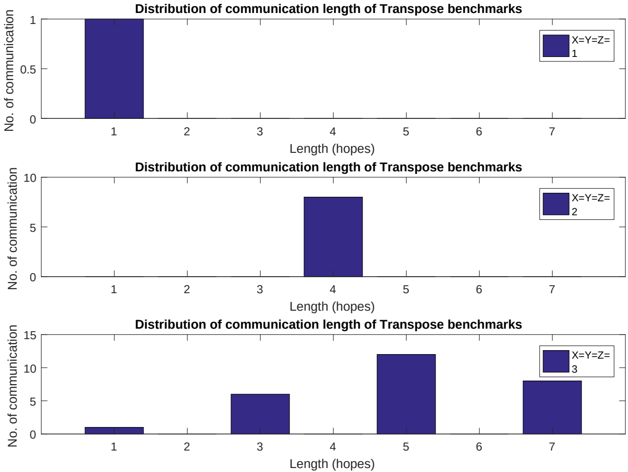



Figure 1: Distribution of communication length. ▸ Matlab code

# Transpose: Communication Length Distribution

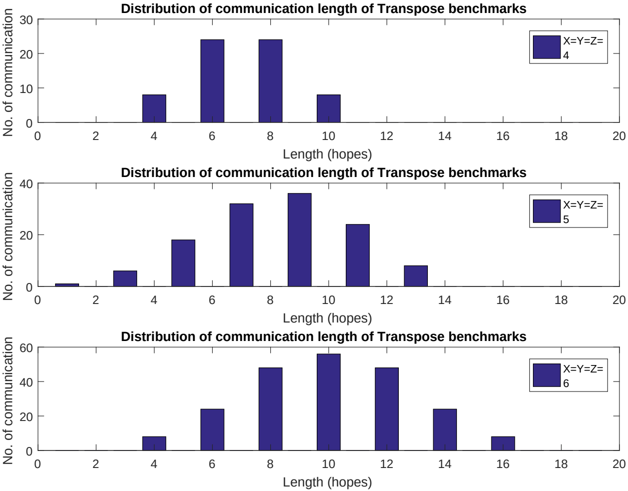



Figure 2: Distribution of communication length.

# Transpose: Communication Length Distribution

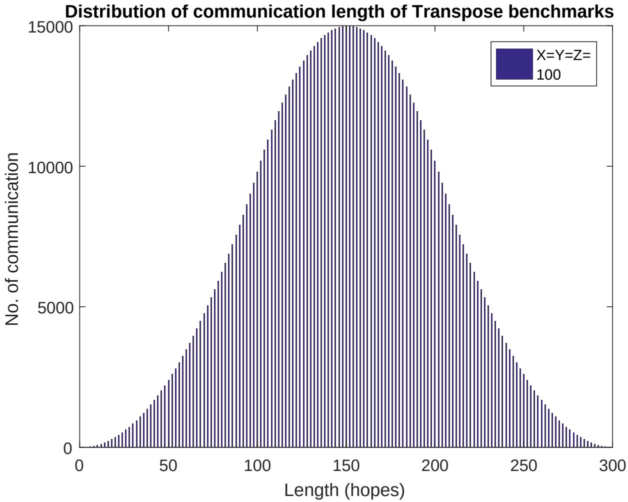
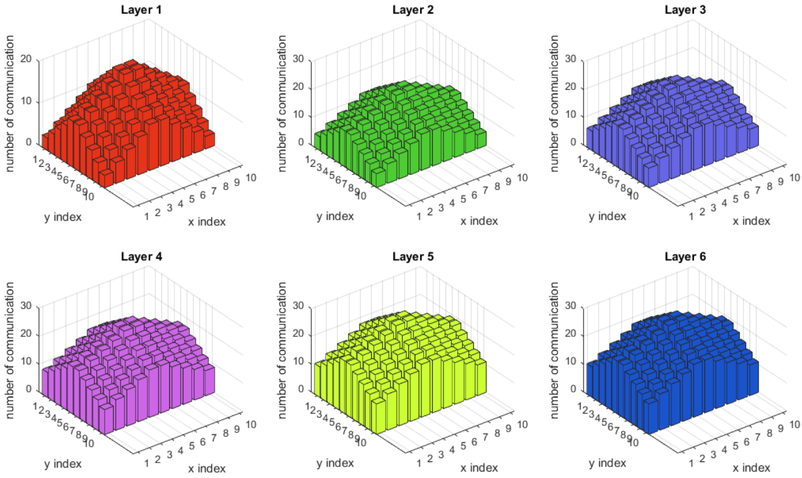



Figure 3: Distribution of communication length. Network size: (100,100,100)

# Transpose: Bottle-neck Analysis / network (10,10,10)




*Note:* This analysis is based on XYZ routing. Each bar represents for the communication of one router.

# Transpose algorithm

**Algorithm 1:** Transpose Algorithm.

```
// Network
```
**Input:** $Network(X, Y, Z)$
```
// Amount of data for each communication
```
**Input:** $D$
```
// Communication set
```
**Output:** $C = \{c_i : (source \rightarrow destination, \text{amount of data})\}$

**foreach** *node (a,b,c) in* $Network(X, Y, Z)$ **do**
  **add** $((a, b, c) \rightarrow (X - a - 1, Y - b - 1, Z - c - 1)$, D packets) **to** $C$
**end**
**return** $C$

# Uniform

**Uniform** is one of standard benchmarks for Network-on-Chip. Each nodes send messages to every node with an equal probability. For example: a network with size (3,3,3). A node (a,b,c) sends the same amount of packets to all node (0,0,0) $\rightarrow$ (2,2,2). In a network (X,Y,Z), probability of source node (a,b,c) is:

$$P_{S==(a,b,c)} = 1/(X \times Y \times Z) \tag{1}$$

Probability of destination node (m,n,p) from source node (a,b,c):

$$P_{D==(m,n,p)} = 1/(X \times Y \times Z) \tag{2}$$

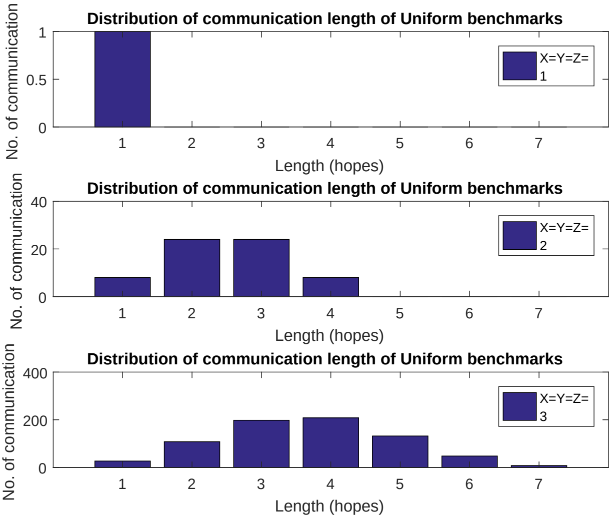
Therefore, probability of a communication is:

$$P_{S==(a,b,c) \text{ and } D==(m,n,p)} = 1/(X \times Y \times Z)^2 \tag{3}$$

Note: if (a,b,c) is eliminated from the destination list, $P_{D==(m,n,p)} = 1/(X \times Y \times Z - 1)$ and $P_{S==(a,b,c) \text{ and } D==(m,n,p)} = 1/((X \times Y \times Z)(X \times Y \times Z - 1)$

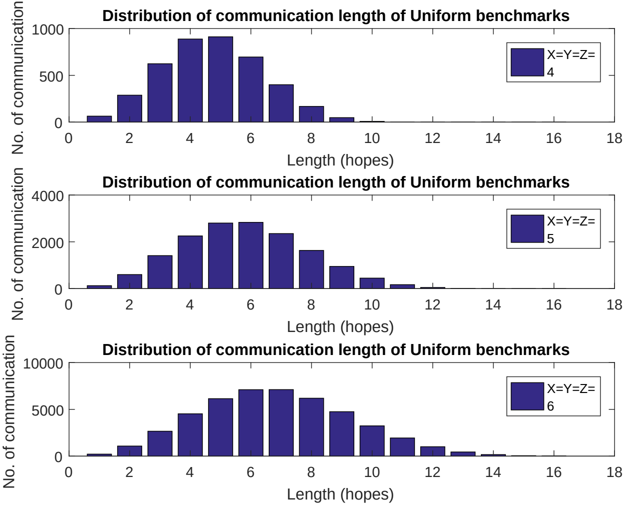
# Uniform Distribution: Communication Length

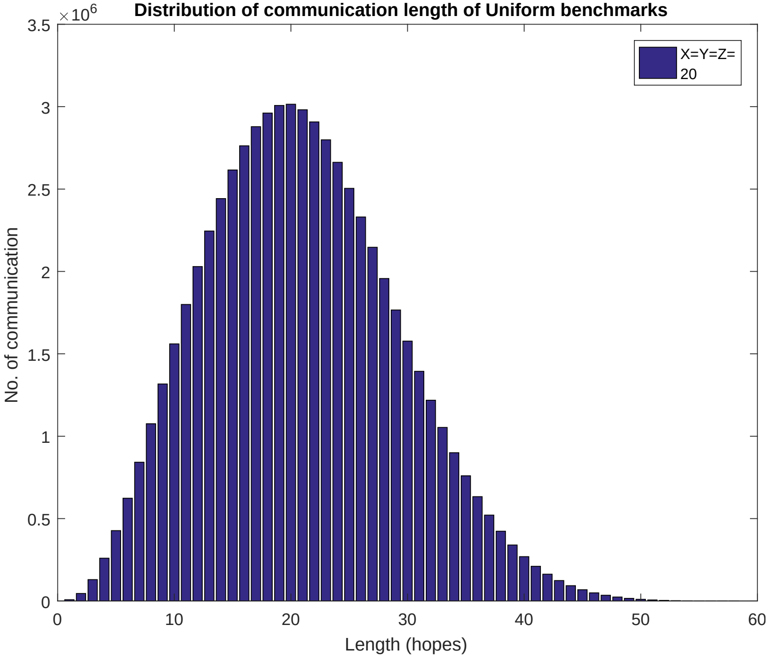
▸ Matlab code



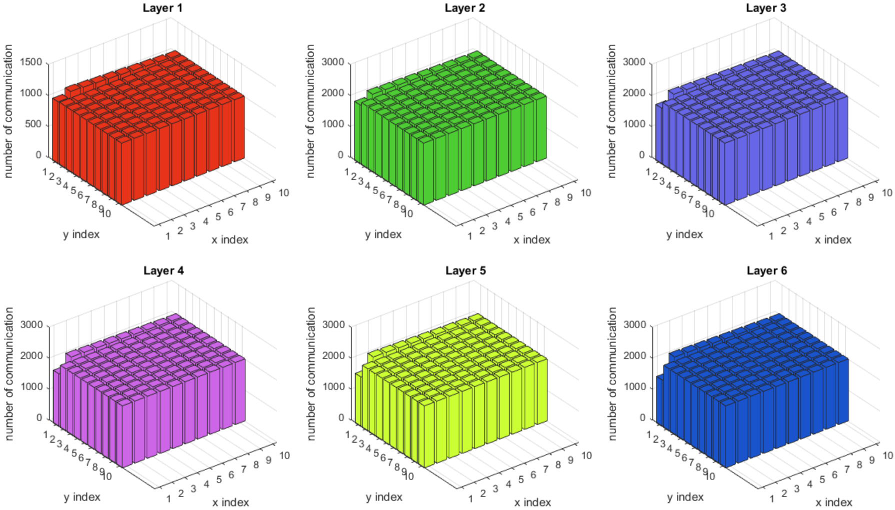
# Uniform Distribution: Communication Length (2)

Matlab code




Distribution of communication length of Uniform benchmarks
×10^6
3.5
3
2.5
2
1.5
1
0.5
0
No. of communication
0
10
20
30
40
50
60
Length (hopes)
X=Y=Z=
20

# Uniform: Bottle-neck Analysis / network (10,10,10)




*Note:* This analysis is based on XYZ routing. Each bar = one router.

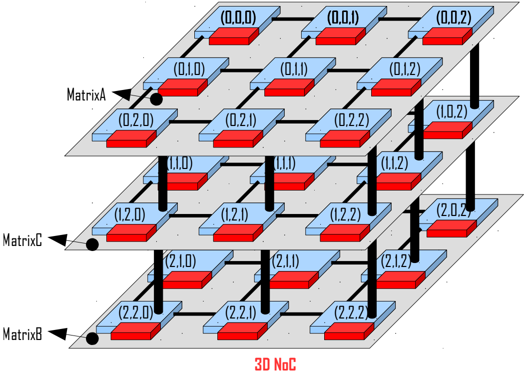
# Uniform algorithm

**Algorithm 2:** Uniform Algorithm.

```
// Network
Input: Network(X, Y, Z)
// Amount of data for each communication
Input: D
// Communication set
Output: C = {c_i : (source → destination, amount of data)}
foreach node (a,b,c) in Network(X, Y, Z) do
    foreach node (m,n,p) in Network(X, Y, Z) do
        add ((a, b, c) → (m, n, p), D packets) to C
    end
end
return C
```

# Matrix-multiplication

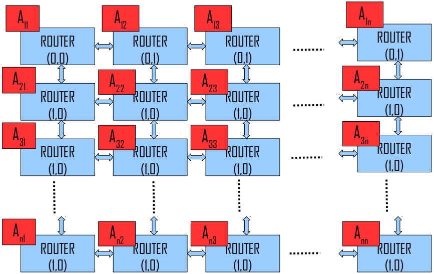
**Matrix multiplication** is one the most common functions for: scientific application, image/video processing, financial calculation. The calculation can be accelerated by utilizing the parallelism of NoC.
Let consider a multiplication: $C = A \times B$ where A,B,C has size (n,n). To calculate the function, matrix A, B, C are mapped to separated layers.



# Matrix-multiplication: Mapping of matrix A

This is how matrix A is mapped. The similar idea is applied for matrix B and C.

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1n} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2n} \\ \multicolumn{5}{c}{\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots} \\ A_{n1} & A_{n2} & A_{n3} & \dots & A_{nn} \end{bmatrix}$$



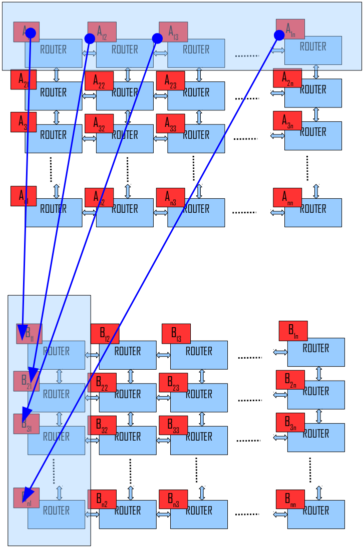
# Matrix-multiplication: Sending data from A to B

Final equation:

$$C_{ij} = \sum_{k=1}^{n} A_{ik} \times B_{kj} \qquad (4)$$

Step 1: Element $A_{ik}$ of matrix A is sent and **multiplied** to element $B_{ji}$ of matrix B.

$$R_{ji} = A_{ij} \times B_{ji} \qquad (5)$$



# Matrix-multiplication: Sending data from A to B

Step 2: Result $R_{ij}$ is sent and **accumulated** to obtain matrix C.

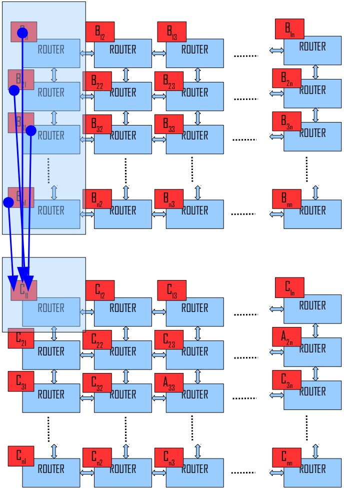
$$C_{ij} = \sum_{k=1}^{n} R_{ki} \tag{6}$$

Where:

$$R_{ji} = A_{ij} \times B_{ji} \tag{7}$$

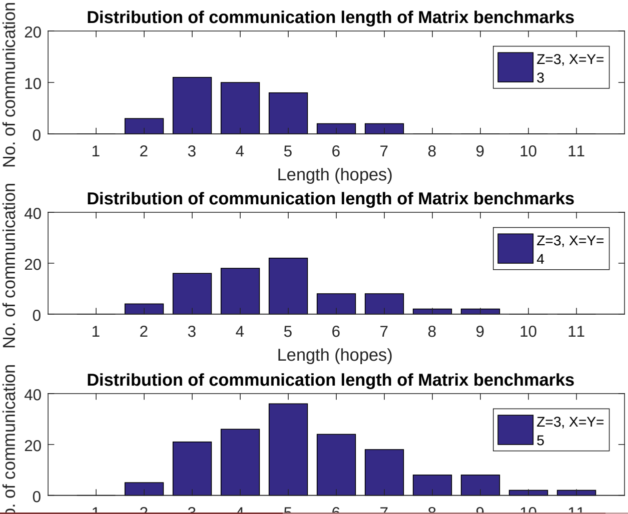
Therefore:

$$C_{ij} = \sum_{k=1}^{n} A_{ik} \times B_{kj} \tag{8}$$



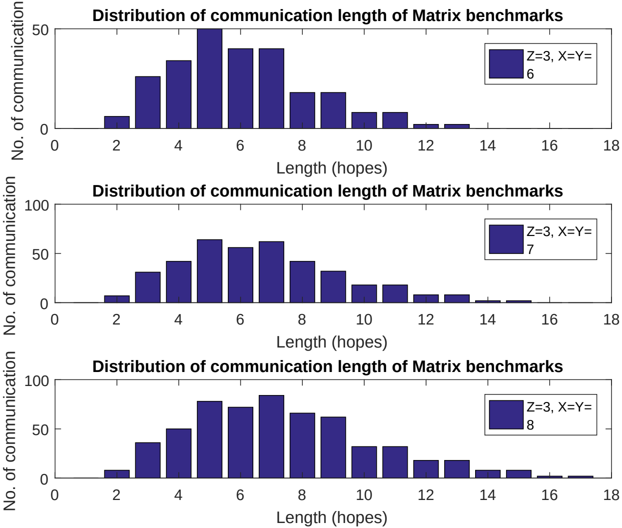
# Matrix-Multiplication Distribution: Communication Length

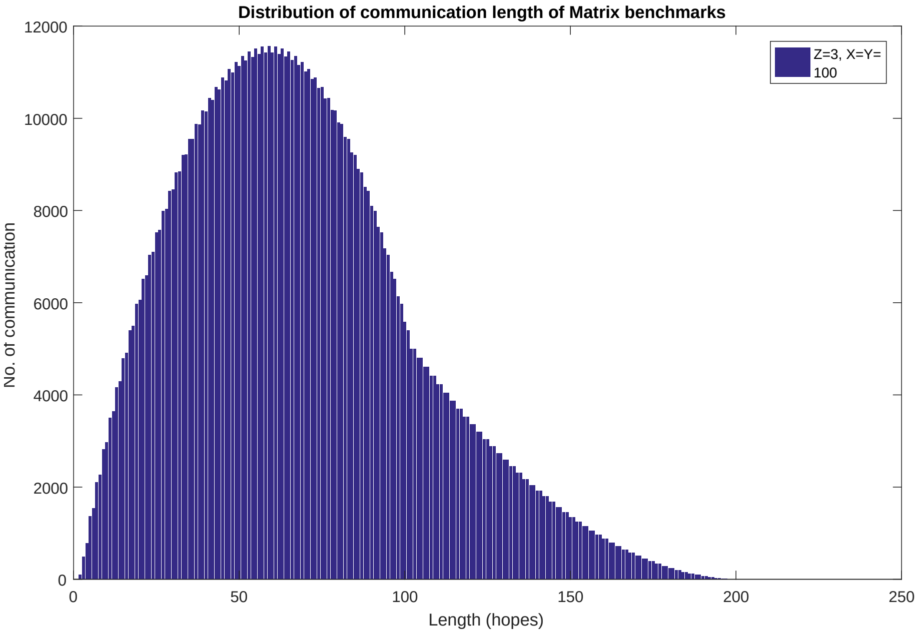
▸ Matlab code



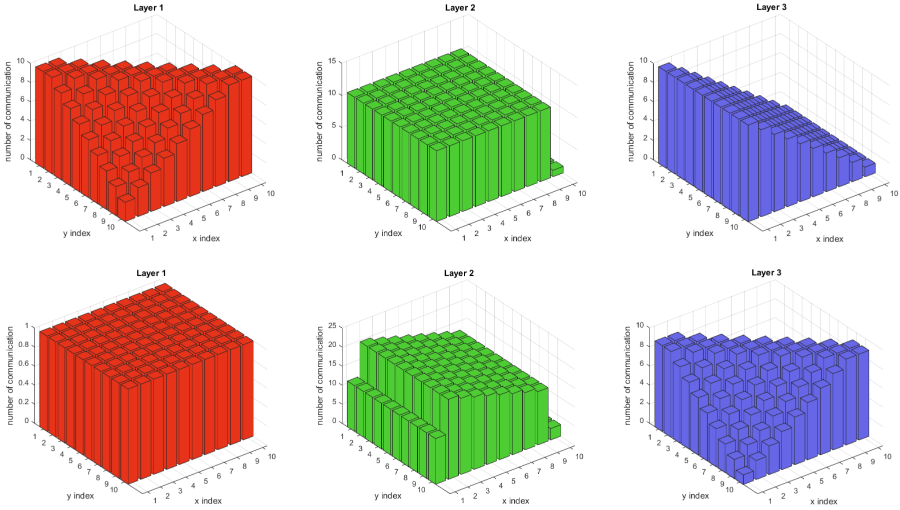
# Matrix-Multiplication Distribution: Comm. Length (2)

▸ Matlab code




Distribution of communication length of Matrix benchmarks
Z=3, X=Y=
100
No. of communication
Length (hopes)
0
2000
4000
6000
8000
10000
12000
0
50
100
150
200
250

# Matrix-multiplication: Bottle-neck Analysis / network (X=10,Y=10,Z=3)



# Matrix-multiplication algorithm

**Algorithm 3:** Matrix-multiplication Algorithm.

**Input:** *layerA*$(n, n)$, *layerB*$(n, n)$, *layerC*$(n, n)$,
**Input:** $A(n, n)$, $B(n, n)$
**Output:** $C(n, n)$

```
foreach node (i,j) in layerA(n, n) do
    send A(i,j) → layerB(j,i)
end
foreach node (i,j) in layerB(n, n) do
    receive A(j,i)
    R(i, j) = A(j, i) × B(i, j)
    foreach k in 1:n do
        send R(i,j) → layerC(i,k)
    end
end
foreach node (i,j) in layerC(n, n) do
    foreach k in 1:n do
        send C(i,j) = C(i,j) + R(k,i)
    end
end
return C(n, n) from layerC(n, n)
```

# Hotspot 10%

**Hotspot** is similar to **Uniform**. Each nodes send messages to all non-hotspot node with an equal probability. The hotspot nodes are received extra E% of probability (e.g: 10%). For example: a network with size (3,3,3). A node (a,b,c) sends the same amount of packets to all node (0,0,0) $\rightarrow$ (2,2,2). In a network (X,Y,Z), probability of source node (a,b,c) is:

$$P_{S==(a,b,c)} = 1/(X \times Y \times Z) \tag{9}$$

# Hotspot algorithm

**Algorithm 4:** Hotspot Algorithm.

`// Network`

**Input:** $Network(X, Y, Z)$

`// Amount of data for each communication`

**Input:** $D$

`// Extra percentage of hotspot node`

**Input:** $E$

`// Communication set`

**Output:** $C = \{c_i : (source \rightarrow destination, \text{amount of data})\}$

**foreach** *node (a,b,c) in* $Network(X, Y, Z)$ **do**<br>
    **foreach** *node (m,n,p) in* $Network(X, Y, Z)$ **do**<br>
        **if** *node (m,n,p) is hotspot node* **then**<br>
            **add** $((a, b, c) \rightarrow (m, n, p)$, (D+D*E/100) packets) **to** $C$<br>
        **else**<br>
            **add** $((a, b, c) \rightarrow (m, n, p)$, D packets) **to** $C$<br>
        **end**<br>
    **end**<br>
**end**<br>
**return** $C$

# Realistic Traffic Pattern

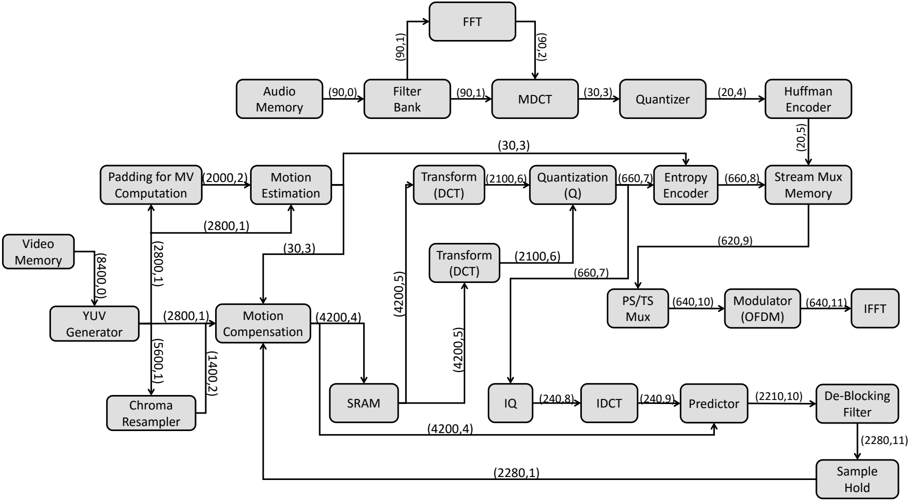
Realisc Traffic Pattern is design to import a mapped task graph to perform a simulation. It requires:

- A task graph from an application.
- Post-mapped topology from the task graph.
- Information of communication (source $\rightarrow$ destination, amount of data).
- Network on Chip model.

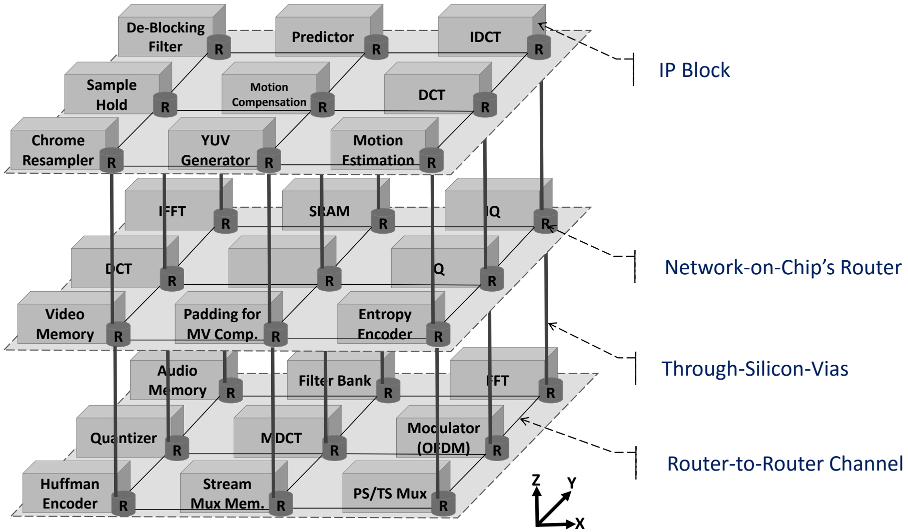
Source code (Verilog HDL): link

# An example task graph: H.264 Encoder

A communication has an extra number: (D, O). D: amount of data (packets), O: order of communication.



# An example of mapped application to 3D NoC



# Algorithm of Realistic Benchmark

**Algorithm 5:** Realistic Benchmark Algorithm.

**Input:** $Network(X, Y, Z)$

// Communication set

**Input:** $C = \{c_i : (source \rightarrow destination, D, O)\}$

ProgramCounter = 0;

**foreach** *node (i,j,k) in* $Network(X, Y, Z)$ **do**

  **foreach** $c_i$ *in* $C$ **do**

    **if** $c_i(source) == (i, j, k)$ *and* $ProgramCounter == O$ **then**

      **send** (i,j,k) $\rightarrow$ $c_i(destination)$ with $c_i(D)$ packets.

    **end**

    **if** $c_i(destination) == (i, j, k)$ *and* $ProgramCounter == O$ **then**

      **receive** $c_i(D)$ packets.

    **end**

  **end**

**end**

**if** *all destinations completedly receive their own* $c_i(D)$ *packets* **then**

  ProgramCounter++;

**end**

*Note:* The analysis for these benchmarks is not completed.

# Conclusion

- This presentation shows the details of how the benchmarks work.
- I explain the algorithm and the distribution of the benchmarks:
  - Transpose
  - Uniform
  - Matrix-multiplication
  - Hotspot 10%
  - Realistic Traffic Pattern
- The whole analysis code can be download from: ▸ this repository.

# References I

[1] A. A. Chien and J. H. Kim, "Planar-adaptive routing: low-cost adaptive networks for multiprocessors," *Journal of the ACM (JACM)*, vol. 42, no. 1, pp. 91–123, 1995.

[2] R. Sivaram, "Queuing delays for uniform and nonuniform traffic patterns in a MIN," *ACM SIGSIM Simulation Digest*, vol. 22, no. 1, pp. 17–27, 1992.

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[5] W. J. Dally and B. P. Towles, *Principles and practices of interconnection networks*.
Elsevier, 2004.

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[7] D. Bertozzi, A. Jalabert, S. Murali, R. Tamhankar, S. Stergiou, L. Benini, and G. De Micheli, "NoC synthesis flow for customized domain specific multiprocessor systems-on-chip," *IEEE Transactions on Parallel and Distributed Systems*, vol. 16, no. 2, pp. 113–129, 2005.

Thank you for your attention!