A Design Methodology and Various Performance and Fabrication Metrics Evaluation of 3D Network-on-Chip with Multiplexed Through-Silicon Vias

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Abstract—The use of short Through-Silicon Vias (TSVs) in 3D integration Technology introduces a significant reduction in routing area, power consumption, and delay. Although, there are still several challenges in 3D integration technology; mainly low yield, which is a direct result of extra fabrication steps of TSVs. Therefore, reducing TSV count has a considerable effect on improving yield and hence reducing cost. A TSV multiplexing technique called TSVBOX was introduced in [1] to reduce the TSV count without affecting the direct benefits of TSVs. Although, the TSVBOX introduces some delay to the signals to be multiplexed, this delay effect of TSV multiplexing is not addressed yet. In this paper, we analyze the TSVBOX timing requirements and propose a design methodology for TSVBOX-based 3D Network-on-Chip (NoC). Then performance and power comparisons are conducted to investigate the direct effects of TSV multiplexing on these two metrics. After that the basic fabrication metrics are compared to investigate the effect of the proposed design methodology on yield and cost. We show that the TSVBOX extremely enhances the fabrication metrics at minimal degradation in performance and power consumption, especially for Hotspot-like traffic patterns.

I. INTRODUCTION

Conventional 2D integration proves to have many limitations for nowadays large systems needs. For example, long wires increase power consumption and routing area. Also, it adds great difficulty to distribute the clock signal with minimum delay for large systems. Such problems make 2D integration unable to follow Moore's law any more [2].

On the other side, 3D integration is an emerging technology that can mitigate the main limitations of conventional 2D integration. However there are still some challenges that need more and more focus and research work to make such promising technology mature and reliable. One of these challenges is the reliability issues in terms of yield and cost. 3D-ICs show very low yield due to extra fabrication steps for bonding dies or wafers to each other to create the 3D stack. These extra steps may result in faulty TSVs due to misalignment of TSVs, partially filled ones, etc. [3]. What makes the situation worse, is that the probability of having faulty TSVs increases as the

total number of TSVs increases. Hence, finding a technique that reduces TSV count without affecting the benefits gained by 3D integration is very important. In [1, 4, 5] the TSV count has been reduced by multiplexing, serialization, or virtualization, respectively. The TSV multiplexing technique introduced in [1] reduces the number of TSVs by half, by multiplexing each two 3D signals¹ into one signal and passing this signal through one TSV instead of two as in the conventional 3D-ICs. Therefore almost 50% reduction in the number of TSVs is achieved. Due to the significant reduction in TSV count, the analysis done in [1] on yield has revealed very high improvement over conventional 3D-ICs.

The investigation in [1] covered area, yield, cost, and power consumption analysis. In [6, 7], other physical effects of reducing TSV count are studied. In [6], the impact of reducing TSV count on maximum temperature is investigated, and as expected the maximum temperature increases as the TSV count decreases. TSVs are usually fabricated using low thermal resistivity materials such as copper or tungsten [2]. Therefore reducing TSV count will increase the total thermal resistance of the 3D stack. In [7] the residual thermal-stress impact created during bonding process in fabrication has been studied carefully to accurately determine the Keep-Out-Zone area overhead around TSVs in order to accurately estimate the yield of the 3D stack.

The TSVBOX uses extra selection signal (S) to control the multiplexer (MUX) and the demultiplexer (DeMUX). This S signal introduces some delay to one of the multiplexed signals besides the parasitics of the TSVBOX itself. Such delay may affect the functional validity of the system to be implemented using TSVBOX. Although, [1, 6, 7] address most of the issues related to TSVs multiplexing and show the advantages and limitations of this technique, the timing requirements and the design methodology based on TSV multiplexing have not

¹A 3D signal is the signal that traverses from one layer to another in the 3D stack

been studied yet. None of the above related works shows any system implementation of a circuit using TSVBOX, so its functionality and applicability in system level have not been proven yet.

Due to its scalability and novelty as a multicore communication architecture for future multiprocessor SoCs, 3D NoC is selected as our target system architecture for applying the TSVBOX technique. In this paper, timing requirements for TSVBOX-based 3D NoC are investigated so that the delay introduced by the TSVBOX is mitigated and the performance degradation and incorrect operation are avoided. Also, the design methodology for the TSVBOX-based 3D NoCs is introduced. For the sake of comparison, two versions of 3D NoCs are introduced, one based on conventional 3D integration without TSV multiplexing, while the other version is TSVBOX-based. Finally, the main aspects of the NoC architecture in terms of performance and power are investigated under different simulation scenarios.

The contribution of this paper can be summarized in the following points:

- A Low-level circuit model for TSVBOX is introduced, in order to estimate the TSVBOX delay and power consumption; showing possible RC parasitics of its different components.
- Studying the timing requirements of the TSVBOX, determining the selection signal properties and its relation to the main clock signal in the case of 3D NoCs.
- Introducing a complete design methodology with detailed steps required to design a 3D NoC involving TSVBOX.
- Investigating the most important aspects of the 3D NoC; performance and power consumption, showing the cases at which the TSVBOX does not affect these metrics.
- Proposing analytical models to compare the basic fabrication metrics; yield and cost of the conventional and TSVBOX-based 3D NoCs.

Finally, this work is an extensive extension of the work of [8] in many ways. All differences between this work and the work of [8] is included in Table I. According to our estimation the extra work is more than 60% of the work of [8].

The rest of this paper is organized as follows: Section II presents the details of the TSVBOX technique. Section III explores the architecture and design of the target 3D NoC and the 3D router used. Sections IV and V highlight the TSVBOX parasitic model and various design aspects. Section VI introduces the TSVBOX timing requirements analysis and the TSVBOX-based 3D NoC design methodology. The scalability analysis is investigated in Section VII, while the fabrication yield and cost are analyzed in Section VIII. Simulation results are discussed and presented in Section IX. Finally, Section X concludes the paper.

II. TSVBOX

Fig. 1a shows the TSVBOX structure. As shown in Fig. 1b, the two inputs of the TSVBOX multiplexer (MUX) are the two signals (V_1, V_2) that are supposed to be multiplexed through single TSV. The S signal (Fig. 1c) is the signal

that controls MUX and DeMUX, and its clocking period T_S is at least equivalent to double the delay of the TSVBOX ($T_{d-TSVBOX}$), where $T_{d-TSVBOX}$ is the delay from the input point V_1 (V_2) to the output point V_1' (V_2'). Assuming that during the first half cycle V_2 is selected, the TSVBOX circuit will hold the charge of V_2 during the second half cycle, therefore

$$V_2'(t) = V_2(t - \frac{T_S}{2}) \quad (1)$$

During the second half cycle similar behavior for V_1' is repeated but with another time shift equal to $\frac{T_S}{2}$ due to the waiting of the selection process of the first half cycle, so at the end we have

$$V_1'(t) = V_1(t - T_S) \quad (2)$$

Fig. 2 shows all the TSVBOX signals and how V_1 and V_2 are affected with the TSVBOX delays. For more details about the TSVBOX functionality refer to [1]. In [1] it is assumed that the delay incurred by the TSVBOX $T_S \ll T_{CLK}$, therefore this delay can be neglected and there would be no incorrectness issues in reading the multiplexed voltages. In real application this situation is feasible for example when both 3D paths of V_1' and V_2' are not part of the critical path, and their delay is at least less than the critical path delay by T_S . However, the general situation when T_S is comparable to the clock signal is not addressed in [1]. Therefore, there are some timing requirements that the TSVBOX must fulfill for the sake of correct operation. In this paper all conditions or requirements will be studied for 3D NoC architecture.

III. THE TARGET 3D NoC ARCHITECTURE

Fig. 3 shows the target 3D NoC architecture, which relies on a $4 \times 4 \times 4$ mesh topology. In [9] an 80 core NoC was presented, so our target NoC matches the trend of NoC domain. For simplicity, each router has core concentration of one [10], which means only one processor core is connected to the local port of the router. To achieve strong fairness between internal requests of the router, separable allocation is adopted with Round-Robin arbitration [11]-[12]. The size of each injected packet is five flits, and each flit in turn is 64 bits. The head flit contains the routing information while the others are supposed to carry the data. We choose wormhole switching and XYZ deterministic routing to be the 3D NoC switching technique and routing algorithm [13], respectively. Each input port in the router contains two virtual channels of size one flit while the local virtual channel buffers are assumed to be with infinite size to serve isolating traffic injection process from the NoC. Therefore the delay after generating the flit and before entering source buffer is accounted for as well as the delay in the source queue buffers [14]. According to [15, 16] the total system area can be assumed 400 mm^2 , thus the area of each layer of the target 3D NoC can be assumed $10 \times 10 \text{ mm}^2$. Hence the length of the horizontal interconnect wires between two neighbor routers are 2.5 mm [16]. For the vertical interconnects, we choose the TSV capacitance to be a parameter in our simulations. The change in TSV capacitance reflects the change in TSV length

TABLE I: Differences and extra contributions of this extended work in comparison to the work of [8].

Facets of comparison	Work of [8]	This paper
3D NoC adopted	$3 \times 3 \times 2$	$4 \times 4 \times 4$
Switching technique	Store-And-Forward	Wormhole
Virtual channels (VCs)	Single buffer per port	2 VCs per port
Technology adopted	180 nm	More finer 65 nm technology
TSV capacitance	Fixed at 15 fF	Considered as a parameter with 15 fF to 500 fF to reflect different TSV technologies
TSVBOX multiplexing ratio used	Fixed at 2×1	Considered as a general parameter $N_{MUX} \times 1$, $N_{MUX} \geq 2$
Yield and cost analysis	-	Included in Section VIII
Analytical analysis on the effect of different traffic patterns on the performance of TSVBOX	-	Included in Subsection VII-D
Power consumption evaluation	-	Included in Subsection IX-E
Scalability analysis	-	Included in Section VII

Fig. 1: (a) TSVBOX schematic, (b) TSVBOX circuit implementation, (c) Selection signal S .

Fig. 2: Various TSVBOX signals; $S(t)$, $V_1(t)$, $V_2(t)$, $V_1'(t)$, and $V_2'(t)$.

and the resistivity of the substrate bulk used which in turn reflects different 3D integration technologies [17]-[20].

The data bus width N_{BW} is assumed to be equivalent to the flit size, as shown in Figs. (5a,5b). For the conventional 3D NoC, the whole 3D data bus width is $N_{BW}+2$, where the extra two bits are required for the handshaking communication protocol which needs request (REQ) and acknowledgement (ACK) signals [21]. For the TSVBOX case, the data bits of the packet are multiplexed and hence $\frac{N_{BW}}{2}+2$ TSVs are required, including REQ and ACK signals. However for each vertical bus width two extra TSVs are required to transfer the S signal and its inverted version $\bar{S}$. Therefore, the vertical connection bus width is $\frac{N_{BW}}{2}+4$ for the TSVBOX-based 3D NoC. Any two neighbor routers are connected by

Fig. 3: $4 \times 4 \times 4$ 3D NoC architecture.

two opposite unidirectional channels. Thus the vertical port contains $2(N_{BW}+2)$ TSVs for conventional 3D NoC, and $2(\frac{N_{BW}}{2}+4)$ for TSVBOX case.

Since SPICE models for such system would be too complicated and time consuming either in design or simulation, SystemC-A is used for our 3D NoC implementation. SystemC supported by the Open SystemC Initiative (OSCI) [22] is an open source language available to meet the ever-increasing needs of system-level design and SoC technologies. Using SystemC-A, high- and low-levels of implementation can be done together for a system. For processor cores, routers, and intra-layer interconnects, we use behavioral system implementation, while for inter-layer interconnects (the vertical connections), we rely on a low-level circuit implementation to be able to estimate delays and power consumption.

IV. MODELING

As shown in Fig. 4a, the 3D signal is assumed to pass through an input inverter driver, a global wiring segment in the first layer, a TSV, a global wiring segment in the second layer, and an output inverter driver. The output inverter driver is assumed always 1x-inverter (minimum size inverter). For the TSV and wiring circuit models, the models introduced in [2, 23] are used, which are shown in Figs. 4(b,c), respectively.

The TSVBOX is composed of MUX and DeMUX circuits and a TSV in between. The MUX or the DeMUX is composed of two transmission gates and each transmission gate is composed of two transistors. Therefore to model TSVBOX, a transistor circuit model that depicts different transistors' RC parasitics is required. Referring to [24], the transistor parasitics can be modeled as shown in Fig. 4(d,e). The parasitics of this model are: ON resistance of $NMOS$ (R_{onN}), ON resistance of $PMOS$ (R_{onP}), $NMOS$ source/drain-bulk capacitance (C_{sbN}/C_{dbN}), $PMOS$ source/drain-bulk capacitance (C_{sbP}/C_{dbP}), $NMOS$ gate capacitance (C_{gN}), and $PMOS$ gate capacitance (C_{gP}). According to [24], $C_{sbN}=C_{dbN}=C_N$ for $NMOS$ and $C_{sbP}=C_{dbP}=C_P$ for $PMOS$. Also, for equivalent

TABLE II: Transistor and other miscellaneous parasitics for 65 nm.

Transistor parasitic	Unit	65 nm
C_{gP}	fF	0.0689
C_{gN}	fF	0.0689
C_{sbP}	fF	0.0832
C_{sbN}	fF	0.0819
C_{dbP}	fF	0.0832
C_{dbN}	fF	0.0819
R_{onP}	k Ω	44.462
R_{onN}	k Ω	21.077
C_W	fF	25
R_W	k Ω	0.04132
$ V_{thP} $	V	0.39
V_{thN}	V	0.4
V_{DD}	V	1
C_L	fF	1.3
C_p	fF	1.5

Fig. 4: (a) The 3D signal path and circuit models of (b) TSV, (c) global wiring, (d) $NMOS$, and (e) $PMOS$.

$NMOS$ and $PMOS$ sizes, both $NMOS$ and $PMOS$ gate capacitances' values are equivalent so $C_{gP}=C_{gN}=C_g$.

A. Conventional 3D-IC 3D signal path modeling

The conventional 3D-IC 3D signal path is shown in Fig. 6 where the signal is assumed to pass through an inverter driver (represented by its ON resistance $R_{dr-Conv}$), a global wiring segment in the first layer, a TSV, a global wiring segment in the second layer, and a load capacitance which is assumed to be the input gate capacitance of a 1x-inverter driver in the second layer.

B. TSVBOX 3D signal path modeling

Fig. 7 shows the TSVBOX circuit model. It is similar to the circuit of the conventional 3D signal path, the difference is that the equivalent RC parasitic circuit of the transistors in MUX and DeMUX are involved. Since there is no transistor models in SystemC-A, the transistors of the transmission gate are modeled using perfect switches. The S signal controls the upper transmission gates of the MUX and the DeMUX, and its inverted version $\bar{S}$ controls the lower ones. Therefore both the lower and upper transmission gates will switch ON or OFF exclusively as required in the original TSVBOX design. The S signal path shown in Fig. 7, is similar to the conventional 3D signal path. However, since the S signal is driving the gates of the transmission gates, therefore for each S path, there are four gate capacitances $4C_g$ involved in the load; $2C_g$ from MUX and $2C_g$ from DeMUX.

V. DESIGN PARAMETERS AND PARASITICS

In this section, parasitics values and technology parameters are introduced and the design considerations are detailed.

A. Technology parasitics and parameters

In this study 65 nm is selected to be our target technology. Technology parasitics and parameters spans the $NMOS$ s' and $PMOS$ s' parasitics shown in Fig. 4 and also their threshold voltages. It also covers the global wiring parasitics which are used for IPs and multicore 3D-ICs [25] and the input and

Fig. 5: Full duplex transmission for (a) conventional and (b) TSVBOX-based 3D NoC.

Fig. 6: Conventional 3D NoC 3D signal path.

Fig. 7: TSVBOX-based 3D NoC 3D signal path.

the output capacitances of 1x-inverter driver shown in Fig. 4a. Table II shows all the values used in this study [24–26], noting that the length of the wires is assumed 200 μm similar to [17].

For the TSV technology, the experiments run once for $C_{TSV}=15$ fF and another for $C_{TSV}=500$ fF to cover the whole range of TSV capacitances and technologies, while the maximum value for $R_{TSV}=1$ Ω is selected for all cases [17].

B. Transmission gate transistors

According to [27], transmission gate transistors are usually selected to have minimum size. Also, as stated in [27], there is

no need to decrease R_{onP} , hence $W_P=L_P$ and $K_N=K_P=1$ (the sizes of $NMOS$ and $PMOS$ transistors, respectively) are our design choices for the transmission gate transistors.

C. Threshold voltage selection for the drivers

There are two input thresholds: $V_{inL-max}$ and $V_{inH-min}$. $V_{inL-max}$ is the maximum low input voltage required to switch $PMOS$ ON and $NMOS$ OFF at the same time. Therefore if $V_{in} \leq V_{inL-max}$, $NMOS$ will be OFF and $PMOS$ will be ON. The other threshold voltage is $V_{inH-min}$, which is the minimum high input voltage required to switch

NMOS ON and *PMOS OFF* at the same time, therefore if $V_{in} \geq V_{inH-min}$, *NMOS* will be *ON* and *PMOS* will be *OFF*. Depending on the previous definitions, the thresholds can be selected as follows

$$V_{inL-max} = V_{thN}, V_{inH-min} = V_{DD} - |V_{thP}| \quad (3)$$

VI. TIMING REQUIREMENTS' ANALYSIS

In this section all timing analysis related to TSVBOX-based 3D NoC is discussed. Timing requirements' analysis include 3D path delays, how to choose the selection signal period T_S , and the relation between S and the main clock signal.

A. 3D signal path Elmore-delay model

The 3D signal path delay for data and S signals in conventional and TSVBOX-based 3D NoCs can be approximated using first order Elmore-delay model [24]. The delay for data signals is the time required for the 3D data signal to reach $V_{inH-min} = V_{DD} - |V_{thP}|$. The 3D data signals passing through the conventional or the TSVBOX 3D paths are to be destined to a 1x-inverter driver load, as shown in Figs. (6,7), respectively. For S signal, the delay is the time required for S to reach $\max(V_{thN}, |V_{thP}|)$, because S is destined to the transmission gate transistors (*PMOS* or *NMOS*). Hence the voltage required for S signal to switch either *NMOS* or *PMOS ON* is V_{thN} or $|V_{thP}|$, respectively. The maximum of these two voltages is selected to meet both conditions.

According to Section V, the wiring and TSV resistances are in order of ohms, therefore their contribution to the total delay is negligible. Thus these resistances will be ignored to simplify the delay analysis in this paper.

1) *Conventional 3D NoC 3D signal delay*: Referring to Fig. 6, the conventional 3D NoC 3D signal path delay (T_{d-Conv}) can be approximated using Elmore-delay as follows:

$$T_{d-Conv} = \ln \frac{V_{DD}}{|V_{thP}|} \cdot (R_{dr-Conv} \cdot (C_p + 2C_W + C_{TSV} + C_L)) \quad (4)$$

2) *TSVBOX-based 3D NoC 3D signal delay*: The TSVBOX has two different paths according to the values of the S signal. Fig. 8 shows the situation when $S=1$ ($\bar{S}=0$) that V_1 passes through the TSVBOX, while Fig. 9 shows the other state when $S=0$ ($\bar{S}=1$) that V_2 passes. As noticed, both paths are similar, therefore the TSVBOX 3D path delay ($T_{d-TSVBOX}$) for both V_1 and V_2 is the same. The Elmore-delay for both V_1 and V_2 can be approximated according to the following equation

$$\begin{aligned} T_{d-TSVBOX} = \ln \frac{V_{DD}}{|V_{thP}|} \cdot & (R_{dr-TSVBOX} \cdot (C_p + C_{PN}) \\ & + (R_{dr-TSVBOX} + R_{PN}) \cdot (4C_{PN} + 2C_W + C_{TSV}) \\ & + (R_{dr-TSVBOX} + 2R_{PN}) \cdot (C_{PN} + C_L)) \end{aligned} \quad (5)$$

$$\text{where } C_{PN} = C_{dbP} + C_{dbN}, R_{PN} = \frac{R_{onP} \cdot R_{onN}}{R_{onP} + R_{onN}}$$

3) *Selection signal delay*: The S signal path is shown previously as a part of the TSVBOX in Fig. 7. As shown, each TSVBOX contributes to the load of S signal by $4(C_{gN} + C_{gP})$. Then for $\frac{N_{BW}}{2}$ data bus width, the TSVBOXes will contribute with $N_{BW} \cdot (C_{gN} + C_{gP})$ in total to the S signal load. As stated in Section V, the transmission gates transistors are equally sized ($C_{gN} = C_{gP} = C_g$), therefore the total gate load for S signal is $2N \cdot C_g$. The Elmore-delay for S signal to reach $\max(V_{thN}, |V_{thP}|)$ is

$$T_{d-S} = \ln \frac{V_{DD}}{V_{DD} - \max(V_{thN}, |V_{thP}|)} \cdot (R_{dr-S} \cdot (C_p + 2C_W + C_{TSV} + 2N_{BW} \cdot C_g)) \quad (6)$$

B. Avoiding concurrent ON state of the TSVBOX switches

As shown in Fig. 10. At $t = \frac{T_S}{2}$, S and $\bar{S}$ will start discharging and charging, respectively. However, $\bar{S}$ will reach the *ON* threshold voltage $\max(V_{thN}, |V_{thP}|)$ at $t = T_1$, while S will reach the *OFF* threshold voltage $\min(V_{thN}, |V_{thP}|)$ at $t = T_2$. This is because $\bar{S}$ is '0' and S is V_{DD} , and '0' is much closer to $\max(V_{thN}, |V_{thP}|)$, than V_{DD} to $\min(V_{thN}, |V_{thP}|)$. It can be seen that during $T_1 \leq t \leq T_2$, all the transmission gate switches of the TSVBOX are *ON* which violates the theoretical behavior of the TSVBOX.

Fig. 11 displays how the above problem could occur as a result of the previously discussed behavior². In this example, V_1 and V_2 are supposed to be logic '1' and '0', respectively. Although, during $[0, \frac{T_S}{2}]$ V_1' reaches ≈ 1.32 V and V_2' is '0' and both are acceptable voltage levels ($V_1' > V_{inH-min}$ and $V_2' < V_{inL-max}$). V_1' reduces in the period of concurrent operation ($T_{overlap}$) to ≈ 1.12 V which is $< V_{inH-min}$. At $t = T_2$, S reaches the *OFF* threshold and the switches of V_1 path become open so V_1' will continue at ≈ 1.12 V till $t = T_S$ (the instant of reading data of downstream router) therefore it can not be considered as the logic high as expected.

To avoid such problem we must be sure that V_1' and V_2' have acceptable voltage levels at $t = T_S$; the time of reading the data by the downstream router. A simple solution is to let both S and $\bar{S}$ to charge and discharge faster in order to tighten the overlap period such that V_1' and V_2' discharge to acceptable levels. For instance, in the above illustrated example in Fig. 11, V_1' and V_2' should discharge to some voltages $> V_{inH-min}$ and $< V_{inL-max}$, respectively.

In summary we will calculate $T_{overlap}$ using two different ways, once by calculating T_1 and T_2 and then subtracting T_1 from T_2 and in this way $T_{overlap}$ would be a function of S and $\bar{S}$ drivers' sizes. And the second way is by using the observation that $T_{overlap}$ should be smaller than or equal the time taken by V_1' to reach $V_{inH-min}$. By equating these two equations together we can determine the driver size of both S and $\bar{S}$ that will result in minimum acceptable $T_{overlap}$ such that at $t = T_S$ V_1' and V_2' would have correct and

²For the sake of better clarity, we derive this example adopting 180 nm technology, in which $V_{DD} = 1.8$ V, $V_{thN} = 0.53$ V, and $|V_{thP}| = 0.51$ V. Therefore, voltage levels would be more clear than the case of 65 nm.

Fig. 8: V_1 3D path.

Fig. 9: V_2 3D path.

Fig. 10: S and $\bar{S}$ signals before (a) and after (b) increasing driver sizes to avoid negative effects of concurrent ON states of the TSVBOX switches.

acceptable voltage levels. To simplify the following analysis two assumptions are made. First, we choose the same driver size for S and $\bar{S}$, so

$$R_{dr-\bar{S}} = R_{dr-S}$$

Second, we will assume that $\frac{T_S}{2}$ is very large so that V_1' charges to V_{DD} not only up to $V_{inH-min}$ during $[0, \frac{T_S}{2}]$ and hence the discharging curve would start from V_{DD} not

$V_{inH-min}$.

Further, for better visualization, Fig. 12 shows a simplified version of the TSVBOX circuit, where $C_{p-PN-1} = C_{p-PN-2} = C_p + C_{PN}$, $C_{PN-L-1} = C_{PN-L-2} = C_{PN} + C_L$, and the intermediate capacitance $C_{int} = 4C_{PN} + 2C_W + C_{TSV}$.

Assuming T_1 is the time taken by $\bar{S}$ to charge to $\max(V_{thN}, |V_{thP}|)$, and T_2 is the time taken by S to discharge to $\max(V_{thN}, |V_{thP}|)$, therefore

$$T_1 = \tau_{\bar{S}} \ln \frac{V_{DD}}{V_{DD} - \max(V_{thN}, |V_{thP}|)} \quad (7)$$

$$T_2 = \tau_S \ln \frac{V_{DD}}{\min(V_{thN}, |V_{thP}|)} \quad (8)$$

And since S and $\bar{S}$ have the same driver sizes, so $\tau_{\bar{S}} = \tau_S = R_{dr-S} \cdot (C_p + 2C_W + C_{TSV} + 2N_{BW} \cdot C_g)$

Then the overlap period can be calculated as

$$T_{overlap} = \tau_S \ln \frac{V_{DD} - \max(V_{thN}, |V_{thP}|)}{\min(V_{thN}, |V_{thP}|)} \quad (9)$$

The second way to calculate $T_{overlap}$ requires the discharge equation of V_1' which is not an easy task since during $T_{overlap}$ C_{L1} is discharging in all other capacitors in the circuit and at the same time it is charging from the source V_1 as well as other capacitors. According to our simulation we found that the discharging current from C_{L1} into C_{L2} , C_{p-PN-1} , C_{p-PN-2} , and C_{int} is the most dominant, thus we developed the following discharge equation:

$$V_1'(t) = V_f + (V_i - V_f) \cdot \exp\left(\frac{-t}{\tau}\right) \quad (10)$$

Fig. 11: SystemC-A output signals showing complemented 3D signals multiplexing issues.

where $V_i = V_{DD}$, $V_f = \frac{V_{DD}}{2}$, and

$$\tau = 2R_{PN} \cdot (C_{PN-L-2} + C_{p-PN-1} + C_{p-PN-2}) + R_{PN} \cdot C_{int}$$

To check the accuracy of Eq. 10, we calculate the theoretical value of V_1' from Eq.10 and compare it with the value gained from simulation using SystemC-A. The error between the theoretical and simulational models does not exceed 8% which indicates the acceptable accuracy of this discharge equation.

Now using Eq.10, the time taken by V_1' to reach $V_{inH-min}$ can be simply determined:

$$T|_{V_1' = V_{inH-min}} = T_{overlap} = \tau \cdot \ln \frac{V_{DD} - 2V_{thp}}{V_{DD}} \quad (11)$$

Finally, by equating Eqs. 9 and 11 the value of R_{dr-S} and the proper size of the S driver can be determined to avoid the concurrent operation problems.

It is worth mentioning that, the above stated steps assumes an ideal case in which V_1' reaches V_{DD} during charging while we assume that $V_{inH-min}$ is the enough level to be considered as logic '1' and $T_{d-TSVBOX}$ is defined according to that. Consequently, the overlap period must be 0 which is realized using zero resistance selection signal driver which means an infinite size inverter driver and this is not possible. To solve such conflict, henceforth we will permit V_1' and V_2' to charge to value slightly higher than $V_{inH-min}$. For example in this paper, we choose V_1' and V_2' to charge to $1.1V_{inH-min}$ which is 10% higher than $V_{inH-min}$. Hence the equations defining

Fig. 12: TSVBOX simplified circuit model.

$T_{d-TSVBOX}$ and $T_{overlap}$ would be changed to

$$T_{d-TSVBOX} = \ln \frac{V_{DD}}{|V_{thp}| - 0.1(V_{DD} - |V_{thp}|)} \cdot \left((R_{dr-TSVBOX} \cdot (C_p + C_{PN}) + (R_{dr-TSVBOX} + R_{PN}) \cdot (4C_{PN} + 2C_W + C_{TSV}) + (R_{dr-TSVBOX} + 2R_{PN}) \cdot (C_{PN} + C_L)) \right) \quad (12)$$

and

$$T_{overlap} = \tau \cdot \ln \frac{V_{DD} - 2|V_{thp}| + 0.2(V_{DD} - |V_{thp}|)}{V_{DD} - 2|V_{thp}|} \quad (13)$$

, respectively. Apparently, both delays are higher than the delays of Eqs. 5 and 11, respectively.

C. Minimum duration of the selection signal

After introducing the driver design of S ($\bar{S}$) in the previous subsection, its clocking period T_S can be derived. As shown in Fig. 10, the period of time between $\frac{T_S}{2} \leq t \leq T_S$, can be divided into three smaller periods:

- (1) T_{d-S} ; the time required by $\bar{S}$ to reach $\max(V_{thN}, |V_{thP}|)$.
- (2) $T_{overlap}$; the permitted overlap period of concurrent ON state of TSVBOX switches.
- (3) T_{rem} ; the remaining time until T_S . During this period, V_2 signal is required to reach an acceptable level '0' or '1', therefore we must select $T_{rem} \geq T_{d-TSVBOX}$.

Based on these observations the minimum clocking period T_{S-min} for S ($\bar{S}$) control signal can be expressed as follows:

$$T_{S-min} = 2(T_{d-overlap} + T_{d-S} + T_{d-TSVBOX}) \quad (14)$$

D. Selection signal generation

In order to simplify the design procedure, S signal should be derived from the clock signal itself. To simplify more, T_S can be selected as an even integer multiple of the clocking period T_{CLK} , i.e. $T_S = 2n \cdot T_{CLK}$, and n is chosen such that the inequality $T_S \geq T_{S-min}$ is fulfilled. To select n , the relation between T_{S-min} and T_{CLK} must be known first. This inequality has three different cases:

- (1) $T_{CLK} < \frac{T_{S-min}}{2}$: we can choose $\frac{T_S}{2} = n \cdot T_{CLK}$, $n=2, 3$, etc., or in other words $T_S = 2n \cdot T_{CLK}$ ³, and we choose n such that $\frac{T_S}{2} \geq \frac{T_{S-min}}{2}$.
- (2) $\frac{T_{S-min}}{2} \leq T_{CLK} < T_{S-min}$: in this case the period of time T_{CLK} is sufficient to pass V_1 or V_2 (but not both) through the TSVBOX, therefore $\frac{T_S}{2}$ can be chosen to be T_{CLK} , or more formally $T_S = 2T_{CLK}$ (n is constant equal 1).
- (3) $T_{CLK} \geq T_{S-min}$: in this case the period of time T_{CLK} is sufficient to pass V_1 then V_2 (or vice versa), serially. Therefore we can choose $T_S = T_{CLK}$ (n is constant equal to $\frac{1}{2}$).

As noticed from the above cases, the TSVBOX degrades the performance of the 3D NoC in cases (1) and (2), where we need more than one clock cycle to transfer the data per vertical hop. In contrast, in case (3) the TSVBOX shows the same performance as conventional 3D NoC, because the multiplexing operation needs only a clock cycle to transfer both signals, in the same way similar to the conventional case. Also, in the last case, there is no need for frequency dividers to generate the S signal, since it can be chosen as the clock signal itself.

E. Communication procedure between two conventional 3D routers

To define a communication protocol for the TSVBOX-based 3D router, the conventional procedure should be explained first. The communication signalling between two conventional

3D routers inside the 3D NoC shown in Fig. 13, is done using the synchronous REQ and ACK signals to transfer a flit from upstream to downstream router. This communication protocol can be summarized as follows:

- (1) The transmitting router initiates a request to the receiving router by raising the REQ signal to '1'. At the same time the data flit is ready on the data bus.
- (2) After at least one cycle, the initiated request will be recognized by the input controller of the receiving router. If there is at least one free slot in the FIFO buffer, the packet will be read and the acknowledgement ACK signal will be set to '1', announcing that the packet is received successfully.
- (3) After another cycle from setting the ACK , the transmitting router will reset the REQ again to '0', upon detecting the assertion of ACK . Resetting REQ is the end of the communication operation.

Fig. 13: Synchronous communication protocol.

F. Communication procedure between two TSVBOX-based 3D routers

The communication protocol for the TSVBOX-based 3D routers, is the same as conventional procedure of the conventional routers for horizontal hops. For vertical hops the procedure is changed to account for extra cycles needed by the TSVBOX to transfer the data. As shown in Fig. 14, a new internal signal called *OnePulse* is introduced. *OnePulse* is used to power gate the driving circuit of the S and $\bar{S}$ signals so as to reduce their power consumption when there is no transmission is in progress. This signal is activated when the output controller decides to send a flit to the downstream router. Since the TSVBOX needs $2n \cdot T_{CLK}$ to transfer two multiplexed signals successfully, the *OnePulse* signal lasts for only $2n \cdot T_{CLK}$, $n=0.5, 1, 2, 3$, etc. as shown in Subsection VI-D. Since both S and $\bar{S}$ are needed only during transmission, the *OnePulse* signal can be used to activate or deactivate those two overhead signals. This activation or deactivation can be translated as power gating technique, as shown in Fig. 15.

³Such clock frequency division can be realized easily using injection-locked frequency dividers (ILFDs). Most of ILFDs have been optimized for division by even numbers [28].

Fig. 14: Vertical communication synchronous protocol between two TSVBOX-based 3D routers.

Now the TSVBOX vertical communication procedure can be summarized as follows:

- (1) The upstream router set the internal *OnePulse* signal that enables both S and $\bar{S}$ signals, so that the two multiplexed signals can pass to the data bus first.
- (2) Since the downstream router takes at least one cycle to read *REQ* after its initiation, *REQ* can be set by the upstream router after $(2n-1) \cdot T_{CLK}$.
- (3) Step 2 of the conventional procedure of Subsection VI-E.
- (4) Step 3 of the conventional procedure of Subsection VI-E.

As observed the TSVBOX-based 3D routers imposes extra waiting cycles (EWCs) equal $(2n-1)$ which is the number of T_{CLK} cycles that the router must wait before initiating a request, and thus it may degrade the overall 3D NoC performance. However, we will show in Section VII-D that this performance degradation is dependent on the traffic pattern of the 3D NoC and other parameters as well.

Fig. 15: Simple power gating technique using *OnePulse* signal.

VII. TSV MULTIPLEXING SCALABILITY ANALYSIS

In the previous sections TSV multiplexing has been studied in details for 2×1 TSV multiplexing ratio. In this section the study is generalized for the general case of $N_{MUX} \times 1$ TSV multiplexing, where N_{MUX} is the TSV multiplexing ratio ($N_{MUX} \geq 2$). N_{MUX} is assumed to be a power of 2 arbitrary integer, i.e. $N_{MUX} = 2, 4, 8$, etc..

Fig. 16 shows the TSVBOX SystemC-A circuit modeling for the general case of $N_{MUX} \times 1$ multiplexing ratio and a special case when $N_{MUX} = 4$. The mechanism can be considered as a generalization for the previous mechanism of 2×1 multiplexing. As shown in Fig. 16a, the multiplexed signals are passing through the TSVBOX during exclusive combination of the selection control signals. And since we have $2^{N_{MUX}}$ different combinations of the S 's signals, i.e. $(S_1 \cdot S_2 \cdots S_{\log_2 N_{MUX}})$, $(S_1 \cdot S_2 \cdots \bar{S}_{\log_2 N_{MUX}})$, $\dots$, $(\bar{S}_1 \cdot \bar{S}_2 \cdots \bar{S}_{\log_2 N_{MUX}})$, each signal from the N_{MUX} different input signals can pass exclusively through the TSVBOX. For example, in 4×1 multiplexing Figs. (16b, 16c), V_1 passes through the TSVBOX if all the S 's signals are '1' ($S_1 \cdot S_2 = 1$), and this is only valid during the first half cycle of S_1 , while V_2 passes if $S_1 \cdot \bar{S}_2 = 1$, and this combination can be logic '1' only during the second half cycle of S_1 . The same logic can be repeated for V_3 and V_4 .

In the following subsections, the analysis of scalability study is provided to show how much higher TSV multiplexing ratios will impact control signals (S 's), EWCs, and TSVBOX delays. In the final subsection, the scalability impact on performance

under different traffic patterns is analyzed.

A. Effect of multiplexing on selection control signals

As shown in Fig. 16a, the number of selection control signals (S 's) used is always $\log_2(N_{MUX})$. However, we need to generate N_{MUX} signals from these $\log_2(N_{MUX})$ signals to drive the TSVBOX. This means that, we need N_{MUX} extra TSVs to transfer them for each vertical bus width. This, of course, enforces a limitation on the multiplexing ratio to be used, especially if N_{BW} is comparable to N_{MUX} . For example, if $N_{BW}=128$ and $N_{MUX}=128$, then no TSV saving will be gained from the TSVBOX. Another limitation comes from the generation circuit needed to generate the S 's signals (AND gates and the inverters). The good point is that, this generation circuit is not repeated in each layer, we assume it is only placed in the first layer beside the clock dividers. We assume also that the area of the system circuit on the first die is extremely larger than the area overhead of the signal generation circuit, hence negligible contribution to the overall area.

The frequencies of the selection control signals are related to each other, e.g. in 4×1 case, $f_{S1}=2f_{S2}$, which is simply synthesized using digital frequency dividers. The selection signal with maximum frequency (f_{S1}) is determined using the same way explained in Subsection VI-D according to the relation between T_{CLK} and $\frac{T_{S1-min}}{2}$ (minimum time duration required to transmit any of the input multiplexed signals).

B. Effect of multiplexing on EWCs

Again the TSVBOX imposes extra delay in the shape of extra waiting cycles (EWCs), and these extra delay cycles depend on T_{CLK} , $\frac{T_{S1}}{2}$, and the TSV multiplexing ratio N_{MUX} . To calculate EWCs in case $N_{MUX} > 2$, we can generalize the 2×1 case of Subsection VI-F. Depending on the relation between T_{CLK} and $\frac{T_{S1-min}}{2}$, the EWCs simply can be shown to be (from Fig. 14):

$$EWCs = \frac{N_{MUX} \cdot \frac{T_{S1}}{2}}{T_{CLK}} - 1$$

and since $\frac{T_{S1}}{2} = n \cdot T_{CLK}$, therefore

$$EWCs = n \cdot N_{MUX} - 1 \quad (15)$$

$$\text{where } n = \begin{cases} 2, 3, \text{ etc.} & : T_{CLK} < \frac{T_{S1-min}}{2} \\ \frac{1}{2} & : \frac{T_{S1-min}}{2} \leq T_{CLK} < T_{S1-min} \\ \frac{1}{2} & : T_{CLK} \geq T_{S1-min} \end{cases}$$

C. Effect of multiplexing ratio on TSVBOX delays

The increase in TSVBOX delay is linear with N_{MUX} multiplexing ratio. The delay of any multiplexed signal passes

Fig. 16: TSVBOX circuit models for (a) the general case $N_{MUX} \times 1$ and special case in (b) 4×1 TSV multiplexing ratios. (C) Selection control signals required for 4×1 TSV multiplexing. V_1 passes when $S_1.S_2=1$, V_2 passes when $S_1.\bar{S}_2=1$, etc..

through the TSVBOX can be calculated as

$$T_{d-TSVBOX} = \ln \frac{V_{DD}}{|V_{thP}| - 0.1(V_{DD} - |V_{thP}|)} \cdot \left((R_{dr-TSVBOX} \cdot (C_p + C_{PN}) + (R_{dr-TSVBOX} + R_{PN}) \cdot (2N_{MUX} \cdot C_{PN} + 2C_W + C_{TSV}) + (R_{dr-TSVBOX} + 2R_{PN}) \cdot (C_{PN} + C_L)) \right) \quad (16)$$

where we considered the overlap penalty explained in Subsection VI-B. As observed, Eq. 12 is a special case of Eq. 16 when $N_{MUX}=2$.

The multiplexing ratio affects the S 's signals' delays as well, but this time, it is a positive effect; in other words, the higher the multiplexing ratio, the smaller the S 's signals' delays. For example, for the case of $N_{MUX}=2$, each transmission gate contributes by $2C_g$, hence the total loading contribution for either S or $\bar{S}$ is $\left(4 \left(\frac{N_{BW}}{N_{MUX}}\right) \cdot C_g = 2N_{BW} \cdot C_g = 128C_g\right)$, as depicted in Eq. 6. Another example, for the case of $N_{MUX}=4$, each TSVBOX contributes to each control signal ($S_1.S_2$, $S_1.\bar{S}_2$, etc.) load by $2C_g$ as well. However, since the total number of TSVBOXes has reduced to 16, i.e. $\frac{N_{BW}}{N_{MUX}} = \frac{64}{4} = 16$, the total loading contribution would be $64C_g$ for each control signal. In general, based on the previous analysis, Eq. 6 can be rewritten as

$$T_{d-S} = \ln \frac{V_{DD}}{V_{DD} - \max(V_{thN}, |V_{thP}|)} \cdot \left((R_{dr-S} \cdot (C_p + 2C_W + C_{TSV} + 4 \frac{N_{BW}}{N_{MUX}} \cdot C_g)) \right) \quad (17)$$

D. Effect of multiplexing ratio on on performance under different traffic patterns

In this subsection we analyze the scalability issues on the performance of TSVBOX-based 3D NoC versus the conventional one. We choose three different traffic patterns; Matrix Transpose⁴, Uniform, and Hotspot. The packet injection process of each traffic flow is chosen to be a Poisson random process where the time interval between successive injections is represented as exponential random variable [29]. Poisson distributed injection rate is adopted in this study because it successfully characterizes the performance of multiprocessor applications [30, 31]. The transmitter waits for $T_{interval} = -\lambda \cdot \ln(U)$ between two successive packet transmissions, where $T_{interval}$ is the exponential random time interval between two successive transmitted packets, λ is the reciprocal of the average injection rate of the process, i.e. the average waiting time between two successive transmissions, and U is a uniform random variable between '0' and '1' [32]. Table III states all the definitions of the terms used in this analysis.

The following three equations⁵ define the average extra waiting cycles $EWCS_{avg}$ per vertical hop faced by packets traverse vertically between 3D stack layers for Transpose,

Uniform, and Hotspot traffics, respectively.

$$EWCS_{avg-Transpose} = 2 \cdot N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot \left[\frac{N^2}{4} \right] \quad (18)$$

$$EWCS_{avg-Uniform} = 2 \cdot N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot \left[\frac{1}{N} \cdot \left(\sum_{i=0}^{\frac{N}{2}-1} \frac{(N-i) \cdot (N-i-1)}{2} + \sum_{i=0}^{\frac{N}{2}-1} i \cdot \left(\frac{N}{2} - i \right) \right) \right] \quad (19)$$

$$EWCS_{avg-Hotspot} = 2 \cdot N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot \left[\frac{(1-h)}{N} \cdot \left(\sum_{i=0}^{\frac{N}{2}-1} \frac{(N-i) \cdot (N-i-1)}{2} + \sum_{i=0}^{\frac{N}{2}-1} i \cdot \left(\frac{N}{2} - i \right) \right) \right] \quad (20)$$

It can be seen that the difference between the above three equations lies in the terms between brackets "[]":

- In Transpose case $I = \frac{N^2}{4}$
- In Uniform case $II = \frac{1}{N} \cdot \left[\sum_{i=0}^{\frac{N}{2}-1} \frac{(N-i) \cdot (N-i-1)}{2} + \sum_{i=0}^{\frac{N}{2}-1} i \cdot \left(\frac{N}{2} - i \right) \right]$
- In Hotspot case $III = \frac{(1-h)}{N} \cdot \left[\sum_{i=0}^{\frac{N}{2}-1} \frac{(N-i) \cdot (N-i-1)}{2} + \sum_{i=0}^{\frac{N}{2}-1} i \cdot \left(\frac{N}{2} - i \right) \right]$

Fig. 17 displays the variation of the previous three terms versus N , when $h=0.5$. We can notice that $I > II > III$ for all values of N . Which means that Hotspot traffic is expected to show better performance than Uniform and Transpose traffics, and Uniform traffic in turn is expected to outperform Transpose.

VIII. FABRICATION YIELD AND COST ANALYSIS

In this section, fabrication yield and cost are analyzed based on the analysis of [1] for W2W bonding process. The design methodology proposed in our study in this paper introduces extra redundant hardware that may affect the overall system area and hence the overall yield and cost. Hence the analysis of this section is crucial for the overall evaluation of the TSV multiplexing technique. In the following subsections we briefly overview the normalized yield models derived in [1]. In the following analysis we use the terms defined in Table IV.

TABLE III: Definitions of all terms used in the performance analysis of the TSVBOX-based 3D NoC.

Parameter	Definition
N	The number of 3D stack layers
N_{PKT}	The number of packets sent by each processing node
N_{MUX}	Multiplexing ratio of the TSVBOX
n	$n=0.5, 1, 2, 3, 4$, etc. dependent on the relation between T_{CLK} and $\frac{T_{S1-min}}{2}$
h	$0 \leq h \leq 1$. In Hotspot traffic, h represents the portion of the total transmitted packets by any node that is directed to the hotspot node in the 3D NoC
$EWCS_{avg}$	The average EWCs exposed by TSVBOX-based 3D NoC per one vertical hop
X_{SIZE}	The number of nodes in X dimension of the 3D NoC
Y_{SIZE}	The number of nodes in Y dimension of the 3D NoC
Z_{SIZE}	The number of nodes in Z dimension of the 3D NoC

⁴Henceforth, we would call it Transpose for simplicity.

⁵The proofs of these three equations are found in Appendix A.

Fig. 17: The relation between the terms I , II , and III .

A. Fabrication yield analysis

As stated in [1], there are two main components that affect the overall yield of the W2W bonding process:

- Normalized stacking yield: According to [1], the normalized stacking yield is equivalent to the normalized TSV yield ($Y_{TSV-norm}$) which is the probability that all TSVs are non-faulty

$$Y_{S,W2W-norm} = Y_{TSV-norm} \quad (21)$$

$$= \frac{(1 - f_{TSV})^{(N_{TSV}|_{after \text{ multiplexing}})}}{(1 - f_{TSV})^{(N_{TSV}|_{before \text{ multiplexing}})}}$$

where $N_{TSV}|_{before \text{ multiplexing}}$ and $N_{TSV}|_{after \text{ multiplexing}}$ can be calculated as follows

$$N_{TSV}|_{before \text{ multiplexing}} = 2M \cdot (N_{BW} + 2) \quad (22)$$

$$N_{TSV}|_{after \text{ multiplexing}} = 2M \cdot \left(\frac{N_{BW}}{N_{MUX}} + 2 + N_{MUX} \right) \quad (23)$$

Of course we can gain TSV yield improvement iff $N_{TSV}|_{after \text{ multiplexing}} < N_{TSV}|_{before \text{ multiplexing}}$. If

TABLE IV: Definitions of all terms used in Eqs. (21-31).

Parameter	Definition
$A_{die} _{before \text{ multiplexing}}$	Die area before TSV multiplexing
$A_{die} _{after \text{ multiplexing}}$	Die area after TSV multiplexing
$A_{routers,cores}$	The aggregate area of NoC routers and cores per one die
M	Mesh size, e.g. $M=4 \times 4$, 8×8 , etc.
D_{TSV}	The TSV diameter
A_{TSV}	The cross-sectional area of one TSV
A_{MUX}	The multiplexer area of the TSVBOX
A_{dr-S}	The S signal driver area
A_{TG}	The transmission gate area used for clock gating of the S 's control signals
f_{TSV}	The probability of fabricating a non faulty TSV
N_{TSV}	The number of TSVs between two layers in a 3D stack
α	A constant depends upon the complexity of the manufacturing process
D_o	Average density of defects per die.

(a) $C_{TSV}=15$ fF.

(b) $C_{TSV}=500$ fF.

(c) Selection control signal delay.

Fig. 18: TSVBOX vs. conventional 3D interconnect delays for (a) $C_{TSV}=15$ fF and (b) $C_{TSV}=500$ fF. The $T_{d-TSVBOX}^*$ is a symbol for the TSVBOX delay of Eq. 5 before adding the 10% increase to $V_{inH-min}$. In (c), the change of the selection control signal T_{d-S} is depicted for $C_{TSV}=15$ fF and $C_{TSV}=500$ fF.

we assume that both N_{MUX} and N_{BW} are power of 2 integers, then, we can show that the condition that makes $N_{TSV}|_{after \text{ multiplexing}} < N_{TSV}|_{before \text{ multiplexing}}$ is simply $N_{MUX} \leq \frac{N_{BW}}{2}$. For example, if $N_{BW}=256$ and $N_{MUX}=128$, so $N_{TSV}|_{before \text{ multiplexing}}=2M \times (258)$ and $N_{TSV}|_{after \text{ multiplexing}}=2M \cdot (132)$. Now,

for the same N_{BW} , if we assume $N_{MUX}=256$, $N_{TSV}|_{after\ multiplexing}$ would be $2M \times (259)$, which is clearly larger than 258; the required TSVs for no TSV multiplexing case.

- Die yield: Recalling [1], the normalized die yield $Y_{die-norm}$ can be represented as

$$Y_{die-norm} = \left(\frac{\alpha + D_o \cdot A_{die}|_{before\ multiplexing}}{\alpha + D_o \cdot A_{die}|_{after\ multiplexing}} \right)^\alpha \quad (24)$$

As observed, $Y_{die-norm}$ is in turn, dependent on the die area before and after TSV multiplexing, therefore it is affected by the proposed design methodology described in this paper. Regarding area, the proposed design methodology may affect the sizes of the drivers, especially for S signal. Also, it requires special TSVs to transfer selection control signals between layers, which in turn adds extra area overhead for those extra TSVs. All these factors affect die area and in turn the die yield. Similar to the analysis of [1], the die area is dependent on die location, and the upper/bottom most dies have different areas than those of intermediate dies. The die area of upper and bottom-most dies (die_1, die_N) before multiplexing can be estimated by

$$A_{die_{1,N}}|_{before\ multiplexing} = A_{routers,cores} + 2M \cdot (N_{BW} + 2) \cdot A_{TSV} \quad (25)$$

and for intermediate dies ($die_2, die_3, \dots, die_{N-1}$)

$$A_{die_{2,3,\dots,(N-1)}}|_{before\ multiplexing} = A_{routers,cores} + 4M \cdot (N_{BW} + 2) \cdot A_{TSV} \quad (26)$$

Similar procedure can be followed for the TSVBOX-based 3D NoC case, therefore, for die_1 and die_N

$$A_{die_{1,N}}|_{after\ multiplexing} = A_{routers,cores} + 2M \cdot \left(\left(\frac{N_{BW}}{N_{MUX}} + 2 + N_{MUX} \right) \cdot A_{TSV} + N_{BW} \cdot A_{TG} + N_{MUX} \cdot (A_{dr-S} + A_{TG}) \right) \quad (27)$$

and for intermediate dies ($die_2, die_3, \dots, die_{N-1}$)

$$A_{die_{2,3,\dots,(N-1)}}|_{after\ multiplexing} = A_{routers,cores} + 4M \cdot \left(\left(\frac{N_{BW}}{N_{MUX}} + 2 + N_{MUX} \right) \cdot A_{TSV} + N_{BW} \cdot A_{TG} + N_{MUX} \cdot (A_{dr-S} + A_{TG}) \right) \quad (28)$$

where the TSV cross-sectional area A_{TSV} can be calculated based on the value of TSV diameter D_{TSV}

$$A_{TSV} = \pi \left(\frac{D_{TSV}}{2} \right)^2 \quad (29)$$

- Overall yield: Finally, the normalized overall yield $Y_{W2W-norm}$ is expressed according to [1] as:

$$Y_{W2W-norm} = (Y_{die-norm-top,bottom})^2 \cdot (Y_{die-norm-intermediate})^{(N-2)} \cdot (Y_{TSV-norm})^{N-1} \quad (30)$$

B. Fabrication cost analysis

As derived in [1], the overall W2W normalized cost $C_{W2W-norm}$ can be considered as the reciprocal of the overall W2W normalized yield

$$C_{W2W-norm} = \frac{C_{W2W}|_{after\ multiplexing}}{C_{W2W}|_{before\ multiplexing}} = \frac{1}{Y_{W2W-norm}} \quad (31)$$

IX. SIMULATION PLATFORM AND RESULTS

A. 3D signal path delays

For the sake of fair comparison between the conventional and TSVBOX-based 3D NoCs, both are operated and designed based on the same input frequency and the same data driver size ($K_N|_{before\ multiplexing} = K_N|_{after\ multiplexing}$).

Figs. (18a,18b) depicts the change in $T_{d-TSVBOX}$ vs. multiplexing ratio N_{MUX} under two different values of C_{TSV} . While T_{Conv} remains constant, $T_{d-TSVBOX}$ increases linearly with increasing N_{MUX} , and this is applicable for both Eqs. (5,12) of the $T_{d-TSVBOX}$ delays. Fortunately, the linear increase is very small, because of the small slope;

$$Slope = 2 \ln \frac{V_{DD}}{V_{thp}} \cdot C_{PN} \cdot (R_{dr-TSVBOX} + R_{PN}) \approx 0.011178 \text{ nsec per unit change in } N_{MUX} \quad (32)$$

An important notice here, is that the slope is independent of the TSV technology. Depending on Fig. (18a,18b) in case of 500 fF TSV capacitance, the increase in $T_{d-TSVBOX}$ delay when N_{MUX} changes from 2 to 256 is 3.35 nsec, while for 15 fF TSV capacitance it was exactly 3.35 nsec, as well. Apparently, those identical values support the theoretical expectation based on Eq. 32.

Also Figs. (18a,18b) depict that the TSVBOX shows a delay impact due to the redundant circuits added for multiplexing. Although, when C_{TSV} is large, e.g. $C_{TSV}=500$ fF, the ratio $\frac{T_{d-TSVBOX}}{T_{Conv}}$ is slowly increasing by the increase of N_{MUX} , reducing the impact of N_{MUX} on $T_{d-TSVBOX}$. For example, in case of $C_{TSV}=500$ fF, for $N_{MUX}=2$, the ratio $\frac{T_{d-TSVBOX}}{T_{Conv}}=1.6631$, and for $N_{MUX}=256$ it is 1.9150. However, for the case of $C_{TSV}=15$ fF, the ratios were, 1.7108 and 3.7991 (more than the double of 1.7108), respectively.

Fig. 18c displays the change in T_{d-S} versus N_{MUX} , and as stated before in Subsection VII-C, the selection control signals show less delay for higher multiplexing ratios. However, the reduction is very small since the term $(4 \frac{N_{BW}}{N_{MUX}} \cdot C_g)$ of Eq. 17 is usually masked by the large values of $(C_{TSV}, 2C_W)$ capacitors and because of the very small value of the gate capacitance C_g itself.

TABLE VI: Theoretical and simulational 3D signals' delays for conventional and TSVBOX paths for 65 nm technology for different TSV capacitances.

3D signal delay	Unit	15 fF			500 fF		
		Theoretical	Simulational	<i>error</i>	Theoretical	Simulational	<i>error</i>
T_{d-Conv}	nsec	1.38	1.44	4.166%	11.27	11.36	0.968%
$T_{d-TSVBOX}$	nsec	2.33	2.31	0.87%	18.75	18.74	0.053%
T_{d-S}	nsec	0.833	0.9	7.44%	6.198	6.42	3.46%

To check the accuracy of the delay models proposed, we compared the theoretical delays calculated from Eqs. (4,12,6), and the SystemC-A simulation delays. As depicted in Table V, it is assumed that all the drivers are 1x-inverters ($K_N=1$, $K_P=2$), thus all the driver resistances are adjusted to their maximum values. As stated in Table VI, the error between the theoretical and the simulational delay results does not exceed 7.5%, which indicates the acceptable accuracy of Elmore-delay model.

B. Performance comparison under synthetic traffic patterns

The simulation results shown in Figs. (19,20,23) indicate the average delay and throughput comparisons of the two implemented $4 \times 4 \times 4$ 3D NoCs; the TSVBOX-based and conventional ones. The average delay of a packet is defined as the total cycles taken by the packet flits to cross the network towards its destination node. That delay spans from creation of the first flit (head flit) of the packet, to when its last flit (tail flit) is ejected at the destination (assuming immediate ejection), including source buffer queuing time in cycles [33]. For the average throughput, it is defined as the average ejection rate of the packets at their destination nodes. We set the simulation warm-up period to 2000 cycles in which we avoid calculating results until the network get congested [14]. Thereafter, similar to the methodology in [33], the simulation is run with 32,000 packets; 500 packet injected from each node, and the simulation continued at the prescribed packet injection rate till these packets have all been received, and their average delay and throughput are calculated.

Based on T_{S-min} we choose to run the simulations for three different clock periods to experience the effect of TSV multiplexing in different situations; $T_{CLK}=T_{S-min}$, $T_{CLK}=\frac{T_{S-min}}{2}$, and $T_{CLK}=\frac{T_{S-min}}{4}$. We choose to calculate T_{S-min} for $C_{TSV}=500$ fF, since it will be an upper bound for the TSVBOX delay degradation. Though, the same conclusions derived later from Figs. (19,20,23) will not change

TABLE V: Simulation setup for the sizes of the inverter drivers and their equivalent ON resistances.

Design parameter	Unit	65 nm	
		15 fF	500 fF
(K_N-Conv, K_P-Conv)	-	(1,2)	(1,2)
$(K_N-TSVBOX, K_P-TSVBOX)$	-	(1,2)	(1,2)
(K_N-S, K_P-S)	-	(1,2)	(1,2)
$R_{dr-Conv}$	k Ω	21.654	21.654
$R_{dr-TSVBOX}$	k Ω	21.654	21.654
R_{dr-S}	k Ω	21.654	21.654

TABLE VII: Different delays for different multiplexing ratios.

Delays	$N_{MUX} \times 1$		
	2×1	4×1	16×1
$T_{d-TSVBOX}$	19.06	19.08	19.22
T_{S-min}	24.40	24.42	24.55

for the case of $C_{TSV}=15$ fF. Since $T_{d-TSVBOX}$ is multiplexing ratio dependent, Table VII displays the values of the $T_{d-TSVBOX}$ and T_{d-S} versus N_{MUX} .

As discussed in Subsection VII-B, depending on the relation between T_{CLK} and T_{S-min} , TSVBOX adds EWCs, which are calculated using Eq. 15 and depicted in Table VIII for different multiplexing ratios.

What has been proven analytically in Subsection VII-D can be deduced clearly from Figs. (19, 20,23). We prove previously in Subsection VII-D that degradation in performance due to EWCs of the design methodology is application dependent, and we show analytically that Hotspot traffic gives closer performance to the conventional case than other traffic patterns. We show also that the performance under Transpose traffic will be the worst against other patterns; Hotspot and Uniform. Those conclusions are very readable from all performance figures.

As expected, for the less T_{CLK} compared to T_{S-min} the degradation in performance metrics will be more. For example when $T_{CLK}=T_{S-min}$ in Figs. 19c and 19f, saturation point occurs at Injection rate (IR) ≈ 0.01 packet per cycle for 16×1 multiplexing, while for the conventional case it is around ≈ 0.05 packet per cycle. This situation is repeated in all cases but it is decreased or worsen according to the traffic pattern used or the relation between T_{CLK} and T_{S-min} .

In Figs. (19a,19d,20a,20d,21a,21d) we observe that the TSVBOX does not degrade the performance for 2×1 multiplexing. This strengthens the multiplexing technique since it can improve the yield without degrading the performance.

In summary, though the TSVBOX increases the delay of the 3D signals, according to the application and the relation between T_{CLK} and T_{S-min} , the TSVBOX-based 3D NoC can mitigate the performance degradation and shows a comparable performance compared to conventional 3D NoC even for high multiplexing ratios.

C. Performance comparison using real Benchmark traffic

In this subsection another performance comparison is shown, this time under real benchmark traffic of the well known dVOPD video application traffic [37]-[40] with task graph shown in Fig. 22. Since mapping the tasks of the

(a) $T_{CLK}=T_{S-min}$

(b) $T_{CLK}=0.5T_{S-min}$

(c) $T_{CLK}=0.25T_{S-min}$

(d) $T_{CLK}=T_{S-min}$

(e) $T_{CLK}=0.5T_{S-min}$

(f) $T_{CLK}=0.25T_{S-min}$

Fig. 19: Average delay and throughput under Transpose traffic pattern.

(a) $T_{CLK}=T_{S-min}$

(b) $T_{CLK}=0.5T_{S-min}$

(c) $T_{CLK}=0.25T_{S-min}$

(d) $T_{CLK}=T_{S-min}$

(e) $T_{CLK}=0.5T_{S-min}$

(f) $T_{CLK}=0.25T_{S-min}$

Fig. 20: Average delay and throughput under Uniform traffic pattern.

Fig. 21: Average delay and throughput under Hotspot traffic pattern.

TABLE VIII: EWCs under different clock periods and multiplexing ratios.

T_{CLK}	EWCs		
	2×1	4×1	16×1
T_{S-min}	0	1	7
$\frac{T_{S-min}}{2}$	1	3	15
$\frac{T_{S-min}}{4}$	3	7	31

task graph to the NoC cores is NP hard problem [37]-[40], we model this mapping problem using MiniZinc modeling discrete optimization language [42]-[43]. Modeling is done to get the mapping with minimum communication cost, where the communication cost is defined as the sum of the communication bandwidth between each two tasks or vertices in the task graph (BW_{ij}) multiplied by the number of hops between those two tasks in the NoC (H_{ij}). Thus the objective function can be represented as

$$\text{minimize } \sum_i \sum_j BW_{ij} \cdot H_{ij} \quad (33)$$

The difference in performance between TSVBOX-based and conventional 3D NoCs arises from the extra hops the TSVBOX may add to the flits going vertically because of the extra waiting cycles. Our implemented simulation platform introduces a 9 cycles delay per one horizontal or vertical hop for conventional 3D NoC while for TSVBOX-based 3D NoC it

gives the same horizontal hop delay of 9 cycles but 9+EWCs per vertical hop. a new metric is introduced to account for this vertical delay which is VHD (Vertical Hop Delay). Of course VHD is constant equal 9 for conventional 3D NoC while it is 9+EWCs for TSVBOX-based 3D NoC.

Similar conclusions to the ones we got in the previous subsection are made from Figs. 23a and 23b, again the performance of the TSVBOX is dependent on the EWCs it introduces. For example if VHD=9 (EWCs=0) we get similar performance to original conventional case without multiplexing and then the performance degrades based on the amount of EWCs being added.

D. Performance comparison with TSV serialization technique

Serialization is the most famous technique to reduce TSVs to increase the yield and reduce the fabrication cost. In this subsection we study the performance of the TSVBOX against the serialization technique. The common impact of both techniques is that they add extra delay to the 3D signals passes the vertical or interlayer interconnects. The EWCs delay added by the serialization is constant equal $N_{SER}+2$ cycles, where N_{SER} is the serialization ratio, e.g. for 2x1 serialization N_{SER} is 2. Though, the TSVBOX extra delay cycles is dependent on the frequency of operation and given by Eq. 15. In Eq. 15 the parameter n is dependent on the relation between the TSVBOX delay and the operational clock. This leads to the fact that the EWCs of the TSVBOX can be less than the one of the serialization and the TSVBOX

Fig. 22: dVOPD communication task graph with communication bandwidth stated in MB/s on each edge [41] between each two tasks (vertices).

can show better performance than the serialization technique. Another advantage for the TSVBOX is that it performs better as the technology scales because we expect lower TSVBOX delay and thus lower n . The latter advantage gives more opportunities for the TSVBOX to be the best candidate to reduce the TSVs for future 3D chips.

Fig. 24 clarify those observations regarding performance difference between serialization and TSVBOX techniques. For example, in Figs. 24a and 24d for 2x1 multiplexing/serialization while serialization technique always adds 4 cycles delay (EWCs=4) the TSVBOX EWCs delays range between 0 and 3 cycles (refer to table VIII) so in all those cases the TSVBOX outperforms the serialization technique. For the other examples in Figs. (24b,24e,24c,24f) and depending on the EWCs that each technique adds the TSVBOX outperforms the serialization in some situations and vice versa, e.g. for 4x1 multiplexing/serialization the TSVBOX outperforms the serialization when EWCs of the TSVBOX less than 6 which is the EWCs added by serialization and same conclusion can be concluded for 16x1 multiplexing/serialization.

E. Power comparison

Since there is no general benchmark method defined for NoCs to measure power consumption [34], we follow the methodology mentioned in [16, 30] to calculate the power

(a) Delay.

(b) Throughput.

Fig. 23: Average delay and throughput under real dVOPD benchmark traffic.

consumption of all power components: the intralayer interconnects, i.e. the 2D interconnects or links between routers located in the same layer of the 3D stack, the interlayer interconnects, i.e. the 3D interconnects or links between routers of two neighbor layers of the 3D stack, and the 3D routers themselves.

For both 3D and 2D interconnects, we developed a specific methodology based on the ability of SystemC-A to measure the currents flow through the modeling circuits of Figs. (6,16a) for different input data. Large sequence of random flits are continuously fed to the 2D or 3D interconnects, at the same time the simulator takes samples of the currents of the interconnects every specified period of time and a counter is continuously counting the number of samples. After receiving all the sent flits, the simulator multiply the sum of the samples by V_{DD} and take the average by dividing the calculated value by the counter value.

Fig. 24: Performance comparison between TSVBOX and Serialization techniques for different TSV Multiplexing/Serialization ratios.

Similarly to the simulation scenario performed in SystemC-A, we developed a model to measure the power consumption of the 3D router when flits pass through. Former, 3D router is written in Register Transfer Level (RTL) using Verilog language. Then, a switching activities scenario is created by injects a long random sequence of flits into the input ports of the 3D router. Afterwards, this scenario is applied on Modelsim to generate the VCD file. Then VCD file is translated to SAIF file. Later, the 3D router is synthesized by Design Compiler (DC) from Synopsys and switching activities scenario is applied using the SAIF file. The synthesis is performed on 65 nm technology.

Power consumption results are shown in Fig. 25. As noticed for high TSV capacitance ($C_{TSV}=500$ fF, Figs. (25a,25b,25c)), the difference in power consumption is clearly against the TSVBOX. But the situation becomes much better for small TSV capacitance ($C_{TSV}=15$ fF, Figs. (25d,25e,25f)) because the 2D interconnects power and router power components are not affected by the reduction in TSV capacitance, and only the 3D interconnects power component does.

The trend in TSV fabrication technology is to decrease its dimensions and hence its capacitance as well. Therefore, and based on the previous results, the TSVBOX is adaptable to recent TSV technologies and its power consumption behavior will enhance more and more for future smaller TSVs.

Each of the various low-power-coding techniques [35] that geared towards minimizing the number of transitions and hence power consumption can be applied here. We expect that

applying such technique will reduce the power consumption of the TSVBOX more and makes it too close or even lower in consumption than the conventional case. This is due to the fact that the coupling parasitics (capcitanace and inductance) in the TSVBOX-based 3D NoCs would be less than the conventional case because the reduction in TSV count results in more space between TSVs. But for simplicity sake, no professional coding techniques is considered in our analysis and we dedicate it as a future work.

F. Yield enhancement and cost reduction versus data bus width and number of 3D stack layers

To know the TSVBOX effect on die yield, the parameters of Table IV should be known first. As explored in [15], microprocessor-like dies are usually large. Sticking to the assumptions stated in [15], $A_{routers,cores}$ is assumed to be 100 mm^2 for $M=4 \times 4$. Also we assume that $A_{routers,cores}$ has direct dependent on mesh size M, i.e. for $M=8 \times 8$, $A_{routers,cores} = \frac{100 \text{ mm}^2 \times (8 \times 8)}{4 \times 4}$, etc.. The number of layers is selected to be in the range from 2 to 8 layers. TSV diameter is assumed $1 \mu\text{m}$ to match the ITRS trends for TSV technology.

In [1], MUX area was $16 \mu\text{m}^2$ for 180 nm technology, so in this paper we estimate the MUX area for 65 nm using ITRS suggested scaling factor of 0.7, thus the MUX area would be $16 \times (0.7)^3 \approx 5.5 \mu\text{m}^2$. Since the MUX circuit is composed of two transmission gates and some small connection wires, the transmission gate area can be assumed half the area of the MUX; $A_{TG} \approx 2.75 \mu\text{m}^2$. Regarding driver area, we depend on

Fig. 25: Power comparison for different TSV technologies, i.e. different TSV capacitances.

the number of transistors in its circuit. Since the driver inverter has two transistors, so we assume also it has half of the area of the MUX but we should account for the sizing of the S signal driver (the sizes of the $PMOS$ and $NMOS$ transistors), therefore $A_{dr-S} \approx \frac{A_{MUX}}{4} \cdot (3K_{N-S})$, where $K_{P-S} = 2K_{N-S}$ to get equal charging and discharging currents during driver operation for 65 nm technology. The fab constants; α , D_o , and f_{TSV} are assumed to have the same values mentioned in [1], so $\alpha=2$, $D_o=0.004$ mm², and $f_{TSV}=10$ ppm. Finally, M is assumed as a parameter taking the values; 4×4 , 8×8 , and 16×16 .

Since die area is very large, the effect of TSV multiplexing area overhead is not high, and the normalized die yield in Fig. 26 is very close to 1, showing no improvement in die yield but very small degradation. This degradation is increasing with the number of layers used, and it is only clear for large M^6 .

The enhancement in TSV yield is dependent mainly on the number of TSVs. In Fig. 27, the TSV yield is always enhanced as long as the number of TSVs is reduced, which was previously proved mathematically in Subsection VIII-A. The enhancement in TSV yield is boosted for large number of 3D stack layers. Extra boosting, comes from the data bus width, which reflects the total number in TSV yield equation (Eq. 21). As fewer as the total number of TSVs used (smaller N_{BW}), the greater will be the TSV yield. The increase in TSV yield with reduction in TSV count used is a very strong exponential relation. As shown in Fig. 27c, when the mesh size is 16×16 , and $N_{BW}=1024$, there are $16 \times 16 \times 2 \times 1024$ which is about half million TSVs between two layers, the enhancement in TSV yield will be enormous; ≈ 86.746 million

⁶Note that the same simulations were done for $D_{TSV}=40$ and the normalized die yield were larger than 1 for all cases we tried, but we show only the case of $D_{TSV}=1$ as it conforms with ITRS trends.

times than the TSV yield without multiplexing.

As depicted from Eq. 30, the normalized overall W2W yield is affected by all the parameters affecting both die and TSV yields. In Figs. (28a,28b,28c), although the die yield was less than 1, the overall yield is still enhanced; thanks to TSV yield.

Since the overall fabrication yield is improved for all the cases we tried, the fabrication cost will be reduced, as depicted from Eq. 31. Though, we do not show the results because they are only the reciprocal values of the overall W2W yield figures.

X. CONCLUSIONS

In this paper, the timing requirements analysis of the TSVBOX-based 3D NoC are investigated and its design methodology is presented. Using the proposed methodology, a $4 \times 4 \times 4$ mesh topology 3D NoC is modeled using SystemC-A to verify various aspects of the target design. Analytical expressions for different 3D interconnect delays were derived using Elmore-delay estimations. The analytical delay models are verified using SystemC-A simulations and the error for different signals delays does not exceed 7.5%, indicating rather acceptable accurate estimations of our proposed models.

Thereafter, performance comparisons in terms of average delay and throughput are conducted to investigate the direct effects of TSV multiplexing on these two metrics. We show that the TSVBOX does not affect 3D NoC performance under some conditions dependent on the application traffic pattern, clock frequency, and the required multiplexing ratio. The TSVBOX shows very close performance compared to the conventional case especially in case of Hotspot traffic pattern which models wide range of on chip processing applications. The side effects of TSVBOX on power consumption is studied also. We show that the TSVBOX power consumption becomes closer and closer to the conventional one as the TSV dimensions gets

Fig. 26: Normalized die yield under different data bus widths, number of 3D stack layers, and mesh sizes.

Fig. 27: Normalized TSV yield under different data bus widths, number of 3D stack layers, and mesh sizes.

Fig. 28: Normalized overall W2W yield under different data bus widths, number of 3D stack layers, and mesh sizes.

smaller which reflects the adaptability of the TSVBOX for the trend of TSV fabrication technology which intends to reduce TSV dimensions and hence its parasitic capacitance as well.

Also, we have investigated the effect of the design methodology on yield and cost. Though, the TSVBOX adds extra circuitry, which might need large sized drivers, the effect on area was minimal and still it can improve enormously the overall yield and reduce fabrication cost.

APPENDIX A PROOFS OF EQS. 18, 19, AND 20

For simplicity, this analysis is done assuming an even number of the number of 3D stack layers (N is even).

A. Performance analysis for Transpose traffic

In Transpose traffic pattern, each node located at (X, Y, Z) coordinates sends all its traffic to the node located at $(X_{SIZE}-X-1, Y_{SIZE}-Y-1, Z_{SIZE}-Z-1)$ [36]. Therefore, nodes located in layer L_0 and layer L_{N-1} ⁷ send packets to each other, so do layer L_1 and layer L_{N-2} , etc.. According to that, packets from each pair of layers encounter the same extra waiting cycles in TSVBOX-based 3D NoC. The extra delay cycles for each pair can be calculated as follows: For (L_0, L_{N-1}) pair, packets make $(N-1)$ hops going up from L_0 to L_{N-1} or down from L_{N-1} to L_0 . According to Eq. 15,

⁷We can consider L_0 as the first layer (layer #0; usually it is the bottom-most layer) and L_{N-1} as the last layer (layer # $N-1$; usually it is the top-most layer) in the 3D stack.

those packets suffer from extra waiting cycles (EWCs):

$$EWCs|_{(L_0, L_{N-1})} = N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot (N - 1)$$

Repeating the same for (L_1, L_{N-2}) pair, we can deduce that packets traverse between these two layers suffer EWCs:

$$EWCs|_{(L_1, L_{N-2})} = N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot (N - 3)$$

In general for any pair (L_m, L_{N-m-1}) , the EWCs:

$$EWCs|_{(L_m, L_{N-m-1})} = N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot (N - 2m - 1)$$

The overall average EWCs (EWC_{avg}) is the sum of the EWCs of all pairs multiplied by 2 (because each layer of any pair has the same EWCs) and divided by $N-1$ ($N-1$ represents the maximum vertical hops) for the sake of averaging

$$\begin{aligned} EWC_{avg-Transpose} &= 2 \cdot N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot \left[\left(\frac{N}{2} \right) \cdot N - (1 + 3 + 5 + \dots + (N - 1)) \right] \\ EWC_{avg-Transpose} &= 2 \cdot N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot \left[\left(\frac{N^2}{2} \right) - \frac{N}{4} \cdot (N) \right] \\ EWC_{avg-Transpose} &= 2 \cdot N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot \frac{N^2}{4} \end{aligned} \quad (34)$$

B. Performance analysis for Uniform traffic

In Uniform traffic pattern, each node uniformly distributes its traffic to all other nodes in the network with equal probabilities. Therefore, each node sends $\frac{N_{PKT}}{N}$ on average to each layer including its own layer. Of course the fraction $\frac{N_{PKT}}{N}$ that is directed to the node's co-layer nodes does not suffer EWCs while others going to other layers do. Just like the previous case of Transpose traffic, the EWCs value depends on the layer location and it is the same per pair of layers, i.e. $EWCs_{L_0} = EWCs_{L_{N-1}}$, $EWCs_{L_1} = EWCs_{L_{N-2}}$, etc.. The EWCs of (L_0, L_{N-1}) pair is

$$\begin{aligned} EWCs|_{(L_0, L_{N-1})} &= \frac{N_{PKT}}{N} \cdot (n \cdot N_{MUX} - 1) \cdot (1 + 2 + 3 + \dots + (N - 1)) \\ &= \frac{N_{PKT}}{N} \cdot (n \cdot N_{MUX} - 1) \cdot \left(\frac{N(N - 1)}{2} \right) \end{aligned}$$

Doing the same for (L_1, L_{N-2}) pair

$$\begin{aligned} EWCs|_{(L_1, L_{N-2})} &= \frac{N_{PKT}}{N} \cdot (n \cdot N_{MUX} - 1) \cdot (1 + 1 + 2 + 3 + \dots + (N - 2)) \\ &= \frac{N_{PKT}}{N} \cdot (n \cdot N_{MUX} - 1) \cdot \left(1 + \frac{(N - 1)(N - 2)}{2} \right) \end{aligned}$$

Continuing in the same way, EWCs for $(L_{\frac{N}{2}-1}, L_{\frac{N}{2}})$ pair

$$\begin{aligned} EWCs|_{(L_{\frac{N}{2}-1}, L_{\frac{N}{2}})} &= \frac{N_{PKT}}{N} \cdot (n \cdot N_{MUX} - 1) \cdot \left[1 + 2 + 3 + \dots + \left(\frac{N}{2} - 1 \right) + \frac{(N - (\frac{N}{2} - 1))(N - \frac{N}{2})}{2} \right] \end{aligned}$$

Now the overall average EWCs (EWC_{avg})

$$\begin{aligned} EWC_{avg-Uniform} &= 2 \cdot \frac{N_{PKT}}{N} \cdot (n \cdot N_{MUX} - 1) \cdot \left[\left(0 + \frac{N(N - 1)}{2} \right) + \left(0 + 1 + \frac{(N - 1)(N - 2)}{2} \right) + \right. \\ &\quad \left(0 + 1 + 2 + \frac{(N - 2)(N - 3)}{2} \right) + \dots + \left. \left(\left(0 + 1 + 2 + 3 + \dots + \left(\frac{N}{2} - 1 \right) \right) + \frac{(N - (\frac{N}{2} - 1))(N - \frac{N}{2})}{2} \right) \right] \\ EWC_{avg-Uniform} &= 2 \cdot N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot \left[\frac{1}{N} \cdot \left(\sum_{i=0}^{\frac{N}{2}-1} \frac{(N - i) \cdot (N - i - 1)}{2} + \sum_{i=0}^{\frac{N}{2}-1} i \cdot \left(\frac{N}{2} - i \right) \right) \right] \end{aligned} \quad (35)$$

C. Performance analysis for Hotspot traffic

In Hotspot traffic pattern, we assume that each node sends some part of its traffic ($h \cdot N_{PKT}$, $0 < h < 1$) to some hotspot node/s and the rest of the traffic $((1 - h) \cdot N_{PKT})$ is uniformly distributed among all other nodes in the network. In our evaluation setup, it is assumed that there is a hotspot node in each layer where it is considered as a hotspot only for its co-layer nodes. According to that assumption, the analysis for Hotspot is the same as for Uniform, but N_{PKT} is substituted by $((1 - h) \cdot N_{PKT})$. Thus, EWC_{avg} for Hotspot traffic can be calculated by the following equation:

$$\begin{aligned} EWC_{avg-Hotspot} &= 2 \cdot N_{PKT} \cdot (n \cdot N_{MUX} - 1) \cdot \left[\frac{(1 - h)}{N} \cdot \left(\sum_{i=0}^{\frac{N}{2}-1} \frac{(N - i) \cdot (N - i - 1)}{2} + \sum_{i=0}^{\frac{N}{2}-1} i \cdot \left(\frac{N}{2} - i \right) \right) \right] \end{aligned} \quad (36)$$

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