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Deterministic scheduling in Networks-on-Chip using the Trajectory approach

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Abstract—In this paper, we consider the problem of guaranteeing real-time end-to-end transmission time for flows sent on a Network-on-Chip (NoC) with First-in First-out (FIFO) scheduling on each node. We show how to adapt the Trajectory approach, used in the context of Avionics Full Duplex switched Ethernet (AFDX) networks to characterize end-to-end transmission delays, to the context of NoC-based Systems-on-Chip (SoCs). We characterize the benefit of the Trajectory approach on an example.

Keywords—Determinism, Network-on-chip, Trajectory approach, real-time.

I. INTRODUCTION

As the number of elements in a Multi-Processor System-on-Chip (MPSoC) increases, so does raw processing power. This introduced augmented complexity that makes certain features such as determinism or Quality of Service (QoS) more and more difficult to maintain. As a result, the gap between performance and predictability (worst-case execution time (WCET)) is quite large, suggesting underused resources. NoCs are a new paradigm for on-chip interconnection that is being adopted by the majority of new SoCs. The concept behind NoCs is to adapt the principles of networks and implement them inside the chip, achieving to transfer packets instead of electric signals [1]. NoCs possess a modular architecture that offers improved spatial and temporal separation. All this creates a natural interest to evaluate the potential to exploit resources in an efficient way, preserving at the same time the system’s determinism [2].

Similar work on real-time scheduling has been realized on [3] with the difference that fixed-priority and virtual channels are considered in the NoC platform. While those characteristics are often adapted, it is not always the case. We chose the Trajectory approach because it has demonstrated low pessimism and will allow to achieve interesting results on a more generic NoC platform.

Our contribution: We show how to adapt the Trajectory approach (successfully applied to off-chip networks such as Switched Ethernet) to NoCs with FIFO scheduling. It is important to note that the constraints in NoCs are very different from those in AFDX Switched Ethernet networks which makes the adaptation to NoC-based systems necessary. In this paper we analyze the worst-case traversal time (WCTT) of sporadic flows to be able to guarantee real-time response on a chip level without requiring implementation of Virtual Channels (VCs). We achieve that by calculating the WCTT between two Intellectual Property (IP) elements using the Trajectory approach.

This paper is organized as follows. In section II, we introduce the NoC platform and the corresponding network model. We then recall existing research on NoCs in section III. The Trajectory approach adapted to the NoC ecosystem is presented in section IV. In section V we examine a use case to illustrate the method along with the results. Finally we conclude our work in section VI.

II. PLATFORM AND NETWORK MODEL

A. Platform

Each router $R_{xy}$ consists of five links, four located at the edges North, East, West, South (NEWS), used to connect with neighbor routers and the fifth is used to connect with the Local (L) IP $x$. An illustration of a router $R_{xy}$ is given in Figure 1. For example, $R_{xy,W}$ signifies the West link of router $R_{xy}$. Here $x$ and $y$ are the coordinates of the router inside the 2D mesh and they range from 0 to 3 for a 4x4 NoC.

In order to traverse a router, there are two levels that a flt has to pass, each taking one clock cycle. In the first one, buffering and routing take place while the second deals with arbitration and output. From a time standpoint, during the first cycle a header flt enters a router and is stored in a small size buffer that can hold up to four flits. At the same cycle it passes through a routing mechanism to determine which output link it wants to reserve. During the second cycle the arbiter (one in each output) will decide which of the potentially competing inputs will take over the output link. At the same time the output register (no output buffers) holds the flt that will traverse the link. These two levels are pipelined and initially two cycles are needed to forward the header flt but each of the payload flits will only require one cycle to follow through the path. In this work, we study the FIFO arbitration scheme in which the output controller reserves the path for the packet whose header flt arrives first. When the path is freed, the arbiter reserves the path for the packet whose header flt arrives secondly and so on.

This platform is implemented in Verilog and is able to synthesize on a Field Programmable Gate Array (FPGA) (Xilinx Virtex-7). Measurements can be taken through a cycle accurate simulator or through traces of the FPGA output stream.
B. Network model

We consider $n$ sporadic flows transmitted in the NoC. A sporadic flow $\tau_i$ sends packets respecting two parameters: 1) the period $T_i$ which is the minimum temporal interval between the arrival of two consecutive packets, and 2) the maximum transmission time $C_i$ which is the maximum time to transmit all the flits of a packet on a router. We denote $D_i$ a bound on the WCTT of any packet of flow $\tau_i$.

The transmission of one flit on a link takes one clock cycle $T_c$, and the period $T_i$ as well as the transmission time $C_i$, are multiples of clock cycle $T_c$. In this work, we consider for each packet of a message a constant transmission cycle $C_i = 4 \times T_c$ including the header flit and three payload flits. For a packet $f_i$ of flow $\tau_i$, we denote the header flit $f_{ih}$ and the payload flits $f_{i1}$, $f_{i2}$ and $f_{i3}$. Due to the dimension-order X-Y routing, each packet of flow $\tau_i$ follows a static path denoted $P_i$ which is composed of the source and destination IPs as well as the input ports of routers along this path. The first buffer of the source IP is denoted first$_i$, while the last buffer of the destination IP is denoted last$_i$. Then the path of flow $\tau_i$ is represented by $P_i = \{\text{first}_i, \ldots, \text{last}_i\}$.

We consider one diffusion path in the network which means that when packets of different flows join one path, they do not leave this path until they are transmitted to the same destination. A real use case that illustrates this concept can be found in memory hierarchies where the last level, a common bottleneck in MPSoCs, is the Random Access Memory (RAM). In such a case a number of IPs will try to access the RAM memory and combined with XY routing, the generated traffic will join a single path leading to the memory controller. An illustrative example of one diffusion path of NoC is shown in Figure 2. Flow $\tau_i$ follows path $P_1 = \{\text{IP}_3, \text{IP}_2, \text{IP}_1\}$. Three flows $\tau_2$, $\tau_3$ and $\tau_4$ join this path till $\text{IP}_{12}$.

![Fig. 1. Architecture of a NoC router $R_{xy}$](image)

Fig. 1. Architecture of a NoC router $R_{xy}$

With the advance of performance requirements in System-on-Chip (SoC), with an increase in the number of IPs to be connected, the interconnect becomes a bottleneck and suffers from scalability issues. Network on Chip (NoC) are seen as a solution to this scalability issue [4] by providing configurable network paradigms at small size (computation and storage functions are implemeted at silicon level). Providing real-time communications bounds in NoCs is therefore a challenge that needs to be addressed with specific approaches that take into account stringent requirements imposed by the hardware (small buffer size, flit level granularity).

Wormhole routing is a popular solution to take into account small buffer size constraints in router [5], [4]. Wormhole routing can lead to contention problems in communication where a packet can delay all packets trying to access the output of the same router. The delay on one router can result in a domino effect eventually delaying directly all packets on the same path as well as indirectly packets on other routers. This contention problem must be taken into account in a worst-case end-to-end delay analysis [6], [7], [3]. In [3], authors prove that the general problem of exact schedulability of real-time traffic-flows sent in NoCs is NP-hard. We must therefore focus on sufficient schedulability analysis. One approach consists of computing bounds on the worst-case end-to-end response times for any flow. In [6], [7], [3], the authors have considered this approach with a priority based transmission preemption method.

In the following section, we show that the trajectory approach, used in the context of switched Ethernet networks can be adapted to the context of NoCs.

![Fig. 2. An example of one diffusion path of NoC](image)

III. CURRENT WORK ON NOCS

Wormhole routing is a popular solution to take into account small buffer size constraints in router [5], [4]. Wormhole routing can lead to contention problems in communication where a packet can delay all packets trying to access the output of the same router. The delay on one router can result in a domino effect eventually delaying directly all packets on the same path as well as indirectly packets on other routers. This contention problem must be taken into account in a worst-case end-to-end delay analysis [6], [7], [3]. In [3], authors prove that the general problem of exact schedulability of real-time traffic-flows sent in NoCs is NP-hard. We must therefore focus on sufficient schedulability analysis. One approach consists of computing bounds on the worst-case end-to-end response times for any flow. In [6], [7], [3], the authors have considered this approach with a priority based transmission preemption method.

In the following section, we show that the trajectory approach, used in the context of switched Ethernet networks can be adapted to the context of NoCs.

IV. TRAJECTORY APPROACH ADAPTED FOR NOCS

The Trajectory approach was introduced for FIFO scheduling in [10] and then applied to real-time full-duplex switched Ethernet networks [11], [12]. This approach considers the worst-case scenario that a packet can face along its path to compute a bound on its WCTT.

More precisely, it maximizes each busy period$^1$ at each buffer along the path where competition occurs. The NoC architecture we study in this work shares common characteristics with real-time full-duplex switched Ethernet networks, like full-duplex links and static routing. We present

$^1$A busy period of packet $f_i$ with FIFO scheduling is defined by a temporal interval $[t_1, t_2]$ during which all the packets that arrive before or at the same time with $f_i$ are transmitted and there is no idle time in $(t_1, t_2)$.
in the following paragraphs how to adapt the Trajectory approach to the context of NoCs with FIFO policy. We explain its main differences with Switched Ethernet networks on a detailed example.

Let us consider packet $f_i$ of a flow $\tau_i$ generated at clock cycle $t_c$. It is transmitted over the NoC following a path $P_i = \{first_i,...,last_i\}$ along which it crosses $|P_i| - 2$ routers where $|P_i|$ represents the number of input buffers in the path (the first and last nodes are IPs).

Then according to the Trajectory approach, the WCTT of flow $\tau_i$ is bounded by:

$$D_i = \max_{0 \leq t_c \leq \frac{T_i}{T}} \left\{ W_{i,t_c}^{\text{last}_i} + C_i - t_c \cdot T_c \right\}$$  \hspace{1cm} (1)

where $B_i$ represents the maximum possible length of the busy period resulting from all flows following the same path as $\tau_i$ and $W_{i,t_c}^{\text{last}_i}$ is the latest starting time at the last visited buffer $last_i$ of flow $\tau_i$ computed by the following equation [10] (with $(x)^+ = \max(0, x))$:

$$W_{i,t_c}^{\text{last}_i} = \sum_{j \in \{1,...,n\}} \left(1 + \left[\frac{t_c \cdot T_c + A_{i,j}}{T_j}\right]\right)^+ \cdot C_j$$  \hspace{1cm} (2)

$$+\left|\{P_{i} - 1\} \cdot t_c \right|$$  \hspace{1cm} (3)

$$+\left|\{P_{i} - 2\} \cdot t_c \right|$$  \hspace{1cm} (4)

$$−C_i$$  \hspace{1cm} (5)

- Term 2 is the delay of packet $f_i$ due to competition with other packets in all the output ports along its path, as well as the transmission delay generated by packet $f_i$ itself. Term $t_c \cdot T_c + A_{i,j}$ represents the maximized interval during which packets of flow $\tau_j$ can arrive before or at the same clock cycle as $f_i$ at the first node where flow $\tau_j$ joins the path of flow $\tau_i$. This node is denoted $first_{i,j}$. Consequently, Term $(1 + \left[\frac{t_c \cdot T_c + A_{i,j}}{T_j}\right]\right)^+$ indicates the maximum number of packets generated by a flow $\tau_j$ that can delay the studied packet $f_i$.

- Term 3 is the sum of transmission delay from one node to the next along the path. Since wormhole switching is adopted and the transmission unit is a flit, the transmission delay from one node to the next is one clock cycle $T_c$ per link. Term 3 represents this transmission delay along the path $P_i$.

- Term 4 is the time for routing and arbitration along the path $P_i$. Each router in the NoC takes one clock cycle $T_c$ for routing and arbitration for each header flit. Since a packet $f_i$ encounters $|P_i| - 2$ routers along its path, the induced delay along the path $P_i$ is upper bounded by Term 4.

- Term 5 is subtracted because $W_{i,t_c}^{\text{last}_i}$ is the latest starting time of transmission of packet $f_i$ at $last_i$. Since the transmission time $C_i$ of $f_i$ has been counted in Term 3, it should be subtracted from $W_{i,t_c}^{\text{last}_i}$.

More details on the classical Trajectory approach can be found in [10].

In order to better understand the adapted Trajectory approach, we illustrate it on the example of Figure 2. Each flow’s temporal parameters are given in Table I. In this example, we consider the clock cycle $T_c = 1 \mu s$.

<table>
<thead>
<tr>
<th>$\tau_1$</th>
<th>$\tau_1$</th>
<th>$\tau_2$</th>
<th>$\tau_3$</th>
<th>$\tau_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{e}$ (multiple of $T_c$)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$T_i$ (multiple of $T_c$)</td>
<td>100</td>
<td>8</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

| TABLE I. FLOW PARAMETERS |

Consider flow $\tau_1$ following the path $P_1 = \{\text{IP}_{32}, R_{32,L}, R_{22,S}, R_{12,S}, \text{IP}_{12}\}$. A packet $f_1$ of flow $\tau_1$ is released by $\text{IP}_{32}$ at clock cycle $t_c = 0$. The corresponding scenario is illustrated in Figure 3 where $f_1$ is marked by bold solid squares. Packet $f_1$ contains one header flit $f_{1h}$ and three payload flits $f_{11}, f_{12}$ and $f_{13}$ which arrive at $\text{IP}_{32}$ at clock cycles 0, 1, 2 and 3, respectively. The header flit $f_{1h}$ advances along the path $P_1$ and arrives at the input buffer of $R_{32,L}$ at clock cycle 1. The payload flits advance in a pipeline way. A packet $f_2$ including four flits $f_{2h}, f_{21}, f_{22}$ and $f_{23}$ competes with packet $f_1$ for the North output port of router $R_{32,L}$. The header flit $f_{2h}$ arrives at the same clock cycle 1 as the header flit $f_{1h}$ and then it gets the access to the output first. After one clock cycle (clock cycle 2 marked by a cross in Figure 3 and Figure 4) dedicated for arbitration and transmission, $f_{2h}$ arrives at the input port $R_{22,S}$ of router $R_{32,L}$ and reserves the input buffer for its following payload flits. Meanwhile, the flits of packet $f_1$ wait in the input buffer of $R_{32,L}$.

In this case, the clock cycle where packet $f_2$ can delay packet $f_1$ is clock cycle 1, and then $t_c \cdot T_c + A_{1,2} = 1 \mu s$. According to Term 2, the delay of packet $f_1$ introduced by packets of flow $\tau_2$ is computed by:

$$\left(1 + \left[\frac{t_c \cdot T_c + A_{1,2}}{T_2}\right]\right)^+ \cdot C_2 = \left(1 + \left[\frac{1}{8}\right]\right)^+ \cdot 4 = 4 \mu s$$

The header flit $f_{2h}$ continues to advance after clock cycle 4 (again dedicated for routing purposes) and arrives at the input buffer of $R_{12,S}$ at clock cycle 5. The payload flits follow the header flit and at the same time free the input buffer of $R_{22,S}$ which allows the flits of packet $f_1$ to advance. However, at clock cycle 7 where the header flit $f_{1h}$ arrives at the input buffer of $R_{22,S}$, there are two more header flits $f_{3h}$ and $f_{4h}$ arriving at the same clock cycle and competing for the same output port in order to reach $R_{12,S}$. Consider the scenario when packets $f_3$ and $f_4$ are transmitted before packet $f_1$ since this is the worst-case scenario for packet $f_1$ with FIFO scheduling. In FIFO scheduling, the worst-case scenario in a buffer happens when all the frames arriving at the same time as the studied frame are transmitted before the studied frame. In that case, packet $f_1$ is blocked in router $R_{22}$ till clock cycle 17 as illustrated in Figure 3.

The clock cycles where packet $f_3$ can delay packet $f_1$ are from clock cycle 3 to clock cycle 7, and then $t_c \cdot T_c + A_{1,3} = 5 \mu s$. Similarly, we have $t_c \cdot T_c + A_{1,4} = 5 \mu s$. Therefore, the delay of packet $f_1$ introduced by packets of flows $\tau_3$ and $\tau_4$ is computed by:

$$\sum_{j \in \{3,4\}} \left(1 + \left[\frac{t_c \cdot T_c + A_{1,j}}{T_j}\right]\right)^+ \cdot C_j$$

$$= \left(1 + \left[\frac{5}{14}\right]\right)^+ \cdot 4 + \left(1 + \left[\frac{5}{14}\right]\right)^+ \cdot 4$$

$$= 4 + 4 = 8 \mu s$$
In addition to the delay introduced by other competing packets, there are also transmission delays and routing/arbitration delays calculated by Term 3 and Term 4:

\[(|P_1| - 1) \cdot T_e + (|P_1| - 2) \cdot T_c = 4 + 3 = 7 \mu s\]

Finally, the header flit \(f_{1h}\) arrives at IP_{12} at clock cycle 19, i.e. \(W_{1,12}^{IP} = 19 \mu s\). According to Equation 1, the delay of packet \(f_1\) generated at clock cycle \(t_c = 0\), is 23 \(\mu s\).

We have illustrated how the Trajectory approach calculates the delay of a packet \(f_1\) in the example of Figure 2 in the particular case where \(t_e = 0\). For the Trajectory approach, each value of the release time \(t_c\) corresponds to a separate scenario. Contrary to the delay analysis in the context of uni-processors which only considers the synchronous scenario as the worst-case, the Trajectory approach verifies all possible scenarios in order to obtain bounds on the WCTT. This verification of all the possible scenarios is done by Equation 1. Indeed, in the example the worst-case scenario is not the one where \(t_e = 0\).

In the following paragraph, we present another scenario which leads to a worse WCTT for packet \(f_1\).

Consider that packet \(f_1\) is released at clock cycle \(t_e = 8\). The header flit \(f_{1h}\) arrives at the input buffer of \(R_{32-L}\) at clock cycle 9 where the header flit \(f_{2h}\) arrives at the input buffer of \(R_{32-E}\) and therefore delays packet \(f_1\). It then leads to the maximized interval \(t_e \cdot T_e + A_{1,2} = 9 \mu s\) for packets of flow \(\tau_2\). Note that there is another packet \(f_2\) of flow \(\tau_2\) which arrives at the input buffer of \(R_{32-E}\) at clock cycle 1 due to its short period \(T_2 = 8 \mu s\). This scenario is illustrated in Figure 4.

Packet \(f_2\) does not delay packet \(f_1\) for the output port of router \(R_{32}\). However, packet \(f_2\) has an indirect influence on packet \(f_1\) which can be observed at router \(R_{22}\). The delay introduced by packets of flow \(\tau_2\) is then calculated by:

\[\left(1 + \frac{t_e \cdot T_e + A_{1,2}}{T_2}\right)^+ \cdot C_2 = \left(1 + \frac{9}{8}\right)^+ \cdot 4 = 8 \mu s\]

Packet \(f_2\)' advances along the path and arrives at the input buffer of \(R_{22-S}\) at clock cycle 3 after a clock cycle dedicated to routing. Meanwhile, a packet \(f_3\) of flow \(\tau_3\) arrives at the input buffer \(R_{32-W}\) and a packet \(f_4\) of flow \(\tau_4\) arrives at the input buffer \(R_{22-E}\) at the same clock cycle. Suppose that packet \(f_2\)' advances first before packets \(f_3\) and \(f_4\) and therefore delays packets \(f_3\) and \(f_4\) which eventually delay the transmission of packet \(f_2\). Contrary to the scenario of \(t_e = 0\) in Figure 3 where packet \(f_2\) advances from router \(R_{22}\) to router \(R_{12}\) without being delayed and releases the input buffer of \(R_{22-S}\) immediately, packet \(f_2\) is delayed for 2 clock cycles in the scenario of \(t_e = 8\) in Figure 4 and then releases the input buffer of \(R_{22-S}\) 2 clock cycles later. It imposes that packet \(f_1\) stays at the input buffer of \(R_{32-L}\) for 2 more clock cycles due to a limited input buffer size of 4 flits. Packet \(f_1\) waits till the clock cycle 17 where the header flit \(f_{21}\) advances and releases input buffer of \(R_{22-S}\). This is the indirect influence introduced by packets \(f_2, f_3\) and \(f_4\) and the corresponding scenario of \(t_e = 8\) is given at the part of \(R_{12-S}\) in Figure 4.

The header flit \(f_{1h}\) arrives at the input buffer of \(R_{22-S}\) resulting in the maximized interval \(t_e \cdot T_e + A_{1,3} = t_e \cdot T_e + A_{1,4} = 15 \mu s\) for frames of flow \(\tau_3\) and \(\tau_4\). Therefore, there can be another two header flits \(f_{3h}\) and \(f_{4h}\) arrive at the same clock cycle 17 due to their short periods \(T_3 = T_4 = 14 \mu s\) and packets \(f_3\) and \(f_4\) are transmitted before packet \(f_1\). Accordingly, the delay introduced by packets of flows of \(\tau_3\) and \(\tau_4\) is computed by:

\[
\sum_{j \in \{3,4\}} \left(1 + \left(\frac{t_e \cdot T_e + A_{1,j}}{T_j}\right)^+ \cdot C_j\right)
\]

\[
= \left(1 + \left(\frac{15}{14}\right)^+\right) \cdot 4 + \left(1 + \left(\frac{15}{14}\right)^+\right) \cdot 4 = 8 + 8 = 16 \mu s
\]

The summation of transmission delays and routing/arbitration delays is 7 \(\mu s\), the same as calculated for scenario \(t_e = 0\). Consequently, the latest starting time of packet \(f_1\) is computed by \(W_{1,8}^{IP} = 31 \mu s\). According to Equation 1, the WCTT of packet \(f_1\) is obtained by:

\[D_1 = W_{1,8}^{IP} + 4 - 8 = 27 \mu s\]

Obviously, the delay 27 \(\mu s\) obtained when \(t_e = 8\) is worse than the delay 23 \(\mu s\) obtained when \(t_e = 0\). The reason of the extra introduced delay is that some packets may not delay the packet under analysis at the beginning of the path, but can eventually delay it when they advance along the path, as for packets \(f_2, f_3\) and \(f_4\). The Trajectory approach verifies all the possible scenarios in order to compute a bound on the WCTT of flow \(\tau_i\). In this example, the obtained bound of flow \(\tau_i\) is equal to 27 \(\mu s\) when \(t_e = 8\).

For the sake of simplicity, we consider an upper bound of the sum of the transmission delay and of the routing/arbitration delay. In order to do so, we combine Term 3 and Term 4 in
the following simplified computation formula of $W_{i,t_c}^{last}$:

$$W_{i,t_c}^{last} = \sum_{j \in \{1,2,3\} \cap \{P_i, P_j\} \neq \emptyset} \left( 1 + \left[ \frac{t_{e} \cdot T_{c} + A_{i,j}}{T_{j}} \right] \right)^{+} \cdot C_{j} + (|P_i| \cdot 2 - 3) \cdot T_{c} - C_{i} \quad (6)$$

**Discussion and Improvement:** The computed delay $D_{i}$ is the exact WCTT of flow $\tau_{i}$ as illustrated in Figure 4. However, it is not always the case for some flows. Let us take flow $\tau_{3}$ in Figure 2 as an example.

Flow $\tau_{3}$ under analysis follows a path $P_{3} = \{P_{23}, R_{23, t}, R_{22, t}, R_{12, e}, IP_{12}\}$. The delay computation of flow $\tau_{3}$ considers the delay introduced by packets $f_{1}$, $f_{2}$ and $f_{4}$ of flows $\tau_{1}$, $\tau_{2}$ and $\tau_{4}$ at router $R_{22}$.

$$W_{3,t_{c}=0}^{IP_{12}} = \sum_{j \in \{1,2,3\} \cap \{P_{i}, P_{j}\} \neq \emptyset} \left( 1 + \left[ \frac{t_{e} \cdot T_{c} + A_{3,j}}{T_{j}} \right] \right)^{+} \cdot C_{j} + (|P_{3}| \cdot 2 - 3) \cdot T_{c} - C_{3} = 16 + 5 \times 2 - 3 - 4 = 19 \mu s$$

After the verification of all the possible scenarios, it is the one of $t_{c} = 0$ leading to the worst-case delay of flow $\tau_{3}$ bounded by:

$$D_{3} = W_{3,t_{c}=0}^{IP_{12}} + C_{3} - t_{c} \cdot T_{c} = 23 \mu s$$

Indeed, packets $f_{1}$ and $f_{2}$ are both transmitted by the link $R_{32} \rightarrow R_{22}$. As they are serialized which means that one packet is transmitted after another, their header flits cannot arrive at router $R_{22}$ at the same clock cycle. Therefore, only one packet ($f_{1}$ or $f_{2}$) can actually cause a delay to packet $f_{3}$ of flow $\tau_{3}$. This scenario is illustrated in Figure 5.

The exact WCTT of flow $\tau_{3}$ is then $19 \mu s$, meaning that the computed delay $D_{3} = 23 \mu s$ is pessimistic but safe. The physical constraint is called packet serialization which has been integrated in the Trajectory approach in the context of switched Ethernet network [11] and has been revisited and corrected in [12] for an optimism problem. In order to improve the delay evaluation, it is important to integrate it in the formula in the context of NoCs.

The part of workload which cannot actually delay the packet under analysis at the router $R_{22}$ due to packet serialization is denoted by $\Delta_{R_{22}}$. This serialization term is subtracted from Equation 6 and has been minimized in [11], [12] in order to guarantee the delay upper bound. As illustrated in the example of packet $f_{1}$, generated at clock cycle $t_{c} = 0$, of Figure 5, packet $f_{1}$ does not delay packet $f_{3}$ at router $R_{22}$ which leads to $\Delta_{R_{22}} = C_{1} = 4 \mu s$. At the other nodes (routers or IPs) along the path $P_{3}$, there is no packet serialization, i.e. $\Delta_{R_{22}} = \Delta_{R_{22}} = 0 = \Delta_{R_{22}} = 0 = 0$. Therefore, the total effect of packet serialization is:

$$\sum_{h \in P_{3}} \Delta_{h,t_{c}=0} = 4 \mu s$$

According to the correction proposed in [12], a part of packet serialization is overlapped with the time interval from time origin 0 to the release time of packet $f_{1}$. The duration fo this time interval is $t_{c} \cdot T_{c}$. Then the corrected serialization term is:

$$\max(\sum_{h \in P_{3}} \Delta_{h,t_{c}=0}, t_{c} \cdot T_{c}) = \max(4, 0) = 4 \mu s$$

Therefore, the improved calculation of the latest starting time of packet $f_{3}$ at its destination IP $IP_{12}$ is given by:

$$W_{3,t_{c}=0}^{IP_{12}} = \sum_{j \in \{1,2,3\} \cap \{P_{i}, P_{j}\} \neq \emptyset} \left( 1 + \left[ \frac{t_{e} \cdot T_{c} + A_{3,j}}{T_{j}} \right] \right)^{+} \cdot C_{j} + (|P_{3}| \cdot 2 - 3) \cdot T_{c} - C_{3} - \max(\sum_{h \in P_{3}} \Delta_{h,t_{c}=0}, t_{c} \cdot T_{c}) = 19 - 4 = 15 \mu s$$

which results in the WCTT of flow $\tau_{3}$ bounded by:

$$D_{3} = W_{3,t_{c}=0}^{IP_{12}} + C_{3} - t_{c} \cdot T_{c} = 19 \mu s$$

With the integration of serialization term, the computation formula of $W_{i,t_{c}}^{last}$ for flow $\tau_{i}$ is improved by:

$$W_{i,t_{c}}^{last} = \sum_{j \in \{1,2,3\} \cap \{P_{i}, P_{j}\} \neq \emptyset} \left( 1 + \left[ \frac{t_{e} \cdot T_{c} + A_{i,j}}{T_{j}} \right] \right)^{+} \cdot C_{j} + (|P_{i}| \cdot 2 - 3) \cdot T_{c} - \max(\sum_{h \in P_{i}} \Delta_{h,t_{c},t_{c}}^{i}, t_{c} \cdot T_{c}) - C_{i} \quad (7)$$

**V. CASE STUDY**

In Figure 6, we consider a 4x4 NoC with 10 flows $\tau_{10}$ reaching three destinations and where each IP is indexed with the coordinates of its router. We focus on flow $\tau_{1}$ following
the path $\mathcal{P}_1 = \{\text{IP}_{32}, R_{32-L}, R_{22-S}, R_{12-S}, \text{IP}_{12}\}$. The paths of the other flows are:

\[
\begin{align*}
\mathcal{P}_2 &= \{\text{IP}_{33}, R_{33-L}, R_{32-E}, R_{22-S}, R_{12-S}, \text{IP}_{12}\} \\
\mathcal{P}_3 &= \{\text{IP}_{23}, R_{23-L}, R_{22-E}, R_{12-S}, \text{IP}_{12}\} \\
\mathcal{P}_4 &= \{\text{IP}_{20}, R_{20-L}, R_{21-W}, R_{22-W}, R_{12-S}, \text{IP}_{12}\} \\
\mathcal{P}_5 &= \{\text{IP}_{10}, R_{10-L}, R_{11-W}, R_{01-S}, \text{IP}_{01}\} \\
\mathcal{P}_6 &= \{\text{IP}_{11}, R_{11-L}, R_{01-S}, \text{IP}_{01}\} \\
\mathcal{P}_7 &= \{\text{IP}_{13}, R_{13-L}, R_{12-E}, R_{11-E}, R_{01-S}, \text{IP}_{01}\} \\
\mathcal{P}_8 &= \{\text{IP}_{21}, R_{21-L}, R_{31-N}, \text{IP}_{31}\} \\
\mathcal{P}_9 &= \{\text{IP}_{22}, R_{22-E}, R_{21-E}, R_{31-N}, \text{IP}_{31}\} \\
\mathcal{P}_{10} &= \{\text{IP}_{00}, R_{00-L}, R_{01-W}, R_{11-N}, R_{21-N}, R_{31-N}, \text{IP}_{31}\}
\end{align*}
\]

All the 10 flows are with the same constant transmission time $C_i = 4 \times T_c = 4 \mu s$. In Table II, we precise for each flow $\tau_i$, its period $T_i$, its destination IP coordinates (xy) and the end-to-end delay $D_i$ computed by formula 1. Note that flows $\tau_1, \tau_2, \tau_3$ and $\tau_4$ in the example in Figure 2 are integrated in this case study.

<table>
<thead>
<tr>
<th>$\tau_i$</th>
<th>$T_i$ (μs)</th>
<th>$D_i$ (μs)</th>
<th>$\text{IP}_{\text{dest}} : x:y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_1$</td>
<td>100</td>
<td>27</td>
<td>12:12</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>8</td>
<td>23</td>
<td>12:12</td>
</tr>
<tr>
<td>$\tau_3$</td>
<td>14</td>
<td>23</td>
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</tr>
<tr>
<td>$\tau_4$</td>
<td>14</td>
<td>23</td>
<td>12:12</td>
</tr>
<tr>
<td>$\tau_5$</td>
<td>100</td>
<td>25</td>
<td>12:12</td>
</tr>
<tr>
<td>$\tau_6$</td>
<td>100</td>
<td>23</td>
<td>12:12</td>
</tr>
<tr>
<td>$\tau_7$</td>
<td>60</td>
<td>19</td>
<td>12:01</td>
</tr>
<tr>
<td>$\tau_8$</td>
<td>60</td>
<td>17</td>
<td>01:01</td>
</tr>
<tr>
<td>$\tau_9$</td>
<td>80</td>
<td>17</td>
<td>01:01</td>
</tr>
<tr>
<td>$\tau_{10}$</td>
<td>80</td>
<td>19</td>
<td>01:31</td>
</tr>
</tbody>
</table>

**VI. CONCLUSION**

In this paper, we show how to characterize a bound on the WCTT in a NoCs with the Trajectory approach. We consider a NoC platform implementing FIFO scheduling and wormhole routing. We revisit the Trajectory approach, adapt it to the context of a NoC and show with an example the benefit it can provide. As a further work, we will characterize the pessimism brought by the Trajectory approach with respect to the exact WCTT obtained on a representative NoC platform.

**REFERENCES**


