On Time Synchronization Issues in Time-Sensitive Networks with Regulators and Nonideal Clocks

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Ludovic Thomas

STORE 14. January 15th, 2021
Introduction

We focus on time-sensitive networks

- IEEE TSN
- IETF Detnet

\{ Goals: 
  - Bounded latency
  - No losses \}
We focus on time-sensitive networks

- IEEE TSN
- IETF Detnet

Goals:
- Bounded latency
- No losses

FIFO per class

Class-based network element
We focus on **time-sensitive networks**

- IEEE TSN
- IETF Detnet

**Goals:**

- Bounded latency
- No losses

FIFO per class
Time sensitive networks: analysis with Network Calculus
Time sensitive networks: analysis with **Network Calculus**

**Arrival curve** $\alpha_f$ of $f$

- **Leaky-bucket**
  - Data
  - Rate $r$
  - Time interval $t$

- **Network element**
  - Input: $f$
  - Output:
Time sensitive networks: analysis with **Network Calculus**

**Arrival curve** $\alpha_f$ of $f$

- **Leaky-bucket**
  - **data**
  - **rate** $r$
  - **time interval** $t$

**Service curve** of the element

**Network element**
Time sensitive networks: analysis with **Network Calculus**

- Computes delay bounds
- Computes burst increase bounds
Time sensitive networks: analysis with **Network Calculus**

**New: join the network calculus mailing list!**

https://lists.geant.org/sympa/info/netcal-list
Tight delay bounds with **Traffic Regulators**

$T = \{ b, b \}$

$D \rightarrow D' = D(b)$

Shaping for free

Control of the output arrival curve
Tight delay bounds with **Traffic Regulators**

**Per-flow regulator**

\[
\text{rate} \equiv r, \quad \text{burst} \equiv b
\]

\[b^* > b\]

**Network Element**

\[D\]
Tight delay bounds with **Traffic Regulators**

Introduction

**Tight delay bounds with Traffic Regulators**
Tight delay bounds with **Traffic Regulators**

- **Introduction**

- **Per-flow regulator**

\[
\begin{align*}
\text{rate} & \triangleq r \\
\text{burst} & \triangleq b
\end{align*}
\]

- **a) Control of the output arrival curve**

- **Network Element**

- **Per-flow regulator**

\[ b^* > b \]

- **D**

- **Burst shaping for free**

- **Control of the output arrival curve**

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Tight delay bounds with Traffic Regulators

a) Control of the output arrival curve

\[
\text{rate } \triangleq r \quad \text{burst } \triangleq b
\]

b) Shaping for free

\[D' = D\]
Introduction

Tight delay bounds with **Traffic Regulators**

- a) Control of the output arrival curve
  - \( \{ \text{rate} \} \)
  - \( \{ \text{burst} \}_f \)
  - \( r, b \)
  - \( f \)
  - \( b^* > b \)

- b) Shaping for free

\( D' = D \)

---

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Tight delay bounds with **Traffic Regulators**

- **FIFO Interleaved regulator**

\[
\begin{aligned}
D' = D \\
r, b, f \\
b^* > b
\end{aligned}
\]

- **Per-flow regulator (PFR) and Interleaved Regulator (IR)**

\[
\begin{aligned}
\{ \text{rate} \} \\
\{ \text{burst} \}_f
\end{aligned}
\]

\[
f, b, f
\]

⇒ A building block of IEEE TSN, called **Asynchronous Traffic Shaping (ATS)**.
Regulators measure **elapsed time**

\[ \forall t, \text{bits} (t) \leq rt + b \]

\[
\begin{cases}
\text{rate} \triangleq r \\
\text{burst} \triangleq b
\end{cases}
\]
Regulators measure \textit{elapsed time}

\[ \forall t, \text{bits}(t) \leq rt + b \left\{ \begin{array}{l}
\text{rate} \triangleq r \\
\text{burst} \triangleq b
\end{array} \right\} \]

- Discussions in TSN ATS (Asynchronous Traffic Shaping) [IEEE, 2019].
- In our paper: theoretical foundations to address the problem.
Contributions

- **Time model** for \{ non-synchronized, synchronized \} networks.

- A toolbox of **Network Calculus** results for \{ non-synchronized, synchronized \} networks.

- Analysis of regulators \{ PFR, IR \} in \{ non-synchronized, synchronized \} networks.
Model for non-synchronized clocks

Definitions and terminology for synchronization networks [ITU, 1996]

\[
h_i(t) - t = x_{i,0} + t\gamma_{i,0} + w(t) + \phi(t)
\]
Model for non-synchronized clocks

Definitions and terminology for synchronization networks [ITU, 1996]

\[
h_i(t) - t = x_i,0 + ty_i,0 + w(t) + \psi(t)
\]
Model for non-synchronized clocks

Definitions and terminology for synchronization networks [ITU, 1996]

\[ h_i(t) - t = x_{i,0} + ty_{i,0} + w(t) + \psi(t) \leq y_{\text{max}} t \]
Model for non-synchronized clocks

*Definitions and terminology for synchronization networks* [ITU, 1996]

\[ h_i(t) - t = x_{i,0} + ty_{i,0} + w(t) + \psi(t) \]
Model for non-synchronized clocks

Definitions and terminology for synchronization networks [ITU, 1996]

\[ h_i(t) - t = x_{i,0} + t y_{i,0} + w(t) + \psi(t) \leq \eta_i \]
Model for non-synchronized clocks

\[ d_{g\rightarrow i}(t) = h_g \circ h_i^{-1}(t) \]
Model for non-synchronized clocks

\[ d_{g \to i}(t) = h_g \circ h_i^{-1}(t) \]
Model for non-synchronized clocks

\[ \forall i, g \frac{1}{\rho} (t - s - \eta) \leq d_{g \rightarrow i}(t) - d_{g \rightarrow i}(s) \leq (t - s) \rho + \eta \]

TSN: \[ \rho = 1 + 200ppm \]
\[ \eta = 4ns \]
Model for synchronized clocks

\[ \forall i, g \]
\[
\left\{ \begin{array}{c}
\frac{1}{\rho} (t - s - \eta) \leq d_{g \rightarrow i}(t) - d_{g \rightarrow i}(s) \leq (t - s) \rho + \eta \\
|d_{g \rightarrow i}(t) - t| \leq \Delta
\end{array} \right.
\]

TSN: \( \Delta = 1 \mu s \)
Toolbox for changing the observing clock
Toolbox for changing the observing clock

\[ f: \mathcal{H}_i \rightarrow \alpha_f^\mathcal{H}_i \]

\[ \text{Device } j \]

\[ \text{data} \]

\[ b \quad t \]

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Toolbox for changing the observing clock

\[ \mathcal{H}_g \rightarrow ? \]

\[ \mathcal{H}_i \rightarrow \alpha_f \mathcal{H}_i \]

Device \( j \)

\[ \text{data} \]

\[ t \]

\[ b \]
Toolbox for changing the observing clock

\[ \mathcal{H}_i \rightarrow \alpha_f \mathcal{H}_i \]

Non-synchronized
\[ \eta, \rho \]

\[ \mathcal{H}_g \rightarrow \alpha_f \mathcal{H}_g \]

Device \( j \)
Toolbox for changing the observing clock

\[ \mathcal{H}_g \xrightarrow{\alpha} \mathcal{H}_g \]

Synchronized
\[ \eta, \rho, \Delta \]

\[ \mathcal{H}_i \xrightarrow{\alpha} \mathcal{H}_i \]
Instabilities with non-adapted regulators

Usual configuration of regulators

= Non-adapted regulator
Instabilities with non-adapted regulators

Usual configuration of regulators

= Non-adapted regulator

Non-synchronized networks:

- Per-flow regulator → penalty
- Interleaved regulator → unstable

∀ ∆ > 0

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On Time Synchronization Issues in Time-Sensitive Networks
Instabilities with non-adapted regulators

Usual configuration of regulators

= Non-adapted regulator

Non-synchronized networks:

Per-flow regulator

Interleaved regulator  \{ unstable

Synchronized networks:

Per-flow regulator  \rightarrow  penalty  [\Delta, 4\Delta]

Interleaved regulator  \rightarrow  unstable  \forall \Delta > 0
Adversarial synchronized clocks for a non-adapted IR (=ATS) (1/3)
Adversarial synchronized clocks for a non-adapted IR (=ATS) (1/3)
Adversarial synchronized clocks for a non-adapted IR (=ATS) (2/3)
Adversarial synchronized clocks for a non-adapted IR (≡ATS) (2/3)

FIFO system

Source 1
\( H_1 \)

Source 2
\( H_2 \)

\( D_{\text{max}} = 5 \)

IR

Source 1, \( H_1 \)

Source 2, \( H_2 \)

Sources 1 + 2, \( H_{\text{IR}} \)
Adversarial synchronized clocks for a non-adapted IR (=ATS) (2/3)

Instability of non-adapted regulators

FIFO system

Source 1, $\mathcal{H}_1$

Source 2, $\mathcal{H}_2$

Sources 1 + 2, $\mathcal{H}_{IR}$

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Adversarial synchronized clocks for a non-adapted IR (=ATS) (3/3)

Validation and extension through ns-3 simulations.

Example at low data rates:

- 3 sources @ 147 kB/s
- 1 queuing element @ 437.5 kB/s
- $\Delta = 1\mu s$, $\rho = 1+100$ ppm
- using adversarial clocks
- $\Rightarrow$ red line is Network Calculus delay bound assuming perfect clocks

Work by Guillermo Aguirre
Computing the configuration of regulators

How to configure the regulators?

∀ flow $f$

Source $\mathcal{H}_{\text{source}}$ → Network element $\mathcal{H}_{\text{Reg}_1}$ → Regulator → Network element $\mathcal{H}_{\text{Reg}_2}$ → Regulator → Network element $\mathcal{H}_{\text{Reg}_3}$ → Regulator → Network element $\mathcal{H}_{\text{TAI}}$
Computing the configuration of regulators

How to configure the regulators?

**Question:** What parameters?

∀ flow $f$

Source $\rightarrow$ Network element $\rightarrow$ Regulator $\rightarrow$ Network element $\rightarrow$ Regulator $\rightarrow$ Network element $\rightarrow$ Regulator $\rightarrow$ Network element

$H_{source}$ $\rightarrow$ $H_{Reg_1}$ $\rightarrow$ $H_{Reg_2}$ $\rightarrow$ $H_{Reg_3}$ $\rightarrow$ $H_{TAI}$
How to configure the regulators?

Question: What parameters?

Question: What is the delay bound?
Two methods for synchronized and non-synchronized networks

Rate-and-burst cascade Works with PFR or IR

Source \( \mathcal{H}_{\text{source}} \) → Network element \( f \) → Regulator \( \mathcal{H}_{\text{Reg}_1} \) → Network element → Regulator \( \mathcal{H}_{\text{Reg}_2} \) → Network element → Regulator \( \mathcal{H}_{\text{Reg}_3} \) → Network element
Two methods for synchronized and non-synchronized networks

**Rate-and-burst cascade** Works with PFR or IR

- **Source** \( H_{\text{source}} \) → **Network element** \( H_{\text{Reg}_1} \) → **Regulator** → **Network element** \( H_{\text{Reg}_2} \) → **Regulator** → **Network element** \( H_{\text{Reg}_3} \) → **Network element**

  - Rate: \( \rho \)
  - Burst: \( b_0 + \eta \rho \)

**ADAM** Works with PFR only

- **Source** \( H_{\text{source}} \) → **Network element** \( H_{\text{Reg}_1} \) → **PFR** → **Network element** \( H_{\text{Reg}_2} \) → **PFR** → **Network element** \( H_{\text{Reg}_3} \) → **Network element**

  - Rate: \( W \rho \)
  - Burst: \( b_0 \)
Performance comparison

Increase of the ETE delay bound wrt ideal clocks.
Conclusion

- **Time-model** for bounding the behavior of the clocks in the network.

- **Instability** of the non-adapted ATS regulator for any $\Delta > 0$.

- Two methods for **configuring the regulators** in a network, relying on a **Network Calculus toolbox**.
Conclusion

- **Time-model** for bounding the behavior of the clocks in the network.
- **Instability** of the non-adapted ATS regulator **for any** $\Delta > 0$.
- Two methods for configuring the regulators in a network, relying on a **Network Calculus toolbox**.

Future work:
- Improvements on the ADAM method.
- Simulation of different (more realistic) clock models in ns-3.
- The toolbox could be of interest when studying other technologies / TSN components.