Real-Time Communications Over Hybrid Wired/Wireless PROFIBUS-Based Networks

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FEUP
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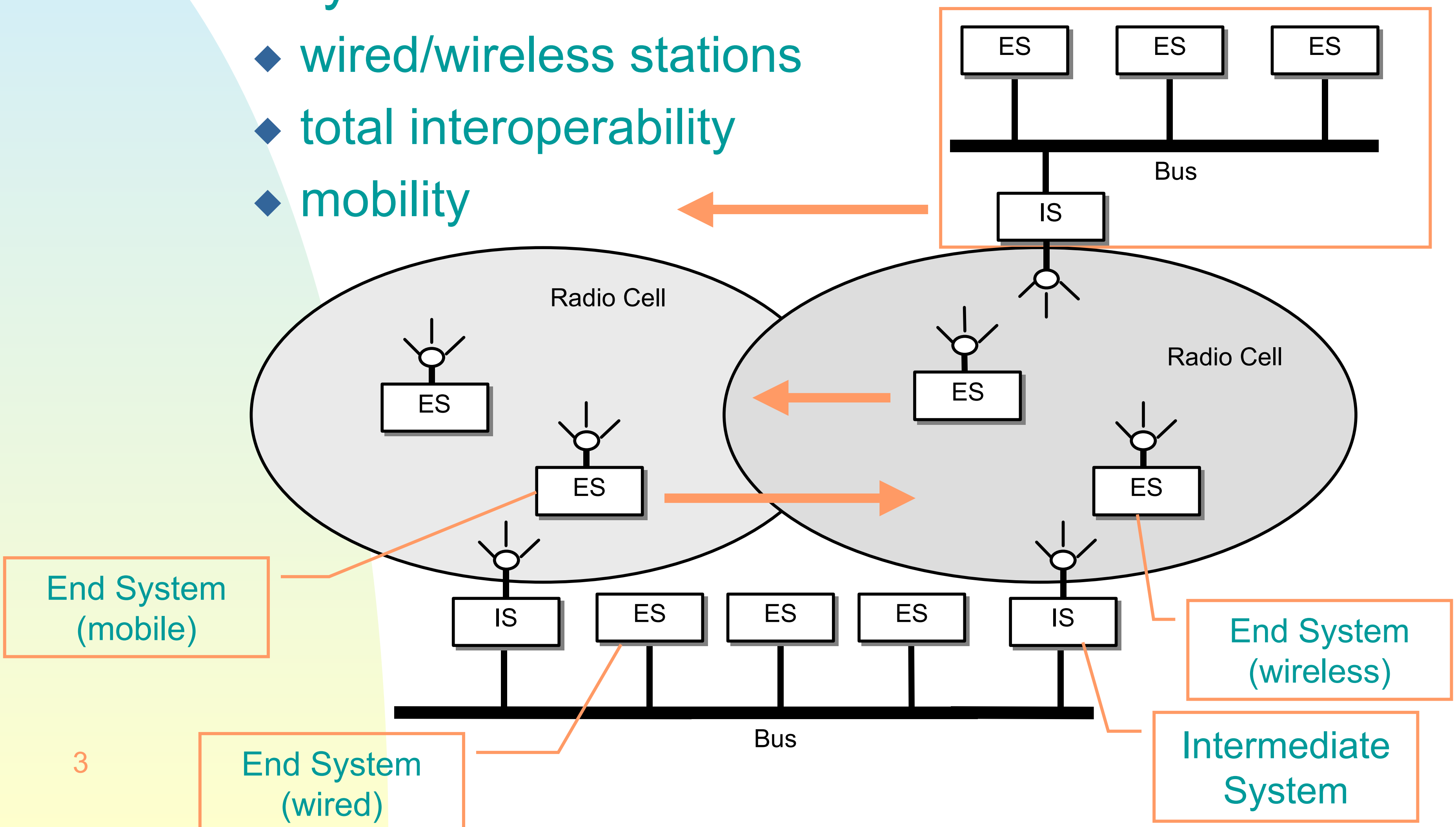
Overview of the presentation

- Part I
  - Context and objectives
  - General aspects of the system architecture
  - Analytical models for the network
- Part II
  - Adapting heterogeneous media
  - Duration of message transactions
  - Supporting inter-cell mobility
- Part III
  - Conclusions and ongoing/future work

Context and objectives

- A hybrid wired/wireless network
  - wired/wireless stations
  - total interoperability
  - mobility



Context and objectives

- Motivation
  - Currently, **no hybrid architecture based on standard fieldbus** supporting mobility (real-time)
- Hypothesis
  - Our hypothesis was that **such an architecture would be possible**
- Different design alternatives were analysed
  - having adopted **PROFIBUS** as the federating communication system and
  - Intermediate Systems operating at the **Physical Layer**

Context and objectives

- To validate the hypothesis, we have devised:
  - a **model** for the network
    - network components, rules, timing behavior, mobility
  - several **methodologies** for supporting and guaranteeing real-time communications
    - traffic adaptation by inserting inactivity (idle) times
    - to compute worst-case turnaround times and WCRT of message transactions (with inter-cell mobility)
    - to compute the mobility management parameters
  - **without changing the PROFIBUS protocol**, but **adding wireless capabilities**:
    - a wireless Physical Layer (radio front-end)
    - a mobility management mechanism (PROFIBUS compliant)

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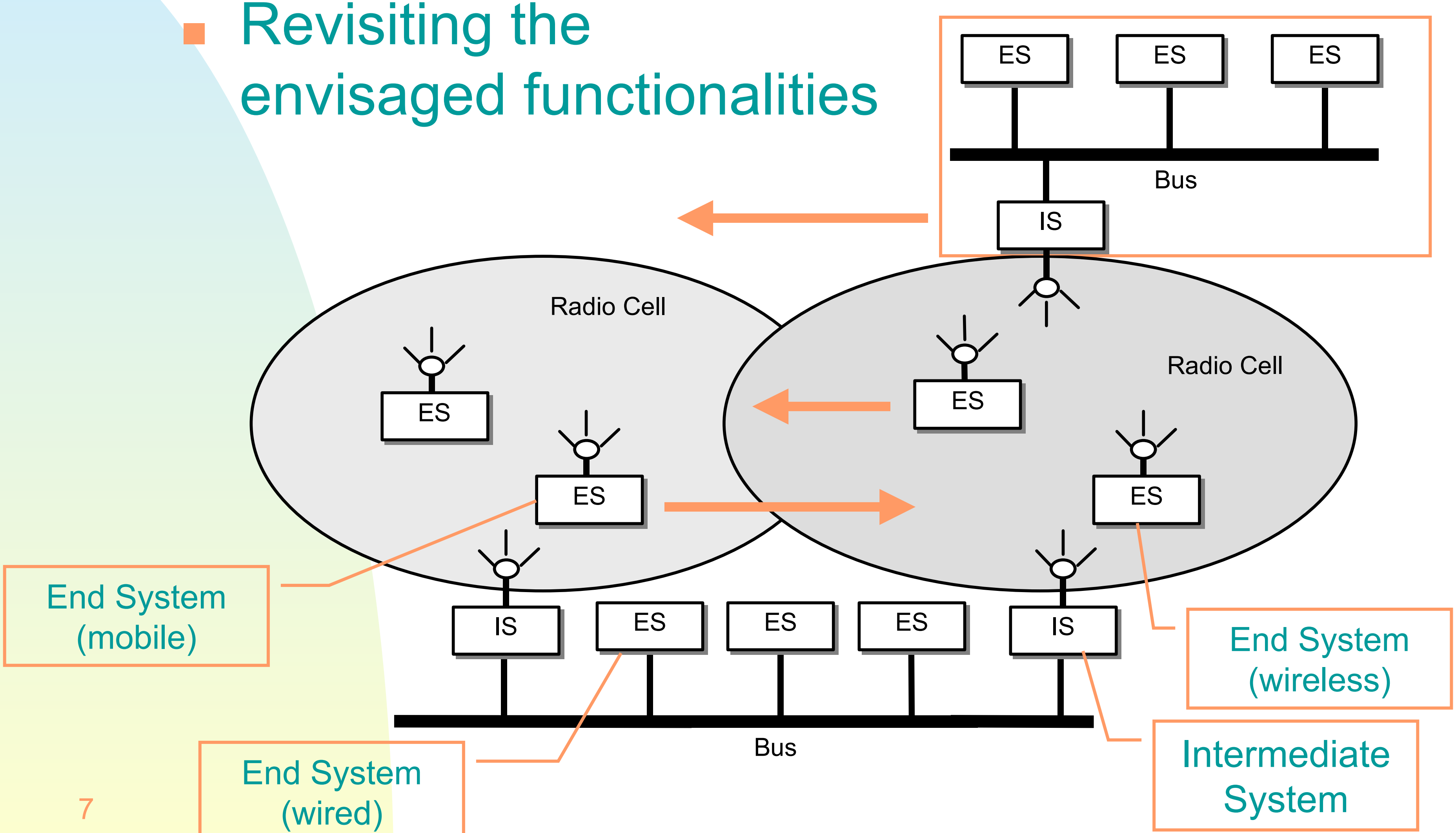
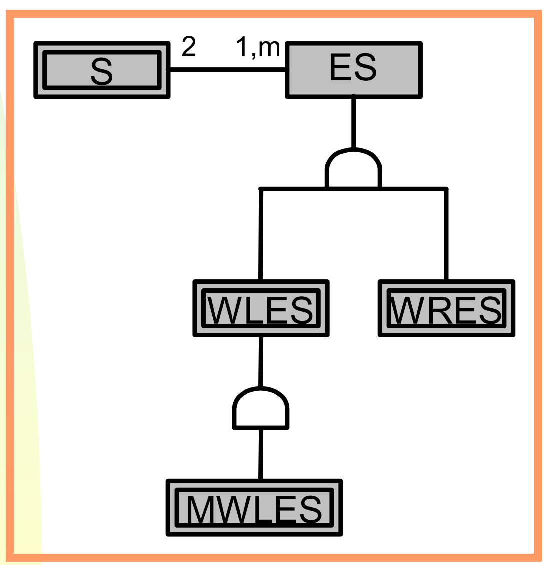
General aspects of the system architecture

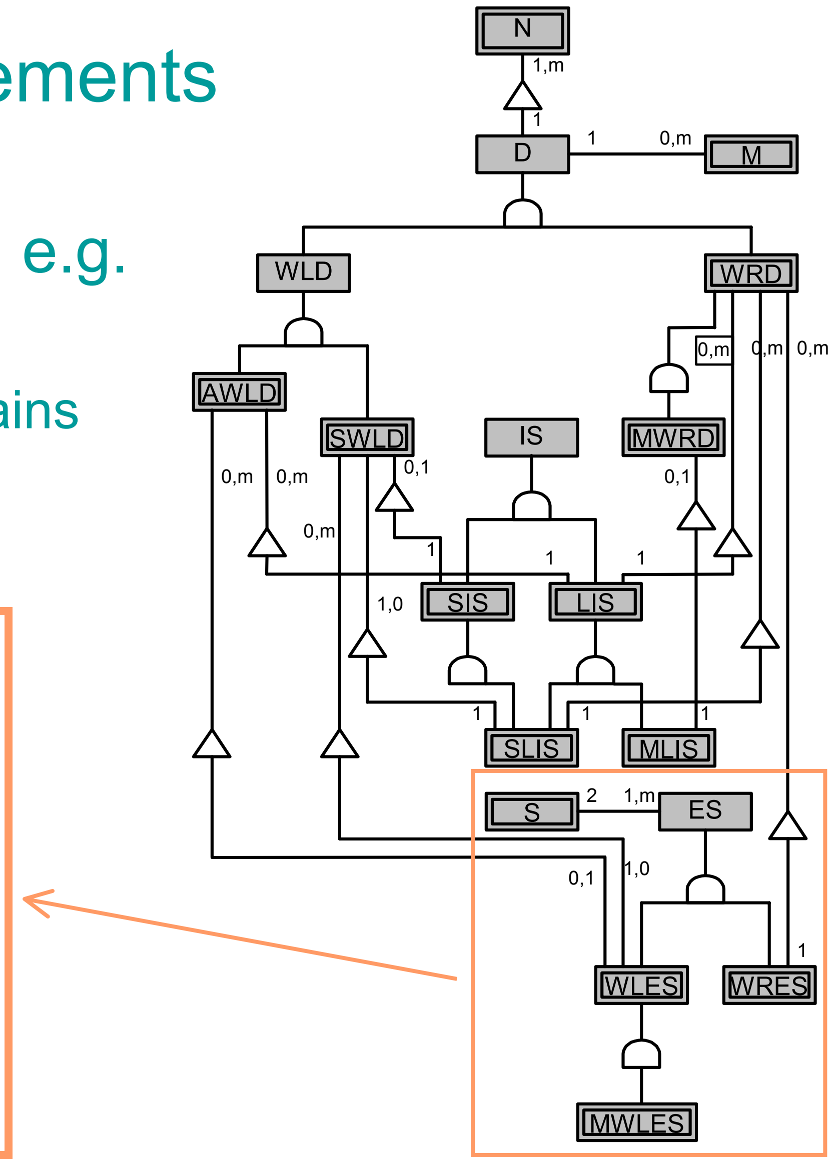
- Revisiting the envisaged functionalities



General aspects of the system architecture

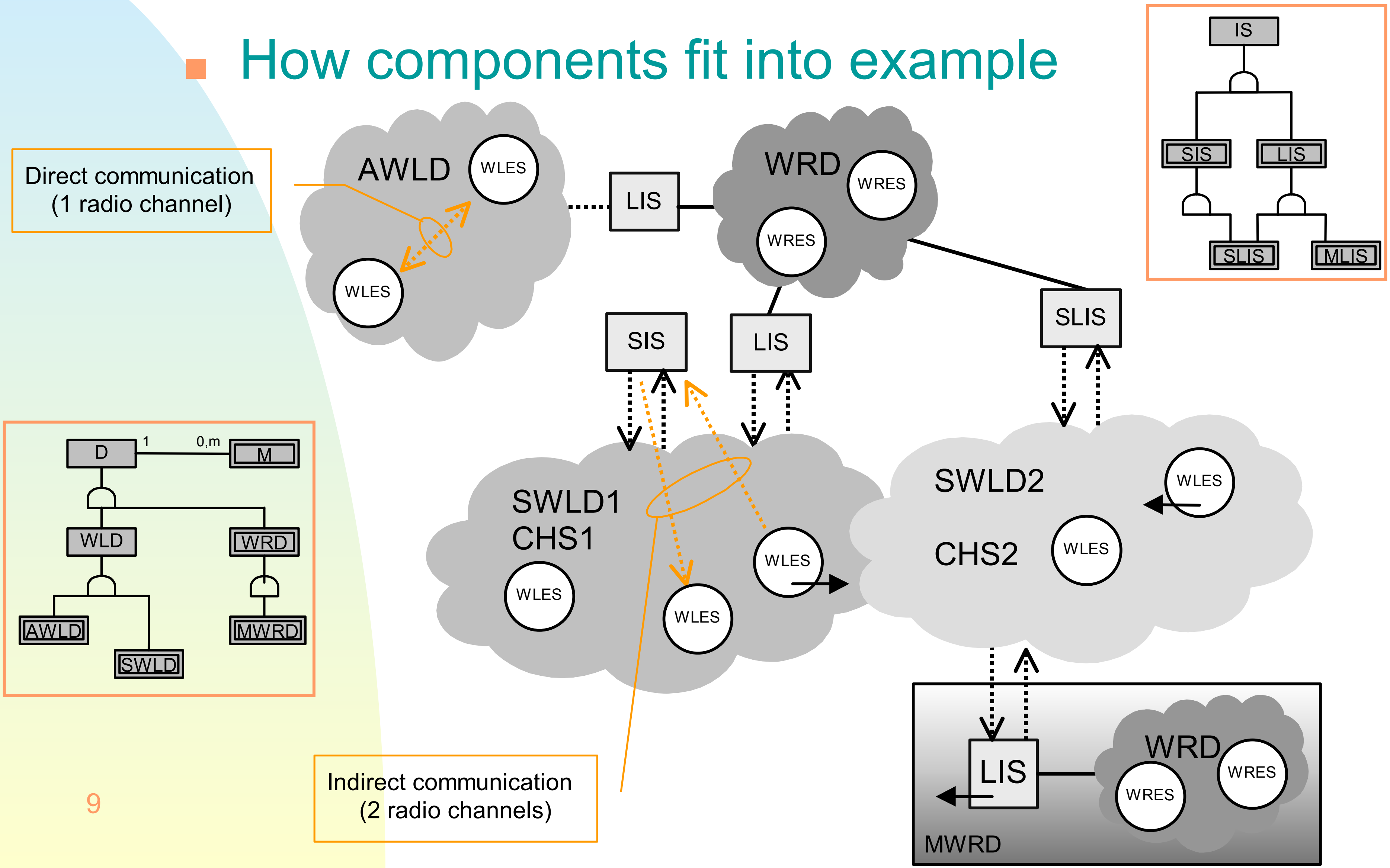
- To fulfil those requirements
  - the network model is composed of objects, e.g.
    - Physical Media
    - Communication Domains
    - Intermediate Systems
    - End systems





General aspects of the system architecture

- How components fit into example



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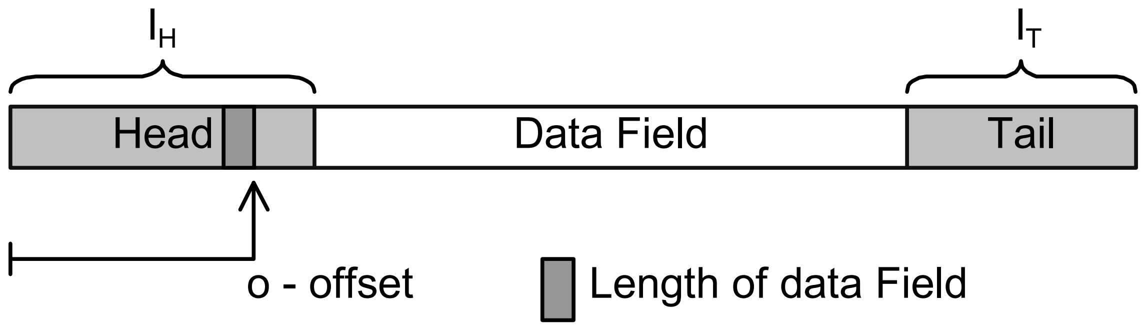
Analytical models for the network

- Physical Media model
  - PhL PDU Format

$$M^l = \left(r^l, l_H^l, l_T^l, k^l\right)$$



  - PhL PDU Duration

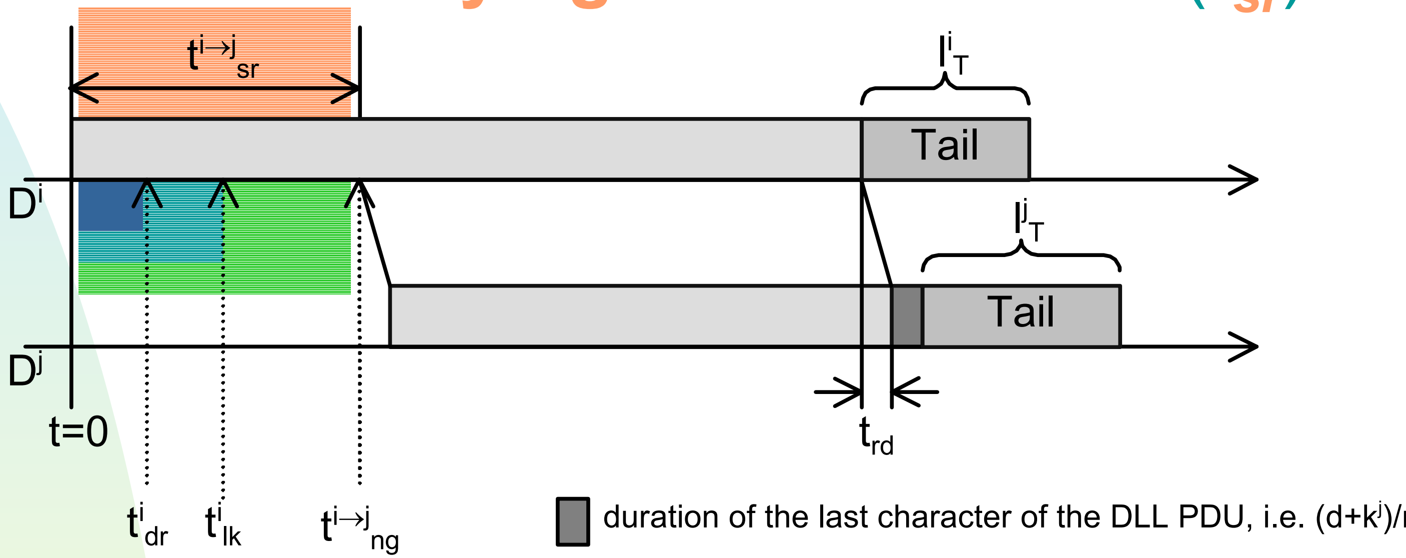
$$C^i = \frac{l_H^i + L \cdot \left(d + k^i\right) + l_T^i}{r^i}$$

- Intermediate Systems model

$$IS^k = \left(IS\_TYPE, m^k, t_{rd}^k, T_{IDm}^k\right)$$

Analytical models for the network

- The **start relaying instant** function (t_{sr})



Data ready instant

$$t^i_{dr} = \frac{l^i_H + k^i + d}{r^i}$$

Length known instant

$$t^i_{lk} = \frac{o^i}{r^i}$$

No gap instant

$$t^{i\to j}_{ng} = \frac{l^i_H}{r^i} - \frac{l^j_H}{r^j} + L \cdot \left(\frac{d+k^i}{r^i} - \frac{d+k^j}{r^j} \right) - \frac{d+k^j}{r^j}$$

Start relaying instant

$$t^{i\to j}_{sr} = \max\left\{ t^i_{dr}, t^i_{lk}, t^{i\to j}_{ng} \right\}$$

Model OK for ∀ M

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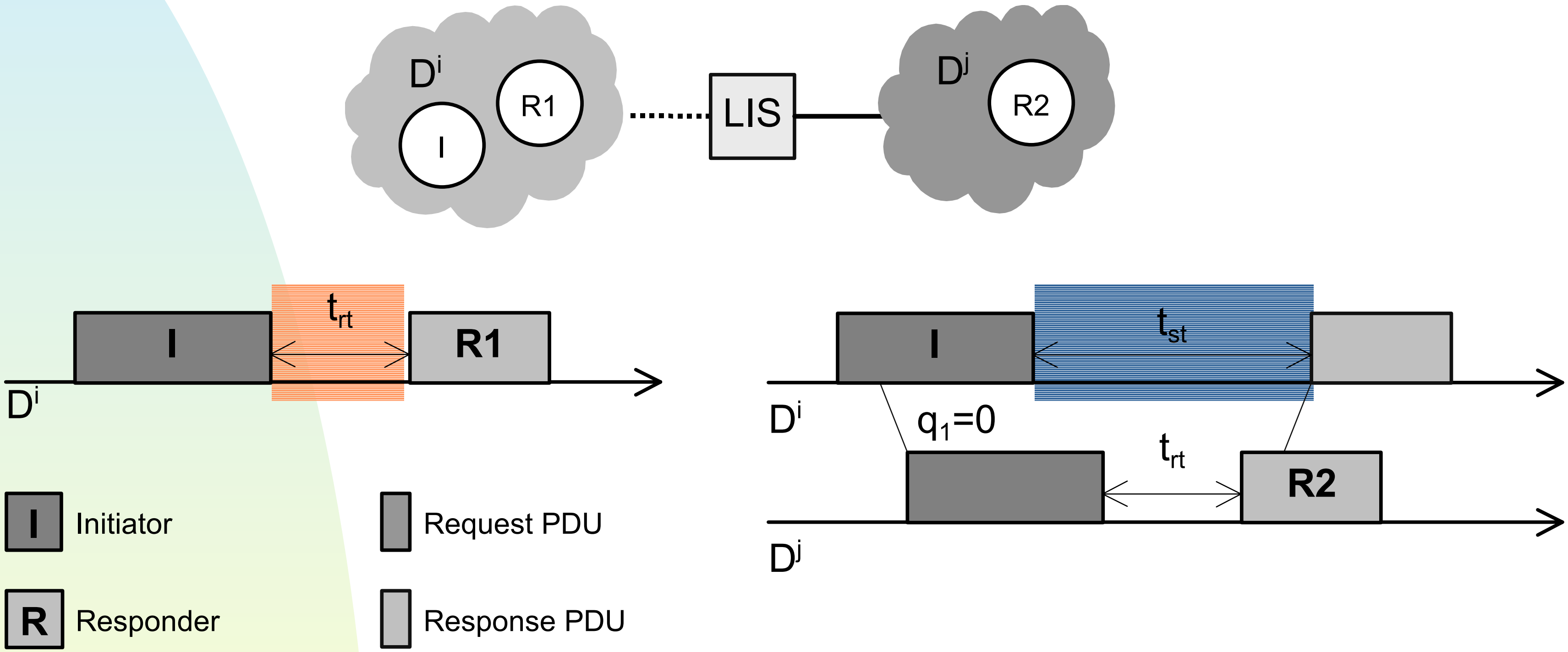
Adapting heterogeneous media

- Important concepts - turnaround times



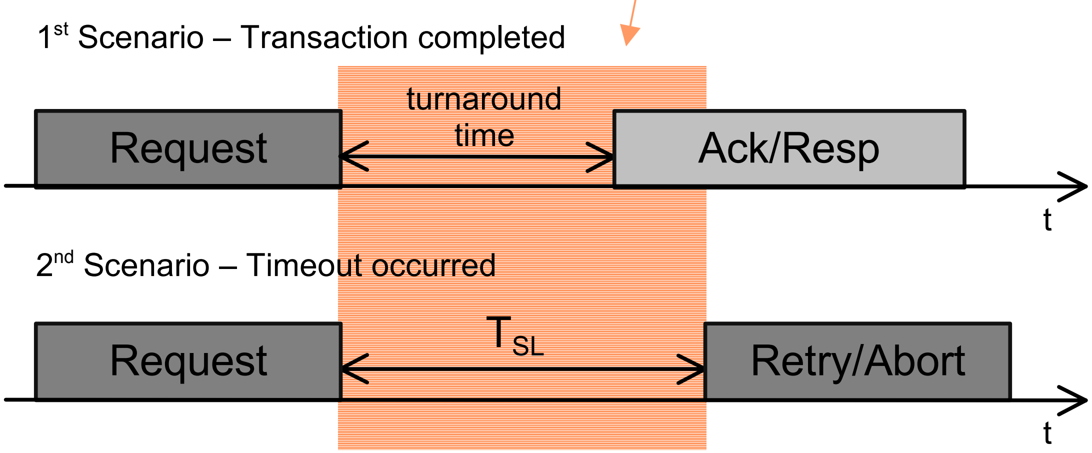
t_{rt} - responder's turnaround time

<

t_{st} - system turnaround time

Adapting heterogeneous media

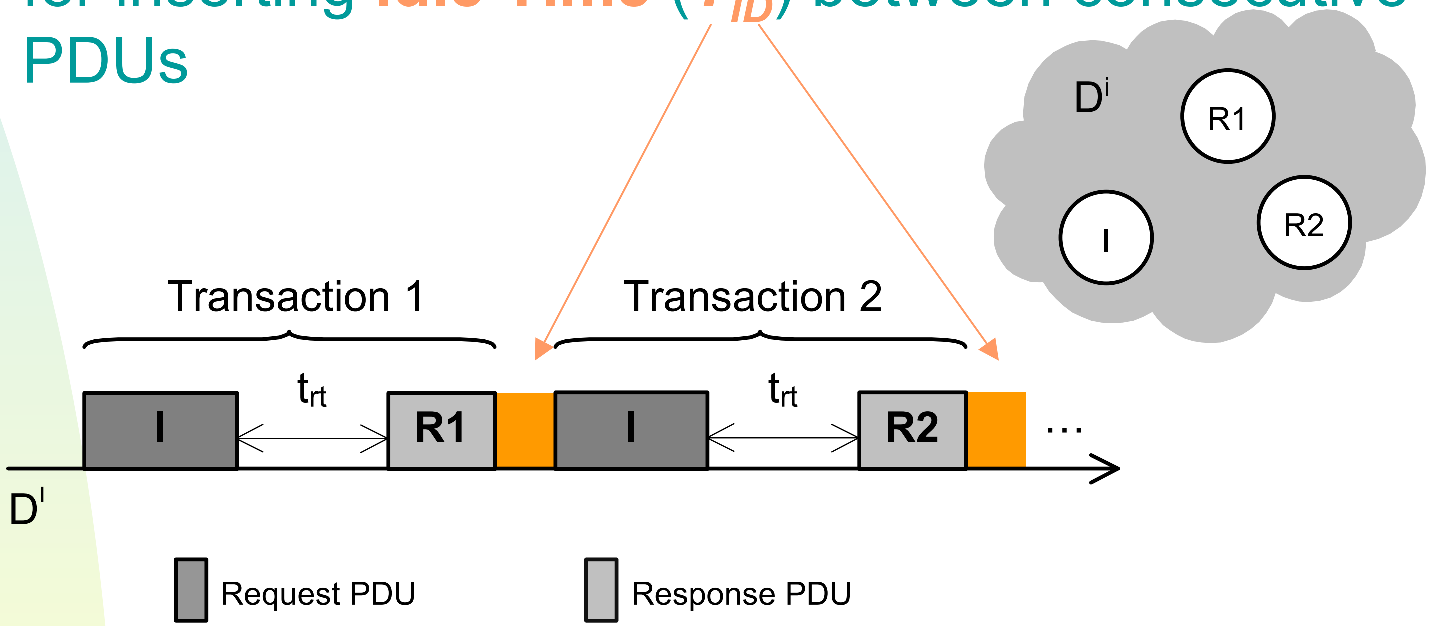
- Important concepts - Slot Time parameter
  - the response/ack to a request must arrive within the PROFIBUS **Slot Time** (*T_{SL}*) parameter
  - if a **timeout** occurs, the master retries the request (token) or aborts the transmission



Setting *T_{SL}* in our architecture requires complex methodology

Adapting heterogeneous media

- Important concepts - Idle Time parameter
  - every PROFIBUS master station is responsible for inserting **Idle Time** (T_{ID}) between consecutive PDUs



Setting T_{ID} in our architecture requires complex methodology

Adapting heterogeneous media

- Let us see **why and how these two PROFIBUS parameters**…

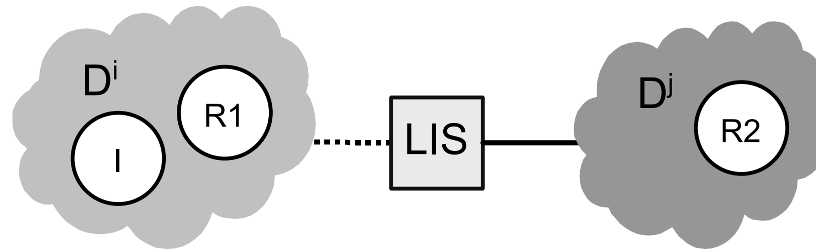
T_{ID} T_{SL}

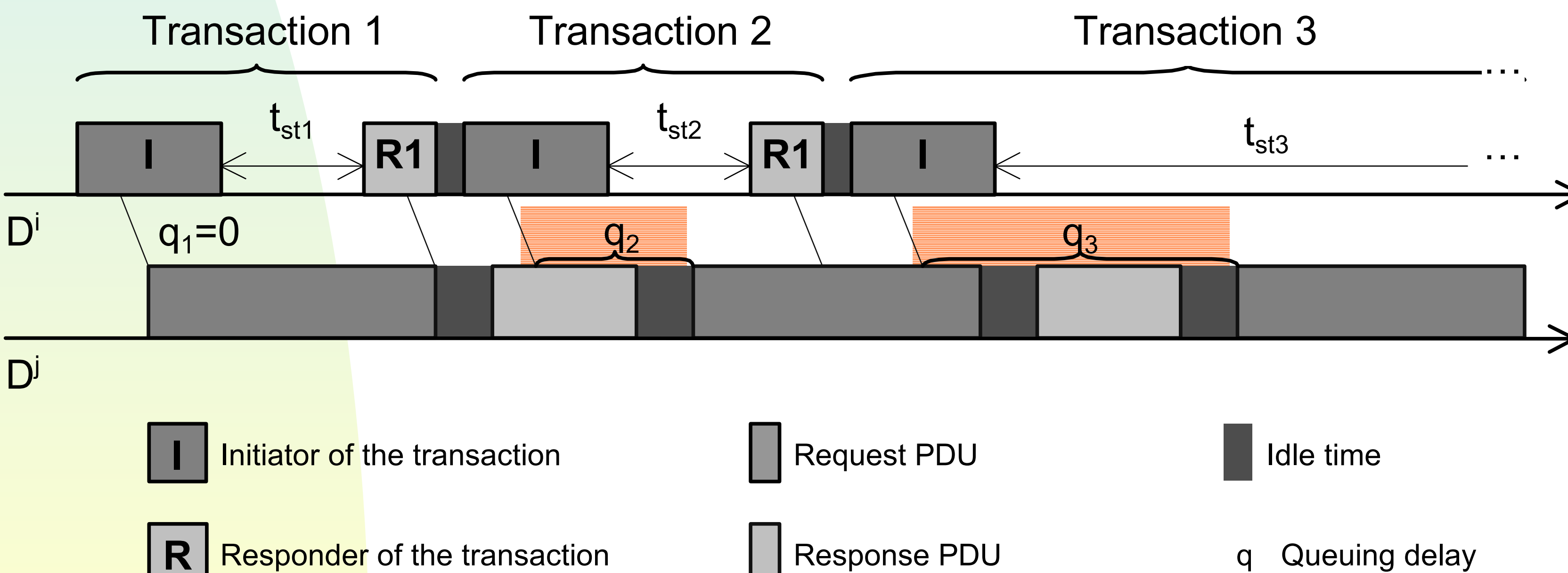
- **are impacted by the proposed architecture**…

Adapting heterogeneous media

- Increasing queuing delays in the ISs

$$q_3 > q_2 > q_1$$





Adapting heterogeneous media

- Why increasing queuing delays cannot occur?
  - System turnaround time (t_{st}) must be **predictable**, **bounded**...
    - to be able to compute the worst-case duration of message transactions (for WCRT analysis)
    - and to set the Slot Time parameter
  - ...and as **small** as possible
    - to minimise WCRT of message transactions
    - to minimise systems' responsiveness to failures

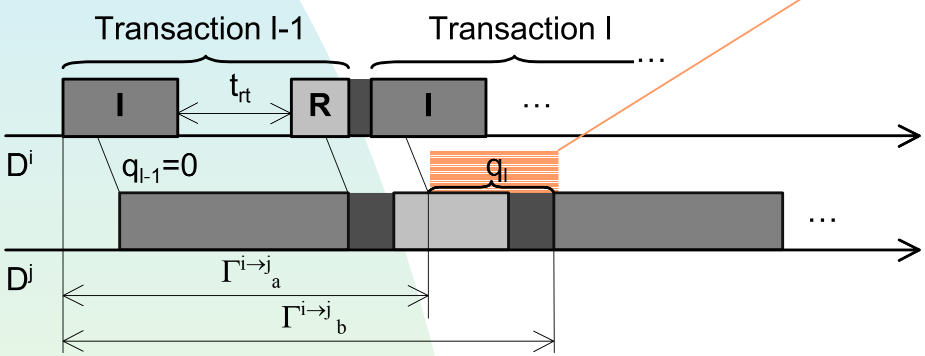
Thus, **increasing and unpredictable queuing delays must be eliminated**

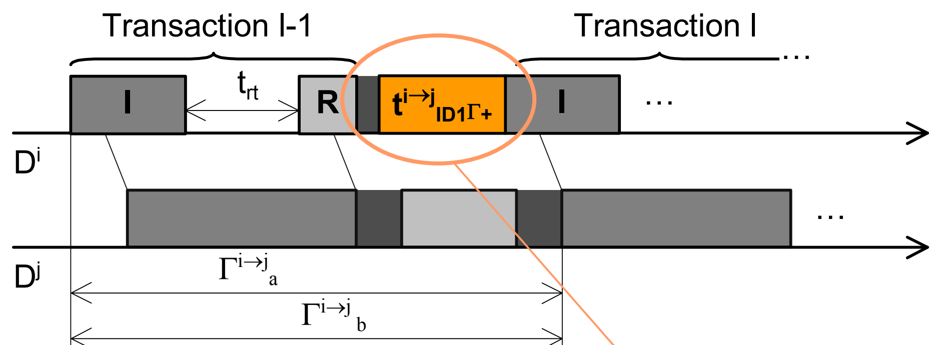
Adapting heterogeneous media

- Our solution...

$q_l > 0$

$\Gamma^{i \to j}_a < \Gamma^{i \to j}_b$





$$\Gamma_a^{i \to j} = C^i_{req(l-1)} + t_{rt} + C^i_{resp(l-1)} + t^i_{ID1m} + t^{i \to j}_{ID1\Gamma+} + t^{i \to j}_{srreq(l)} + t_{rd}$$

$$\Gamma_b^{i \to j} = \max\left\{\gamma_a^{i \to j}, \gamma_b^{i \to j}\right\} + C^j_{resp(l-1)} + t^j_{ID1m} = \max\left\{C^i_{req(l-1)} + t_{rt} + t^{i \to j}_{srresp(l-1)} + t_{rd}, t^{i \to j}_{srreq(l-1)} + t_{rd} + C^j_{req(l-1)} + t^j_{ID1m}\right\} + C^j_{resp(l-1)} + t^j_{ID1m}$$

$$t^{i \to j}_{ID1\Gamma+} \geq C^j_{req(l-1)} - C^i_{req(l-1)} + C^j_{resp(l-1)} - C^i_{resp(l-1)} + 2 \cdot t^j_{ID1m} - t^i_{ID1m} - t_{rt} + + t^{i \to j}_{srreq(l-1)} - t^{i \to j}_{srreq(l)} + + \max\left\{t^{i \to j}_{srresp(l-1)} - t^{i \to j}_{srreq(l-1)} + C^i_{req(l-1)} - C^j_{req(l-1)} + t_{rt} - t^j_{ID1m}, 0\right\}$$

Insert extra **Idle Time** such as:

$\Gamma^{i \to j}_a \geq \Gamma^{i \to j}_b$

$$t^i_{ID1\Gamma+} = \max\left\{t^{i \to j}_{ID1\Gamma+}\right\}$$

$$\begin{cases} \forall\, i, j \in \{1, \ldots, nm\} \text{ physical media} \\ \forall\, \mathrm{L}_{req(l-1)}, \mathrm{L}_{resp(l-1)} \in \text{DLL PDUs length from the message streams of I} \\ \forall\, \mathrm{L}_{req(l)} \in \text{DLL PDUs length from the message streams of I or the token} \end{cases}$$

For each master
- for every Media
- for every mess. stream

Adapting heterogeneous media

- It is also mandatory to compute the idle times that must be inserted
  - after receiving the token
  - after issuing an unacknowledged request
  - **for every master, for every Physical Media**
- Finally, the **(total) idle time** that must be set in each master station can be computed

$$T^{i}_{ID1} = T_{ID1m} + \lceil t^{i}_{ID1+} \cdot r^{i} \rceil$$

Idle Time after response/token

$$T^{i}_{ID2} = T_{ID2m} + \lceil t^{i}_{ID2+} \cdot r^{i} \rceil$$

Idle Time after unacknowledged req

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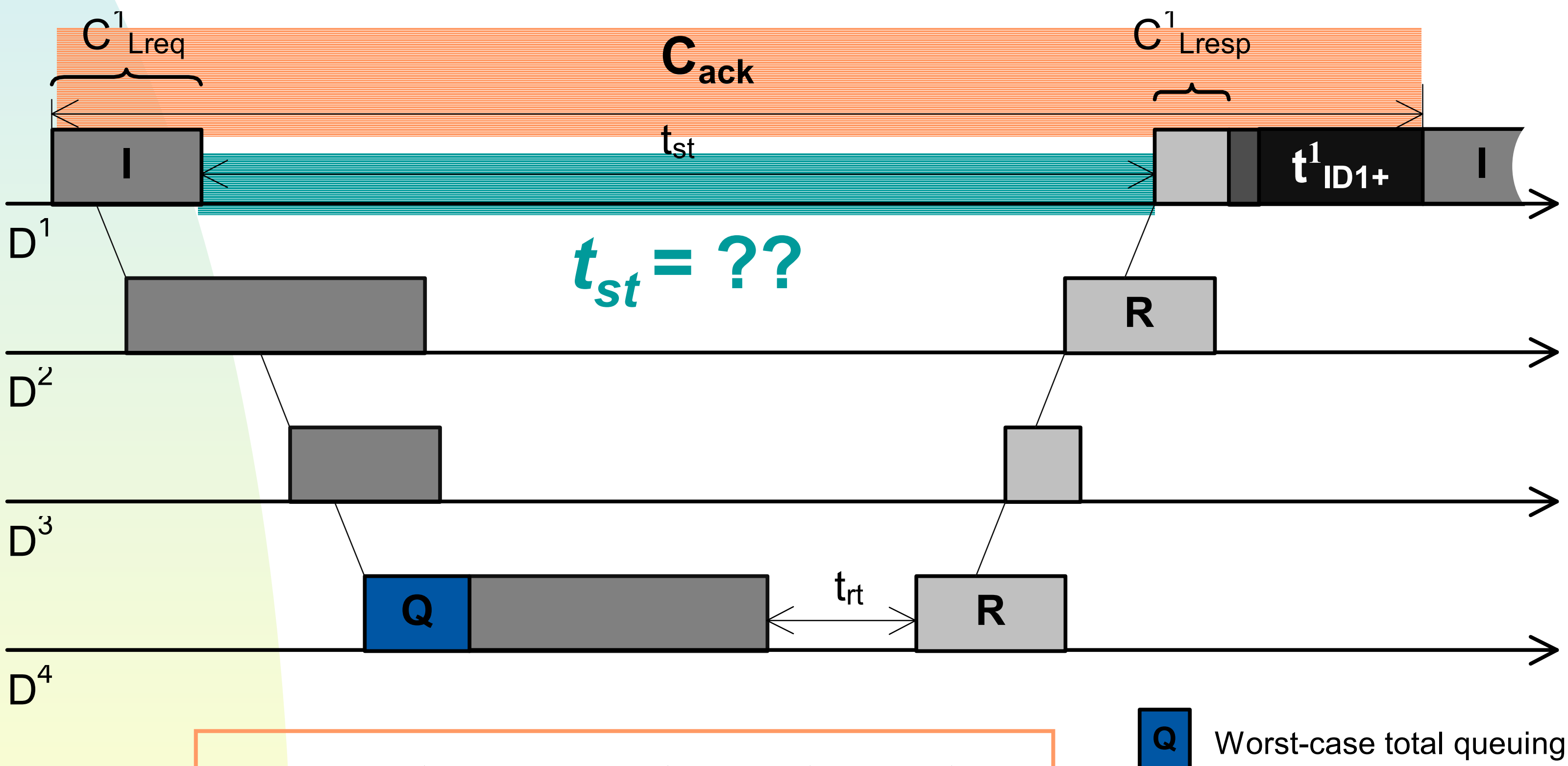
Duration of message transactions

- Worst-case duration of message transactions
  - Considering **3 ISs** between **I** and **R**

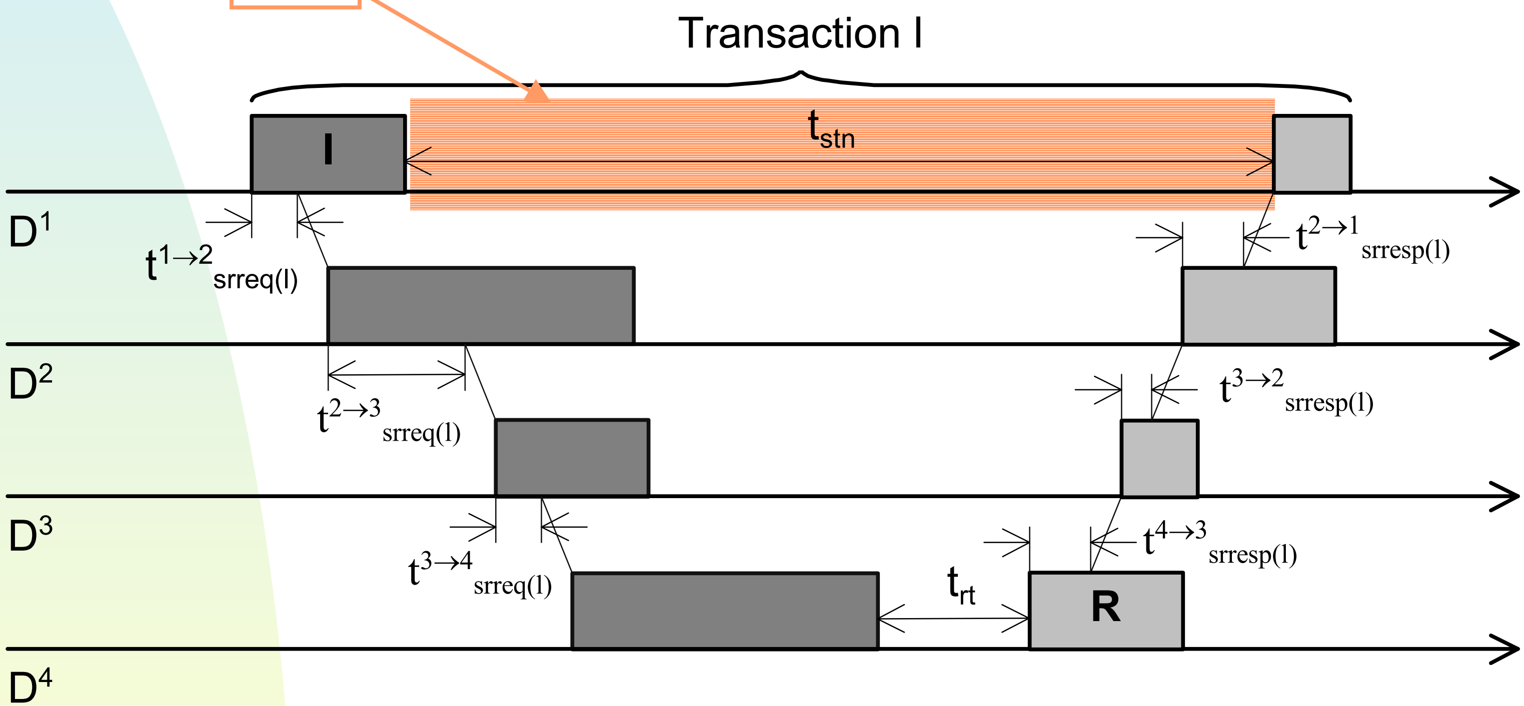


$$C_{ack} = C^1_{Lreq} + t_{st} + C^1_{Lresp} + t^1_{ID1m} + t^1_{ID1+}$$

Duration of message transactions

- Worst-case system turnaround time (t_{st})

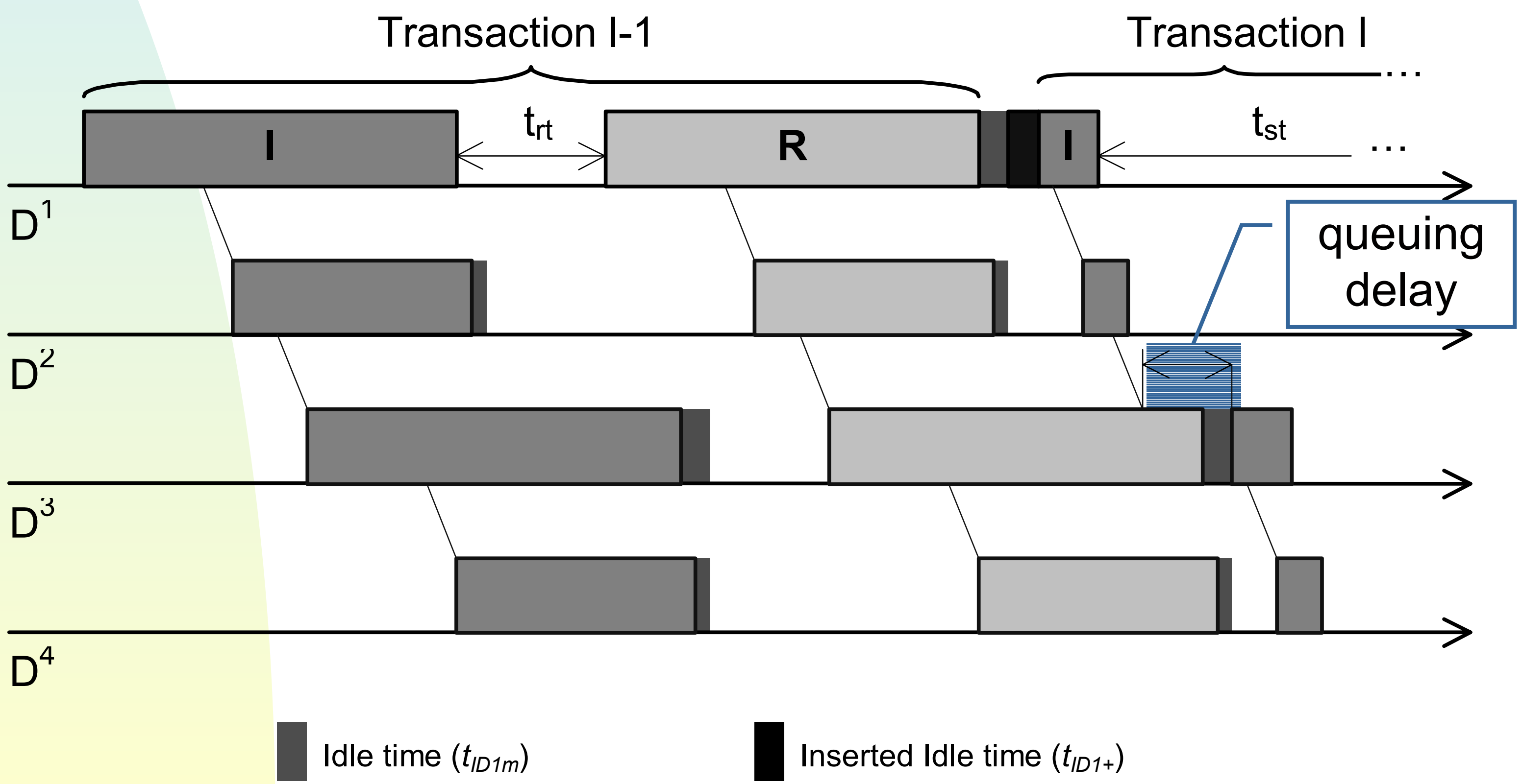
$t_{st} = t_{stn} + Q$



$$t^{1\to n}_{stn(l)} = \sum_{i=1}^{n-1}\left(t^{i\to i+1}_{srreq(l)} + t_{rd}\right) + C^{n}_{req(l)} + t_{rt} + \sum_{i=n}^{2}\left(t^{i\to i-1}_{srresp(l)} + t_{rd}\right) - C^{1}_{req(l)}$$

Duration of message transactions

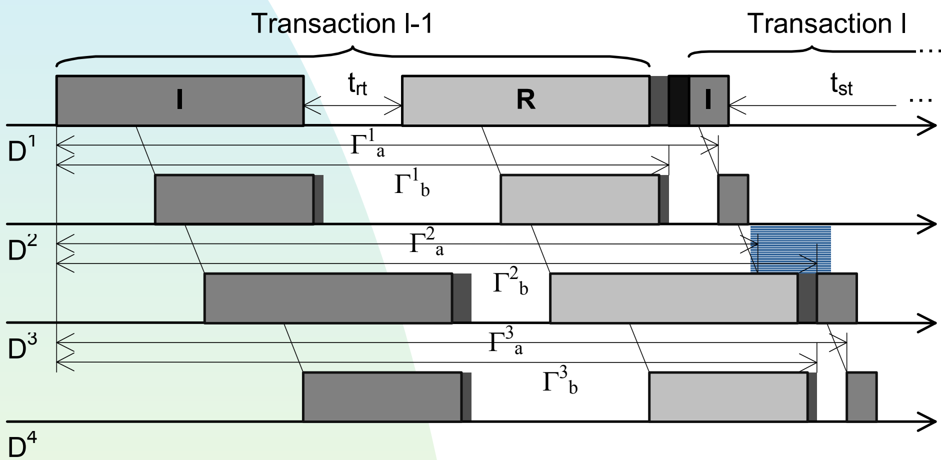
- ***Q*** is the worst-case total queuing delay
  - affecting the request PDU
  - due to previous transaction



Duration of message transactions

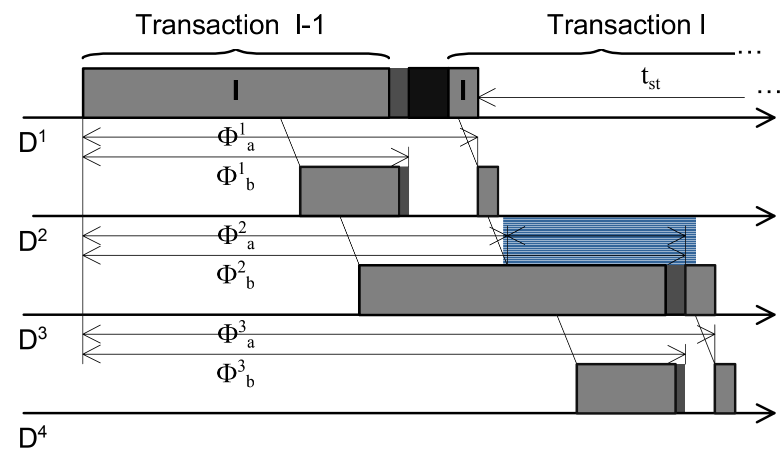
- Computing ***Q***

Q = Σ*q* for prev. ack&unk



$$\begin{cases} \Gamma_a^1 = C^1_{req(l-1)} + t_{rt} + C^1_{resp(l-1)} + t^1_{ID1m} + t^1_{ID1+} + t^{1\to 2}_{srreq(l)} + t_{rd} \\ \Gamma_b^1 = \max\left\{C^1_{req(l-1)} + t_{rt} + t^{1\to 2}_{srresp(l-1)} + t_{rd}, t^{1\to 2}_{srreq(l-1)} + t_{rd} + C^2_{req(l-1)} + t^2_{ID1m}\right\} \\ \quad + C^2_{resp(l-1)} + t^2_{ID1m} \end{cases}$$

$$\begin{cases} \Gamma_a^i = \max\left\{\Gamma_a^{i-1}, \Gamma_b^{i-1}\right\} + t^{i\to i+1}_{srreq(l)} + t_{rd} \\ \Gamma_b^i = \max\left\{\begin{matrix} \Gamma_b^{i-1} - C^i_{resp(l-1)} - t^i_{ID1m} + t^{i\to i+1}_{srresp(l-1)} + t_{rd}, \\ \sum_{j=1}^{i}\left(t^{j\to j+1}_{srreq(l-1)} + t_{rd}\right) + C^{i+1}_{req(l-1)} + t^{i+1}_{ID1m} \end{matrix}\right\} + C^{i+1}_{resp(l-1)} + t^{i+1}_{ID1m} \end{cases}$$



$$\begin{cases} \Phi_a^1 = C^1_{req(l-1)} + t^1_{ID2m} + t^1_{ID2+} + t^{1\to 2}_{srreq(l)} + t_{rd} \\ \Phi_b^1 = t^{1\to 2}_{srreq(l-1)} + t_{rd} + C^2_{req(l-1)} + t^2_{ID2m} \end{cases}$$

$$\begin{cases} \Phi_a^i = \max\left\{\Phi_a^{i-1}, \Phi_b^{i-1}\right\} + t^{i\to i+1}_{srreq(l)} + t_{rd} \\ \Phi_b^i = \sum_{j=1}^{i}\left(t^{j\to j+1}_{srreq(l-1)} + t_{rd}\right) + C^{i+1}_{req(l-1)} + t^{i+1}_{ID2m} \end{cases}$$

$$q^i_\Gamma = \max\left\{0, \Gamma^i_b - \Gamma^i_a\right\}$$

$$Q_\Gamma = \sum_{j=1}^{ndp-1}\left(q^j_\Gamma\right)$$

$$Q = \max\left\{Q_\Gamma, Q_\Phi\right\}$$

$$q^i_\Phi = \max\left\{0, \Phi^i_b - \Phi^i_a\right\}$$

$$Q_\Phi = \sum_{j=1}^{ndp-1}\left(q^j_\Phi\right)$$

Duration of message transactions

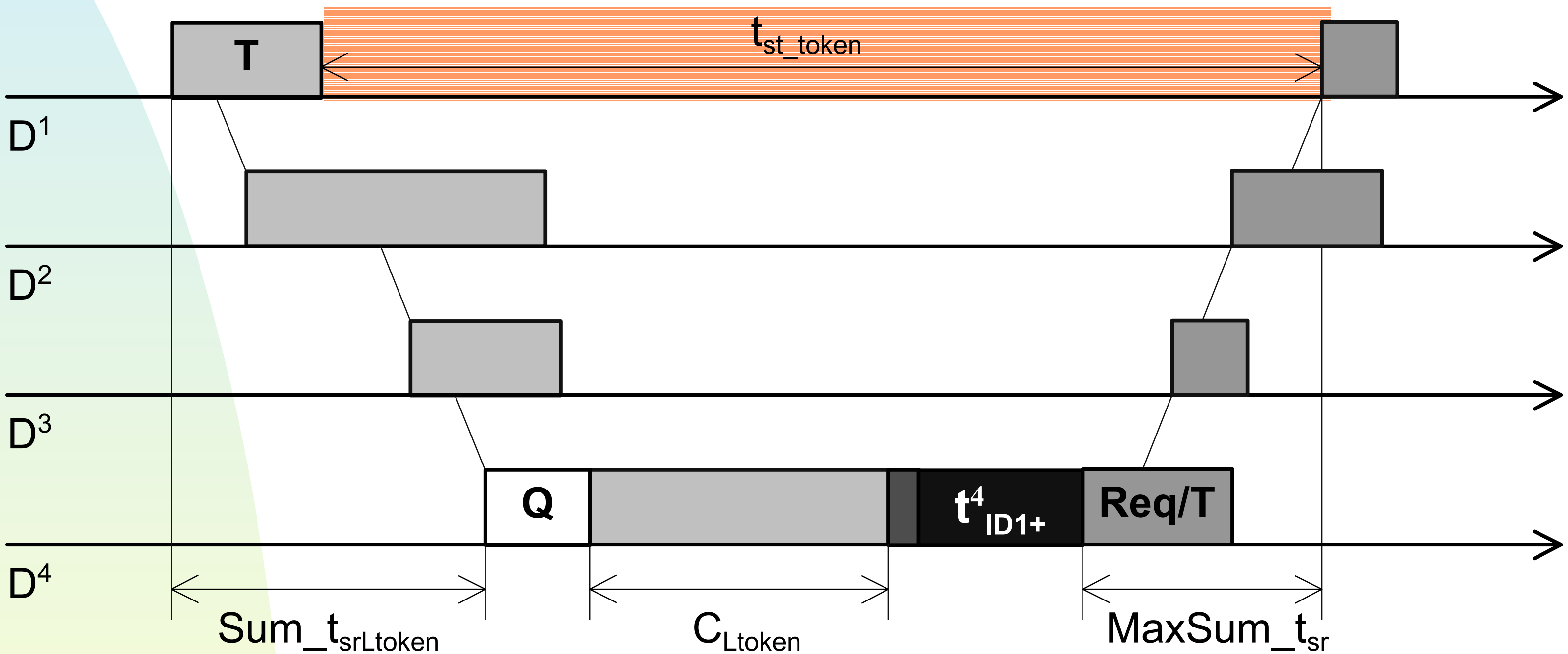
- The Slot Time parameter
  - $t_{SL} = \max(t_{SL1}, t_{SL2})$
    - t_{SL1} is the maximum time the initiator waits after transmitting a request PDU
    - t_{SL2} is the maximum time the initiator waits after having transmitted the token PDU
  - Computing t_{SL1} requires the computation of t_{st} for all message streams in the network

$$t_{SL1} = \max\{t_{st}(S[i])\}$$

  - Computing t_{SL2} requires the computation of
    - the worst-case system turnaround time after transmitting the token PDU - t_{st_token}

Duration of message transactions

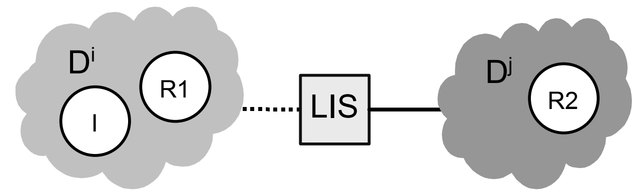
- Computing t_{st_token}



$$t_{st\_token} = Q + Sum\_t_{srLtoken} + C^{ndp}_{Ltoken} + t^{ndp}_{ID1m} + t^{ndp}_{ID1+} + MaxSum\_t_{sr} - C^{1}_{Ltoken}$$

Duration of message transactions

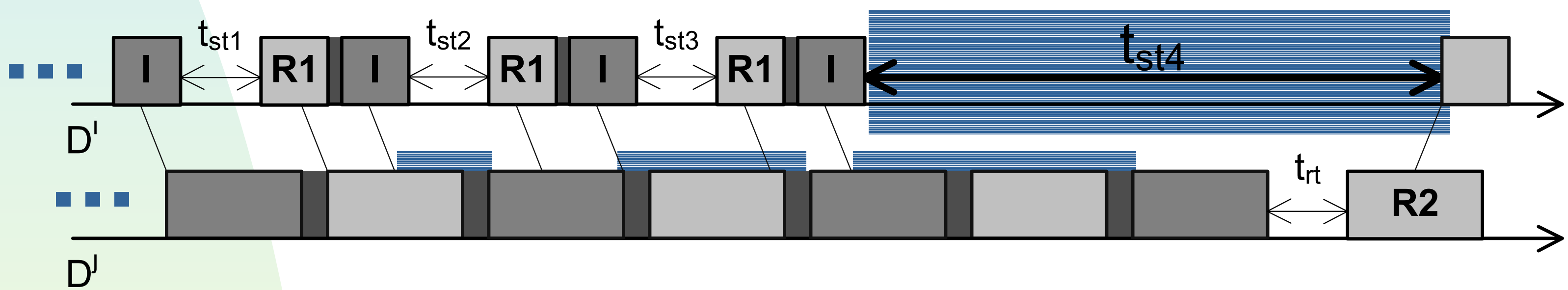
- Revisiting the pros of the approach



Without **extra idle time:**

Unbounded queuing → Unbounded t_{st} , T_{SL}

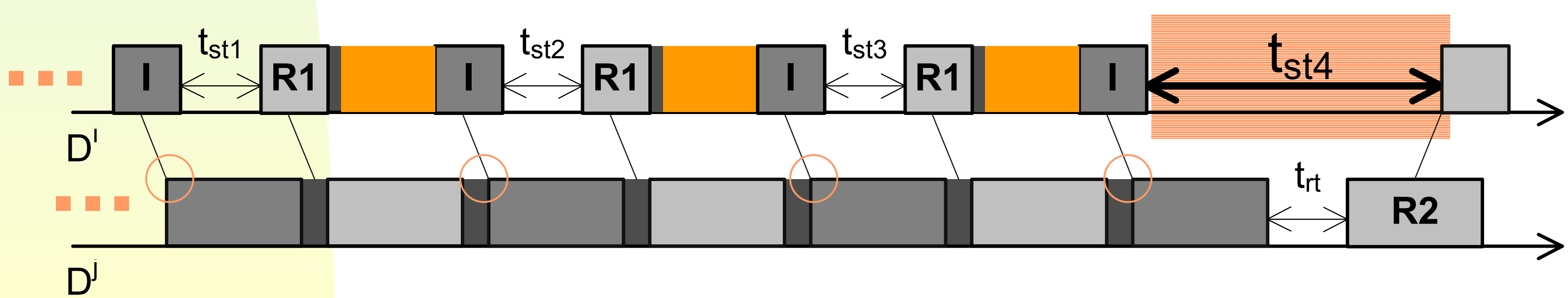
max t_{st} = ??



With **extra idle time:**

Bounded queuing → Bounded and smaller t_{st} , T_{SL}

T_{SL} = max t_{st}



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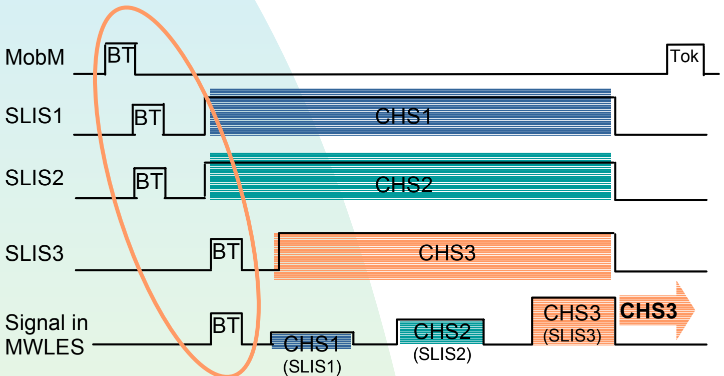
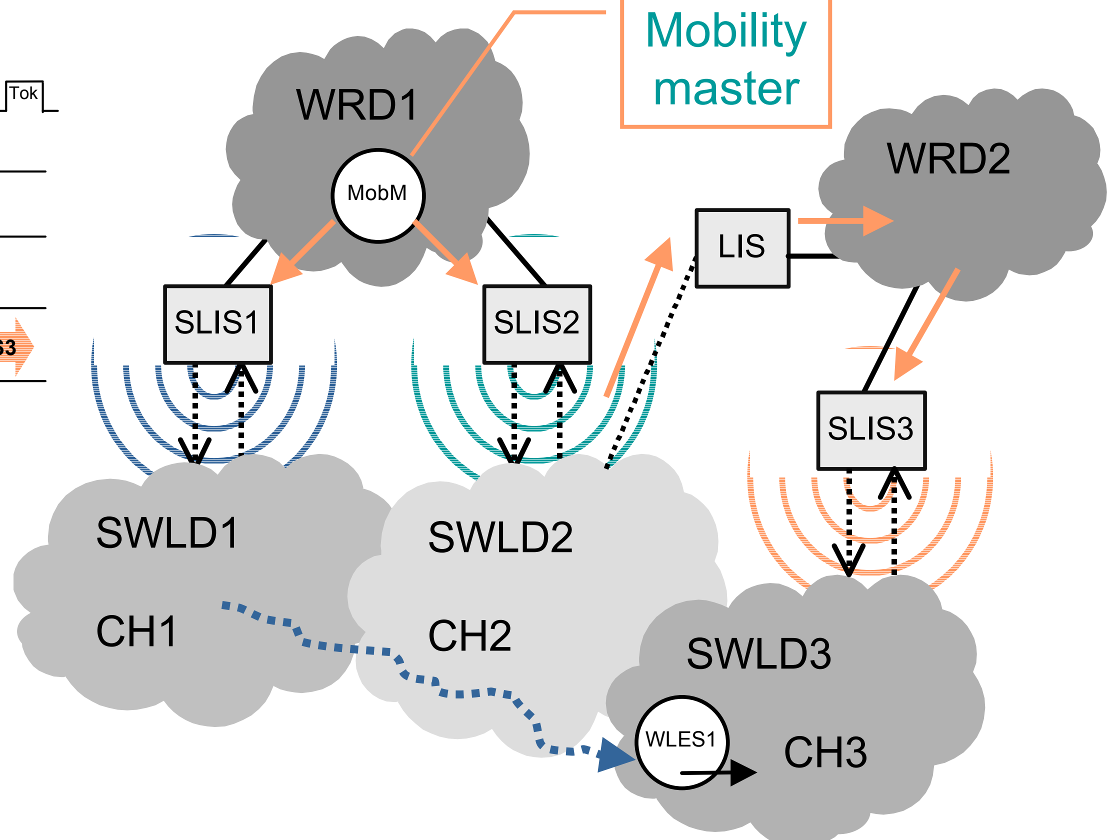
Supporting inter-cell mobility

- Mobility management mechanism





1: BT broadcast to all the network

2: SIS/SLIS send beacons in their CHS

3: MWLES assess RC quality and switch

No PDU loss

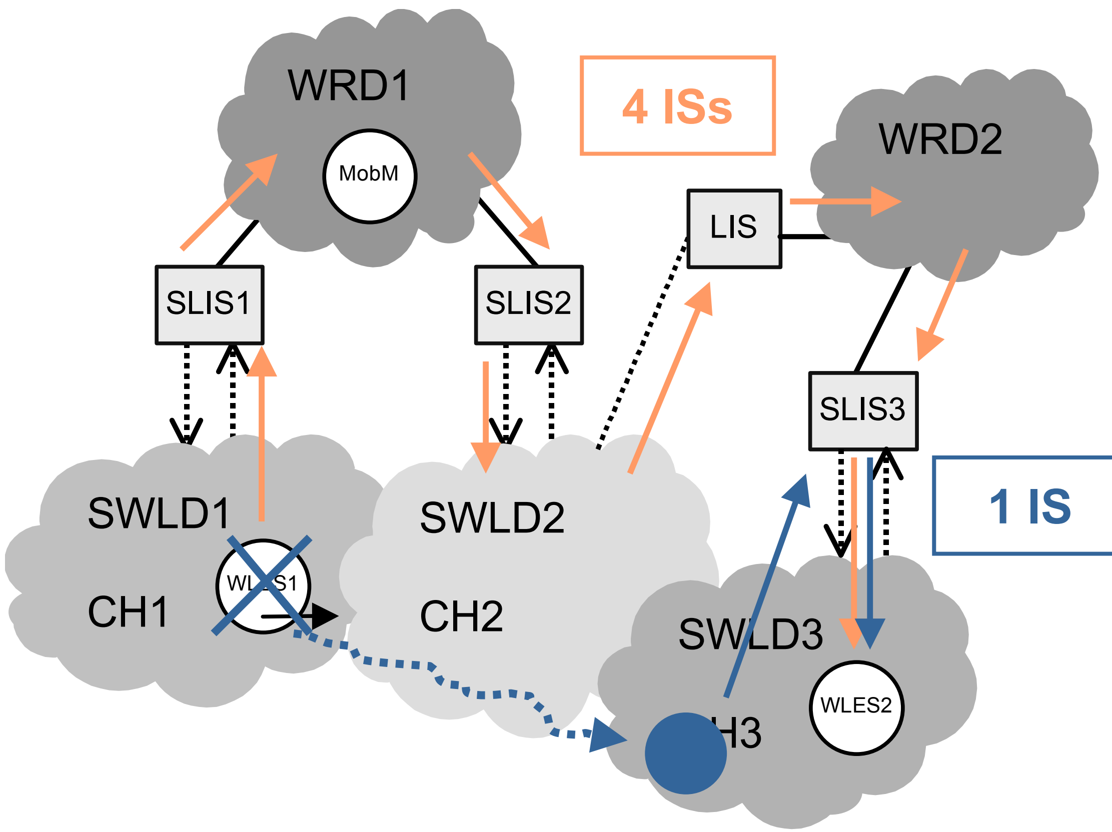
Time bounded

Supporting inter-cell mobility

- Impact on previous results...
  - **Great impact** on the computation of t_{st} and T_{SL}

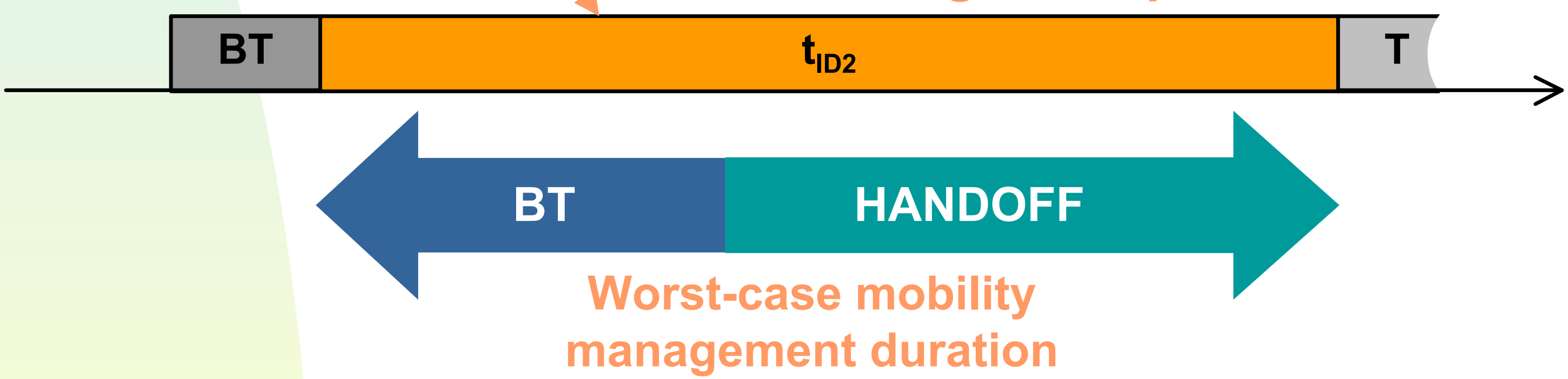
All possible paths must be considered

No impact on the Idle Time par.



Supporting inter-cell mobility

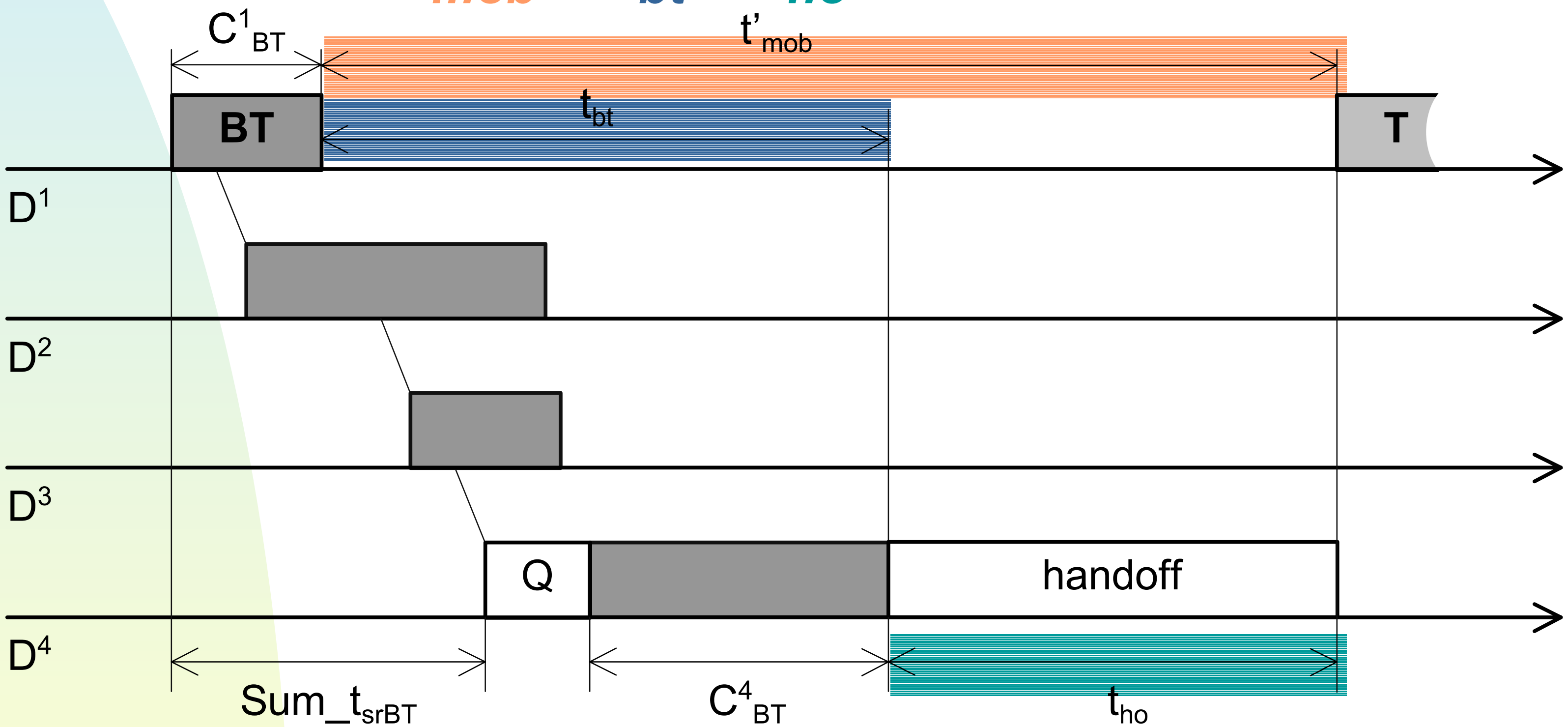
- For proper operation of the mobility management mechanism
  - The T_{ID2} parameter in the Mobility Master (MobM) must be set
    - considering the **worst-case duration of the mobility management procedure**



  - It is also necessary to set the **number of beacons** in each SIS/SLIS (to be transmitted after receiving the BT PDU)

Supporting inter-cell mobility

- Computing the mobility management duration $t'_{mob} = t_{bt} + t_{ho}$



$$t_{bt} = t_{btn} + Q$$

$$t_{btn} = \sum_{j=1}^{ndp-1} \left(t_{srBT}^{j \to j+1} + t_{rd} \right) + C_{BT}^{ndp} - C_{BT}^{1}$$

$$Q = \ldots$$

Supporting inter-cell mobility

- Computing t_{ho}

...and the MINIMUM number of beacons

$$t_{ho} = (2 \cdot nch - 1) \cdot C_{beacon} + nch \cdot (t_{bgap} + t_{sw})$$

For every SWLD

$$t'_{bp}(SWLD) = t'_{mob} - t_{btn}(SWLD)$$

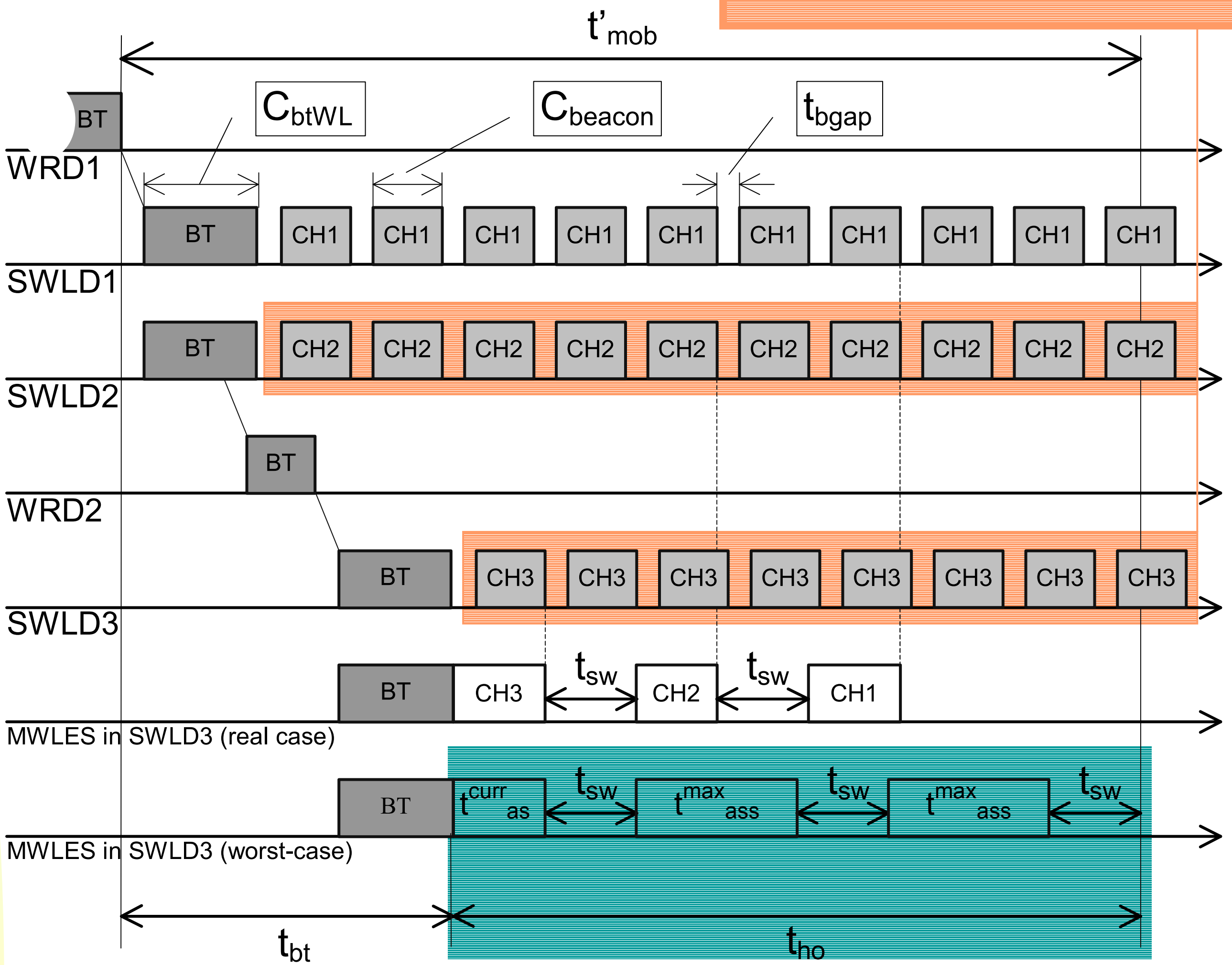
$$n_b(SWLD) = \left\lceil \frac{t'_{bp}(SWLD)}{t_{bgap} + C_{beacon}} \right\rceil$$

$$t_{bp}(SWLD) = n_b(SWLD) \cdot (t_{bgap} + C_{beacon})$$

$$t_{mob}(SWLD) = t_{bt}(SWLD) + t_{bp}(SWLD)$$

$$t_{mob} = \max\{t_{mob}(SWLD)\}$$

$$T_{ID2} = \lceil t_{mob} \cdot r_{MobM} \rceil$$



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Conclusions

- In this work we have:
  - **devised a hybrid architecture**
    - legacy (wired) and wireless/mobile PROFIBUS nodes
    - network model: components, rules, timing behavior
  - **proposed methodologies for guaranteeing real-time communications in such a network**
    - traffic adaptation inserting extra idle time (T_{ID});
    - computation of the worst-case duration of message transactions and of T_{SL} (with mobility)
    - computation of the mobility management parameters

Initial Hypothesis ✓

  - **a system planning software application**
    - computes all parameters, for any scenario

Ongoing/future work

- Guidelines for **ongoing** and **future** work:
  - Analyse and measure data throughput for different scenarios/topologies and different wired/wireless bit rates and PhL PDU formats
  - Improve current methodologies for **simultaneous use of cut-through and store&forward ISs**
  - Analyse ISs buffer requirements
  - Analyse behaviour in the presence of faults
  - Investigate other types of ISs (e.g. bridges)
  - Address other fieldbuses (WorldFIP, FF)

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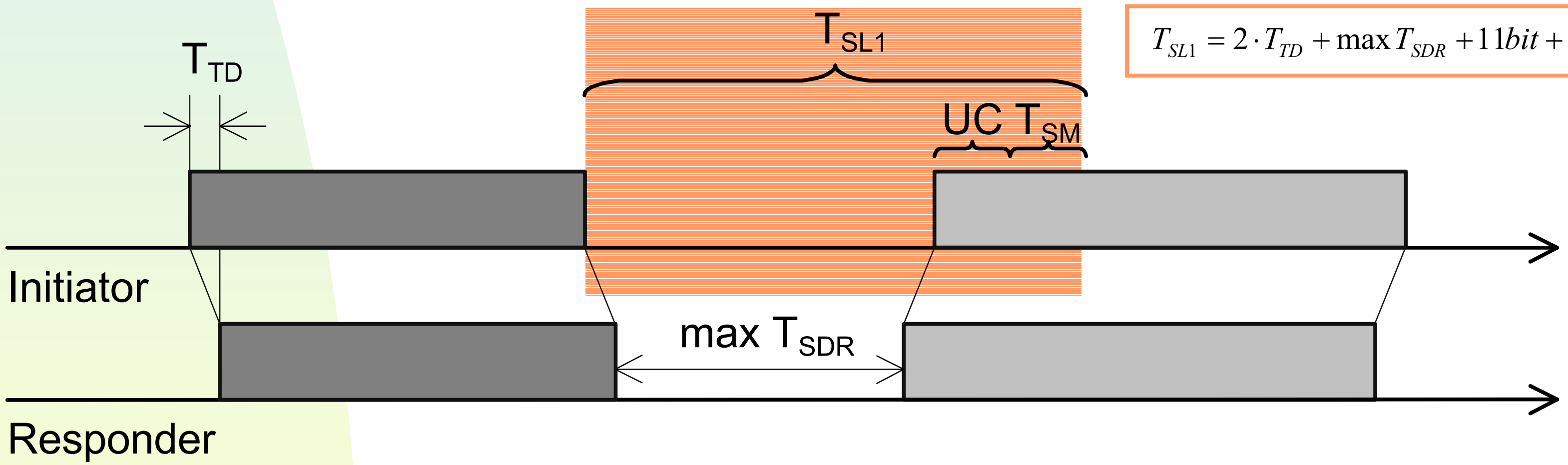
Slot Time details

- T_{SL1} details...
  - T_{SL1} is the maximum time the initiator waits for the complete reception of the first frame character of the acknowledgement/response frame, after transmitting the last bit of the request frame



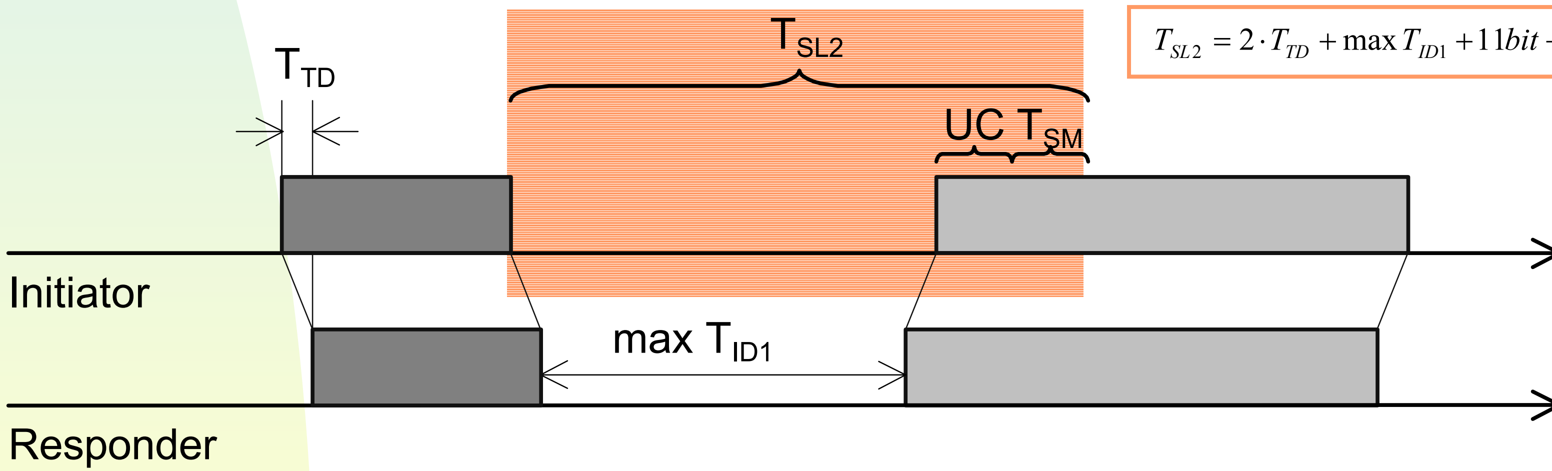
$$T_{SL1} = 2 \cdot T_{TD} + \max T_{SDR} + 11 bit + T_{SM}$$

Request frame	T_{TD} Transmission Delay	T_{SM} Safety Margin
Ack/Resp frame	UC UART character (11 bits)	T_{SDR} Station Delay of Responder

Slot Time details

- T_{SL2} details...
  - T_{SL2} is the maximum time the initiator waits after having transmitted the last bit of the token frame until it detects the first bit of a frame (either a request or the token) transmitted by the station that received the token

$$T_{SL2} = 2 \cdot T_{TD} + \max T_{ID1} + 11 bit + T_{SM}$$

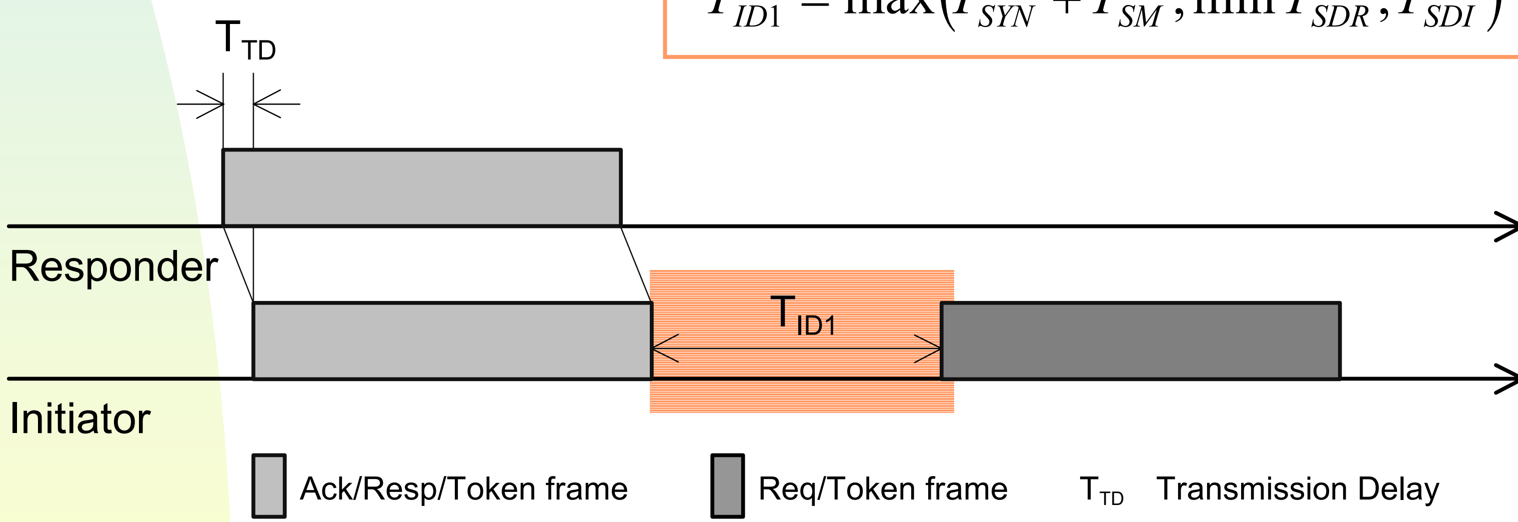


Token frame	T_{TD} Transmission Delay	T_{SM} Safety Margin
Req/Token frame	UC UART character (11 bits)	T_{ID1} Idle Time

Idle Time details

- T_{ID1} details...
  - T_{ID1} is the idle time a master stations inserts after receiving a response/token and before issuing a(nother) request (or token) PDU:

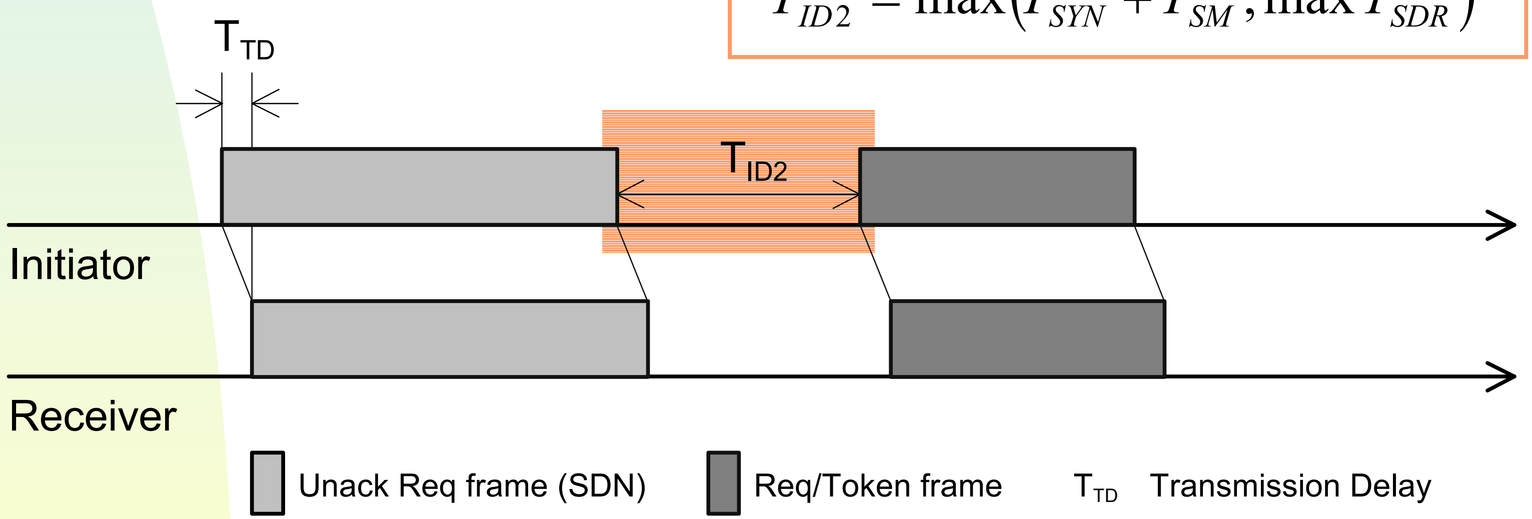
$$T_{ID1} = \max\left(T_{SYN} + T_{SM}, \min T_{SDR}, T_{SDI}\right)$$



Idle Time details

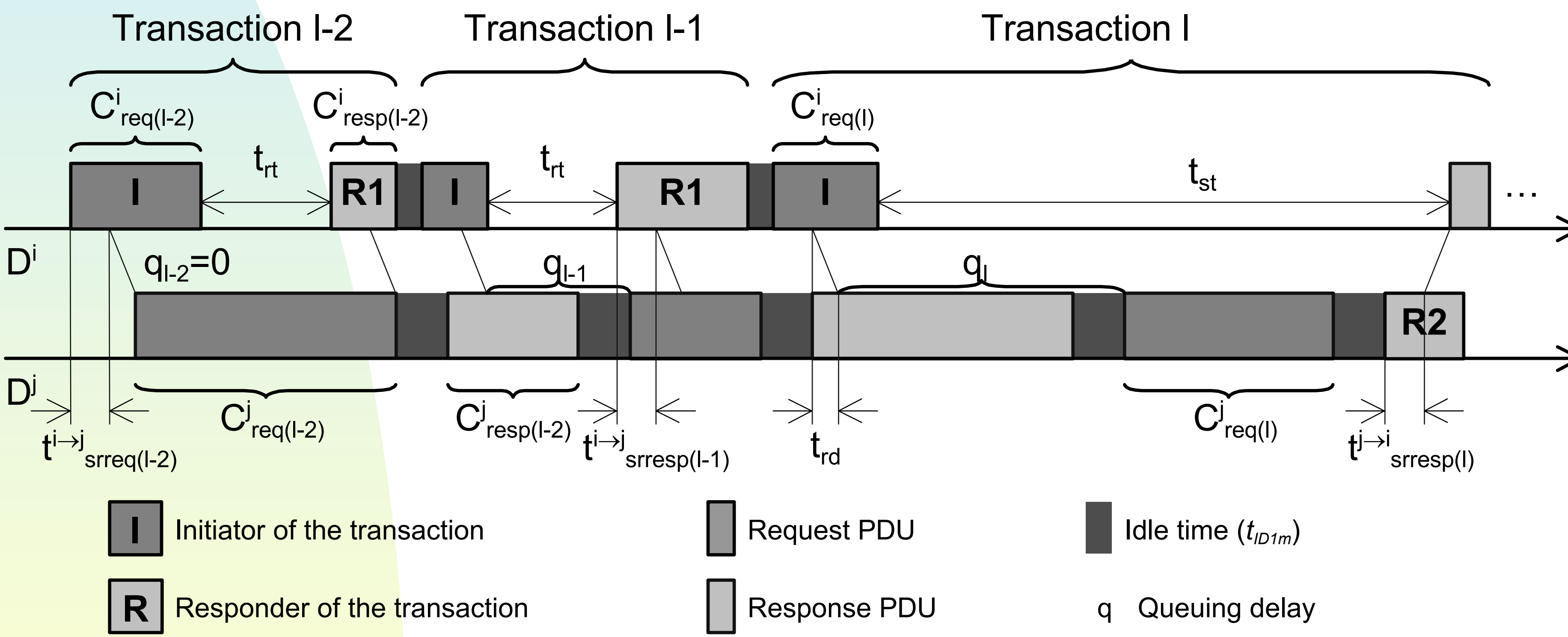
- T_{ID2} details...
  - T_{ID2} is the idle time a master stations inserts after issuing an unacknowledged request and before issuing a(nother) request (or token) PDU:

$$T_{ID2} = \max\left(T_{SYN} + T_{SM}, \max T_{SDR}\right)$$



Time variables details

- Increasing queuing details...

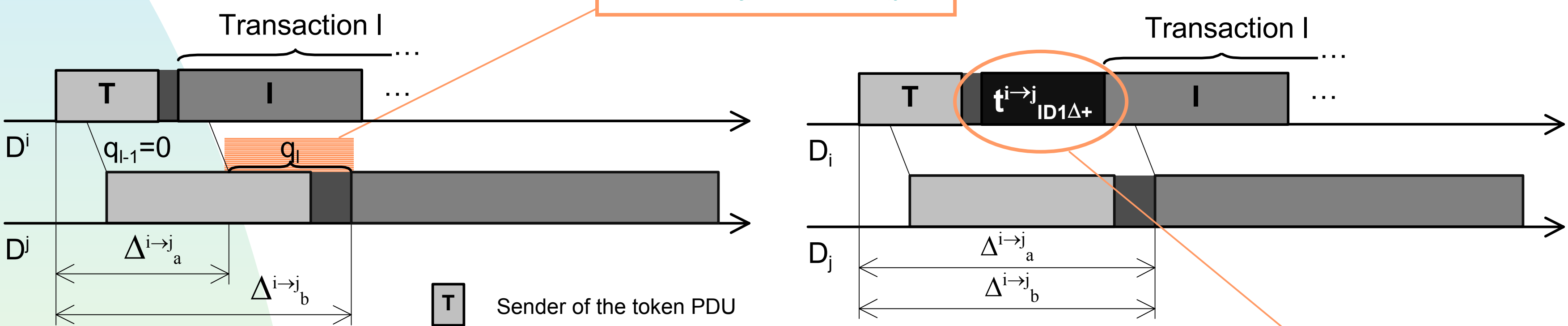


Inserted Idle Time details

- $t_{ID1\Delta+}$ details...

$q_l > 0$

$\Delta^{i \to j}_{a} < \Delta^{i \to j}_{b}$



Insert idle time in a way that

$\Delta^{i \to j}_{a} \geq \Delta^{i \to j}_{b}$

$$\Delta^{i \to j}_{a} = C^{i}_{token} + t^{i}_{ID\,1m} + t^{i \to j}_{ID\,1+} + t^{i \to j}_{srreq\;(l)} + t_{rd}$$

$$\Delta^{i \to j}_{b} = t^{i \to j}_{srtoken} + t_{rd} + C^{j}_{token} + t^{j}_{ID\,1m}$$

$$t^{i \to j}_{ID\,1\Delta +} \geq t^{i \to j}_{srtoken} - t^{i \to j}_{srreq\;(l)} + C^{j}_{token} - C^{i}_{token} + t^{j}_{ID\,1m} - t^{i}_{ID\,1m}$$

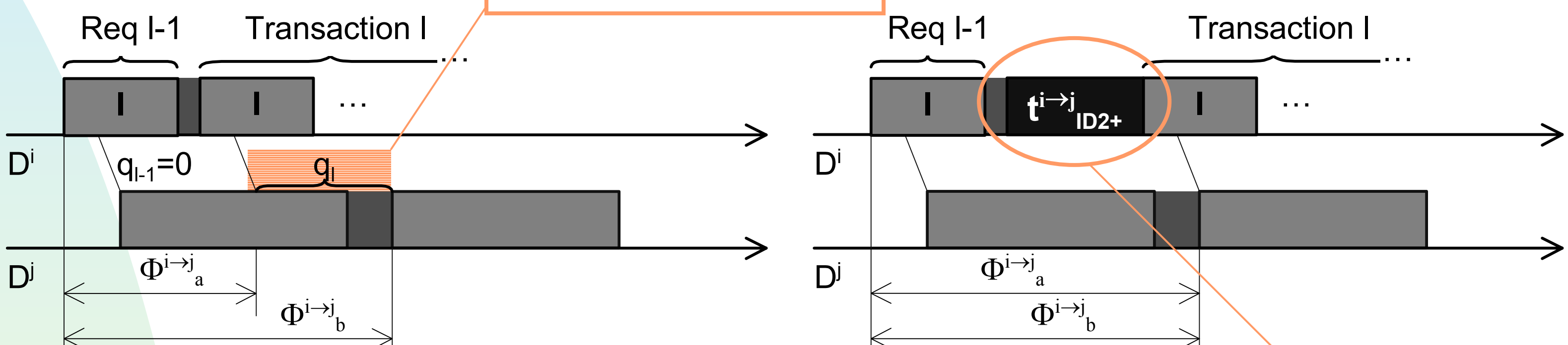
$$t^{i}_{ID1\Delta+} = \max\left\{t^{i \to j}_{ID1\Delta+}\right\} \begin{cases} \forall\, i, j \in \{1, \ldots, nm\} \text{ physical media} \\ \forall\, L_{req(l)} \in \text{DLL PDUs length from the message streams of I or the token} \end{cases}$$

Inserted Idle Time details

- t_{ID2+} details…

$q_l > 0$

$\Phi^{i\rightarrow j}_{a} < \Phi^{i\rightarrow j}_{b}$



Insert idle time in a way that

$\Phi^{i\rightarrow j}_{a} \geq \Phi^{i\rightarrow j}_{b}$

$$\Phi^{i\rightarrow j}_{a} = C^{i}_{req\,(l-1)} + t^{i}_{ID\,2m} + t^{i\rightarrow j}_{ID\,2+} + t^{i\rightarrow j}_{srreq\,(l)} + t_{rd}$$

$$\Phi^{i\rightarrow j}_{b} = t^{i\rightarrow j}_{srreq\,(l-1)} + t_{rd} + C^{j}_{req\,(l-1)} + t^{j}_{ID\,2m}$$

$$t^{i\rightarrow j}_{ID\,2+} \geq t^{i\rightarrow j}_{srreq\,(l-1)} - t^{i\rightarrow j}_{srreq\,(l)} + C^{j}_{req\,(l-1)} - C^{i}_{req\,(l-1)} + t^{j}_{ID\,2m} - t^{i}_{ID\,2m}$$

$$t^{i}_{ID\,2+} = \max\left\{t^{i\rightarrow j}_{ID\,2+}\right\},\quad \begin{cases} \forall\, i, j \in \{1,\dots,nm\}\ \text{physical media} \\ \forall\, L_{req(l-1)} \in \text{DLL PDUs length from the message streams of I} \\ \forall\, L_{req(l)} \in \text{DLL PDUs length from the message streams of I or the token} \end{cases}$$