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Energy-Efficient Packet Scheduling under Two-Sided Delay Constraints

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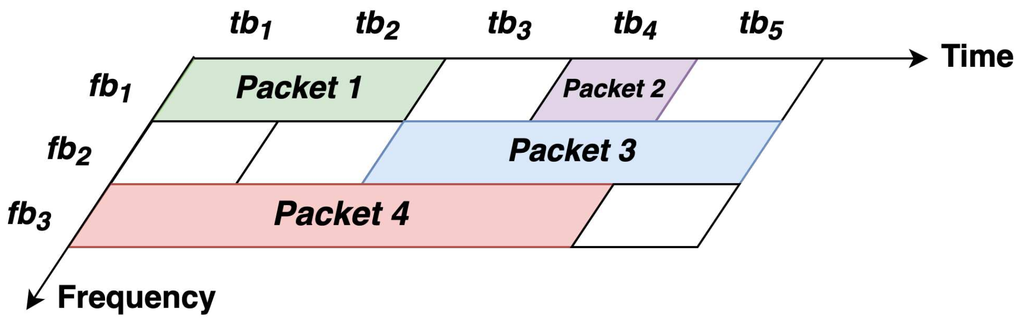
Introduction

*Cisco Annual Internet Report: 2018-2023 White Paper

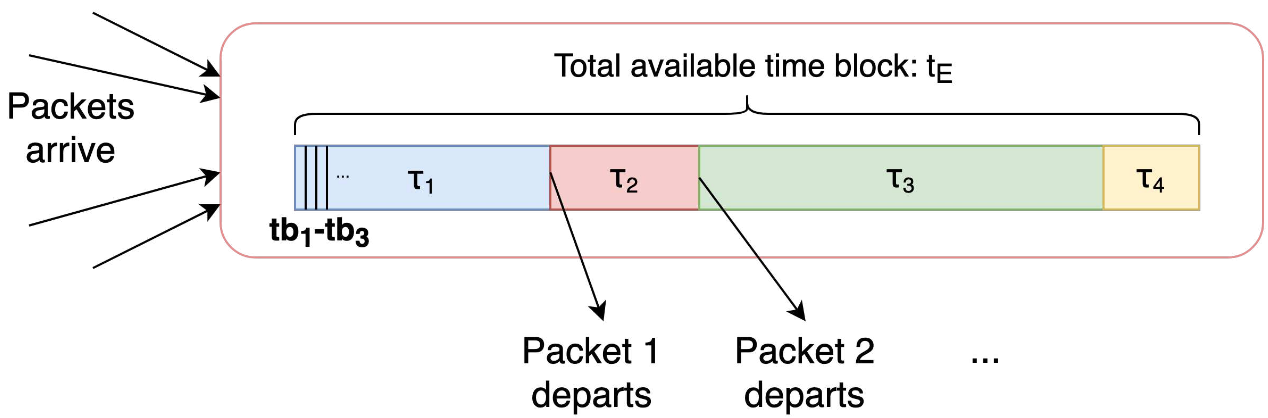
- Ubiquity of networks
  - Estimated to have ~29 billion IP-connected devices by 2023 – 3.6 x World population!*
  - Ever-growing number of connected devices
- Finite and limited resources (blocks of time, bands of frequency, *etc.*)
  - Need to effectively allocate
- Packet scheduling: A classical problem in wireless communications
  - Allocating finite resources…
  - … to optimize an objective (energy consumption, delay minimization, quality-of-service requirements, *etc.*)



Introduction

- Our focus: Scheduling **time** to minimize **energy consumption**
  - **Goal:** Serve all packets within a total time block

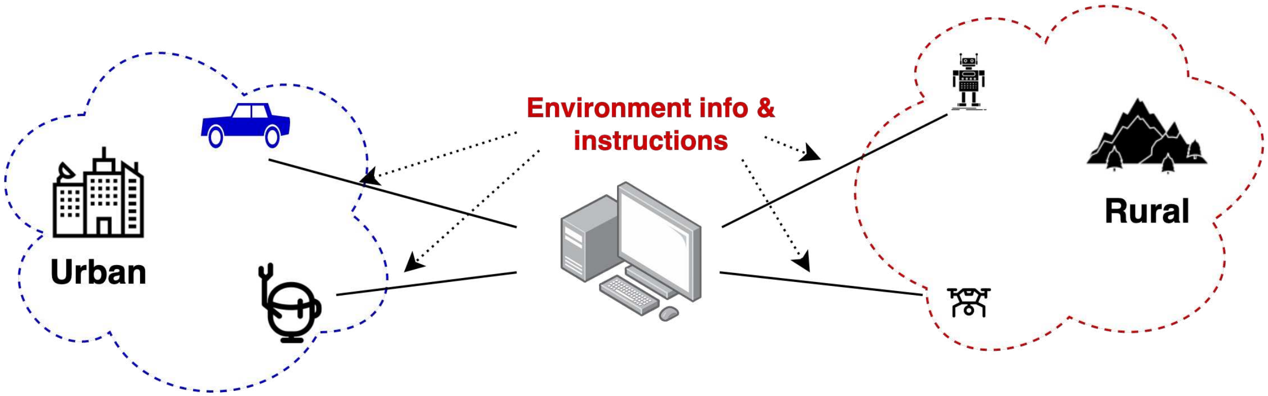
- Original version [Uysal-Biyikoglu, Prabhakar, El Gamal, ToN ‘02]



$$\sum_{i=1}^{4} \tau_i = t_E$$

- Each packet has individual deadlines = “Delay constraint”
  - Late transmission is bad, avoid it! [Chen, Neely, Mitra, T-IT ‘08], [Zafer, Modiano, ToN ’09], [Shan, Luo, Shen, ComNet ‘14], *etc.*

A Motivating Example



- Want to achieve coordinated action @ t_R
  - Central unit sends each agent a packet
    - Instructions & environmental information
- Need to send packets in advance (enough time to prepare)
  - Earlier the better! (conventional)
- Environmental information needs to be up-to-date at @ t_R
  - Later the better! (new)

Contributions

- Other applications
  - Secure relaying → packet expiration
  - Molecular communication → molecule degradation
  - Delay requirements & freshness
  - *etc.*

Early and late BOTH bad!

- **Need to expand!**

- Our work:
  - "Not too late transmission (conventional), but also not too early (new)"
  - Generalizes one-sided formulation to two-sided delay constrained scheduling
  - Provides energy-optimal offline scheduling under two-sided delay deadlines (provable)

Problem Formulation

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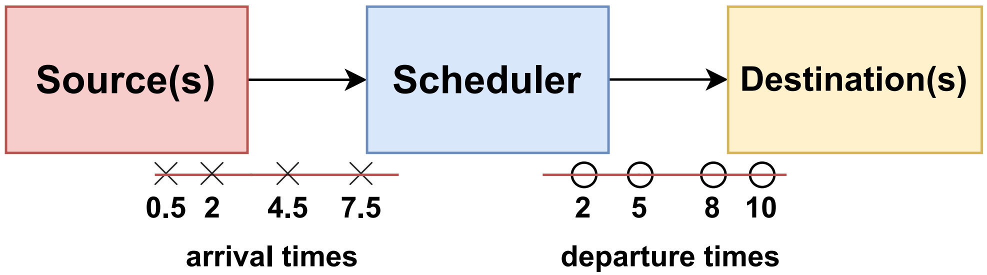
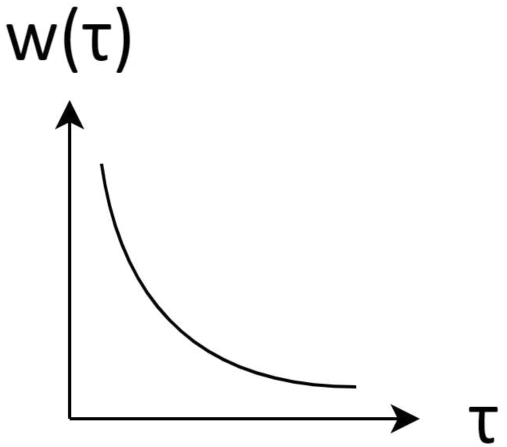


- Application-agnostic
- Packets arrive at the scheduler as a time sequence
  - Arrival time of i^{th} packet: t_i
  - *M:* Total number of packets
  - Inter-arrival times: $d_i = t_{i+1} - t_i$
- ***τ:*** The vector that holds each transmission's duration
  - Packet cannot be processed before arrival (causality)
  - The scheduler transmits each packet on the order of reception → first-in first-out (FIFO)

System Setup: The Objective Function

- Goal: Transmitting all arriving packets within $[0, t_E]$,while minimizing an energy cost $w(\boldsymbol{\tau})$

- Assumptions on the cost:
  - $w(\boldsymbol{\tau}) = \sum_{i=1}^{M} w(\tau_i)$
  - $w(\tau) > 0$
  - $w(\tau)$ decreasing in argument τ
  - $w(\tau)$ strictly convex in τ



- Processing faster requires increasingly large energy

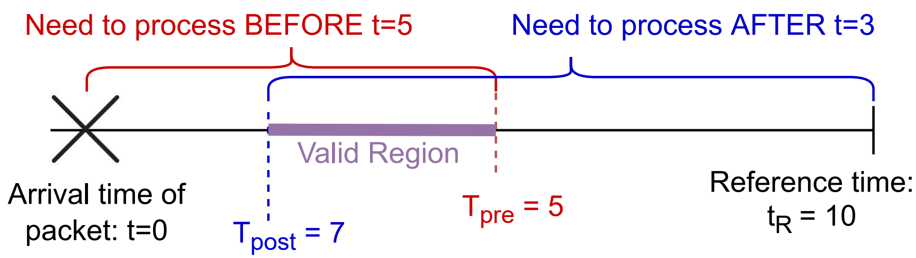
System Setup: Constraints

- **Successful Communication:** All M packets are available at the destination(s) at a reference time t_R

- Two main requirements:
  1. All packets successfully transmitted towards its destination by the reference time t_R
  2. All packets are active/not expired at time t_R

- 1: cannot be too late (conventional)
  - Upper bounds departure time: *"Pre"-delay constraint* ⟶ T_{pre}
- 2: cannot be too early (new)
  - **Lower** bounds departure time: *"Post"-delay constraint* ⟶ T_{post}

The Optimization Problem



- We consider two-sided delay constraints!

$$\min_{\boldsymbol{\tau}} \quad w(\boldsymbol{\tau}) = \sum_{i=1}^{M} w(\tau_i)$$

$$\text{s.t.} \quad \sum_{i=1}^{k} \tau_i \geq \sum_{i=1}^{k} d_i, \quad k \in \{1, \ldots, M-1\},$$

$$\sum_{i=1}^{M} \tau_i = t_E = \sum_{i=1}^{M} d_i,$$

Non-idling constraints (no unused interval)

$$\sum_{i=1}^{k} \tau_i \geq t_R - T_{\text{post},k}, \quad k \in \{1, \ldots, M\},$$

Post-delay constraints

$$\sum_{i=1}^{k} \tau_i - \sum_{i=1}^{k-1} d_i \leq T_{\text{pre},k}, \; k \in \{1, \ldots, M\}.$$

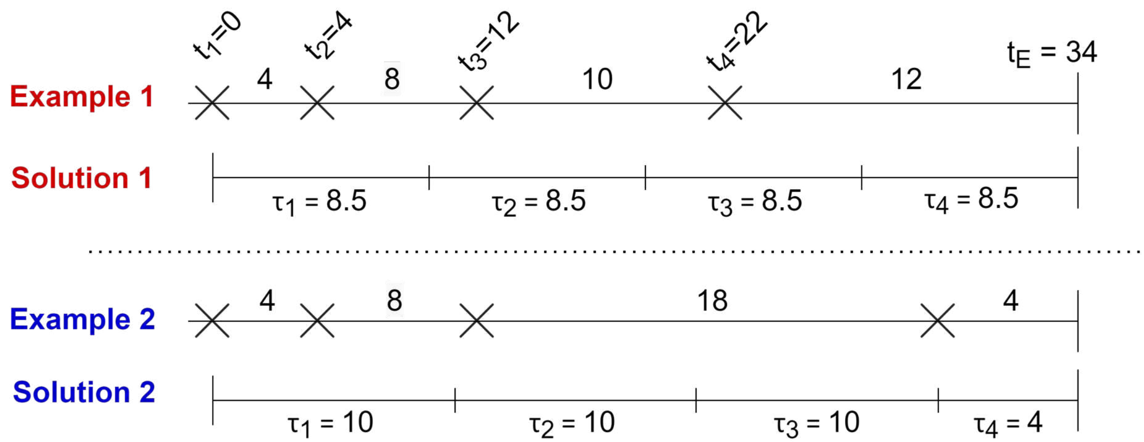
Pre-delay constraints

The Optimization Problem

$$
\begin{aligned}
\min_{\boldsymbol{\tau}} \quad & w(\boldsymbol{\tau}) = \sum_{i=1}^{M} w(\tau_i) \\
\text{s.t.} \quad & \sum_{i=1}^{k} \tau_i \geq \sum_{i=1}^{k} d_i, \quad k \in \{1, \ldots, M-1\}, \\
& \sum_{i=1}^{M} \tau_i = t_E = \sum_{i=1}^{M} d_i, \\
& \sum_{i=1}^{k} \tau_i \geq t_R - T_{\text{post},k}, \quad k \in \{1, \ldots, M\}, \\
& \sum_{i=1}^{k} \tau_i - \sum_{i=1}^{k-1} d_i \leq T_{\text{pre},k}, \; k \in \{1, \ldots, M\}.
\end{aligned}
$$

- Address ***offline*** scheduling:
  - Idealized scheduler
  - Knows all arrival times non-causally
  - Knows all $T_{pre,i}$ and $T_{post,i}$ beforehand
- Solution provides a lower bound on the cost
  - Future Work: Algorithms that rely on statistical information & online algorithms

Demonstrative Example: The Unconstrained Case



No restricting pre- and post-delays

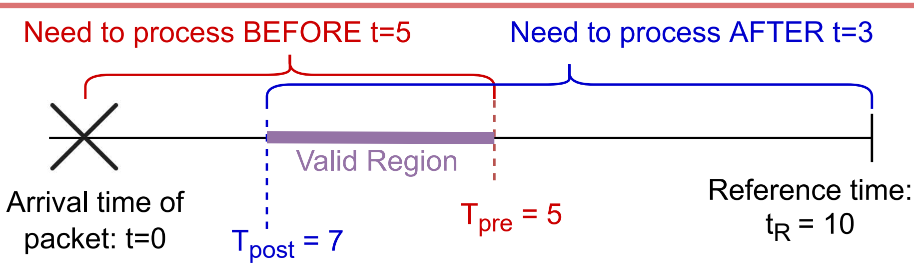
Corresponds to [Uysal-Biyikoglu, Prabhakar, El Gamal, IEEE T-oN '02]

- **Example 1:** Fully balancing feasible. Lowest cost incurred due to convexity
- **Example 2:** Fully balancing not feasible (fourth molecule arrives late)
  - Next best (balancing [τ_1, τ_2, τ_3]) feasible
  - τ_4 = 4 trivial
- **Key idea:** ***Balance durations as much as possible + Maximally exploit future arrival times***

The Two-Sided Case: Feasibility

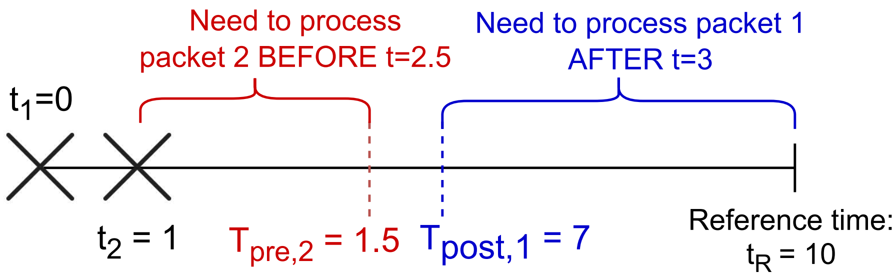
- For the two-sided case, a feasible solution is not guaranteed
  - Under one-sided pre-delay constraints, it is [Chen, Neely, Mitra, IEEE T-IT ’08]
- For feasibility:

1) Everyone has a valid region



2) No post-delay cross-overs (FIFO)

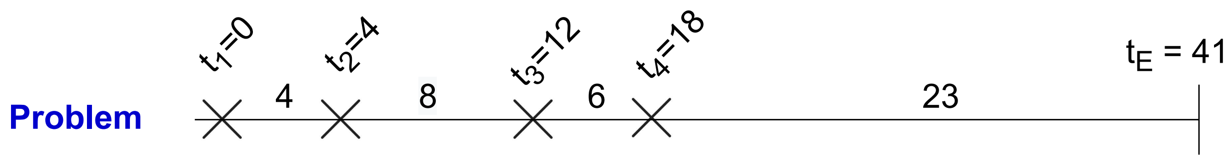
$$t_i + T_{\text{pre},i} > t_R - T_{\text{post},j}, \ \forall j = 1, \ldots, i-1$$



INFEASIBLE! Packet 1 has to wait until t=3

Guaranteed loss of packet 2

The Two-Sided Case

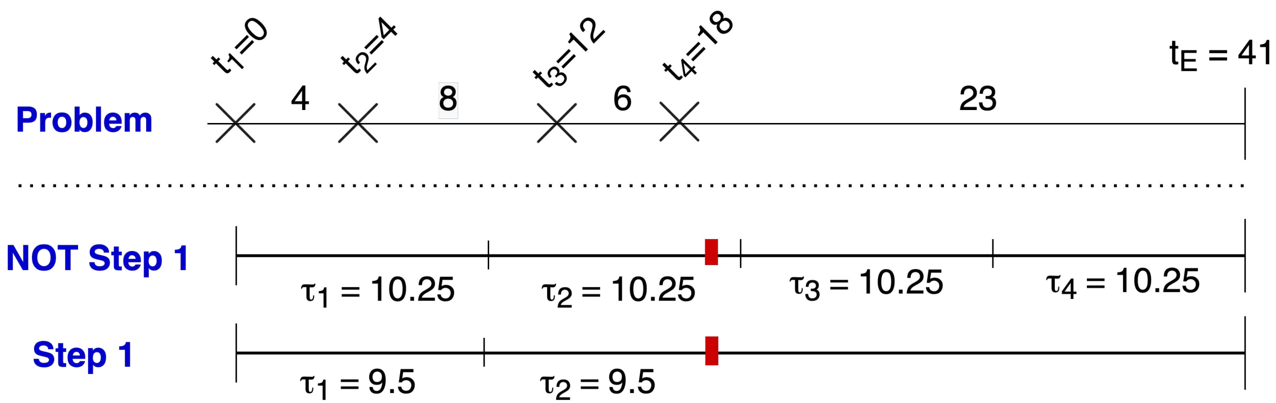


$T_{pre,2}$ = 15 (before t=19)

$T_{post,3}$ = 10 (after t=31)

- Key idea: Balance as much as possible

The Two-Sided Case

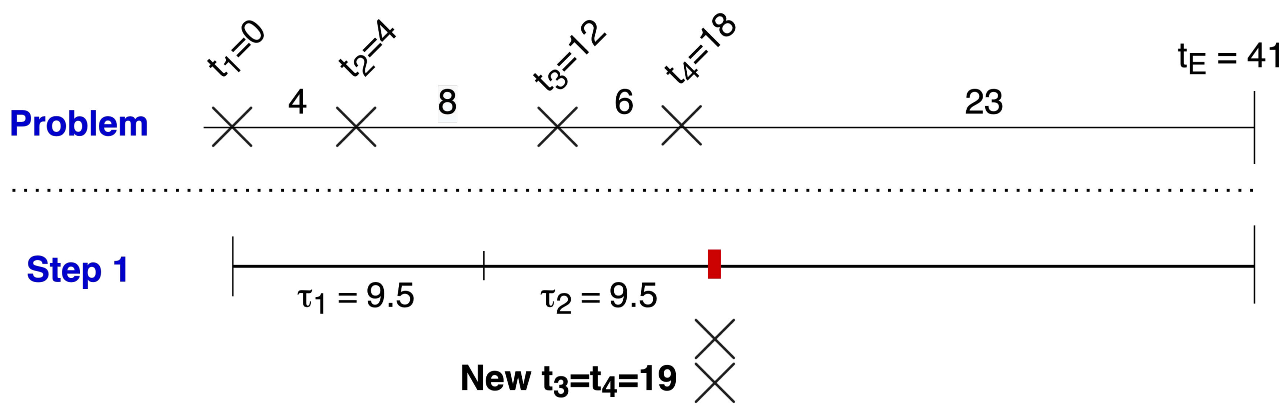


$T_{pre,2}$ = 15 (before t=19)

$T_{post,3}$ = 10 (after t=31)

- Key idea: Balance as much as possible
- **For pre-delays: If need be, satisfy critically!** → $\tau_1 + \tau_2 = t_2 + T_{\text{pre},2}$

The Two-Sided Case

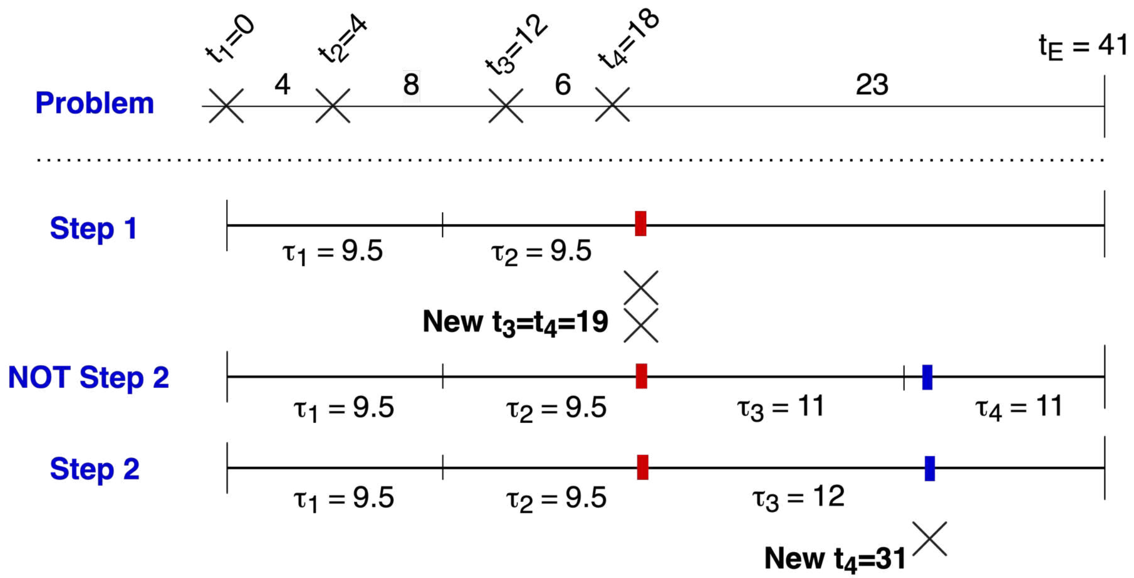


$T_{pre,2}$ = 15 (before t=19)

$T_{post,3}$ = 10 (after t=31)

- Key idea: Balance as much as possible
- **For pre-delays: If need be, satisfy critically!**
- "Shift" arrivals to the critical point

The Two-Sided Case



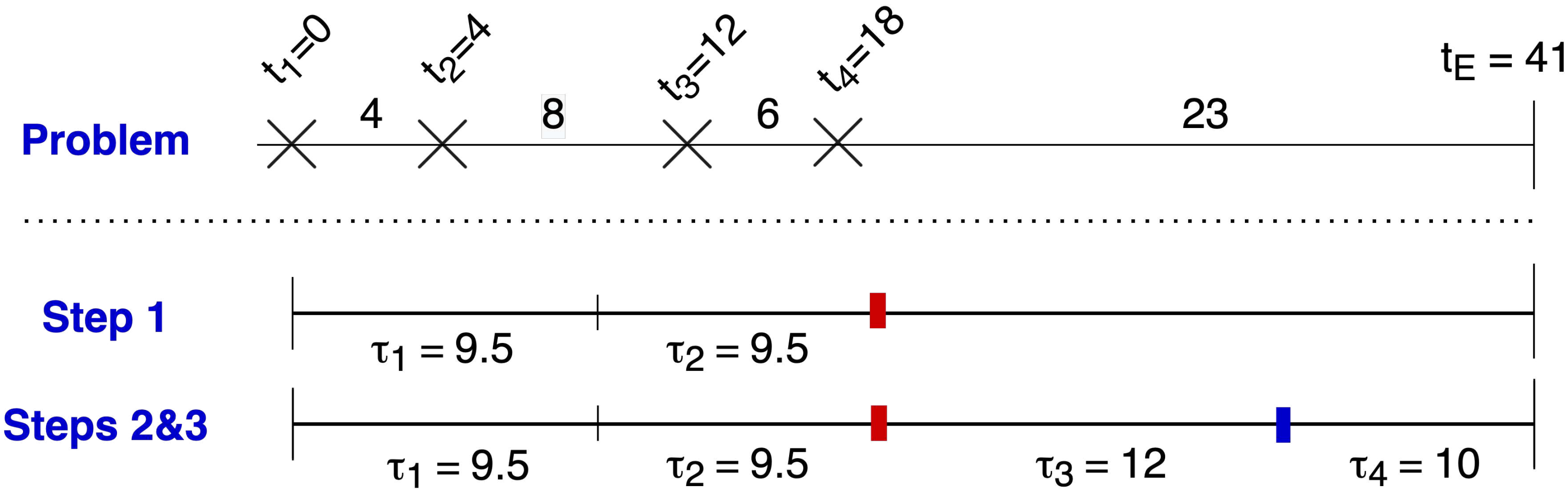
$T_{pre,2}$ = 15 (before t=19)

$T_{post,3}$ = 10 (after t=31)

- Key idea: Balance as much as possible
- **For both pre- and post-delays: If need be, satisfy critically!**
- "Shift" arrivals to the critical point

$$\tau_1 + \tau_2 + \tau_3 = t_R - T_{\text{post},3}$$

The Two-Sided Case



- **Provably Optimal!**
- **Proof strategy:**
  1) *w(**τ**)* Schur-convex
  2) Showed our algorithm's ***τ*** gets majorized by any other valid ***τ'***
  3) Combine 1 & 2

Conclusions

- Expanded packet scheduling to two-sided delay constraints
  - Covers many new applications
  - Feasible solution may not exist! → provided conditions
  - Devised a **provably optimal** scheduling algorithm
    - Minimizes a convex energy cost

- Solution can also extend to solve the “dual problem”: energy constrained total delay minimization
  - Solved under two-sided delay constrained framework!
    - [**MCG**, UM, 2nd round of review @ IEEE T-WC], available on arXiv

- Idealized assumptions on non-causal arrival time information, and pre-/post-delays
  - Future work: Algorithm that rely on only statistical/no information