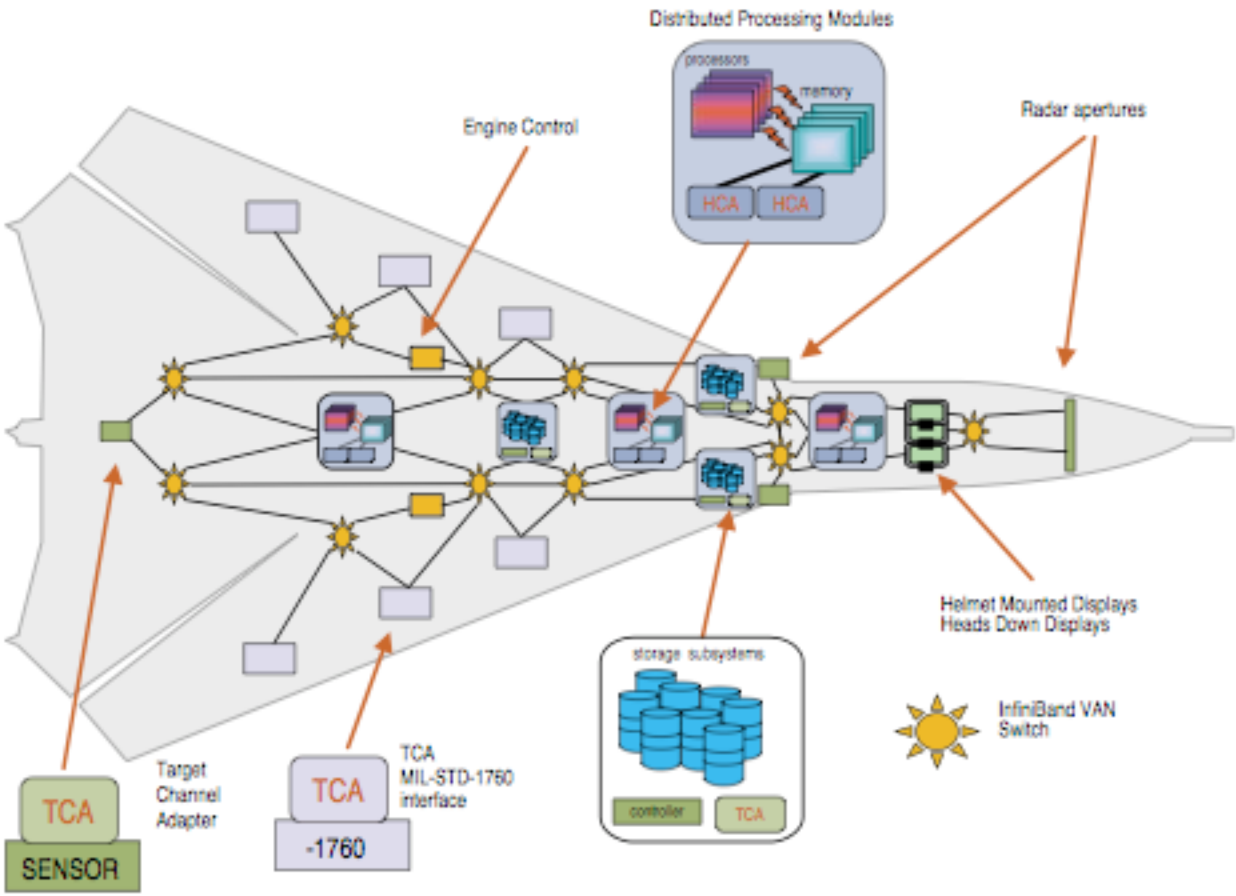
# Real-time systems on a distributed platform

Multi-stage systems
Schedulability analysis for distributed systems
Restrictions that make analysis easier

# Lecture overview

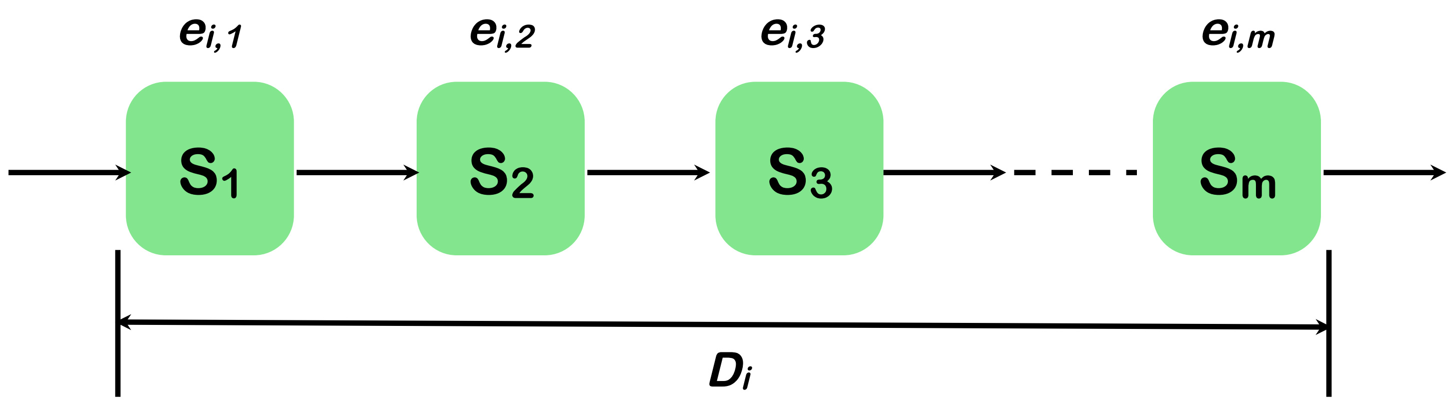
- So far we have spent a lot of time discussing small (uniprocessor) systems
- We studied the behavior of periodic tasks on uniprocessors subject to fixed and dynamic priority policies
- But many computer systems run on distributed components
- In this lecture we will study **distributed real-time systems**
- Understand the basic elements of schedulability analysis for these systems

# Example: Avionics systems




**Data is processed at multiple nodes**
**One task in this application may have multiple stages**
**The entire sequence, however, has to meet a deadline**

# Schematic of a distributed system

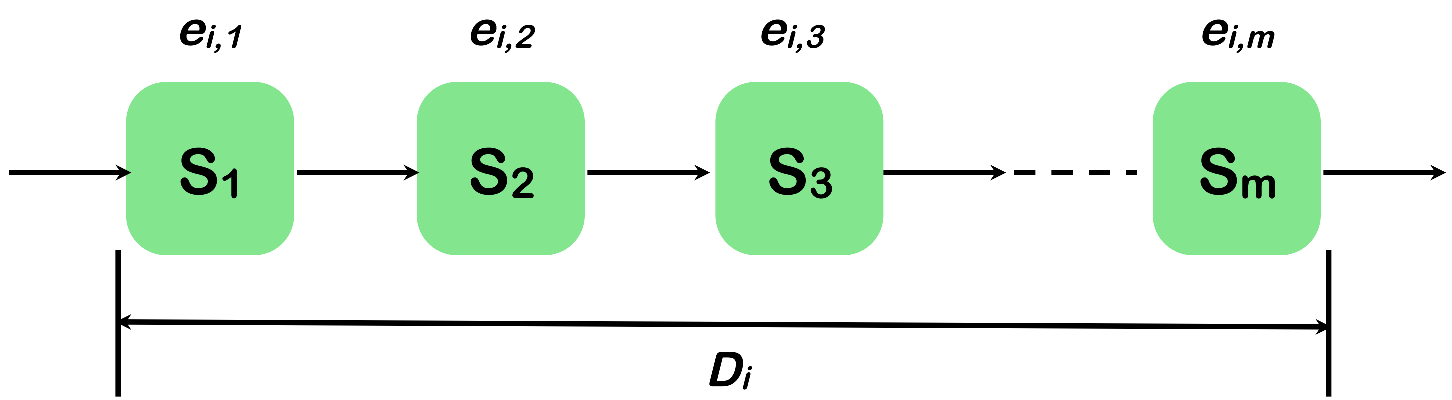



Task $T_i$ has to be processed in $m$ stages
The end-to-end deadline for the task is $D_i$
The task is periodic with period $P_i$
The execution time of the task at stage $j$ is $e_{i,j}$

# Deadlines in a distributed system

- Typically: **relative deadlines are greater** than the periods of the tasks
- Sometimes, relative deadlines >> periods
- Example: video transmission in aircraft may involve capturing images at **24 frames per second** (period = 1/24 = 41.7ms) but a **deadline of 125ms** is sufficient for the captured image to reach the pilot
  - Why? Human reaction time is about 125ms, and in all situations a total response time of 250ms (time to deliver data + reaction time) is typically sufficient
  - In this example, $D_i/P_i > 3$

# Applying known techniques

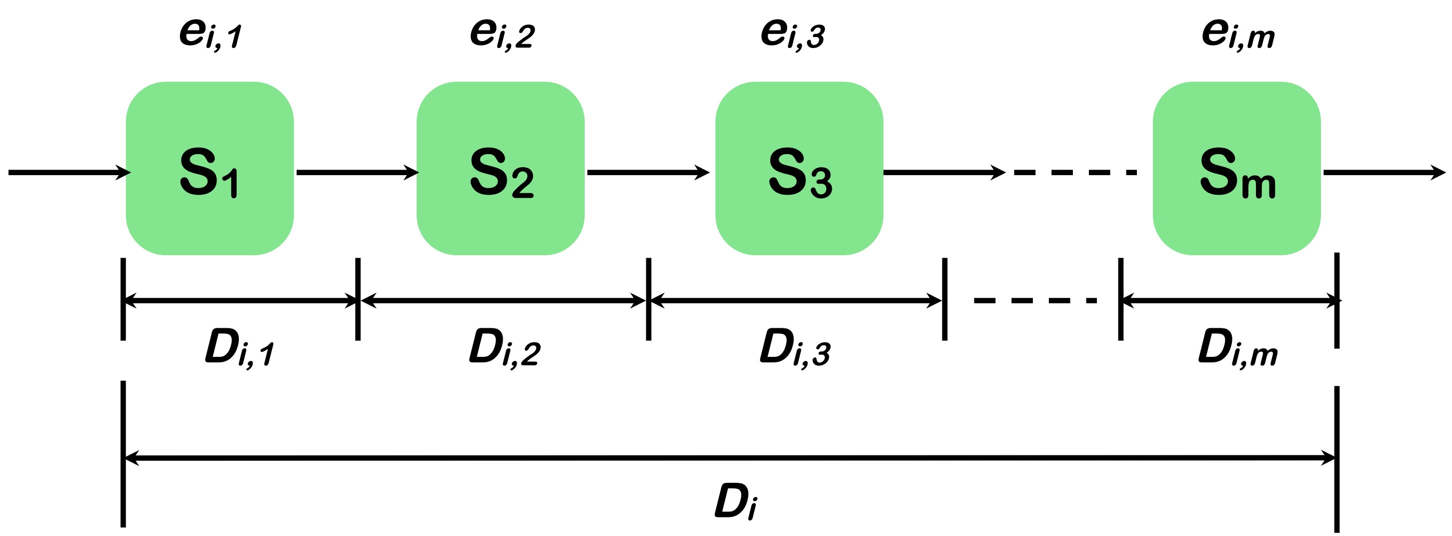



- Treat each stage independently
- We need tasks to be periodic at each stage
- We need to set a relative deadline $D_{i,j}$ for stage $j$ such that

$$\sum_{j=1}^{m} D_{i,j} = D_i$$

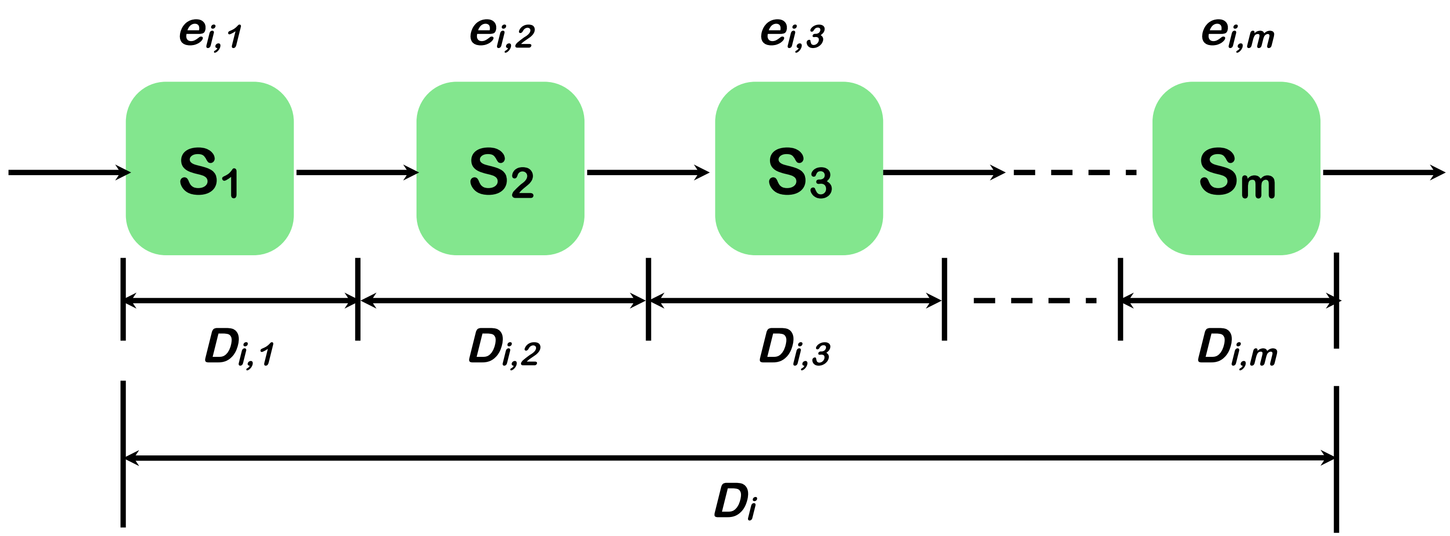
- Then we can apply known results to verify that per-stage deadlines are met

# Deadline distribution




- **How do we distribute the end-to-end deadline over multiple stages?**
- **Hard problem: no efficient method to determine the optimal distribution**

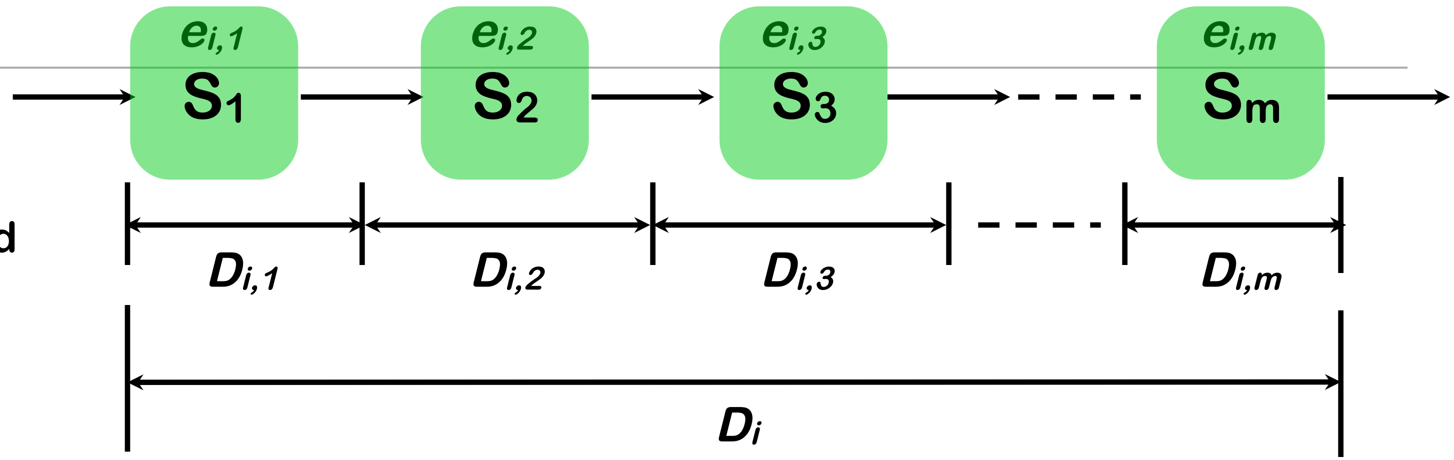
# Deadline distribution




- We can use **heuristics**: their performance may vary based on the task set being scheduled
- Some examples
  - Even distribution: $D_{i,j} = D_i/m$
  - Proportional distribution: $D_{i,j} = D_i \times e_{i,j}/(e_{i,1}+e_{i,2}+\ldots+e_{i,m})$

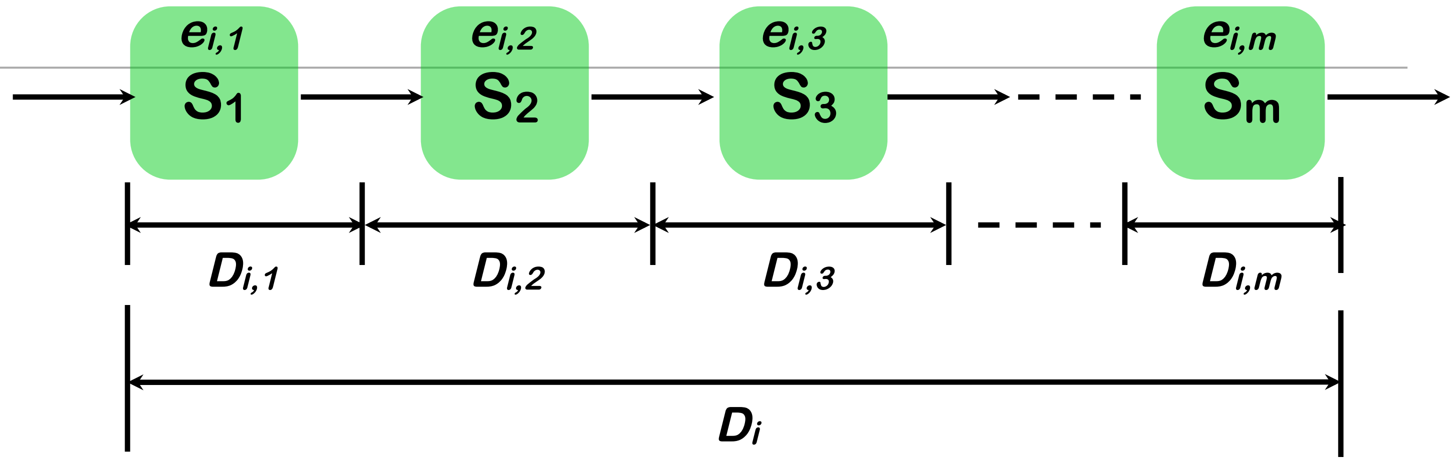
# Technicalities

Suppose $P_1$=6 and $D_{i,1}$=9




- How do we ensure that tasks arrive at each stage periodically? Consider if:
  - job 1 of task 1 finishes at stage 1 at time 4
  - job 2 of task 1 finishes at stage 1 at time 9 (inter-arrival time of 5)
  - job 3 of task 1 finishes at stage 1 at time 17 (inter-arrival time of 8)
  - job 4 of task 1 finishes at stage 1 at time 23 (inter-arrival time of 6)
- **Our theory so far assumes that job arrivals are strictly periodic if we want a schedulability guarantee**
- We could ensure that **a job reaches the next stage only at the relative deadline of the previous stage**: requires extra mechanisms (overhead at the OS level)

# Technicalities




- How do we ensure that tasks arrive at each stage periodically?
- We could ensure that **a job reaches the next stage only at the relative deadline of the previous stage**: requires extra mechanisms (overhead at the OS level)
- Alternatively, we could also ensure that each job was released to the next stage only after the worst-case response time
- Compute WCRTs for each stage
- If a job completes early, buffer it and release it to the next stage only when the WCRT is reached

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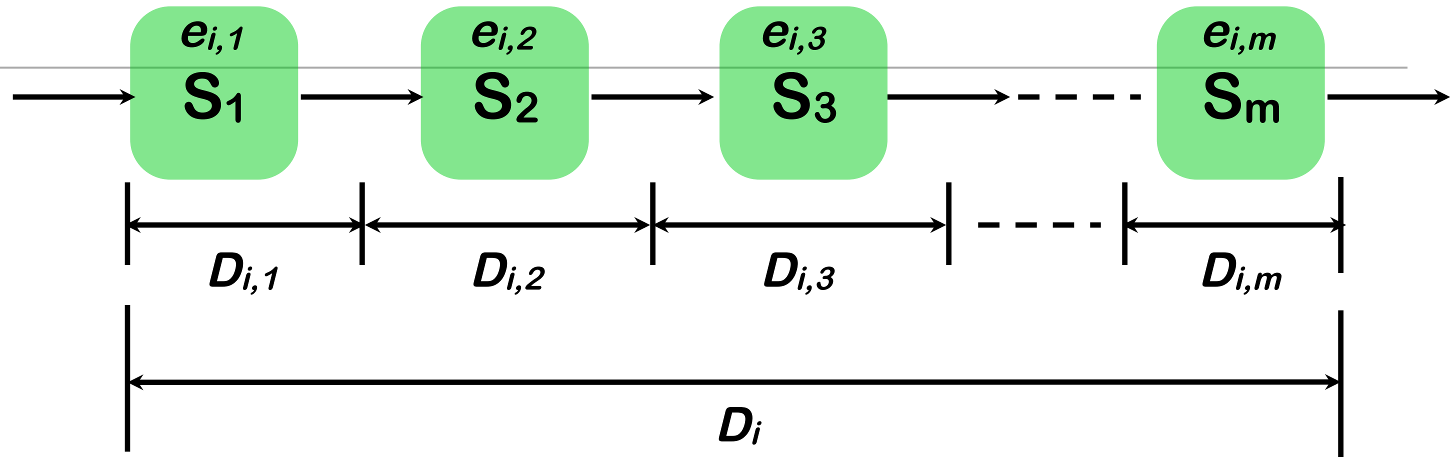


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# Synchronization for distributed real-time systems

- **Synchronization protocols** for distributed real-time systems address how tasks flow from stage to stage
- Requirements of a synchronization protocol
  - Enforce precedence constraints
  - Allow schedulability analysis
  - Low worst-case response time
  - Low overhead
  - Low average response time

# Synchronization for distributed real-time systems

- **Greedy protocol**
- Release a job to the next stage as soon as it completes at the current stage
- Job arrivals may not be periodic (with the exception of the first stage)
  - Difficult for schedulability analysis
  - Higher priority tasks may arrive early: increased worst-case response time for lower priority tasks

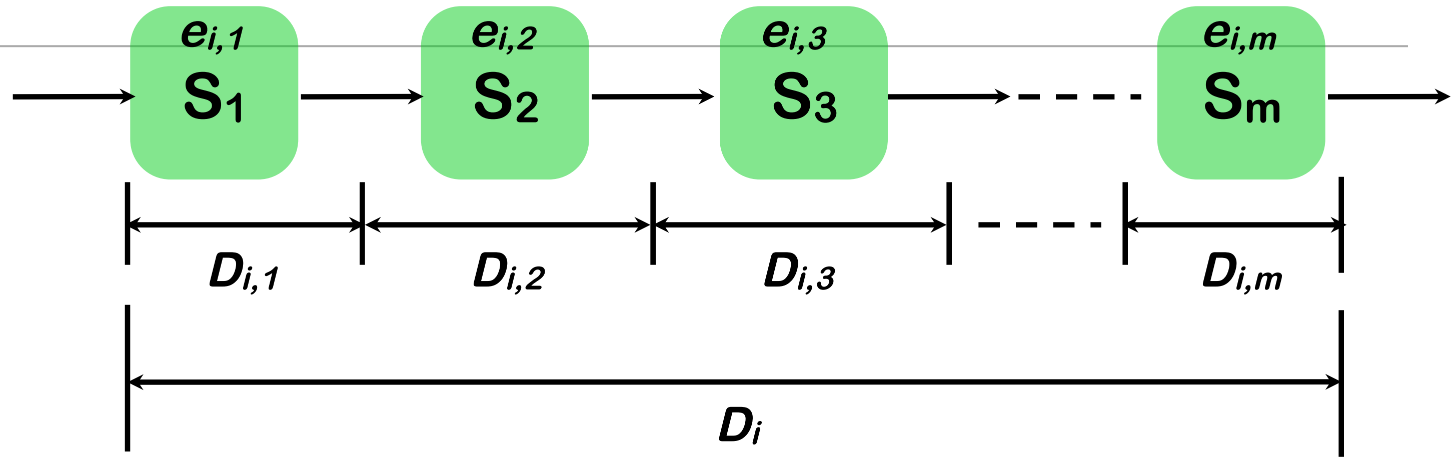
# Synchronization for distributed real-time systems

- Phase modification protocol
- Release a job to the next stage only when the worst-case response time for the job is reached at the current stage
  - Let us suppose that the worst-case response time of task $T_i$ at stage j is $R_{i,j}$
  - Jobs of $T_i$ are released to stage j+1 at time $R_{i,j}$, $R_{i,j}+P_i$, $R_{i,j}+2P_i$, …
- Require upper-bound on response times of tasks
- Require global clocks (subtle point: each stage should be time synchronized)
  - Allows schedulability analysis
  - Low worst-case response time
  - Overhead: global clock, buffering requirement

# Synchronization for distributed real-time systems

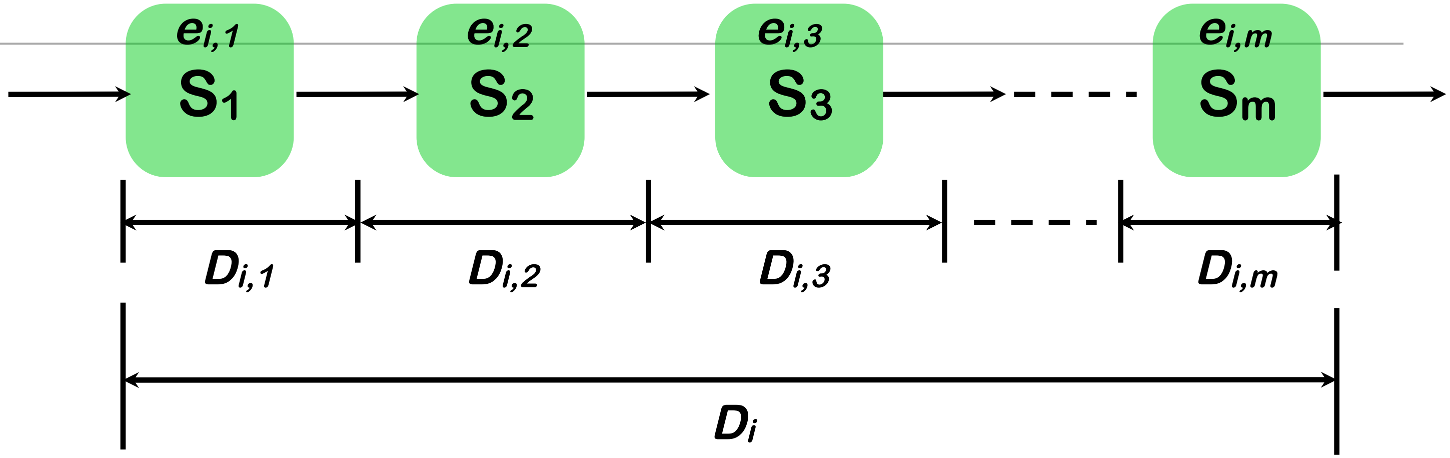
- **Release guard protocol**
- Relax the requirement on global clocks
- At each stage, release an instance of a $T_i$ only if the previous instance of $T_i$ was released at least $P_i$ time units earlier

# Buffering and its problems



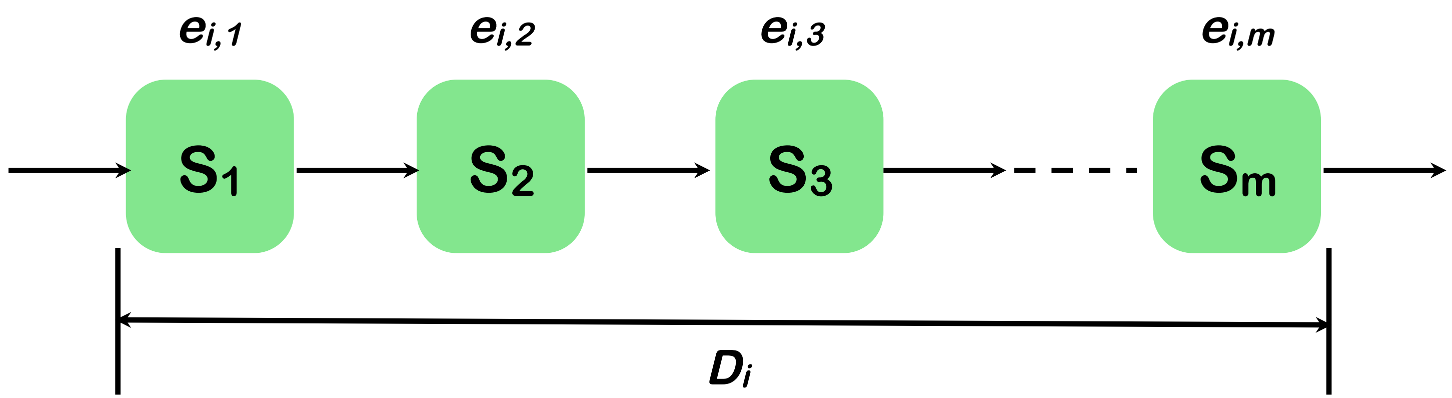

- The difficulty with ensuring periodicity in a multi-stage (distributed) system is the need for buffering
- Most current distributed real-time systems do make use of buffering because they were designed when better tests were not known
- It is easier to build systems if we did not have to buffer
- But a challenge arises because of the loss of periodicity
- Is this a real problem? **Can we determine if tasks are schedulable even if we assume they are aperiodic?**
- Our study till date assumes workload (or utilization) is easy to compute because tasks were periodic. How does this change with aperiodic tasks?

# Highlights




- Many modern real-time systems are built on a distributed platform because it is not possible to perform all operations on one processor
- **Tasks thus flow through multiple stages and each instance of a task needs to meet an end-to-end deadline**
- It is possible to guarantee schedulability by setting **intermediate (or per-stage) deadlines**
- We need to identify a heuristic to set the intermediate deadlines
- Then we use the standard uniprocessor analysis for each stage
- Setting intermediate deadlines and requiring periodicity at each stage calls for buffering: **buffering adds to complexity and overhead in a system**

# Real-time communication




- **What about communication? How does information flow from one stage to the next?**
- **Several possibilities**
  - **Communication is instantaneous (Unlikely!)**
  - **Communication has bounded latency (Somewhat more likely. Add communication latency and then ensure that deadlines are met.)**
  - **Treat the communication channel as a stage (Most general. Better way to understand distributed systems.)**

# Communication media

- Data buses
- Ethernet
- ATM

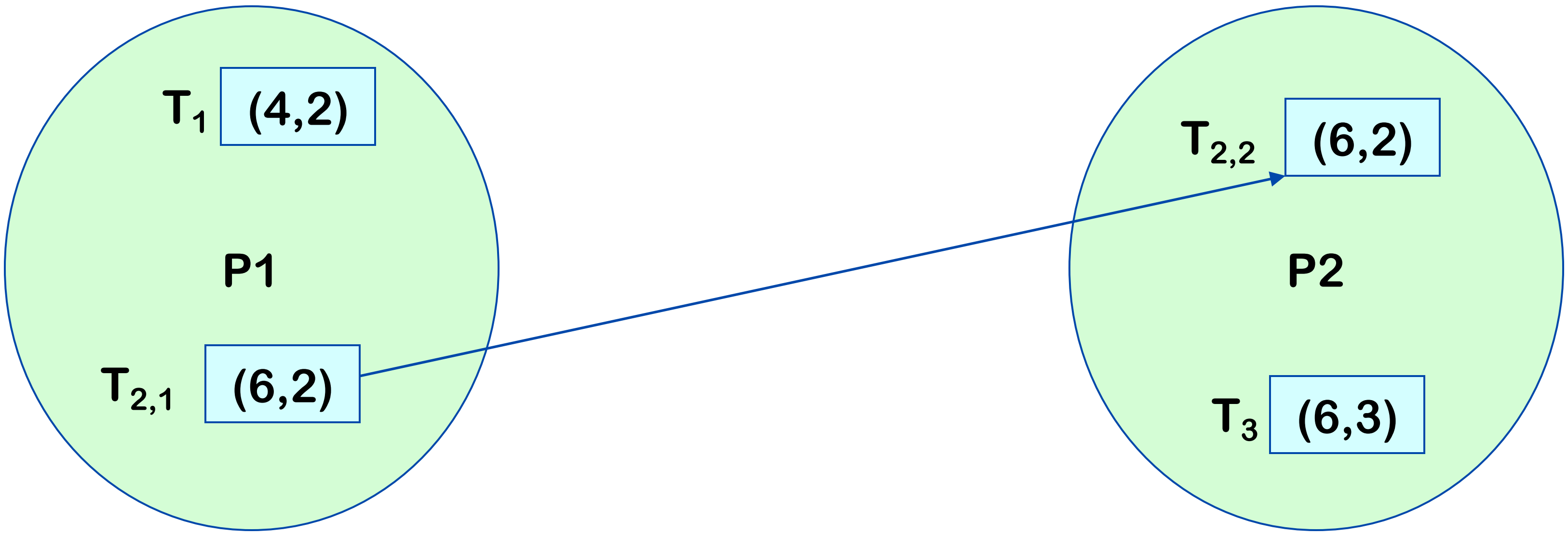
- If these media support prioritized scheduling of messages (packets), we can derive latencies introduced because of communication

**More details:**
**Optional reading;**
**Improvements to protocols are discussed.**

# Synchronization Protocols

- Goal: Reduce end-to-end response times (EER)
- Direct Synchronization (DS) Protocol
  - Simple and straightforward
- Phase Modification (PM) Protocol
  - Proposed by Bettati
- Release Guard Protocol
  - Proposed by Sun

# Synchronization Protocol - Example




$T_{i,j}$ – $j^{th}$ subtask of task $T_i$

Task T3 has a phase of 4 time units

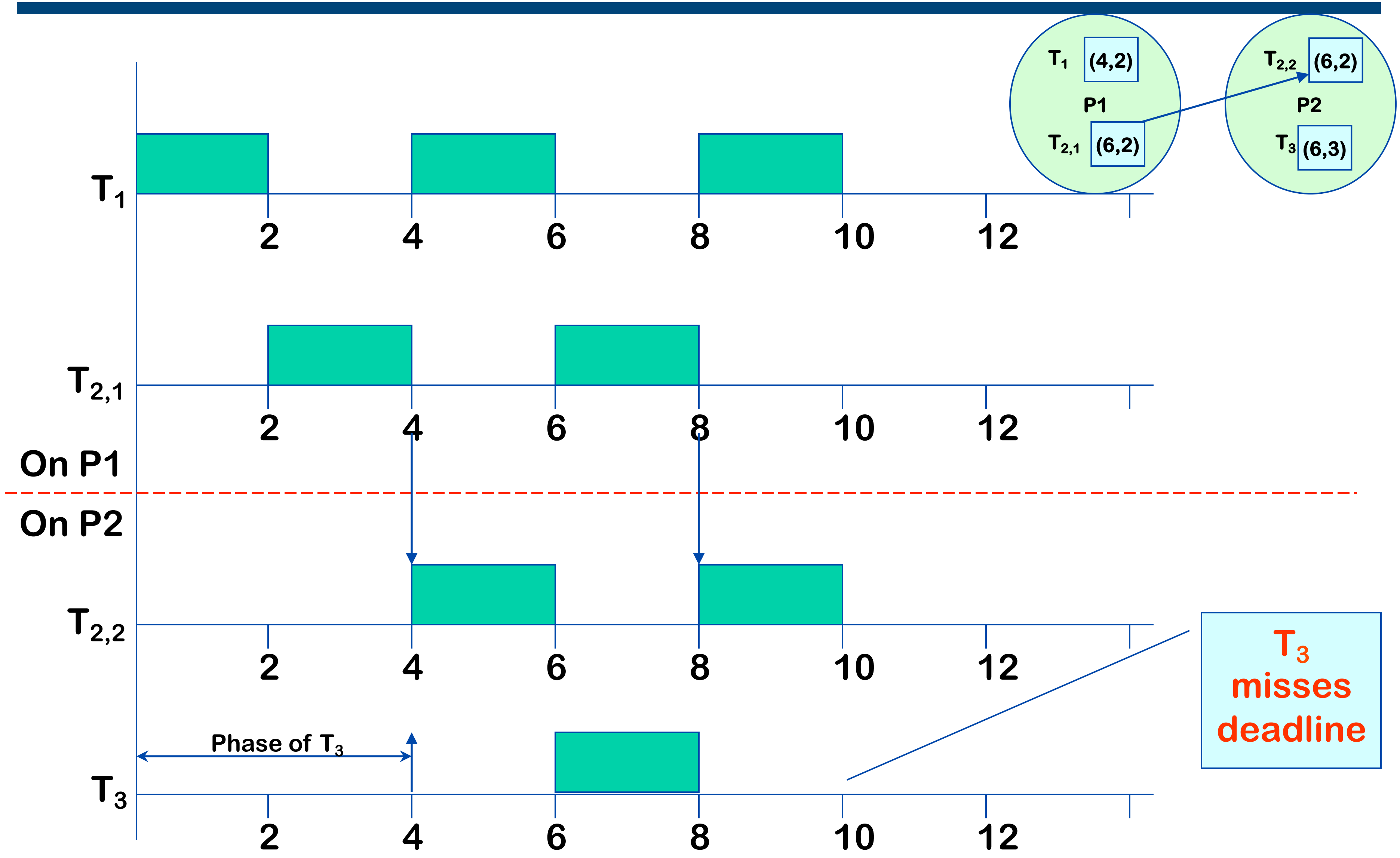
(period,execution time)

Period = relative deadline of parent task

# Direct Synchronization Protocol

- Greedy strategy
- On completion of subtask
  - A synchronization signal sent to the next processor
  - Successor subtask competes with other tasks/subtasks on the next processor

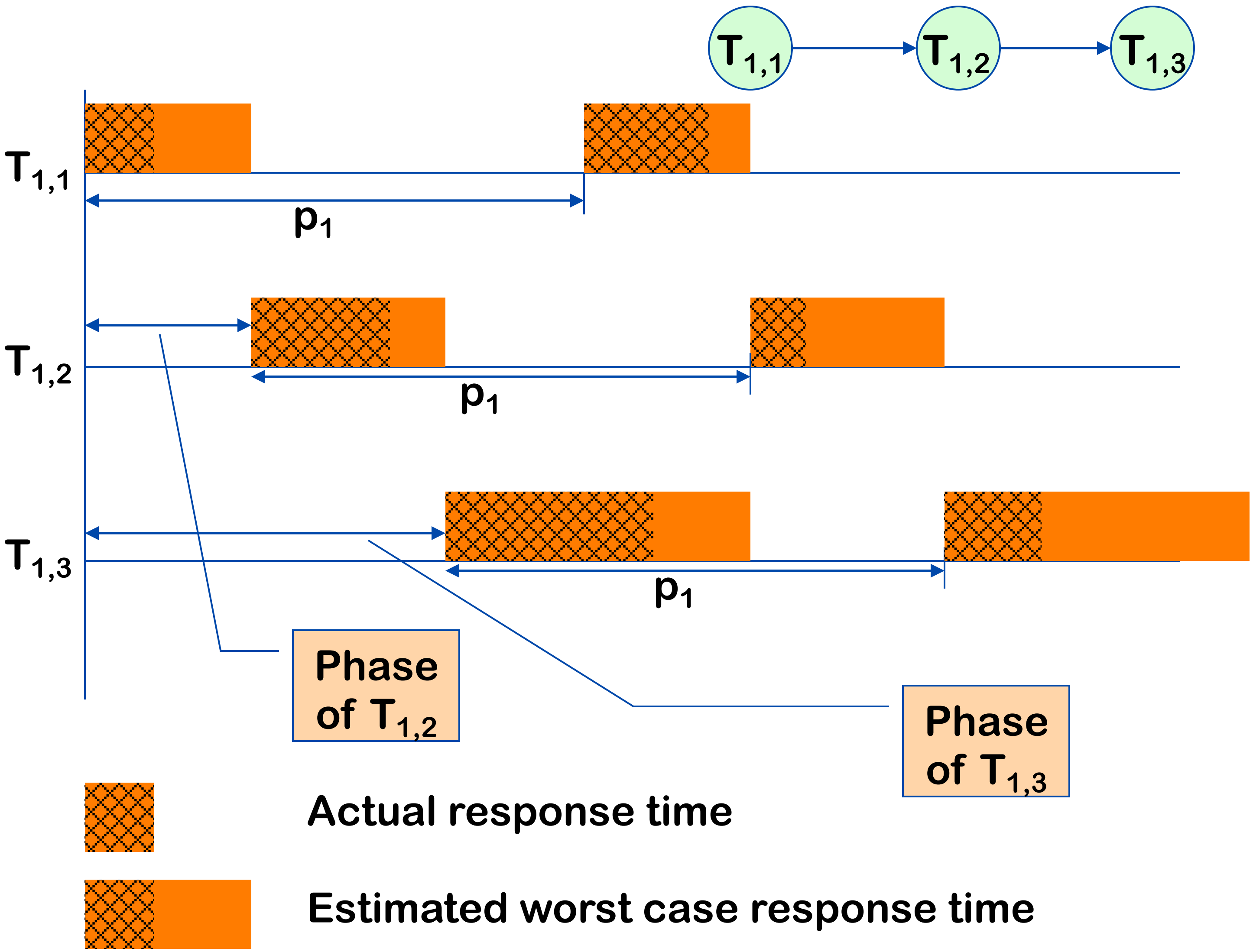
# Direct Synchronization Illustrated



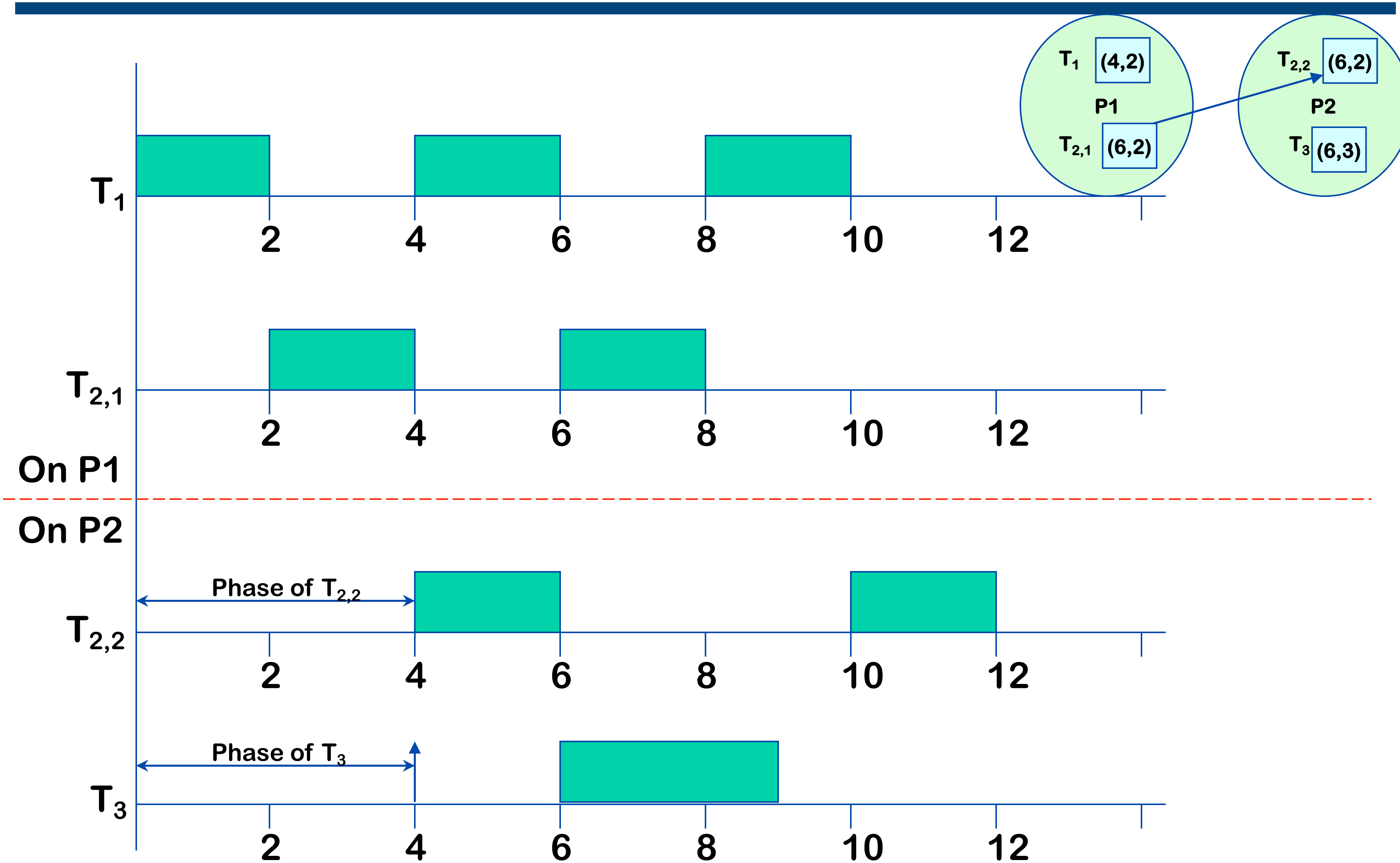
# Phase Modification Protocol

- Proposed by Bettati
- Release subtasks periodically
  - According to the periods of their parent tasks
- Each subtask given its own phase
- Phase determined by subtask precedence constraints

# Phase Modification Protocol Illustrated (1/2)



# Phase Modification Protocol Illustrated (2/2)



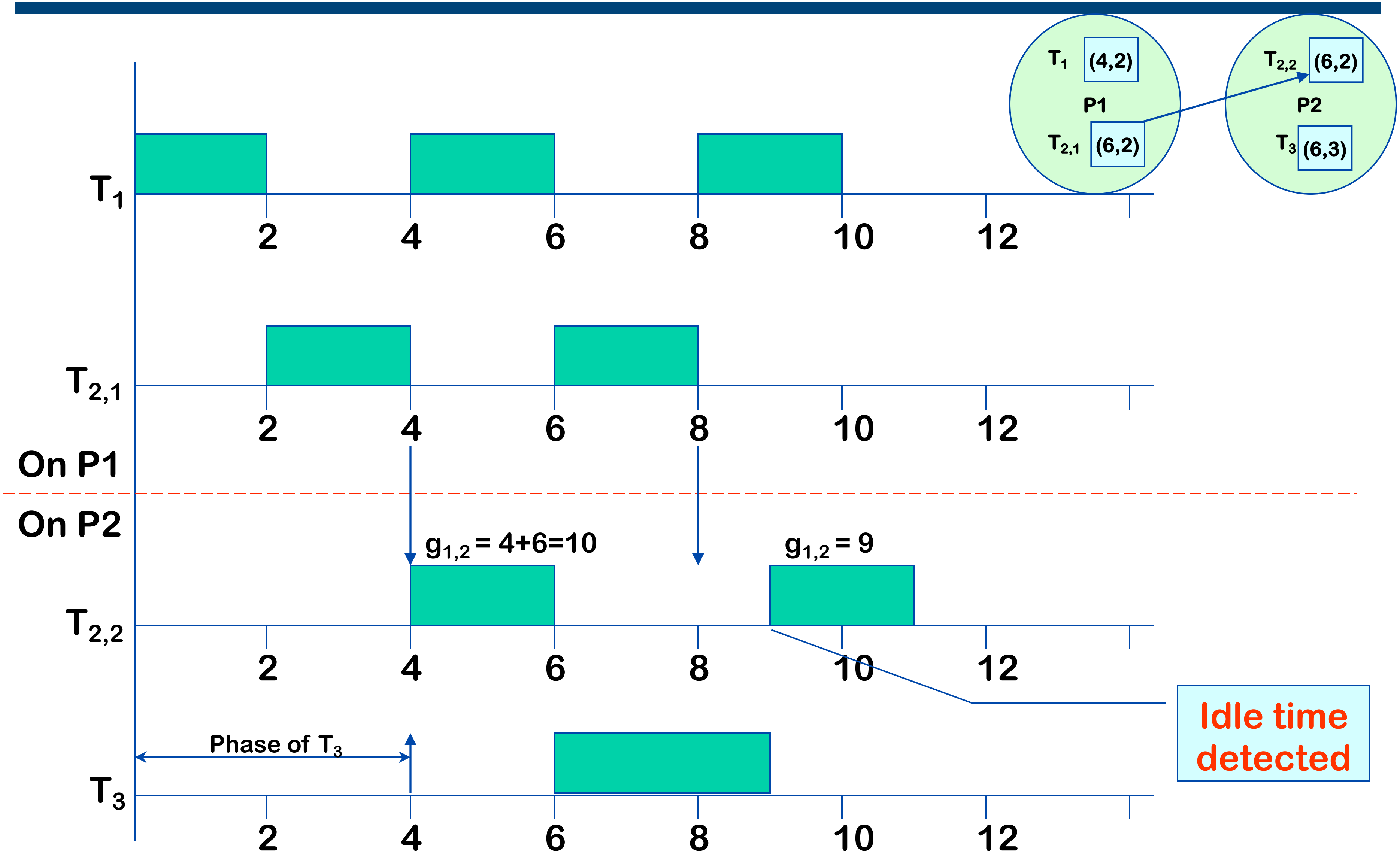
# Phase Modification Protocol - Analysis

- Periodic Timer interrupt to release subtasks
- Centralized clock or strict clock synchronization
- Task overruns could cause Precedence constraint violations

# Release Guard Protocol

- Proposed by Sun
- A guard variable – *release guard* - associated with each subtask
- Release guard used to control release of each subtask
  - Contains next release time of subtask
- Synchronization signals just like MPM
- Release guard updated
  - On getting synchronization signal
  - During idle time

# Release Guard Protocol Illustrated



# Release Guard Protocol - Analysis

- Shares the same advantages as MPM
- Upper bound on EER still the same as MPM
  - Since upper bound on release time enforced by release guard

$$\sum_{k=1}^{n_i} R_{i,k}$$

$R_{i,k}$ is the response time of the $k^{th}$ subtask of $T_i$

$n_i$ is the number of subtasks for the task $T_i$

- Lower bound on EER less than that of MPM
  - If there are idle times
  - Results in lower average EER