# Scheduling Multi-Periodic Mixed-Criticality DAGs on Multi-Core Architectures

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# Outline

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# Research context

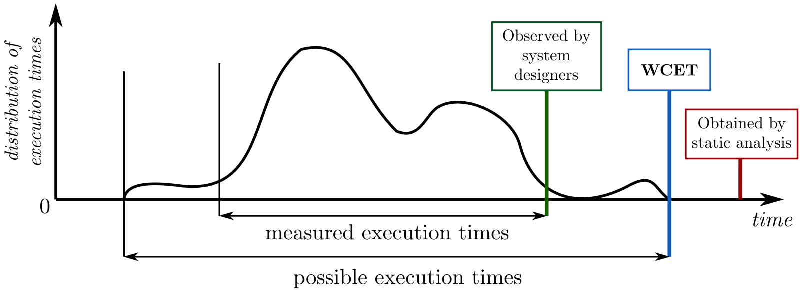
- **Safety-critical systems**: stringent time requirements + software components with different criticalities.
  - Outputs on time.
  - Life-critical, mission-critical and non-critical.
  - Often isolated: architecture or software level.

## Current industrial trends

- Reduce size, weight, power consumption, heat.
- Integrate and deliver more services.
- **Multi-core architectures**: great processing capabilities

- Large overestimation of execution time $\rightarrow$ waste of CPU.

# Timeliness: WCET estimation



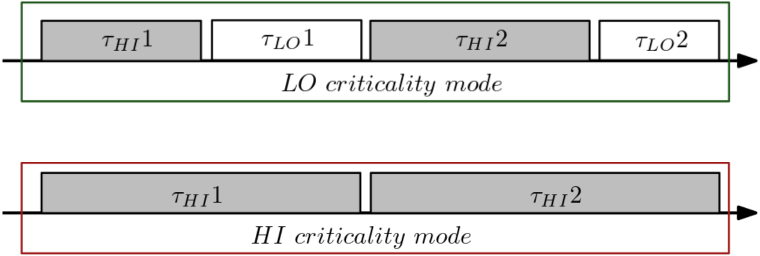

- Real-time systems dimensioned with Worst Case Execution Time (WCET).
- Estimating the WCET: a difficult problem[1].
  - Various methods to obtain an estimate.
  - Multi-core architectures hardly predictable.
  - Task rarely executes until its WCET.

[1] R. Wilhelm et al. "The worst-case execution-time problem - overview of methods and survey of tools". In: *ACM Transactions on Embedded Computing Systems* (2008).

# Mixed-Criticality (MC) model

MC model to overcome poor resource usage[2].

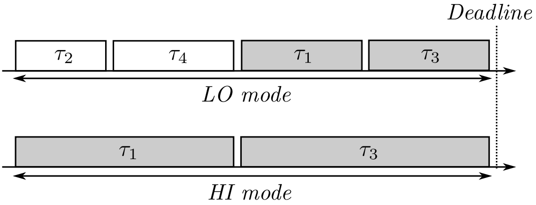
1. Different timing budgets.
   - $C_i(LO)$: Max. observed execution time (system designers).
   - $C_i(HI)$: Upper-bounded execution time (static analysis).
2. Incorporate tasks with different criticality levels: HI and LO.
3. Execution modes:
   - LO-criticality mode: HI tasks + LO tasks.
   - HI-criticality mode: **only HI tasks** → LO tasks *discarded*.




[2] Steve Vestal. "Preemptive scheduling of multi-criticality systems with varying degrees of execution time assurance". In: *Real-Time Systems Symposium*. IEEE. 2007.

# Schedulability with mode transitions

- Example: schedule the task set $\{\tau_1, \ldots, \tau_4\}$.
- HI-criticality tasks: $\tau_1, \tau_3$. LO-criticality tasks: $\tau_2, \tau_4$.



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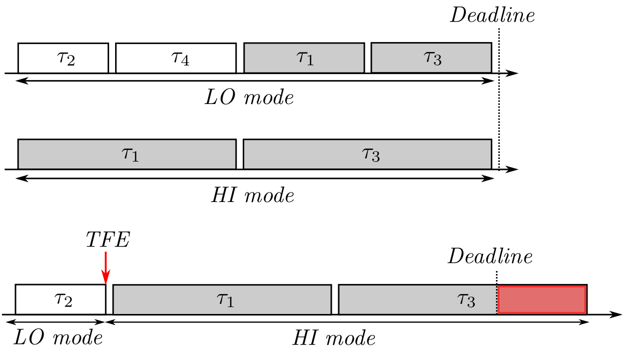
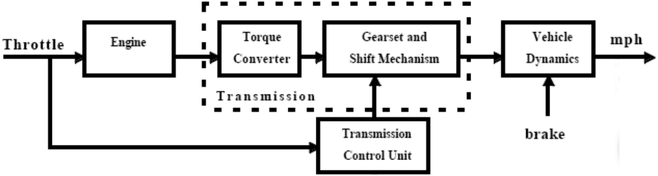



- Mode transitions: **potential deadline misses**.
- Time drifts when tasks are data-dependent...

# Designing safety-critical applications thanks to data-flows

- Models of Computation: data-flow & Directed Acyclic Graphs (DAGs).
  - Deterministic communication patterns.
  - Boundedness in memory, deadlock/starvation freedom...
- Industrial tools based on these model (*e.g.* Simulink, SCADE).
  - Code generation, automatic deployment into architecture.



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# Problem statement: scheduling data-dependent MC tasks

- MC scheduling is intractable: **NP-hard** problem[3].
- Multiple DAG scheduling in multi-core architectures: **NP-complete** problem[4].

Industrial systems with **both**: MC task + DAGs

[3] Sanjoy Baruah. "Mixed criticality schedulability analysis is highly intractable". In: 2009. URL: http://www.cs.unc.edu/~baruah/Submitted/02cxty.pdf.

[4] Yu-Kwong Kwok and Ishfaq Ahmad. "Static scheduling algorithms for allocating directed task graphs to multiprocessors". In: *ACM Computing Surveys* 31.4 (1999).

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Existing works and current limitations

- For DAGs: List Scheduling efficient heuristic.
  - **No variations in execution time** in the literature.
  - **No mode transitions for the system**.
- For MC task sets: many different scheduling policies.
  - Rarely take into account **data-dependencies** (DAG).
  - When they do, **systems are overdimensioned... again!**

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[3] Baruah, "Mixed criticality schedulability analysis is highly intractable".

[4] Kwok and Ahmad, "Static scheduling algorithms for allocating directed task graphs to multiprocessors".

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# MC-correct schedules for MC-DAGs on multi-cores

## Definition

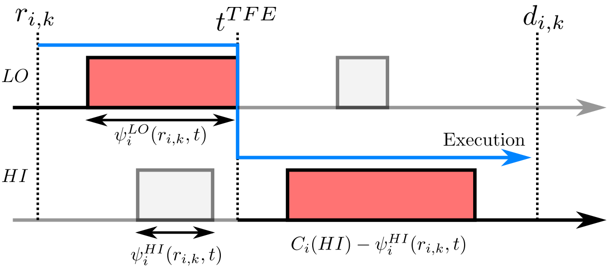
A **MC-correct**[5] schedule is one which guarantees:

1. **Condition LO-mode**: If no vertex of any MC-DAG executes beyond its $C_i(LO)$ then all the vertices complete execution by their deadlines.
2. **Condition HI-mode**: If no vertex of any MC-DAG executes beyond its $C_i(HI)$ then all the vertices designated as being of HI-criticality complete execution by their deadlines.

[5] Sanjoy Baruah. "The federated scheduling of systems of mixed-criticality sporadic DAG tasks". In: *Real-Time Systems Symposium*. IEEE. 2016.

# Safe mode transitions general property

- *Intuition*: At any instant $t$, HI task execution time given in LO mode at least equal to the execution time given in HI mode.
- $\psi_i^{\chi}(t_1, t_2)$: cumulative execution time given to task $\tau_i$ in mode $\chi$ from $t_1$ to $t_2$.




**Safe Transition Property**

$$\psi_i^{LO}(r_{i,k}, t) < C_i(LO) \implies \psi_i^{LO}(r_{i,k}, t) \geq \psi_i^{HI}(r_{i,k}, t). \quad (1)$$

# Meta-heuristic for MC-DAGs Scheduling

- Solve the complex scheduling problem off-line: computing **static scheduling tables**.
  - Easier to verify and have certified.
  - Easier to calculate $\psi_i^\chi$, enforce **Safe Transition Property**.

**MH-McDag**

1. Compute static scheduling in HI-criticality mode.
2. Compute static scheduling in LO-criticality mode, enforcing **Safe Transition Property**.

Produces **MC-correct** schedulers for MC-DAGs.

- Existing multi-core schedulers can be adapted **to produce MC-DAG schedulers**.
  - Global-Least Laxity First and Global-Earliest Deadline First.

# Outline

# Case Study: unmanned air vehicle (UAV)

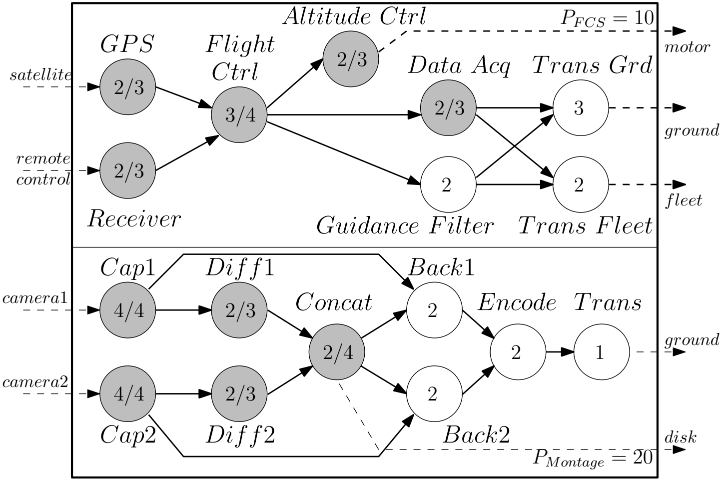



Figure 1: UAV with a Flight Control System and image processings

- $U_{max} = U_{FCS} + U_{Montage} = 1.8 + 1.05 = 2.85.$

# Application of the federated approach

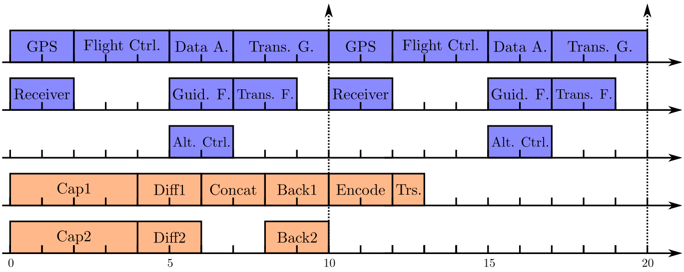



Figure 2: Five cores required for the federated scheduling approach[5]

## Limitations

1. Single DAG has *exclusive access* to a cluster of cores.
2. HI tasks scheduled ASAP in the LO-criticality mode.
   - Respects **Safe Trans. Prop.** but...
   - LO-criticality task scheduling too constrained.
   - No longer necessary with **Safe Trans. Prop.**

# How to improve resource usage with MC-DAGs?

## Two main strategies

- Adopt a **global multi-core scheduling**
  $\rightarrow$ MC-DAGs share cores (better resource usage)
- As late as possible (ALAP) policy in the HI mode
  $\rightarrow$ Relax HI-criticality tasks execution in the LO mode.

## **Genericity** of our implementation (G-ALAP)

- *Deadlines* (based on Global-Earliest Deadline First).
- *Laxities* (based on Global-Least Laxity First).

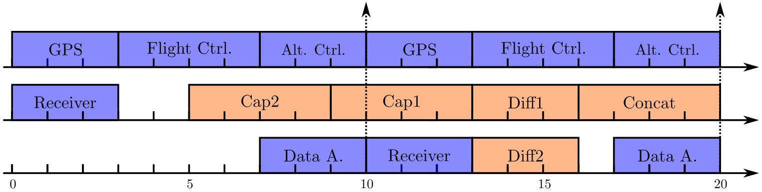
# Earliest deadline priority ordering

- Ready task jobs sorted by a "virtual deadline".
- Virtual deadline for a job $k$ of task $\tau_i$ in mode $\chi$:

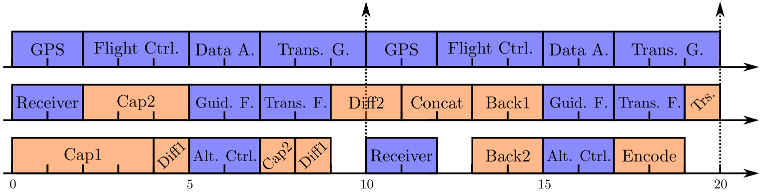
$$D_{i,k}^{\chi} = d_{i,k} - CP_i^{\chi}. \tag{2}$$

- $d_{i,k}$ deadline of the $k$-th activation of the MC-DAG.
- $CP_i^{\chi}$ critical path to the vertex.

# Computed scheduling tables w/ G-ALAP-EDF




(a) HI-criticality scheduling w/ ALAP behavior




(b) LO-criticality scheduling

From five cores to **three cores**

# Laxity-based priority ordering

- Ready tasks sorted by their laxities.
- Laxity for a job $k$ of task $\tau_i$:

$$L_{i,k}^{\chi}(t) = d_{i,k} - t - (CP_i^{\chi} + R_{i,k}^{\chi}). \quad (3)$$

- $d_{i,k}$ deadline of the $k$-th activation of the MC-DAG.
- $t$ current time slot.
- $CP_i^{\chi}$ critical path to the vertex.
- $R_{i,k}^{\chi}$ remaining execution time.
  - Initialized with $C_i(LO)$ or $C_i(HI)$.

# Outline

# MC-DAG generation

- Unbiased random generation of MC-DAGs.
  - Avoid particular DAG shapes[6].
  - System's utilization is uniformly distributed among vertices[7].
- Configurable parameters:
  - Edge probability.
  - Number of vertices.
  - Number of MC-DAGs.
  - Utilization of the system.
  - Ratio HI/LO-criticality tasks.
- Open source framework[8].

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[6] Takao Tobita and Hironori Kasahara. "A standard task graph set for fair evaluation of multiprocessor scheduling algorithms". In: *Journal of Scheduling* 5.5 (2002), pp. 379–394.

[7] Enrico Bini and Giorgio C Buttazzo. "Measuring the performance of schedulability tests". In: *Real-Time Systems Symposium* 30.1 (2005).

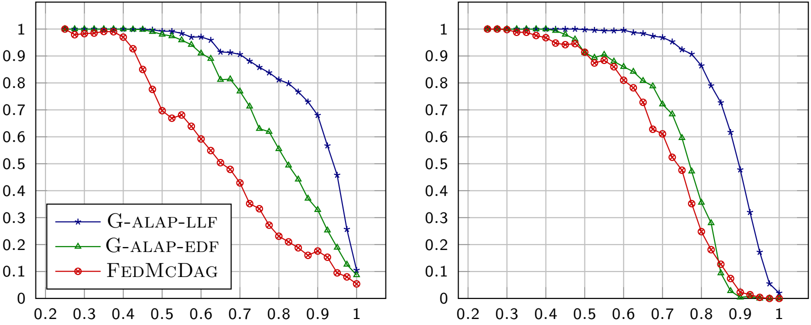
[8] MC-DAG framework - `https://github.com/robertoxmed/MC-DAG`

# Experimentation setup

- Generated large number of MC systems (1000 systems/configuration).
- Fixed the number of cores and vertices.
- Vary the utilization of the sysetem.
- Vary the number of MC-DAGs.
- Vary the density of the graph (probability to have an edge).
- Measured the acceptance rate in function of the normalized utilization.

# Significant performance increase

- Comparison between our G-ALAP implementations and FEDMCDAG[5].

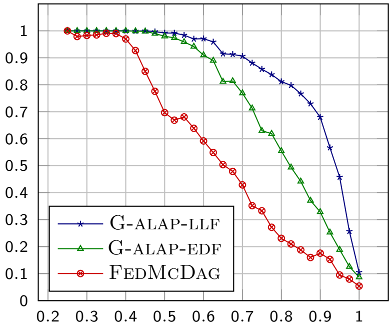



(a) $e = 20\%, |\mathcal{G}| = 2$ and $m = 4$.

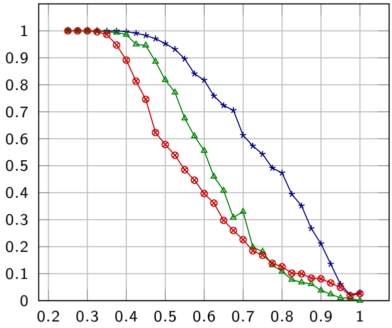
(b) $e = 20\%, |\mathcal{G}| = 4$ and $m = 4$.

- Better schedulability when the number of MC-DAGs increases.

# Significant performance increase




(c) $e = 20\%, |\mathcal{G}| = 2$ and $m = 4$.




(d) $e = 40\%, |\mathcal{G}| = 2$ and $m = 4$.

When MC-DAGs are denser (parameter $e$):

- More difficult to schedule a MC system.
- Still better schedulability than existing approaches.

# Outline

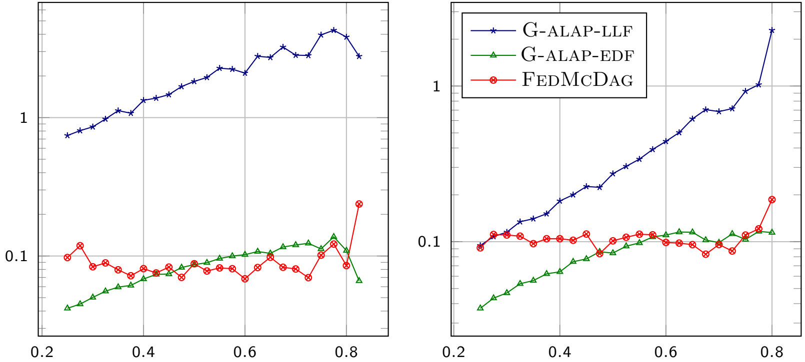
# Conclusion on MC-DAG scheduling

- Designed a meta-heuristic to obtain various schedulers for DAGs on Mixed-Criticality systems.
- Meta-heuristic proven to be correct:
  - Schedulability on both modes (HI & LO).
  - Safe mode transitions to higher criticality mode.
- Our implementations outperform the state of the art.
  - More systems are schedulable considering a given architecture.
  - Good acceptance rate even when the utilization is high.

**Perspectives**

- Support an arbitrary number of criticality levels.
- Perform benchmarks on number of preemptions.

# Entailed number of preemptions




(a) $e = 20\%,\ |G| = 2,\ m = 4.$

(b) $e = 40\%,\ |G| = 2,\ m = 4.$

Figure 3: Average number of preemptions per job (log scale)

- Number of preemptions for systems schedulable with all methods.