

Mixed Criticality Systems - A Review*

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Abstract

This review covers research on the topic of mixed criticality systems that has been published since Vestal's 2007 paper. It covers the period up to end of 2021. The review is organised into the following topics: introduction and motivation, models, single processor analysis (including job-based, hard and soft tasks, fixed priority and EDF scheduling, shared resources and static and synchronous scheduling), multiprocessor analysis, related topics, realistic models, formal treatments, systems issues, industrial practice and research beyond mixed-criticality. A list of PhDs awarded for research relating to mixed-criticality systems is also included.

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Contents

1	Introduction	4
2	Mixed Criticality Models	6
3	Single Processor Analysis	8
3.1	Job Scheduling	9
3.2	Fixed Priority Scheduling	9
3.2.1	RTA-Based approaches	9
3.2.2	Slack scheduling	13
3.2.3	Period transformation	14
3.3	EDF Scheduling	16
3.4	Shared Resources	18
3.5	Static and Synchronous Scheduling	19
3.6	Varying Speed Processors	20
3.7	Semi-Clairvoyant Scheduling	20
4	Multiprocessor Analysis	21
4.1	Task Allocation	21
4.2	Schedulability Analysis	24
4.3	Communication and other Resources	25
5	Links to other Research Topics	29
5.1	Hard and Soft Tasks	29
5.2	Fault Tolerant Systems (FTS)	30
5.3	Security	32
5.4	Hierarchical Scheduling	32
5.5	Cyber Physical Systems and the Internet of Things	33
5.6	Probabilistic Real-Time Systems	34
6	More Realistic MCS Models	36
7	More Formal Treatments	41
7.1	Utilisation Bounds	41
7.2	Speedup Factors	41
7.3	Formal Language and Modelling Issues	42
8	Systems Issues	44
8.1	Run-Time Monitoring and Overheads	44
8.2	Virtualisation and Operating System Support	44

8.3	Hardware Aspects	46
8.4	Benchmarks and Comparative Studies	47
8.5	Criticality-Aware Power Consumption	48
8.6	Issues Relating to Modelling and Tool Support	49
9	Industry Practice and Standards	50
10	Beyond Mixed-Criticality	51
11	PhD Awards for Research within the Field of MCS	52
12	Conclusion and Directions for Future Work	53
	Literature	57

1 Introduction

An increasingly important trend in the design of real-time and embedded systems is the integration of components with different levels of criticality onto a common hardware platform. At the same time, these platforms are migrating from single cores to multi-cores and in the future many-core architectures. Criticality is a designation of the level of assurance against failure needed for a system component. A mixed criticality system (MCS) is one that has two or more distinct levels (for example safety critical, mission critical and low-critical). Perhaps up to five levels may be identified (see, for example, the IEC 61508, DO-178B and DO-178C, DO-254 and ISO 26262 standards). Typical names for the levels are ASILs (Automotive Safety and Integrity Levels), DALs (Design Assurance Levels or Development Assurance Levels) and SILs (Safety Integrity Levels). It should be noted that not all standards and papers on MCS assign the same meaning to ‘criticality’, an issue explored by Graydon and Bate [263], Esper et al. [227], Paulitsch et al. [501], Ernst and Di Natale [226], Wilhelm [620], Jiang [348, 349, 354] and Lee and Kim [406].

Most of the complex embedded systems found in, for example, the automotive and avionics industries are evolving into mixed criticality systems in order to meet stringent non-functional requirements relating to cost, space, weight, heat generation and power consumption (the latter being of particular relevance to mobile systems). Indeed the software standards in the European automotive industry (AUTOSAR¹) and in the avionics domain (ARINC²) address mixed criticality issues; in the sense that they recognise that MCS must be supported on their platforms.

The fundamental research question underlying these initiatives and standards is: how, in a disciplined way, to reconcile the conflicting requirements of *partitioning* for (safety) assurance and *sharing* for efficient resource usage. This question gives rise to theoretical problems in modelling and verification, and systems problems relating to the design and implementation of the necessary hardware and software run-time controls.

A key aspect of MCS is that system parameters, such as tasks’ worst-case execution times (WCETs), become dependent on the criticality level of the tasks. So the same code will have a higher WCET if it is defined to be safety-critical (as a higher level of assurance is required) than it would if it is just considered to be mission critical or indeed non-critical. This property of MCS significantly modifies/undermines many of the standard scheduling results. This report aims to review the research that has been published on MCS.

The first paper on the verification of a Mixed Criticality System used an exten-

¹<http://www.autosar.org/>

²<http://www.arinc.com/>

sion of standard fixed priority (FP) real-time scheduling theory, and was published by Vestal (of Honeywell Aerospace) in 2007 [607]³. It employed a somewhat restrictive work-flow model, focused on a single processor and made use of Response Time Analysis [36]. It showed that neither rate monotonic [434] nor deadline monotonic [417] priority assignment is optimal for MCS; however Audsley's optimal priority assignment algorithm [34] was found to be applicable.

This paper was followed by two publications in 2008 by Baruah and Vestal [95], and Huber et al. [331]. The first of these papers generalises Vestal's model by using a sporadic task model and by assessing fixed job-priority scheduling and dynamic priority scheduling. It contains the important result that EDF (Earliest Deadline First) does not dominate FP when criticality levels are introduced, and that there are feasible systems that cannot be scheduled by EDF. The latter paper addresses multi-processor issues and virtualisation (though it did not use that term). It focused on AUTOSAR and resource management (encapsulation and monitoring) with time-triggered applications and a trusted network layer.

Further impetus to defining MCS as a distinct research topic came from the white paper produced by Barhorst et al. [56], the keynote talk that Baruah gave at the 2010 ECRTS conference⁴ and a workshop report from the European Commission [596]. These have been followed up by tutorials on MCS at ESWEEK in 2012 and 2013⁵, a workshop at HiPEAC in January 2013⁶, a workshop (WICERT) at DATE 2013⁷, a workshop (ReTiMiCS) at RTCSA 2013⁸, workshops (WMC) at RTSS 2013⁹, RTSS 2014¹⁰, RTSS 2015¹¹, RTSS 2016¹², RTSS 2017¹³, RTSS 2018¹⁴, RTSS 2019¹⁵ (although unfortunately this workshop did not take place as RTSS was cancelled; however many of these papers were presented at the 2020

³The term Mixed Criticality had been used before 2007 to address issues of non-interference in non-federated architectures such as IMA [306]; Vestal changed the focus of research by concentrating on real-time performance. Systems with more than one criticality level but aim to only give complete isolation are called *multiple-criticality systems*; the use of *mixed-criticality* implies some tradeoff between isolation and integration that involves resource sharing.

⁴Available from the conference web site: <http://ecrts.eit.uni-kl.de/index.php?id=53>.

⁵Embedded Systems Week: <http://www.esweek.org/>

⁶<http://www.hipeac.net/conference/berlin/workshop/integration-mixed-criticality-subsystems-multi-core-processors>

⁷<http://atcproyectos.ugr.es/wicert/index.php/conference-proceedings>

⁸<http://igm.univ-mlv.fr/rtalgo/Events/RETIMICS/>

⁹<http://www.cs.york.ac.uk/robdavis/wmc2013/>

¹⁰<http://www.cs.york.ac.uk/robdavis/wmc2014/>

¹¹<http://www.cs.york.ac.uk/robdavis/wmc/>

¹²<https://gsathish.github.io/wmc2016/>

¹³<https://cps-research-group.github.io/WMC2017/>

¹⁴<https://drive.google.com/file/d/14sLpczS6wpQN99dPET08sZP3qjvEr5S2/view?usp=sharing>

¹⁵<https://sites.google.com/njit.edu/wmc2019>

workshop) and RTSS 2020¹⁶; a workshop at the 19th International Conference on Reliable Software Technologies (Ada-Europe) in June 2014, and Dagstuhl Seminars on Mixed Criticality and Many Core Platforms in 2015¹⁷ and 2017¹⁸.

This review [140] is organised as follows. In Section 2 we first consider mixed criticality models. Then in Section 3 single processor systems are covered (including fixed priority and EDF scheduling). Section 4 covers multiprocessor issues and Section 5 links this research to other topics such as hard and soft real-time scheduling and hierarchical scheduling. More realistic models are covered in Section 6, more formal work is covered in Section 7 and systems work is covered in Section 8. Industry practice and safety standards provide a somewhat different perspective on MCS to Vestal’s model; these differences are discussed in Section 9. Section 11 lists PhD dissertations that have been produced on MCS since 2014. The review concludes with Section 12 which outlines a number of open problems and areas where further research is needed.

An adaptation of this review, covering publications up to the end of 2016, has been published in ACM Computer Surveys [138]. This should be used as the main citation for this report. Other overviews/surveys on MCS have also been produced [25, 29, 154, 175, 281, 635].

2 Mixed Criticality Models

Inevitably not all papers on mixed criticality have used the same system or task model. Here we define a model that is generally applicable and is capable of describing the main results considered in this review.

A system is defined as a finite set of components \mathcal{K} . Each component has a level of criticality (designated by the systems engineer responsible for the entire system), L , and contains a finite set of *sporadic tasks*. Each task, τ_i , is defined by its period (minimum arrival interval), deadline, computation time and criticality level: (T_i, D_i, C_i, L_i) . Tasks give rise to a potentially unbounded sequence of *jobs*.

The primary concern with the implementation of MCS is one of separation. Tasks from different components must not be allowed to interfere with each other. In particular, mechanisms must be in place to prevent a job from executing for more than the computation time C defined for its task, and to ensure that a task does not generate jobs that are closer together than T ¹⁹.

The requirement to protect the operation of one component from the faults of

¹⁶<http://2020.rtss.org/wmc2020/>

¹⁷<http://www.dagstuhl.de/15121>

¹⁸<http://www.dagstuhl.de/17131>

¹⁹Or (period minus release jitter) if that is part of the task model.

another is present in all systems that host multiple applications. It is however of particular significance if components have different criticality levels. Since without such protection, all components would need to be engineered to the strict standards of the highest criticality level, potentially massively increasing development costs.

After concerns of partitioning comes the need to use resources efficiently. This is facilitated by noting that the task parameters are not independent, in particular the worst-case computation/execution time estimate, C_i , will be derived by a process dictated by the criticality level. The higher the criticality level, the more conservative the verification process and hence the greater will be the value of C_i . This was the observation at the heart of the paper by Vestal [607].

For systems executing on hardware platforms with deterministic behaviour, any particular task will have a single real WCET (worst-case execution time); however, this value typically cannot be known with complete certainty. This uncertainty is primarily epistemic (uncertainty in what we know, or do not know, about the system) rather than aleatory (uncertainty in the system itself). Although it is reasonable to assume confidence increases (i.e. uncertainty decreases) with larger estimates of worst-case execution time, this may not be universally true [263]. It would certainly be hard to estimate what increase in confidence would result from, say, a 10% increase in all C s.

For systems executing on hardware platforms with time-randomised hardware components [153], then a probabilistic WCET (pWCET) [26, 184, 194, 218, 523] can be obtained. The exceedance function for this probability distribution defines for any specific probability, derived from a required maximum failure rate associated with a criticality level, an execution time budget which has no greater probability of being exceeded on any given run [183]. The pWCET distribution therefore effectively defines different estimates of the WCET budget for the same task, for different criticality levels due to their different requirements on the maximum tolerable failure rate.

The focus on different computation times was extended to task periods in subsequent papers [64, 68, 70, 78, 83, 131, 135, 643]. Here tasks are event handlers. The higher the criticality level the more events must be handled, and hence the task must execute more frequently even if it does not execute for longer.

In MCS a task is now defined by: (\vec{T}, D, \vec{C}, L) , where \vec{C} and \vec{T} are vectors of values – one per criticality level, with the constraints:

$$L1 > L2 \Rightarrow C(L1) \geq C(L2)$$

$$L1 > L2 \Rightarrow T(L1) \leq T(L2)$$

for any two criticality levels $L1$ and $L2$.

Note the completion of the model, by making D criticality dependent [78] has not as yet been addressed in detail. But it could have the constraint:

$$L1 > L2 \Rightarrow D(L1) \geq D(L2)$$

So a task may have a ‘safety critical’ deadline and an early Quality of Service (QoS) deadline. Alternatively:

$$L1 > L2 \Rightarrow D(L1) \leq D(L2)$$

in which case the conservative ‘safety critical’ deadline is shorter than the one deemed necessary if the criticality level is lower.

Another feature of many of the papers considered in this review is that the system is defined to execute in a number of criticality *modes*. A system starts in the lowest criticality mode. If all jobs behave according to this mode then the system stays in that mode. But if any job attempts to execute for a longer time, or more frequently, than is acceptable in that mode then a criticality mode change occurs. Ultimately the system may change to the highest criticality mode.

Some papers allow the criticality mode to move down as well as up, but others (indeed the majority) restrict the model to increases in criticality only. We return to this issue in Section 6.

Many papers also restrict themselves to just two criticality levels; high (HI) and low (LO) with $HI > LO$. These are referred to as *dual-criticality* systems. Where modes are used, the system is either in a LO -criticality (or normal) mode or a HI -criticality mode. And the set of task parameters is typically: $(T_i, D_i, C_i(HI), C_i(LO), L_i)$. At the other extreme are the models presented by Ekberg et al. [219, 221, 223] in which any number of modes are allowed and the movement between modes is represented by a directed acyclic graph.

The volume of material published on MCS is perhaps surprising as there is not a consensus as to the definition and use of the notion of criticality. Burns [129] notes that much of the published material does not require a precise definition of ‘criticality’. Burns argues that the core notion in MCS research is the existence of multiple interpretations of one or more of the defining parameters of the application. It follows, he argues, that perhaps the general term for this body of results should be Multi-Model Systems rather than Mixed-Criticality Systems. However, a new name is unlikely to have traction at this late stage.

3 Single Processor Analysis

Since Vestal’s 2007 paper [607] there has been a series of publications. Most of these papers address single processor platforms and independent components.

3.1 Job Scheduling

Initially a number of papers considered the restricted problem of scheduling, on a single processor, a finite set of mixed criticality jobs with criticality dependent execution times [63, 71, 73, 87, 89, 94, 269, 285, 369, 419, 420, 496, 554, 567, 568, 572, 574]. This work has, however, largely been superseded by work on the more widely applicable task model.

3.2 Fixed Priority Scheduling

In this section we look at MCS schemes that are based on applying Response-Time Analysis (RTA), then those that consider slack scheduling and finally approaches that are derived from period transformations.

3.2.1 RTA-Based approaches

Vestal's approach was formalised (i.e. proof that the use of Audsley's priority assignment algorithm [34] was optimal) by Dorin et al. [206] in 2010. They also extended the model to include release jitter, and showed how sensitivity analysis could be applied.

Vestal's approach allowed the priorities of high and low criticality tasks to be interleaved, but all tasks had to be evaluated as if they were of the highest criticality. By introducing monitoring of task execution time, and the prevention of execution time over-runs, higher resource usage can be delivered [78]. This is a crucial issue in mixed criticality scheduling; by the introduction of more trusted components a high utilisation of the available resources is facilitated.

In 2011 this approach was further extended [81, 131] to give a scheduling model and associated analysis framework for a single processor system that dominates all previous published analysis for MCS (using fixed priority scheduling) in that it made better use of the processor and could schedule all systems that could be guaranteed by other approaches, plus many that could not. These papers were however restricted to just two criticality levels (or modes). The system's run-time behaviour is either *low-criticality* (which relies on all execution times being bound by the low-criticality values and guarantees that all deadlines are met) or *high-criticality* (where only high criticality work is guaranteed but the bound on high-criticality execution times is increased). The system's criticality change (from Low to High, i.e. *LO* to *HI*)²⁰ is triggered by the observation, at run-time, that a low-criticality condition has been violated. In the context of control applications Cheng

²⁰These modes are sometimes called *Normal* and *HI*.

et al [160] also allow the state of the controlled plant to trigger a criticality mode change.

This change in criticality level has a number of similarities to systems that move between different operational modes (although there are also some significant differences [126, 263]). In the *HI*-criticality mode there are fewer tasks, but they have longer execution times or shorter periods. The literature on mode change protocols [49, 144, 224, 504, 528, 558, 597, 598], however, highlights one important problem: a system can be schedulable in every mode, but not schedulable during a mode change [598]. This is also true for systems that change criticality levels.

An optimal priority ordering is defined in the paper from Baruah et al. [81] in that it maximises the priority of high criticality tasks, subject to the system being schedulable. Both the high and low criticality tasks are ordered via deadline (deadline monotonic) and a simplified version of Audsley’s algorithm is used to assign priorities from the lowest to the highest level. At each priority level the lowest priority task from the low criticality task set is tried first, if it is schedulable then the algorithm moves up to the next priority level; if it is not schedulable then the lowest priority task from the high criticality set is tested. If it is schedulable then again the algorithm moves on to the next level. But if neither of these two tasks are schedulable then the search can be abandoned as the task set is unschedulable. In total a maximum of $2N$ tests are needed (where N is the number of tasks in the system)²¹. Note that this result follows from work on robust priority assignment [192]. As each set of *LO/HI* criticality tasks can be viewed as additional interference on the other subset, an optimal priority ordering can be obtained with each subset in Deadline Monotonic priority order and a merge operation between them.

The protocol (dropping all *LO*-criticality work if any task executes for more than its $C(LO)$ value²²), the derived analysis and the use of optimal priority ordering is shown [81] to out-perform other schemes (in terms of success ratio for randomly generated task sets). The analysis is based on standard RTA (Response-Time Analysis). For any task, τ_i , first its *LO*-criticality response-time ($R(LO)$) is computed using *LO*-criticality parameters for all the tasks. A criticality switch must occur before this value if the task is to be impacted by the change, otherwise it will have completed execution. The worst-case response-time in the *HI*-criticality mode ($R(HI)$) is computed by noting that all *LO*-criticality tasks must be abandoned by time $R(LO)$. The paper contains two methods for computing $R(HI)$ ²³, one involves a single upper bound, the other looks at all the possible critically

²¹Strictly, only $2N-1$ tests are needed as the highest priority task must be schedulable as its computation time is less than its deadline.

²²First proposed by Baruah [63, 71].

²³In [81] the example in Section IV.B (final step) should have a worst-case response-time of 90, not 85 as reported in the paper; however 90 is still below the deadline of 100.

change points before $R(LO)$ and computes the worst-case. The latter is more accurate, though still not exact; however, the gain in performance is not significant and the simple upper bound test is probably sufficient in most cases.

To illustrate the above approaches one of the graphs from [81] is reproduced in Figure 1. This figure plots the percentage of task sets generated that were deemed schedulable for a system of 20 tasks, with on average 50% of those tasks having high criticality and each task having a high criticality execution time that is twice its low criticality execution time. The compared approaches are (from least effective to most effective): CrMPO which assigned priorities in criticality order, SMC-NO (static mixed criticality with no run-time monitoring) which is Vestal’s original approach, SMC which is an adaptation of Vestal’s approach in which LO -criticality tasks are monitored at run-time and are prevented from executing for more than $C(LO)$, and AMC-rtb and AMC-max which are the two methods introduced in the previous paragraph (AMC for adaptive mixed criticality). In the graph the UB-H&L line bounds the maximum possible number of schedulable task sets. It serves to illustrate the quality of the AMC-max approach. Almost all publications on MCS assume that the task deadlines are constrained ($D \leq T$). For AMC, Burns and Davis [137, 139] removed this constraint and a version of the analysis for AMC now allows arbitrary deadlines.

The AMC-rtb approach was extended by Zhao et al [649, 650, 653] in 2013 to incorporate preemption thresholds [540] into the model. They demonstrated a reduction in stack usage and improved performance for some parameter ranges. AMC and preemption thresholds were combined with the semi-clairvoyant scheduling by Zhao et al. [654]. Another approach to combining AMC-rtb and existing scheduling theory is taken by Burns and Davis [136]. They consider the use of deferred preemption [124, 189] and demonstrate a significant improvement over fully preemptive AMC-rtb. The gain in schedulability they demonstrate is obtained by having a final non-preemptive region (FNPR) at the end of $C(LO)$ and $C(HI)$, and by combining the assignment of priority and the determination of the size of these FNPRs. Where scheduling analysis is part of a design optimisation Zhao and Zeng [655] argue that even AMC-rtb is too complex. They propose a new simpler test that is still safe and has bounded pessimism. At the other extreme, Asyaban and Kargahi [31] develop exact analysis for AMC, unfortunately at the cost of losing optimal priority ordering /footnoteThere are also some corrections noted by Pavic and Dzapo [503].. In keeping with a number of papers on MCS, the work of Baruah et al. [81] (and most of the subsequent modifications) restricted itself to dual criticality systems. Fleming and Burns [237] extended these models to an arbitrary number of criticality levels, focusing particularly on five levels as this is the maximum found in automotive and avionics standards. They observed that AMC-rtb remains a good approximation to AMC-max, and that AMC-max

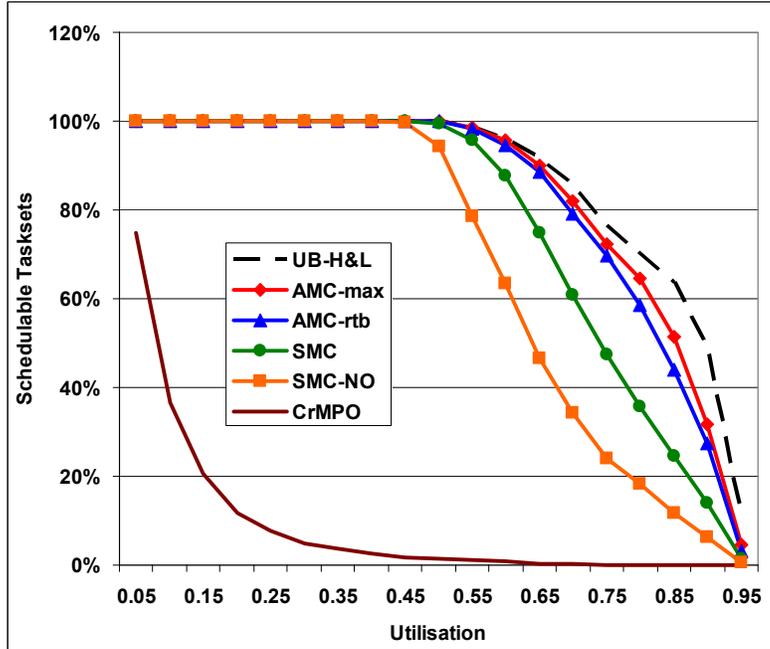


Figure 1: Percentage of Schedulable Task Sets

became computational expensive for increased numbers of criticality levels. They concluded that AMC-rtb represented an adequate and effective form of analysis. A relatively minor improvement to AMC-max was published by Huang et al. [319] (they termed it AMC-IA); however there are cases where their analysis is optimistic (i.e. unsound) [241].

One characteristic of all the schemes defined above is that tasks do not change their priority after a criticality mode change. If priorities can change then a simple form of sufficient analysis is possible [82]. This work defines a new approach, PMC (priority may change). Evaluations show that PMC performs similarly to AMC-rtb, though neither dominates the other. An improved scheme, GFP (Generalised Fixed Priority) is proposed by Chen et al. [159]. They assign (using an heuristic) three priorities to each task. One for each of the two criticality levels, and one for the transition between the criticality modes. They demonstrate an improvement over AMC-rtb.

It was noted in the section on Mixed Criticality Models that the period parameter (T) can be criticality dependent as well as the worst-case execution time estimate (C). An application may consist of event handlers, and have different levels of constraint over the arrival patterns of the events. The higher the criti-

cality, the closer together the events are assumed to arrive; and hence the smaller the T parameter. Baruah and Chattopadhyay [83] have reformulated the SMC and AMC analysis (introduced above) to apply to this model, in which the T s rather than the C s vary with criticality. Their evaluation results show similar behaviour to that depicted in Figure 1. Criticality specific periods are also address by Burns and Davis [135], Baruah [70], and by Zhang et al. [643] (who derived an improved analysis that they termed SAMC – Sufficient AMC).

For periodic task sets with offsets, Asyaban et al. [32] has produced feasibility analysis showing that simulation over an interval of length four times the hyper-period plus the largest offset forms a sufficient test of schedulability.

An alternative to switching all tasks to the *HI* criticality mode is proposed by Boudjadar et al. [118]. They assume tasks behave independently; and so it will often be the case that only one task switches to the *HI* criticality mode. This task has its priority raised, and if necessary some *LO*-criticality tasks have their period stretched (extended) to accommodate this. These show how this task-level behaviour can be combined with the more normal system-level response. Task-level scheduling is also address by Lee [401]. The notion of Flexible Mixed-Criticality (FMC) scheduling is introduced by Chen et al. [158,203] to model task-level overruns; it is extended in the work of Chwa et al. [204,205].

A natural extension to fixed-priority scheduling and response-time analysis is the multi-frame model [61,660]. A mixed-criticality version of this analysis is provided by Hussain et al. [333–335].

Another extension to AMC analysis is to incorporate implementation overheads into the model. This is done, within the context of a DAL-A Full Authority Digital Engine Control (FADEC), by Law et al. [399].

Given a protocol such as AMC, Ranjbar et a. [524] attempt to provide bounds on the probability that a mode change will take place.

3.2.2 Slack scheduling

An alternative approach to scheduling mixed criticality fixed priority systems is, for dual-criticality systems, to use a *slack scheduling* scheme in which low criticality jobs are run in the slack generated by high criticality jobs only using their low criticality execution budgets. This was first explored by Niz et al. [482]. One difficulty with this approach is to incorporate sporadic tasks. At what point can the ‘slack’ of a non-appearing sporadic task be allocated to low criticality jobs? Even for periodic tasks, ensuring schedulability of high criticality tasks in all circumstances is not straightforward. Niz et al. [482] compute the time at which a high criticality task must be released to ensure that it meets its deadline (a scheme similar to the dual-priority approach outlined in Section 5.1). However, Huang et

al. [318] demonstrated that if a low criticality (high priority) task executes beyond its deadline, a high criticality (lower priority) task could miss its deadline. They show that either the low criticality task must be aborted at its deadline or (more practically) its priority must be reduced to a background level. They then derive safe analysis. Niz et al. subsequently modified the enforcement rule in their model to remove the problem and improved its performance [483, 484]. Progress-aware Dynamic Slack Exploitation in MCS is examined further by Kritikakou and Skalis-tis [392].

While slack is usually generated by tasks not executing for their full budget, it is also produced by the arrival of jobs being less frequent than anticipated in the worst-case. Neukirchner et al. [477, 478] adapt and extend a number of schemes for monitoring activation patterns. Their multi-mode approach is proved to be safe (no false negatives) and efficient (few false positives). Hu et al. [315] also consider budget management, and produce an effective scheme for minimising the overheads associated with slack management.

For a dual-criticality system $C(LO)$ values must, of course, be known. Once schedulability has been established however, it is possible to derive [547], using sensitivity analysis [111, 512], a scaling factor F ($F > 1$) such that the system remains schedulable with all $C(LO)$ values replaced by $F \cdot C(LO)$. Using these scaled values at run-time will increase the robustness of the system, as the LO -criticality tasks will be able to execute for a greater time before a criticality change is triggered. Scaling can also be applied to the $C(HI)$ values. Volp et al. [612] look at an alternative means of obtaining $C(LO)$ and $C(HI)$ values; they do not consider them to be estimates of worst-case execution time, but budgets set by some design optimisation process. Sensitivity analysis is also addressed by Santinelli and Guo [544].

As scaling involves changing a task's computation time, and computation time influences priority assignment, it is possible to extend this approach by also allowing priorities to change as the system is made more robust [132]. A more dynamic budget management scheme is used by Gu and Easwaran [271, 273] to postpone criticality level mode changes within the context of the EDF-VD scheme (see Section 3.3). Hu et al. [312] also look to postpone the criticality mode change by tighter control over the available slack.

Sciandra et al. [553] are extending and applying scaling factors to intelligent transport systems. Issues of robustness are also addressed by Herman et al. [302].

3.2.3 Period transformation

As Vestal noted [607], an older protocol *period transformation* [556, 557] (PT), is also applicable to the mixed criticality scheduling problem. Period transformation

splits a task with period T and computation time C into two (or more) parts so that the task now has the parameters $T/2$ and $C/2$. Assuming all tasks have deadlines equal to their periods, the application of the optimal rate monotonic priority assignment scheme [434] will increase the relative priority of all transformed tasks. If all high criticality tasks are transformed so that their transformed periods are shorter than all low criticality tasks then the rate monotonic algorithm will deliver partitioned (i.e. criticality monotonic) priorities. All high criticality tasks will have priorities greater than all lower criticality tasks. The scheme can easily be extended to task sets with constrained deadlines ($D < T$). However, the scheme does introduce extra overheads from the increased number of context switches, and these could be excessive if there are low criticality tasks with short deadlines. A simple example of a period transformed task would be one with $T = D = 16$, $C(HI) = 8$ and $C(LO) = 4$; this task could be transformed to one with $T = D = 4$ and $C = 2$. Note, this is $C(HI)/4$, not $C(LO)/4$. The computation time is such that if the task executes according to its *HI*-criticality parameter it will take four invocations of the transformed task to complete, but if the *LO*-criticality assumption is valid it will only take two.

If overheads are ignored then Period Transformation performs well. Baruah and Burns postulate [79] (and prove for two tasks) that this is primarily due to the inherent property of PT to deliver tasks sets with harmonic periods (that are then more likely to be schedulable). It does not seem that PT is of specific benefit to MCS.

To split the code of a task, either a static code transformation process must be used or the run-time must employ an execution-time server. With code transformation, the programmer must identify where in the code the split should be made. This does not lead to good code modularisation and is similar to the problems encountered when functions must to be split into short sections so that they can be ‘packed’ into the minor cycles of a cyclic executive [145]. There is also the problem of OS locks being retained between slices of the code; making the protected resource unavailable to other tasks.

With a dual-criticality task such as the one in the example above the point at which the task can be assumed to have executed for two units of time is itself criticality dependent. This to all intents and purposes makes code transformation impractical. Therefore, if the code is not to be changed then a run-time server must be used to restrict the amount of computation allowed per release of the (transformed) task. In practice this means that:

- Without PT, *LO*-criticality tasks may have high priorities and hence their execution times must be monitored (and enforced); *HI*-criticality tasks must also be monitored as they may need to trigger a criticality change if they

execute for more than $C(LO)$ thereby triggering the abandonment of *LO*-criticality tasks.

- With PT, *LO*-criticality tasks have the lower priorities and hence they do not need to be monitored, *HI*-criticality tasks must be monitored to enforce the per release budget.

In general, there is less run-time intervention with PT. But recall there is considerably more task switching overhead if the periods of all *HI*-criticality tasks are reduced to less than all *LO*-criticality task periods.

For multiple criticality levels a number of transformations may be required to generate a criticality monotonic ordering [237]. For example if there are three tasks (H, M, and L) with criticality levels implied by their names, and periods 5, 33 and 9. Then first M must be divided by 11 to get a period of 3 (so less than 9), but then H must be divided by 5 to move it below the new value for M. As a result the transformed periods become 1, 3 and 9. It also seems that the theoretical benefit of PT diminishes with an increased number of criticality levels [237].

An alternative to the fixed priority scheduling schemes described above, is that proposed by Li et al. [426]. They assume there are a small number of supported priority levels, and show how a resource-efficient scheduler can be derived from an initial unprioritised schedule.

3.3 EDF Scheduling

The first paper to consider MCS with EDF scheduling was Baruah and Vestal [95] in 2008. Park and Kim [496] later introduced a slack-based mixed criticality scheme for EDF scheduled jobs which they called CBEDF (Criticality Based EDF). In essence they use a combination of off- and on-line analysis to run *HI*-criticality jobs as late as possible, and *LO*-criticality jobs in the generated slack. In effect they are utilising an older protocol developed by Chetto and Chetto [161] for running soft real-time tasks in the ‘gaps’ produced by running hard real-time tasks so as to just meet their deadlines.

A more complete analysis for EDF scheduled systems was presented by Ekberg and Yi [220, 276]. They mimicked the FP scheme by assigning two relative deadlines to each high criticality task. One deadline is the defining ‘real’ deadline of the task, the other is an artificial earlier deadline that is used to increase the likelihood of high criticality tasks executing before low criticality ones. At the point that the criticality of the system changes from low to high (due to a task exceeding its low criticality budget), all low criticality tasks are abandoned and the high criticality tasks revert to their defining deadlines. They demonstrate a clear improvement over previous schemes [277]. Later work [221] generalises the model to include

changes to all task parameters and to incorporate more than two criticality levels. Tighter analysis is provided by Easwaran [215], although it is not clear that the method will scale to more than two criticality levels. Further improvements are presented by Yao et al. [633]. They use an improved schedulability test for EDF (a scheme called QPA [642]), and a genetic algorithm (GA) to find better artificial deadlines.

A similar scheme was presented by Baruah et al. [74,76], called EDF-VD (EDF - with virtual deadlines). Again for a dual-criticality system, *HI*-criticality tasks have their deadlines reduced (if necessary) during *LO*-criticality mode execution. All deadlines are reduced by the same factor. They demonstrate both theoretically and via evaluations that this is an effective scheme. Note, however, that this scheme is not as general as those reported above [215,220,276]. In these approaches a different reduction factor is used for each task. Nevertheless the use of a single value does allow schedulability bounds to be derived (see Section 7). An intermediate approach that uses just two scaling factors is provided by Masrur et al. [449]; there motivation being to develop an efficient scheme that could be used at run-time. In later work [96] Baruah has generalised the underlying MCS model to include criticality-specific values for period and deadline as well as WCET. EDF-VD was further improved by Gu and Easwaran [272] by the development of a new scheduling test.

EDF scheduling of MCS is also addressed by Lipari and Buttazzo [433] using a reservation-based approach. Here sufficient budget is reserved for the high criticality tasks, but if they only make use of what is assumed by their low criticality requirements then a set of low criticality tasks can be guaranteed. Again only two criticality levels are assumed. In effect low criticality tasks run in capacity reclaimed from high criticality tasks. Deadlines for the high criticality tasks are chosen to maximise the amount of capacity reclaiming.

A different approach to using spare capacity was derived by Su et al. [583,584] by exploiting the *elastic task model* [147] in which the period of a task can change. They propose a minimum level of service for each *LO*-criticality task τ_i that is defined by a maximum period, T_i^{max} . The complete system must be schedulable when all *HI*-criticality tasks use their $C(HI)$ values and all *LO*-criticality tasks use their $C(LO)$ and T^{max} values. At run-time if *HI*-criticality tasks use less than their full *HI*-criticality entitlement then the *LO*-criticality tasks can run more frequently. They demonstrate that for certain parameter sets their approach performs better than EDF-VD.

Alternative analysis for EDF scheduled MCS is presented by Mahdiani and Masrur [445,446], and Santinelli et al. [542]. The latter make use of multiple demand-bound curves to allow sensitivity analysis to be derived that can be applied to the trade-off between resource usage and schedulability (within the con-

text of MCS). Feasibility analysis is provided by Chwa et al. [167, 168]. Schmidt and García-Ortiz [550] use non-uniform deadline scaling to improve the quality of service of EDF scheduled systems.

3.4 Shared Resources

With mixed criticality systems it is not clear to what extent data should flow between criticality levels. There are strong objections to data flowing from low to high criticality applications unless the high criticality component is able to deal with potentially unreliable data [555] – this happens with some security protocols [110]. Even with data flowing in the other direction there remains the scheduling problem of not allowing a high criticality task to be delayed by a low criticality task that has either locked a shared resource for longer than expected or is executing at a raised priority ceiling level for too long.

Sharing resources within a criticality level is however a necessary part of any usable tasking model. In single criticality systems a number of priority ceiling protocols have been developed [53, 559]. These are beginning to be assessed in terms of their effectiveness for mixed criticality systems. Burns [125] extends the analysis for fixed priority systems by adding criticality specific blocking terms into the response-time analysis, and notes that the original form of the priority ceiling protocol (OPCP) [559] has some useful properties when applied to MCS. Resources can be easily partitioned between criticality levels and starvation of *LO*-criticality tasks while holding a lock on a resource can be prevented. With AMC-OPCP, a task can only suffer direct blocking if a resource is locked by a lower priority task of the same criticality.

Rather than use a software protocol, Engel [225] employs Hardware Transactional Memory to roll back any shared object to a previous state if a *LO*-criticality task overruns its budget while accessing the object.

For EDF-based scheduling Zhao et al. [649, 652] attempt to integrate the Stack Resource Protocol (SRP) [53] and Preemption Threshold Scheduling [617] with approaches to EDF scheduling that involve tasks having more than one deadline. This is not straightforward as these schemes assume that relative deadlines are fixed.

Alternative approaches are proposed by Lakshmanan et al. [396] by extending their single processor zero slack scheduling approach [482] to accommodate task synchronisation across criticality levels for fixed priority systems. They define two protocols: PCIP (Priority and Criticality Inheritance Protocol) and PCCP (Priority and Criticality Ceiling Protocol). Both of these contain the notion of criticality inheritance. This notion is also used by Zhao et al. [651] in their HLC-PCP (Highest-Locker Criticality Priority Ceiling Protocol) which they apply to the

AMC scheduling scheme (see Section 3.2.1). For a dual criticality system they define three modes of execution, the usual two plus an intermediate mode which covers the time during which *LO*-criticality tasks are allowed to continue to execute if they are holding a lock on a resource that is shared with a *HII*-criticality task.

A more systematic scheme is proposed by Brandenburg [119]. Here all shared resources are placed in *resource servers* and all access to these servers is via a MC-IPC protocol. As a result only these servers and the support for the MC-IPC protocol have to be developed to the highest criticality level. Resource users can be of any criticality level, including non-critical. Data sharing within the context of the MC^2 architecture (see Section 4) is addressed by Chisholm et al. [163].

3.5 Static and Synchronous Scheduling

The move between criticality levels can be captured in a static schedule by switching between previously computed schedules; one per criticality level. This is explored by Baruah and Fohler [88]. Socci et al. [570, 572, 573] show how these Time-Triggered (TT) tables can be produced via first simulating the behaviour one would obtain from the equivalent fixed priority task execution. Their approach is improved upon by Behera and Bhaduri [101, 102] (their algorithm has lower computational complexity). Construction of the tables via tree search is addressed by Theis et al [592], and via the use of linear programming (LP) by Jan et al. [346]. Behera [99], more recently, added fault tolerance to the time-triggered approach. For legacy systems Theis and Fohler [591] show how an existing single table may be used to support MCS.

A particularly simple table driven approach is to use a cyclic executive, this is investigated by Burns et al. [80, 133, 141, 198, 236, 239, 240] for multiprocessor systems in which the change from minor cycle to minor cycle is synchronised as is the change from executing code of one criticality to that of another. Both global and partitioned approaches are investigated, as are systems that use less processors for the *HII*-criticality work than they do for the *LO*-criticality work [240]. Both LP and ILP based formulations are used to construct the cyclic executives.

A hyper-period optimisation algorithm is used to reduce the size of the static tables in the work of Zhou et al. [656, 657]. They also address the issue of reducing the run-time overheads with these partitioning schemes. A more dynamic, work conserving, allocation scheme for a time slotted architecture is proposed by Hebbache et al. [300]. The more formal problem of minimising the makespan on a static schedule is addressed by Novak et al. [487]. They consider non-preemptive tasks but multiple criticality levels.

The use of tables is extended to synchronous reactive programs by Baruah [65,

66]. Here a DAG (Directed Acyclic Graph), of basic blocks that execute according to the synchrony assumption, is produced that implements a dual-criticality program. The synchronous approach is also considered by Yip et al. [634] and by Cohen et al. [177]. The latter proving an application of mixed criticality from the railway industry, and an example of why data needs to flow between criticality levels.

3.6 Varying Speed Processors

Most analysis for MCS assumes a constant speed processor, but there are situations in which the speed of the processor is not known precisely (for example with asynchronous circuitry). Baruah and Guo [90] consider power issues that could lead to a processor having variable speed. As a processor slows down the execution time of the tasks increase. They simplify the model by assuming two basic speeds, normal and degraded. At the normal speed a scheduling table is used; at the degraded speed only *HI*-criticality jobs are executed and they use EDF. The authors have extended this work [91, 280, 282, 628] to include a more expressive model, issues of processor self-monitoring (or not), a probabilistic approach to performance variation, and fluid scheduling. They have also considered system which have both uncertainty in execution times and processor speed [283]; and they have addressed multiprocessor systems [561].

Voltage scheduling, and thereby variable speed computation, is used by Huang et al. [325, 326] to respond to a temporal overload – if a $C(HI)$ value is exceeded and could lead to a *LO*-criticality task missing its deadline then energy is utilised to enable the processor to reduce computation times. Overall, their approach aims to reduce the system’s expected energy consumption. Taherin et al. [586] present some alternative DVFS schemes and compare their results with those of Huang. DVFS management is also addressed by Haririan and Garcia-Ortiz [296] in their provision of a simulation framework for power management.

A link between imprecise (and precise) executions and varying speed processors is made by Sruto et al. [106, 578] in the context of EDF-VD scheduling.

3.7 Semi-Clairvoyant Scheduling

All of the models described above that involve a mode change between normal and *HI*-criticality behaviour assume that the earliest time that a mode change can be triggered is when a job from a *HI*-criticality task has executed for duration $C(L)$ without signalling completion. An alternative model introduced by Agrawai et al. [9] assumes that as a job arrives it can indicate whether it will ‘over-run’. It can do this from knowledge of the state of the system at the time of its

arrival. They show that considerable advantage can be obtained from this assumption. Semi-Clairvoyant scheduling is also addressed by Burns and Davis [139]. An extension of this work is to look at the graceful degradation of Semi-Clairvoyant scheduling [59]. A further extension is reported by Radulescu et al. [514]. The combination of Semi-Clairvoyant scheduling, Adaptive Mixed Criticality (AMC) scheduling and Preemption Threshold scheduling is addressed by Zhao et al. [654]. Jiang et al. [353] utilise the notion of ‘Quarter-Clairvoyance’ in I/O-Driven MCS.

4 Multiprocessor Analysis

The first paper to discuss mixed criticality within the context of multiprocessor or multi-core platforms was by Anderson et al. [28] in 2009 and then extended in 2010 [464]. Five levels of criticality were identified; going from level-A (the highest) to level-E (the lowest). They envisaged an implementation scheme, which they call MC^2 , that used a cyclic executive (static schedule) for level-A, partitioned preemptive EDF for level-B, global preemptive EDF for levels C and D and finally global best-effort for level-E. They considered only harmonic workloads but allowed slack to move between containers (servers). Each processor had a container for each criticality level, and a two-level hierarchical scheduler (see Section 5.4). Later work from this group [164, 302] evaluates the OS-induced overheads associated with multiprocessor platforms. They also experimented with isolation techniques for LLC (last level cache) and DRAM. And have demonstrated, using MC^2 , the benefits of having different isolation techniques for each criticality level [379, 380]. The support for mode changes within MC^2 is considered by Chrisholm [162]. This MC^2 framework is also used by Bommert [117] to support segmented mixed criticality parallel tasks; and by Bakita et al. [54] to include simultaneous multithreading (SMT).

In the remainder of this section we first look at task allocation (with global or partitioned scheduling), then consider analysis and finally communications and other systems resources. We note that there has also been work on implementing mixed-criticality synchronous systems on multiprocessor platforms [67].

4.1 Task Allocation

The issue of allocation was addressed by Lakshmanan et al. [397] by extending their single processor slack scheduling approach [482] to partitioned multiprocessor systems employing a Compress-on-Overload packing scheme. Allocation in a distributed architecture was addressed by Tamas-Selicean and Pop [587–590] in the context of static schedules (cyclic executives) and temporal partitioning. They

observed that scheduling can sometimes be improved by increasing the criticality of some tasks so that single-criticality partitions become better balanced. This increase comes at a cost and so they employ search/optimisation routines (Simulated Annealing [247, 588] and Tabu [336, 337, 587, 589]) to obtain schedulability with minimum resource usage. Search routines, this time GAs (Genetic Algorithms), are also used by Zhang et al. [644] to undertake task placement in security-sensitive MCS. Their objective is to minimise energy consumption “while satisfying strict security and timing constraints”. A toolset to aid partitioning is provided by Alonso et al. [24].

A more straightforward investigation of task allocation was undertaken by Kelly et al [375]. They considered partitioned homogeneous multiprocessors and compared first-fit and best-fit approaches with pre-ordering of the tasks based on either decreasing utilization or decreasing criticality. They used the original analysis of Vestal to test for schedulability on each processor, and concluded that in general first-fit decreasing criticality was best. For heterogeneous multiprocessors Awan et al. [47] propose a mapping scheme that is energy efficient. Energy efficient partitioning is also addressed by Guasque et al. [278].

A comprehensive evaluation of many possible schemes is reported by Rodriguez et al. [533]. They consider EDF scheduling and used the analysis framework of EDF-VD (see Section 3.3). One of their conclusions is the effectiveness of a combined criticality-aware scheme in which *HI*-criticality tasks are allocated Worst-Fit and *LO*-criticality tasks are allocated using First-Fit; both with Decreasing Density. The same result is reported by Gu et al. [268]. They additionally note that if there are some very ‘heavy’ *LO*-criticality tasks (i.e. high utilisation or density) then space must be reserved for them before the *HI*-criticality tasks are allocated. Partitioning with EDF-VD is also addressed by the work of Han et al. [290]. Ramanathan and Easwaran [516] demonstrate that an effective partitioning scheme can be derived from evenly distributing the differences between *HI*-criticality and *LO*-criticality utilisation. Their results being applicable to EDF-VD and fixed-priority AMC.

A global allocation scheme for MCS is proposed by Gratia et al. [260, 262]. They adapt the RUN scheduler [531], which uses a hierarchy of servers, to accommodate *HI* and *LO* criticality tasks. The latest version of their scheduler (GMC-RUN) [261] has been extended to deal with more criticality levels. In a different study, Koc et al. [382] look to improve the reliability of the highest criticality tasks running on a hardware/software (HW/SW) co-design environment. Muttillio et al. [468] also consider HW/SW co-design to support Xtratum-based SW partitions.

Between fully partitioned and fully global scheduling is the class of schemes termed *semi-partitioned*. This is being addressed by Bletsas et al. [39, 41, 114, 115]

and Al-Bayati et al. [14]. The latter work uses two allocations for their two criticality modes. *HI*-criticality tasks do not migrate. During a mode change, carry-over *LO*-criticality jobs are dropped and new *LO*-criticality jobs executing on a different processor are given extended deadlines/periods (i.e. they utilise the elastic task model). A different approach is taken by Xu and Burns [625]; here a mode change on one processor results in *LO*-criticality jobs migrating to a different processor that has not suffered a criticality mode change. No deadlines are missed. If all processors suffer such a mode change then at least the timing needs of all *HI*-criticality tasks are protected. Naghavi et al. [472] also allow *LO*-criticality tasks to migrate. Zhang [640] considers semi-partitioning within the context of cyclic executive execution; and Wang et al. [616] uses the techniques in 6G-based edge computing. Qian et al. [QIAN2021] consider the allocation problem with the semi-partitioned approach. And Huang et al. [330] consider some EDF-based semi-partitioning schemes. Further consideration of the allocation problem is provided by Yang et al. [627].

A different approach, that aims to maximise the benefits of partitioning and global scheduling, is that based on clusters. A multi-core platform is statically partitioned into a number of clusters, within a cluster tasks execute ‘globally’. Ali and Kim [20] investigate a scheme in which small clusters are used when the system is in the *LO*-criticality mode, but larger clusters are employed when the system moves to the *HI*-criticality mode. Nagalakshmi and Gomathi [470] also use clusters but within a EDF-scheduled fully partitioned approach. Within each cluster is a single *HI*-criticality task and one or more *LO*-criticality tasks. As a result the impact of a *HI*-criticality task executing beyond its $C(LO)$ value is limited to just those *LO*-criticality tasks within the same cluster.

With dual-criticality fault tolerant systems, a scheme in which high criticality tasks are replicated (duplicated) while low criticality tasks are not is investigated by Axer et al. [48] for independent periodic tasks running on a MPSoC (multi-processor system-on-chip). They provide reliability analysis that is used to inform task allocation.

A more theoretical approach (i.e. it is not directly implementable) is proposed by Lee et al. [408] with their MC-Fluid model. A fluid task model [85, 308] executes each task at a rate proportional to its utilisation. If one ignores the cost of slicing up tasks in this way then the scheme delivers an optimal means of scheduling multiprocessor platforms. To produce a mixed criticality version of the fluid task model the fact that tasks do not have a single utilisation needs to be addressed. Lee et al. [408, 409] do this and they also produce an implementable version of the model that performs well in simulation studies (when compared with other approaches). Baruah et al. [60, 86] derived a simplified fluid algorithm which they call MCF. Two further algorithms, MC-Sort and MC-slope, are proposed by Ra-

manathan and Easwaran [515, 518].

Fluid scheduling is also employed by She et al. [560] in, what they term, precise MC scheduling. In this work the number of processors available increases when necessary to ensure that no *LO*-criticality tasks miss their deadlines.

For static scheduling schemes, such as a FlexRay-based ECU network, Roy et al. [534] propose a scheme they call *GoodSpread* to spread out the use of the QoS resources.

All the above work is focussed on standard single threaded tasks. In addition there has been some studies on parallel tasks and MCS – see Liu et al. [422, 423, 437], Pathan [500], Agrawal and Baruah [5], Gill et al. [251] and Bhuiyan et al. [108, 109].

4.2 Schedulability Analysis

For globally scheduled systems Li and Baruah [421] take a ‘standard’ multiprocessor scheme, fpEDF [62] and combine it with their EDF-VD approach (see Section 3.3). Evaluations indicate that this is an effective combination. Extensions of this work [84] compare the use of partitioning or global scheduling for MCS. Their interim conclusion is that partitioning is by far the most effective approach to adopt.

Notwithstanding this result, Pathan derives [497] analysis for globally scheduled fixed priority systems. They adopt the single processor approach [81] (see Section 3.2) and integrate this with a form of analysis for multiprocessor scheduling that is amenable to optimal priority ordering, via Audsley’s algorithm [34]. They demonstrate the effectiveness of their approach (by comparing success ratios). Jung and Lee subsequently improved on this analysis [363]. The global scheduling scheme of EDZL (Earliest Deadline first until Zero Laxity) is also adapted for MCS by Jung et al. [51, 362]. They show how it can be used with EDF-VD and fixed-priority scheduling.

A different and novel approach to multi-core scheduling of MCS is provided by Kritikakou et al. [388, 391]. They identify that a *HI*-criticality task will suffer interference from a *LO*-criticality task running on a different core due to the hardware platform’s use of shared buses and memory controllers etc.. They monitor the execution time of the *HI*-criticality task and can identify when no further interference can be tolerated. At this point they abort the *LO*-criticality task even though it is not directly interfering. An implementation on a multi-core platform demonstrated effective performance of their scheme [391]. They subsequently improved on this static approach by utilising a dynamic version that reduces the time spent in the controller [389].

Extensions to deal with precedence constraints were given by Socci et al. [571] but only for jobs (not tasks). A full pipeline scheme is considered by de Niz et

al. [197].

4.3 Communication and other Resources

With a more complete platform such as a multiprocessor or System on Chip (SoC), perhaps with a NoC (Network-on-Chip), more resources have to be shared between criticality levels. The first design issue is therefore one of partitioning (as addressed above), how to ensure the behaviour of low criticality components does not adversely impact on the behaviour of higher criticality components. Pellizzoni et al. [505] in 2009 was the first to consider the deployment of mixed criticality systems (MCS) on multi-core and many-core platforms. They defined an Architectural Analysis and Design Language (AADL), a form of ADL (Architectural Description Language), for mixed criticality applications that facilitates system monitoring and budget enforcement of all computation and communication. Later Obermaisser et al. [490, 491] introduce a system model with gateways and end-to-end channels over hierarchical, heterogeneous and mixed criticality networks.

For a bus-based architecture it is necessary to control access to the bus so that applications on one core do not impact unreasonably on applications on other cores (whether of different or indeed the same criticality level). Pellizzoni et al. [506] show that a task can suffer a 300% increase in its worst-case execution time due to memory access interference even when it only spends 10% of its time on fetching from external memory on an 8-core system. To counter this, Yun et al. [636] propose a memory throttling scheme for MCS. Kotaba et al [386] also propose a monitoring and control protocol to prevent processes flooding any shared communication media be it a bus or network. Kritikakou et al. [390] consider a scenario in which there are a few critical tasks that can suffer indirect interference from many lower critical tasks. They attempt to allow as much parallelism as possible commensurate with the critical tasks retaining their temporal validity. Hassan and Patel [298] claim an improved bus arbitrator, called Carb, that is more criticality aware. Bounding the interference that a safety-critical task can suffer from lower criticality tasks using the same shared communication resources on a multi-core platform is also addressed by Nowotsch et al. [488]. Freitag et al. [242] utilise a fully isolated model (each core only has tasks of only one criticality), those core that have *LO*-criticality tasks are slowed down (or even stopped) if their measured interference on the *HI*-criticality cores is above statically derived bounds.

Within the time-triggered model of distributed computation and communication a mixed criticality system is often viewed as one that has both time-triggered and event-triggered activities, also referred to as synchronous and asynchronous [511, 579]. The time-triggered traffic is deemed to have the highest criticality, the event-triggered traffic can be either just best-effort or can have some level of

assurance if its impact on the system is bounded; what Steiner [579] calls *rate-constrained*. Protocols that support this distinction can be supported on networks such as TTEthernet. Another TDMA-based approach, though this time built into the Real-Time Ethernet protocol, is proposed by Carvajal and Fischmeister in their open-source framework, *Atacama* [151]. Cilku et al. [171] describe a TDMA-based bus arbitration scheme. Novalk et al. [485] propose a scheduling algorithm for time-triggered traffic that minimises jitter while allowing *HI*-criticality messages to be re-transmitted (following failure) at the expense of *LO*-criticality messages (which are abandoned). They also [486] consider how to produce an effective static schedule when there are unforeseen re-transmissions (for two and three levels of criticality). Analysis of AFDX (Avionics Full Duplex Switched Ethernet) within the context of MCS is provided by Finzi et al. [235].

A model that does not preclude concurrent transmissions, but limits the number of clashes that need be tolerated is provided by Agrawal et al. [8].

A reconfigurable SDRAM controller is proposed by Goossen et al. [257] to schedule concurrent memory requests to the same physical memory. They also use a TDMA approach to share the controller's bandwidth. A key aspect of this controller is that it can adapt to changes in the run-time characteristics of the application(s). For example, a criticality mode change which should result in more bandwidth being assigned to the higher criticality tasks can be accommodated by what the authors call a *use-case switch*. Criticality aware DRAMs are also addressed by Jalle et al [345] in the context of a Space case study in which there are two criticality levels: 'control' and 'payload'.

Virtual DRAMs are adapted by Ecco et al. [217] to isolate critical tasks (which are guaranteed) from non-critical tasks that, although not guaranteed, do perform adequately. Each virtual device represents a group of DRAM banks supports one critical task and any number of non-critical tasks. All critical tasks run on dedicated cores, and hence the only potential source of inter-criticality interference is from the interconnection fabric (bus). By use of virtual devices, the critical tasks benefit from interference-free memory access. DRAMs are also the focus of the work by Hassen et al. [299], Awan et al. [40] and Guo and Pellizzon. [279].

Kim et al. [377] propose a priority-based DRAM controller for MCS that separates critical and non-critical memory accesses. They demonstrate improved performance for the non-critical traffic. Note this work is focussed on supporting critical and non-critical traffic on the same memory banks (rather than mixed-criticality). A similar approach and result is provided by Goossens et al. [256] with their open-page policy.

Giannopoulou et al. [247, 248] use a different time-triggered approach. They partition access to the multiprocessor bus so that at any time, t , only memory accesses from tasks of the same criticality can occur. This may introduce some in-

efficiencies, but it reduces the temporal modelling of a mixed criticality shared bus to that of a single criticality shared bus. The latter problem is not, however, straightforward (but is beyond the scope of this review). In later work they generalise their approach by introducing the notion of isolation scheduling [322]. They also demonstrate the implementation of their approach on a Layray MPPA-256 many-core platform [601].

The problems involved in using a shared bus has lead Giannopoulou et al. to also include a Network-on-Chip (NoC) in their later work [250]. Burns et al. [80, 133, 141, 239] apply a ‘one criticality at a time’ approach to MCS scheduled by the use of a Cyclic Executive; they considered both partitioned and global allocation of jobs to frames.

Tobuschat et al. [599, 600] have developed a NoC explicitly to support MCS. Their IDAMC protocol uses a *back suction* technique [200] to maximise the bandwidth given to low (or non) critical messages while ensuring that high-criticality messages arrive by their deadlines. The more familiar wormhole routing [481] scheme for a NoC has been expanded by Burns, Harbin and Indrusiak [142, 340] to provide support for mixed criticality traffic. Response-time analysis, already available for such protocols [562]²⁴, is augmented to allow the size and frequency of traffic to be criticality aware. Wormhole routing is also used by Hollstein et al [307] to provide complete separation of mixed-criticality code; they also support run-time adaptability following any fault identified by a Built-In Self Test. Another wormhole router (DAS - double arbiter and switching) is described by Dridi et al. [210–212]; they use wormhole for the *LO*-criticality traffic, but store-and-forward for the *HI*-criticality messages.

On-chip networks require reliable/trusted interfaces to prevent babbling behaviour [122]; Ahmadian and Obermaisser [12] describe how to provide this via a time-triggered extension layer for a mixed-criticality NoC. Dynamic and adaptive control of a mixed-criticality NoC is considered by Kostrzewa et al. [384, 385]. Other work focuses on COTS RTOS solutions [38, 229]. Control over I/O contention via an Ethernet-based criticality-aware NoC is advocated by Abdallah et al. [1]. A focus on NoC security, in which *HI*-criticality messages need more protection than *LO*-criticality is taken by Papastefanakis et al. [495].

An alternative to using a NoC for all traffic (task to task and task to off chip memory) is proposed by Audsley [35, 253]. They advocate the use of a separate memory hierarchy to link each core to off chip memory. A criticality aware protocol is used to pass requests and data through a number of efficient multiplexers. If the volume of requests and data is criticality dependent then analysis similar to

²⁴This analysis has been shown to be optimistic in some circumstances, see discussion by Xiong et al. [624].

that used for processor scheduling can be used on this memory traffic. The separation of execution-time from memory-access time is explored by Li et al. [425,428]. They demonstrate that this distinction improves schedulability.

Controller Area Network (CAN) [252] is a widely used network for real-time applications, particularly in the automotive domain. It has been the subject of considerable attention with Response-Time Analysis derived [193] for what is, in essence, a fixed priority non-preemptive protocol. The use of CAN in mixed criticality applications has been addressed by Burns and Davis [135]. In this work it is the period of the traffic flows and the fault model that changes between criticality levels. A MixedCAN protocol was developed that makes use of a Trusted Network Component that polices the traffic that nodes are allowed to send over the network. Evaluations are used to show the advantages of using MixedCAN rather than a criticality agnostic approach. However the paper, in keeping with many other publications, only considered dual-criticality systems.

Herber et al. [301] also addressed the CAN protocol. They replaced the physical network controller with a set of virtual controllers that facilitate spatial separation. A weighted round robin scheduler is then used to give temporal isolation. Their motivation is to support virtualisation in an automotive platform. They do not however use criticality specific parameters for the different applications hosted on the same device. Nager et al. [471] show how CAN can be used in a more flexible way to support MCS.

Other protocols that have been considered in terms of their support for mixed criticality systems include FlexRay [258] and switched Ethernet [181, 182]. In the latter work, a change in criticality mode is broadcast to the entire system by adding a new field to the IEEE 1588 PTP (Precision Time Protocol). The work by Lee et al. [411, 412] makes use of SDN (Software-Defined Networking) architecture on switched Ethernet.

George et al. [244] assume the speed of the wireless communication media varies over time. Each node monitors this speed and only send messages that are compatible with its current estimate. Offline analysis partitions the messages according to criticality and required speed.

A further communication protocol is addressed by Addisu et al. [4]. They consider JPEG2000 Video streaming over a wireless sensor network. With such a network the available bandwidth varies in an unpredictable way. They propose a bandwidth allocation scheme that is criticality aware. A wireless protocol (WirelessHART) is also used by Jin et al. [356, 357] to support delay analysis with fixed priority scheduling for sensor networks. A hybrid scheduling approach for sensor nodes with mixed-criticality tasks is investigated by Micea et al. [460].

AirTight [143, 293, 295] is a wireless protocol that has been designed specifically to support mixed-criticality traffic. High criticality packets must be able to

survive a greater intensity and frequency of faults than lower criticality packets. This is modelled by means of criticality-aware fault models. Carvalho et al. [152] also address low power wide area network technologies and show how redundant transmissions within LoRaWAN can be improved for mixed-criticality IoTs.

A means of modelling an entire end-to-end vehicular embedded system including various forms of networking is provided by Mubeen et al. [466].

A novel scheduling approach (triangle scheduling) for mixed-criticality messages is proposed by Dürr et al. [213]. The adaptation of synchronisation protocols such as MSRP (Multiprocessor Stack Resource Policy) to multiprocessor platforms and mixed-criticality software scheduled using partitioned EDF is addressed by Han et al. [291].

Mixed-criticality Industrial Data Scheduling on 5G NR (new radio) is addressed by Jin et al. [355].

5 Links to other Research Topics

5.1 Hard and Soft Tasks

Although the label ‘Mixed Criticality Systems’ is relatively new, many older results and approaches can be reused and reinterpreted under this umbrella term. In particular dual-criticality systems in which there are hard and soft tasks combined has been studied since at least 1987 [415]. Hard tasks must be guaranteed. Soft tasks are then given the best possible service. But soft tasks are usually unbounded in some sense (either in terms of their execution time or their arrival frequency) and hence they must be constrained to execute only from within *servers* (execution-time servers). Servers have bounded impact on the hard tasks. Since 1987 a number of servers have been proposed. The major ones for fixed priority systems being the Periodic Server, the Deferrable Server, the Priority Exchange Server (all described by Lehoczky et al. [415]), and the Sporadic Server [575]. The ability to run soft tasks in the slack provided by the hard tasks is also supported by the Slack Stealing schemes [186, 195, 414, 522] which have similar properties to servers. These all have equivalent protocols for dynamic priority (EDF) systems; and some EDF specific ones exist such as the Constant Bandwidth server [431].

Since their initial specification, analysis has improved and means of allocating and sharing capacity between servers have been investigated (see for example [103, 104, 637]). However, these results on servers (and examples of how they can be implemented in Operating Systems and programming languages) are generally known (see standard textbooks [145, 148, 438]), hence they are not reviewed in more detail here. Note however, that standard servers only deal with the isolation/partitioning aspect of MCS. To support sharing (of resources) there must be some

means of moving capacity from the under utilised servers of high criticality tasks to the under provisioned servers of lower criticality tasks. The Extended Priority Exchange server [575] as well as work on making use of gain time, show how this can be achieved.

Another way of maximising the slack available for soft tasks is the dual-priority scheme [146, 196]. Here there are three bands of priority. The soft tasks run in the middle band while the hard tasks start in the lower band but are promoted to the higher band at the latest possible time commensurate with meeting their deadlines. So hard tasks execute when they have to, or when there are no soft tasks, soft tasks run otherwise.

Run-time adaptability for MCS has been addressed by Hu et al. [312–314, 316]. They present an approach to adaptively shape at runtime the inflow workload of *LO*-criticality tasks based on the actual demand of *HI*-criticality tasks. This improves the QoS of *LO*-criticality tasks; but it not clear what level of guarantee is provided for these tasks. An alternative scheme, with the same aim, is given by Hikmet [305]. A QoS focus is also taken by Vaidhun et al. [604] with respect to pervasive systems. Schlatow et al. [549] propose a self-aware budget control system to manage run-time variability in resource usage. Monitoring and control is also the focus of the work presented by Loche et al. [440].

Awan et al. [45] consider the use of periodic servers for uniprocessor systems. They consider how server budgets can be dynamically adjusted in the event of a mode change.

5.2 Fault Tolerant Systems (FTS)

Fault tolerant systems typically have means of identifying a fault and then recovering before there is a system failure. Various recovery techniques have been proposed including exception handling, recovery blocks, check-points, task re-execution and task replication. If, following a fault, extra work has to be undertaken then inevitably some existing work will need to be abandoned, or at least postponed. And this work must be less important than the tasks that are being re-executed. It follows that many fault tolerant systems are, in effect, mixed criticality.

To identify a fault, timeouts are often used. A job not completing before a deadline is evidence of some internal problem. Earlier warning can come from noting that a job is executing for more than its assumed worst-case execution time. Execution-time monitoring is therefore common in safety critical systems that are required to have at least some level of fault tolerance. Again this points to common techniques being required in FTS and MCS.

As noted earlier, in the discussion on CAN (Section 4.3), a fault model can be

criticality dependent [135] – a task may, for example, be required to survive one fault if it is mission critical, but two faults if it is safety critical. The difference between the assumed computation times at different criticality levels may be a result of the inclusion or not of recovery techniques in the assumed worst-case execution time of tasks.

Although there is this clear link between FTS and MCS there was not initially much work published that directly addresses fault-tolerant mixed criticality systems. Exceptions being work by Huang et al. [328, 329], a paper by Pathan [498] that focuses on service adaptation and the scheduling of fault-tolerant MCS, and a four-mode lockstep model developed by Al-Bayati et al. [13] (the requirement for lockstep execution is relaxed in later work [150]). This idea is also addressed by Kempf et al. [376].

Work by Thekkilakattil uses Zonal Hazard Analysis and Fault Hazard Analysis [594] and Error-Burst models [593] to deliver both flexibility and real-time guarantees for the most critical tasks. Thekkilakattil et al. [595] also considers the link between MCS and the tolerance of permanent faults. Lin et al. [429] attempt to integrate mixed criticality with the use of primary and backup executions in both of the two criticality modes they consider. Guo et al. [287] use the notion of failure probability to define a new scheduling scheme that accommodates failure dependent tasks.

Islam et al. [341], in a paper that preceded that of Vestal, looked at combining different levels of replication for different levels of criticality. Co-scheduling loosely-coupled replicas for MCS is shown to be effective by Rambo and Ernst [520, 521]. These authors also develop [519] a AIQ (Advanced Integrity Q-service) for a fault-tolerant NoC that can support MCS. Related work [365] looks at safe re-configuration of a many-core platform following a foreseen system failure.

Ahmadian et al. [11] invoke reconfiguration to provide for fault tolerance in the context of a time-triggered NoC based MCS. Alahmad and Gopalakrishnan [16] use what they term ‘isochronous’ execution to synchronise the execution of redundant versions of critical software over ‘regular’ and ‘safe’ processors. Improved response-time analysis for FT MCS is provided for multi-core systems by Choi et al. [165]. Kajmakovic et al. [371] proposed a soft error correction strategy called Redundant Parity (RP), which is itself an enhanced version of existing 1002 architectures.

Standby-Sparing (SS) is an approach to FT that uses two processors, every task runs on the primary processor (which uses voltage management to execute as slowly as feasible). If for any reason this version of the task fails an identical copy runs on the second (share) processor. This version runs as late as possible, with the processor running at maximum speed. CASS [647] is a criticality-aware version of SS in which the lower criticality tasks are less tolerant of faults. Naghavi et

al. [472] also use a spare processor for *HI*-criticality tasks so that they can survive permanent faults. *LO*-criticality tasks migrate when there is a failure.

As highlighted already in this review, many models and protocols for mixed criticality behaviour allow the system to move through a sequence of criticality modes. With a two mode system (*HI* and *LO*) the system starts in the *LO* mode in which all deadlines of all tasks are guaranteed, but can then transition to the *HI* mode in which only the *HI*-criticality tasks are guaranteed (and the *LO*-criticality tasks may actually be abandoned). It may, or may not, later return to the *LO* mode when it is safe to do so. Burns [126] attempts to compare these criticality mode changes with the more familiar system mode change, and concludes that the *LO* mode behaviour should be considered to be the ‘normal’ expected behaviour. A move away from this mode is best classified as a fault; with all other modes being considered forms of *graceful degradation*. Such a mode change is *planned but may never occur*. A move back to the fully functional *LO* mode is closest in nature to an *operational* (sometime known as exceptional) mode change.

5.3 Security

Many MCS papers have, either explicitly or implicitly, focused on issues of safety and reliability. Criticality can however also refer to security. Within this domain it is usual to have different security levels. And hence much of the extensive literature on security is relevant, but is out of scope of this review. Some work is nevertheless applicable to safety and security; for example the definition of a *separation kernel* for a system-on-chip built using a time-triggered architecture [618]. An overview of the security (and other) issues associated with MPSoCs is provided by Hassan [297].

Another paper directly linking security and MCS is from Baek and Lee [50]. They incorporate the cost of flushing between security levels in a non-preemptive version of AMC (for fixed priority scheduling). Woolley et al. [621] focus on security aspects of hierarchical scheduling of mixed safety and security-critical MCS.

Kadar et al. [364] propose a safety-aware method to integrate hardware-assisted control flow based security monitoring with ARM CoreSight into a MCS, and provide metrics to evaluate the trade-off between performance impact and security monitoring coverage.

5.4 Hierarchical Scheduling

One means of implementing a MCS where strong partitioning is needed between applications is to use a hierarchical (typically two-level) scheduler. A trusted base

scheduler assigns budgets to each application. Within each application a secondary scheduler manages the threads of the application. There are a number of relevant results for such resource containment schemes (e.g. [156, 190, 191, 432, 536, 630, 641]). Both single processor and multiprocessor platforms can support hierarchical scheduling.

Unfortunately when hierarchical scheduling is applied to MCS there is a loss of performance [395]. A simple interface providing a single budget and replenishment period (which is often associated with virtualisation or the use of a hypervisor [23]) is too inflexible to cater for a system that needs to switch between criticality levels. To provide a more efficient scheme, Lackorznschi et al. [395] propose ‘flattening’ the hierarchy by exposing some of the interval structure of the scheduled applications. They develop the notion of a scheduling context which they apply to MCS [611]. In effect they assign more than one budget to each ‘guest’ OS. As a result, applications that would otherwise not be schedulable are shown to utilise criticality to meet all deadlines. An alternative, but still flexible approach, is provided by Groesbrink et al. [265, 266]. They allow budgets to move between virtual machines executing on a hypervisor that is itself executing on a multi-core platform. The hypervisor controls access to the processor, the memory and shared I/O devices. Yet another scheme is described by Marinescu et al [447]; they are more concerned with partitioning as opposed to resource usage, but they do address distributed heterogeneous architectures. Hypervisors are also used by Cilku and Puschner [172], to give temporal and spacial separation on a multiprocessor platform, and Perez et al. [508] use a hierarchical scheduler to statically partition a wind power mixed criticality embedded system requiring certification under the IEC-61508 standard. A hypervisor for a mixed criticality on-board satellite software system is discussed by Salazar et al. [22, 541]. And one that uses and supports general control theory is addressed by Crespo et al [179, 180]. The issue of minimising the overheads of a hypervisor is addressed by Blin et al. [116].

Section 8.2 continues this discussion on hypervisors and virtualisation.

5.5 Cyber Physical Systems and the Internet of Things

In parallel with the development of a distinct branch of research covering MCS has been the identification of Cyber Physical Systems (CPS) as a useful focus for system development. Not surprisingly it has been noted that many CPS are also mixed criticality. For example Schneider et al. [551] note that many CPS are a combination of deadline-critical and QoS-critical tasks. They propose a layered scheme in which QoS is maximised while hard deadline tasks are guaranteed. Izosimov and Levholt [344] use a safety-critical CPS to explore how metrics can be used to map potential hazards and risk from top level design down to mixed criticality compo-

nents on a multi-core architecture. Issues of composability within an open CPS are introduced in the short paper by Lee et al. [403].

Maurer and Kirner [451] consider the specification of cross-criticality interfaces (CCI) in CPSs that define the level of communication allowed between ‘open’ subsystems/components. J. Lee et al. [402] also look at interfaces and composition for mixed criticality CPSs.

The link between the Internet of Things, IoT, and MCS is made by Kamienski et al. [373] in the context of development methods for energy management in public buildings. Smart buildings are also the focus of the work of Dimopoulos et al. [202] on a context-aware management architecture. The Smart City Paradigm is considered by Naveen Balaji et al. [55]. A Model-based approach for managing criticality in an e-health IoT system is developed by Kotronis et al. [387]. A Jitter-based analysis of a distributed real-time system is presented by K. Lee et al. [410], they are motivated by the requirements of IoT. Rashtian and Gopalakrishnan [527] look at soft real-time IoTs and propose a method of balancing criticality and timeliness. A link between MCS, scheduling, security and IoT is explored by Ali et al. [19].

Mirhosseini and Wenisch [462] consider a microservice architecture and show how a mixed-criticality approach can help structure a feedback controller to control request on microservice instances.

5.6 Probabilistic Real-Time Systems

In mixed criticality systems, the worst-case execution time of a task is expressed as a function of the criticality level (e.g. $C(LO)$ and $C(HI)$) with larger values for the WCET obtained for higher criticality levels. Research into probabilistic hard real-time systems can be viewed as extending this model to a continuum (or at least a large number of discrete values). Instead of a number of single values for the WCET with different levels of confidence, the worst-case execution time is expressed as a probability distribution, referred to as a pWCET [105].

The exceedance function (or $1 - \text{CDF}$ ²⁵) for the pWCET gives the probability that the task will exceed the specified execution time budget on any given run. Conversely, the exceedance function may be used to determine the execution time budget required such that the probability of overrunning that budget does not exceed a specified probability. This is illustrated in Figure 2. Here, an execution time budget of 55 has a probability of being exceeded of 10^{-5} , whereas the execution time budget required to ensure that the probability of exceedance is at most 10^{-9} is 70. We note that exceedance probabilities and failure rates (e.g. 10^{-9} fail-

²⁵Cumulative Distribution Function.

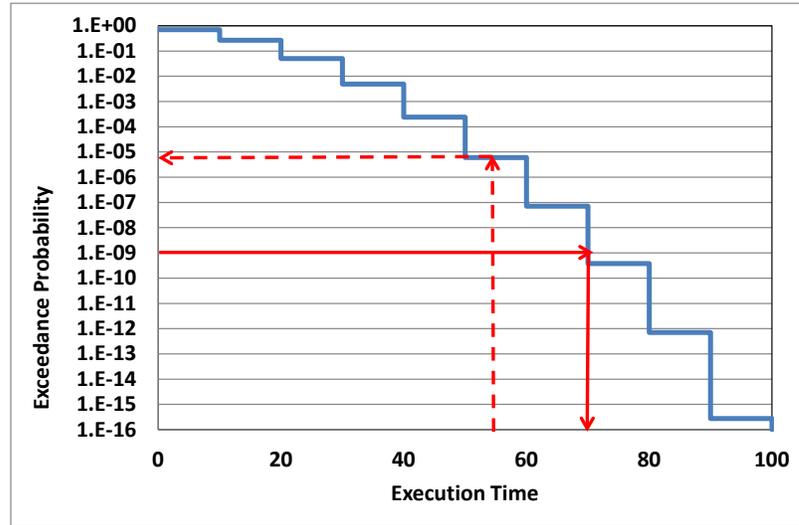


Figure 2: pWCET distribution as an Exceedance function

ure per hour) are not the same, but that such probabilities can be transformed into failure rates by accounting for the number of jobs in a given time period, or via probabilistic schedulability analysis techniques.

Probabilistic analysis provides an alternative treatment for mixed criticality systems, where high criticality tasks are specified as having an extremely low acceptable failure rate (e.g. 10^{-9} per hour), whereas a higher failure rate (e.g. 10^{-6} or 10^{-7} per hour) is permitted for lower criticality tasks. Probabilistic worst-case execution times [26,153] and the probabilistic worst-case response times [199,441] derived from them provide a match to requirements specified in this way. These techniques can potentially be used to show that pathological cases with very high execution times / high response times have a provably vanishingly low probability of occurring, thus avoiding the need to over-provision compute resources to handle these cases.

Just as MCS has expanded from a focus on worst-case execution times to one that includes arrival rates (for sporadic work), probabilistic analysis has been developed [18] for the case where the arrival rate of tasks is described by a probability distribution. This work could form a further link between MCS and probabilistic analysis. Indeed Masrur [448] uses random jitter on the arrival time of *LO*-criticality tasks to improve schedulability.

Guo et al. [284] demonstrate the usefulness of a probabilistic framework in

their analysis of an EDF scheduled system in which there is a permitted (but low) probability of timing faults. The chances of a *HI*-criticality task executing for more than its *LO*-criticality value is also expressed as a probability²⁶. Their current work assumes that task execution times are independent; this is an unrealistic assumption, but one that could be weakened in future work. Santinelli and George [543] also explore the probability space of worst-case execution times for MCS. Probabilistic analysis for the SMC and AMC schemes is derived by Maxim et al. [452, 453]. And a constrained Markov decision process is used by Alahmad and Gopalakrishnan [15, 17] to model job releases in MCS. A discrete time Markov chain is also used by Singh et al. [565].

Probabilistic analysis is used, by Draskovic et al. [207, 209], to investigate the safety of each criticality level. Abdeddaim and Maxim [3] derived probabilistic response time analysis for mixed criticality tasks under fixed priority preemptive scheduling, computing the probability of deadline misses for each task in each criticality mode. Their work does not assume any monitoring, hence they assume that lower criticality tasks continue to execute in higher criticality modes. Küttler et al. [394] use symbolic execution to derive probabilistic estimates of the *LO*-criticality tasks' completing before their deadlines. Lee [401] provides probabilistic performance evaluations for task-level mode changes. Singh et al. [566] use pWCET in their analysis of non-preemptive period tasks. Safety is also the primary driver for the work of Draskovic et al. [208].

Novak et al. [487] look at uncertain processing times in various contexts including replicated task execution.

One further use of stochastic models is to estimate the amount of time that *LO*-criticality tasks are unavailable (not executed). Medina et al. [454, 456] provide such availability analysis for MCS hosted on multi-core platforms scheduled using data-flow graphs.

6 More Realistic MCS Models

The abstract behavioural model described in Section 2 has been very useful in allowing key properties of mixed criticality systems to be derived, but it is open to criticism from systems engineers that it does not match their expectations. In particular:

- In the *HI*-criticality mode, *LO*-criticality tasks should not be abandoned. Some level of service should be maintained if at all possible, as *LO*-criticality tasks are still critical.

²⁶An approach also investigated by Zeng et al. [639].

- For systems which operate for long periods of time it should be possible for the system to return to the *LO*-criticality mode when the conditions are appropriate. In this mode all functionality should be provided.

It can be argued that these criticisms are, at least partly, misplaced as any high integrity system should remain in the *LO*-criticality mode for its entire execution: the transition to *HI*-criticality mode is only a theoretical possibility that the scheduling analysis can exploit [81]. Nevertheless, in less critical applications (such as those envisaged in the automotive industry) actual criticality mode changes may be experienced during operation and the above criticisms should be addressed. Of course for some applications it is acceptable to provide only limited timing guarantees during these rare events, and hence no online controls are required [613].

Recent reflections (at two 2017 events – the WMC workshop and Dagstuhl seminar) has identified two distinct roles for what is now called the ‘Vestal Model’: the verification of a MCS, and its run-time survivability. For the former it may be only necessary to argue that the *HI*-criticality work is guaranteed (in all circumstances) and hence no guarantees need be developed for the *LO*-criticality work. But survivability concerns all criticality levels. If faults are occurring (in particular timing overruns) then criticality-aware graceful degradation should result. Note material linking MCS and fault tolerance was reviewed in Section 5.2.

With this dual role for the Vestal Model it is not true to say that it advocates dropping all *LO*-criticality tasks as soon as there is any, even minor, budget overrun. Rather it is saying that for static verification the interference from lower criticality tasks must be demonstrably bounded. Within this bound a variety of techniques are available to increase the survivability of the *LO*-criticality work.

To distinguish between two forms of survivability, Burns et al. [58, 134] define Robustness to imply those techniques used to deliver full functionality within an explicit bound on the duration and severity of the temporal faults, and Resilience to encompass the wide range of techniques available to give different levels of graceful degradation when the system’s faulty behaviour is beyond the lower bound. Means of enhancing Robustness (by *mode-switch procrastination* and *deferred switching*) are considered by Hu et al. [312–314, 316], Gu and Easwaran [271, 273] and by Huang et al. [320].

The wide range of techniques addressing Resilience include:

1. Letting any *LO*-criticality job that has started, run to completion (this is in effect what is assumed by many forms of analysis [81]).
2. Reducing the priorities of the some of the *LO*-criticality tasks [78, 338], or similar with EDF scheduling [323, 324].

3. Increasing the periods and deadlines of some or all of the *LO*-criticality jobs [251, 347, 517, 580, 582–584, 631], called *task stretching*, the *elastic task model* or *multi-rate*.
4. Imposing a weakly-hard constraint on the *LO*-criticality jobs [245, 360, 455, 526].
5. Decreasing the computation times of some or all of the *LO*-criticality tasks [132]²⁷ [60], perhaps by utilising an imprecise mixed-criticality (IMC) model [320, 321, 351, 435, 436, 499] or budget control [271, 273].
6. Moving some *LO*-criticality tasks to a different processor that has not experienced a criticality mode change [52, 339, 625, 626]. Offloading is also considered by Schonberger et al. [552].
7. Abandoning *LO*-criticality work in a disciplined sequence [2, 238, 275, 327, 404, 407, 532].

The fifth action leads to a modification to the system model; whereas for *HI*-criticality tasks we have $C(HI) \geq C(LO)$, for *LO*-criticality tasks we now have $C(HI) \leq C(LO)$. For some tasks $C(HI) = 0$, that is they are abandoned. For others a lower level of service can be guaranteed. For some they may be able to continue with their full computation time budgets.

The final approach is addressed by Fleming and Burns [238]; they introduce a further notion into the standard model; tasks are allocated to *applications* and each application is assigned (by the system designers) an *importance* level. *LO*-criticality tasks are abandoned in inverse order of importance. The notion of *importance* is explored further by Bletas et al. [112]; they draw a distinction between *criticality* as used for verification and *importance* to control run-time graceful degradation. A task may have low criticality but high importance, or *vice versa* (though of course there is often a close coordinated relation). This approach is explored further by Sundar and Easwaran [585].

Huang et al. [327] introduce an extension to the standard model by the use of an ICG (Interference Constraint Graph) to capture more specifically which tasks need to be dropped when particular higher criticality tasks exceed their allocated criticality-aware execution times. Controlled abandonment by the use of partitioning is advocated by Mahdiani and Masrur [444] in the context of the EDF-VD scheduling.

Obviously all seven schemes can be used together: complete or move all started jobs, allow some new jobs to have an extended deadline or reduced computation

²⁷Note equation (6) in this paper has a typo, both $R_i(LO)$ terms should be starred ($R_i^*(LO)$).

time or a weakly-hard constraint, reduce the priorities of some others jobs and abandon those of lowest importance in particular partitions. Such an approach is advocated by Su et al. [581]; here *LO*-criticality tasks have two periods (short and long) and two priorities. At the criticality mode change these tasks switch to their longer periods and new priorities. Analysis is provided to show that all modes are schedulable.

A flexible scheme utilising hierarchical scheduling is proposed by Easwaran et al. [216, 274]. They differentiate between minor violations of *LO*-criticality execution time which can be dealt with within a component (an internal mode change) and more extensive violations that requires a system-wide external mode change. In doing so they introduce a new mixed-criticality resource interface model for component-based systems which supports isolation, virtualisation and compositionality. Compositionality is also addressed by Yang and Dong [629] in the context of budget estimation.

Within the context of EDF-VD Chen et al. [157] allow the overrunning *HI*-criticality task to progress through multiple intermediate levels rather than assume a single jump to $C(HI)$. They term this a Multiple-Shot transition. It facilitates a more control impact on *LO*-criticality tasks. A similar idea is utilised by Chwa et al. [169].

Papadopoulos et al. [494] also address small overruns of *LO*-criticality budgets, they use a control-theoretic approach to automatically make minor and stable modifications to future budgets so as to return the system to normal behaviour without the need for mode changes or other significant reductions in system functionality. A more controlled response to small overruns is also considered by Massaro et al. [450]; they use a proactive mode change to anticipate an overrun before it actually occurs, thereby reducing its impact.

In keeping with other mode change situations ([144, 224, 504, 528, 558, 597, 598]) a simple protocol for controlling the time of the change of mode back to *LO*-criticality is to wait until the system is idle (has no application tasks to run) and then the change can safely be made [597]. Santy et al. [548] extend this approach and produce a somewhat more efficient scheme that can be applied to globally scheduling multiprocessor systems, in which the system may never get to an idle tick. With a dual criticality system that has just transitioned into the *HI*-criticality mode (and hence no low-criticality jobs are executing); their protocol first waits until the highest priority *HI*-criticality job completes, then its waits until the next highest priority job is similarly inactive. This continues until the lowest priority job is inactive; it is then safe to reintroduce all *LO*-criticality tasks. Obviously if there is a further violation of the $C(LO)$ bound then the protocol is abandoned and subsequently restarted. The authors call this a SCR (Safe Criticality Reduction); their paper also has a second protocol, but this is less intuitive and considerably

more expensive at run-time.

A more aggressive scheme for returning a system back to its *LO*-criticality mode is proposed by Bate et al. [97, 98]. In this approach a bailout protocol is proposed. *HI*-criticality tasks take out a loan if they execute for more than their $C(LO)$ estimate. Other tasks repay the loan by either not executing at all or by executing for less than expected. When the loan is repaid (and a further condition is met) the system returns to its normal mode. The authors demonstrate, using a scenario-based assessment, that the bailout protocol returned the system to the normal mode much quicker than the ‘wait for idle tick’ scheme. Law et al. [400] also look at reducing the time a system spends in the degraded mode, and provide supporting evidence based on a real life avionics case study. The bailout protocol has been improved by Iacovelli and Kirner [338] by allowing *LO*-criticality tasks to run at a background priority rather than being aborted.

As well as experiencing a criticality mode change a system can, of course, be structured to behave in a number of operational or behavioural modes. As indicated earlier, Burns [126] compares and contrasts these two forms of mode change. De Niz and Phan [483] note that the criticality of a task can depend on the behavioural mode of the system. They develop scheduling analysis for this dependency and consider the static allocation of such tasks to multiprocessor platforms.

Another aspect of the ‘standard model’ for MCS that can be argued to be unrealistic is the idea that a system with, say, five criticality levels would also have five different estimates of worst-case execution time for its most critical tasks. An augmented model has been proposed [127, 482] that restricts each task to having just two estimates of WCET. So, in the general case where there are V criticality levels, L_1 to L_V (with L_1 being the highest criticality), each task just has two C values. One represents its estimated execution time at its own criticality level ($C_i(L_i)$) and the other an estimate at the base (i.e., lowest) criticality level ($C_i(L_V)$). It follows that if a job is of the lowest criticality level (i.e., $L_i = L_V$) then it only has one WCET parameter. For all other jobs, $C(L_i) \geq C(L_V)$. The two parameters of this augmented model have been referred to as $C(self)$ (or $C(SF)$) and $C(normal)$ ($C(NL)$); the model seems to be sufficiently expressive to capture most of the key properties of mixed criticality systems. However, Baruah and Guo [92] has shown that: “*The Burns model is strictly less expressive than the Vestal model. Determining whether a given instance can be scheduled correctly remains NP-hard in the strong sense. Lower bounds on schedulability, as quantified using the speedup factor metric, are no better for the Burns model than for the Vestal model.*” This quote makes use of terms described in the next section.

An important property of any realistic form of analysis is that it is sustainable [77]. This, informally, implies that a system that is deemed schedulable by some appropriate test will remain schedulable when the application’s characteris-

tics improve (for example, worst-case execution times are reduced, or period and deadlines extended). Guo et al [286] consider the sustainability of various forms of analysis for MCS. For example, they showed that AMC and EDF-VD are sustainable forms of analysis. This not only included reductions in $C(HI)$ and $C(LO)$ but also a reduction in the criticality level assigned to a task (e.g. a reduction from HI -criticality to LO -criticality). They showed that other methods of implementing MCS such as criticality-monotonic are not sustainable. Sustainability of MCS is also considered by Kahil et al [366, 368] who introduce the notion of MC-Sustainable, and link sustainability to predictability.

7 More Formal Treatments

In this section we consider utilisation bounds, speedup factors and (formal) language issues.

7.1 Utilisation Bounds

For normal single criticality systems there are well known bounds on task set utilisation that will deliver a schedulable system with either fixed priority or EDF scheduling. Although the definition of utilisation is not straightforward when a task has more than one worst-case computation time, it is possible to give an effective definition and to derive least upper bounds (LUBs) for MCS. Santos-Jr et al. [546] derive a number of useful results for LUB. They construct a task set that is unschedulable (during a criticality mode change) with LUB arbitrarily close to 0. But where tasks have harmonic periods LUB can reach 1 (for a uniprocessor system). Between these two extremes they show that if higher criticality tasks do not have periods longer than lower criticality tasks then LUB lies between $\ln 2$ and $2(\sqrt{2} - 1)$.

7.2 Speedup Factors

It has been shown [63, 65, 71, 73, 292] that the mixed criticality schedulability problem (preemptive or non-preemptive) is strongly NP-hard even if there are only two criticality levels. Hence only sufficient rather than exact analysis is possible. A list of open problems with regard to the schedulability of MCS was provided by Ekberg and Yi [222] in 2015. More recently (in 2017) Kahil et al. [366, 367] claim to have found a counter-example to the proof that the mixed-criticality optimality problem belongs to the class NP. This study was continued [369] with an exploration of the algorithmic complexity of correctness testing (simulation) for job-based MCS.

For approaches and tests that are only sufficient, an assessment of their quality is possible if a *speedup factor* can be computed. A speedup factor [372] of $X (X > 1)$ for schedulability test S implies that a task set that is schedulable on a processor of speed 1 will be deemed schedulable by S if the processor's speed is increased to X . Of course, in general, it is not possible to know if the task set is schedulable on the original speed 1 processor (this would require an exact and possibly even a clairvoyant test), but a real scheduling scheme and test with a speedup factor of say 2 is clearly better than one with a speed up factor of 10.

For job-based fixed priority scheduling, a priority assignment scheme and test has been found [6, 72, 73, 93, 420] with a speed up factor of S_L (for L criticality levels), where S_L is the root of the equation $x^L = (1+x)^{L-1}$. For $L = 2$ the result is $S_2 = (1 + \sqrt{5})/2$ which is equal to the golden ratio, $\phi = 1.618$. This can be compared with a partitioned approach (all *HI*-criticality jobs have priorities higher than all *LO*-criticality jobs) which has an unbounded speedup factor. This latter result is easily illustrated by considering a two job system. The *LO*-criticality job has a small computation time, 1, and deadline of 2. The *HI*-criticality job has a huge computation time of G and a deadline of $G + 1$. These two jobs will both meet their deadlines if the *LO*-criticality task is given the highest priority. But the reverse priority assignment (which executes the *HI*-criticality job first) will only be schedulable if $G + 1$ will fit into the deadline 2. To obtain this a speedup of $(G + 1)/2$ is required. As G can be arbitrary large the speedup factor is effectively unbounded.

For EDF scheduled systems Baruah et al. [76, 93] prove that a variant of EDF (EDF-VD, described in Section 3.3) in which *HI*-criticality sporadic tasks (in a dual-criticality system) have their deadlines reduced (in the *LO*-criticality mode) is also schedulable on a single processor that is speeded up by a factor ϕ . They also show that a finite set of independent jobs? scheduled on m identical multiprocessors is schedulable with a speed-up factor of $\phi + 1 + 1/m$. And on a partitioned system a speed-up factor of $\phi + \epsilon$ is derivable for any value of $\epsilon > 0$. In later work [75] they improve this bound to $4/3$ (1.333) rather than ϕ (1.618). Further formal analysis of EDF-VD is provided by Li [418], Muller and Masrur [467] and Gu and Easwaran [270]. The MC-Fluid approach also has a speed-up factor of $4/3$ [86], as does EDF-VD when applied to systems with degraded/imprecise guarantees [436].

7.3 Formal Language and Modelling Issues

The application of formal design languages, such as real-time BIT (Behavior Interactions Priorities), are being used to model MCS. And verification approaches such as model checking or simulation are being applied to both application software and

multi-core platforms. See, for example, the work of Socci et al. [569]. State-space explosion is of course always an issue with these approaches.

A 2005 paper by Amey et al. [27], which predates Vestal's work, looked at the (smart) certification of mixed criticality systems. They report real industrial application of formal code analysis to prove isolation between tasks of different criticality levels. In one application, concerning safety-critical landing guidance for ship-borne helicopters, SIL 4 code (the highest in UK Defence Standard 00-55 [461]) was executing in the same processor and memory space as SIL3 and SIL2 code. Another application (a civil jet engine monitoring unit) has Level-C and Level-E code co-located (DO-178B standard [535] has levels A down to E). In both of these examples formal analysis of information flow at the program level was able to demonstrate code segregation.

Compile time checking is also advocated by Lindgren et al. [430] with their experimental RTFM-language. Language constructs allow static assessment of the interfaces between critical and non-critical code. At run-time however separation is achieved by assigning higher priorities to the critical tasks. As indicated earlier this is not a very effective strategy in terms of efficient resource usage.

Model-based design using Synchronous Reactive models is used to design embedded control systems and is formalised within languages such as LUSTRE, SIGNAL and Simulink. Its application to MCS is considered in detail by Zhao et al. [648]; where they adopt the elastic mixed-criticality task model for fixed-priority scheduling.

As run-time behaviours become more complicated, with many possible scheduling schemes being proposed for MCS, there is a need to precisely (indeed formally) specify the relationship between the tasks/jobs of the application and the scheduler. An initial attempt to use the Rely/Guarantee framework [358] has been reported [130, 359].

An alternative task model to that which underpins most scheduling research on MCS is the sporadic DAG (Directed Acyclic Graph) task model. An initial study, within the context of multiprocessor federated systems, is provided by Baruah [69]. Wang and Wang [615], Medina et al. [455, 457, 458] and Liu et al. [439] also consider this model. A semi-federated approach is proposed by Yang et al. [632] and is shown to be more efficient. Hu et al. [311] also address DAG-based applications but use a least laxity scheduling scheme to give adaptive support on heterogeneous distributed platforms.

8 Systems Issues

In this section we consider a number of what are often terms systems issues. These include run-time monitoring and system overhead, virtualisation and Operating System support, hardware aspects, benchmarks and comparative studies, power consumption, and issues relating to modelling and tool support.

8.1 Run-Time Monitoring and Overheads

A fundamental issue with MCS is separation. Many of the more theoretical papers reviewed here assume various levels of run-time monitoring and control. However, few papers consider or demonstrate how the required mechanisms can be implemented, Neukirchner et al. [479] presented one such paper. They consider memory protection, timing fault containment, admission control and (re-)configuration middleware for MCS. Their framework [233] is aimed at supporting AUTOSAR conforming applications within the automotive domain. An early paper looking at non-interference at the memory level for IMA platforms within the avionics industry is that of Hill and Lake [306].

Another detailed study of the overheads for two common implementations schemes for MCS is presented by Sigrist et al. [563]. They conclude that overheads of up to 97% can be encountered and they recommend that all scheduling models be extended to include parameters to capture the impact of run-time overheads. One source of overhead is the context switch time between tasks. Davis et al. [187] note that switching between tasks of the same criticality should be quicker than between tasks of different criticality. They produce analysis for the standard fixed priority approach for MCS (AMC and SMC) that explicitly caters for varying context switch times; they note however that priority assignment is not straightforward for this model [188].

The issue of monitoring is also addressed by Motruk et al. [465] in the context of their IDAMC (Integrated Dependable Architecture for Many Cores). This work builds on the more general (i.e. not MCS specific) work on separation, isolation and monitoring for SoC/NoC architectures.

8.2 Virtualisation and Operating System Support

The MultiPARTES project is addressing virtualisation in terms of Model Driven Engineering for MCS [23, 170, 171, 602, 603]. Goossens et al. [254, 255] are also looking at virtualisation “to allow independent design, verification and execution” with their CompSOC architecture. Paravirtualisation of legacy RTOSs to provide the necessary memory isolation is considered by Armbrust et al. [30].

However, Hughes and Awad warn of the difficulties that can arise from increased non-determinism with virtualised platforms [332].

Hypervisor technology is also being used to give the appropriate level of isolation in MCS. The DREAMS architecture uses it [214,398] to minimise interference via modelling patterns of execution, and to provide for levels of fault tolerance. Evripidou and Burns [232] employ different execution-time servers (deferrable server for short deadline event-triggered work, and periodic server for periodic work) under the control of a hypervisor to bound the overheads associated with server technology. If there is a criticality induced mode change then the deferrable servers are transposed to the much more efficient (but less responsive) periodic servers. General hypervisor architectures for multi-core MCS are proposed by Pérez et al. [507] and Avramenko et al. [37]. Within the context of ARMv8-A, Lucas et al. [442] have developed a VOSYSmonitor that allows a safety-critical RTOS and a non-critical general purpose OS to co-exist on the same hardware platform. With a large Nuclear Fusion project, Cinque et al. [176] argue that virtualisation will not scale to the ‘tens of thousands’ of threads envisaged in this application. They propose a more lightweight solution using containers [173,174]. The Jailhouse hypervisor is used by Gracioli et al. [259] to support mixed criticality applications running on a heterogeneous MPSoC platform. They address issues of resource sharing and isolation, and utilise programmable logic and ScratchPad memory. A hypervisor approach for mixed-criticality UAV applications is provided by Fautrel et al. [234].

The issue of monitoring and testing MCS, including the use of HIL (hardware-in-the-loop), is addressed in a number of papers. Particular attention being given to multi-core platforms [230,231,489].

A separation kernel has been developed by West et al. [424,463,619]. They can host guest operating systems, such as Linux or their own real-time operating system (RTOS), QUEST-V. They partition the available cores into Sandboxes that have different criticality levels. Their architecture is aimed at achieving efficient resource partitioning and performance isolation. One means of achieving this is for interrupts to go directly to the appropriate partition, they do not have to be first handled by the hypervisor. An RTOS that addresses partitioning for the NoC (network-on-chip) as well as the processor is developed by Esposito et al. [229] and extended by Avramenko and Violante [38]. A capability-based structuring of OS interactions is proposed by Gadepalli et al. [243] to provide fine-grain control over sharing and separation.

PikeOS [370] also employs a separation microkernel to provide ‘a powerful and efficient paravirtualization real-time operating system’ [539] for a partitioned multi-core platform. Vanga et al. [606] present a case study in the use of PikeOS in which they aim to give effective support to low criticality tasks that have short

deadlines (low latency). Another high-assurance (micro) kernel is sel_4. Lyons and Heiser [443] show how the sel_4 model can be extended to cater for mixed criticality. VMs (virtual machines) that are appropriate for real-time Java-based mixed-criticality systems have been designed by Ziarek and Blanton [658] and Hamza et al. [289]. Mginkgo [317] is another microkernel aimed at MCS.

To implement the criticality mode change the run-time support system must support execution time monitoring, the modes and mode changes. Baruah and Burns [78] show how this can be achieved within the facilities provided by the Ada programming language. Kim and Jin do the same for a standard RTOS [381]. They make use of bitmaps to provide a very efficient implementation. DMPL [155] is a language designed specifically for distributed real-time MCS. Natarajan and Broman [476] look at the programming language Timed C with reference to its ability to address the run-time monitoring functions needed to implement MCS.

A further operating system designed to support mixed criticality is Kron-OS [185]. This controls the execution of RSFs (Repetitive Sequence of Frames) that is partitioned between two criticality levels. Instead of a purpose built RTOS a COTS platform is preferred by Raghenzani et al. [529]. They focus on Linux and attempt to characterise the interference that the platform can produce. HIPPEROS [493] is a multi-core OS designed for use in the avionics domain. They use one core to make all scheduling decisions. They also use the elastic task model (see Section 3.3) to allow *LO*-criticality tasks to degrade when an overrun occurs. Vetter et al. [608] show how a low latency criticality-aware network channel can be constructed between different OSs, in particular between Linux and one utilising an ARM TrustZone. Extensions to the OSEK RTOS to support mixed-criticality is considered by Gupta et al. [288] and Bril and Luit [120].

8.3 Hardware Aspects

As an alternative to using an RTOS to give the right level of protection and (safe) resource sharing, Zimmer et al. [659] have designed a processor (FlexPRET) to directly support MCS. They use fine-grained multithreading and scratchpad memory to give protection to hard real-time tasks while increasing the resource utilisation of soft tasks. In effect soft tasks (threads) can safely exploit the spare capacity generated from the hard tasks at the cycle level. They have a soft-core FPGA implementation that caters for up to 8 hardware threads, each of which can support a number of software threads. A more focused scheme aimed at partitioning the cache is described by Lesage et al. [416]. An LC (least critical) cache replacement policy is evaluated by Kumar et al. [393]. The effective use of cache, for a multi-core platform, is also considered by Chrisholm et al. [166]. Similarly, Ali Awan et al. incorporate criticality into their dynamic last-level cache partitioning

scheme [42], and memory bandwidth regulation [43, 44]. Partial lockdown and cache reclamation is also considered by this group [113]. Sritharan et al. [576, 577] propose a time-based cache coherence protocol called PENDULUM for bounding latencies from critical memory accesses.

The development of purpose built hardware (FPGA based) to support reliable MCS is being undertaken as part of the RECOMP project. They aim to reduce the cost of certification for MCS on multiprocessor architectures by use of open source hardware and software [459, 480, 510]. Santos et al. [545] are also looking at systems built on FPGA platforms. They have developed a criticality-aware scrubbing mechanism that improves system reliability by up to 79%. Scrubbing is a technique for recovering from SEU (single event upsets) that affect FPGA platforms in harsh environments such as space. Another hardware implementation of a MCS scheduler is being considered by Housinou et al. [310]. Kohutka et al. [383] provides an ASIC design of a coprocessor that schedules MCS using a Robust Earliest Deadline algorithm.

A hardware platform that supports applications of different criticality must manage its I/O functions in a partitioned and hence safe (and secure) way. If lower criticality work can cause an interrupt to occur ‘at any time’ then unpredictable overheads may be suffered by high criticality applications. This is a topic addressed by Paulitsch et al. [501]. They rightly claim that this topic is often overlooked. Later, support for I/O and IPC via fine-grained OS isolation is considered by Kim et al. [378] within the context of MC^2 (see Section 4). Valente et al. [605] provide lightweight hardware support for isolation within a multi-core platform using a NoC. Kaushik et al. [374] develop a hardware cache coherence protocol, called CARP, that allows safe data communication between criticality levels. Jiang et al. [350, 352] also consider hardware-assisted I/O virtualization for MCS.

8.4 Benchmarks and Comparative Studies

Although research on MCS has generated many different approaches, there have been few empirical benchmarks or comparative studies. One useful study however was published in 2012 by Huang et al. [318]. They compared Vestal’s scheme with its optimal priority assignment, their improved slack scheduling scheme and Period Transformation (PT) (see Section 5.1). They conclude that Vestal’s approach and period transformation usually, though not always, outperform slack scheduling; and that there are additional overheads with period transformation and slack scheduling. Nevertheless the overheads were not excessive, typically an extra 0.3%. Later Fleming and Burns [237] compared Vestal’s approach, AMC (see Section 3.2) and PT for multiple criticality levels. As the number of criticality levels increased the relative advantage of PT, even when overheads are ignored, was ob-

served to decrease. This observation was also supported by Huang et al. [319] who updated their study in 2014 and concluded that AMC-based scheduling gave the best performance for fixed priority sporadic task systems. This study also looked at the overheads involved in user-space implementation of AMC on top of Linux, without kernel modifications.

The need for useful benchmarks is noted in a number of papers. One industrially inspired case study is provided by Harbin et al. [294]. The use of realistic simulations to evaluate schemes is discussed by Bate et al. [97, 98], Griffin et al [264] and Ittersshagen et al. [342]. A brief comparison of approaches to multiprocessor scheduling of MCS is provided by Osmolovskiy et al. [492]. The evaluation of communications within a MCS is considered by the work of Napier et al. [474] and Petrakis et al. [509]. A testbed for MCS design is discussed by Sundar and Easwaran [169]. And a framework for evaluating schedulability tests is provided by Pavic and Dazpo [502].

8.5 Criticality-Aware Power Consumption

Another systems issue of crucial important in many mobile embedded systems is power consumption. The work of Broekaert et al. [121] allocates and monitors power budgets to different criticality levels. If a crucial VM (Virtual Machine) “*overpassed its power budget during its time partition, the extra power consumed will be removed from the initial power budget of the next low critical VM scheduled*”. Energy consumption is also addressed by Legout et al. [413]. They trade energy usage with deadline misses of low-criticality tasks, and claim a 17% reduction in energy with deadline misses kept below 4%. The objective of minimising energy usage is used by Zhang et al. [644] to drive task allocation in a multiprocessor system. As discussed earlier, a slightly different approach is taken by Huang et al. [325]. They advocate the use of DVFS (Dynamic Voltage and Frequency Scaling) to increase the speed of the processor if *HI*-criticality tasks need more than their $C(LO)$ requirement. Hence *LO*-criticality work is not abandoned, but more energy is used. They integrate their approach with the EDF-VD scheduling scheme (see Section 3.3) and have, more recently, addressed multi-core platforms [475]. Behera and Bhaduri [100] address the same problem with their TT-Merge scheme [101, 102] which they claim outperforms EDF-VD when all tasks are periodic. For sporadic task systems Zhang [645] shows how energy use can be reduced by taking into account the random arrival of such tasks.

This approach is extended by Ali et al. [21] who propose a new dynamic power-aware scheduling scheme for hardware with discrete frequency levels. Awan et al. [46] consider how energy-aware task allocation can be utilised in the context of heterogeneous multi-core systems. A leakage aware DVFS scheme is proposed

by Digalwar et al. [201] and is shown to be more energy efficient when compared to existing approaches. Slack scheduling and DVFS are combined in the work of Ranjbar et al. [525].

Cao et al. [149] directly model transient and permanent faults on a uniprocessor with DVFS in order to address the “lifetime optimisation problem”. They utilise a MILP (mixed-integer linear programming) method; but for large-scale problems rely on a cross-entropy heuristic. Energy-aware fault-tolerance, via replication, is also considered by Safari et al. [537].

Where energy is limited or indeed the system is energy neutral, then criticality-aware energy usage becomes crucially important [610]. ENOS [614] is an experimental OS that addresses mixed resources (time and energy) and mixed criticality. It transforms the system through a series of ‘energy modes’ including one that ensures all state is safely stored in persistent memory before system blackout.

Energy harvesting in the context of a battery-less real-time system is considered by Asyaban et al. [33]. They propose a scheduling scheme that satisfies both temporal and success-ratio constraints whilst addressing uncertainty in the platform’s power management. Xiang and Pasricha [623] also look at harvesting for multicore heterogeneous MCS. Wu et al. [622] extend this idea to include distinct energy levels.

Even where energy is not limited, isolation in terms of power usage and temperature control is important; an issue addressed by Grüttner in the context of heterogeneous MPSoCs [267]. Power management is also addressed by Juhasz and Jantsch [361] in order to manage QoS in a MCS. A measurement-based probabilistic approach to energy-constrained MCS is proposed by Reghenzani et al. [107, 530]. They employ non-preemptive scheduling, as does Zhang [646]. And a thermal-aware server framework is proposed by Hosseinimotlagh et al. [309] to safely upper-bound the maximum operating temperature of multi-core MCS. Thermal-aware scheduling is also addressed by Safari et al. [538].

8.6 Issues Relating to Modelling and Tool Support

Complex mixed criticality systems also present a number of significant challenges at the specification and design stage [427]. Herrera et al. [303,304] propose a modelling and design framework for MCS hosted on Systems-on-Chip and/or Systems-of-Systems. They present a core ontology but freely admit that there is considerable work to do before a sound engineering process is available for system builders/architects. Ittershagen et al. [343] go further and propose a systematic method for constructing workload and integration flow models for time-triggered MPSoC platforms. Design space exploration for MCS is considered by Muttillio et al. [469].

Giannopoulou et al. [246] support the development of MCS on multi-core plat-

forms by the development of an appropriate tool chain. This group has also considered [249, 638] the mapping and design of fault-tolerant MCS to multi-core platforms.

9 Industry Practice and Standards

This survey covers the considerable body of research into MCS stemming from the model presented by Vestal [607]. Industry practice and safety standards; however, provide a somewhat different perspective on MCS [228]. There are different meanings assumed for some of the commonly used terms, and different objectives.

Determining the criticality of an application (or system function implemented via both hardware and software) is done via a system safety assessment that involves Hazard Analysis (HA) Failure Modes and Effects Analysis (FMAE) and Fault Trees Analysis (FTA). The criticality level typically depends on (i) an evaluation of the consequences of a failure, (ii) the probability that the failure occurs, and (iii) the provision of means to mitigate or cope with the fault. Hence the criticality level of an application may not necessary reflect the severity or consequences of failure. An example given by Esper et al. [227] and Ernst and Di Natale [226] comes from ISO 26262. If the probability of failure occurrence is very low, the ASIL level assigned may be low, despite severe consequences if a failure actually happens. A different application with a high probability of failure may be assigned a higher ASIL despite having lower severity consequences. With this interpretation, the idea of dropping low-criticality functionality in favour of completing that of higher criticality does not hold; the consequences would be more severe. ISO 26262 also permits high-criticality applications to be composed from lower criticality components with diverse implementations, again dropping one of the lower criticality components would remove the diversity and undermine the safety argument for the high-criticality function. The message here is that the criticality level is not the same as the importance of the application. Functionality that has low criticality cannot simply be dropped.

The standards require that “*sufficient independence*” or “*freedom from interference*” is demonstrated between functions of different criticality levels in both spatial and timing domains. If this is not done, then the whole system needs to be designed and developed according to methods appropriate for the highest criticality level involved, which would be untenable in practice for cost reasons. It remains a significant challenge to achieve the necessary separation, while also providing an efficient means of sharing resources. This is particularly apposite with the advent of multi-core and many-core platforms. Tool are required to verify that the necessary level of independence is indeed manifest in the design of MCS [609].

A focus on industrial practice in the automotive industry is presented by Lee and Kim [405, 406] within the context of the AUTOSAR standard. Farrall et al. [233] and Copic et al. [178] also address supporting AUTOSAR; the latter looking at both Classic and Adaptive AUTOSAR. The evolution of the industrial component model for multi-criticality vehicular software is addressed by Bucaioni et al. [123]. In a wider context, Simo et al. [564] discuss the role of MCS within the context of Industry 4.0. An analysis of task parameters for automotive application is presented by Nair et al. [473].

10 Beyond Mixed-Criticality

One of the more recent outcomes from the extensive research that has taken place on mixed-criticality systems is the application of the notions, models, concepts and approaches that have been developed for MCS to other, largely unrelated, areas of research. Here we note some of these developments.

The key element of Vestal's model [607] is that a task can have more than one estimate of worst-case execution time, with each estimate being a function of a stateholder's view of the criticality of the task. Quinton et al. [513] reinterpret this property to imply that a task has a *worst-case* estimate and a *typical* estimate. The worst-case value has the usual definition; the typical value is the upper bound you get when you eliminate, exceedingly unlikely to occur, outliers. These outliers may actually never be experienced at run-time but the means of obtaining the worst-case values was unable to eliminate them (i.e. the worst-case estimates are unavoidably pessimistic). Algorithms that have been developed for MCS can be applied directly to systems that are modelled using typical and worst-case values.

For example, Agrawal and Baruah [7, 57] considered real-time routing problems on graphs in which each edge is labeled with a pair of edge-weights, one denoting the maximum delay one could encounter while traversing the edge, and the other an estimate of the delay one typically encounters upon traversing the edge. They develop routing algorithms that minimise the cost when typical values are experienced, but at the same time meet an imposed deadline when/if the worst-case costs are encountered. A similar approach is proposed by Agrawal et al. [10] for optimising the order in which Learning-Enabled Components (LEC), within a safety-critical system, are executed. Each LEC has a minimum value and a (larger) typical value. Overall, a safe threshold must be delivered (by LECs that only contribute their minimum value). However, if typical values are witnessed then an optimal (minimum duration) sequence is followed.

More generally, Burns argues [128] that the key characteristic of what is currently called a mixed-criticality system is the existence of multiple interpretations

of one or more of the defining parameters of the tasks/agents that make up the real-time system. This emphasis leads naturally to the term *Multi-Model Systems* (MMS). MMS are those that are defined by more than one model. Each model relating to a distinct stakeholder or a distinct environmental mode of operation. MCS are just one example of the more general construct of MMS.

11 PhD Awards for Research within the Field of MCS

As an indication of the richness of the landscape for research within the many aspects of MCS we note (some) of the PhDs (or equivalent) that have been awarded to students studying topics within the domain of mixed criticality systems:

Mohemed El Mehdi Aichouch, *Evaluation of a Multiple-Criticality Real-Time Virtual Machine System and Configuration of an RTOS Resource Allocation Techniques*, INSA Rennes, 2014.

Serhiy Avramenko, *Network-on-Chip-based Multi-Processor System-on-Chip: Towards Mixed-Criticality System Certification*, Politecnico di Torino, 2019.

Christos Evripidou, *Scheduling for Mixed-criticality Hypervisor Systems in the Automotive Domain*, University of York, 2016.

Thomas Fleming, *Allocation and Optimisation of Mixed Criticality Cyclic Executives*, University of York, 2017.

Georgia Giannopoulou, *Implementation of Mixed-Criticality Applications on Multi-Core Architectures*, ETH Zurich, 2016.

Chetan Govindaiah, *Hardware Architecture Support for Mixed-Criticality and Real-Time Systems*, Iowa State University, 2016.

Romain Gratia, *A Generic, Efficient Approach to Mixed Criticality Sequencing for Multi-Core Processors*, Telecom Paristech, 2017.

Xiaozhe Gu, *Schedulability Analysis and Low-Criticality Execution Support for Mixed-Criticality Real-Time Systems on Uniprocessors*, Nanyang Technological University, 2017.

Zhishan Guo, *Real-Time Scheduling of Mixed-Criticality Workloads upon Platforms with Uncertainty*, University of North Carolina at Chapel Hill, 2016.

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12 Conclusion and Directions for Future Work

As identified in the introduction, the fundamental issue with MCS is how to reconcile the differing needs of separation (for safety) and sharing (for efficient resource usage). These concerns have led to somewhat of a bifurcation in the resulting research. Much of the implementation and systems work has concentrated on how to safely partition a system so that high-integrity components can, in some way, share computational and communication resources. By comparison, the more theoretical and scheduling research has largely focused on how criticality-specific worst-case

execution times can be utilised to deliver systems that are schedulable at each criticality level but have high processor utilisation. Unfortunately these two areas of research are not easily integrated. Flexible scheduling requires, at least, dynamic partitioning. Certified systems require complete separation or at least static partitioning. Future work must address this mismatch.

A second topic for future work is a move away from a processor-centric view of MCS to one that incorporates other shared resources, for example communication; particularly on a multi-core or many-core platform. Can a shared bus provide the required separation, or is a Network-on-Chip protocol required? Work is only beginning to address these issues.

What becomes clear from reading the extensive literature that has been produced since the seminal paper of Vestal [607] in 2007, is that MCS presents a collection of interesting issues that are both theoretically intriguing and challenging from the perspective of implementation.

We finish this survey by listing open issues identified from reading the extensive research literature. (Many of these issues were presented by Alan Burns in his keynote talk at the Dagstuhl Seminar on Mixed Criticality Systems on Multi-core/Many-core Platforms in March 2015).

1. Holistic analysis is needed considering *all* system resources, particularly communications buses, networks, and access to memory, as well as the processor(s).
2. Appropriate models of system overheads and task dependencies are required, and need to be integrated into the analysis. In particular, attention needs to be paid to how overheads arising from tasks of one criticality level may impact tasks of different (particularly higher) criticality.
3. More work is needed to integrate run-time behaviour, i.e. monitoring and control, with the assumptions made during static analysis and verification.
4. Effective protocols are needed for sharing information between criticality levels.
5. There are a number of open issues with regards to graceful degradation and fault recovery. These include timely recovery back to the low-criticality mode of operation, and support for limited low-criticality functionality in higher criticality modes, avoiding the abandonment problem.
6. To be of practical use, techniques need to scale to more than two (possibly up to five) levels of criticality.

7. Better WCET analysis is needed to reduce the sound $C(HI)$ and $C(LO)$ estimates used, and to improve confidence in these values.
8. How many different WCET estimates are required (or useful) for the same software?
9. Much of the existing research has looked at mixed criticality within a single scheduling scheme; however, further work is needed on integrating different schemes (e.g. cyclic executives for safety-critical applications, fixed priority for mission-critical applications, on the same processor).
10. Mechanisms are needed to tightly bound the impact of lower criticality tasks on those of higher criticality, independent of the behaviour or misbehaviour of the former, without significantly compromising performance, which may happen if strict isolation is enforced.
11. Time composability is needed across different criticality levels, so that the timing behaviour of tasks determined in isolation can be used when they are composed during system integration.
12. So far there has been little work on security as an aspect of criticality in real-time systems.
13. Probabilistic and statistical methods are a good match to requirements specified in terms of failure rates for different criticality levels; however, little work has been done on applying these techniques to MCS.
14. There are a number of formal aspects of scheduling still to be investigated.
15. Openly available benchmarks and case studies are needed for the evaluation of MCS techniques and analysis.
16. For research on MCS to have real impact it will be necessary to influence the relevant standards in the various application domains (e.g. automotive, aerospace).

Returning to the fundamental question underlying MCS research: how, in a disciplined way, to reconcile the conflicting requirements of *partitioning* for safety assurance and *sharing* for efficient resource usage. As yet we do not have the structures (models, methods, protocols, analysis etc.) needed to allow the tradeoffs between partitioning and separation to be properly evaluated. It is clear that MCS will continue to be a focus for practical and theoretical work for some time to come.

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