Task Scheduling of SDR Kernels in Heterogeneous Chips
Opportunities and Challenges

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Outline

- **Part 1: The Hardware Specialization Era**
  – And its impact on SDR applications

- **Part 2: Task Scheduling on Heterogeneous Platforms**
  – STOMP: Scheduling Techniques Optimization in heterogeneous Multi-Processors

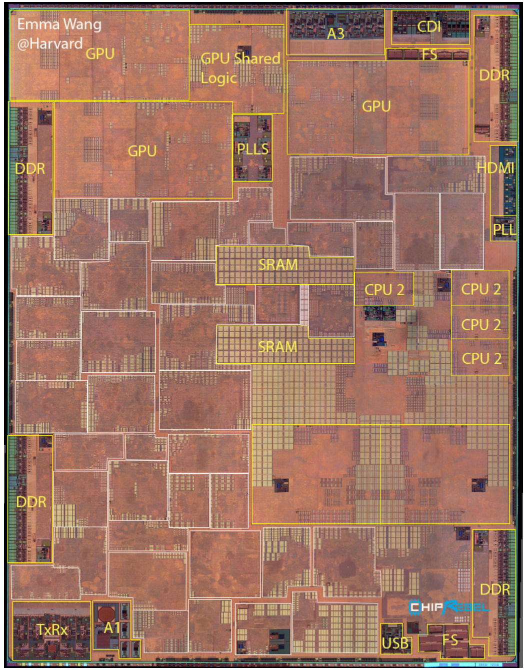
- **Part 3: New Scheduling Techniques**
  – Evaluation and future work

The Hardware Specialization Era Is Already Here...

- Heterogeneous system-on-chips (SoCs) are single chips comprising of many processing elements (PEs) of different nature like CPUs, GPUs and hardware accelerators

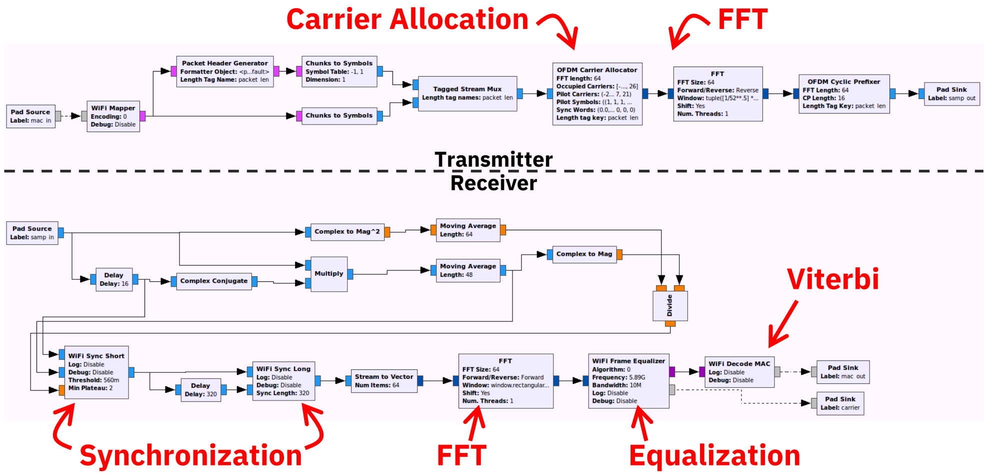
- Heterogeneous SoCs are **extensively** used today
  - Adopted by domains historically dominated by homogeneous architectures
  - Exploit heterogeneous characteristic of applications
  - Significant performance and power efficiency gains

Conventional schedulers are **not optimized** for the characteristics of heterogeneous chips which calls for more intelligent and efficient scheduling

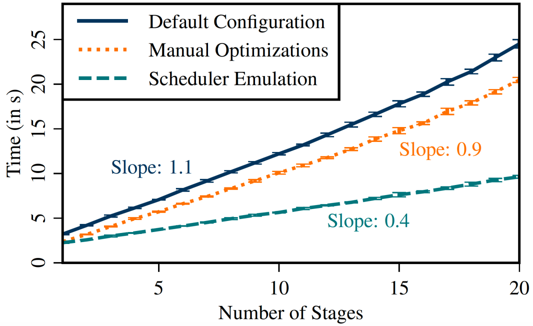


Source: https://www.sigarch.org/mobile-socs/

SDR and the Impact of Specialization & Task Scheduling



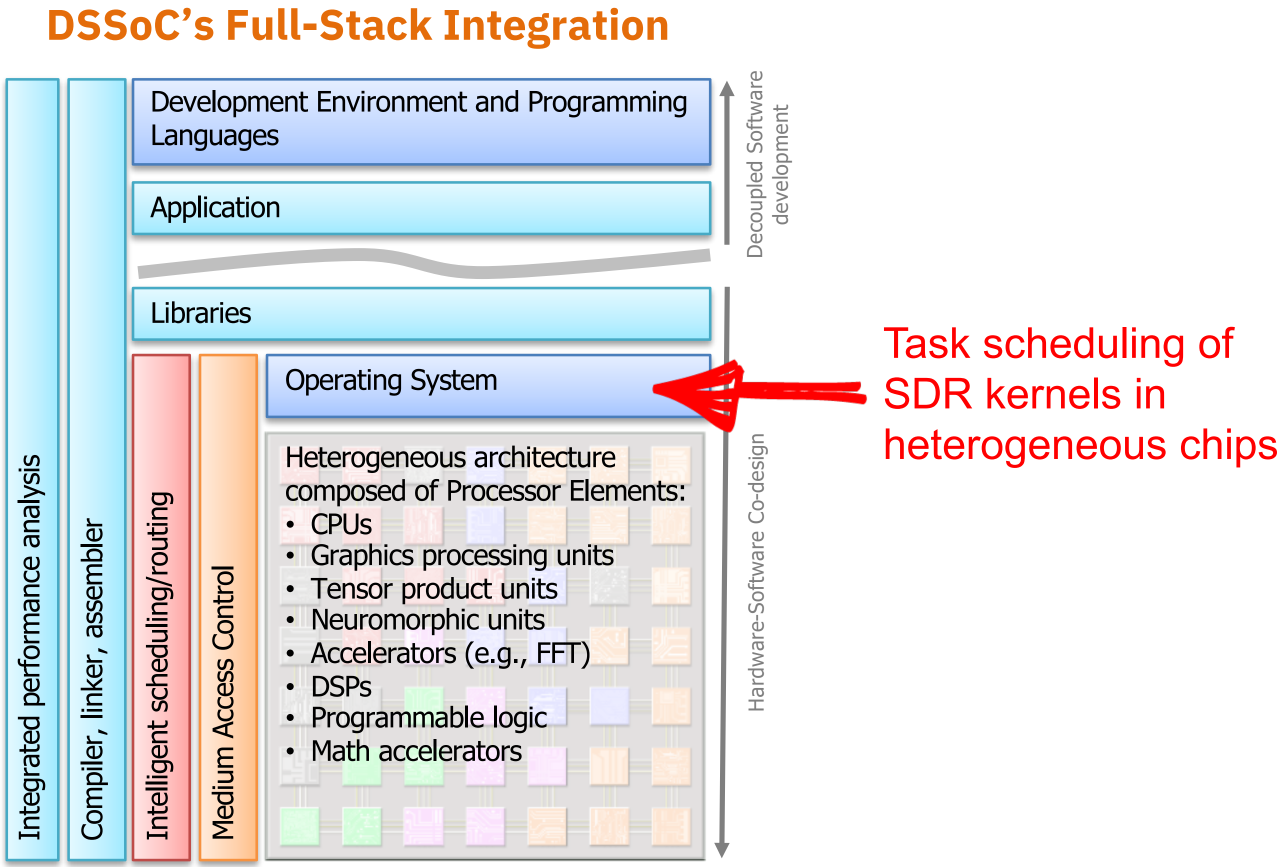
- A typical SDR application may consist of multiple and disparate kernels
- The underlying hardware may also provide accelerators for some or all of them
- However, in frameworks like GNU Radio, the scheduler mostly “ignores” these degrees of heterogeneity – which may provide significant benefits when properly exploited



Prior works have shown that there is significant room for improvement in the GNU Radio scheduler
– E.g. via simple scheduling optimizations to increase cache effectiveness [1]

[1] B. Bloessl, M. Müller, M. Hollick. “Benchmarking and Profiling the GNURadio Scheduler.” Proceedings of the 9th GNU Radio Conference. 2019.

The Big Picture (Where Does This Talk Fit In?)



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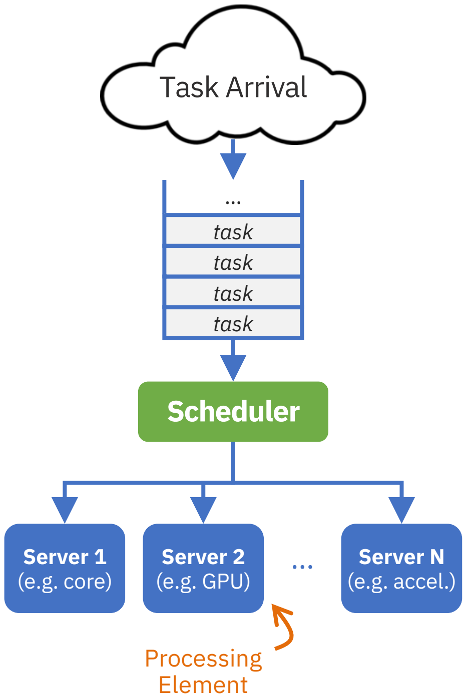
STOMP

- STOMP (**S**cheduling **T**echniques **O**ptimization in heterogeneous **M**ulti-**P**rocessors) is an open-source customizable Python-based simulator for fast prototyping of SoC scheduling policies
  - Check it out: https://github.com/IBM/stomp

- It consists of three main elements:
  - **Tasks:** units of work (aka *jobs*, *threads*, *processes*)
    - Executed in the heterogeneous SoC
    - Typically described as task types (e.g. *fft*, *decoder*, etc.)
  - **Servers:** processing units that can execute tasks
    - Different servers execute tasks with different "efficiency"
    - E.g. an FFT task on DSP accelerator *vs* general-purpose CPU
  - **Scheduler:** dynamically maps tasks to servers during the execution
    - It supports user-defined scheduler algorithms



STOMP Overview

Python

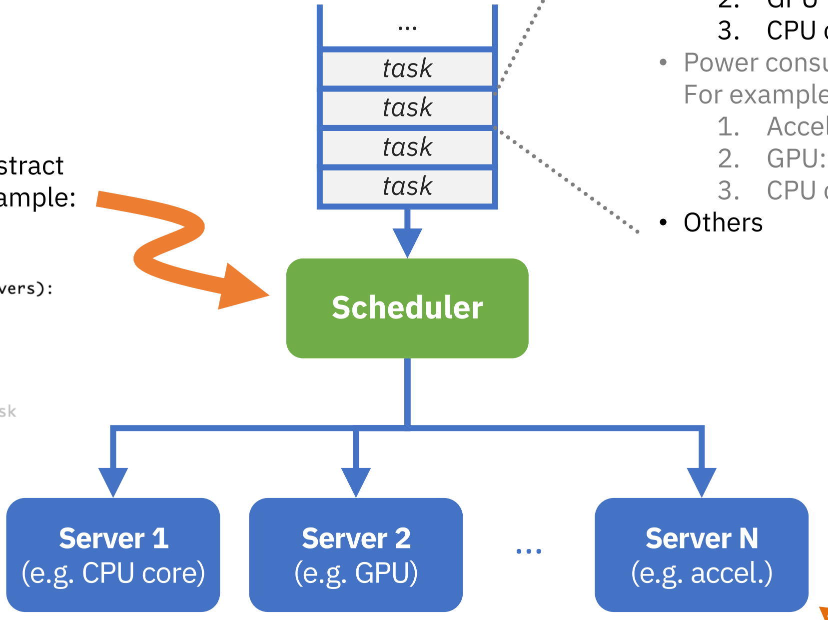
“Pluggable” Scheduling Policy

- The user is only required to implement the abstract Python class `BaseSchedulingPolicy` – for example:

```
class SchedulingPolicy(BaseSchedulingPolicy):

    def assign_task_to_server(self, sim_time, tasks, servers):

        if (len(tasks) == 0):
            # There aren't tasks to serve
            return None

        # Look for an available server to process the task
        for server in servers:

            if (not server.busy):

                # Pop task in queue's head
                task = tasks.pop()
                server.assign_task(sim_time, task)

                return server

        return None
```

Task arrival

- Probabilistic (e.g. exponential)
- Realistic (trace-based)



Processing Element

JSON

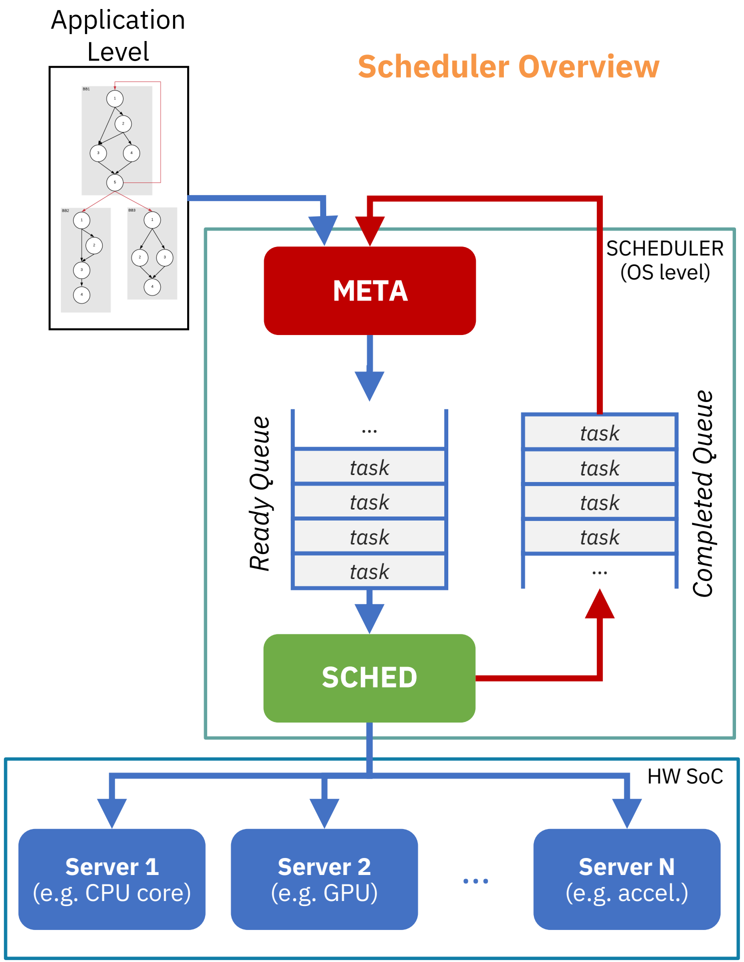
Task attributes

- Service time (probabilistic or trace-based)
- Target processing elements
  For example:
  1. Accelerator
  2. GPU
  3. CPU core
- Power consumption
  For example:
  1. Accelerator: 100 mW
  2. GPU: 400 mW
  3. CPU core: 900 mW
- Others

Future work

STOMP Intrinsic Operation

- STOMP consists of two integral parts:
  - **Meta scheduler** (“META”) ➜ pre-processor that aids in the scheduling decision
  - **Task scheduler** (“SCHED”) ➜ assigns ready tasks to available servers (PEs) to optimize the overall response time
- META and SCHED communicate via two queues: *ready* and *completed*
- **Input:** directed acyclic-graphs (DAGs) of multiple tasks with associated real-time constraints (priority and deadline)

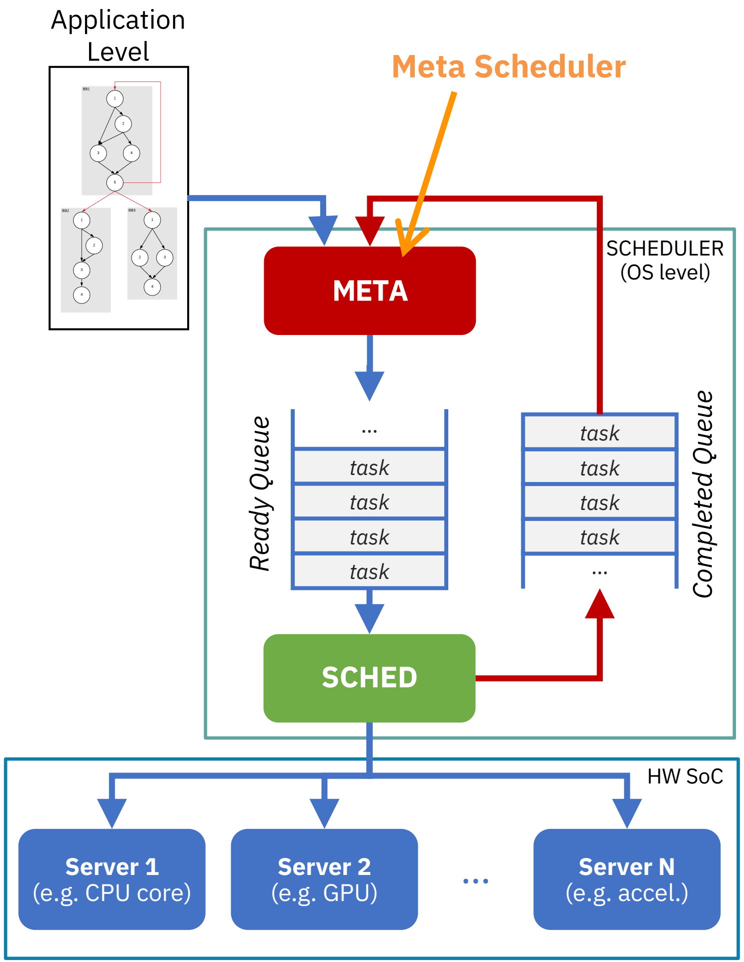


Meta Scheduler ("META")

- META tracks heuristics associated with the DAG:
  - Task dependencies, DAG deadline and available slack, DAG and tasks priority
- Then orders *ready* tasks based on a **"rank"**
  - Can be computed in different ways
  - For example, as a function of task's priority, slack and worst-case execution time (WCET)

$$Rank_i = \frac{Task_i\ Priority}{Task_i\ Slack\ - Task_i\ WCET}$$

- Drops non-critical priority DAGs if deadline is missed
  - All remaining tasks in the DAG are dropped
  - Help reduce task traffic in the system

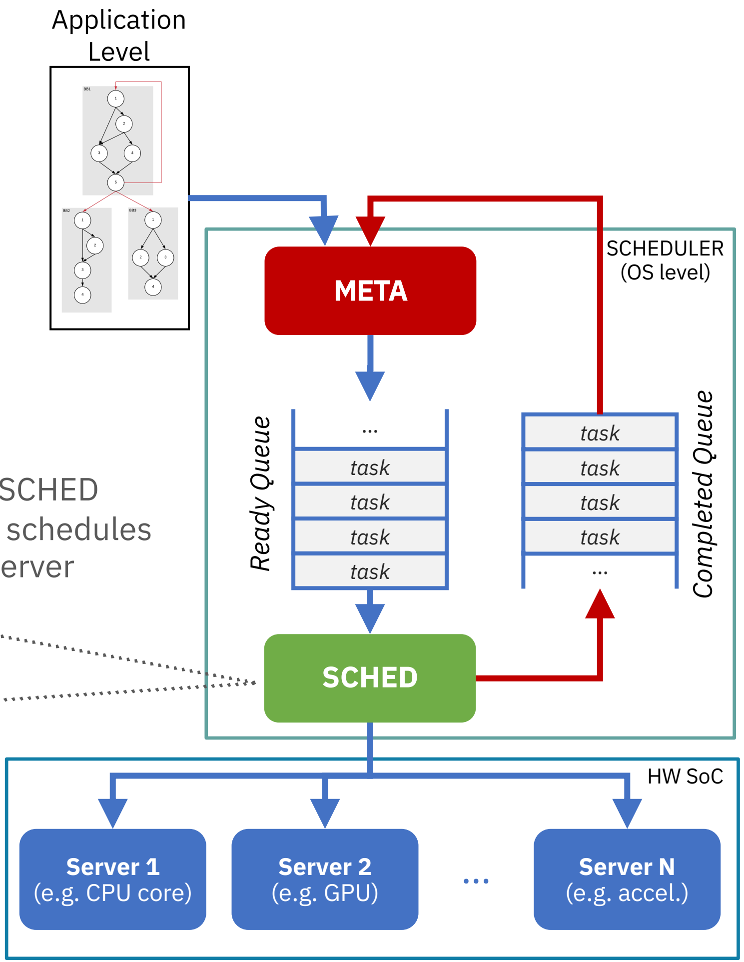


Task Scheduler ("SCHED")

The user primarily defines the assignment actions:
(here the task is scheduled to the fastest server type)

```
from stomp import BaseSchedulingPolicy

class SchedulingPolicy(BaseSchedulingPolicy):

  def init(self, servers, stomp_stats, stomp_params):
    ...

  def remove_task_from_server(self, sim_time, server):
    ...

  def assign_task_to_server(self, sim_time, tasks):

    if (len(tasks) == 0):
    # There aren't tasks to serve
      return None

    # Determine task's best scheduling option (target server)
    target_server_type = tasks[0].mean_service_time_list[0][0]

    # Look for an available server to process the task
    for server in self.servers:
      if (server.type == target_server_type and not server.busy):
        # Pop task in queue's head and assign it to server
        server.assign_task(sim_time, tasks.pop(0))
        return server
    return None
```

Invoked by SCHED each time it schedules a task to a server



Simulation Parameters and Configuration

- Example `stomp.json` configuration file:

```
"general" : {
    "logging_level":        "INFO",
    "random_seed":          0,
    "working_dir":          ".",
    "basename":             "",
    "pre_gen_arrivals":     false,
    "input_trace_file":     "",
    "output_trace_file":    ""
},

"simulation" : {
    "sched_policy_module":  "policies.simple_policy_ver3",
    "max_tasks_simulated":  10000,
    "mean_arrival_time":    50,
    "distribution":         "Poisson",
    "power_mgmt_enabled":   false,
    "max_queue_size":       1000000,
```

```
"servers" : {
          "cpu_core" :  { "count" : 8 },
          "gpu" :       { "count" : 2 },
          "fft_accel" : { "count" : 1 }
      },

"tasks" : {
          "fft" : {
              "mean_service_time" : {
                  "cpu_core"  : 500,
                  "gpu"       : 100,
                  "fft_accel" : 10
              },

              "stdev_service_time" : {
                  "cpu_core"  : 5.0,
                  "gpu"       : 1.0,
                  "fft_accel" : 0.1
              }
          },
   ...
```

Example Using a Simple DAG

- **Input:** priority-1 5-node DAG with varying kernels
  – Deadline of DAG is set to 1100 units of time

- Time 0: META pushes *Task 0* to *ready queue* with a rank

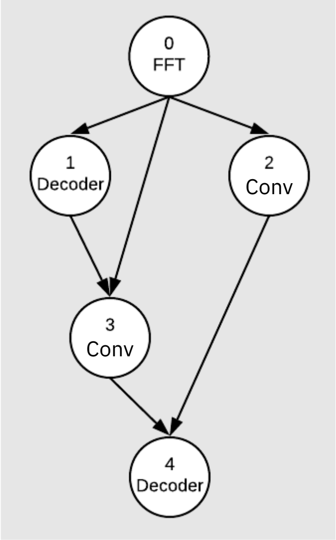
$$Rank_i = \frac{Task_i\ Priority}{Task_i\ Slack\ - Task_i\ WCET}$$

DAG's priority

$$Rank_0 = \frac{1}{500\ - 500} = \infty$$

- *Task 0* completes execution in 10 units of time because it was run on the accelerator
  – META then calculates the remaining slack of the DAG and next available tasks

5-node DAG



Task	CPU	GPU	Accel
FFT	500	100	10
Convolution	200	150	10
Decoder	200	150	None

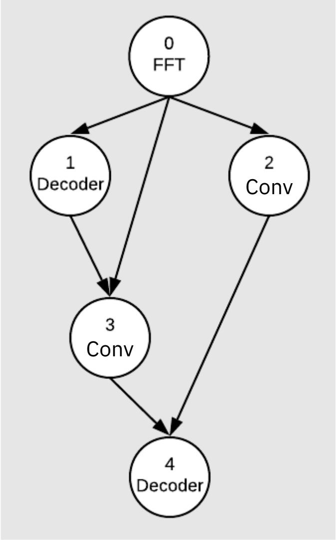
Tasks' Execution Times

Example Using a Simple DAG (cont'd)

- Time 10: *Task 1* and *Task 2* become ready
  - Scheduled in the order of their rank
  - *Task 1* has a higher rank than *Task 2*
    - $Rank_1 = 1/(363-200) = 1/163$
    - $Rank_2 = 1/(545-200) = 1/345$
  - **This process continues for all tasks in the DAG**

- **Multi-DAG execution:**
  - Multiple DAGs arrive consecutively
  - At every stage, ready tasks are scheduled in rank order across all DAGs

5-node DAG



Task	CPU	GPU	Accel
FFT	500	100	10
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Decoder	200	150	None

Tasks' Execution Times

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Evaluation

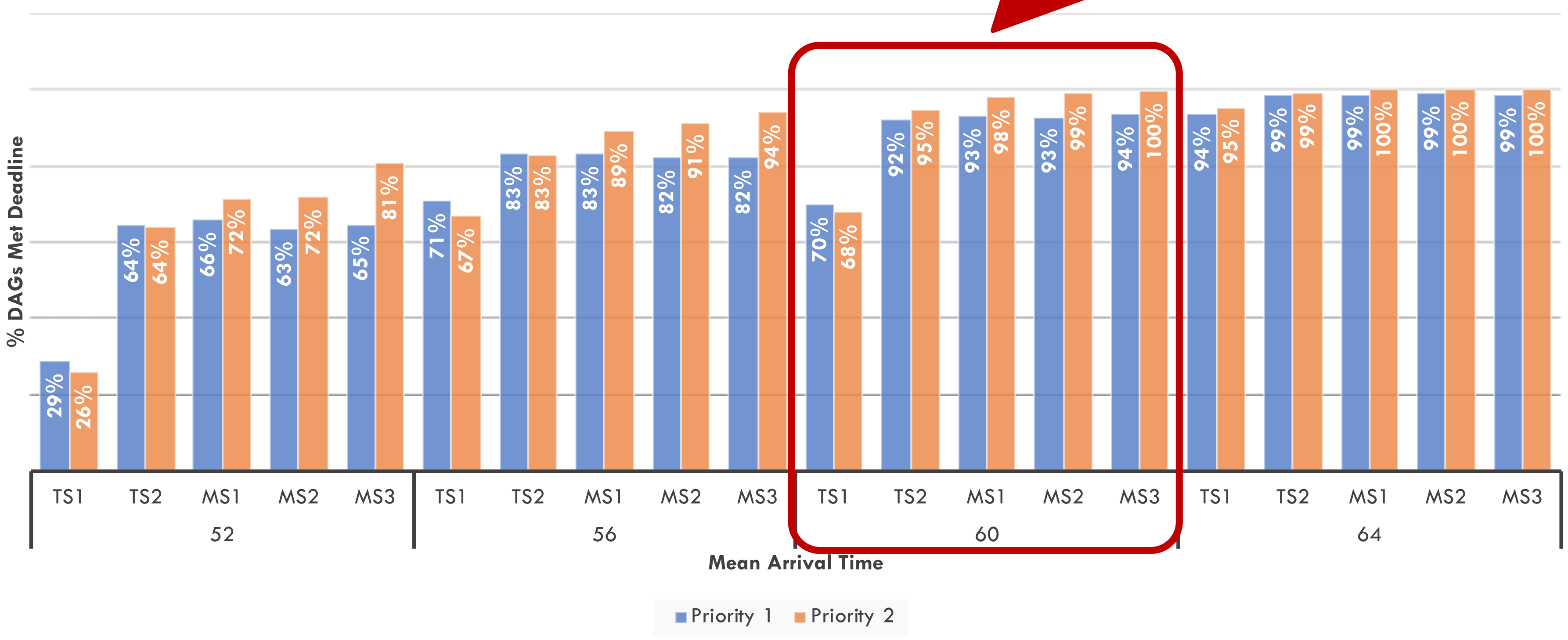
- DAG trace: **1,000** 5- and 10-node static DAGs
  - Priority: 1 or 2 assigned randomly
  - Deadline: critical path length considering worst-case execution times
- Task types:
  - FFT, Convolution, Decoder
- Metric of evaluation:
  - Met deadline

Task	CPU	GPU	Accel
FFT	500	100	10
Convolution	200	150	10
Decoder	200	150	None

- Baseline task schedulers with META dependency tracking only
  - **TS1:** non-blocking task scheduler
  - **TS2:** non-blocking task scheduler assuming tasks ahead in queue are scheduled
- TS2 scheduler with both META dependency tracking *and* pre-processing
  - **MS1:** rank based on task's deadline and average execution time, and priority
  - **MS2:** rank based on task's deadline and maximum execution time, and priority
  - **MS3:** rank based on task's available slack and maximum execution time, and priority

Evaluation: Met Deadline

MS3 meets deadline for 33% and 5% more tasks than TS1 and TS2, respectively



Running STOMP

```
ripper 00:44 ~/research/IBM/STOMP/stomp_clean:
```

Summary and Path Forward

- STOMP is in active development with a number of additional items being worked on
  - More complete input trace format, more statistics and data about the runs

- And there are some extensions planned
  - Power consumption models and power management features
  - **Machine learning-based scheduling policies**

- And work to move from the abstract to the more concrete
  - Analysis of GNU Radio workloads to generate more realistic DAG traces

- **But STOMP already provides plenty of opportunity and capability to explore the problem space – readily available now:**

https://github.com/IBM/stomp

(check out *dev* for leading-edge features)

Thank You!

Photo by Balthazar Korab
Source: http://www.shorpy.com/node/15488

ajvega@us.ibm.com

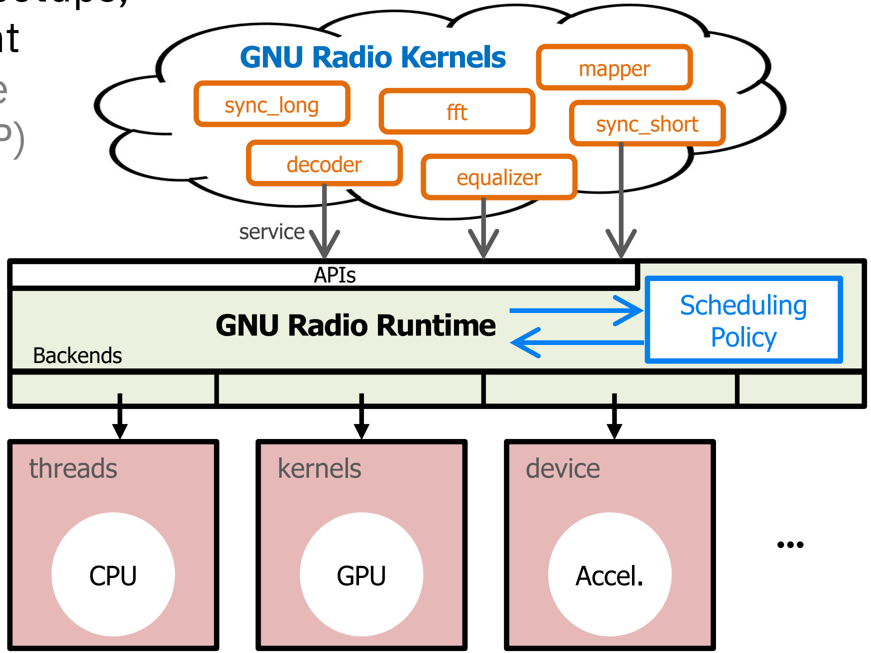
https://github.com/augustojv

Smart Scheduler Roadmap and Big Picture

- **STOMP is only intended for early-stage evaluation of smart scheduling policies**

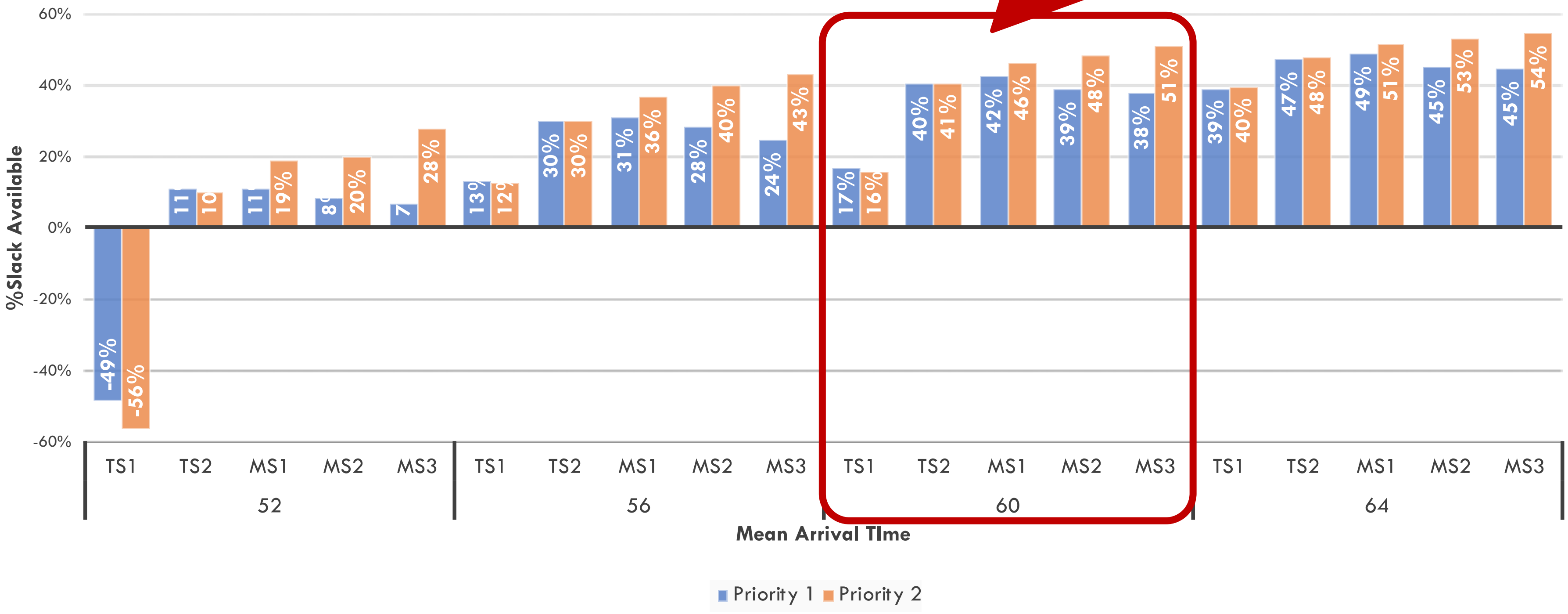
- Ultimately these policies should be ported to real setups, e.g. as part of the GNU Radio run-time environment
  - GNU Radio makes run-time decisions using the specified policy (originally developed in STOMP)

- We can also use existing software middleware frameworks (e.g. OpenCL, OpenMP, OpenSSL) to prototype scheduling policies
  - Target architectures: IBM P9, NVIDIA Xavier



Evaluation: Slack Available

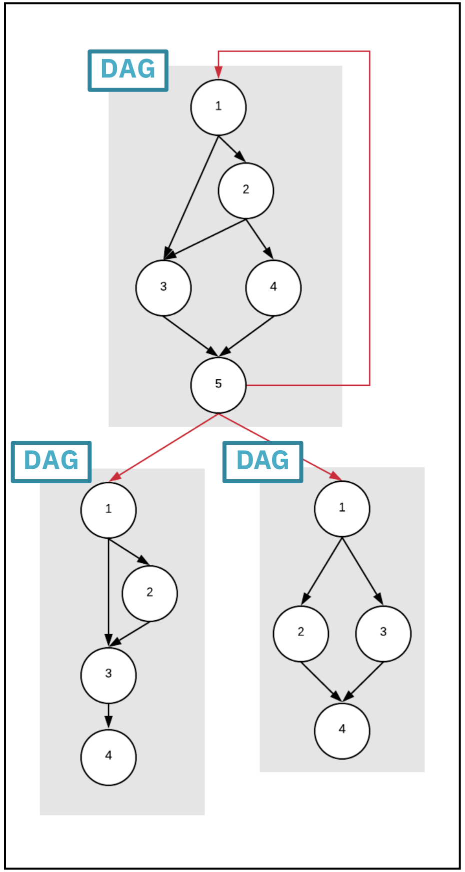
MS3 results in 35% and 10% more slack than TS1 and TS2, respectively



STOMP Inputs

- Domain-specific applications ➜ control flow graphs
- Control flow graphs are divided into directed acyclic-graphs (DAGs) of multiple tasks
  – **Task:** unit of work that can execute on a server (PE)
- DAG trace as input
  – **Compile-time:** applications are known and DAGs are static
  – **Runtime:** DAGs arrive dynamically with variable arrival rate
- Each DAG has real-time constraints associated to it
  – A priority and a deadline
  – Determined at run-time based on the environment and functions of each DAG

Control Flow Graph



Scheduling Mechanism

- When a DAG arrives, META pushes ready tasks to the *ready queue* ordered by rank
  - SCHED then schedules them onto servers (PEs)
- Once a task completes:
  - SCHED pushes it into the *completed queue*
  - Task ID and execution time are passed back to META
  - META pops the completed task and finds its parent DAG
- META checks for resolved dependencies and finds ready tasks, then:
  - Calculates deadline of the new ready tasks
  - Assigns new priority based on the remaining slack
  - Updates rank of ready tasks and re-orders them
  - If remaining slack is negative and task has non-critical priority, drops the DAG