IDEA 2015

Investigating
Dataflow in
Embedded computing
Architecture

Pipelined Scheduling of Acyclic SDF Graphs using SMT Solvers

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Motivation

- **from hardware to software, due to embedded multi-cores**

  Kalray MPPA256, Tilera GX, ST Micro P2012/Shtorm

- **SDF – important programming model [Lee, Messerschmitt 1987]**

  SDF compilers :

  SDF3, DOL, StreamIT, SigmaC, …

compiler optimizations may require generic problem-solvers :

model-checking (UPPAAL,…), ILP (lpsolve,…), SMT (Z3, …), etc…

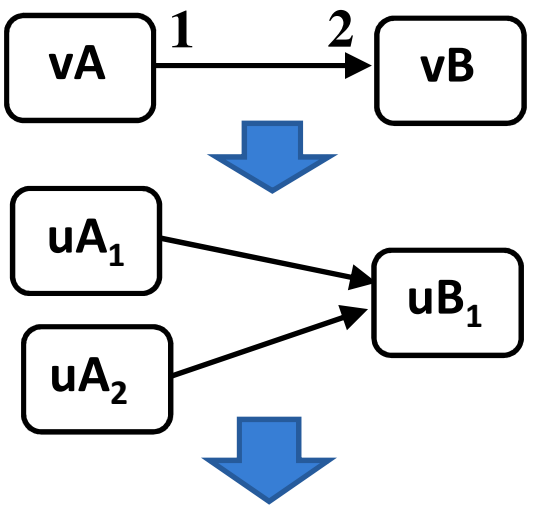
- **multi-criteria optimization, whereby constraints and costs may undergo frequent modification**
- **real-time constraints apply, schedulability analyses require support of preemption, missing in DSP/many-cores**

Real-time Constraints

- **Real-time systems: tasks $\mathcal{T}_i : (C_i, D_i, T_i)$**
  - **C_i - WCET**
  - **D_i - deadline** **PIPELINING : $T < D$**
  - **T_i - period**

- **DAG tasks**
  - **$\mathcal{T}_i$ is a DAG**
  - **sub-tasks U and predecednce arcs $\mathcal{E}$: $(U_i, \mathcal{E}_i, C_i(u \epsilon U), D_i, T_i)$**
  - **for simplicity: one DAG task $\mathcal{T}$**
    - **call it task graph**
    - **it is SDF translated to HSDF**
    - **pipelining for task graph**

SDF – synchronous dataflow




```
Thread T      -- in general, must be multi-thread
    A__B : new FIFO;
    procedure A is SubroutineA (A__B);  -- actor vA
    procedure B is SubroutineB (A__B);  -- actor vB
    k : Integer;
begin
            for k  in 1 . . ∞ loop
               A(1);  A(2);  B(1); -- uA1 uA2 uB1
             end loop
end
```

SDF graph $S\ (V, E)$

vA, vB – actors
atomic software subroutines

derived HSDF

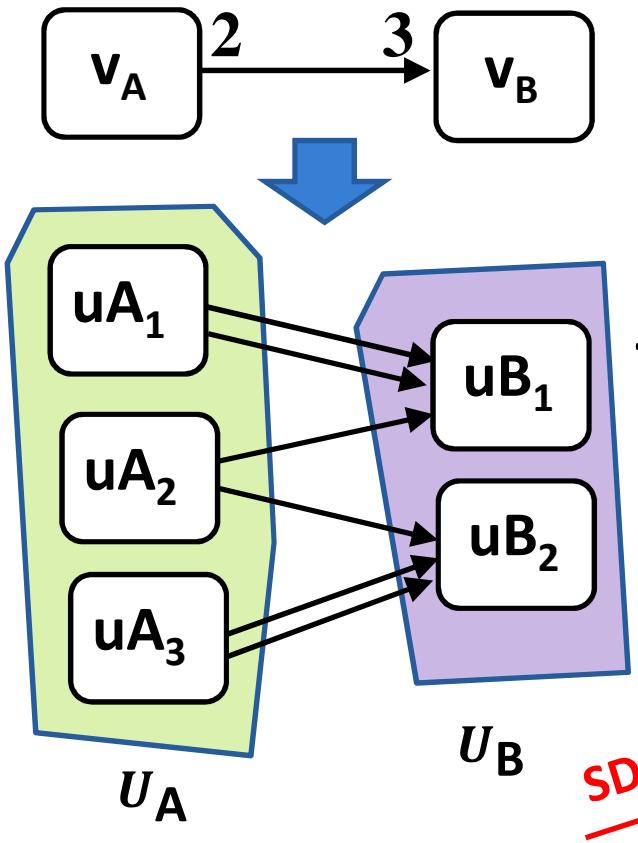
task graph: $T\ (U, \mathcal{E})$

U **– uA$_1$, uA$_2$, uB$_1$ – tasks**

instances (copies) of actor subroutines

$\mathcal{E}$ **– precedence arcs;**

SDF – synchronous dataflow



SDF graph
V actors

Task graph
EXP tasks

$U = U_A \cup U_B$; $U_A = \{uA_1, uA_2, uA_3\}$

task-to-SDF connection

SDF symmetry

SDF schedule schemes:
from general to restrictive

$s(u, k)$ - "schedule" variable
start time of *k*-th execution of task *u*

1. Self-timed (no restrictions)

2. Frame-periodic tasks
$s(u, k + W) = s(u, k) + WT$
W free variables per task O (EXP)

3. Periodic tasks: (DAG tasks)
$W = 1$ O (EXP)

4. Periodic actors: (common for SDF)
uA_m have period T/U_A
uB_h have period T/U_B
one free variable per actor O(V)

Multi-core Architecture

- homogeneous multiprocessor
- consists of clusters (islands, tiles)
  - cluster = *M* cores + shared memory
- between clusters – network on chip communication
  future work
- e.g. Shtorm (ST Micro), MPPA 256 (Kalray)
  - 16 clusters x 16 cores, *M*=16

- this work – assume one cluster with *M* processors
- inside cluster – instantaneous communication

Problem Encoding for an SMT Solver (1)

- **atom:** difference logic $\mathbf{A}: x \leq C$ or $\mathbf{B}: x - y \leq C$
- **constraint:** Boolean $(\mathbf{A} \vee \mathbf{B}) \wedge \neg \mathbf{C}$
- **constraint logic programming**

  find variable assignment satisfying all the constraints

  SMT = satisfiability modulo theory tools, Yices, Z3, MathSAT, …

  satisfiability – for Boolean constraints

  theory – for difference logic | linear arithmetic | … atoms

Problem Encoding for an SMT Solver (2)

- **Variables:** $s(u)$ **and** $\mu(u)$ **for** $u \epsilon U$

$s(u) \in [0, +\infty)$: the first scheduled time :

$$s(u) = s(u,k)\,|_{k=0}$$

$$s(u,k) = s(u) + kT$$

$\mu(u) \in \{1, 2, \dots\}$: the processor core id

- **a typical atom for scheduling :**

$$\Phi_{u,\hat{u}} \; : \; s(u) + C(u) \leq s(\hat{u})$$

task u comes before task $\hat{u}$

- **Constraint I : Precedence in graph** $(U, \mathcal{E})$ **:**

for $(u, \hat{u}) \in \mathcal{E}$: $\Phi_{u,\hat{u}}$

Problem Encoding for an SMT Solver (3)

- **Constraint II : Mutual exclusion of tasks U:**

$$\text{for } u \neq \hat{u} \in U: \quad \mu(u) = \mu(\hat{u}) \Rightarrow \quad \Phi_{u,\hat{u}} \vee \Phi_{\hat{u},u,}$$

- **Constraint III: Core Count Cost M**

$$\text{for } u \in U: \quad \mu(u) \leq M$$

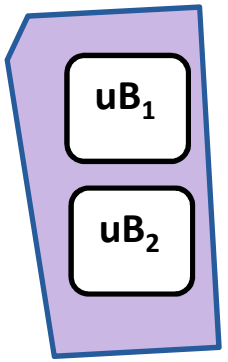
- **Constraint IV: Deadline Cost D**

$$\text{for } u \in U: \quad s(u) + C(u) \leq D$$

- **Constraint V: SDF Symmetry Breaking**

for v $\in V$, actor instances uV_1 uV_2 , …$\in U_v$:

$$s(uV_1) \leq s(uV_2) \leq \cdots \leq \cdots$$



U_B

most efficient in combination with processor symmetry breaking (omitted)

Problem Encoding for an SMT Solver (4)

contribution of this paper: period locality principle

if the maximal timespan of tasks running on the same core

$$s(\hat{u}) + C(\hat{u}) - s(u)$$

fits within the period T then we can guarantee periodic repetition without processor core conflicts

- **Constraint VI: Period Cost T**

for $u, \hat{u} \in U : \mu(u) = \mu(\hat{u}) \Rightarrow \; s(\hat{u}) + C(\hat{u}) - s(u) \leq T$

advantages

permits binary-search on optimal period T

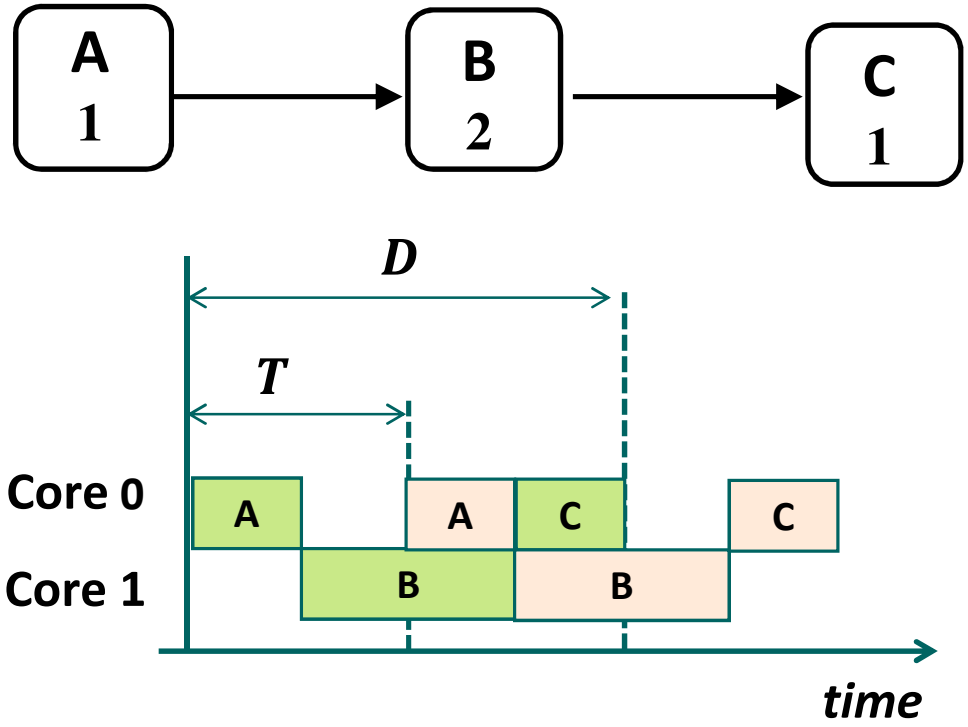
permits monotonic cost space search = extensions of binary search

sustainable for sporadic inter-arrival superior to T, keeping the same D

disadvantage

excludes some optimal (but non-sustainable) schedules

Period Locality Counter-example



Experiment Summary

- **implemented in our many-core compiler: StreamExplorer**

  http://www-verimag.imag.fr/~poplavko/streamExplorer.html
- **Z3 solver for SMT**
- **StreamIt application benchmarks**
- **Kalray MPPA-256 many-core**

  used a cluster with 16 cores
- **Main results:**

  - trade-offs between processor count and period

  - 15% maximal timing error of benchmark execution on hardware

Related Work

- **DAG-task preemptive scheduling**
  - schedulability analyses developed, see e.g. [Bonifaci ECRTS'13]
  - require preemption
- **SDF scheduling**
  - actor-periodic, see e.g. [Stefanov DATE'14]
  - more restrictive than task-periodic
- **Non-preemptive pipelined scheduling with model checking, ILP, SMT,…**

  (a) unfolding [Legriel ECRTS'11]

  (b) modulo scheduling, e.g. [Lombardi CPAIOR'11]

  SMT encoding : e.g. our tech rep. [TR-2014-5]

  - previously, for plain task graphs, unaware of SDF symmetry
  - more complex SMT encoding than period locality
  - may produce more optimal but non-sustainable results
  - additional experiments show similar performance

Conclusions

- SMT solvers to address SDF pipelined scheduling
- assuming no preemption, often the case in DSP and many-core processors, invalidating real-time theory
- task-periodic, being more general than actor-periodic, yet SDF symmetry was exploited
- more restrictive in theory than previously existing methods
- yet in practice similar performance, and offering sustainable schedules and monotonic search

Thank you!

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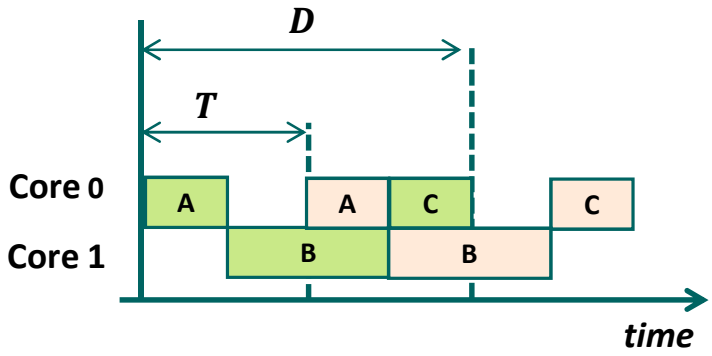

$$\mu(u) = \mu(\hat{u}) \Rightarrow \quad s(\hat{u}) + C(\hat{u}) - s(u) \leq T$$

http://www-verimag.imag.fr/~poplavko/streamExplorer.html