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Optimal and fast throughput evaluation of CSDF

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ABSTRACT

The Synchronous Dataflow Graph (SDFG) and Cyclo-Static Dataflow Graph (CSDFG) are two well-known models, used practically by industry for many years, and for which there is a large number of analysis techniques. Yet, basic problems such as the throughput computation or the liveness evaluation are not well solved, and their complexity is still unknown. In this paper, we propose K-Iter, an iterative algorithm based on K-periodic scheduling to compute the throughput of a CSDFG. By using this technique, we are able to compute in less than a minute the throughput of industry applications for which no result was available before.

Keywords

Cyclo-Static Dataflow Graph, Static analysis, Throughput

1. INTRODUCTION

The execution of streaming applications such as multimedia streaming or signal processing by an embedded system must respect strict constraints of throughput, latency, memory usage, and power consumption. Several dataflow programming languages have been developed to express this class of applications in order to handle such requirements.

Dataflow modeling involves designing an application as a set of tasks which communicate only through channels. Synchronous Dataflow Graph (SDFG) and more generally Cyclo-Static Dataflow Graph (CSDFG) are two models to statically specify an application behavior. They are commonly used to evaluate applications in term of throughput or memory consumption using dataflow static analysis techniques.

The exact determination of the throughput requires to compute an optimal schedule. Most of the authors considered as soon as possible schedules [14, 8]. Their computation has an exponential complexity with respect to the dataflow size in the worst case, and is usually too long for real-life applications. Approximative methods were also developed to get polynomial-time evaluations. They usually limit their space of solutions to particular categories of schedules such as the periodic ones [1] (or equivalently strictly periodic). A periodic schedule is a cyclic schedule whose definition is only composed of a first execution time per task and a period of execution per task. Polynomial methods have been proposed to compute periodic schedules of SDFG [1] and CSDFG [4], and these methods can be applied to throughput estimation or buffer sizing.

Meanwhile, existing static dataflow languages are revealing new cases which are not well supported by these techniques [4]. These cases are too complex to be used with exact schedules: as an example, there is no optimal throughput result for the H264 application proposed by [4]. Furthermore, periodic solutions remain an over-approximation which might be insufficient to be applied for embedded systems.

K-periodic scheduling [3] was developed as an alternative method when both as soon as possible and periodic methods are not satisfactory. A K-periodic schedule is built by periodically repeating a schedule of its $K_1$ first executions. The estimated value of the throughput directly depends on the periodicity vector $K$. A periodic schedule can be seen as a particular case of K-periodic schedule for which $K_2 = 1$ for every task. Setting $K$ equal to what is called the repetition vector provides the optimal value of the throughput, but space and time complexities are not scalable.

An exponential number of pertinent values $K$ may be considered between these two extreme solutions to exactly evaluate the throughput. This paper aims to optimally compute the throughput by iteratively increasing a periodicity vector $K$ until an optimal solution is reached. From a theoretical point of view, the computation of a K-periodic schedule of minimum period is presented, followed by an original optimality test of a periodicity vector. Our algorithm is successfully compared for both SDFG and CSDFG with classical approaches and solves several classical benchmarks.

The contributions of this paper are:

• an extension of K-periodic scheduling to CSDFG,
• an optimality test of a K-periodic schedule,
• and K-Iter, an heuristic to efficiently explore the possible K-periodic schedules for a CSDFG.

Section 2 introduces the model, notations and some definitions on K-schedules. Our algorithm is presented in Section 3. Section 4 is devoted to the experimentations. Related works are presented in Section 5. Section 6 is our conclusion.
2. CYCLO-STATIC DATAFLOW GRAPHS

This section is devoted to the presentation of the model and notations of Cyclo-Static Dataflow Graphs, followed by the definition of the throughput. K-periodic schedules are lastly introduced.

2.1 Model definition

A Cyclo-Static Dataflow Graph (CSDFG) is a directed graph in which nodes model tasks, and arcs correspond to buffers. It is denoted by $G = (T, B)$ where $T$ (resp. $B$) is the set of nodes (resp. arcs).

Every task $t \in T$ is decomposed into $\varphi(t)$ phases; for every value $p \in \{1, \ldots, \varphi(t)\}$, the $p^{th}$ phase of $t$ is denoted by $t_p$ and has a constant duration $d(t_p) \in \mathbb{N}$. One iteration of the task $t \in T$ corresponds to the ordered executions of the phases $t_1, \ldots, t_{\varphi(t)}$.

Furthermore, every task $t \in T$ is executed several iterations: for every integer $n$ and for every phase $p$, $(t_p, n)$ denotes the $n^{th}$ execution of the $p^{th}$ phase of $t$.

Every buffer $b = (t, t') \in B$ represents a buffer of unbounded size from the task $t$ to $t'$ with an initial number of stored data, $M_0(b) \in \mathbb{N}$. $\forall p \in \{1, \ldots, \varphi(t)\}$, $i_n(b(p))$ data are written in $b$ at the end of an execution of $t_p$. Similarly, $\forall p' \in \{1, \ldots, \varphi(t')\}$, $o_n(b(p'))$ data are read from $b$ before the execution of $t_p$.

In addition, we set

$$i_b = \sum_{p=1}^{\varphi(t)} i_n(b(p))$$

and $o_b = \sum_{p=1}^{\varphi(t')} o_n(b(p'))$.

A Synchronous Dataflow Graph (SDFG) can be seen as a special case of CSDFG where each task has only one phase: $\forall t \in T$, $\varphi(t) = 1$.

Figure 1 shows a buffer $b$ between the two tasks $t$ and $t'$. The respective numbers of phases of the two tasks are $\varphi(t) = 3$ and $\varphi(t') = 2$. The two associated vectors of $b$ are $i_n(b) = [2, 3, 1]$ and $o_n(b) = [2, 5]$, thus $i_b = 6$ and $o_b = 7$. The initial number of data is $M_0(b) = 0$.

![Figure 1: An simple buffer between two tasks t and t'.](image1)

2.2 Schedules and consistency

A feasible (or valid) schedule associated with a CSDFG is a function $S$ that associates, for every triple $(t, p, n)$ with $t \in T$, $p \in \{1, \ldots, \varphi(t)\}$, and $n \in \mathbb{N} - \{0\}$, $S(t_p, n) \in \mathbb{R}$, the starting time of $(t_p, n)$, such that the number of data in every buffer $b \in B$ remains non-negative, i.e. no data are read before they are produced.

Consistency is a necessary (but non-sufficient) condition for the existence of a valid schedule within bounded memory that was first established for SDFG [10]. It has been extended to CSDFG [2] by considering the cumulative number of data produced/consumed by one iteration of its tasks. A CSDFG is consistent if there exists a repetition vector $q \in (\mathbb{N} - \{0\})^{\mid T\mid}$ such that

$$\forall b = (t, t') \in B, \quad q_t \times i_b = q_{t'} \times o_b.$$
3. THROUGHPUT EVALUATION METHOD

This section presents our algorithm. Subsection 3.1 recalls the characterization of periodic schedules of a CSDFG, which is extended to K-periodic schedules in subsection 3.2 using a simple transformation. Next subsection treats the computation of the minimum period of a K-periodic schedule. Subsection 3.4 is devoted to an original optimality test of a fixed K. Subsection 3.5 is devoted to our algorithm K-Iter which heuristically explores the possible K-periodic schedules for a CSDFG in order to optimally provide its maximal throughput.

3.1 Periodic scheduling of a CSDFG

The following Theorem 2 defines a feasible periodic schedule as a set of linear constraints. This set of constraints composes a linear program which solve the maximal throughput of a periodic schedule. In order to define the Theorem 2, several definition are required.

First, the total number of data produced by t in the buffer b at the completion of (t, n) is defined as

\[ I_a(t, n) = \sum_{\alpha=1}^{n} m_b(a) + (n - 1) \times i_b. \]

Similarly, the number of data consumed by t' in the buffer b at the completion of (t', n') is defined by

\[ O_a(t', n') = \sum_{\alpha=1}^{n'} o_{tb}(a) + (n' - 1) \times i_b. \]

The total number of data contained in a buffer must remain non-negative. That is, any execution (t', n') can be done at the completion of (t, n) if and only if

\[ M_0(a) + I_a(t, n) - O_a(t', n') \geq 0. \]

For example, considering the CSDFG pictured in Figure 1, the execution (t', 1) can be done at the completion of (t, 2) since

\[ M_0(a) + I_a(t, 2) - O_a(t', 1) = 0 + 8 - 7 \geq 0. \]

Then the data points contained in a buffer are defined by:

\[ \tilde{G} \subseteq T \times B \times Z \times \{0\}, \text{ with } \tilde{G} = \{ (t, b, a, \gamma) : 0 \leq \gamma \leq \gamma_{\tilde{G}} \}. \]

Let us consider a buffer b = (t, t') ∈ B. For any pair (p, p') ∈ \{1, \ldots, φ(t')\} \times \{1, \ldots, φ(t')\}, let us define

\[ Q^o_{\tilde{G}}(p, p') = O_a(t', 1) - I_a(t, 1) - M_0(b) + in_b(p). \]

We also note

\[ a^o_{\tilde{G}}(p, p') = \left( Q^o_{\tilde{G}}(p, p') - \min \{ in_b(p), out_b(p') \} \right) \frac{\gcd_a}{\gcd_a}. \]

and

\[ \beta^o_{\tilde{G}}(p, p') = \left( Q^o_{\tilde{G}}(p, p') - 1 \right) \frac{\gcd_a}{\gcd_a}. \]

We now recall Theorem 2 which characterizes any feasible periodic schedule.

**Theorem 2.** ([3]). Let G be a consistent CSDFG. Any periodic schedule S of period \( \Omega_{\tilde{G}} \) is feasible if and only if, for any buffer b = (t, t') and for every pair (p, p') ∈ \{1, \ldots, φ(t')\} \times \{1, \ldots, φ(t')\} with \( a^o_{\tilde{G}}(p, p') \leq \beta^o_{\tilde{G}}(p, p') \),

\[ S(t', 1) - S(t, n) \geq d(t, n) + \Omega_{\tilde{G}} \times \frac{\beta^o_{\tilde{G}}(p, p')}{\gcd_a}. \]

### 3.2 Extension to K-Periodic scheduling

The extension of Theorem 2 to K-periodic schedules with a fixed periodicity factor K comes from a transformation of the initial CSDFG \( \tilde{G} = (T, B) \) to another equivalent one \( \tilde{G} = (T, \tilde{B}) \) of the same structure for which the adjacent vectors of any task t are duplicated Kt times.

For any vector v of size s, and any integer P > 0, \( [v]^P \) denotes the vector of size s × P obtained by duplicating v exactly P times, i.e., \( \forall k \in \{1, \ldots, s\} \),

\[ [v]^P(k) = [v]^P(k + s) = \cdots = [v]^P(k + (P - 1) \times s) = v(k). \]

For any task t ∈ T, we set

\( \tilde{\varphi}(t) = Kt \times \varphi(t) \)

and for any p ∈ \{1, \ldots, \varphi(t')\},

\( d(t) = [d(t)]^{Kt} \).

For any buffer b = (t, t') ∈ B, we set

\( i_b = [i_b]^{Kt} \) and \( o_{tb} = [o_{tb}]^{Kt} \).

A consequence of this transformation is

\( i_b = Kt \times i_b \) and \( o_{tb} = Kt \times o_{tb} \).

\( \tilde{G} \) is a consistent graph. Indeed, by definition of q, for any buffer b = (t, t') ∈ B,

\( q_t \times \frac{\gcd(K)}{Kt} = q_t \times \frac{\gcd(K)}{Kt} \times o_{tb} \),

where \( \gcd(K) \) is the least common multiple of values \( Kt \), \( t \in T \). Let \( \tilde{q}_t = q_t \times \frac{\gcd(K)}{Kt} \) for \( t \in T \) be a repetition vector of \( \tilde{G} \).
Let us set for any buffer $b = (t, t') \in \mathcal{B}$,
\[ \mathcal{V}(a) = \{ (p, p') \in \{1, \cdots, \tilde{\varphi}(t)\} \times \{1, \cdots, \tilde{\varphi}(t')\}, \]
\[ \alpha_{\tilde{V}}^\delta(p, p') \leq \tilde{\beta}_{\tilde{V}}^\delta(p, p') \}, \]
The determination of the minimum period $\Omega_S^g$ of a periodic schedule can be modeled with the following linear program following Theorem 2:

\[
\begin{align*}
\text{Minimize } \Omega_S^g \text{ with } \\
\forall a = (t, t') \in \mathcal{B}, \forall (p, p') \in \mathcal{V}(a), \\
\tilde{S}(t', 1) - \tilde{S}(t, 1) \geq d(t_p) + \Omega_S^g \times \frac{\tilde{\beta}_{\tilde{V}}^\delta(p, p')}{i_a \times \hat{q}_t} \\
\forall t \in T, \forall p \in \{1, \cdots, \tilde{\varphi}(t)\}, \tilde{S}(t, 1) \in \mathbb{R}^+ \\
\Omega_S^g \in \mathbb{R}^+ - \{0\} 
\end{align*}
\]

The next theorem highlights the relationship between the periods of $\tilde{G}$ and $\mathcal{G}$:

**Theorem 3.** Let $\tilde{S}$ be a 1-periodic feasible schedule of $\tilde{G}$ of period $\Omega_S^g$. Starting times of $\tilde{S}$ define a $K$-periodic feasible schedule $S$ of $\mathcal{G}$ with normalized period $\Omega_S^g = \Omega_S^g / \text{lcm}(K)$.

**Proof.** By construction of $\tilde{G}$, any periodic feasible schedule $\tilde{S}$ is a $K$-periodic feasible schedule $S$ of $\mathcal{G}$. Then, for any task $t \in T, \mu^\delta(t) = \mu^\delta(t) \tilde{S}$ and $\Omega_S^g = \frac{\text{lcm}(K)}{K_t}$, thus

\[ \Omega_S^g = \hat{q}_t \tilde{S} = q_t \times \frac{\text{lcm}(K)}{K_t} \times \mu^\delta(t) = \Omega_S^g \times \text{lcm}(K). \]

\[ \square \]

### 3.3 Resolution of the linear program

The linear program for the determination of a minimum period can be transformed to a Max Cost-to-time Ratio Problem (MCRP in short), which is a polynomially solved problem [5]. Considering a bi-valued directed graph $G = (N, E)$ where any arc $e \in E$ is bi-valued by $L(e)$ and $H(e)$, the Cost-to-time Ratio of any circuit $c = (e_1, e_2, \cdots, e_p)$ is defined as

\[ R(c) = \frac{\sum_{i=1}^p L(e_i)}{\sum_{i=1}^p H(e_i)}. \]

Let $\mathcal{C}(G)$ be the set of elementary circuits of $G$. The maximum Cost-to-time Ratio of a graph $H$ is then

\[ \lambda_H = \max_{c \in \mathcal{C}(G)} R(c). \]

An elementary circuit $c \in \mathcal{C}(G)$ is critical if $R(c) = \lambda_H$.

The bi-valued directed graph $G = (N, E)$ associated with our linear program is defined as follows:

- $N = \{(t_p, 1), t \in T, p \in \{1, \cdots, \tilde{\varphi}(t)\}\}$ is the set of nodes;
- $E = \{(t_p, 1), (t_p', 1), a = (t, t') \in \mathcal{B}, (p, p') \in \mathcal{V}(a)\}$ is the set of arcs; any arc $e = ((t_p, 1), (t_p', 1)) \in E$ is bi-valued by

\[ (L(e), H(e)) = (d(t_k), -\frac{\tilde{\beta}_{\tilde{V}}^\delta(p, p')}{{i_a} \times \hat{q}_t}). \]

The determination of the minimum period $\Omega_S^g$ of $\mathcal{G}$ is then equivalent to the computation of the maximum Cost-to-time Ratio, i.e. $\Omega_S^g = \lambda_H$.

Figure 5 presents the bi-valued graph $H$ that corresponds to the CSDFG pictured in Figure 2 with $K = [1, 1, 1, 1]$. The maximum Cost-to-time Ratio equals 108 and is reached by the circuit $c = \{A_1, D_1, C_1\}$ with $H(c) = \frac{1}{7}$ and $L(c) = 3$. This therefore implies that the minimum period of a feasible periodic schedule for the CSDFG is $\Omega_S^g = 108$.

### 3.4 K-periodic Schedule optimality test

A method based on the MCRP returns critical circuits, i.e. circuits $c$ for which the value $R(c)$ is maximum. We take advantage of them to testify the optimality of a K-periodic schedule. The next theorem will allow us to test if the maximum throughput associated with a periodicity vector $K$ is the maximal reachable throughput of the graph $G$.

**Theorem 4 (Optimality test).** Let $\mathcal{G} = (T, B)$ be a consistent CSDFG, a periodicity vector $K$ and the associated bi-valued graph $G = (N, E)$. Let us suppose that $c \in \mathcal{C}(G)$ is a critical circuit such that for every execution $(t_p, 1)$ of $c$, $K_i$ is a multiple of $\hat{q}_t = \frac{q_t}{\text{gcd}(q_t, t') \in C}$. Then, the maximum reachable throughput of $G$ equals $\frac{\text{lcm}(K)}{H(c)}$.

**Proof.** By using Theorem 3, the minimum period of the CSDFG $\tilde{G}$ associated with $G$ and $K$ verifies $\Omega_S^g = R(c)$. Let $C$ be a sub-graph of $\mathcal{G}$ composed of the task from the circuit $c$. The minimum period of $C$ is obtained for a K-periodic schedule with $K$ following the assumption of the theorem. $\square$

For instance, let us consider the bi-valued graph from Figure 5. With the critical circuit $A, D, C$, we observe $\tilde{q}_B = 2$ and $K_B = 1$, thus $K_B$ is no a multiple of $\tilde{q}_B$, the optimality test is not checked.

### 3.5 The K-iter algorithm

Algorithm 1 computes iteratively a sequence of critical circuits by increasing the periodicity factor until the optimality test from Theorem 4 is fulfilled. The update of the periodicity factor ensures that the circuit $c$ will realize the optimality test if it remains critical at the next step.

The values of the periodicity factor necessarily increase at every time the loop test is false. The convergence of the algorithm is guaranteed since the number of elementary circuits of a graph $G$ is bounded and each circuit $c$ is modified at most once: indeed, any modified circuit tested subsequently in the algorithm will fulfill the optimality test.

![Figure 5: A bi-valued graph $H = (N, E)$ that corresponds to the CSDFG pictured in Figure 2 when the periodicity vector is $[1,1,1,1]$. The maximum Cost-to-time Ratio is reached by the circuit $c = \{A_1, D_1, C_1\}$ and is equal to $\Omega_S^g = 108$.](image)
Compute the CSDFG maximal throughput

Require: A CSDFG $G = (T, B)$
Ensure: A vector $K$ and a circuit $c$ of $G$ such that the maximal reachable throughput of $G$ verifies $T_{h, G} = \frac{\text{lcm}(K)}{R(c)}$.

Set $K_1 = 1$, $\forall t \in T$;
repeat
Compute a critical circuit $c$ associated with $G$;
OptCircuitFound := $\forall t \in c$, $K_1$ is a multiple of $q_t$;
if not OptCircuitFound then
$\forall t \in c$, set $K_1 = \text{lcm}(K, t; \text{gcd}(t, q_t; \text{gcd}(q, \forall c \in G)))$;
until OptCircuitFound

As an example, with the previous bi-valued graph from Figure 5, because the optimality test is not checked, the algorithm would continue to run with a new K-periodic schedule of periodicity vector $K = [1, 2, 1, 1]$.

4. EXPERIMENTAL RESULTS

The K-Iter algorithm is implemented as a C++ application and is available online\(^1\). We compared K-Iter with the state-of-the-art throughput evaluation methods for SDFG [7, 6] and CSDFG [16, 4]. SDFG\(^3\) benchmarks [8] are considered for SDFG. Our experiments are summarized in Table 1 and is composed of four categories of graphs, including an actual DSP category. For CSDFG, we considered IB+AG5CSDF [4]; our results are presented in Table 2, which is also composed of actual and synthetic applications. All these experiments were performed on an Intel i5-4570 computer with 16GB RAM.

4.1 Evaluation of SDFG

We compare K-Iter with two optimal SDFG techniques. First, the symbolic execution based method [8], which consists of executing an application until it reaches a previously known state. This ensures a cyclic execution pattern, and then the application throughput can be computed. Second, we consider the cycle-induced sub-graph method [6], which consists of producing a dependency graph, similar to expansion techniques [10], and solving its maximal cycle ratio problem. These experiments are summarized in Table 1.

We observe that for the two category MimicDSP and LgTransient, the overall performance of K-Iter is between one and two orders of magnitude better than [6] and [8]. For the LgHSDFG category, the performance of [6] and K-Iter are similar when [8] is two orders of magnitude slower. For the ActualDSP category, K-Iter is slower in average. When we look at the detail of these experiments, K-Iter is only slower for a particular graph. For this graph (namely, H263 Decoder) K-Iter computation time is 148 ms when [6] is 4ms and [8] is 36ms. This is the longest computation time observed for K-Iter in the whole SDF3 benchmark. In comparison, the longest duration for [6] was 3 sec and 22 sec for [7].

4.2 Evaluation of CSDFG

For the CSDFG evaluation, we compared the K-Iter algorithm with two existing techniques: an approximative method [4] based on periodic scheduling, and an exact technique based on symbolic execution [16]. The symbolic execution technique we used was the publicly available implementation of SDF\(^3\) [15], including a correction of the repetition vector computation method to avoid integer overflow. For this reason, our results differ from [4]. These experiments are summarized in Table 2.

The industry cases are considered with and without buffer size constraints. In both cases K-Iter performs well. The K-Iter algorithm is several order of magnitude faster than the symbolic execution. Furthermore, K-Iter provides optimal results for applications which haven’t be done before (namely, the JPEG200 and the H264 with buffer size constraints). Indeed, if [4] provided an optimal solution for one of them, because this was an approximative method, there was no way to prove optimality until now.

For the synthetic graphs, if the periodic method always provides a solution, these solutions are not necessarily optimal. In contrast the K-Iter algorithm does provide optimal solutions for three examples and is always faster than the symbolic execution. For the two most complex examples ($\sum q_t$ greater than a billion) K-Iter doesn’t provide solution, nor does the symbolic execution method.

5. RELATED WORK

A first throughput evaluation method has been proposed [10] which consists of the transformation of an SDFG to a particular HSDFG (a case of SDFG for which every production and consumption rate is equal to 1) where each node corresponds to a task execution and where edges are precedence relationships. This is the expansion. However, this transformation is not polynomial, its complexity is related to the repetition vector of an SDFG. Later, it was proved that this transformation was considering more arcs and nodes than required and two solutions were proposed to reduce the HSDFG’s size [12, 6]. More recently, a max-plus algebra solution proposed to progressively build an expansion until it reaches optimality [9]. This solution uses pessimistic and optimistic throughput evaluation methods to test optimality.

In contrast, a throughput evaluation technique based on symbolic execution has been proposed for SDFG [8] and extended to CSDFG [16]. These methods rely on the fact that the state-space of a consistent (C)SDFG is a finite set. By executing every tasks as soon as possible, a previously known state has to be met again. Then, when a cyclic execution pattern is revealed, the throughput can easily be computed. Yet the minimal distance between two identical states is not polynomially related to the instance size. In consequence the complexity of this method is exponential.

When the throughput evaluation is used as a decision function (such as in design space exploration), accurate solutions are no longer required and approximative methods can be used. Several solutions were proposed to reduce the complexity of the problem by ignoring cycles [13] or restricting the considered schedules to periodic schedules [1, 4, 11].

6. CONCLUSION

This article presents K-Iter, an optimal algorithm to fastly evaluate CSDFG throughput and which is based on a K-periodic scheduling technique. If its worst case complexity is comparable to other optimal methods, it has been observed to be more efficient. However several cases exist for which the K-Iter algorithm is as slow as or even slower than other

\(^1\)https://github.com/bbobin/kiter
optimal solutions. We believe such cases are key to study the complexity of the throughput evaluation problem. This is an opportunity for future direction.

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8. REFERENCES