Buffer sizing for rate-optimal single-rate data-flow scheduling revisited

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Buffer Sizing for Rate-Optimal Single-Rate Data-Flow Scheduling Revisited

Orlando Moreira, Twan Basten, Senior Member, IEEE, Marc Geilen, and Sander Stuijk

Abstract—Single-Rate Data-Flow (SRDF) graphs, also known as Homogeneous Synchronous Data-Flow (HSDF) graphs or Marked Graphs, are often used to model the implementation and do temporal analysis of concurrent DSP and multimedia applications. An important problem in implementing applications expressed as SRDF graphs is the computation of the minimal amount of buffering needed to implement a static periodic schedule (SPS) that is optimal in terms of execution rate, or throughput. Ning and Gao [1] propose a linear-programming-based polynomial algorithm to compute this minimal storage amount, claiming optimality. We show via a counterexample that the proposed algorithm is not optimal. We prove that the problem is, in fact, NP-complete. We give an exact solution, and experimentally evaluate the degree of inaccuracy of the algorithm of Ning and Gao.

Index Terms—Scheduling, single-rate data flow, homogeneous synchronous data flow, buffer minimization, throughput optimization.

1 INTRODUCTION

Many flavors of data-flow formalisms are used to express, model, analyze, and map signal processing and multimedia streaming applications. Data-flow paradigms fit well with these application domains, as they can represent the inherent concurrency, the pipelined behavior, and data-oriented style of streaming algorithms, while at the same time allowing analysis and synthesis. One of the simplest but still rather expressive data-flow models is the Single-Rate Data-Flow (SRDF) model, also referred to as Homogeneous Synchronous Data-Flow (HSDF) or Marked Graphs. SRDF describes an application as a graph where nodes—typically referred to as actors—represent computation functions and edges represent first-in-first-out (FIFO) communication channels.

SRDF graphs have strong analytical properties. If a worst case execution time is known for every actor, polynomial algorithms [2] can be used to derive the maximum guaranteed rate of output production (the throughput) that the iterative execution of the graph may achieve. This allows to verify real-time requirements. It is, furthermore, possible to use the abstract concepts of actors and edges to model properties of communication channels, memory mapping, and scheduler settings [3], [4], [5], therefore, allowing for the analysis of data-flow graph implementations onto specific architectures.

When implementing an application described as an SRDF graph onto an architecture, finite sizes for the implementation of FIFO buffers need to be determined. Several variants of the buffer-size minimization problem exist. The most elementary one is the problem of finding minimal buffer sizes that guarantee a deadlock-free execution. However, in signal and multimedia processing, deadlock-free execution is often insufficient. It is often important to maximize the throughput, i.e., the rate of execution and output production. In that context, a very relevant variant of the buffer sizing problem for SRDF is the one described by Ning and Gao [1], the Optimal Scheduling and Buffer Allocation (OSBA) problem. The goal in this problem formulation is to find a periodic rate-optimal schedule of execution for an SRDF graph with minimal buffer requirements, i.e., buffer sizes whose sum is minimal among all those buffer allocations that allow periodic rate-optimal graph execution. The restriction to periodic execution schedules is advantageous from the code-size point of view. The authors claim a linear-programming-based solution of polynomial complexity for this problem.

The complexity result of Ning and Gao has been unchallenged until now, and based on the results presented in [1] it has been widely accepted that the problem of finding the minimum buffer capacity that allows an SRDF graph to execute at its maximum throughput is a problem of polynomial complexity (see, for instance, [3], [6], [7], [8], [9], [10]). This is incorrect.

With a counterexample, we show in this paper that the algorithm proposed in [1] is not optimal. We, in fact, prove that (the decision variant of) the OSBA problem is NP-complete. Based on the buffer sizing technique for multirate data-flow graphs of [11], [12], we provide an exact solution to the OSBA problem, that is efficient in practice. We estimate the difference between the results of the algorithm of Ning and Gao [1] and the exact solution. The NP-completeness proof for the original OSBA formulation goes via a generalization of OSBA in which nonperiodic schedules are allowed, while making assumptions on required buffer space that are more conservative than in [1]. We argue that in this generalized setting, an SRDF graph always has a
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A directed graph \( G \) is a pair \( (V, E) \), with \( V \) the set of vertices, or nodes, and \( E \subseteq V^2 \) the set of directed edges. For \( (i, j) \in E \), \( i \) is the source and \( j \) the sink of the edge. A (directed) path in the graph is simple if the source nodes of all edges on the path are all different. A path is a cycle if and only if it is simple and the source of the first edge equals the sink of the last edge. An undirected path is a path that ignores edge directions. A graph is connected if and only if there is an undirected path between any pair of nodes; it is strongly connected if and only if there is a directed path between any pair of nodes.

### 2.2 Single-Rate Data-Flow Graphs

An SRDF graph—also known as Homogeneous Synchronous Data-Flow graph [13]—is a directed graph, where nodes are referred to as actors and represent data transformation or control entities, and edges represent FIFO queues that direct values from an actor output to an actor input. Data are transported in discrete chunks, called tokens. When an actor is activated by data availability it is said to be fired. The firing rule defines what happens upon firing an actor. SRDF prescribes that the number of tokens produced (consumed) by an actor on each output (from each input) per firing is always one. We assume SRDF graphs to be connected (but not necessarily strongly connected). Assumptions made throughout this section are listed in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SRDF</strong></td>
</tr>
<tr>
<td>- graphs are connected and live</td>
</tr>
<tr>
<td>- positive cycle mean, integer MCM</td>
</tr>
<tr>
<td><strong>Scheduling</strong></td>
</tr>
<tr>
<td>- non-negative integer firing start and end times</td>
</tr>
<tr>
<td>- actor firings may not overlap in time</td>
</tr>
<tr>
<td>(actors have implicit self-edges with 1 initial token)</td>
</tr>
<tr>
<td><strong>Buffering</strong></td>
</tr>
<tr>
<td>- all output edges of an actor share one buffer</td>
</tr>
<tr>
<td>- input space is released at firing start</td>
</tr>
<tr>
<td>- output space is claimed at firing start</td>
</tr>
<tr>
<td>- buffers can be read and written simultaneously</td>
</tr>
<tr>
<td>- implicit self-edges do not require buffering</td>
</tr>
</tbody>
</table>

For performance analysis, actors in an SRDF graph \((V, E)\) have a valuation \( e : V \rightarrow \mathbb{N} \); \( e(i) \) is the execution time of actor \( i \). Edges have a valuation \( d : E \rightarrow \mathbb{N}_0 \); \( d(i, j) \) is called the delay of edge \((i, j)\) and represents the number of initial tokens in \((i, j)\). An SRDF is completely defined by the tuple \((V, E, e, d)\). Fig. 1 illustrates an example SRDF graph, with tokens shown as black dots on the edges and execution time annotations inside the actors. (Note that an actor execution time of zero is allowed. This will not occur for any realistic data transformation entities, but it is sometimes convenient to model certain (control) aspects.)

We are interested in applications that process data streams, which typically involve computations on indefinitely long data sequences. Therefore, we are only interested in SRDF graphs that can execute in a nonterminating fashion. We want schedules that execute all actors indefinitely within a finite amount of memory. An SRDF graph that allows to fire all actors infinitely often is called live. It follows from the results in [14, Section 3] for multirate data-flow graphs that a live SRDF graph can always be scheduled using a finite amount of memory, and that an SRDF graph is live if and only if all cycles contain at least one initial token. A consequence of the latter is that liveness of an SRDF graph can be verified efficiently by performing, e.g., an all-pairs shortest path algorithm on the SRDF graph with the initial delays as edge weights or a cycle detection via a depth-first search on the graph with all edges with initial tokens removed. Therefore, in the remainder, we limit ourselves to live SRDF graphs.

#### 2.3 Throughput

The cycle mean \( \mu(c) \) of a cycle \( c \) in an SRDF graph \( G = (V, E, e, d) \) is defined as

\[
\mu(c) = \frac{\sum_{i \in N(c)} e(i)}{\sum_{(i,j) \in E(c)} d(i, j)},
\]

where \( N(c) \) is the set of all nodes traversed by cycle \( c \) and \( E(c) \) is the set of all edges traversed by cycle \( c \).

The Maximum Cycle Mean (MCM) \( \mu(G) \) of SRDF graph \( G \), with set of cycles \( C(G) \), is defined as

\[
\mu(G) = \max_{c \in C(G)} \mu(c).
\]

1. Note that liveness corresponds to deadlock freeness for strongly connected SRDF graphs; for arbitrary (connected) graphs, liveness is a stronger property than deadlock freeness, and the latter is insufficient to always allow execution within bounded memory.
The inverse of the MCM of an SRDF graph provides a fundamental upper bound to its maximal attainable throughput, and it is known that every SRDF graph has at least one execution that achieves this maximal attainable throughput [15]. Many algorithms of polynomial complexity have been proposed to find the MCM (see [2] for an overview). The MCM of the SRDF graph of Fig. 1 is 5, resulting from the cycle through actors A, F, G, and E. The maximum attainable throughput is therefore 1/5 firings per time unit.

An MCM may be a fractionary value. The original OSBA formulation of [1] assumes that the MCM of an SRDF graph is a positive integer, as it is always possible to unroll a given SRDF graph to a graph with an integer MCM. We keep the assumption of [1] of a positive integer MCM, although this is not strictly necessary. We, furthermore, exclude cycles with zero cycle mean zero (i.e., with execution time zero) because such cycles are not meaningful from a practical point of view whereas they complicate the reasoning in the remainder.

### 2.4 Schedule Functions and Buffer Capacities

Since actors are supposed to fire indefinitely, we can per actor index firings using the natural numbers, starting from 0. A schedule function is a function \( s : V \times \mathbb{N}_0 \rightarrow \mathbb{N}_0 \) where \( s(i, k) \) represents the time at which instance \( k \) of actor \( i \) is fired. We denote the finishing time of firing \( k \) of actor \( i \) by \( f(i, k) = s(i, k) + e(i) \). As in [1], we assume that scheduling times are non-negative integer values, although this could be relaxed to non-negative fractional values.

Not all schedule functions can be realized. A schedule is admissible if and only if all actor firing start times satisfy the firing rule. This means that all input edges of an actor must always have sufficient tokens to accommodate the firings. In [15], necessary and sufficient conditions for an admissible schedule are given. For notational convenience, assume that for any schedule \( s \) and actor \( i \), \( s(i, k) = -e(i) \) if \( k \) is negative, which allows us to see initial tokens as being produced at time 0 by a firing with negative start time. A schedule \( s \) is admissible if and only if, for every \( (i, j) \in E \) and any \( k \in \mathbb{N}_0 \),

\[
s(j, k) \geq s(i, k - d(i, j)) + e(i). \tag{3}
\]

Consider the example of Fig. 1. Schedule \( s \) with \( s(A, k) = s(G, k) = 5k \), \( s(B, k) = s(C, k) = s(F, k) = 1 + 5k \), \( s(D, k) = 2 + 5k \), and \( s(E, k) = 3 + 5k \) is an admissible schedule that realizes the maximal throughput of 1/5 firings per time unit. All actors fire as soon as they are enabled.

Equation (3) assumes that tokens are consumed at the beginning of a firing and produced at the end of a firing. An admissible schedule allows multiple firings of the same actor to overlap in time (so-called autoconcurrency). This is consistent with the general interpretation of SRDF graph execution, but in [1], it is assumed that firings of the same actor in a graph cannot overlap in time. We adhere to this assumption, excluding schedules in which firings of the same actor overlap. It is possible to enforce the restriction to nonautoconcurrent schedules in an SRDF graph, by introducing a self-edge for every actor in the graph with a single initial token for each of these edges. We implicitly assume that such self-edges are present when referring to

the MCM of a graph and/or the maximal throughput that can be obtained. (This implies that the MCM is always at least the maximum actor execution time.) However, in line with [1], these implicit self-edges are not considered for buffer minimization.

In an implementation of a data-flow application, data may be consumed from input edges and produced on output edges at arbitrary points in time during an actor firing. To guarantee that buffers are sufficiently large, we need to make some assumptions. The most conservative buffer sizes are obtained when assuming that each SRDF edge needs its own buffer, that output space needed by actors is claimed at a firing start, and that input space is freed at the end of a firing. Claimed input and output space can then be used as working memory during actor execution. This type of behavior may typically be seen in multimedia applications in which an actor communicates substantial amounts of different data to different actors. Ning and Gao, however, assume that all output edges of an actor share buffer space and that input data are read at a firing start and stored internally, releasing input space at that point in time. They do assume that output space is claimed at the firing start. This type of behavior may be seen in DSP applications where actors reflect simple scalar operations of which the outcome is communicated to several successor actors simultaneously. We adhere to the choices made by Ning and Gao, but as part of our NP-completeness proof for OSBA we also study OSBA with the most conservative buffering assumptions in Section 6. Ning and Gao, moreover, assume that buffer space can be read and written simultaneously when actors \( i \) and \( j \) connected via edge \((i, j)\) start their firings at the same time. The space released by the start of \( j \) can then be claimed as output space with the start of \( i \). We also follow this assumption.

Minimum buffer sizes required to execute an admissible schedule can be derived from the schedule. We introduce an auxiliary notion, namely, the token count \( c(i, j, t) \) on an edge \((i, j)\) after the occurrence of all firing starts and endings scheduled at time \( t \). Given the initial tokens \( d \) in an SRDF graph and a schedule \( s \), \( c(i, j, t) \) is defined inductively as follows: Since execution times may be zero, the inductive computation starts at “time” \(-1\).

\[
c(i, j, -1) = d(i, j), \text{ and, for } t \in \mathbb{N}_0,
\]

\[
c(i, j, t) = c(i, j, t - 1) - |\{s(j, k) = t \mid k \in \mathbb{N}_0\}| + |\{f(j, k) = t \mid k \in \mathbb{N}_0\}|. \tag{4}
\]

The buffer space needed by an SRDF graph to execute a schedule is defined by a buffer-capacity distribution function. The buffering assumptions imply that buffer space can be assigned on a per actor basis. Hence, a buffer-capacity distribution function \( b : V \rightarrow \mathbb{N}_0^+ \) is a function that assigns to each actor \( i \in V \) the buffer capacity \( b(i) \) required for the data on its output edges to implement a given schedule \( s \). The basic idea is to take per actor per time point, including the artificial time point \(-1\), the maximum of all token counts for all the actor’s output edges and, furthermore, the maximum of all these values over time, while accommodating for actor firings that are in progress, because these firings imply the reservation of output space. At any point
in time at most one firing of an actor can be in progress due to the restriction to nonautoconcurrent schedules. Assume \( c(i, j, t) = 0 \) if \((i, j) \notin E\).

\[
    b(i) = \max_{t \in \mathbb{N}_0} \left( \max_{j \in V} c(i, j, t) + \sum_{k \in \mathbb{N}_0} \left[ \{k \in \mathbb{N}_0 \mid s(i, k) \leq t < f(i, k)\} \right] \right).
    \tag{5}
\]

For example, to execute schedule \( s \) for the running example introduced above, a buffer size of 1 token for every actor in the graph of Fig. 1 is sufficient except for actor \( D \), which needs a buffer of size 2 to store tokens on edge \((D, E)\). This yields a total buffer requirement of 8. Fig. 2 visualizes the buffer requirements of actor \( D \), and maximal presence of two tokens in the channel, during time \( t \). The graph does not contain any cycles with negative accumulative weight, which implies that \( G \) has an SPS if and only if the constraint graph does not contain any cycles with negative accumulative weight. Thus, \( G \) has an SPS if and only if the constraint graph does not have any cycles with negative accumulative weight.

Recall (2), defining the MCM. It follows that

\[
    P \geq \mu(G) \iff P \geq \max_{\epsilon \in C(G)} \left( \sum_{i \in \epsilon} \sum_{j \in \epsilon} d(i, j) \right) \geq 0.
\]

The last condition is equivalent to the condition that the constraint graph introduced above does not have any cycles with negative accumulative weight. Thus, \( G \) has an SPS if and only if \( P \geq \mu(G) \).

2.5 Static Periodic Schedules

An SPS of an SRDF graph is a schedule such that, for all nodes \( i \in V \):

\[
    s(i, k) = s(i, 0) + P \cdot k, \tag{6}
\]

where \( P \) is the period of the SPS. Given \( P \), an SPS is defined by the values \( s(i, 0) \), for all \( i \in V \). We use \( s(i) \) as an abbreviation for \( s(i, 0) \) for an SPS \( s \). The example schedule given above is an SPS with period 5. An important observation is that firing all actors the same number of times preserves the token distribution over the edges. Therefore, the minimal buffer sizes needed to execute an SPS can be computed from a prefix of an SPS consisting of one period plus any transient part that may be present. It is sufficient to consider an SPS \( s \) up to time point \( \max_{i \in V} s(i) + P \) (i.e., the latest start time of any actor plus one period). For the example schedule, it is sufficient to consider the execution up to time point 8.

The following theorem reestablishes, in a somewhat different form, a relation between SPSs and the MCM, first presented in [16]:

**Theorem 1.** A live SRDF graph \( G \) has an SPS with period \( P \) if and only if \( P \geq \mu(G) \).

**Proof.** Let \( G = (V, E, e, d) \). According to (3), every edge \((i, j)\) in \( G \) imposes a constraint \( s(j, k) \geq s(i, k - d(i, j)) + e(i) \) to any admissible schedule. For an SPS, from (6), we obtain for every \((i, j) \in E \) a constraint \( s(i) + P \cdot k \geq s(i) + P \cdot (k - d(i, j)) + e(i) \), which is equivalent to

\[
    s(i) - s(j) \leq P \cdot d(i, j) - e(i). \tag{7}
\]

These inequalities define a system of linear constraints. Since (3) defines necessary and sufficient conditions, \( G \) has an SPS if and only if the system of constraints of (7) has a solution. The system consists of so-called difference constraints [17], that can be turned into a constraint graph \((V, E)\), with edge weights \( w(i, j) = P \cdot d(i, j) - e(i) \). According to [17], the system of constraints has a solution if and only if the constraint graph does not contain any cycles with negative accumulative weight, which implies that \( G \) has an SPS if and only if the constraint graph does not have any cycles with negative accumulative weight.

Recall (2), defining the MCM. It follows that

\[
    P \geq \mu(G) \iff P \geq \max_{\epsilon \in C(G)} \left( \sum_{i \in \epsilon} \sum_{j \in \epsilon} d(i, j) \right) \geq 0.
\]

The last condition is equivalent to the condition that the constraint graph introduced above does not have any cycles with negative accumulative weight. Thus, \( G \) has an SPS if and only if \( P \geq \mu(G) \). \( \square \)

Given an SRDF graph \( G \) with MCM \( \mu(G) \), \( 1/\mu(G) \) is the fastest possible firing rate of any actor in \( G \) [15]. A schedule realizing this maximal throughput is rate optimal, where the throughput of a schedule is defined as the average number of firings of any actor over time. If an SPS has a period \( P \) equal to the MCM \( \mu(G) \), we say that this SPS is a Static Periodic Rate-Optimal Schedule (SPROS). The example schedule given in the previous section for our running example is an SPROS. Theorem 1 means that an SPROS always exists. An SPS for graph \( G \) can be constructed for any given period \( P \geq \mu(G) \) by solving the system of constraints of (7) in the proof of Theorem 1. A straightforward algorithm uses a shortest path algorithm that can cope with negative weights, such as Bellman-Ford [15]. Thus, it is possible to construct an SPROS in polynomial time.

**Corollary 1.** A live SRDF graph has an SPROS, that can be constructed in polynomial time.
3 THE OSBA PROBLEM

Ning and Gao formalize the OSBA problem in [1] as an Integer Programming (IP) problem. The following definition formalizes OSBA as an optimization problem:

**OSBA**

Given a live SRDF graph \( G = (V, E, e, d) \), construct an SPROS for \( G \) that has a buffer-capacity distribution function \( b \) such that \( \sum_{i \in V} b(i) \) is minimal among all buffer-capacity distribution functions for all SPROSs.

**OSBA-IP** [1]

Let \( G = (V, E, e, d) \) and \( P = \mu(G) \). Minimize \( \sum_{i \in V} b(i) \) subject to

\[
\forall (i, j) \in E, \quad P \cdot b(i) + s(i) - s(j) \geq P \cdot (d(i, j) + 1) - 1.
\]

The constraints are labeled to allow easy referencing.

5.1 The Counterexample

Consider again the example of Fig. 1. This is a graph for which Ning and Gao’s algorithm does not compute the optimal buffer sizes for rate-optimal scheduling. Table 2 shows where the reasoning of Ning and Gao is flawed.

Ning and Gao proceed to show that the constraint matrix of the OSBA-LP problem is unimodular, and that, because of this, the obtained solution is always integral. However, while OSBA-LP returns all-integer solutions, the \( b(i) \) obtained by dividing the \( b(i) \) results by the period \( P \) may be fractional. Ning and Gao solve this by discarding the \( b(i) \) results and simply simulating the obtained SPROS (given by the values of the \( s(i) \) variables obtained from OSBA-LP) to compute the actual buffer-capacity distribution function \( b \) for \( s \).

Since the MCM computation, needed as input for the OSBA-LP problem, the LP problem itself, and the buffer-capacity computation from the obtained SPROS can be solved in polynomial time, the proposed approach has polynomial complexity. Ning and Gao also claim optimality of the approach. However, their reasoning is flawed. OSBA-IP and OSBA-LP are truly different problems: while OSBA-IP requires the \( b(i) \) to be integer, OSBA-LP requires instead the products \( P \cdot b(i) \) to be integer. The next section shows that there are cases where the values of \( s(i) \) for an optimal sum of integer \( P \cdot b(i) \) (or, in other words, fractional \( b(i) \)) are different from the values of \( s(i) \) for an optimal sum of integer \( b(i) \).

4 NING AND GAO’S APPROACH TO SOLVE OSBA

As mentioned, Ning and Gao formalize OSBA in [1] as an IP problem. The LP formulation includes the sum of buffer capacities for a given schedule as an objective function, and the constraints necessary for an admissible schedule as in (7) with period \( P \) equal to the MCM of the graph. If, furthermore, contains a set of constraints implied by the limited buffer capacities.\(^2\) Given an actor \( i \) with buffer capacity \( b(i) \), for every edge \((i, j)\), we have the constraint that

\[
P \cdot b(i) + s(i) - s(j) \geq P \cdot (d(i, j) + 1) - 1.
\]

These buffer-capacity constraints are only valid if firings of the same actor do not overlap. The derivation of these constraints can be found in [1]. The free variables in the integer program are the start times \( s(i) \) of the first firings of all actors for an SPROS schedule \( s \) and the buffer capacities \( b(i) \).

**OSBA-LP** [1]

Let \( G = (V, E, e, d) \) and \( P = \mu(G) \). Minimize \( \sum_{i \in V} b(i) \) subject to

\[
\begin{align*}
\forall (i, j) \in E, & \quad b(i) + s(i) - s(j) \geq P \cdot (d(i, j) + 1) - 1, \\
\forall (i, j) \in E, & \quad s(j) - s(i) \geq e(i) - P \cdot d(i, j), \\
\forall i \in V, & \quad s(i), b(i) \text{ integers}.
\end{align*}
\]

In general (the decision variant of) the Integer Programming problem is NP-complete [18], [19]. The Linear Programming (LP) problem, dropping the requirement that the free variables should be integer, is known to be efficiently solvable. There are special classes of IP problems that can be solved as LP problems because, for these classes, any solution of the LP problem is guaranteed to be integral. Ning and Gao transform the OSBA-IP problem into such a problem by means of a simple variable substitution. For every \( i \in V \),

\[
b(i) = P \cdot b(i).
\]

**TABLE 2**

Counterexample for Ning and Gao’s Optimality Claim

<table>
<thead>
<tr>
<th>( i )</th>
<th>( e(i) )</th>
<th>( s_0(i), P = 5 )</th>
<th>( s_1(i), P = 5 )</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
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<td>0</td>
</tr>
<tr>
<td>((i, j))</td>
<td>( d(i, j) )</td>
<td>( b_0(i) )</td>
<td>( b_1(i) )</td>
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<td>10 - 1</td>
<td>9</td>
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<tr>
<td>(E, A)</td>
<td>1</td>
<td>6 + 3</td>
<td>9</td>
</tr>
<tr>
<td>(F, G)</td>
<td>1</td>
<td>8 + 1</td>
<td>9</td>
</tr>
<tr>
<td>(G, E)</td>
<td>0</td>
<td>7 - 3</td>
<td>4</td>
</tr>
<tr>
<td>sum</td>
<td>46</td>
<td>8</td>
<td>48</td>
</tr>
</tbody>
</table>

2. Subsequent papers, also by one of the authors of the original paper (see, e.g., [6], [7]), consider also a variant of OSBA in which every edge in an SRDF graph has its own buffer. This does not significantly change the IP formulation, and the counterexample for the optimality claim given in the next section applies to both versions.
summarizes the properties of the SRDF graph, the schedule 
$s_0$ resulting from OSBA-LP with corresponding buffer sizes 
$b_0$, a buffer-optimal schedule $s_1$ with buffer sizes $b_1$, and the 
minimum values of the free variables $b'_0$ and $b'_1$ for the two 
 schedules computed from the buffer constraints of OSBA-
LP, where the corresponding constraint is given as well. 
Note that only actor $A$ has more than one output edge. 
However, each of these edges results in the same constraint, 
which is only mentioned once in the table (in the row with 
first entry $(A,i)$). As a result, every actor has exactly one 
in the bottom part of the table. The bottom line gives the 
values for the OSBA-LP objective function and the total 
buffer requirements for the schedule. The example shows 
that the OSBA-LP schedule has a lower value for the 
objective function than the optimal schedule, but a higher 
buffer requirement. Differences between the OSBA-LP and 
optimal solutions are highlighted in italics. The problem that 
the OSBA-LP approximation has with this counterexample 
is caused by the scheduling freedom for actor $D$ within the 
SPROS, as the reasoning below clarifies. 

First, two observations imply that schedule $s_1$ of Table 2 
is indeed a solution to the OSBA optimization problem. 

1. The example graph has an MCM of 5, resulting from the 
$(A,F), (F,G), (G,E), (E,A)$ cycle. Since schedule $s_1$ has a period of 5, it is rate optimal. 

2. It is straightforward to verify the buffer sizes for $s_1$. 
Consider, for example, actor $D$. Schedule $s_1$ results in 
a buffer size of 1. Initially, edge $(D,E)$ has one token, 
which is consumed by the first firing of $E$ at time 3. 
Furthermore, space for a token produced by $D$ is 
needed from the start of firing $k$ of $D$ at time $4 + 5k$, till 
the start of firing $k + 1$ of $E$ at time $8 + 5k$ that 
consumes that token. So, space for one token is needed 
in interval $[0,3]$ and in intervals $[4 + 5k, 8 + 5k]$, which 
do not overlap for different $k$. Hence, buffer size 1 
suffices for actor $D$. Since buffer-capacity distribution 
function $b_1$ yields buffer sizes of 1 for all actors and 
size 1 is always minimal, $b_1$ gives the minimal buffer 
sizes among all rate-optimal schedules. 

Second, it can be argued that OSBA-LP yields schedule $s_0$ 
as a solution. 

3. Schedule $s_0$ is the schedule already given in Sect-
on 2.4, where it was already mentioned that all actors 
fire as soon as they are enabled. This follows in a 
straightforward way from the precedence constraints in 
the example SRDF graph, corresponding to constraint set (b) in the OSBA-LP formulation. 

4. An important consequence of the previous observation 
is that actor firings can only be delayed with 
respect to schedule $s_0$. Let us consider the effect of 
delaying an actor firing in $s_0$ on the values of $v(i)$ in 
the OSBA-LP formulation. Consider, for example, a 
delay of two time units of firings of actor $D$, which 
in fact turns schedule $s_0$ into schedule $s_1$. Since $D$ has 
two input edges $(B,D)$ and $(C,D)$, the effect of this 
delay on the sum of the $v(i)$ values is, on the one 
hand, a decrease of 2 for the $(D,E)$ edge and, on the 
other hand, an increase of $2 \cdot 2$ for the $(B,D)$ and 
$(C,D)$ edges, as illustrated by the italics constraints 
in the bottom part of Table 2. 

5. Reconsidering the example graph shows that there is 
no freedom in scheduling actors $A, F, G,$ and $E$ 
without affecting the throughput (excluding a shift 
in time of the entire schedule, which is not meaning-
ful); $B$ and/or $C$ can be delayed but only if $D$ is 
also delayed. A crucial observation now is that any 
group of actors from $B, C,$ and $D$ whose firings 
might be delayed thus has only one outgoing edge, 
whereas it has two incoming edges. This means that 
the net effect of any delay of actor firings on the $v(i)$ 
in OSBA-LP is always an increase, just as in the 
example given for delaying $D$ only. But this means 
that no delay of actor firings in $s_0$ can result in a 
better value of the objective function in OSBA-LP, 
and hence that $s_0$ is the optimal schedule according 
 to OSBA-LP. 

Finally, we compare the buffer requirements of $s_0$ and $s_1$. 

6. Observation 2 above argues that the buffer sizes 
defined by $b_1$ are correct. In Section 2.4 and Fig. 2, the 
buffer-capacity distribution function $b_0$ was already 
explained, and in particular it was already argued that 
the buffer space needed by schedule $s_0$ to store the 
data on edge $(D,E)$ is 2. This shows that $s_0$ needs 
a larger buffer size for actor $D$ than $s_1$ and, hence, 
haves larger total buffering requirements than $s_1$. 

The above reasoning shows that schedule $s_1$ is a solution 
to OSBA for the SRDF graph of Fig. 1. It also shows that $s_0$ is 
the solution to OSBA for this graph according to the 
solution method proposed by Ning and Gao [1], but that it 
is in fact not a solution to OSBA. 

5.2 Analysis of the Counterexample 
It is interesting to consider potential causes for the 
suboptimality of Ning and Gao’s approach to solve OSBA. 
A first observation is that Ning and Gao observe in their 
paper that the buffer constraints $b(i) \geq (s(j) - s(i) - 1) / P + 
d(i,j) + 1$ obtained from (8) are conservative approxima-
tions, in the sense that buffer capacities that satisfy those 
constraints are guaranteed to be sufficiently large. This 
suggests that it might be possible that an obtained SPROS uses 
less buffer capacity than the constraints specify. 
Schedules $s_0$ and $s_1$ with their buffer-capacity distribution 
functions $b_0$ and $b_1$ show that this is indeed possible. 
Consider, for example, edge $(F,G)$ of the SRDF graph. 
The start times of $F$ and $G$ and the buffer capacity assigned to $F$ 
are equal in both schedules. However, for these values, the 
above constraint on the buffer capacity yields $1 \geq 1 \frac{1}{2}$, which 
is obviously not true. Thus, the buffer constraints of OSBA-
IP exclude the solution to the OSBA optimization problem 
for the example graph of Fig. 1, as well as the solution 
obtained via the LP approach of Ning and Gao themselves. 
In fact, also the obtained result for the running example that 
Ning and Gao use in [1] to illustrate their approach is 
excluded by the LP formulation of OSBA. 

These observations may suggest that the IP formulation 
is the root cause of the suboptimality of the approach of 
Ning and Gao. However, this is not the case. Ning and Gao 
do not further comment on the fact that their buffer 
constraints are not exact but only conservative, nor on the 

3. This is, in fact, only true for actors with nonzero execution times.
Consequences for their approach. However, it is not difficult to derive exact constraints for the required buffer capacities, and study the consequences of using exact constraints.

Consider an actor \( i \) of an SRDF graph with buffer capacity \( b(i) \) and output edge \((i, j)\) with \( d(i, j) \) initial tokens. The buffer has then, at most, \( b(i) - d(i, j) \) empty places. (Note that, in line with [1], we do not assume that all output edges of an actor have the same number of initial tokens; some space in the buffer may be occupied by tokens still needed by other actors than \( j \) consuming data produced by \( i \).) Consider firing \( k + 1 \) of actor \( i \), which in an SPS with period \( P \) starts at time \( s(i) + P \cdot k \). Due to the limited buffer capacity, this firing can only take place if actor \( j \) has started sufficiently many firings to provide space, i.e., actor \( j \) should start firing \((k + 1) - (b(i) - d(i, j))\), which occurs at time \( s(j) + P \cdot (k - (b(i) - d(i, j))) \), no later than the start of firing \( k + 1 \) of actor \( i \). Thus,

\[
\begin{align*}
  s(j) + P \cdot (k - (b(i) - d(i, j))) & \leq s(i) + P \cdot k \\
  \Rightarrow P \cdot b(i) + s(i) - s(j) & \geq P \cdot d(i, j).
\end{align*}
\] (10)

This last inequality differs in its right-hand side from the constraint of (8). This right-hand side is never greater than the right-hand side in (8). Thus, the following IP formulation of OSBA, combining the precedence constraints of OSBA-IP with the exact buffer constraints, allows strictly more solutions than OSBA-IP:

**OSBA-eIP**

Let \( G = (V, E, c, d) \) and \( P = \mu(G) \).

Minimize \( \sum_{i \in V} b(i) \)

subject to

\[
\forall (i, j) \in E_i, \quad P \cdot b(i) + s(i) - s(j) \geq P \cdot d(i, j),
\]

\[
\forall (i, j) \in E_j, \quad s(j) - s(i) \geq c(i) - P \cdot d(i, j),
\]

\[
\forall i \in V, \quad s(i), b(i) \text{ integers}.
\]

We can now investigate what happens if we follow the approach of [1], turning OSBA-eIP into an LP via the variable substitution of (9), and computing buffer capacities from the SPROS obtained from that LP. Consider the example of Table 2. The crucial observation is that, when using the exact buffer constraints, the right-hand sides of the constraints in the bottom half of the table are all reduced by four. This implies that also the \( b'_1(i) \) and \( b'_2(i) \) are all reduced by four. Thus, essentially, nothing has changed. SPROS \( s_0 \), with buffer capacities \( b_0 \), is still the solution found by the LP-based approach, whereas the optimal solution is \( s_1 \), with buffer capacities \( b_1 \) (which now satisfy the IP constraints). This leads to the already mentioned conclusion that the reasoning of Ning and Gao is flawed in the assumption that the schedule corresponding to an optimal sum of integer \( P \cdot b(i) \) always results in an optimal sum of integer \( b(i) \). This assumption is not correct, neither for the original approximate IP formulation nor for the exact IP formulation given in this section.

6 The Generalized OSBA Problem

This section introduces a generalized version of OSBA, referred to as gOSBA, which is not only interesting in itself, but also forms the basis for the NP-completeness proof for the original OSBA formulation. After defining gOSBA and showing that it always has a solution, we proceed with proving NP-completeness of gOSBA.

6.1 Problem Definition

Our generalized OSBA problem makes more conservative buffering assumptions than the original formulation. The following definition of a buffer-capacity distribution function differs from the one given in (5) in that it assigns a separate buffer to each edge, and that it reserves space in each buffer for an active firing of the consuming actor. This definition captures the most conservative buffering requirements that are possible.

\[
B(i, j) = \max_{t \in \mathbb{N}_0 \cup \{-1\}} \{ c(i, j, t) + |\{ k \in \mathbb{N}_0 | s(i, k) \leq t < f(i, k) \} | + |\{ k \in \mathbb{N}_0 | s(j, k) \leq t < f(j, k) \} | \}.
\] (11)

The generalized OSBA problem now differs from the original OSBA problem in the sense that it assumes these most conservative buffer requirements, but also in the sense that it requests a total buffer size that is minimal among all rate-optimal schedules, not necessarily only among periodic ones. This version of OSBA is interesting in, for example, multiprocessor applications in which sharing of buffers among multiple data edges in an SRDF graph may not be possible and in situations where an actor produces different data for different successor actors. This makes it a relevant problem for, for example, modern multimedia applications implemented on multiprocessor systems-on-chip (see, e.g., [3]).

**gOSBA**

Given a live SRDF graph \( G = (V, E, c, d) \), construct an SPROS for \( G \) that has a buffer-capacity distribution function \( B \) such that \( \sum_{(i, j) \in E} B(i, j) \) is minimal among all buffer-capacity distribution functions for all rate-optimal (not necessarily periodic) schedules.

Schedule \( s_1 \) of Table 2 turns out to be a solution to gOSBA for the running example. It requires a buffer of size one for each of the edges in the graph, except for edge \( (F, G) \) which needs a size of 2, leading to a total buffer requirement of 10. From the execution times of 4 and 3 for actors \( F \) and \( G \), respectively, it follows that in any rate-optimal schedule with period \( \mu(G) = 5 \), firings of \( F \) and \( G \) must necessarily overlap. This means that the conservative assumptions captured in (11) result in a minimal size of 2.

6.2 gOSBA Always Has a Solution

It is not entirely trivial that gOSBA always has a solution, i.e., that it is always possible to construct an SPROS with buffer sizes that are minimal among all rate-optimal schedules. In other words, is it possible to achieve periodicity and buffer minimality simultaneously? Using the so-called capacity-constrained SRDF model of an SRDF graph with a given buffer-capacity distribution function (see, e.g., [11]), it can be proven that gOSBA always has a solution.

The capacity-constrained model \( C_{\text{con}} \) of an SRDF graph \( G \) with buffer-capacity distribution function \( B \) is itself an SRDF graph that is obtained from \( G \) by adding, for every edge \((i, j)\), a reverse edge \((j, i)\) with \( B(i, j) - d(i, j) \) initial
tokens. (This may, in fact, turn the graph into a multigraph. All the results in this paper generalize to multigraphs in a trivial way.)

Given an edge \((i, j)\), a reverse edge \((j, i)\) in \(G_{ccm}\) captures precisely the remaining buffer space for edge \((i, j)\). The start of a firing of \(i\) claims space by consuming a token from edge \((j, i)\); the end of a firing of actor \(j\) releases space in the buffer of \((i, j)\) by producing a token on \((j, i)\). This is in line with the conservative buffer assumptions captured by buffer-capacity distribution function \(B\). As a result, any schedule of \(G\) that never uses more buffer space on any edge than allowed by \(B\), is also a schedule of \(G_{ccm}\). Theorem 1 then yields the desired result that gOSBA always has a solution.

**Theorem 2.** Consider a live SRDF graph \(G = (V, E, e, d)\) with a buffer-capacity distribution function \(B\) such that \(\Sigma_{(i,j) \in E} B(i,j)\) is minimal among all buffer-capacity distribution functions for all rate-optimal schedules. Then, \(G\) has an SPROS with buffer-capacity distribution function \(B\).

**Proof.** Since \(G\) allows a rate-optimal schedule with buffer-capacity distribution function \(B\), by Theorem 1, the capacity-constrained model \(G_{ccm}\) derived from \(G\) and \(B\) has an SPROS. By the construction of \(G_{ccm}\) this SPROS respects the buffer capacities specified by \(B\). Since \(B\) is such that \(\Sigma_{(i,j) \in E} B(i,j)\) is minimal among all buffer-capacity distribution functions for all rate-optimal schedules, it follows that the SPROS has buffer-capacity distribution function \(B\).

**Corollary 2.** gOSBA always has a solution.

The buffer-sizing techniques of [11] and [12], that are efficient in practice, can be used to compute buffer sizes that are minimal under the conservative assumptions of (11) while allowing a rate-optimal schedule of a given SRDF graph. The capacity-constrained model can then be used to construct an SPROS with these buffer sizes in the way explained in Section 2.5.

### 6.3 The Constraint Graph

Our NP-completeness proof for gOSBA uses a constraint representation of gOSBA, which we introduce in this section. Corollary 2 shows that it is allowed to limit our attention to SPROSs when solving gOSBA, making it in this respect similar to OSBA. As we have seen, the OSBA problem can be captured by two types of linear constraints, the data precedence constraints introduced in (7), and the buffer constraints of (10). (The buffer constraints of (8) cannot be used, because these are not exact.) Also gOSBA can be captured via two sets of constraints, that are very similar to the mentioned constraints. The precedence constraints, labeled (b) below, are actually identical. The buffer-capacity constraints can be derived in the same way as those in Section 5.2, while taking into account the separate buffers per output edge of an actor and the fact that input buffer space is only released at the end of a firing. These two aspects explain the occurrence of the \(B(i,j)\) and the \(e(j)\) in the right-hand side of the buffer constraints given as (a) below. For any given SRDF graph \(G = (V, E, e, d)\), given period \(P\), and buffer-capacity distribution function \(B\), the following system of constraints captures gOSBA. For all \((i,j) \in E\),

\[
\begin{align*}
(a) \quad & s(j) - s(i) \leq P \cdot (B(i,j) - d(i,j)) - e(j), \\
(b) \quad & s(i) - s(j) \leq P \cdot d(i,j) - e(i). 
\end{align*}
\]

This system is a system of difference constraints [17], i.e., a system of linear constraints where each constraint is a maximum difference between two variables. As shown in [17], a system of difference constraints can be turned into a constraint graph that has a node for every variable and an edge \((u, v)\) with edge weight \(m\) for any constraint of the form \(v - u \leq m\). As a consequence, it is possible to create a constraint graph for any given SRDF graph \(G\), period \(P\), and buffer-capacity distribution function \(B\). Fig. 3 shows the constraint graph for our example SRDF graph of Fig. 1, period \(P = 5\), and the optimal buffer-capacity distribution function resulting from schedule \(s_1\) of Table 2, as discussed at the end of Section 6.1.

Before formally defining the constraint graph, it should be noted that the set of constraints of (12) may contain redundant constraints. If actors \(i\) and \(j\) of the SRDF graph are connected by edges \((i,j)\) and \((j,i)\), there are two constraints of the form \(s(i) - s(j) \leq m\), one precedence constraint and one buffer-capacity constraint, and two constraints of the form \(s(j) - s(i) \leq n\), as well. In both cases, the constraint with the largest right-hand side is redundant. The constraint graph is constructed after removal of these redundant constraints. Let \(c_{p(i,j)}\) refer to any precedence constraint corresponding to edge \((i,j)\) in \(E\), i.e., a constraint of type (b) above, and let \(c_{b(i,j)}\) refer to the buffer constraint (a) corresponding to edge \((i,j)\). We use \(w_{p(i,j)}\) to refer to any precedence constraint \(c_{p(i,j)}\) and \(w_{b(i,j)}\) to refer to the right-hand sides of \(c_{p(i,j)}\) and \(c_{b(i,j)}\), and assume that \(w_{p(i,j)}\) and \(w_{b(i,j)}\) are infinite if the corresponding constraint is not present. Constraint graph \(G'(G, P, B)\) is then the weighted graph \((V_C, E_C, w_C)\), with \(w_C : E_C \rightarrow \mathbb{Z}\), defined as follows:

\[
\begin{align*}
V_C &= \{s(i) \mid i \in V\}, \\
E_C &= \{(s(i), s(j)) \mid (i, j) \in E \vee (j, i) \in E\}, \\
w_C &= \{(e, w_{b(i,j)} \min w_{p(i,j)}, i) \mid e = (s(i), s(j)) \in E_C\}. 
\end{align*}
\]

The following proposition is important later:

**Proposition 1 [17].** A set of difference constraints has a solution if and only if the corresponding constraint graph has no cycles with negative accumulative weight.

---

4. The constraint graph as defined in [17] has one extra auxiliary source node and some extra edges originating from this source node, which are not relevant for our purposes, and hence ignored in the remainder.
The constraint graph of Fig. 3 does not have cycles with negative accumulative weight. This conforms to the fact that the system of difference constraints of (12) has solutions, schedule $s_1$ of Table 2 being one of them.

### 6.4 Minimal Buffering for Live Execution

In his dissertation [20], Murthy proves NP-completeness of another buffer optimization problem for data-flow graphs. Murthy’s graphs are equivalent to our SRDF graphs, except that our actors have a time valuation. We reformulate the problem of [20] as a decision problem in the setting of this paper, and refer to it as the Minimal Buffering for Live Execution (MBLE) problem. We use MBLE to prove that gOSBA is NP-complete. The NP-completeness proof for Murthy’s M BLE formulation carries over trivially to the current setting. A schedule is sequential if no two actor firings overlap in time.

**MBLE**

Given a live SRDF graph $G = (V, E, e, d)$ with $e(i) = 1$ for all $i \in V$ and a positive integer $K$, does $G$ have a sequential SPS that has a buffer-capacity distribution function $B$ such that $\sum_{i,j \in E} B(i, j) \leq K$?

**Theorem 3 [20].** M BLE is NP-complete.

Murthy gives a reduction from the feedback-arc-set (FAS) problem [19], which for a given directed graph essentially asks for a subset of edges of a given size that breaks all cycles in the graph. Given an FAS graph, the reduction creates an SRDF graph by, for the sake of reasoning, reversing the edges in the FAS graph and by adding one initial token to each of these edges. The crucial observation is then that a sequential SPS for an SRDF graph created by taking

$$G = (V, E, e, d)$$

and adding a new node $n \notin V$ as illustrated in Fig. 4 and formalized as follows:

- $V_g = V \cup \{n\}$;
- $E_g = E \cup \{(x, n), (n, x)\}$;
- $e_g = e \cup \{(n, |V|)\}$;
- $d_g = d \cup \{(x, 1), ((x, x), 0)\}$.

The idea behind the transformation is that the new actor creates a sufficiently long critical cycle, implying 1) that an M BLE solution extended for the new actor is an SPROS of the resulting gOSBA graph with, except for the new edges, the same buffer capacities, and 2) that any SPROS of the gOSBA graph can be sequentialized to form a solution to the original M BLE instance. The reduction from M BLE to gOSBA-D cannot be applied directly to the original OSBA formulation because sequentializing an SPS may adversely affect the required buffer capacities under the buffering assumptions made by Ning and Gao, whereas it does not under the more conservative gOSBA assumptions.

The fact that $K_g = K + 2$ in the gOSBA-D instance follows from the observation that the buffer capacity for edges $(n, x)$ and $(x, n)$ is one in any admissible schedule of $G_g$.

**Corollary 3.** If $B_g$ is a buffer-capacity distribution function for an admissible schedule of gOSBA-D instance $G_g$, then $B_g(n, x) = B_g(x, n) = 1$.

We proceed with two lemmas needed in the NP-completeness proof.

**Lemma 2.** The MCM $\mu(G_g)$ of $G_g$ is $|V| + 1$.

**Proof.** Lemma 1 applies to M BLE graph $G$, implying that $\mu(G) \leq |V|$. By construction, the critical cycle in $G_g$ is, therefore, the cycle $(n, x), (x, n)$ with cycle mean $|V| + 1$.

**Lemma 3.** If buffer-capacity distribution $B$ results from a solution of M BLE instance $G$, then constraint graph $C(G, P, B)$ does not have negative cycles for any $P \geq |V|$. 

**Proof.** By definition of M BLE, $G$ has a sequential SPS that respects buffer capacities $B$. Since all actors of $G$ have an execution time of one, their sequential execution takes $|V|$ time units. Thus, an SPS respecting $B$ with period $|V|$ exists, and therefore there exists also an SPS respecting $B$ for any $P \geq |V|$. It follows that the system of difference constraints of (12) has a solution for such a $P$ and $B$, which in turn implies the desired result based on Proposition 1.

**Theorem 4.** gOSBA-D is NP-complete.

**Proof.** It is straightforward to see that gOSBA-D is in NP. If we have a proposed solution $B$ for gOSBA-D instance $G$, we can build the constraint graph $C(G, \mu(G), B)$ of $G$.
with period \( \mu(G) \) and buffer-capacity distribution \( B \). A search for negative cycles in \( C(G, \mu(G), B) \) can be done polynomially [17]. If no negative cycles are found, then, according to Proposition 1, the set of constraints of (12) has a solution, showing that \( B \) is a solution of \( g\text{OSBA-D} \).

For the proof of NP-hardness, we show that \( \text{MBLE} \) is reducible to \( g\text{OSBA-D} \). Let \( G = (V, E, e, d) \), with positive integer \( K \) be an \( \text{MBLE} \) instance. Let \( G_g \) with \( K_g = K + 2 \) be the corresponding \( g\text{OSBA-D} \) instance as defined above.

First, if buffer-capacity distribution function \( B \) with \( \Sigma_{(i,j) \in E} B(i,j) \leq K \) is a solution of the \( g\text{OSBA-D} \) instance, then buffer-capacity distribution \( B_g = B \cup \{((n, x), 1), ((x, n), 1)\} \) is a solution of the corresponding \( \text{MBLE} \) instance, as the following shows. By Lemma 3, constraint graph \( C(G, |V| + 1, B) \) does not have negative cycles. Thus, by Proposition 1, there is an SPS \( s \) for \( G \) with period \( \mu(G_g) = |V| + 1 \) that respects \( B \). As a consequence, \( s_g = s \cup \{s(n(x + 1))\} \) is an SPS for \( G_g \) that by Corollary 3 and Lemma 2 has buffer-capacity distribution \( B_g \) and is rate optimal, showing that \( s_g \) and \( B_g \) form a solution of the \( g\text{OSBA-D} \) instance \( G_g \).

Second, if schedule \( s \) with buffer-capacity distribution function \( B_g \) with \( \Sigma_{(i,j) \in E} B_g(i,j) \leq K_g \) is a solution of the \( g\text{OSBA-D} \) instance, then buffer-capacity distribution function \( B = B_g \setminus \{((n, x), B_g(n,x)), ((x, n), B_g(x,n))\} \) is a solution of the corresponding \( \text{MBLE} \) instance, as the following shows. Observe that \( B \) respects the bound \( K \) of the \( \text{MBLE} \) instance by Corollary 3. Since \( s \) and \( B \) are a solution of the \( g\text{OSBA-D} \) instance, the system of constraints of (12) has \( s \) as a solution and by Proposition 1 constraint graph \( C(G_g, \mu(G_g), B_g) \) has no negative cycles. If we remove node \( s(n) \) with its input and output edge from this graph, we obtain constraint graph \( C(G, \mu(G_g), B) \). Since we only removed a node and two edges from \( C(G_g, \mu(G_g), B_g) \), no new cycles have been created, and so \( C(G, \mu(G_g), B) \) does not have negative cycles. Again using Proposition 1, this means that \( G \) has an SPS with period \( \mu(G_g) \) that respects buffer capacities \( B \). Since by Lemma 2 \( \mu(G_g) = |V| + 1 \), and since all actor execution times in \( G \) are one, this SPS can be sequentialized without affecting the period and without negatively affecting the required buffer capacities. The latter follows from a simple inductive reasoning. Thus, the resulting sequential SPS is a solution of the \( \text{MBLE} \) instance.

This shows that \( \text{MBLE} \) is reducible to \( g\text{OSBA-D} \). Since \( g\text{OSBA-D} \) is NP-hard and in NP, it is NP-complete.  

7 Complexity of OSBA

To prove the NP-completeness of the original OSBA formulation, we first phrase OSBA as a decision problem.

**OSBA-D**

Given a live SRDF graph \( G = (V, E, e, d) \) and a positive integer \( K \), does \( G \) have an SPROS with buffer-capacity distribution function \( b \) such that \( \Sigma_{v \in V} b(v) \leq K? \)

We show that \( \text{gOSBA-D} \) can be reduced to \( \text{OSBA-D} \), thus showing that \( \text{OSBA-D} \) is NP-complete. Fig. 5 illustrates the reduction.

The basic idea is that any SPROS of the \( \text{gOSBA-D} \) instance, say \( G_{\gamma} \), has a one-to-one correspondence with an SPROS of the \( \text{OSBA-D} \) instance, say \( G_{\Omega} \), while every buffer needed by \( G_{\gamma} \) has a one-to-one correspondence with a buffer of \( G_{\Omega} \). As in the previous construct, the firings of these three actors occur as soon as the firing of the preceding actor finishes. As a consequence, the buffers of \( A \) and \( P_{A_j} \) in \( G_{\Omega} \) are 0 and (due to the initial token) 1, respectively.5 As another consequence, the firing of \( A_j \) in \( G_{\Omega} \) completes at the same point in time as the corresponding firing of \( A \) in \( G_{\gamma} \). Edge \( (A_j, j) \) and the buffer of actor \( A_j \) now take the role of edge \( (A, j) \) with its buffer in \( G_{\gamma} \).

Second, consider actor \( B \) with its input edge \( (A, B) \). In \( \text{gOSBA-D} \), actor \( B \) releases input space at the end of its firing. In \( \text{OSBA-D} \), \( B \) would release input space at the firing start. To mimic the \( \text{gOSBA-D} \) behavior, actor \( B \) is embedded in a cycle of length \( \mu \) with actor \( R_{AB} \). As in the previous construct, the firings of these two actors occur in a rate-optimal execution as soon as the firing of the preceding actor finishes.

5. Buffer size 0 may seem artificial, but it is caused by the fact that we only consider buffer requirements after all firing starts and ends at a certain moment in time have occurred. The size 0 is, in fact, convenient in the reduction.
actor finishes. Thus, in a rate-optimal schedule, actor $R_{AB}$ starts at the same time as actor $B$ finishes. By adding now an edge $(A_B, R_{AB})$, which in OSBA-D shares its buffer with edge $(A_B, B)$, space in this buffer in $G_O$ is now only released at the start of a firing of $R_{AB}$, which corresponds exactly with the release of space in $G_g$ at the end of the corresponding firing of $B$.

In summary, the two sketched constructs address precisely the two differences between gOSBA-D and OSBA-D. Of course, they can also occur in combination, and edges may contain initial tokens, as illustrated for actor $C$ and edge $(A,C)$ in the figure. The initial token on $(A,C)$ is copied to both the corresponding $(A;C)$ and $(A;RACX)$ edges. The remainder of this section gives a formal NP-completeness proof for OSBA-D based on the sketched transformation.

Consider gOSBA-D instance $G_g = (V_g, E_g, e_g, d_g)$ with positive integer $K_g$. OSBA-D instance $G_O = (V_O, E_O, e_O, d_O)$ with positive integer $K_O = K_g + |E_g| + |\{(i,j,k) | ((i,j) \in E_g)\}$ is created as follows: To simplify notations and reasoning, we apply the first construct sketched above to all edges in the graph, not only to those that are an output edge of an actor with multiple output edges. This transformation, therefore, affects all actors, except those without any output edges. Assume that $V_g$ is partitioned into actors with output edges $V'_{g}$ and actors without output edges $V''_{g}$.

$V_O = V'_g \cup \bigcup_{(i,j) \in E_g} \{i, j\}$

$E_O = \bigcup_{(i,j) \in E_g} \bigcup_{(i,j,k) \in E_g} \{(i,j,k) | ((i,j,k) \in E_g)\}$

$e_O = \bigcup_{(i,j) \in E_g} \bigcup_{(i,j,k) \in E_g} \{(i,j,k) | ((i,j,k) \in E_g)\}$

$d_O = \bigcup_{(i,j) \in E_g} \bigcup_{(i,j,k) \in E_g} \{(i,j,k) | ((i,j,k) \in E_g)\}$

The following lemma shows that, given the actor firing times of the actors in $V'_g$ in any SPROS of $G_g$, the firing times of all the additional actors are fixed. It also shows that, except for the buffers needed for the $i_j$ actors, all buffer sizes are fixed and independent of the particular SPROS.

**Lemma 5.** Let $s_O$ be an SPROS of $G_O$ with buffer-capacity distribution function $b_O$. For edges $(i,j), (j,k) \in E_g$,

1. $s_O(i) = s_O(i) + s_O(j) + e_g(i,j)$;
2. $(j,k) = s_O(j) + s_O(k) + e_g(j,k)$;
3. $b_O(i) = b_O(j) = 0 \land b_O(i,j) = b_O(i,j) = 1$.

**Proof.** Properties 1 and 2 follow from the actor execution times of $G_g$ and the observations that, by Lemma 4, $s_O$ has period $\mu(G_g)$, that the $i_i$ actors are on a cycle of length $\mu(G_g)$ with an initial token on edge $(P_i,i)$, that the $j_j$ and $P_j$ actors are on a cycle of length $\mu(G_g)$ with an initial token on edge $(P_j,j)$, and that the $j_k$ and $R_{jk}$ actors are on a cycle of length $\mu(G_g)$ with an initial token on edge $(R_{jk},j)$. Property 3 then follows directly from (5) and the derived relations between the various actor start times.

The following two propositions prove a one-to-one correspondence between SPROSs of $G_g$ and $G_O$ and their buffer sizes:

**Proposition 2.** A schedule $s_g$ is an SPROS of $G_g$ if and only if $s_O$ with, for all actors $i \in V'_g$, $s_O(i) = s_g(i)$ is the start times of the other actors of $G_O$ as in Lemma 5, is an SPROS of $G_O$.

**Proposition 3.** Consider two corresponding SPROSs $s_g$ of $G_g$ and $s_O$ of $G_O$. If $s_g$ has buffer-capacity distribution function $B_g$, then $s_O$ has buffer-capacity distribution function $b_O$ with, for any edge $(i,j) \in E_g$, $b_O(i,j) = B_g(i,j)$, and the buffer capacities of the other actors of $G_O$ as in Lemma 5.

**Proposition 4.** $\mu(G_O) = \mu(G_g)$.

**Proof.** All the cycles of $G_g$ are still present in $G_O$ with the same total execution time and the same number of initial tokens but with for any edge $(i,j) \in E_g$ the extra $i_j$ actors inserted. This means that $\mu(G_O) \geq \mu(G_g)$. The transformation from $G_g$ to $G_O$ adds cycles $(i,j), (i,j,P_j), (P_j,i)$ with execution time $\mu(G_g)$ and one initial token. It, furthermore, adds cycles $(j_k,R_{jk}), (R_{jk},j)$ with execution time $\mu(G_g)$ and one initial token. None of these cycles causes $\mu(G_O)$ to be strictly larger than $\mu(G_g)$.

Finally, for every cycle of $G_g$ going through edges $(i,j), (j,k) \in E_g$, the transformation adds a cycle with extra actor $R_{jk}$ through edges $(i,j,R_{jk})$ and $(R_{jk},j)$. However, the additional execution time $\mu(G_g) - e_g(i,j)$ is compensated by one extra token, on the $(R_{jk},j)$ edge, which means that all these extra cycles do not increase the MCM. Hence, $\mu(G_O) = \mu(G_g)$.

In the remainder of this section, we assume for simplicity that every actor has an output edge. The reasoning for actors without an output edge is simpler and goes along the same lines.

First, we observe that $G_g$ and $G_O$ have the same MCM.

**Lemma 4.** $\mu(G_O) = \mu(G_g)$.

**Proof.** All the cycles of $G_g$ are still present in $G_O$ with the same total execution time and the same number of initial tokens but with for any edge $(i,j) \in E_g$ the extra $i_j$ actors inserted. This means that $\mu(G_O) \geq \mu(G_g)$. The transformation from $G_g$ to $G_O$ adds cycles $(i,j), (i,j,P_j), (P_j,i)$ with execution time $\mu(G_g)$ and one initial token. It, furthermore, adds cycles $(j_k,R_{jk}), (R_{jk},j)$ with execution time $\mu(G_g)$ and one initial token. None of these cycles causes $\mu(G_O)$ to be strictly larger than $\mu(G_g)$.

Finally, for every cycle of $G_g$ going through edges $(i,j), (j,k) \in E_g$, the transformation adds a cycle with extra actor $R_{jk}$ through edges $(i,j,R_{jk})$ and $(R_{jk},j)$. However, the additional execution time $\mu(G_g) - e_g(i,j)$ is compensated by one extra token, on the $(R_{jk},j)$ edge, which means that all these extra cycles do not increase the MCM. Hence, $\mu(G_O) = \mu(G_g)$.
been able to develop a similar capacity-constrained model for OSBA. Nevertheless, the technique of [11], [12] forms the basis of an exact solution to OSBA, by applying it on a transformed graph that preserves SPROSs with their buffer requirements.

Given a graph $G$, let $G_{spros}$ be the SRDF graph obtained by adding for each actor $i$ an actor $P_i$, with execution time $\mu(G) - \epsilon(i)$ and two edges $(i, P_i)$ and $(P_i, i)$, the latter with initial token. The transformation is illustrated in Fig. 6. Clearly, the MCM of $G_{spros}$ is $\mu(G)$.

Consider now an SPROS $s$ of $G$. Schedule $s_{spros}$ obtained from $s$ by defining $s_{spros}(i) = s(i)$ and $s_{spros}(P_i) = s(i) + \epsilon(i)$ for all $i$ is an SPROS of $G_{spros}$, because every actor is forced in a periodic regime with period $\mu(G)$. Conversely, any SPROS of $G_{spros}$ can be turned into an equivalent SPROS of $G$, by simply omitting the schedule times of actors $P_i$. If an SPROS $s$ of $G$ has buffer-capacity distribution function $b$, then $s_{spros}$ has buffer-capacity distribution function $b_{spros}$ with, for all actors $i$, $b_{spros}(i) = b(i)$ and $b_{spros}(P_i) = \epsilon(i)$. The addition of an actor $P_i$ does not affect the required buffer size of actor $i$ because $P_i$ always immediately starts its firing when $i$ finishes its firing. The buffer for $P_i$ is clearly 1 (even when $P_i$'s execution time is 0, because of the initial token). Thus, the buffer-optimal SPROSs of $G$ and $G_{spros}$ coincide, yielding the same buffer sizes for the actors of $G$.

The technique of [11], [12] can now be used to solve OSBA for a given SRDF graph $G$ by applying it to the transformed graph $G_{spros}$, as the following reasoning shows:

As shown in [21] and [12], the result of the buffer analysis is a periodic rate-optimal schedule with an initial transient part. By the construction of $G_{spros}$, every actor is forced to fire in a strictly periodic regime eventually in any rate-optimal execution of $G_{spros}$. Thus, the buffer-optimal SPROSs of $G$ and $G_{spros}$ coincide, yielding the same buffer sizes for the actors of $G$.

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inductive argument on the length of the transient, i.e., the first \( N \) firings of all actors. The key point is that, by the construction of \( G_{\text{sprs}} \), all firings of one actor in \( s \) are at least \( \mu(G) \) time units apart. Maximally delaying the first \( N \) firings of all actors in \( s \) yields the desired SPROS. If \( N = 0 \), then \( s \) is an SPROS. For the inductive step, assume \( N > 0 \); consider the actor firings in the transient in reverse order, ordered by their finishing times, and assuming some arbitrary order for firings finishing at the same point in time. The first actor in this sequence, which is (one of) the last actor(s) to complete its \( n \)th firing, can now be delayed as follows: Assume the considered actor is actor \( i \). The considered firing has index \( N - 1 \) and start time \( s(i, N - 1) \). By construction of \( G_{\text{sprs}} \), \( s(i, N - 1) = s(i, N) - \mu(G) - \delta \) for some non-negative integer \( \delta \in \mathbb{N} \). The start time \( s(i, N - 1) \) can now be delayed by \( \delta \) to \( s(i, N - 1) + \delta \), at the same time setting the start time of the extra actor \( P_i \) to \( s(i, N - 1) + \delta + e(i) \). Thus, these two firings are added to the strictly periodic part of the schedule. Since all the required input tokens for firing \( N - 1 \) of \( i \) are already available at \( s(i, N - 1) \), they are also available at \( s(i, N - 1) + \delta \). Delaying an actor firing delays the production of output tokens. The start time of firing \( N - 1 \) of actor \( P_i \) is adapted appropriately. A crucial point now is that no firings with index \( N \) or greater are affected. Firing all actors the same number of times, as in one period of the schedule, leaves the token distribution over the edges of the graph unchanged. Since the periodic part of \( s \) has period \( \mu(G) \), this means that the production of output by firing \( N - 1 \) of actor \( i \) at time \( s(i, N) - \mu(G) \) is in time to allow the start of all firings with index \( N \) of all the actors of \( G_{\text{sprs}} \). Again using the fact that firing all actors the same number of times does not affect the token distribution, the periodic part of the new schedule still has buffer-capacity distribution \( b_{\text{sprs}} \). Assuming now that the first \( n \) firings in the considered sequence, i.e., the last \( n \) firings in the transient of \( s \), have been delayed maximally, the same reasoning applies to firing \( n + 1 \) in the sequence, completing the inductive argument.

In summary, given an SRDF graph \( G \), OSBA can be solved by transforming \( G \) into \( G_{\text{sprs}} \) and then apply the analysis of [11], [12]. The periodic part of the computed schedule and the derived buffer sizes form a solution to OSBA, when ignoring the additional actors \( P_i \). Both the number of investigated buffer sizes and the length of the execution of an SRDF with a given buffer size may be exponential in the size of the graph. Nevertheless, the technique turns out to work well in practice, as illustrated in [11] and [12] and the next section.

8.2 Error Quantification

To get some insight in the degree of inaccuracy of the OSBA solution of [1], we used the SDF\textsuperscript{3} [22] toolset to construct a benchmark of two sets of 10,000 synthetic SRDF graphs each. The first set contains graphs with seven nodes and on average 9.5 edges. The second set contains graphs with 40 nodes and on average 57.6 edges. The graphs have been constructed with an average in/out-degree of 1.5 edges per node and a maximum of three input/output edges per node. These characteristics are chosen to reflect the characteristics of medium-sized and large models one may expect in the DSP and multimedia domains. We use synthetic examples to create a sufficiently large test set. Experiments were performed on a 3.4 GHz Pentium 4 PC with 4 GB of internal memory. The runtime needed to compute the buffer sizes and the SPROS with the method presented in the previous section is on average 2.06 ms for the first set with a maximum of 684 ms. The second set has an average runtime of 156 ms with a maximum of 9,786 ms. The experiments never need more than a few MB of memory at a time. These results indicate that the exact solution, despite its theoretical complexity, is efficient in practice.

Table 3 compares the original and the exact OSBA solutions. It shows the average overestimation in buffer sizes of Ning and Gao’s approach for the two sets. This average also takes into account those graphs for which the original algorithm gives an optimal schedule. Table 3 also shows how often Ning and Gao’s algorithm provides a suboptimal solution, and the average overestimation for those cases.

For the medium-sized graphs, set 1, Ning and Gao’s algorithm gives a suboptimal solution in about one out of six cases. For the large graphs, set 2, the algorithm is suboptimal in about one out of two cases. This difference is expected because the type of subgraphs for which Ning and Gao’s approach is suboptimal may occur more frequently in larger graphs. If the result is suboptimal, the overestimation is larger for smaller graphs. Also this is as expected, since smaller graphs typically have smaller absolute total buffer sizes, which means that the relative overestimation is larger. The overestimation is small in all cases, which may explain in part why the suboptimality of the approach remained undetected up to now.

9 Conclusion

This paper revisits buffer sizing for rate-optimal single-rate data-flow scheduling, in particular the OSBA problem defined in [1]. We have shown that the linear-programming-based polynomial solution proposed in [1] is suboptimal, in contrast to the optimality claim made in [1]. We have proven that the problem is in fact NP-complete. Along the way, we have shown that also a generalized version of OSBA with commonly assumed more conservative buffering assumptions is NP-complete as well. We developed exact solutions to both OSBA variants that are efficient in practice. These solutions have been implemented in the tool SDF\textsuperscript{3} [22], that is available via http://www.es.ele.tue.nl/sdf3.

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