On the Complexity of Protocol Validation Problems for Protocols with Bounded Capacity Channels

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SUMMARY In this paper, it is proven that the following three decision problems on validation of protocols with bounded capacity channels are NP-complete. (1) Given a protocol with the channel capacity being 1, determine whether or not there exist deadlocks in the protocol. (2) Given a protocol with the channel capacity being 1, determine whether or not there exist unspecified receptions in the protocol. (3) Given a protocol with the channel capacity being 2, determine whether or not there exist overflows such that the channel capacity is not bounded by 1 in the protocol. These results suggest that, even when all channels in a protocol are bounded by 1 or 2, protocol validation should be in general interactive. It also clarifies the boundary of computational complexity of protocol validation problems because the channel capacity 0 does not allow protocols to transmit and receive messages.

key words: computational complexity, deadlock, NP-complete, protocol, protocol validation

1. Introduction

A protocol consists of processes and channels where each pair of two distinct processes are connected by a channel. Messages are transmitted and received through channels. Protocol validation is to check whether or not the specification of a protocol includes protocol errors such as unspecified receptions, redundant transmissions/receptions, deadlocks, livelocks, and overflows [2]-[5]. Among them, deadlocks, unspecified receptions and overflows are typical protocol errors that should be detected by protocol validation. Intuitively, deadlocks, unspecified receptions and overflows are as follows. A deadlock is a global state of a protocol such that the protocol cannot execute any transmission and reception of messages. An unspecified reception is a process state such that a message has been transmitted but cannot be received at the state. An overflow is a channel state such that the number of messages which have been transmitted but not yet received through the channel is larger than a given positive number.

This paper discusses the computational complexity of the following three decision problems on the protocol validation; the deadlock detection problem, the unspecified reception detection problem and the overflow detection problem. Brand and Zafiropulo showed that these problems for general protocols are undecidable when the channel capacity of the protocol is unbounded [2]. In practice, however, the channel capacity is bounded by a finite constant. West proposed an algorithm to detect deadlocks, unspecified receptions and overflows when the channel capacity is bounded by a constant and the number of processes is constant [6]. Rüchel and Toueg showed that the deadlock detection problem is PSPACE-complete in case that the channel capacity is bounded by a finite constant and the number of processes is 2 [5]. It is thus interesting to find the computational complexity of the decision problems on the protocol validation when the channel capacity is bounded by a constant and there is no restriction on the number of processes.

This paper shows that both the deadlock detection and the unspecified reception detection problems are NP-complete, even if the channel capacity is restricted to 1, and that the overflow detection problem of deciding whether or not there exist overflows such that the number of messages left in a channel is larger than 1, even if the channel capacity is restricted to 2, is also NP-complete. These results mean that, even if the channel capacity is bounded by 1 or 2, the problems are difficult to solve efficiently in the worst case.

The rest of this paper is organized as follows. In Sect. 2, three decision problems on protocol validation, i.e., the deadlock detection problem, the unspecified reception detection problem and the overflow detection problem, are formulated. In Sect. 3, the NP-completeness of the deadlock detection problem for protocols with bounded capacity channels is proven, and in Sect. 4, that of the other problems is also proven. In Sect. 5, conclusions are described with future research direction.

2. Protocol Validation Problems

A protocol consists of processes and channels. Each pair of two distinct processes are connected by a channel. Messages are transmitted and received through channels. The model in this paper uses explicit finite state machines to represent processes and implicit FIFO queues to represent channels.

Definition 1 (Protocol): A protocol among N processes is a quadruple $P = (Q, q, M, succ)$, where $Q = (Q_1, \cdots, Q_N)$, $q = (q_1, \cdots, q_N)$, $M = (M_{1,1}, \cdots, M_{1,N}, M_{2,\cdots})$.
Fig. 1 Protocol example.

\[ \ldots, M_{N, N} \) and \text{succ} = (\text{succ}_1, \ldots, \text{succ}_N). \]

Each \( Q_i \) represents a set of states of the \( i \)-th process. For any \( i \) and \( j (i \neq j) \), \( Q_i \cap Q_j = \emptyset \). A symbol \( \emptyset \) denotes an empty set.

Each \( o_i (o_i \in Q_i) \) represents the initial state of the \( i \)-th process.

Each \( M_{i,j} \) represents a set of message types that can be transmitted through the channel from the \( i \)-th process to the \( j \)-th process. For any \( i, j, i' \) and \( j' (i \neq i' \) or \( j \neq j') \), \( M_{i,j} \cap M_{i',j'} = \emptyset \) and \( M_{i,j} = \emptyset \).

Each \( \text{succ}_i \) is a partial mapping \( Q_i \times M_{i,j} \to Q_i \) which represents how the \( i \)-th process transmits or receives a message and changes its state. The set \( M_i \) is a set of message types that the \( i \)-th process can transmit or receive (\( M_i = M_{i,i} \cup \ldots \cup M_{i,N} \cup M_{j,1} \cup \ldots \cup M_{N,N} \)).

The value of \( \text{succ}_i (s, x) \) represents either the state of the \( i \)-th process after it transmits a message \( x \) in state \( s (s \in Q_i) \), if \( x \in M_{i,j} \), or the state after it receives a message \( x \) in state \( s \), if \( x \in M_{i,i} \).

The \( i \)-th process is formally defined as the quadruple \( (Q_i, o_i, M_{i,i} \cup M_{i,j}, \text{succ}_i) \).

A pair \( (s, x) \) for a state \( s (s \in Q_i) \) and a message \( x (x \in M_{i,j}) \) is said to be a transmission of the \( i \)-th process, and a pair \( (s, x) \) for a state \( s (s \in Q_i) \) and a message \( x (x \in M_{i,i}) \) is said to be a reception. A state transition is either a transmission or a reception.

(End of Definition)

Example 1: Figure 1 shows an example of a protocol with 2 processes. In the figure, ‘\( \circ \)’ depicts a state and ‘\( \bullet \)’ depicts an initial state. Arrows ‘\( \to \)’ depict state transitions. Symbols ‘\( -x \)’ and ‘\( +x \)’ represent transmissions and receptions of a message \( x \), respectively.

The protocol represents that, for example, process 1 transmits message \( v_1 \) at state \( s_1 \) and enters state \( s_1 \), and process 2 receives it at state \( s_0 \).

(End of Example)

Definition 2 (Global state and transitions): In a protocol \( P \), a global state is a pair \( G = (S, C) \), where \( S = (s_1, \ldots, s_N) \) and \( C = (c_{1,1}, \ldots, c_{1,N}, c_{2,1}, \ldots, c_{N,N}) \).

Each \( s_i \) represents a state of the \( i \)-th process \( (s_i \in Q_i) \). Each \( c_{i,j} \) represents a state of the channel from the \( i \)-th process to the \( j \)-th process, i.e., \( c_{i,j} \) is a sequence of messages that the \( i \)-th process transmitted to the \( j \)-th process but the \( j \)-th process does not receive yet. Each message in \( c_{i,j} \) belongs to \( M_{i,j} \).

The initial global state is the global state \( G_0 = (S_0, C_0) \) with all channels empty and with each process in its initial state, where \( S_0 = (o_1, \ldots, o_N) \) and \( C_0 = (\varepsilon, \ldots, \varepsilon) \). A symbol \( \varepsilon \) denotes an empty sequence.

A global state transition is defined as a binary relation ‘\( \vdash \)’ on global states. We denote \( (S, C) \vdash (S', C') \) if and only if the global state \( (S, C) \) can transit to \( (S', C') \) by exactly one state transition of one process. In other words, \( (S, C) \vdash (S', C') \) if and only if there exist some \( i, j \) and \( x \) satisfying one of the following two conditions. (1) \( s_i = \text{succ}_i (s_i, x) (x \in M_{i,j}) \), \( c_{i,j} = c_{i,j} \cdot x \), and for any \( j (j \neq i) \), \( s_j = s_j \) and \( c_{i,j} = c_{i,j} \).

Here, \( s_1 \cdot s_2 \) denotes a concatenation of sequences \( s_1 \) and \( s_2 \). (2) \( s_j = \text{succ}_j (s_j, x) (x \in M_{i,j}) \), \( c_{i,j} = x \cdot c_{i,j} \), and for any \( j (j \neq i) \), \( s_j = s_j \) and \( c_{i,j} = c_{i,j} \).

Let ‘\( \vdash \)’ be the reflexive and transitive closure of ‘\( \vdash \)’. A global state \( G = (S, C) \) is said to be reachable if and only if \( G_0 \vdash G \).

(End of Definition)

Definition 3 (Specified and executable): In a protocol \( P \), a state transition \( (s_i, x) \) is specified if and only if \( \text{succ}_i (s_i, x) \) is defined. A transmission \( (s_i, x) \) is executable if and only if there exists a reachable global state \( G = (S, C) \) such that \( S = (s_1, \ldots, s_i, \ldots, s_N) \). The reception \( (s_i, x) \) is executable if and only if there exists a reachable global state \( G = (S, C) \) such that \( S = (s_1, \ldots, s_i, \ldots, s_N) \) and \( C = (c_{1,1}, \ldots, c_{1,i}, \ldots, c_{N,N}) \) where \( Y \) is a sequence of messages in \( M_{i,j} \).

(End of Definition)

Definition 4 (Bounded and fixed channel): In a protocol \( P \), let \( N \) be the number of processes, let \( |Q| \) be the number of states of all processes, let \( |M| \) be the number of distinct message types and let \( h \) be a positive integer that is polynomial with respect to \( N, |Q| \), and \( |M| \). A channel from the \( i \)-th process to the \( j \)-th process is said to be bounded by \( h \) if and only if, for every reachable global state \( G = (S, C) \), the length of each \( c_{i,j} \) is less than or equal to \( h \).

Let \( h \) be a positive integer constant independent of \( N, |Q| \), and \( |M| \). A channel from the \( i \)-th process to the \( j \)-th process is said to be fixed to \( h \) if and only if, for every reachable global state \( G = (S, C) \), the length of each \( c_{i,j} \) is less than or equal to \( h \). This \( h \) is said to be channel capacity. If a channel is fixed, the channel is bounded.

A protocol \( P \) is said to be fixed to \( h \) if and only if all channels in \( P \) are fixed to \( h \).

(End of Definition)

Definition 5 (Protocol errors): (1) Deadlock: A global state \( G = (S, C) \) is said to be stable if and only if \( G \) is reachable and \( C = (\varepsilon, \ldots, \varepsilon) \). A stable global state \( G = (S, C) \) is said to be a deadlock if and only if \( S = (s_1, \ldots, s_N) \) and there exist no specified transmissions \( (s_i, x) (1 \leq i \leq N, 1 \leq j \leq N, s_i \in Q_i, x \in M_{i,j}) \).

(2) Unspecified Reception: An unspecified reception is a reception that is executable but not specified.
(3) Overflow: An overflow is a channel state such that the channel is not fixed to a predefined positive integer $h$.

(End of Definition)

**Definition 6** (Protocol validation problems): (1) Given a protocol $P$ fixed to $h$, determine whether or not there exist any deadlocks. This decision problem is called the **deadlock detection problem**, which is abbreviated as DDP hereinafter.

(2) Given a protocol $P$ fixed to $h$, determine whether or not there exist any unspecified receptions. This decision problem is called the **unspecified reception detection problem**, which is abbreviated as URDP hereinafter.

(3) Given a protocol $P$ fixed to $h'$ and a positive integer $h$ ($h < h'$), determine whether or not there exist any overflows such that a channel is not fixed to $h$. This decision problem is called the **overflow detection problem**, which is abbreviated as ODP hereinafter.

(End of Definition)

In the following sections, these three decision problems, DDP, URDP and ODP, are discussed in case that $h=1$ and $h'=2$.

### 3. Deadlock Detection Problem

It is obvious that DDP is in NP. In order to prove that DDP is NP-complete, it suffices to show that any NP-complete problem is polynomially transformable to DDP. In this section, the 3-satisfiability problem is proven to be polynomially transformable to DDP, and the following theorem is proven.

**Theorem 1**: DDP is NP-complete even when protocols are fixed to $h$ ($h=1$).  

(End of Theorem)

The 3-satisfiability problem is a problem to determine whether a boolean expression is satisfiable or not.

The rest of this section is organized as follows. In Sect. 3.1, the 3-satisfiability problem is introduced. In Sect. 3.2, the construction of a protocol $P$ based on a given boolean expression $B$ is described. There exist deadlocks in the constructed $P$ if and only if $B$ is satisfiable. In Sect. 3.3, it is proven that the 3-satisfiability problem is transformable to DDP by using the construction described in Sect. 3.2.

#### 3.1 3-Satisfiability Problem

The 3-Satisfiability Problem is as follows.

**Definition 7** (3-Satisfiability Problem): Let a set of boolean variables be $V$. A boolean expression can be generally denoted by a conjunctive normal form $B = (u_{i_1} + u_{i_2} + \cdots + u_{i_{L_i}}) \times (u_{j_1} + u_{j_2} + \cdots + u_{j_{L_j}}) \times \cdots \times (u_{k_1} + u_{k_2} + \cdots + u_{k_{L_k}})$. Each $u_{i_l}$ ($1 \leq i \leq L, 1 \leq i \leq L_i$) is either $v_k$ or $\neg v_k$ ($v_k \in V$) and is said to be a **literal**. Operators $+$, $\times$ and $\neg$ denote boolean sum, product and negation, respectively. For each $i$ ($1 \leq i \leq I$), $(u_{i_1} + u_{i_2} + \cdots + u_{i_{L_i}})$ is said to be a **clause**. We assume, without loss of generality, that the same variable does not appear more than once in one clause, although two literals $u_{i,k}$ and $u_{i,l} (i \neq j)$ in distinct clauses can possibly have the same variable.

An **assignment** is a mapping $V \rightarrow \{\text{true}, \text{false}\}$ which assigns true or false to each variable in $B$. A **truth assignment** is an assignment when $B$ holds true. A conjunctive normal form $B$ is said to be **satisfiable** if and only if there exists at least one truth assignment.

The **3-Satisfiability problem** is defined as follows. Given a boolean expression $B = (u_{i_1} + u_{i_2} + u_{i_3}) \times (u_{j_1} + u_{j_2} + u_{j_3}) \times \cdots \times (u_{k_1} + u_{k_2} + u_{k_3})$ in a conjunctive normal form where each clause consists of three literals, determine whether $B$ is satisfiable or not. This decision problem is abbreviated as **3SAT** hereinafter.

(End of Definition)

As for the computational complexity of the above 3-Satisfiability problem, the following theorem is known.

**Theorem 2**: 3SAT is NP-complete [1].

(End of Theorem)

#### 3.2 Construction of Protocol Based on Boolean Expression

This section describes how to construct a protocol $P$ based on a boolean expression $B$ in a conjunctive normal form where each clause consists of three literals. In the constructed $P$, there exist deadlocks if and only if $B$ is satisfiable.

The construction is stated informally as follows. When the boolean expression $B$ consists of $I$ clauses, the protocol $P$ consists of $(I+3)$ processes. The $i$-th process $(1 \leq i \leq I)$ corresponds to the $i$-th clause in $B$. At first, the $(I+1)$-th process determines an assignment for $B$ and transmits messages to each $i$-th process $(1 \leq i \leq I)$ according to the assignment. Each the $i$-th process $(1 \leq i \leq I)$ receives $l$ messages $(0 \leq l \leq 3)$ from the $(I+1)$-th process when $l$ literals in the $i$-th clause in $B$ are assigned false. If the $i$-th clause in $B$ is assigned false, i.e., all three literals in the clause are assigned false, the $i$-th process receives three messages from the $(I+1)$-th process, and then transmits a message $x_l$ to the $(I+2)$-th process. When $m$ clauses are assigned false, the $(I+2)$-th process receives $m$ messages from $m$ processes. Then the $(I+2)$-th process transmits a message $y_l$ back to one of these $m$ processes. If the $j$-th process $(1 \leq j \leq I)$ receives the message $y_l$, the $j$-th process transmits a message $z_l (1 \leq l \leq I+2, i \neq j)$ to every process in order that all processes return to their initial states. If no clauses are assigned false, no processes transmit $x_l$ to the $(I+2)$-th process, and then a deadlock occurs.

For convenience of explanation, the construction of the protocol $P$ based on the boolean expression $B$ is divided into the fundamental part and the additional part. We describe the protocol $P$ as $(Q, o, M, succ)$ where $Q = (Q_0 \cup Q_1 \cup \cdots, Q_{I+3} \cup Q_{I+4})$, $o = (o_1, \cdots,$
Fig. 2 Example of fundamental transformation for deadlock detection problem (The 4th process does not appear in this figure).

\( \sigma_{t+3} \), \( M = (M^1_{t+1} \cup M^2_{t+1} \cup \cdots \cup M^3_{t+3, t+3} \cup M^4_{t+3, t+3}) \) and \( \text{suc} = \langle \text{suc}_1, \cdots, \text{suc}_t, \cdots \rangle \). Each \( Q^i \) represents a set of states in the fundamental part of the \( i \)-th process, and each \( Q^i \) represents a set of states in the additional part. Each \( M^i_{f, j} \) represents a set of message types in the fundamental part, and each \( M^i_{l, j} \) represents a set of message types in the additional part. Each \( \text{suc}_i \) is also divided into two parts.

**Example 2**: The fundamental part of a protocol \( P \) based on a boolean expression \( B = (v_1 + v_2 + v_3) \times (\neg v_1 + v_2 + v_3) \) is shown in Fig. 2. The protocol \( P \) is shown in Fig. 3. In the figures, ‘0’ depicts a state and ‘.’ depicts an initial state. Arrows ‘→’ depict state transitions. Symbols ‘−x’ and ‘+x’ represent transmissions and receptions of a message \( x \), respectively. In this example, \( I = 2 \).

(End of Example)

The fundamental part of the \((i+1)\)-th process is constructed in the following manner. Suppose that the sequence of distinct variables in \( B \) in the order of their appearance is \( W = \langle v_1, \cdots, v_K \rangle \), where \( K = |V| \) is the number of variables and \( v_k \) (\( 1 \leq k \leq K \)) is the \( k \)-th variable in \( B \). Let the number of appearances of a literal \( u_k \), which is either \( v_k \) or \( \neg v_k \), in \( B \) be \( \text{cnt}(u_k) \).

Let the clauses which include a literal \( u_k \) be the \( \text{cls}(u_k, 1) \)-th clause, the \( \text{cls}(u_k, 2) \)-th clause, \cdots and the \( \text{cls}(u_k, \text{cnt}(u_k)) \)-th clause. (In Example 2, \( K = 4 \), \( W = \langle v_1, v_2, v_3, v_4 \rangle \), \( \text{cnt}(v_2) = 2 \), \( \text{cls}(v_2, 1) = 1 \), \( \text{cls}(v_1, 2) = 2 \), \( \text{cnt}(v_1) = 1 \) and \( \text{cls}(v_1, 1) = 2 \).) The \((n+1)\)-th process selects either \( v_k \) or \( \neg v_k \) as \( u_k \) for each \( k \) (\( 1 \leq k \leq K \)), and then transmits messages \( u_k \) to all the \( \text{cls}(u_k, 1) \)-th clause, the \( \text{cls}(u_k, 2) \)-th clause, \cdots and

Fig. 3 Example of transformation for deadlock detection problem.

the \( \text{cls}(u, \text{cnt}(u_k)) \)-th clause.

\[
Q^i_{t+1} = [q_0, \cdots, q_K] \cup \{ w_{k,1,1}, s_{k,1,1}, \cdots, w_{k,\text{cnt}(u_k)-1,1}, s_{k,\text{cnt}(u_k)-1,1}, w_{k,\text{cnt}(u_k)-1,1} \}
\]

\( \text{cnt}(v_k) > 0 \) \cup \( \neg w_{k,1,1}, \neg s_{k,1,1}, \cdots, \neg w_{k,\text{cnt}(u_k)-1,1}, \neg s_{k,\text{cnt}(u_k)-1,1} \)

\( \text{cnt}(v_k) > 0 \) \cup \( \{ q_{k-1,1,1} | 1 \leq k \leq K, \text{cnt}(v_k) = 0 \) or \( \text{cnt}(v_k) = 0 \).

\( \sigma_{t+1} = q_0 \).

\( M^i_{t+1, t+3} = [d_{u,1,1}] | 1 \leq k \leq K, \text{cnt}(v_k) = 0 \) or \( \text{cnt}(v_k) = 0 \).

For each \( i (1 \leq i \leq I) \),

\( M^i_{t+1} = \{ q_{v_k} | 1 \leq k \leq K, v_k \text{ is in the } i \text{-th clause} \} \cup (\neg v_k | 1 \leq k \leq K, \neg v_k \text{ is in the } i \text{-th clause}) \).
If $cnt(v_k)=0$, for each $k (1 \leq k \leq K)$,

$$
succ^k_{i+1}(q_{k-1}, v_k) = q_{k-1,k} \quad (d_k \in M_{i+1,t+3})$$

$$
succ^k_{i+1}(q_{k-1,k}, d_k) = q_k \quad (d_k \in M_{i+2,t+1})$$

If $cnt(v_k) \neq 0$, for each $k (1 \leq k \leq K)$,

$$
succ^k_{i+1}(q_{k-1}, v_k) = w_{k,1} \quad (v_k \in M_{i+1,t+3}(v_{k-1}))$$

$$
succ^k_{i+1}(w_{k,1}, v_k) = s_{k,1} \quad (v_k \in M_{i+2,t+1}(v_{k-1}))$$

$$
succ^k_{i+1}(s_{k,1}, v_k) = w_{k,2} \quad (v_k \in M_{i+2,t+3}(v_{k-2}))$$

$$
\vdots$$

$$
succ^k_{i+1}(w_{k,cont(v_k)-1}, v_k) = s_{k,cont(v_k)-1} \quad (v_k \in M_{i+2,t+3}(v_{k-1}), t+1)$$

$$
succ^k_{i+1}(s_{k,cont(v_k)-1}, v_k) = w_{k,cont(v_k)} \quad (v_k \in M_{i+2,t+3}(v_{k-1}))$$

$$
succ^k_{i+1}(w_{k,cont(v_k)}, v_k) = q_k \quad (v_k \in M_{i+2,t+3}(v_{k-1}), t+1)$$

In case $cnt(\neg v_k)=0$ and case $cnt(\neg v_k)=0 (1 \leq k \leq K)$, $succ_{i+1}$ is defined in a similar way and their descriptions are omitted. Note that $cnt(v_k)=0$ and $cnt(\neg v_k)=0$ do not hold simultaneously because there exists at least one variable $v_k$ in $B$. Each $M^F_{i+1}$ ($1 \leq i \leq I$) is described later as a component of the $i$-th process.

The fundamental part of the $i$-th process ($1 \leq i \leq I$) is constructed in the following manner. Suppose for each $i$ ($1 \leq i \leq I$) that the $i$-th clause is composed of three literals $u_{var(i,1)}$, $u_{var(i,2)}$, and $u_{var(i,3)}$, where each $u_{var(i,j)}(1 \leq j \leq 3)$ is either $v_{var(i,j)}$ or $\neg v_{var(i,j)}$ ($v_{var(i,j)} \in V$) and $1 \leq var(i,1) < var(i,2) < var(i,3) \leq K$. (In Example 2, var (2, 1) = 1, var (2, 2) = 2, var (2, 3) = 4 and $u_{var(i,3)} = v_{k}$. The $i$-th process receives a message $u_{var(i,j)}$ from the $(I+1)$-th process if a literal $u_{var(i,j)}$ is assigned false. If the $i$-th clause is assigned false, i.e., all the three literals in the $i$-th clause are assigned false, then the $i$-th process receives three messages and reaches state $s_0$.

$$Q^F_i = \{s_0, w_1, s_2, w_2, s_3, w_3, q_0, q_1\},$$

$$o_i = s_0,$

$$M^F_{i+1} = (v_k || \text{literal } v_k \text{ is in the } i\text{-th clause}) \cup (\neg v_k || \text{literal } \neg v_k \text{ is in the } i\text{-th clause}).$$

In the following $suc_{i+1}$, suppose that $u_{var(i,1)} = v_{var(i,1)}$ and $u'_{var(i,1)} = v_{var(i,1)}$ if the $i$-th clause includes the literal $\neg v_{var(i,1)},$ and $u_{var(i,2)} = \neg v_{var(i,2)}$ and $u'_{var(i,2)} = \neg v_{var(i,2)}$ if the $i$-th clause includes the literal $\neg v_{var(i,2)}$.

$$suc_{i+1}(s_0, u_{var(i,1)}) = w_1 \quad (u_{var(i,1)} \in M_{i+1,t+1}),$$

$$suc_{i+1}(w_1, u'_{var(i,1)}) = s_1 \quad (u'_{var(i,1)} \in M_{i+1,t+1}),$$

$$suc_{i+1}(s_1, u_{var(i,2)}) = w_2 \quad (u_{var(i,2)} \in M_{i+1,t+1}),$$

$$suc_{i+1}(w_2, u'_{var(i,2)}) = s_2 \quad (u'_{var(i,2)} \in M_{i+1,t+1}),$$

$$suc_{i+1}(s_2, u_{var(i,3)}) = w_3 \quad (u_{var(i,3)} \in M_{i+1,t+1}),$$

$$suc_{i+1}(w_3, u'_{var(i,3)}) = s_3 \quad (u'_{var(i,3)} \in M_{i+1,t+1}),$$

$$suc_{i+1}(s_3, u_{var(i,4)}) = w_4 \quad (u_{var(i,4)} \in M_{i+1,t+1}),$$

$$suc_{i+1}(w_4, u'_{var(i,4)}) = s_4 \quad (u'_{var(i,4)} \in M_{i+1,t+1}),$$

$$\vdots$$

$$suc_{i+1}(s_{k-1}, u_{var(i,k)}) = w_k \quad (u_{var(i,k)} \in M_{i+1,t+1}),$$

$$suc_{i+1}(w_k, u'_{var(i,k)}) = s_k \quad (u'_{var(i,k)} \in M_{i+1,t+1}).$$

The $(I+2)$-th process has no fundamental part and its additional part is described later.

The fundamental part of the $(I+3)$-th process is constructed in the following manner, although it does not have any additional part.

$$Q^F_{i+3} = \{q_0\} \cup \{q_k \mid 1 \leq k \leq K, \text{cnt}(v_k) = 0 \text{ or } \text{cnt}(\neg v_k) = 0\},$$

$$o_{i+3} = q_0,$$

$$M^F_{i+3,t+1} = (d_k \mid 1 \leq k \leq K, \text{cnt}(v_k) = 0 \text{ or } \text{cnt}(\neg v_k) = 0),$$

$$suc_{i+3}(q_0, d_k) = q_k \quad (d_k \in M_{i+3,t+3}),$$

$$suc_{i+3}(q_k, d_k) = q_0 \quad (d_k \in M_{i+3,t+3}).$$

The additional part of the $(I+1)$-th process is constructed in the following manner.

$$Q^A_i = \{r_1, r_2\},$$

$$M^A_{i+1,t+2} = \{e\},$$

$$suc_{i+1}(q_k, e) = r_1 \quad (e \in M_{i+1,t+2}),$$

$$suc_{i+1}(r_1, e') = r_2 \quad (e' \in M_{i+2,t+1}).$$

For each $i (1 \leq i \leq I)$,

$$suc_{i+1}(r_1, z_i) = q_0 \quad (z_i \in M_{i+1,t+1}).$$

The additional part of the $i$-th process ($1 \leq i \leq I$) is constructed in the following manner. The $i$-th process transmits a message $x_i$ to the $(I+2)$ process when the $i$-th clause in $B$ is assigned false.

$$Q^A_i = \{w_4, s_4, r_1, r_2, \ldots, r_{i-1}, r_{i-1,i}, r_i\} \cup \{s_{j,i} \mid 0 \leq i \leq 4, 1 \leq j \leq I, j \neq i\},$$

$$M^A_{i+2,t+3} = \{x_i\},$$

$$suc_{i+1}(s_4, x_i) = w_4 \quad (x_i \in M_{i+2,t+2}),$$

$$suc_{i+1}(w_4, x_i') = s_4 \quad (x_i' \in M_{i+2,t+2}),$$

$$suc_{i+1}(s_4, y_i) = r_1 \quad (y_i \in M_{i+2,t+2}),$$

$$suc_{i+1}(r_1, z_i) = r_2 \quad (z_i \in M_{i+1,t+1}),$$

$$suc_{i+1}(r_2, z_i') = r_2 \quad (z_i' \in M_{i+1,t+1}).$$


\[ \text{succeeding: } r_{i-2, j} \rightarrow r_{i-1, j} \]
\[ \text{succeeding: } r_{i-1, j} \rightarrow r_i \]
\[ \text{succeeding: } r_i \rightarrow r_{i+1} \]
\[ \text{succeeding: } r_{i+1} \rightarrow r_{i+2} \]
\[ \text{succeeding: } r_{i+2} \rightarrow r_{i+3} \]

For each \( i \) and \( j \) (\( 1 \leq i \leq I, 1 \leq j \leq I \)),
\[ M_{i,j} = \{ z_i, z_j \} \]
\[ \text{succeeding: } s_{i,j} \rightarrow s_{i+1,j} \]
\[ \text{succeeding: } s_{i+1,j} \rightarrow s_{i+2,j} \]

The \((I+2)\)-th process \((1 \leq i \leq I)\) is constructed in the following manner. Each the \(i\)-th process \((1 \leq i \leq I)\) transmits a message \(x_i\) if the \(i\)-th clause is assigned false. The \((I+2)\)-th process selects one \(x_j\) of these messages and transmits a message \(y_j\) to the \(j\)-th process.

\[ Q_{i+2} = \{ r_o, r_i, r_j, r_k \} \]
\[ \{ w_i, q_i, p_i | 1 \leq i \leq I \} \]
\[ \text{assign: } \sigma_{i+2} = \{ r_0 \} \]
\[ M_{i+2,j} = \{ e \} \]
\[ \text{succeeding: } r_{i+2, j} \rightarrow r_{i+3, j} \]
\[ \text{succeeding: } r_{i+3, j} \rightarrow r_{i+4, j} \]

For each \( i \) (\( 1 \leq i \leq I \)),
\[ M_{i+2,j} = \{ y_i, x_i, z_i \} \]
\[ \text{succeeding: } s_{i+2} \rightarrow s_{i+3} \]
\[ \text{succeeding: } s_{i+3} \rightarrow s_{i+4} \]

In this paper, we may use the same message name in distinct channels and the same state name in distinct processes, although \( M_{i,j} \cap M_{i',p} = \phi \) and \( Q_i \cap Q_j = \phi \) as described in Definition 1. In case that there exist the same name in distinct channels or processes in \( P \), suppose that those names are translated into distinct names by adding the distinct channel names or process names.

### 3.3 Proof of NP-Completeness

It is obvious that DDP is in NP. In order to prove that DDP is NP-complete, it suffices to show that the 3SAT is polynomially transformable to DDP. As described in Sect. 3.2, a protocol \( P \) can be constructed for any boolean expression \( B \) in a conjunctive normal form where each clause consists of three literals. There exists the following relation between \( B \) and \( P \).

**Relation 1:** A sequence of executable state transitions through states \( q_0, q_1, \ldots, q_k \) in the \((I+1)\)-th process in the constructed protocol \( P \) is called a cycle. There exists a one-to-one correspondence between cycles and assignments for \( B \). If the variable \( v_k (1 \leq k \leq K) \) in \( B \) is assigned false, then the \((I+1)\)-th process of \( P \) transmits the message \( v_k \) to all processes which correspond to clauses including the literal \( v_k \), otherwise the \((I+1)\)-th process of \( P \) transmits the message \( \neg v_k \).

(End of Relation)

According to Relation 1, the following lemma holds true for the constructed protocol \( P \) based on \( B \).

**Lemma 1:** When a protocol \( P \) based on a boolean expression \( B \) is constructed as described in Sect. 3.2, there exist deadlocks in \( P \) if and only if \( B \) is satisfiable.

(End of Lemma)

**Proof 1 (Lemma 1):** First, the sufficiency will be shown below. Suppose that there exist no truth assignments for \( B \), i.e., \( B \) is always false for any assignment \( a \). This implies that at least one clause of \( B \) is false for any assignment \( a \). Suppose that the \(i\)-th clause \((u_{i,1} + u_{i,2} + u_{i,3})\) is assigned false, i.e., \( u_{i,1} \), \( u_{i,2} \), and \( u_{i,3} \) are all false. The \((I+1)\)-th process in \( P \) transmits three messages \( u_{i,1} \), \( u_{i,2} \), and \( u_{i,3} \) to the \(i\)-th process, as described in Relation 1. The \(i\)-th process receives these three messages and reaches state \( s_0 \) accordingly. Then, the \((I+2)\)-th process transmits a message \( x_i \) on state \( s_0 \) to the \((I+2)\)-th process. Since more than one clause may possibly be assigned false, more than one process may transmit messages \( x_i \) to the \((I+2)\)-th process. Then, the \((I+2)\)-th process receives one \( x_j \) of these messages on state \( s_0 \), and transmits a message \( y_j \) to the \(j\)-th process. The other messages \( x_i (i \neq j) \) are received by the \((I+2)\)-th process on state \( s_0 \). When the \(j\)-th process receives a message \( y_j \), and transmits messages \( z_i \) to all processes except itself and the \((I+3)\)-th process. Then, every process returns to the initial states again by receiving \( z_i \). Therefore, there exist no deadlocks in \( P \).

Second, the necessity will be shown below. Suppose that there exist no deadlocks in protocol \( P \) in the first cycle. According to the construction of \( P \), every process returns to the initial state at the end of the first cycle by receiving a message \( z_i (1 \leq i \leq I) \). Suppose that the \(j\)-th process transmits these messages \( z_j (1 \leq j \leq I) \). Since the \(j\)-th process has to reach state \( s_0 \) in order to transmit these messages \( z_j (1 \leq j \leq I) \), the \(j\)-th process reaches state \( s_0 \) through states \( s_1 \) and \( s_2 \). This
implies that the \((I+1)\)-th process transmits three messages \(u_{1,1}, u_{1,2}\) and \(u_{1,3}\) and the \(j\)-th process receives these three messages in the first cycle. As described in Relation 1, the first cycle corresponds to an assignment \(a\) for \(B\). Since the \((I+1)\)-th process transmits the three messages \(u_{1,1}, u_{1,2}\) and \(u_{1,3}\), the corresponding three literals \(u_{1,1}, u_{1,2}\) and \(u_{1,3}\) in \(B\) is assigned false in the assignemnt \(a\). Hence, at least the \(j\)-th clause is assigned false and \(B\) is not satisfied by the assignment \(a\). According to the construction of \(P\), the above discussion holds true for any cycle and any assignment. Therefore, \(B\) is not satisfied by any assignment \(a\).

Since the sufficiency and the necessity were shown, it is proven that there exist deadlocks in \(P\) if and only if \(B\) is satisfiable.

Theorem 1 is proven as follows.

**Proof 2 (Theorem 1):** As described in Sect. 3.2, a protocol \(P\) can be constructed for any boolean expression \(B\) in a conjunctive normal form where each clause consists of three literals. According to Lemma 1, there exist deadlocks in the constructed \(P\) if and only if \(B\) is satisfiable. This construction can be done in polynomial time obviously.

The channel in the constructed protocol \(P\) is fixed to \(h\) \((h=1)\) because a handshake communication mechanism is introduced for all channels where more than one message may possibly be stored. The handshake communication mechanism means a mechanism such that, when the \(i\)-th process transmits a message \(x\) to the \(j\)-th process \((j+i)\), the \(j\)-th process always returns an acknowledgement message \(x'\) to the \(i\)-th process.

Therefore, 3SAT is polynomially transformable to DDP for fixed channel capacity \(h\) \((h=1)\). Since DDP is in NP obviously, DDP is proven to be NP-complete.

(End of Proof)

4. Unspecified Reception Detection Problem and Overflow Detection Problem

The proof of NP-completeness of URDP and ODP for fixed protocols can be proven in a similar way of the proof of Theorem 1.

**Theorem 3:** URDP is NP-complete even when protocols are fixed to \(h\) \((h=1)\).  

(End of Theorem)

**Proof 3 (Theorem 3):** To prove that Theorem 3 holds, a protocol \(P\) based on a boolean expression \(B\) in a conjunctive normal form is constructed. Since the fundamental part of the construction of a protocol \(P\) is the same as that described in Sect. 3.2, only the additional part is described below.

The additional part of the \((I+1)\)-th process is constructed in the following manner.

\[ Q_{I+1}^I = \{n_0, n_1\}, \]
\[ M_{I+1,1}^I = \{x\}, \]
\[ \text{succ}^I_{I+1} (q_k, x) = n_0 \quad (x \in M_{I+1,1}), \]
\[ \text{succ}^I_{I+1} (n_0, x') = n_1 \quad (x' \in M_{I+1,1}). \]

The additional part of the 1-st process is constructed in the following manner.

\[ Q_I^I = \{p_i | 0 \leq i \leq 3\} \cup \{r_i', r_i'', r_i'', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i', r_i'
\[ M_{i+2,I} = \{ r', s' \}, \]
\[ M_{i+2,I+3} = \{ u \}, \]
\[ \text{succeeds}(r, f) = p' \quad (f \in M_{I+2,I+2}), \]
\[ \text{succeeds}(p', s') = q^u \quad (f' \in M_{I+2,I+1}), \]
\[ \text{succeeds}(r, s) = p' \quad (t \in M_{I+2,I+2}), \]
\[ \text{succeeds}(p', s) = q^u \quad (t' \in M_{I+2,I+1}), \]
\[ \text{succeeds}(q^u, u) = q^u \quad (u \in M_{I+2,I+3}), \]
\[ \text{succeeds}(q^u, u) = q^u \quad (u' \in M_{I+3,I+2}). \]

There does not exist any additional part in the \((I+3)\)-th process.

It is obvious that the above construction of a protocol \( P \) based on \( B \) can be done in polynomial time. Any unspecified receptions do not appear in the fundamental part of protocol \( P \).

The constructed protocol \( P \) behaves as follows. If \( B \) is satisfiable, then there exists a case such that all the 1-st process, the 2-nd process, \( \ldots \), and the \( I \)-th process do not reach state \( s_0 \). In this case, each of these processes transmits a message \( t \) rather than a message \( f \) to another process. Consequently, the \((I+2)\)-th process receives a message \( t \), and transmits a message \( u \) to the \((I+3)\)-th process. Since no reception of the message \( u \) is specified in the \((I+3)\)-th process, an unspecified reception occurs here. If \( B \) is not satisfiable, then at least one of the 1-st process, the 2-nd process, \( \ldots \), and the \( I \)-th process reaches state \( s_0 \). Suppose that the \( i \)-th process \((1 \leq i \leq I)\) reaches state \( s_0 \). The \( i \)-th process transmits a message \( f \) and each \( j \)-th process \((i \leq j \leq I)\) transmits messages \( f \) to another process. Consequently the \((I+2)\)-th process receives a message \( f \), and unspecified receptions do not occur. Therefore, there exist unspecified receptions in \( P \) if and only if \( B \) is satisfiable.

The constructed protocol \( P \) is fixed to \( h = 1 \) because of the similar reason in the proof of Theorem 1.

Therefore, 3SAT is polynomially transformable to URDP for fixed channel capacity. Since URDP is in NP obviously, URDP is proven to be NP-complete.

(End of Proof)

Theorem 4: ODP is NP-complete for a positive integer \( h = 1 \) even when protocols are fixed to 2.

(End of Theorem)

Proof 4 (Theorem 4): To prove that Theorem 4 holds, a protocol \( P \) based on a boolean expression \( B \) in conjunctive normal form is also constructed. Since the construction of the protocol \( P \) is the same as that in the proof of Theorem 3 except the construction of the \((I+2)\)-th process, only the additional part of the \((I+2)\)-th process is described below.

The \((I+2)\)-th process is constructed in the following manner.

\[ Q_{I+2} = \{ r_0, p_1, p_2, q^u, q^v, q^w, q^x, q^y, q^z \}, \]
\[ o_{I+2} = r_0, \]
\[ M_{i+2,I} = \{ t', s' \}, \]
\[ M_{i+2,I+3} = \{ z \}, \]
\[ \text{succeeds}(r_0, f) = p' \quad (f \in M_{I+2,I+2}), \]
\[ \text{succeeds}(p', s') = q^u \quad (f' \in M_{I+2,I+1}), \]
\[ \text{succeeds}(r_0, t) = p' \quad (t \in M_{I+2,I+2}), \]
\[ \text{succeeds}(p', s) = q^u \quad (t' \in M_{I+2,I+1}), \]
\[ \text{succeeds}(q^u, u) = q^u \quad (u \in M_{I+2,I+3}), \]
\[ \text{succeeds}(q^u, u) = q^u \quad (u' \in M_{I+3,I+2}). \]

It is obvious that the above construction of a protocol \( P \) based on \( B \) is polynomially transformable and in the protocol all channels except a channel from the \((I+2)\)-th process to the \((I+3)\)-th process are fixed to 1 and the channel from the \((I+2)\)-th process to the \((I+3)\)-th process is fixed to 2.

If \( B \) is satisfiable, then the \((I+2)\)-th process transmits a message \( z \) twice. Suppose that a positive integer \( h = 1 \) is given. There exist an overflow for

![Fig. 4 Example of transformations for unspecified reception detection problem and overflow detection problem.](image-url)
the positive integer \( h (h=1) \) if and only if \( B \) is satisfiable.

Therefore, 3SAT is polynomially transformable to ODP for the protocol fixed to 2 and the positive integer \( h (h=1) \). Since the restricted ODP is in NP obviously, the restricted ODP is proven to be NP-complete.

(End of Proof)

Example 3: An example of the transformation from a boolean expression \( B = (v_1 + v_2 + v_3) \times (\neg v_1 + v_2 + v_3) \) to a protocol \( P \) is shown in Fig. 4. Any symbols in the figure are the same as those in Figs. 2 and 3. The part for URDP is depicted by solid lines and bold lines. The part for ODP is the same as that for URDP except addition of state transitions depicted by dotted lines and deletion of state transitions depicted by bold lines.

(End of Example)

5. Conclusions

It is known that in order to solve the deadlock detection problem, the unspecified reception detection problem and the overflow detection problem for bounded protocols we have only to enumerate reachable global states \([6]\). The number of such global states is at most \( |Q|^N (|M|+1)^N \times |Q| \), where \( |Q| \) is the number of states, \( N \) is the number of processes, \( |M| \) is the number of distinct message types and \( h \) is the capacity of bounded channels. If both the capacity \( h \) and the number of processes \( N \) are fixed, then these problems can be solved in a polynomial time.

This paper has shown their NP-completeness in case of fixed \( h (h=1) \) and unlimited \( N \). Räuchle and Toueg showed PSPACE-completeness of the deadlock detection problem in case of finite \( h \) and limited \( N (N=2) \) \([5]\). Therefore, the new result on the deadlock detection problem clarifies the boundary of computational complexity of the problem, which is shown in Fig. 5.

Since the NP-completeness of the deadlock detection problem, the unspecified reception detection problem and the overflow detection problem were shown, there does not seem to exist any algorithms efficient in the worst case, even when all channels in protocols are fixed to 1 or 2. This suggests that, for protocols without any restriction on the number of processes, algorithms efficient in average should be developed \([3], [4]\).

Acknowledgments

The authors would like to thank the referees for their valuable suggestions and constructive comments.

References


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