Assessment of Service Protocols Adaptability Using a Novel Path Computation Technique*

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Abstract. In this paper we propose a new kind of adaptability assessment that determines whether service protocols of a requestor and a provider are adaptable, computes their adaptation degree, and identifies conditions that determine when they can be adapted. We also propose a technique that implements this adaptability assessment: (1) we construct a complete adaptation graph that captures all service interactions adaptable between these two service protocols. The emptiness or non-emptiness of this graph corresponds to the fact that whether or not they are adaptable; (2) we propose a novel path computation technique to generate all instance sub-protocols which reflect valid executions of a particular service protocol, and to derive all instance sub-protocol pairs captured by the complete adaptation graph. An adaptation degree is computed as a ratio between the number of instance sub-protocols captured by these instance sub-protocol pairs with respect to a service protocol and that of this service protocol; (3) and finally we identify a set of conditions based on these instance sub-protocol pairs. A condition is the conjunction of all conditions specified on the transitions of a given pair of instance sub-protocols. This assessment is a comprehensive means of selecting the suitable service protocol among functionally-equivalent candidates according to the requestor's business requirements.

1 Introduction

Given the inherent autonomy, heterogeneity, and continuous evolution of Web services, mediated service interactions are a common style of Web service interactions [9]. Hence, adaptability assessment is as important as compatibility analysis that targets direct service interactions. Following [3,4], by adaptation we mean the act of identifying, classifying, and reconciling mismatches between service behaviourial interfaces (the so-called service protocols) [5]. Adaptability assessment is further defined as the act of deciding whether or not service protocols of a requestor and a provider are adaptable without constructing an adapter,

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computing their adaptation degree, and identifying conditions that determine when these two service protocols can be adapted. This assessment enables a requestor to identify and thus to select the most suitable service provider among functionally-equivalent candidates according to her business requirements.

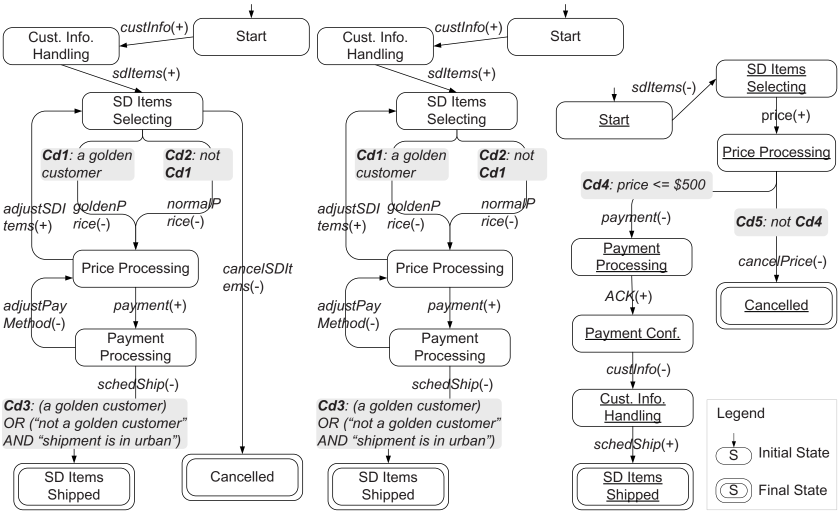
As reviewed by Dumas et al. [5], previous works related to service interaction analysis mainly focus on either compatibility analysis [1,2] or adapter construction [3,4,7,9,12,13]. Adaptability can somehow be studied by techniques that construct adapters. However, these approaches are inadequate to provide the level of assessment we target. Indeed, being able to build an adapter merely implies that there are some situations where service protocols are possibly adaptable, while unsupported scenarios (due to un-reconcilable deadlocks [7] for instance) are excluded from the adapter protocol specification. An adapter does not differentiate the different possibilities of adaptability (i.e., the adaptation degree) between adaptable service protocols, and hence, these protocols are assumed to be the same to the requestor although they are actually different in the adaptation possibility. In addition, an adapter does not specify conditions that determine when two service protocols are adaptable. Consequently, these two service protocols may behave in such a way that their interaction fails, either because it is an unsupported scenario, or because some conditions are not satisfiable according to the exchanged message instances.

1.1 Motivating Example

Fig. 1 depicts, using guarded finite state automata (i.e., GFSA), the service protocols of two soft-drinks provider services (denoted *SP* and *SP_A*) and a possible interaction with a soft-drinks requestor service (denoted *SR*). A requestor, using *SR*, intends to buy soft-drinks online through one of these two provider services. Guards denoted Cd_i ($i \in [1, 5]$) correspond to conditions in the BPEL specification. Therefore we use guard and condition interchangeably in this paper.

The only difference between *SP* and *SP_A* is that *SP* allows canceling an interaction if some selected soft-drink is presently out of stock. *SP* and *SP_A* may apply a discount on the price depending on a *custInfo*. Hence, a *custInfo* is expected by *SP* (or *SP_A*) before the price is decided. Due to privacy concerns, *SR* only sends *custInfo* if the *price* is acceptable. This example shows a deadlock that occurs when *SR* directly interacts with *SP* (or *SP_A*). *SP* (or *SP_A*) is requesting a *custInfo* before sending a *price*, while *SR* is expecting a *price* before deciding upon continuation and sending *custInfo* or not. Adapters, such as the ones described in [13,7] can circumvent this problem if either (1) one of the receiving transitions is neither control nor mandatorily data dependent on one of its direct-succeeding-transitions [13], and hence, a *mock-up custInfo* message can be generated to resolve this deadlock, or (2) the adapter developer can provide a *custInfo* message using *evidences* [7], and thus, this deadlock is reconciled.

The *custInfo* is used for deciding whether or not a discount is to be applied. However, a *normalPrice* is always applied by default. For the requestor, both *SP* and *SP_A* are adaptable with *SR* (according to [13,7]) if the *price* is acceptable. Naturally, the requestor also wants to know whether the conclusion also holds



A Soft-Drinks Provider (SP) Another Soft-Drinks Provider (SP_A) A Soft-Drinks Requestor (SR)

Fig. 1. Service protocols for soft-drink providers and requestor (SP, SP_A and SR)

when the *price* is unacceptable, so that the interaction can be cancelled if the price is unacceptable. SP can support this scenario according to [13,7], but, SP_A does not support this interaction because the interaction cannot be cancelled after the *Price Processing*.

Consequently, the requestor is given an initial impression that SP is more adaptable with SR than SP_A. If an expected interaction (for instance, the soft-drink items are to be shipped) can be supported by both SP and SP_A, SP is a more suitable candidate service provider because additional interactions (for instance, the interaction is to be cancelled) are also supportable by SP but not by SP_A. An adapter is ineligible to detect this difference since, in principle, an adapter can detect whether or not, but not how far, an adaptation is possible.

The reasoning so far only explores the legal message exchanges between SP (or SP_A) and SR. The success of an interaction in general and an adaptation in particular, however, depends also on conditions that guide which branches to follow and check whether transitions can be enabled. For instance, for an adaptation between SP (or SP_A) and SR leading to soft-drink items being shipped, a prerequisite is that Cd_2, Cd_3 and Cd_4 are able to be respected. Hence, $Cd_2 \bigwedge Cd_3 \bigwedge Cd_4$ is a condition that determines when SP, as well as SP_A, can be adapted with SR. For another adaptation between SP and SR leading to the interaction to be cancelled, a prerequisite is that Cd_2 and Cd_5 are able to be respected. However, this cancellation scenario is not supportable for SP_A and SR, and hence, $Cd_2 \bigwedge Cd_5$ is a condition for SP and SR, but is not a condition for SP_A and SR, that determines when they can be adapted.

To summarise, the conditions and the adaptation possibility (or the adaptation degree) are two complementary criteria to the requestor for selecting the suitable candidate service provider. Based on the conditions, the requestor first filters candidate service providers through checking whether the expected interactions can be supported. Thereafter, the requestor can choose a suitable service provider (possibly with the highest adaptation degree) among these functionally-equivalent candidates. The selected service provider is ensured to be interacted properly with the requestor service for achieving a certain goal.

The identification of these conditions, as well as the computation of the adaptation degree as mentioned above, is beyond existing adapter construction approaches, but is the concern of this paper. In the following sections, we show how they can be addressed in this particular example and in general.

1.2 Approach

We understand under adaptability assessment a combination of the following three perspectives: determining whether or not service protocols of a requestor and a provider are adaptable, computing their adaptation degree, and identifying conditions that determine when they can be properly adapted. In the following, we show how these three aspects are to be addressed in this paper.

1. We first construct a complete adaptation graph that captures all legal message exchanges between service protocols of a requestor and a provider (Section 3). A *complete* sequence of legal message exchanges reflects a mediated service interaction between a pair of instance sub-protocols of these two service protocols. An instance sub-protocol is a part of a service protocol that may be executed for a particular instance of this service protocol (Section 2). The emptiness or non-emptiness of the complete adaptation graph corresponds to the fact that whether these two service protocols are adaptable.
2. Assume m is the number of instance sub-protocols captured by the complete adaptation graph with respect to a certain service protocol p, and n is the number of instance sub-protocols specified by the specification of p. An adaptation degree is computed as a ratio between m and n (Section 5.1). Based on a novel path computation technique we propose in Section 4, we compute all instance sub-protocols for a service protocol specification (Section 4), and derive all instance sub-protocol pairs captured by the complete adaptation graph (Section 5.2).
3. Based on all instance sub-protocol pairs captured by the complete adaptation graph, we identify a set of conditions that determine when an adaptation is possible. For each pair, a condition is provided which corresponds to the conjunction of all conditions specified on the transitions of these two instance sub-protocols (Section 5.1).

Finally, we review the related work and conclude this paper in Section 6.

Our adaptability assessment builds upon our Space-based Process Mediator (SPM) that is detailed in our previous work [13]. It is important to notice that our technique is general and can be applied to other adapters as well.

This SPM is able to reconcile the deadlock in our motivating example in the *SD Items Selecting* state by providing a *mock-up custInfo* which is replaced whenever the *custInfo* arrives from *SR* to enable the *schedShip*(-) transition. Generally, the SPM can circumvent this kind of deadlock, if the dependency that exists between one of the receiving transitions with the state *enabled* and one of its direct- succeeding-transitions is neither control nor mandatorily data dependent. Then, the SPM can produce a *mock-up* message that acts as the data expected by this receiving transition. This *mock-up* message is replaced (through the space-based mechanism of the SPM) by a concrete message whenever it is produced by a peer protocol. More detail about the SPM is available at [13].

2 Preliminaries: Service Protocol, Control and Data Dependencies, and Instance Sub-protocol

Following [2], we adopt deterministic finite state automata for modeling service protocols, where transitions are triggered by message exchanges among partners. It should be noted that, a service protocol, or more generally a state automata, is sequentially executed. In other words, a state in a service protocol specification allows multiple transitions to follow, and hence, can lead to multiple states. However, at a certain point at runtime, only one transition can be enabled, and then be fired, and consequently, this state evolves to one of the following states.

In [2], the authors claim that different message and condition pairs are always possible to be mapped into new distinct message labels, and hence, conditions can be abstracted away. However, this simplification loses important information of conditions. For instance, the price in *SP* is mapped into *goldenPrice* and *normalPrice*. If Cd_1 and Cd_2 are not specified, the rationale for choosing *goldenPrice* or *normalPrice* is lost. Indeed, conditions are fundamental to retrieve prior known service protocols and to ensure possible interactions between these service protocols. Hence, we model service protocols in terms of GFSA. Note that the time property [17] is also an essential dimension of a service protocol specification, which is considered as our future work.

Formally, a service protocol is a tuple $p = (M, S, s, F, C, T)$, where M is a finite set of messages. Following [2], for each message $m \in M$, we use notations: $m(+)$ and $m(-)$, to denote the incoming or outgoing of m. S is a finite set of states, where s is the initial state and F is a finite set of final states. C is a finite set of conditions. $T \subseteq S^2 \times M \times C$ is a finite set of transitions. Each transition $\tau = (s_s, s_t, m(+/-), c \mid true) \in T$ defines a source state s_s, a target state s_t, an incoming or outgoing message m, and a condition $c \in C$ where $true$ is the condition of default. Transitions are semantically described by specifying their *input*, *output*, *precondition*, and *effect* (i.e., IOPE in the OWL-S specification[1]).

As presented in [11], different kinds of dependencies can exist between transitions. These dependencies are often obfuscated by a service protocol specification that defines all possible execution sequencings of transitions. A sequencing constraint in a service protocol may originate from one or multiple kinds of dependencies [11]. We consider two kinds, namely control and data dependencies.

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[1] See `http://www.w3.org/Submission/OWL-S/`

A transition τ_b is control dependent on another transition τ_a if the *completion* of τ_a (marked by its *effect*) is a necessary condition for the *enablement* of τ_b (guarded by its *precondition*). Data dependencies are classified as mandatory or optional. τ_b is mandatorily data dependent on τ_a if common data exist between the *output* of τ_a and the *input* of τ_b, whereas τ_b is optionally data dependent on τ_a if no common data exist between the *output* of τ_a and the *input* of τ_b, but, incoming conditions of τ_b use the data in the *output* of τ_a. We extract control and data dependencies from the semantic description of transitions [14].

Next, we introduce the concept of an instance sub-protocol. An instance sub-protocol represents a *valid* part of a service protocol that may be executed for a particular instance of this service protocol. *Valid* means free of dependency conflicts. Generally, if the destination transition of a dependency relation is in an instance sub-protocol, the source transition of this dependency relation must be in this instance sub-protocol as well. An instance sub-protocol itself is a *smaller* service protocol in size. For instance, *SP_A* is an instance sub-protocol of *SP*. However, *SP* itself is not an instance sub-protocol since no execution can lead a service protocol to two final states.

Formally, an instance sub-protocol of a service protocol $p = (M, S, s, F, C, T)$ is a tuple $ISP = (M_I, S_I, s_I, f_I, C_I, T_I)$ where: (1) $M_I \subseteq M$, $S_I \subseteq S$, $s_I = s$, $f_I \in F$, $C_I \subseteq C$, and $T_I \subseteq T$; (2) ISP is valid with respect to control and data dependencies of p; (3) there exists an execution instance of p with T_e as the set of transitions to be enabled and executed in this instance, then, $T_e = T_I$.

3 Service Protocols Adaptation Graph

This section addresses a joint analysis of two service protocols, that of a requestor and a provider, to decide whether they are able to be adapted. Intuitively, we need to examine all pairs of instance sub-protocols in these two service protocols to study whether each pair is adaptable. However, a service protocol may have many instance sub-protocols if it contains loop segments (for instance, *SP* has 17 instance sub-protocols, while *SR* has only 2). In addition, some instance sub-protocols in a service protocol may be much similar in their specifications, i.e., they share some transitions. Hence, an examination following this brute-force strategy is usually inefficient.

Inspired by the complete interaction tree proposed in [2], we introduce the notion of an adaptation graph that explores possible mediated service interactions between two service protocols. A mediated service interaction captures a legal message exchange sequence of two service protocols between a pair of their instance sub-protocols. As such, a mediated service interaction corresponds to a *complete* adaptation of these two service protocols leading from their initial states to a pair of their final states.

We also define an adaptation graph using GFSA, where a state is a combination of two states of participating service protocols. A transition is either a message exchange between these two service protocols, or a service protocol sending a message through an adapter (the SPM in our case), or an adapter forwarding a message (either a concrete message generated by a partner, or a *mock-up* message generated by the SPM) to a service protocol. Conditions associated with a transition in an adaptation graph are inherited from those of relevant transitions in service protocols. Note that conditions are not to be evaluated at the adaptation graph construction phase, since the evaluation of conditions depends on the exchanged message instances.

Definition 1 (Adaptation Graph). *Let* $p_1 = (M_1,\ S_1,\ s_1,\ F_1,\ C_1,\ T_1)$ *and* $p_2 = (M_2,\ S_2,\ s_2,\ F_2,\ C_2,\ T_2)$ *be two service protocols. An adaptation graph for* p_1 *and* p_2 *is a tuple* $adapt_{graph} = (M,\ S,\ s,\ F,\ C,\ T)$*.* $M \subseteq M_1 \cup M_2 \cup M_{SPM}$*, where* M_{SPM} *is a finite set of* mock-up *messages generated by SPM. The message polarity is defined as follows: messages outgoing in* M_1 *and* M_2 *are sent to SPM or a peer protocol, messages incoming in* M_1 *and* M_2 *are sent by SPM or a peer protocol, and messages in* M_{SPM} *are sent to* p_1 *or* p_2*.* $S \subseteq S_1 \times S_2$*, where* $s = (s_1, s_2)$ *and* $F \subseteq F_1 \times F_2$*.* $C \subseteq C_1 \cup C_2$*, and* $T \subseteq S^2 \times M \times C$*.*

An adaptation graph is complete if it includes all possible mediated service interactions between two service protocols. As an example, Fig. 6 in Section 5 illustrates the complete adaptation graph for *SP* and *SR* (denoted $adapt_{graph}$).

Due to space considerations we refer the interested reader to our technical report [16] for the algorithm to generate a complete adaptation graph, as well as its correctness proof. In a nutshell, the algorithm traverses from the initial states of two service protocols (i.e., p_1 and p_2) to their final states, and constructs the intermediate states through combining the intermediate states of p_1 and p_2 on the condition that there are legal message exchanges leading to them. A legal message exchange means either (1) a message exchange between p_1 and p_2, or (2) a message reordering and remembering [3,4,7,9,13] by means of SPM, or (3) a *mock-up* message generation by the SPM if one of receiving transitions (with the state *enabled*) in p_1 or p_2 is neither control nor mandatorily data dependent on one of its direct- succeeding-transitions [13].

The worst case time complexity of the algorithm is $O(k^3n^6)$ where k is the upper bound of transitions between a pair of source and target states, and n is the maximum number of states in two service protocols. Notice that as observed by [8], a service protocol tends to be a fairly simple model, because a service protocol, as well as a service in general, is designed by humans. This indicates that k is usually quite small. Moreover, the number of states in a service protocol is typically not big. Concretely, n is typically less than *100* [10], while n ranging from *50* to *100* is regarded as a large service protocol [1]. This indicates that our algorithm is able to construct a complete adaptation graph of practical relevance.

We also recognise that the size of a complete adaptation graph (i.e., the number of states and transitions) is not big. Since transitions in a service protocol are constrained by control and/or data dependencies, a state in a service protocol can combine with limited states (assume that l is the upper bound) in another service protocol which construct the states and transitions in this graph. Hence, the complete adaptation graph has $l \times n$ states in maximum, and there are k transitions at most between a pair of states.

We next explore how a complete adaptation graph contributes to the adaptability assessment. Given two service protocols p_1 and p_2, partial adaptability specifies that, some, but not all, instance sub-protocols in p_1 can be adapted with those in p_2, whereas full adaptability mandates that all instance sub-protocols in p_1 can be adapted with those in p_2. If this graph is not empty, which means that at least one pair of instance sub-protocols in p_1 and p_2 can be adapted, and hence, p_1 and p_2 are adaptable. However, to differentiate between partial and full adaptability requires checking whether or not all instance sub-protocols are reflected by the paths in this graph. To generate all instance sub-protocols of a service protocol is not a trivial task, which will be discussed in the next section. Hence, the emptiness or non-emptiness of the complete adaptation graph corresponds to the fact that whether or not p_1 and p_2 are adaptable.

4 Instance Sub-protocol Computation

Each path in a service protocol p, which leads from the initial state to one final state and is free of dependency conflicts, constitutes an instance sub-protocol of p. Hence, the problem of instance sub-protocol generation is reducible to that of path computation of a service protocol which is a directed cyclic graph. This path computation takes exponential time to the size of the graph in general.

As far as we know, *Path_BTC* [6] is the only promising technique that tackles this path computation problem. However, some assumptions made may not be satisfiable in our context. *Path_BTC* requires that two functions *concatenate* and *aggregate* are distributive. An example is given by [6] to explain this requirement as follows. Consider the case where there are two paths p_1 and p_2 from node j to k with associated labels l_1 and l_2 respectively. Let there also be a path p_3 from node i to j with label l. Then the path set from i to k (denoted P) is $\{p_3.p_1,\ p_3.p_2\}$. The symbol "." means path concatenation. This assumption may not be satisfied in our context since, in a service protocol, P may include another path that directly links i to k with label l_3. In addition, self-loops, which are excluded in *Path_BTC*, can exist in a service protocol.

In the following, we introduce a novel path computation technique to compute all paths in a service protocol. We use the service protocol SP_{Sib} depicted in Fig. 2 as a running example. SP_{Sib} is similar to SP apart from a self-loop specified on the state *SD Items Selecting* with a transition *moreSDItems*(+). This path computation procedure is composed of the following sequential steps:

1. Based on a service protocol we generate a FSA that (1) abstracts away conditions and self-loops, and then, (2) folds multiple transitions that share the source and target states into a single transition. Fig. 2 illustrates the FSA generated out of SP_{sib}, namely abstracted SP_{sib}. Thereafter, we identify back transitions in the generated FSA (detailed in Section 4.1).
2. We then compute all paths in the generated FSA. This path computation procedure is detailed in Section 4.2.

   By a path, we mean a sequence of alternating states and transitions from the initial state of this generated FSA to one of its final states. To align a path with an instance sub-protocol, we represent a path in terms of an FSA. Examples of paths are shown in Fig. 3. Note that multiple paths may share

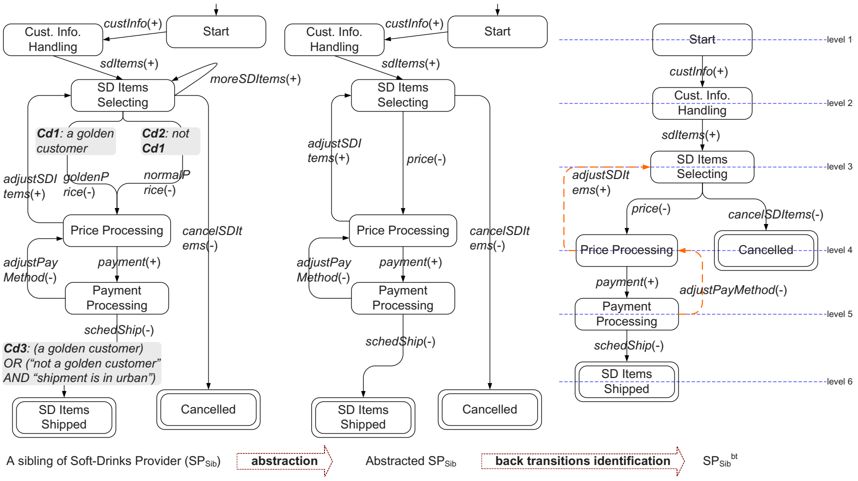

Fig. 2. Abstraction and back-transitions identification

the same FSA representation if (1) they share the same sets of states and transitions, and (2) they are different merely because of the number of times some states and/or transitions can be traversed.

3. Based on the paths computed in Step 2, we generate all paths of a service protocol by (1) unfolding transitions that have been folded in the first step, by (2) considering self-loops, and thereafter, by (3) integrating conditions that have been abstracted away previously. This procedure is detailed in Section 4.3. All paths free of dependency conflicts constitute the complete set of instance sub-protocols.

Except Step 2, other steps are computation light (with linear or polynomial time complexity). Regarding Step 2, as mentioned in Section 3, both a service protocol and a complete adaptation graph are typically not big in size. Hence, our technique is feasible to be used for the path computation of our context.

4.1 Back-Transitions Identification

A transition τ in the generated FSA is identified as a back-transition if (1) its target state is not a final state, and (2) the *distance* from the initial state of this FSA to the target state of τ is not longer than that to the source state of τ. We borrow the notion of *level* from tree automata to specify the level of a state in this generated FSA.

For instance, the level of the initial state *Start* in SP_{Sib} FSA is 1. The level of its immediately following state namely *Cust. Info Handling* is 2, and so on. The levels of states are computed using a breadth-first search, while ignoring all transitions whose level of the target state is not bigger than the level of the source state. These transitions ignored are in fact back-transitions. We refer by SP_{Sib}^{bt} in Fig. 2 to the generated FSA of SP_{Sib} where back transitions are identified and marked using dashed lines.

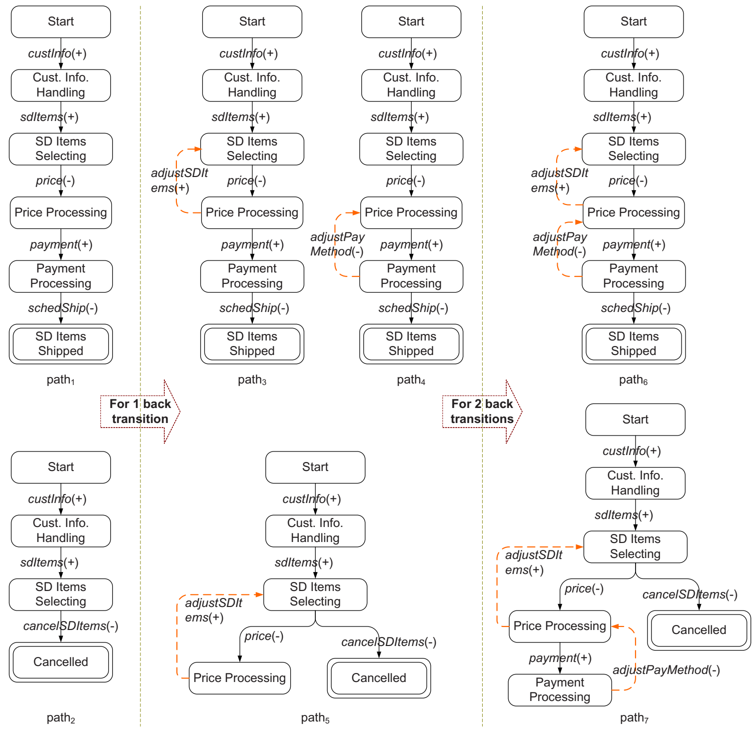

Fig. 3. Path computation

4.2 Path Computation of a Generated FSA

First, we generate all paths in the generated FSA while ignoring back-transitions using a breadth-first search. For instance, SP^{bt}_{Sib} has two paths $path_1$ and $path_2$, as shown on the left part of Fig. 3.

Based on the paths with i back-transitions (i = 0, 1, 2, ..., k-1, where k is the number of back-transitions in the generated FSA), we compute paths that contain i+1 back-transitions. In the following we show how, given a path (denoted p_{th}) with i back transitions and one of these k back-transition (denoted τ), we compute new paths with i+1 back-transitions. s_s and s_t denote the source and target states of τ respectively.

We distinguish between four situations for this path computation. The first situation corresponds to ***Case 1*** that (1) neither s_s nor s_t belongs to p_{th}, or (2) τ is a transition in p_{th} already. In this situation, no new path is to be generated.

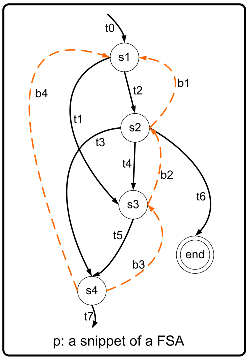

Fig. 4. A snippet of p

The remaining three situations correspond to ***Case 2:*** both s_s and s_t belong to p_{th}, ***Case 3:*** s_t but not s_s belongs to p_{th}, and ***Case 4:*** s_s but not s_t belongs to p_{th}. For page limitation, we detail ***Case 2*** in this paper and refer the interested reader to our technical report [16] for the description about ***Case 3*** and ***4***.

Since SP^{bt}_{Sib} is simple and does not cover all possible situations, we use a more general FSA called p, and whose snippet is depicted in Fig. 4, to explain our computation steps. For ***Case 2***, we detail different steps to compute new paths. After each step, we refer to our example to illustrate how this step applies.

Case 2: Both s_s and s_t belong to p_{th}. This situation is illustrated in Fig. 5 where pa_{th} corresponds to p_{th} and $b2$ (see Fig. 5) corresponds to τ.

Step 1: We initialise two state sets ST_{upp} and ST_{low} to $\{s_t\}$ and $\{s_s\}$ respectively.

In our example, these correspond to $ST^{b2}_{upp} = \{s2\}$ and $ST^{b2}_{low} = \{s3\}$.

Step 2: We explore back-transitions in p_{th} to update ST_{upp} and ST_{low}. For each back-transition τ_1 in p_{th} (whose source state is s^1_s and whose target state is s^1_t), if $s^1_s \in ST_{upp}$ then $ST_{upp} = ST_{upp} \cup \{s^1_t\}$, and if $s^1_t \in ST_{low}$ then $ST_{low} = ST_{low} \cup \{s^1_s\}$. This procedure stops when no back-transition can be explored anymore.

In our example, this step leads to $ST^{b2}_{upp} = \{s1, s2\}$ and $ST^{b2}_{low} = \{s3, s4\}$.

Step 3: While ignoring back-transitions, we construct the set, denoted SEG, of all segments in p that start at one state in ST_{upp} and end at one state in ST_{low}.

In our example, SEG_{b2} = {s2-t4-s3, s2-t4-s3-t5-s4, s2-t3-s4, s1-t1-s3, s1-t1-s3-t5-s4, s1-t2-s2-t4-s3, s1-t2-s2-t4-s3-t5-s4}.

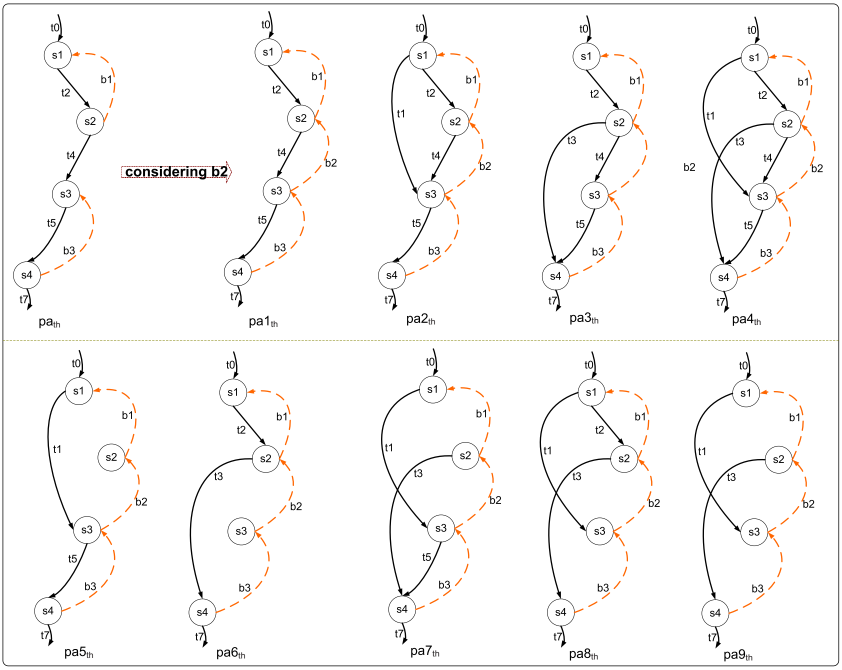

Fig. 5. Path computation for Case 2

Step 4: We remove each segment $seg \in SEG$ where all its states and transitions are contained in p_{th}. For SEG_{b2}, since some segments, such as s2-t4-s3, are already contained in pa_{th}, they are removed. This step leads to $SEG_{b2} = \{$s2-t3-s4, s1-t1-s3, s1-t1-s3-t5-s4$\}$.

Step 5: If two segments seg_1 and seg_2 in SEG are different merely because seg_2 includes more states and transitions than seg_1, and these additional states and transitions are already in p_{th}, seg_2 is removed. The reason for this removal is that, if two new paths (denoted p^1_{th} and p^2_{th}) are generated, p^1_{th} includes seg_1, and p^2_{th} includes seg_2, then p^2_{th} is actually a duplicate path with p^1_{th}.

Hence, $SEG_{b2} = \{$s2-t3-s4, s1-t1-s3$\}$ since s1-t1-s3-t5-s4 is excluded. We use m to denote the number of segments in SEG. In our case, $m = |SEG_{b2}| = 2$.

Step 6: Then, 2^m new paths with $i+1$ back-transitions are generated. Each new path is made through cloning p_{th}, adding τ, and including either zero, or one, or multiple (even all) segments in SEG. The reason for this procedure is that, due to back-transitions in p_{th}, a new path with $i+1$ back-transitions possibly loops back from one state in ST_{low} to one state in ST_{upp} for traversing some or even all segments in SEG. In our case, $2^2 = 4$ new paths are generated as illustrated in Fig. 5, where $pa1_{th}$ is the new path that no segment in SEG_{b2} is included, $pa2_{th}$ and $pa3_{th}$ show the cases that one segment in SEG_{b2} is considered, and $pa4_{th}$ is the new path that includes both these two segments in SEG_{b2}.

Step 7: Each new path generated in Step 6 containing a segment seg in SEG, has another segment, alternative to seg, connecting the start state of seg to its final state. For instance, in $pa2_{th}$, besides the segment s1-t1-s3 which belongs to SEG_{b2}, there is another segment s1-t2-s2-t4-s3 starting at s1 and ending at s3. For each path of this kind, we generate an additional new path by removing the segment alternative to those in SEG. For instance, $pa5_{th}$ (see Fig. 5) is a new path generated from $pa2_{th}$ by removing s1-t2-s2-t4-s3, which is an alternative segment to s1-t1-s3 that belongs to SEG_{b2}. $pa6_{th}$ is another new path generated from $pa3_{th}$ following the same principal.

If a new path generated in Step 6 contains k segments in SEG, $2^k - 1$ additional new paths (some may be duplicate) are generated that correspond to all possible combinations of the k segments removal including the case where all of them are removed. As an example, $pa4_{th}$ in Fig. 5 contains 2 segments in SEG_{b2}. then $2^2 - 1 = 3$ additional new paths are generated, namely $pa7_{th}$, $pa8_{th}$ and $pa9_{th}$. $pa7_{th}$ is generated by removing s1-t2-s2-t4-s3, $pa8_{th}$ by removing s2-t4-s3-t5-s4, and $pa9_{th}$ by removing both s1-t2-s2-t4-s3 and s2-t4-s3-t5-s4.

A new path is discarded if it is duplicate with another path generated previously. By iteratively applying the steps above, all paths are generated. As shown in Fig. 3, there are 7 paths for SP^{bt}_{Sib} in total. Since there are finite paths with i back-transitions, this procedure stops with k times recursion, and each checks all k back-transitions with respect to all previously generated paths.

4.3 Path Computation of a Service Protocol

This section shows how we generate all instance sub-protocols of a service protocol based on the paths computed above. This procedure is achieved mainly by(1) unfolding transitions folded in the first step, and thereafter, by (2) taking self-loops and conditions into consideration that were abstracted away initially.

Given a transition τ in a path p_{th}, and assume that τ is folded from n transitions (i.e., they share the same source and target states), τ is to be unfolded as follows: (1) if τ is a part of a loop segment (including the case where τ is a back transition), then τ is unfolded to all possible combinations of these n transitions. Consequently, $2^n - 1$ additional paths are generated, and each path is made through cloning p_{th} where τ is replaced by a possible combination, otherwise, (2) τ is unfolded to these n transitions. Thereafter, n additional paths are generated, and each path is made through cloning p_{th} where τ is replaced by one of these n transitions.

A path that contains m folded transitions where each of them leads to t_j alternatives when unfolding it, is replaced by $\prod_{j=1}^{m} t_j$ new paths that correspond to all possible combination of unfolding these m folded transitions. For instance, assume that p_{th} contains m=2 folded transitions τ_a and τ_b. τ_a is folded from two transitions τ_1 and τ_2, and τ_a is a part of a loop segment. τ_b is folded from two transitions τ_3 and τ_4, and τ_b is not a part of a loop segment. Then, the alternatives to τ_a are τ_1, or τ_2, or both τ_1 and τ_2, i.e., $t_a = 3$. The alternatives to τ_b are τ_3 or τ_4, i.e., $t_b = 2$. Consequently, $t_a \times t_b = 6$ new paths are generated for p_{th}, τ_a and τ_b, where, as an example, one new path corresponds to the combination of (1) both τ_1 and τ_2 for τ_a, and (2) τ_3 for τ_b. In our case, there are 17 paths in total for SP_{Sib} after studying folded transitions in SP_{Sib}^{bt}.

After exploring folded transitions, we take self-loops into consideration. For a path p_{th} containing m self-loops, $2^m - 1$ new paths are generated where all possible combinations of these self-loops are considered. p_{th} represents the situation that no self-loop is included. For instance, there are 34 paths in total for SP_{Sib} after studying self-loops.

Finally, we reattach conditions with associated transitions (that have been abstracted away in Step 1). Paths free of dependency conflicts are instance sub-protocols. In our case, SP_{Sib} has 34 instance sub-protocols and SP has 17.

5 Service Protocols Adaptability Assessment

5.1 Computing the Adaptation Degree and the Condition Set

For two service protocols p_1 and p_2, and their complete adaptation graph $adapt_{graph}$, the adaptation degree is computed by means of Equation 1. The function $instSubProtocol(p_1, adapt_{graph})$ counts instance sub-protocols in p_1 that are captured by instance sub-protocol pairs of $adapt_{graph}$. The procedure of generating all instance sub-protocol pairs captured by $adapt_{graph}$ is to be detailed in Section 5.2. If the parameter $adapt_{graph}$ is set to $null$, the number of instance sub-protocols in p_1 is returned. The procedure of generating all instance sub-protocols in p_1 has been presented in Section 4.

$$adaptation(p_1, p_2) = \frac{instSubProtocol(p_1, adapt_{graph})}{instSubProtocol(p_1, null)} \tag{1}$$

For instance, $adaptation(SP, SR) = 8/17 \approx 0.471$, whereas $adaptation(SR, SP) = 2/2 = 1$. These show that the adaptability is an asymmetric relation between service protocols. In our motivating example, $adaptation(SR, SP\_A) = 1/2 = 0.5$. These mean that the adaptation degree informs the requestor about different adaptation possibilities between candidate service providers.

We next re-explore the problem of distinguishing between partial and full adaptability (pending in Section 3) by means of the adaptation degree. If $adaptation(p_1, p_2) = 1$, then p_1 is called fully adaptable with p_2, because each instance sub-protocol in p_1 can perform a mediated service interaction with at least one instance sub-protocol in p_2. If $adaptation(p_1, p_2) = 0$, p_1 is assumed not adaptable with p_2 since no instance sub-protocol in p_1 can have an adaptable instance sub-protocol in p_2. Otherwise, p_1 is regarded partially adaptable with p_2.

We recall that an adaptation graph reflects legal message exchanges between pairs of instance sub-protocols. For a particular pair of instance sub-protocols, the conjunction of conditions associated with their transitions constitutes another prerequisite for ensuring a proper adaptation. Such a *must-be-held* condition set is generated through studying all instance sub-protocol pairs. For instance for SP and SR, the condition set is expressed as follows: $\{Cd_2 \bigwedge Cd_3 \bigwedge Cd_4, Cd_1 \bigwedge Cd_2 \bigwedge Cd_3 \bigwedge Cd_4, Cd_2 \bigwedge Cd_4, Cd_2 \bigwedge Cd_5, Cd_1 \bigwedge Cd_2 \bigwedge Cd_4\}$. It is important to note that some conditions contain both Cd_1 and Cd_2. This reflects the fact that, in some adaptation scenarios, when SP loops back to the state *SD Items Selecting*, the transition *custInfo*(-) in SR has been executed, and the message *custInfo* can make Cd_1 satisfiable.

5.2 Instance Sub-protocols Pairs in an Adaptation Graph

Based on the complete adaptation graph and all instance sub-protocols of a service protocol generated previously, in this section, we explore how to generate all pairs of instance sub-protocols that can conduct mediated service interactions between service protocols of a requestor and a provider. This procedure includes the following two sequential steps: we first generate all paths captured by this complete adaptation graph, and then, we project each path to a pair of instance sub-protocols and thereafter cluster these instance sub-protocol pairs.

Path Computation for a Complete Adaptation Graph. As the first step, we generate all paths in the complete adaptation graph using the technique presented in Section 4. For instance for $adapt_{graph}$ as shown in Fig. 6, since it has 11 back-transitions and this graph is complex, thousands of paths are to be generated. Generally, computing all paths for a complete adaptation graph directly is usually inefficient.

Indeed, different from transitions in a service protocol where all transitions are necessary for achieving a particular business objective, some back-transitions in a complete adaptation graph may have no contribution to static analysis, and hence, can be ignored. Recall Definition 1, a transition in an adaptation graph specifies a legal message exchange either (1) between two service protocols (like $SP \rightarrow SR$: *normalPrice* in Fig. 6 that is between SP and SR through the SPM) or (2) between a service protocol and the SPM (like $SP \rightarrow SPM$:

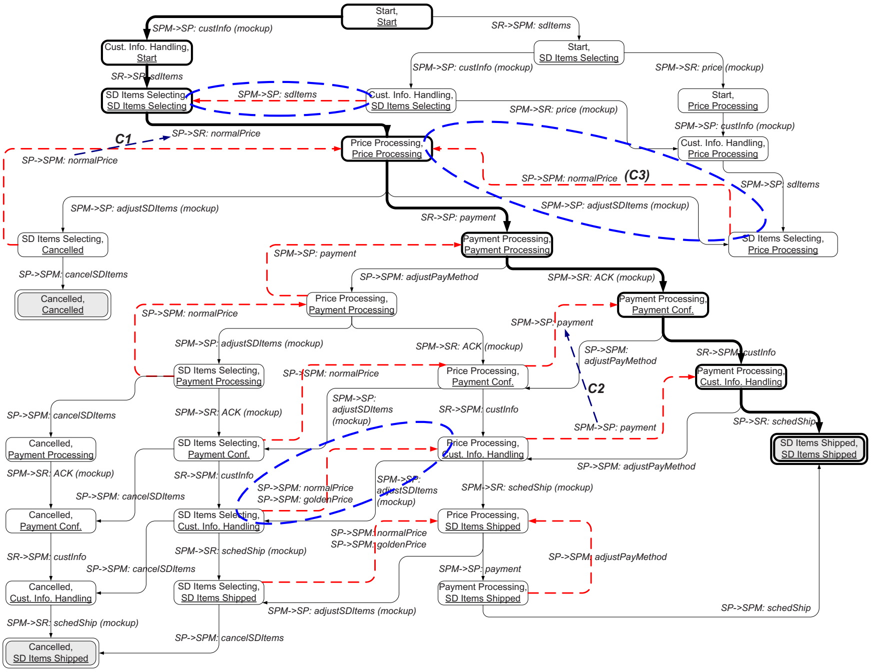

Fig. 6. $adapt_{graph}$: the complete adaptation graph for SP and SR service protocols

normalPrice in Fig. 6 that is between SP and SPM). Given a back transition, if its message exchange has been covered by all traces from the initial state of the complete adaptation graph to the source state of this back transition (i.e. the back transition repeats a message exchange that has been performed before), this back transition can be ignored for static analysis purposes.

A back-transition τ (the source state s_s and target state s_t) in a complete adaptation graph can be ignored if the following two conditions are satisfied:

Condition 1: For any trace from the initial state of the complete adaptation graph to s_s, another (back) transition exists in this graph which (1) is *before* τ, and (2) covers the message exchange by τ. An example is the exchange for message *normalPrice* by the back transition $SP \rightarrow SPM$: *normalPrice* and by the transition $SP \rightarrow SR$: *normalPrice* as shown in Fig. 6 by a dashed line with a mark *C1*. The transition $SP \rightarrow SR$: *normalPrice* implicitly specifies the following two message exchanges through the SPM: $SP \rightarrow SPM$: *normalPrice* and $SPM \rightarrow SR$: *normalPrice*. Hence, the message exchange specified by the back transition $SP \rightarrow SPM$: *normalPrice* has been covered by that of the transition $SP \rightarrow SR$: *normalPrice*. Another example is two back transitions $SPM \rightarrow SP$: *payment* as shown in Fig. 6 by a dashed line with a mark *C2*. The back transition, which is the source of this dashed line, meets this condition.

Condition 2: Ignoring τ does not cause that s_s is unreachable to any final state of this graph. A counterexample is the back transition $SP \rightarrow SPM$: *normalPrice* in Fig. 6 with a mark *C3*. If it is ignored, its source state (*SD Items Selecting*, *Price Processing*) is unreachable to any final state of this complete adaptation graph.

The first condition can be checked by a reversed breadth-first search on the graph starting at s_s, while the second condition can be verified through checking whether s_s has other outgoing transitions which are not back-transitions.

After examining all back-transitions in $adapt_{graph}$, only three out of these eleven back-transitions, which are enclosed by means of dotted ellipses as shown in Fig. 6, are necessary. Hence, there are 432 paths to be computed in total.

Instance Sub-protocol Pairs Generation. From the perspective of legal message exchange, each path in the complete adaptation graph leading from the initial state to one final state respects a mediated service interaction between a pair of instance sub-protocols. For instance, in Fig. 6, a path leading from the initial state (*Start*, *Start*) to one final state (*SD Items Shipped*, *SD Items Shipped*) (denoted p_{th}) is marked by means of thick lines on the states and transitions. The instance sub-protocol of SP involved in this adaptation (denoted ISP_{SP}) is $path_1$ in Fig. 3 where the transition *price*(-) is to be unfolded to *normalPrice*(-). The instance sub-protocol of SR involved is the one that leads to the final state *SD Items Shipped*.

On the other hand, for a certain instance sub-protocol pair, it possibly corresponds to more than one mediated service interaction since some messages can be exchanged in different orders. For instance, transitions *adjustPayMethod*(+) in SP and *custInfo*(-) in SR can be enabled in any order. Thereafter, multiple paths may reflect the mediated service interactions of the same instance sub-protocol pair. For instance, another path (denoted pd_{th}) shares the same instance sub-protocol pair as that of p_{th}, if p_{th} and pd_{th} have a common segment as specified in p_{th} from the intermediate state (*SD Items Selecting*, *SD Items Selecting*) to the final state (*SD Items Shipped*, *SD Items Shipped*).

To make the instance sub-protocol pairs unique, we cluster paths if they are captured by the same pair of instance sub-protocols. This requires a technique to identify the pair of instance sub-protocols that a path reflects. We project a path to a service protocol. The result is a complete execution path [2] leading from the initial state to one final state. The projection is an operator [2] that identifies transitions in a path associated with a service protocol, and restores their polarity according to the service protocol specification. For instance, the transition $SP \rightarrow SR$: *normalPrice* as indicated in Fig. 6 by a dashed line with a mark *C1* is projected into one transition in SP (i.e., *normalPrice*(-)) and another transition in SR (i.e., *price*(+)), while $SP \rightarrow SPM$: *normalPrice* is projected into a transition in SP (i.e., *normalPrice*(-)).

We then identify which instance sub-protocol this projected path belongs. This is achieved by comparing the transition set in this projected path to that in an instance sub-protocol. For instance, after projecting p_{th} to SP, the transition set is the same as that of ISP_{SP}. Hence, the instance sub-protocol pair is provided. We study other paths in such fashion. In our case, these 432 paths in $adapt_{graph}$ are clustered into 8 instance sub-protocol pairs of SP and SR.

6 Related Work and Conclusion

Adaptability analysis. A work similar to ours is the *adapter compatibility* analysis in the *Y-S* model [12] which checks whether or not two component protocols are adaptable with a particular adapter. The criteria are (1) no *unspecified receptions*, and (2) *deadlock free.* No *unspecified receptions* is restrictive, since message production and consumption in mediated service interactions are time-decoupled, and extra messages are often allowed. Our approach does not have this limitation. We give an adaptation degree which is more accurate than a binary answer. Since conditions in protocols are not explored, this work does not specify conditions that determine when two protocols are adaptable. Our approach specifies such necessary conditions. In addition, this work depends on the synchronous semantics. This assumption simplifies the problem, but it fails to capture most Web service interactions, since they are normally asynchronous. Our approach does not depend on such an assumption.

Adapter construction. Adapters are important for supporting interactions in the context of both software components [12] and Web services [3,4,7,9,13].

As shown in [12], an adapter is automatically constructed for two incompatible protocols. The adapter tackles order mismatches with *unspecified receptions*, but considers any deadlock as unresolvable. The same limitation exists in the adaptation mechanisms of mediation-aided service composition approaches [9].

In [3,4], possible mismatches are categorised into several mismatch patterns, and adaptation templates [3] or composable adaptation operators [4] are proposed for handling these mismatch patterns. However, mismatches between two protocols are identified by a developer and an adapter is constructed manually.

Besides the mismatches covered by adapters above, [7] handles a deadlock through *evidences.* The choice of an *evidence* for reconciling a given deadlock is decided by adapter developers, and hence, this method is not generic. This technique presumes that recommended business data is consistent with a certain interaction context, but data recommended by some *evidences*, (e.g., *enumeration with default* and *log based value/type interface*) may not satisfy this assumption, since enumeration may not be the default value, and some business data may differ in different interactions. In contrast, a *mock-up* message, generated by the SPM [13], is consistent with a certain interaction context.

In a nutshell, adapter construction means that service protocols are adaptable in some case. The possibility and the conditions are not specified. Adapter building constitutes a starting point, but is inadequate for assessing the adaptability. This paper builds upon the adapter construction presented in our previous work [13] and provides adaptability assessment, whose result is a key criterion to a requestor for identifying and selecting a suitable service provider from functionally-equivalent candidates according to her specific business requirements.

In conclusion, the two major contributions of this paper are as follows: first, our adaptability assessment, as reflected by the motivating example, is a comprehensive means of selecting the appropriate service provider among functionally-equivalent candidates. To the best of our knowledge, this assessment is new. Besides the technique presented in this paper, we have proposed another approach in [15] that assesses the adaptability using protocol reduction and graph-search with backtracking techniques. Compared with [15], this paper's second major contribution is a novel path computation technique which computes all instance sub-protocols in a service protocol as well as their pairs in a complete adaptation graph. This computation is general and can be applied, besides adaptability assessment, also to compatibility assessment where a numerical compatibility degree and a set of conditions are still unaccounted.

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