Long-running Transactions: semantics, schemas, implementation

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Abstract—In this paper we describe a formal model for the distributed coordination of long-running transactions in a Digital Ecosystem for business, involving Small and Medium Enterprises (SMEs). The proposed non-interleaving model of interaction-based service composition allows for communication between internal activities of transactions. The formal semantics of the various modes of service composition are represented by standard xml schemas. The current implementation framework uses suitable asynchronous message passing techniques and reflects the design decisions of the proposed model for distributed transactions in digital ecosystems.

Index Terms—service orchestration, concurrency, vector semantics, schema, message passing.

I. INTRODUCTION

The concept of a Digital Ecosystem for business emerges as a key feature in the era of the *Digital Economy*. The importance of a pool of rare species in sustaining (innovation in) an ecosystem is well understood in the studies of biodiversity. In a digital ecosystem for business, SMEs can be seen to play the role of ‘rare species’.

A business transaction between SMEs in a Digital Ecosystem can be either a simple usage of a web service or a mixture of different levels of composition of several services from various service providers. The specification of a business transaction may allow it to be completed over a period of minutes, hours, or even days – hence, the term long-lived or *long-running* transaction. The execution of a long-running transaction corresponds to conducting a business activity and typically comprises a number of *sub-transactions* or *activities* that involve the execution of a number of underlying services.

This makes Service-Oriented Computing (SOC) [1], whose goal is to enable applications from different providers to be offered as services that can be used, composed and coordinated in a *loosely-coupled* manner, the prevalent computing paradigm in a digital business ecosystem. The actual architectural approach of SOC is called SOA [2] and is particularly applicable when multiple distributed applications are running on varied technologies and platforms need to communicate with each other.

Business transactions in a B2B context typically involve interactions between multiple partners, either service providers, or service consumers, or both. This requires that all partners behave in a coordinated manner – partners must follow some protocol to execute a transaction effectively.

Conventional transaction models such as *Sagas* [3] or the more recent models targeting web services *Web Services*

Transactions (WS-Tx) [4] and *Business Transaction Protocol* (BTP) [5] seem to be geared towards centralised control (using the WS-Coordination framework [6]) which means some knowledge of the internal build-up of the participants is required. This violates the primary requirement of SOA for loosely-coupled services and may not be acceptable or even possible in a business environment – in a digital ecosystem involving communities of SMEs this raises a barrier for the adoption of SOA as it violates local autonomy. Part of the problem seems to be that these frameworks lack a formal model for the coordination of the underlying services involved in the execution of a long-running transaction.

In this paper we give a formal description of long-running multi-service transactions in terms of the distributed orchestration of the underlying service executions. The formal semantics, in the first instance, is aimed at describing the behavioural patterns services should follow in order to increase confidence in a successful outcome. The coordination of a transaction in our approach amounts to interaction-based composition of the underlying services and thus we advocate the use of XML schemas that reflect the message-based protocol used in a transaction. Finally, we describe a prototype implementation of our ideas on the distributed coordination of long-running transactions and the associated structural schemas.

The remainder of this paper is structured as follows. Section II outlines earlier work on a distributed transaction model for digital ecosystems. Section III introduces the formal description of a transaction in terms of its underlying service executions. Section IV provides a XML schema that captures the formal model for service coordination and reflects the resulting transaction structure. The prototype implementation of the transaction structure schema is then presented in Section V. The paper finishes with some concluding remarks and ideas for future work given in Section VI.

II. DISTRIBUTED TRANSACTION MODEL FOR DES

In earlier work [7], we have described a distributed transaction model for networked organisations in the digital ecosystem paradigm. Here we outline the basic ideas.

It is often the case that internal activities of a transaction need to share results before the termination of the transaction (*transaction commit*). More generally, dependencies may exist between activities inside a transaction due to the required ordering on service invocations (e.g. book a hotel

Drawing upon the latest work on an extended service-oriented architecture for a business environment [2], we have considered five different types of coordinators which allow for various modes of service interaction in our model. In the transaction tree of Fig. 1, the services s3 and s4 for example are children of a sequential coordinator and hence s4 can only be executed after s3. In other words the execution of s4 is dependent on the (successful) execution of s3, e.g. s4 uses the results released by s3.

Fig. 1 Transactions in a tree structure

III. TRANSACTION CONTEXT SCHEMA

The nested transaction structure is imposed in the schema using the ‘Coordinator’ element which can include a service composition (‘Composition’ element in the schema) or usage of a simple web service (‘WebService’) including a purely data-oriented web service (a leaf of the tree). Each service composition (‘Composition’) has a type (‘CompositionType’), which determine the mode of the interaction-based composition (sequential, parallel or alterna-

[illegible]

Fig. 2 Transaction Context Schema

IV. A FORMAL LANGUAGE FOR TRANSACTIONS

The semantics is intended to describe the behaviour of a transaction in terms of its services at the deployment level, but not the low-level computations performed by the services themselves. Note that services are offered in a digital ecosystem for business from different service providers and it is important that we defer from interfering with the local state of the service execution. This means it is appropriate to consider that any action within the transaction model has no significant duration, in the sense that (i) it either occurs as a whole or not at all; (ii) it occurs either wholly before, or wholly after, or wholly in parallel with, every other action.

A transaction T is associated with a set of leaves or *access points* L which consists of a set of basic services S , a set of data-oriented coordinators D and a set of delegation coordinators Dlg . Hence, $L = S \cup D \cup Dlg$. We further require that the sets S , D and Dlg are pairwise disjoint.

Actions within a long-running transaction take place on the leaves and therefore each leaf is in turn associated with a set of actions that may occur on that leaf, depending on its nature. We denote this set by $\mu(l)$, $l \in L$, and require that

$$\bigcup_{l \in L} \mu(l) \subseteq M.$$

As can be seen in Fig. 1 a transaction has a number of activation points, namely the leaves of the corresponding transaction tree. Thus, instead of modelling a transaction by a sequential process that would generate a trace of a single access point, we model the behaviour of a transaction by considering a set of such sequences at the same time, one sequence for each leaf. This draws upon Shields' *vector languages* [9] and allows us to capture what is happening on each access point of a long-running transaction.

Transaction vectors. Let T be a transaction. We define V_T to be the set of all functions $\underline{v}: L \rightarrow M^*$ such that $v(l) \in \mu(l)^*$.

By $\mu(l)^*$ we denote the set of finite sequences over $\mu(l)$. Mathematically, the set V_T is the Cartesian product of the sets $\mu(l)^*$, for each l . Effectively, transaction vectors are n -tuples of sequences where each coordinate corresponds to a leaf in the transaction tree (hence, n is the number of leaves) and contains a finite sequence of actions that have occurred on that leaf or access point.

When an action occurs on a leaf of the transaction tree, that is to say when an action associated with some subtransaction takes place on an access point, it appears on a new transaction vector and at the appropriate coordinate. For example, the vector (s_1, Λ, Λ) describes that portion of behaviour of the transaction in which an action s_1 (e.g. service invocation) has taken place on the corresponding service allocated to the first coordinate. The vector (s_1, s_2, Λ) describes that portion of behaviour in which both s_1 and s_2 have happened on the corresponding services while the vector $(s_1 s_3, s_2, \Lambda)$ describes an occurrence of s_1 and an occurrence of s_3 on the service corresponding to the first coordinate, and an occurrence of s_2 on the second coordinate. Nothing has happened on the service corresponding to the third coordinate.

In this sense, each transaction vector provides a snapshot of behaviour in which the transaction has executed the actions appearing on the vector's coordinates – it describes what actions have already occurred and on which part of the transaction tree. Fig. 3 shows the xml schema types for building a single transaction vector. Each transaction vector comprises a specific number of 'access points' (five in our example), and each access point corresponds to a service, a data-oriented coordinators or a delegation coordinator, all presented as 'DE-WebServices' in our xml schema.

Fig. 3 A single vector type (xml schema presentation)

It can be seen from the example given above that there is already an ordering among actions on a particular access point or subtransaction, e.g. s_1 followed by s_3 . This vector-based behavioural description of transactions can also capture the orderings between different subtransactions, which amounts to actions appearing on different vector coordinates. This requires however a more careful consideration of the mathematical properties of such vectors which we briefly describe in the sequel.

Before examining the mathematical properties of our construction so far, we introduce a specific kind of transaction vector, which is used in our model to describe actions (events or activations) within a transaction.

Column vectors. Let T be a transaction and V_T its set of transaction vectors. We define

$$A_T = \{ \underline{a} \in V_T \setminus \{ \underline{\Lambda}_T \} : l \in L \Rightarrow |\underline{a}(l)| \leq 1 \}$$

where $|x|$ denotes the length of sequence x . We refer to elements of A_T as *column vectors*.

Thus, column vectors are themselves transaction vectors, but have the additional constraint that each of their coordinates is either the empty sequence or a single action. For example, the vector (s_1, Λ, Λ) represents the occurrence of an action s_1 on the service associated with the first coordinate.

We will use the term *transaction language* to refer to a subset V of all possible vectors V_T formed over a given transaction T . Hence, a transaction T comes with a language V , where $V \subseteq V_T$. The idea is that the particular set of transaction vectors for a specific transaction expresses the ordering constraints necessary in the corresponding service orchestration.

We have seen that transaction vectors are essentially tuples of sequences. This can be exploited in defining operations on vectors in terms of well-known operations on sequences.

Operations on vectors. For $\underline{u}, \underline{v} \in V_T$, we define

- $\underline{u} \cdot \underline{v}$ to be the unique vector $\underline{w}$ such that $\underline{w}(l) = \underline{u}(l) \cdot \underline{v}(l)$, for each $l \in L$ (*concatenation*)
- $\underline{u} \leq \underline{v}$ iff $\underline{u}(l) \leq \underline{v}(l)$, for each $l \in L$ (*prefix ordering*)
- $\text{glb}(\underline{u}, \underline{v})$ to be the vector $\underline{w}$ such that $\underline{w}(l) = \min(\underline{u}(l), \underline{v}(l))$, for each $l \in L$
- $\text{lub}(\underline{u}, \underline{v})$ (if it exists) to be the vector $\underline{w}$ such that $\underline{w}(l) = \max(\underline{u}(l), \underline{v}(l))$, for each $l \in L$
- if $\underline{u} \leq \underline{v}$, then we define $\underline{v} / \underline{u}$ to be the unique element $\underline{z} \in V_T$ such that $\underline{u} \cdot \underline{z} = \underline{v}$ (*right-cancellation*)

Thus, the operation of concatenation on vectors is defined in terms of the concatenation of sequences appearing on their respective coordinates. For example,

$$(s_1 s_3, s_2, \Lambda) \cdot (\Lambda, s_4, \Lambda) = (s_1 s_3, s_2 s_4, \Lambda)$$

The ordering amongst vectors is defined in terms of the usual prefix ordering operation on sequences appearing on their coordinates. For example, $(s_1, s_2, \Lambda) \leq (s_1 s_3, s_2, \Lambda)$ since $s_1 \leq s_1 s_3$ and $s_2 \leq s_2$ and $\Lambda \leq \Lambda$. In other words, the second vector 'wins' on the first coordinate (since it has a sequence of greater length in this coordinate) while the two vectors draw on all other coordinates.

It is not hard to see that some vectors will be incomparable. It turns out that such vectors describe either parallel

or alternative behaviours of the transaction in question, and this will be further discussed in the following sections.

The operations $glb()$ and $lub()$ give the greatest lower bound and the least upper bound, respectively of $\underline{u}, \underline{v} \in V_T$, in the usual sense of lattices and domain theory [11]. As we will see, these operations are central to the treatment of concurrency in our approach.

The right cancellation operator $/$ says that if $\underline{u}$ is a transaction vector describing an initial part of the behaviour described by $\underline{v}$ so that $\underline{u} \leq \underline{v}$, then $\underline{v} / \underline{u}$ is the ‘continuation’ of $\underline{u}$ that extends it to $\underline{v}$. This operation is central to the treatment of compensations in our approach. We return to this discussion in the concluding section of the paper.

It is important to stress the fact that all operations on vectors are performed coordinate-wise and this simplifies the proofs but also makes the formal model feasible for implementation.

Transaction vectors can be seen to be built up from the empty vector $\underline{\Delta}_T$ by a series of concatenations with column vectors that represent actions. In fact, in describing the behaviour of a transaction we are interested only in those vectors describing (orderings of) actions that we expect the transaction to engage in during the course of its execution. This is the subset of all possible transaction vectors, over a given T , we referred to as transaction language.

A. Sequential service compositions

The prefix ordering relation on transaction vectors can be viewed as an ordering on partial executions, where each vector corresponds to that portion of behaviour in which the transaction has already engaged in the actions appearing on its coordinates. This can be expressed more succinctly by saying that $\underline{u} \leq \underline{v}$ in a transaction language means that $\underline{u}$ is an earlier part of behaviour leading to $\underline{v}$.

A more careful examination of the mathematical construction shows that we can say more than that. Indeed, we find it useful to determine *immediate predecessors* (or successors) of a transaction vector.

Cover. Suppose that $\underline{u}, \underline{v} \in V \subseteq V_T$. We say that $\underline{v}$ *covers* $\underline{u}$ in V , and we write $\underline{u} \triangleleft_V \underline{v}$, if (i) $\underline{u} \leq \underline{v}$ and $\underline{u} \neq \underline{v}$ and (ii) If $\underline{z} \in V$ such that $\underline{u} \leq \underline{z} \leq \underline{v}$, then $\underline{z} = \underline{u} \vee \underline{z} = \underline{v}$.

Thus, whenever $\underline{u} \leq \underline{v}$, and we also have that $\underline{u} \triangleleft_V \underline{v}$, then the last actions that went into forming each vector have occurred in sequence - one after the other. This allows to model sequential dependency among services inside a transaction. Recall the example of Fig. 1 where service s_3 feeds service s_4 .

Fig. 4 presents the corresponding schema for sequential service composition. The ‘TransactionVectors-Type’ has a TransactionVector element which includes a single transaction vector (e.g. describing the service invocation s_3) and the immediate successor (describing the service invocation s_4). The latter is captured by the ‘FollowedBy’ element. The type of ‘SequentialComposition’ simply includes a single transaction vector followed by another transaction vector.

Fig. 4 Sequential service composition (xml schema presentation)

B. Parallel service compositions

Our approach towards modelling concurrent actions, actions that can happen in parallel, draws upon the concepts in Shields’ *vector languages* [10] and Mazurkiewicz *trace languages* [12] where concurrent events are considered as being unordered, in contrast to CSP trace theory where it is assumed that observations are sequential in nature and concurrent events are understood to occur in either order (non-deterministic interleaving).

The treatment of concurrency within our formal model of transactions thus takes up on non-interleaving models of concurrency, which introduce additional structure into formal languages in order to describe non-sequential behaviour. The additional structure is given in terms of an independence relation over action symbols, which describes potential concurrency.

Drawing upon the extension of the independence relation ι to *behaviour vectors* in [9], the notion of independence between actions in *Mazurkiewicz traces* can be readily interpreted into transaction vectors in our approach.

Independence. For $\underline{u}, \underline{v} \in V \subseteq V_T$, we define

$$\underline{u} \text{ ind } \underline{v} \iff \forall l \in L : \underline{u}(l) > \Lambda \implies \underline{v}(l) = \Lambda$$

This definition says that two transaction vectors are independent if the behaviours they describe concern distinct services (correspond to activation on different leaves of the corresponding transaction tree). This means that the behaviours described by $\underline{u}$ and $\underline{v}$ may occur independently.

In the case of column vectors, independence captures the fact that actions appearing in one vector may occur independently of those appearing in the other. If in addition the vectors representing these actions are adjacent in an expression (of the series of concatenations that went into forming the corresponding transaction vectors), then the actions are concurrent. Thus, whenever two actions are independent and are both enabled (can both occur at some point, after some behaviour) then, their corresponding column vectors commute, i.e. $\underline{a}_1.\underline{a}_2 = \underline{a}_2.\underline{a}_1$, and in the resulting behaviour the two actions are concurrent.

The parallel service composition schema is depicted in Fig. 5. A ‘ParallelComposition’ consists of two or more (up

to the number of its access points, in this example 5) transaction vectors, followed by a ‘TransactionVectors-Type’, which imposes that all transaction vectors describing parallel executions have one immediate successor (their *lub()* identified in the schema by the ‘FollowedBy’ element) and the concurrent service invocations can happen on different access points (recall the independence relation - two actions are independent, and potentially concurrent, if they engage different access points).

Fig. 5 Parallel service composition (xml schema presentation)

C. Alternative service compositions

Based on the prefix ordering between transaction vectors in the set V we may also model a choice between actions. That is, actions which are mutually exclusive in that occurrence of one excludes occurrence of the other.

In discussing concurrent actions in a long-running transaction, we saw that the two incomparable transaction vectors represent concurrent behaviour. The vector they both *cover* is in fact their greatest lower bound and is obtained by applying the operation *glb()* given earlier. The fact the two incomparable vectors represent concurrent actions is only because they are bounded above in the set (by the transaction vector which is their *lub()* and is sitting on top of the lozenge). Whenever this latter requirement does not hold we may talk about events in conflict.

It might be instructive to make the distinction in terms of pictures and associated Hasse diagrams. In the diagram of Fig. 1, s_1 and s_2 are sequential (s_2 can only be invoked after s_1) in Fig.6(i) while there is a choice between them (alternative) in Fig.6(ii) and they are concurrent in Fig.6(iii).

Fig. 6 Order structure of transaction vectors

Notice that the set of vectors in (i) does not include (Λ, s_2, Λ) , which means that s_2 never occurs before s_1 ; in (ii) it does not include (s_1, s_2, Λ) which means there is no valid behaviour of the transaction processing system in which both s_1 and s_2 have taken place; in (iii) it includes all four vectors, which means that s_1, s_2 and both s_1 and s_2 are all valid observations of the behaviour of the transaction system in which s_1 and s_2 happened concurrently. This is indicated by the familiar lozenge shape that exhibits the charac-

teristic structure of a finite lattice.

In further explanation, the vector sitting at the bottom of the lozenge is the *glb()* of the two incomparable vectors (s_1, Λ, Λ) and (Λ, s_2, Λ) sitting at the middle of the lozenge represent while the vector at the top is their *lub()*. The lozenge as a whole describes that part of behaviour of the transaction in which s_1 and s_2 happened concurrently, as indicated by the vector at its top. Further details on how the ordering relations between actions are manifested in the resulting order structure of the resulting set of vectors can be found in [13].

Fig. 7 presents the alternative service composition schema. An ‘AlternativeComposition’ consists of two or more (up to the number of its access points, here 5) alternative transaction vectors. Notice that in this case there is no ‘FollowedBy’ element as vectors describing alternative service deployment do not lead to a common vector, i.e. do not have a *lub()* in the formal language.

Fig. 7. Alternative service composition (xml schema presentation)

V. IMPLEMENTATION

We have used JAX-WS 2.1, Java 5, and Netbeans IDE 5.5.1 in our implementation framework. The JAX-WS is a new standard for message passing, it supports both synchronous and asynchronous message passing by the polling model and the call-back model, respectively. In the polling model, the client continuously polls the service response. In the call-back model, the client creates a call-back handler. JAX-WS is shown to perform better than JAX-RPC in certain aspects [14]. Furthermore, JAX-WS supports static and dynamic generation of web service client stubs.

In our implementation, the JAX-WS call-back message passing and dynamic client stub generation are used. The call-back message passing is suitable for asynchronous message passing, which is important for long term transactions. The dynamic WS client creation enables web service invocation chains. Three participants are required in order to make a service X work: 1) X web service; 2) X TransactionAgent web service; 3) the client stubs for the X web service. The dependencies between web services are captured in a XML file, as discussed before.

From the transaction vector schema, we can create different transaction scenarios (as xml file). The generated xml file shows the various states of a transaction for a specific scenario. We have designed a software agent coordinator which can perform the transaction vector in fully distributed manner. As a case study we analyse a simple transaction, with a sequential service composition, which involves the interactions shown in the Sequence diagram of Fig. 8.