Semantic Web Technology for Agent Communication Protocols

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Abstract. One relevant aspect in the development of the Semantic Web framework is the achievement of a real inter-agents communication capability at the semantic level. The agents should be able to communicate and understand each other using standard communication protocols freely, that is, without needing a laborious a priori preparation, before the communication takes place.

For that setting we present in this paper a proposal that promotes to describe standard communication protocols using Semantic Web technology (specifically, OWL-DL and SWRL). Those protocols are constituted by communication acts. In our proposal those communication acts are described as terms that belong to a communication acts ontology, that we have developed, called COMMONT. The intended semantics associated to the communication acts in the ontology is expressed through social commitments that are formalized as fluents in the Event Calculus.

In summary, OWL-DL reasoners and rule engines help in our proposal for reasoning about protocols. We define some comparison relationships (dealing with notions of equivalence and specialization) between protocols used by agents from different systems.

Key words: Protocol, Communication acts, agents.

1 Introduction

In the scenario that promotes the emergent Web, administrators of existing Information Systems, that belong to nodes distributed along the Internet network, are encouraged to provide the functionalities of those systems through agents that represent them or through Web Services. The underlying idea is to get a real interoperation among those Information Systems in order to enlarge the benefits that users can get from the Web by increasing the machine processable tasks.

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Although agent technology and Web Services technology have been developed in a separate way, there exists a recent work of several members from both communities trying to consolidate their approaches into a common specification describing how to seamlessly interconnect FIPA compliant agent systems [1] with W3C compliant Web Services. The purpose of specifying an infrastructure for integrating these two technologies is to provide a common means of allowing each to discover and invoke instances of the other [2]. Considering the previous approach, in the rest of this paper we will only concentrate on inter-agent communication aspects.

Communication among agents is in general based on the interchange of communication acts. However, different Information Systems have incorporated different classes of communication acts as their Agent Communication Language (ACL) to the point that they do not understand each other. Moreover, protocols play a relevant role in agents communication. A protocol specifies the rules of interaction between agents by restricting the range of allowed follow-up communication acts for each agent at any stage during a communicative interaction. It is widely recognized the interest of using standard communication protocols.

We advocate so that the administrators of the Information Systems proceed in the following way. When they wish to implement the agents that will represent their systems, they first select, from a repository of standard protocols (there can exist one or more repositories), those protocols that fulfill the goals of their agents. Sometimes a single protocol will be sufficient and other times it will be necessary to design a protocol as a composition of some other protocols. Next, they can customize the selected protocols before they incorporate them to the agents. In that setting, when agents of different Information Systems want to interoperate it will be relevant to reason about the protocols embedded in the agents in order to discover relationships such as equivalence or restriction between them. Moreover, once those relationships are discovered both agents can use the same protocol by replacing dynamically in one agent the protocol supported by the other. Finally, in our opinion it will be desirable to use a formal language to represent the protocols.

In this paper we present a proposal that promotes to describe standard communication protocols using Semantic Web Technology (OWL-DL and SWRL). In addition, communication acts that take part of the protocols are described as terms that belong to a communication acts ontology, that we have developed, called CommOnt (see more details about the ontology in [3]). The use of that ontology favours on the one hand, the explicit representation of the meaning of the communication acts and on the other hand, the customization of existing standard protocols by allowing the use of particular communication acts that can be defined as specializations of existing standard communication acts.

Terms of the CommOnt ontology are described using OWL-DL and we have adopted the so called *social approach* [4,5] for expressing the intended semantics of the communication acts included in the protocols. According to the social approach, when agents interact they become involved in social commitments or obligations to each other. Those commitments are public, and therefore they

are suitable for an objective and verifiable semantics of agent interaction. Social commitments can be considered as *fluents* in the Event Calculus, which is a logic-based formalism for representing actions and their effects. Fluents are propositions that hold during time intervals. A formula in the Event Calculus is associated to a communication act for describing its social effects. The set of fluents that hold at a moment describes a state of the interaction. DL axioms and Event Calculus formulae apply to different facets of communication acts. DL axioms describe static features and are principally used for communication act interpretation purposes. Event Calculus formulae describe dynamic features, namely the social effects of communication acts, and are principally used for communication act operational contexts such as supervising conversations.

In summary the main contributions of the proposal presented in this paper are:

- It favours a flexible interoperation among agents of different systems by using standard communication protocols described through tools promoted by the W3C.
- It facilitates the customization of those standard communication protocols allowing to use communication acts in the protocols that belong to specific ACL of Information Systems. The particular communication acts are described in an ontology.
- It provides a basis to reason about relationships between two protocols in such a way that the following relations can be discovered: equivalence or restriction (and also considering a notion of specialization). Moreover, notice that our approach allows to get protocols classification in terms of the intended semantics of communication acts that appear in the protocols.
- It allows modeling the communication among agents without regarding only to the lower level operational details of how communication acts are interchanged but taking also into account the meaning of those acts.

The rest of the paper is organized as follows: Section 2 provides background on the communication ontology, that contains terms corresponding to communication acts that appear in the protocols, and on the semantics associated to those acts. Section 3 explains how protocols are described using Semantic Web Technology and presents the definitions of the relationships considered between protocols. Section 4 discusses different related works, and conclusions appear in the last section.

2 Two basic supports for the proposal: the CommOnt Ontology and the representation of the semantics of communication acts

Among the different models proposed for representing protocols one which stands out is that of State Transition Systems (STS).

Definition 1. *A State Transition System is a tuple (S, s_0, L, T, F), where S is a finite set of states, $s_0 \in S$ is an initial state, L is a finite set of labels, $T \subseteq S \times L \times S$ is a set of transitions and $F \subseteq S$ is a set of final states.*

In our proposal we use STS where transitions are labeled with communication act classes described in a communication acts ontology called CommOnt. That is to say, the set of labels L is a set of class names taken from that ontology. Moreover, as mentioned before, the intended semantics associated to the communication acts in the ontology is expressed through predicates in the Event Calculus that initiate or terminate fluents. In our case, each state is associated to the set of fluents that holds at that moment.

In the following two subsections we present the main features of the CommOnt ontology and of the intended semantics associated to communication acts, respectively.

2.1 Main features of the CommOnt Ontology

The goal of the CommOnt ontology is to favour the interoperation among agents belonging to different Information Systems. The leading categories of that ontology are: first, *communication acts* that are used for interaction by *actors* and that have different purposes and deal with different kinds of contents; and second, *contents* that are the sentences included in the communication acts.

The main design criteria adopted for the communication acts category of the CommOnt ontology is to follow the *speech acts* theory [6], a linguistic theory that is recognized as the principal source of inspiration for designing the most familiar standard agent communication languages. Following that theory every communication act is the sender's expression of an attitude toward some possibly complex proposition. A sender performs a communication act which is expressed by a coded message and is directed to a receiver. Therefore, a communication act has two main components. First, the attitude of the sender which is called the *illocutionary force* (F), that expresses social interactions such as informing, requesting or promising, among others. And second, the *propositional content* (p) which is the subject of what the attitude is about. In CommOnt this $F(p)$ framework is followed, and different kinds of illocutionary forces and contents leading to different classes of communication acts are supported. More specifically, specializations of illocutionary forces that facilitate the absorption of aspects of the content into the illocutionary force are considered.

CommOnt is divided into three interrelated layers: *upper*, *standards* and *applications*, that group communication acts at different levels of abstraction. Classes of the CommOnt ontology are described using the Web Ontology Language OWL-DL. Therefore, communication acts among agents that commit to CommOnt have an abstract representation as individuals of a shared universal class of communication acts.

In the upper layer, according to Searle's speech acts theory, five upper classes of communication acts corresponding to *Assertives*, *Directives*, *Commissives*, *Ex-*

pressives and *Declaratives* are specified. But also the top class `CommunicationAct`[1] is defined, which represents the universal class of communication acts. Every particular communication act is an individual of this class. In COMMONT, components of a class are represented by properties. The most immediate properties of `CommunicationAct` are the content and the actors who send and receive the communication act. There are some other properties related to the context of a communication act such as the conversation in which it is inserted or a link to the domain ontology that includes the terms used in the content.

A standards layer extends the upper layer of the ontology with specific terms that represent classes of communication acts of general purpose agent communication languages, like those from KQML or FIPA-ACL. Although the semantic framework of those agent communication languages may differ from the semantic framework adopted in COMMONT, in our opinion enough basic concepts and principles are shared to such an extent that a commitment to ontological relationships can be undertaken in the context of the interoperation of Information Systems.

With respect to FIPA-ACL, we can observe that it proposes four primitive communicative acts [1]: *Confirm*, *Disconfirm*, *Inform* and *Request*. The terms `FIPA-Confirm`, `FIPA-Disconfirm`, `FIPA-Inform` and `FIPA-Request` are used to respectively represent them as classes in COMMONT. Furthermore, the rest of the FIPA communicative acts are derived from those mentioned four primitives. Analogously, communication acts from KQML can be analyzed and the corresponding terms in COMMONT specified. It is of vital relevance for the interoperability aim to be able of specifying ontological relationships among classes of different standards.

Finally, it is often the case that every single Information System uses a limited collection of communication acts that constitute its particular agent communication language. The applications layer reflects the terms describing communication acts used in such particular Information Systems. The applications layer of the COMMONT ontology provides a framework for the description of the nuances of such communication acts. Some of those communication acts can be defined as particularizations of existing classes in the standards layer and maybe some others as particularizations of upper layer classes. Interoperation between agents of two systems using different kinds of communication acts will proceed through these upper and standard layer classes.

Following we show some axioms in the COMMONT ontology. For the presentation we prefer a logic notation instead of the more verbose OWL/XML syntax.

$$\text{CommunicationAct} \sqsubseteq\ =1\ \text{hasSender.Actor} \sqcap \forall \text{hasReceiver.Actor} \sqcap$$
$$\forall \text{hasContent.Content}$$
$$\text{Request} \sqsubseteq \text{Directive} \sqcap \exists \text{hasContent.Command}$$
$$\text{Accept} \sqsubseteq \text{Declarative}$$
$$\text{Responsive} \sqsubseteq \text{Assertive} \sqcap \exists \text{inReplyTo.Request}$$

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[1] `This type` style refers to terms specified in the ontology.

2.2 Semantics associated to Communication Acts

Formal semantics based on mental concepts such as *beliefs*, *desires* and *intentions* have been developed for specifying the semantics of communication acts. However, they have been criticized on their approach [4] as well as on their analytical difficulties [7]. We have adopted the so called social approach [5,8,9] to express the intended semantics of communication acts described in the COMmONt ontology. According to the social approach, when agents interact they become involved in social commitments or obligations to each other.

Definition 2. *A base-level commitment* $C(x, y, p)$ *is a ternary relation representing a commitment made by x (the debtor) to y (the creditor) to bring about a certain proposition p.*

Sometimes an agent accepts a commitment only if a certain condition holds or, interestingly, only when a certain commitment is made by another agent. This is called a conditional commitment.

Definition 3. *A conditional commitment* $CC(x, y, p, q)$ *is a quaternary relation representing that if the condition p is brought out, x will be committed to y to bring about the proposition q.*

Moreover, the formalism we use for reasoning about commitments is based on the Event Calculus. The basic ontology of the Event Calculus comprises *actions*, *fluents* and *time points*. It also includes predicates for saying what happens when (*Happens*), for describing the initial situation (*Initially*), for describing the effects of actions (*Initiates* and *Terminates*), and for saying what fluents hold at what times (*HoldsAt*). See [10] for more explanations.

Commitments (base-level and conditional) can be considered fluents, and semantics of communication acts can be expressed with predicates. For example:

- *Initiates(Request(s,r,P)*, $CC(r, s, accept(r,s,P), P), t)$
  A Request from s to r produces the effect of generating a conditional commitment expressing that if the receiver r accepts the demand, it will be commited to the proposition in the content of the communication act.
- *Initiates(Accept(s,r,P), accept(s,r,P), t)*
  The sending of an Accept produces the effect of generating the accept fluent.

Furthermore, some rules are needed to capture the dynamics of commitments. Commitments are a sort of fluents typically put in force by communication acts and that become inoperative after the appearance of other fluents. In the following rules $e(x)$ represents an event caused by x. The first rule declares that when a debtor of a commitment that is in force causes an event that initiates the proposition committed, the commitment ceases to hold.

RULE 1: *HoldsAt($C(x, y, p), t$) $\land$ Happens(e(x), t) $\land$ Initiates(e(x), p, t) $\rightarrow$ Terminates(e(x),$C(x, y, p), t$).*

The second rule declares that a conditional commitment that is in force disappears and generates a base-level commitment when the announced condition is brought out by the creditor.

Rule 2: *HoldsAt(CC(x, y, c, p), t) ∧ Happens(e(y), t) ∧ Initiates(e(y), c, t) → Initiates(e(y),C(x, y, p), t) ∧ Terminates(e(y),CC(x, y, c, p), t).*

Following we state some predicates that describe the semantics asociated to some of the communication acts of the upper level of the CommOnt ontology. This semantics is determined by the fluents that are initiated or terminated as a result of the sending of a message between agents.

- *Initiates(Assertive(s,r,P), P, t)*
- *Initiates(Commissive(s,r,C,P), CC(s,r,C,P), t)*
- *Initiates(Responsive(s,r,P, RA), P, t)*
  Terminates(Responsive(s,r,P, RA),C(s,r,RA), t)

Effects of these predicates can be encoded with SWRL rules. For instance, the predicate *Initiates(Request(s, r, P), CC(r, s, accept(r, s, P), P), t)* can be encoded as follows:

Request(x) ∧ hasSender(x,s) ∧ hasReceiver(x,r) ∧ hasContent(x,p) ∧ hasCommit(x,c) ∧ isConditionedTo(c,a) ∧ atTime(x, t) → initiates(x,c) ∧ hasDebtor(c,r) ∧ hasCreditor(c,s) ∧ hascondition(c,p) ∧ Acceptance(a) ∧ hasSignatory(a,r) ∧ hasAddressee(a,s) ∧ hasObject(a,p) ∧ atTime(c, t)

3 Protocol Description

As mentioned in the introduction, our proposal promotes to describe standard protocols using Semantic Web technology. We use STS as models of protocols. More specifically, we restrict to deterministic STS (i.e. if $(s, l, s') \in T$ and $(s, l, s'') \in T$ then $s' = s''$). In order to represent protocols using OWL-DL, we have defined five different classes: `Protocol`, `State`, `Transition`, `Fluent` and `Commitment`, which respectively represent protocols, states, transitions in protocols, fluents and commitments associated to states.

We model those class descriptions with the following guidelines: A state has fluents that hold in that point and transitions that go out of it. A transition is labelled by the communication act that is sent and is associated to the state that is reached with that transition. A fluent has a time stamp that signals the moment it was initiated. An actual conversation following a protocol is an individual of the class `Protocol`. Following are some of the ontology axioms:

$$
\begin{aligned}
\texttt{Protocol} &\equiv \exists\texttt{hasInitialState.State} \sqcap \\
&\quad \forall\texttt{hasInitialState.State} \\
\texttt{State} &\equiv \forall\texttt{hasTransition.Transition} \sqcap \\
&\quad \exists\texttt{hasFluent.Fluent} \sqcap \\
&\quad \forall\texttt{hasFluent.Fluent} \\
\texttt{Transition} &\equiv \texttt{=1 hasCommAct.CommunicationAct} \sqcap \\
&\quad \texttt{=1.hasNextState.State} \\
\texttt{FinalState} &\sqsubseteq \texttt{State} \sqcap \\
&\quad \forall\texttt{hasFluent.(Fluent} \sqcap \neg\texttt{Commitment)} \\
\texttt{Fluent} &\sqsubseteq \texttt{=1 atTime}
\end{aligned}
$$

$$\text{Commitment} \sqsubseteq \text{Fluent} \sqcap \ =1 \ \text{hasDebtor.Actor} \sqcap$$
$$=1 \ \text{hasCreditor.Actor} \sqcap$$
$$=1 \ \text{hasCondition.Fluent}$$
$$\text{ConditionalCommitment} \sqsubseteq \text{Fluent} \sqcap \ =1 \ \text{hasDebtor.Actor} \sqcap$$
$$=1 \ \text{hasCreditor.Actor} \sqcap$$
$$=1 \ \text{hasCondition.Fluent} \sqcap$$
$$=1 \ \text{isConditionedTo.Fluent}$$

The OWL-DL description of protocols reflects their static features and can be used to discover structural relationships between protocols. For instance, in Fig. 1 we show a simple protocol where agent A asks for time to agent B. The protocol description appears in the following:
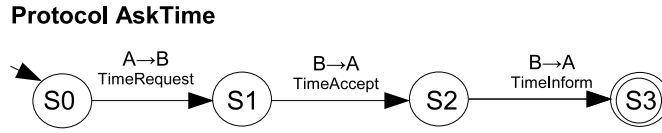
Protocol AskTime

Fig. 1. Protocol AskTime.

$$\text{Asktime} \equiv \text{Protocol} \sqcap \exists \text{hasInitialState.S0}$$
$$\text{S0} \equiv \text{State} \sqcap \exists \text{hasTransition.T01} \sqcap \exists \text{hasFluent.F0}$$
$$\text{S1} \equiv \text{State} \sqcap \exists \text{hasTransition.T12} \sqcap \exists \text{hasFluent.F1}$$
$$\text{S2} \equiv \text{State} \sqcap \exists \text{hasTransition.T23} \sqcap \exists \text{hasFluent.F2}$$
$$\text{S3} \equiv \text{FinalState} \sqcap \exists \text{hasFluent.F3}$$
$$\text{T01} \equiv \text{Transition} \sqcap \exists \text{hasCommAct.TimeRequest} \sqcap \exists \text{hasNextState.S1}$$
$$\text{T12} \equiv \text{Transition} \sqcap \exists \text{hasCommAct.TimeAccept} \sqcap \exists \text{hasNextState.S2}$$
$$\text{T23} \equiv \text{Transition} \sqcap \exists \text{hasCommAct.TimeInform} \sqcap \exists \text{hasNextState.S3}$$
$$\text{TimeRequest} \equiv \text{Request} \sqcap \ =1 \ \text{hasContent.TimeReq}$$
$$\text{TimeAccept} \equiv \text{Accept} \sqcap \ =1 \ \text{hasContent.TimeReq}$$
$$\text{TimeInform} \equiv \text{Responsive} \sqcap \ =1 \ \text{hasContent.TimeInfo} \sqcap \ =1 \ \text{inReplyTo.TimeRequest}$$

However, dealing only with structural relationships is too rigid if a flexible interoperation among agents that use different standard protocols is promoted. For that reason, we propose to consider what we call *protocol traces*.

Definition 4. *A protocol trace is a sequence of time stamped fluents sorted in increasing order of time stamp.*

Notice that protocol traces are defined in terms of the semantics of communication acts, not in terms of the communication acts themselves; in contrast with many other related works (see section 4) that consider messages as atomic acts without considering their content, neither their semantics.

During a simulation of a protocol run we apply the SWRL rules that encode the semantics of the communication acts (see section 2.2) appearing in the run.

Then, we can consider the sorted set of time stamped fluents that hold at a final state of the protocol. That set represents the effects of the protocol run. Following we show an example of the application of the rules to a run of protocol AskTime in Fig. 1.

In Fig. 2 we show which are the fluents associated to the states of the protocol and how they vary as a consequence of the communication acts that are sent and the rules described in section 2.2. We depart from a situation where the set of flu-
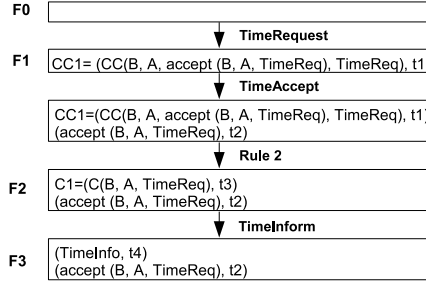
Fig. 2. Protocol fluents

ents is empty (F0). When the `TimeRequest` message is sent, due to the predicate *Initiates(Request(s, r, P),* $CC(r, s, accept(r,s,P), P), t)$ the conditional commitment `CC1` is initiated, which states that if agent B accepts to give information about the time, then it will be committed to do so; t_1 is the time stamp associated. By convention we sort time stamps by their subindexes, that is: $t_i < t_j$ if $i < j$. Then agent B agrees to respond by sending the `TimeAccept` message, and due to the predicate *Initiates(Accept(s,r,P), accept(s,r,P), t)*, the fluent *accept(B, A, TimeReq)* is initiated at time t_2. At this point, Rule 2 (see section 2.2) can be applied, so `CC1` is terminated and the base commitment `C1` is initiated at time t_3. Finally, agent B sends the `TimeInform` message, and because of the predicates *Initiates(Responsive(s,r,P, RA), P, t)* and *Terminates(Responsive(s,r,P, RA), C(s,r,RA), t)*, `C1` is terminated and a new fluent, *TimeInfo*, is initiated at time t_4. So, at this point we can say that the fluents that hold at the final state of the protocol are (*accept(B, A, TimeReq)*, t_2) and (*TimeInfo*, t_4).

Then, we say that the protocol trace [(*accept(B, A, TimeReq)*, t_2), (*TimeInfo*, t_4)] is *generated* by the protocol. We denote $\mathcal{T}(A)$ to the set of all protocol traces generated by a protocol A.

Now, we proceed with the definitions of relationships between protocols we are considering. Our relationships are not structure-based but effect-based. Intuitively, two protocols are equivalent if the same effects take place in the same relative order. Runs of a protocol are made up of communication acts, and fluents are the effects they leave.

Definition 5. *Protocol A is equivalent to protocol B if* $\mathcal{T}(A) = \mathcal{T}(B)$.

Sometimes, a protocol is defined by restrictions on the allowable communication acts at some states of a more general protocol. In those situations the application of those restrictions is reflected in the corresponding effects.

Definition 6. *Protocol A is a restriction of protocol B if $\mathcal{T}(A) \subset \mathcal{T}(B)$.*

Protocols for specific Information Systems may use specialized communication acts. Specialization can also be applied also to domain actions that can be represented by specialized fluents.

Definition 7. *A protocol trace t is a specialization of a protocol trace s, written $t \ll s$, if $\forall i.\ t(i) \sqsubseteq s(i)$ in an ontology of fluents.*

Definition 8. *Protocol A is a specialized-equivalent of protocol B if $\forall t \in \mathcal{T}(A)$. $\exists s \in \mathcal{T}(B).\ t \ll s$ and $\forall s \in \mathcal{T}(B).\ \exists t \in \mathcal{T}(A).\ t \ll s$.*

Definition 9. *Protocol A is a specialized-restriction of protocol B if $\forall t \in \mathcal{T}(A)$. $\exists s \in \mathcal{T}(B).\ t \ll s$.*

Notice that all those relationships can be easily discovered by straightforward algorithms supported by OWL-DL reasoners. Those reasoners deal with the ontology descriptions and rule engines that consider our semantic rules for generating protocol traces.

Moreover, sometimes we may be interested in comparing protocol traces independently of time stamps. That is, we may be interested in knowing if a protocol produces the same fluents as another, in whatever order. For example, in Fig. 3 we show two protocols that can be used to ask for information related to the vital signs temperature and pulse. In fact, for that purpose it is irrelevant the order in which the two requests are done.
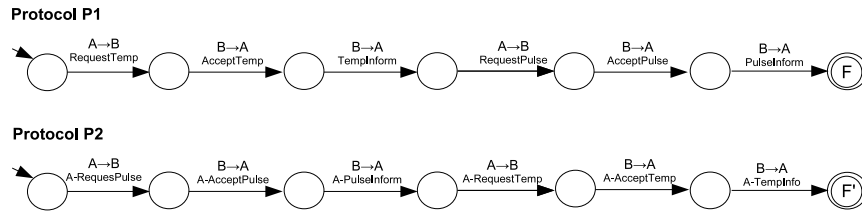
Fig. 3. Specialization of protocols.

In protocol P1 we can find a general protocol, in which agent A makes a request about the temperature using the communication act `RequestTemp` for that purpose. Then, agent B accepts and replies with a `TempInform` message, which is used to give information about the temperature. Once agent A receives this information, it asks agent B information about the pulse using a `RequestPulse`. Finally agent B accepts and replies with a `PulseInform` message and the final

state F is reached. On the other hand, in protocol P2 we can find the specific protocol used by the agents of a specific system, called AINGERU[2], to exchange information about vital signs. Protocol P2 may be a specialization of an standard protocol. First, agent A asks for the pulse, using the communication act `A-RequestPulse`. Then, agent B accepts and responds to the request using the `A-PulseInform` message. Next, agent A sends a `A-RequestTemp` message to ask about the temperature. Finally, agent B accepts and replies using the `A-TempInform` message and reaches state F'. Following we show the OWL specification for the communication acts used in this example.

```
    RequestTemp ≡ Request ⊓ =1 hasContent.TempReq
     AcceptTemp ≡ Accept ⊓ =1 hasContent.TempReq
      TempInform ≡ Responsive ⊓ =1 hasContent.TempInfo ⊓ =1 inReplyTo.RequestTemp
   RequestPulse ≡ Request ⊓ =1 hasContent.PulseReq
    AcceptPulse ≡ Accept ⊓ =1 hasContent.PulseReq
     PulseInform ≡ Responsive ⊓ =1 hasContent.PulseInfo ⊓ =1 inReplyTo.RequestPulse
  A-RequestTemp ≡ RequestTemp ⊓ =1 theSystem.Aingeru ⊓ =1 hasContent.A-TempReq
   A-AcceptTemp ≡ AcceptTemp ⊓ =1 theSystem.Aingeru ⊓ =1 hasContent.A-TempReq
   A-TempInform ≡ TempInform ⊓ =1 theSystem.Aingeru ⊓ =1 hasContent.A-TempInfo ⊓
                  =1 inReplyTo.A-RequestTemp
  A-RequestPulse ≡ RequestPulse ⊓ =1 theSystem.Aingeru ⊓ =1 hasContent.A-PulseReq
   A-AcceptPulse ≡ AcceptPulse ⊓ =1 theSystem.Aingeru ⊓ =1 hasContent.A-PulseReq
   A-PulseInform ≡ PulseInform ⊓ =1 theSystem.Aingeru ⊓ =1 hasContent.A-PulseInfo ⊓
                  =1 inReplyTo.A-RequestPulse
```

Notice that every communication act in protocol P2 is a subclass of its counterpart in protocol P1 (i.e. `A-RequestPulse` ⊑ `RequestPulse`, etc.) and correspondingly `A-PulseInfo` ⊑ `PulseInfo`, etc., is also satisfied.

Through a reasoning procedure analogous to that explained with the example of the AskTime protocol, we get the following sets of protocol traces:

$\mathcal{T}(P1) = \{[(accept(B, A, TempReq), t_2), (TempInfo, t_4), (accept(B, A, PulseReq), t_6), (PulseInfo, t_8)]\}$

$\mathcal{T}(P2) = \{[(accept(B, A, A\text{-}PulseReq), t_2), (A\text{-}PulseInfo, t_4), (accept(B, A, A\text{-}TempReq), t_6), (A\text{-}TempInfo, t_8)]\}$

Even if the structure of the protocols is not exactly the same, we can relate both protocols by a shallow notion of specialization from the following point of view. If we get abstracted from time stamps, we can see protocol traces as multi-sets. Let us denote *abstract-time(t)* to the multi-set formed by the fluents appearing in the protocol trace t, without any time stamp associated. Now, we define

$\mathcal{S}(A) = \{abstract\text{-}time(t) | t \in \mathcal{T}(A)\}$

Then, we are in condition to define analogous relationships to the previous five, but in a shallow mood.

Definition 10. *1. Protocol A is shallow-equivalent to protocol B if $\mathcal{S}(A) = \mathcal{S}(B)$.*

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[2] The A- prefix intends to label the AINGERU terminology

2. *Protocol A is a shallow-restriction of protocol B if $\mathcal{S}(A) \subset \mathcal{S}(B)$.*
3. *A protocol trace t is a shallow-specialization of a protocol trace s, written $t \ll_s s$, if there is a map ϕ from abstract-time(t) to abstract-time(s) such that $\forall f \in abstract\text{-}time(t). f \sqsubseteq \phi(f)$ in an ontology of fluents.*
4. *Protocol A is a shallow-specialized-equivalent of protocol B if $\forall t \in \mathcal{S}(A)$. $\exists s \in \mathcal{S}(B)$. $t \ll_s s$ and $\forall s \in \mathcal{S}(B)$. $\exists t \in \mathcal{S}(A)$. $t \ll_s s$.*
5. *Protocol A is a shallow-specialized-restriction of protocol B if $\forall t \in \mathcal{S}(A)$. $\exists s \in \mathcal{S}(B)$. $t \ll_s s$.*

Finally, using our proposal, we can conclude that protocols P1 and P2 are *shallow-specialized-equivalent*, although they use different communications acts and have different structure.

4 Related Works

Among the different related works that we can find in the specialized literature, the closer work is [11], where protocols are represented as transition systems and subsumption and equivalence of protocols are defined with respect to three state similarity funtions. We share some goals with that work, but the protocol description formalism used by them is not considered in the paper and there is no references to how protocol relationships are computed. In contrast, we describe protocols with a description logic language and protocol relationships can be computed by straightforward algorithms. It is worth mentioning that protocol relationships considered in that paper deserve study in our framework.

The works of [12] and [13] are quite similar one to each other. Both capture the semantics of communication acts through agents' commitments and represent communication protocols using a set of rules that operate on these commitments. Moreover those rule sets can be compiled as finite state machines. Nevertheless, they do not consider the study of relationships between protocols. In addition, in [14], protocols are also represented with a set of rules with terms obtained from an ontology, but their main goal is protocol development and, in order to reason about protocol composition, they formalize protocols into the π-calculus. Then, equivalence through bisimulation is the only process relationship considered. In [15], they also consider commitment protocols; however, their main focus is on combining them with considerations of rationality on the enactment of protocols. Our proposal could be complemented with their approach.

An alternative way to describe finite state machines with a description logic language is to take advantage of the relationship of that logic with Deterministic Propositional Dynamic Logic, see [16] for an example in the context of Web Services composition. The approach of that paper is very different in purpose from ours. Their states and transitions descriptions are not prepared to be confronted in a comparison. In constrast, our state and transition descriptions are carefully modelled as class descriptions such that semantics relationships between protocols can be captured.

Also in the context of Web Services, state transition systems are used in [17] for representing dynamic behaviour of services and they define some notions of

compatibility and substitutability of services that can be easily translated to the context of compatibility of protocols. Relationships between their compatibility relations and our defined relationships deserve study.

In [18] protocols are defined as a set of permissions and obligations of agents participating in the communication. They use an OWL ontology for defining the terms of the specification language, but their basic reasoning is made with an ad hoc reasoning engine. We share their main goal of defining protocols in a general framework that allows reutilization. Nevertheless, they do not consider relationships between protocols.

The problem of determining if an agent's policy is conformant to a protocol is a very important one, but we are not treating that topic in this paper. Nevertheless, the topic is close to ours and it is worth mentioning the following papers that consider different notions of conformance: In [19], deterministic finite state machines are the abstract models for protocols, which are described by simple logic-based programs. Three levels of conformance are defined: weak, exhaustive and robust. They consider communication acts as atomic actions, in contrast to our semantic view. In [20]a nondeterministic finite state automata is used to support a notion of conformance that guarantees interoperabiliy among agents conformant to a protocol. Their conformance notion considers the branching structure of policies and protocols and applies a simulation-based test. Communication acts are considered atomic actions, without considering their semantics. In [21], communication acts semantics is described in terms of commitments but it is not used for the conformance notion. A third different notion of conformance is defined and, moreover, it is proved orthogonal to their proposed notions of coverage and interoperability.

Finally, [22] and [23] use finite state machines and Petri nets, respectively, but without taking into account the meaning of the communication acts interchanged, neither considering relationships between protocols.

5   Conclusions

Increasing machine-processable tasks in the Web is a challenge considered at present. In this line we have presented in this paper a proposal that favours the communication among agents that represent to different Information Systems accessible through the Web. The main contributions of the proposal are:

- The management of the semantics aspects when dealing with agent communication protocols.
- The provision of the possibility of customizing standard communication protocols and management of them.
- The use of standard Semantic Web tools to describe protocols.
- The support for discovering different kinds of relationships between protocols.

References

1. FIPA: FIPA communicative act library specification (July 2005) http://www.fipa.org/specs/fipa00037/SC00037J.html.
2. Greenwood, D., M.Lyell, A. Mallya, H.S.: The IEEE FIPA approach to integrating software agents and web services. In: International Conference on Autonomous Agents and Multiagent Systems AAMAS, Hawaii USA (2007) 14–18
3. Bermúdez, J., Goñi, A., Illarramendi, A., Bagüés, M.I.: Interoperation among agent-based information systems through a communication acts ontology. Inf. Syst. **32**(8) (2007) 1121–1144
4. Singh, M.P.: Agent Communication Languages: Rethinking the Principles. IEEE Computer **31**(12) (December 1998) 40–47
5. Singh, M.P.: A social semantics for agent communication languages. In: Issues in Agent Communication, Springer-Verlag (2000) 31–45
6. Austin, J.L., ed.: How to do things with words. Oxford University Press (1962)
7. Wooldridge, M.: Semantic Issues in the Verification of Agent Comunication Languages. Journal of Autonomous Agents and Multi-Agent Systems **3**(1) (February 2000) 9–31
8. Venkatraman, M., Singh, M.P.: Verifying compliance with commitment protocols. Autonomous Agents and Multi-Agent Systems **2**(3) (1999) 217–236
9. Fornara, N., Colombetti, M.: Operational specification of a commitment-based agent communication language. In: AAMAS '02: Proceedings of the first international joint conference on Autonomous agents and multiagent systems, New York, NY, USA, ACM Press (2002) 536–542
10. Shanahan, M.: The event calculus explained. Lecture Notes in Computer Science **1600** (1999) 409–430
11. Mallya, A.U., Singh, M.P.: An algebra for commitment protocols. Autonomous Agents and Multi-Agent Systems **14**(2) (2007) 143–163
12. Yolum, P., Singh, M.P.: Flexible protocol specification and execution: Applying event calculus planning using commitments. In: Proceedings of the 1st International Joint Conference on Autonomous Agents and MultiAgent Systems (AAMAS), ACM Press (July 2002) 527–534
13. Fornara, N., Colombetti, M.: Defining interaction protocols using a commitment-based agent communication language. In: AAMAS '03: Proceedings of the second international joint conference on Autonomous agents and multiagent systems, New York, NY, USA, ACM Press (2003) 520–527
14. Desai, N., Mallya, A.U., Chopra, A.K., Singh, M.P.: Interaction protocols as design abstractions for business processes. IEEE Trans. Softw. Eng. **31**(12) (2005) 1015–1027
15. Yolum, P., Singh, M.: Enacting protocols by commitment concession. In: International Conference on Autonomous Agents and Multiagent Systems AAMAS, Hawaii USA (2007) 116–123
16. Berardi, D., Calvanese, D., Giacomo, G.D., Lenzerini, M., Mecella, M.: Automatic service composition based on behavioral descriptions. Int. J. Cooperative Inf. Syst. **14**(4) (2005) 333–376
17. Bordeaux, L., Salaün, G., Berardi, D., Mecella, M.: When are two web services compatible? In: TES. (2004) 15–28
18. Kagal, L., Finin, T.: Modeling conversation policies using permissions and obligations. Autonomous Agents and Multi-Agent Systems **14**(2) (2007) 187–206

19. Endriss, U., Maudet, N., Sadri, F., Toni, F.: Logic-based agent communication protocols. In: Workshop on Agent Communication Languages. (2003) 91–107
20. Baldoni, M., Baroglio, C., Martelli, A., Patti, V.: A priori conformance verification for guaranteeing interoperability in open environments. In: ICSOC. (2006) 339–351
21. Chopra, A.K., Singh, M.P.: Producing compliant interactions: Conformance, coverage, and interoperability. In: DALT. (2006) 1–15
22. d'Inverno, M., Kinny, D., Luck, M.: Interaction protocols in agentis. In: In Proceedings of the Third International Conference on Multi-Agent Systems (ICMAS98). (1998) 261–268
23. Mazouzi, H., Seghrouchni, A.E.F., Haddad, S.: Open protocol design for complex interactions in multi-agent systems. In: AAMAS '02: Proceedings of the first international joint conference on Autonomous agents and multiagent systems, New York, NY, USA, ACM Press (2002) 517–526