Multi-Agent Communication Heterogeneity

Maricela Bravo  
Systems Department  
Autonomous Metropolitan University, UAM  
Azcapotzalco, DF, Mexico  
mcbc@correo.azc.uam.mx

José A. Reyes-Ortiz  
Systems Department  
Autonomous Metropolitan University, UAM  
Azcapotzalco, DF, Mexico  
jaro@correo.azc.uam.mx

José Rodríguez  
Computing Department  
CINVESTAV  
México D.F, México  
rodriguez@cs.cinvestav.mx

Blanca Silva-López  
Systems Department  
Autonomous Metropolitan University, UAM  
Azcapotzalco, DF, Mexico  
rbsl@correo.azc.uam.mx

Abstract—Multi-agent communication represents a fundamental activity to enable efficient knowledge exchange towards the fulfillment of a shared goal. Achieve total automation of communication between intelligent agents is one of the most difficult challenges to overcome. This is a problem that occurs when multiple highly heterogeneous agents participate in virtual environments such as Internet. This paper offers an analysis of the components involved in communication and how their characteristics generate heterogeneity. The aim of this study is to provide an analysis tool to describe and quantify the characteristics of heterogeneity during communication between agents. A formal model for the measurement of heterogeneity and an example in which these measurements apply are described.

Keywords—Multi-agent system; communication heterogeneity; similarity measures; protocols; ontologies

Full/Regular Research Papers, CSCI-ISA1

I. INTRODUCTION

One of the first notions of intelligent agents appeared in 1973 [1], when Hewitt defined Actor Model as “A self-contained, interactive and concurrently-executing object, possessing internal state and communication capability”. In the last decade there has been a renewed interest in developing and researching intelligent agents. This interest is due to the evolution of Web technologies and their combination with artificial intelligence mechanisms to support complex tasks.

Distributed Problem Solving (DPS), as defined by Smith [2], requires the incorporation of multiple distributed and specialized intelligent agents which cooperate among them or through a mediator to solve complex problems which are beyond their individual capabilities. In DPS, multi-agent communication represents a fundamental activity to enable efficient knowledge exchange. However, considering the distributed nature of a DPS environment the set of participating agents in MAS very often have to face heterogeneity mismatches. This heterogeneity is because these agents represent different software solvers located at different processor nodes, which were developed by different companies, using different implementation techniques, with different design goals, etc. Therefore it is important to characterize the different sources of communication heterogeneity, with the objective to build solutions that consider all aspects involved in multi-agent communications.

The rest of the paper is organized as follows: in Section 2, platform heterogeneity is described; in Section 3, agent communication language heterogeneity is presented; in Section 4, ontology heterogeneity is delineated; in Section 5, interaction protocol heterogeneity is analyzed; in Section 6, heterogeneity measures are presented; in Section 7, experimental results are discussed; and finally, in Section 8 conclusions.

II. PLATFORM HETEROGENEITY

The term platform is defined as the combination of computer architectural configuration and operating system in our context. The problem of Platform Heterogeneity is concerned with the incorporation of multiple intelligent agents developed in diverse platforms. One of the main causes of platform heterogeneity is due to the selection of the development environment, which restricts of transport protocols, communication language and interaction protocols.

A. Message Transport Protocol

Multi-agent communication occurs over a message transport protocol (MTP). Some of these protocols are: HTTP, Java-RMI, IIOP, JMS, SOAP, etc. The existence of multiple MTPs increases the problem of heterogeneity, although they have similar architectures, the technical details for sending and receiving of messages vary from one to another.

B. Development Environment

Development environments group all programming resources which support agent developers. For a comprehensive list of existing agent based modeling platforms see the survey reported in [3]. This layer represents an important source of possible upper-layer heterogeneity problems. When the original agent developer selects implementation technologies, he is selecting a programming language, agent communication language (ACL) specification compliance, interaction protocols and related terminology. This means, that there is a close relation between development environments with remaining upper-layers.

III. COMMUNICATION LANGUAGE HETEROGENEITY

Communication in MAS occurs in peer to peer connections, where agents exchange messages by means of an ACL. This
layer consists of: specific ACL, supported set of performatives, content language and ontology.

A. ACL
Is the medium through which the attitudes regarding the content of a message exchanged between software agents are communicated, Labrou and Finin [4]. The main heterogeneity problem is the message structure, the set of supported performatives and the content language. On the selection of the ACL depends the set of supported performatives and supported content languages. KQML [5] was the first standardized ACL. KQML consists of a set of communication primitives aiming at supporting interaction between agents. Another ACL [6] standard comes from the Foundation for Intelligent Physical Agents (FIPA) initiative. FIPA ACL is based on speech act theory, and the messages generated are considered as communicative acts. The objective of using a standard ACL is to achieve effective communication without misunderstandings. However, implementations of ACL specifications vary from one environment to another, in the cases where such development environments adhere to an ACL standard specification.

B. Performatives
Austin [7] stated that a performative is a sentence uttered in the communication of an illocutionary act. In ACL performatives allow agents to communicate attitudes, believes, desires, and intentions to other agents. The following are the sources of heterogeneity: differences in the implementation of the selected ACL specification and as a consequence the set of performatives may differ from one company to another; the implementation and use of custom additional performatives even when adhering to an ACL standard specification; and use of some agent development environments which do not fully support a standard ACL or do not adhere to any ACL. For instance the AgentBuilder tool allows the developer to define new performatives in response to particular needs.

C. Content Language
According to FIPA ACL Specification1, an ACL message consists of: type of communicative act, participants in communication, content of message, description of content and control of conversation. The content of message meaning is intended to be interpreted by the receiver agent. The content language is used to denote the language in which the content parameter is described. Diverse content languages (CL) have been proposed: FIPA SL, RDF CL, Constraint Choice Language (CCL), Knowledge Interchange Format (KIF CL), Prolog Content Language (PCL). The problem of heterogeneity of CL is generated when agents use different message representation languages. The solution to this type of problem requires identification of the CL first, then get and compare the grammars of languages, and develop translators or interpreters to enable communication between agents with different CLs. This is a problem whose solution is highly complex, and is out of the scope of this study.

1 http://www.fipa.org/specs/fipa00061/SC00061G.pdf

IV. ONTOLOGY HETEROGENEITY

An ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary [8]. Each ontology represents the agent conceptualization of a particular domain, including hierarchical relations; semantic relations between concepts and individuals; axioms; and a set of rules to execute inference. Each agent uses its own ontology to generate messages and communicate its beliefs, desires and intentions to the rest of participating agents. Possible heterogeneity sources related with the agent ontologies are: differences at the conceptual level, hierarchical level, and semantic relationships.

V. INTERACTION PROTOCOL HETEROGENEITY

According to Endriss et.al [9] a protocol specifies the rules of interaction between communicating agents by restricting the range of allowed utterances for each agent. Sources of heterogeneity are: the type of dialog (protocol intention), the representation language (protocol modeling formalism and protocol language implementation), and protocol mismatch Quenum et.al [10] (use of different control structures).

A. Types of Dialogue
Protocol type defines the shared intention of the participants in a conversation. Walton and Krabbe [11] identified six types of dialogue based on the information available to the agents, the goal of the dialog itself, and the individual goals of the participants. These types are: information-seeking, inquiry dialogues, persuasion dialogues, negotiation dialogues, deliberation dialogues, and eristic dialogues. Additionally, authors introduced Dialectical Shifts (DS), to identify a change in the context of dialog during a conversation from one type of dialogue to another. These DS, allowed the notion of composition of dialog types into a single conversation.

B. Protocol Representation Language
Protocol heterogeneity occurs when agents use different representation languages for modeling their protocols. There are various formalisms used for representing protocols: Petri Nets [12], Colored Petri Nets [13], Pi-Calculus [14], Agent Unified Modeling Language [15], Finite State Machines [16], among others. FSM are suitable for implementing communication protocols, control interactions and describe transitional functions. Implementation of interaction protocol depends on the development environment selected. The evolution of middleware technologies provide adequate solutions for this heterogeneity. Web service communication protocols and standards offer platform independent interoperability to support interaction across heterogeneous agents.

C. Protocol Control Structures
The control structures define the flow of a conversation. Solution approaches address properties such as flexibility and
VI. MEASURES OF HETEROGENEITY

In this section a formal reference of MAS communication is provided, and a set of heterogeneity measures.

Definition 1. A MAS environment is represented as a tuple \(\text{MAS} = (A, C, Pr, O, P, \alpha, \rho, \beta, \lambda)\), where

- \(A\) is a finite set of \(n\) participating agents, where \(A = \{a_1, a_2, a_3, ..., a_n\}\).
- \(C\) is a finite set of communication languages,
- \(Pr\) represents the union set of all sets of performatives in use by each agent,
- \(O\) is a finite set of ontologies, and
- \(P\) is a finite set of protocols.

With these symbols denoting functions:

- \(\alpha(a_i)\) is a function that returns the communication language used by agent \(a_i\)
- \(\rho(a_i)\) is a function that returns the set of performatives in use by agent \(a_i\)
- \(\beta(a_i)\) is a function that returns the reference ontology in use by agent \(a_i\)
- \(\lambda(a_i)\) is a function that returns the protocol specification of agent \(a_i\).

Given a set of \(n\) agents, the possible number of peer to peer communication links \((nl)\) among them is given by:

\[
nl = \frac{n^2-n}{2}
\]

Considering a MAS with a set of \(n\) agents \(A = \{a_1, a_2, a_3, ..., a_n\}\), where every agent may establish conversations links with the rest of agents, the set of heterogeneous communication links \((CL)\) between them is:

\[
CL = \{(ai, aj), (ai, aj+1), ..., (an-1, an)\},
\]

where \(|CL| \leq nl\), with \(0 < i < n, 1 < j < n, i \neq j\).

A. Communication Language

A measure is defined, assuming a moment in time, into which all communications links are enabled, and that all performatives are to be exchanged causing the need for translation. To measure the level of heterogeneity, the sets of performatives are obtained by \(Pa1 = \rho(a1)\) and \(Pa2 = \rho(a2)\) from two different agents participating, the number of performatives that agent \(a1\) does not know is equal to the set of performatives from agent \(a2\), minus the set of performatives that are common for both. The heterogeneity between them is calculated as follows:

\[
\text{PerHet}(Pa1, Pa2) = 1 - \frac{|Pa1 \cap Pa2|}{|Pa1 \cup Pa2|}
\]

(2)

PerHet measure will return a value in the range from 0 to 1, where a returned value of 0 represents total similarity, and a value of 1 represents total lexical difference.

To get a general average of the level of performatives heterogeneity \((lph)\) between all agents, partial heterogeneity is calculated, then all heterogeneity values are accumulated and divided by \(nl\).

\[
lph = \sum \left[ \text{PerHet}(\rho(a_i), \rho(a_j)) \right] / nl
\]

where \(|CL| \leq nl\), with \(0 < i < n, 1 < j < n, i \neq j\).

The \(lph\) measure will return a value in the range from 0 to 1, where a 0 value indicates that all agents share identical performatives, and returned value of 1 represents a fully syntactical heterogeneity.

B. Ontologies

Given the sets of ontology concepts obtained by \(Ta_1 = \beta(a_1)\) and \(Ta_2 = \beta(a_2)\), the level of ontology heterogeneity is obtained by pairs of agents, first calculating the intersection of the terms divided by the union of terms. To get the value that represents the diversity, the result is subtracted from 1.

\[
\text{OntHet}(Ta_1, Ta_2) = 1 - \frac{|Ta_1 \cap Ta_2|}{|Ta_1 \cup Ta_2|}
\]

(4)

OntHet measure will return a value in the range from 0 to 1. Average of all the partial results is calculated dividing the sum by \(nl\), where \(nl\) is the number of communication links.

\[
\text{lohl} = \sum \left[ \text{OntHet}(Ta_i, Ta_j) \right] / nl
\]

where \(|CL| \leq nl\), with \(0 < i < n, 1 < j < n, i \neq j\).

The \(lohl\) measure will return a value in the range from 0 to 1, where a 0 value indicates that all agents share identical terms, and returned value of 1 represents a fully heterogeneity.

C. Protocols

Agent communication protocol is represented formally as a finite state machine (FSM) [16]. Using FSM, an agent communication protocol is defined as follows:

Definition 2. An agent communication protocol is a tuple \(P = (S, s_0, M, \delta, F)\), where

- \(S\) is a finite set of states,
- \(s_0\) is the initial state,
- \(M\) is the set of messages to be processed by \(C\),
- \(\delta: S \times M \rightarrow S\) is the transition relation, given a state \(s \in S\) and a message \(m \in M\), \(\delta\) returns the state resulting from the utterance of the message \(m\) in \(s\),
- \(F\) is the subset of final states, with \(F \subseteq S\).

In Fig. 1 the initial state \((s_0)\) contains all data that will be required for messages to be emitted and that represents the beginning of subsequent runs. On the other hand, state \(s_f\) represents an internal state which represents the changes after
the emission of the message (action) \( m_1 \) and \( s_j \) represents the final resulting state after the execution of the action \( m_2 \).

![Interaction protocol represented as a FSM.](image)

Given a pair of state and action \((s, m)\) the transition \( \delta(s, m) \) can lead to more than one state. As the emission of any message can return different results, therefore the transition is characterized as a relation not a function, and the FSM is non-deterministic.

Recalling that one of the important elements of a MAS is the union set of all agents protocols identified by \( P = \{ p_1, p_2, p_3, ..., p_n \} \), the set of states from any agent communication protocol is defined as a set \( S = \{ s_1, s_2, s_3, ..., s_n \} \), and a function \( S(p) \) that returns the set of states defined for protocol \( p_i \). In order to compare the set of states from two protocols \( p_1 \) and \( p_2 \), their respective sets of states are obtained as follows:

\( S_1 = S(p_1) = \{ s_1, s_2, s_3, ..., s_i \} \), and

\( S_2 = S(p_2) = \{ s_1, s_2, s_3, ..., s_j \} \)

Let \( r \) be the number of elements of set \( S_1 \), and \( t \) the number of elements of set \( S_2 \). The size of the relation set \( S_1 \times S_2 \) is \( r \times t \).

The relation set \( RS \) of comparison pairs is defined as:

\[
RS = \{ (s_1, s_1), (s_1, s_2), ..., (s_i, s_j) \},
\]

where \( RS / \times r \times t \).

To measure the heterogeneity the following elements are considered: the set of possible states of each protocol, state transitions and messages that cause changes between states.

1) **State Heterogeneity**

The measure of heterogeneity between states considers three characteristics: state name, state type and message type.

A state in a conversation scenario represents a resulting situation that occurred after the execution of a message. The context associated to a state is measured as follows:

a. State name. This data is based on the general assumption that the designer of conversation protocols provides descriptive names to identify the possible states. Let \( SName(s_i) \) be a function that returns the name of a given state.

b. State type. There are three possibilities: starting, if the state represents the init of the FSM; final, if the state is not part of any transition to another state; and intermediate, for the rest of states. Let \( SType(s_i) \) be a function that returns the type of a given state.

c. Type of message. To find the real similarity considering the context, the domain type of the message should be considered. Let \( SMessType(s_i) \) be a function that returns the message type that caused the given state.

2) **State Name Heterogeneity Measure**

Let \( SName_1 \) and \( SName_2 \) be two state names from different protocols, \( STokens_1 \) and \( STokens_2 \) representing the set of lexical tokens extracted from the names of each state respectively. The lexical heterogeneity between them is calculated as:

\[
NameHet(SName_1, SName_2) = 1 - \frac{|STokens_1 \cap STokens_2|}{|STokens_1 \cup STokens_2|} \tag{6}
\]

The \( NameHet \) measure will return a value in the range from 0 to 1, where a 0 value represents a total similarity, and a returned value of 1 represents a total lexical difference.

3) **State Type Heterogeneity Measure**

Let \( SType_1 \), \( SType_2 \), be two state types from different protocols. The state type heterogeneity between them is calculated by:

\[
TypeHet(SType_1, SType_2) = \begin{cases} 1, & \text{if } SType_1 \neq SType_2 \\ 0, & \text{if } SType_1 = SType_2 \end{cases} \tag{7}
\]

The state type heterogeneity measure will return a value in the range from 0 to 1.

4) **Message Type Heterogeneity Measure**

Let \( MType_1 \), \( MType_2 \), be two message types from different protocols. The message type heterogeneity between them is calculated by:

\[
MessHet(MType_1, MType_2) = \begin{cases} 1, & \text{if } MType_1 \neq MType_2 \\ 0, & \text{if } MType_1 = MType_2 \end{cases} \tag{8}
\]

The message type heterogeneity measure will return a value in the range from 0 to 1.

D. **Average State Heterogeneity Measure**

Let \( s_1 \) and \( s_2 \) denote two states from different agents, the average state heterogeneity between them is calculated as the mean of state name heterogeneity, state type and message type, as follows:

\[
AverageStateHet(s_1, s_2) = \frac{NameHet(SName(s_1), SName(s_2)) + TypeHet(SType(s_1), SType(s_2)) + MessHet(SMessType(s_1), SMessType(s_2))}{3} \tag{9}
\]

The average state heterogeneity measure will return a value in the range from 0 to 1.

Let \( S_1 \) and \( S_2 \) be two sets of states. Formula 9 is applied for all comparison pairs of \( RS \). The average \( StatesHet \) measure represents the sum of all pairs heterogeneity divided by the number of comparison pairs (\( cp \)).

\[
StatesHet(S_1, S_2) = \frac{\sum \text{AverageStateHet}(s_i, s_j)}{cp} \tag{10}
\]

where \( |RS| \leq cp \).

The average \( StatesHet \) measure will return a value in the range from 0 to 1, where a 0 value represents a null lexical similarity, and returned value of 1 represents a full lexical similarity. The level of states heterogeneity (\( Ish \)) is calculated as the sum of all partial states heterogeneity divided by the number \( nl \) of pairs from \( CL \).

\[
Ish = \frac{\sum \text{StatesHet}(S(\alpha_i, \alpha_j), S(\lambda, \alpha_i))}{nl} \tag{11}
\]

where \( |CL| \leq nl \),

with \( 0 < i < n, 1 < j < n, i \neq j \).
The Ish measure will return a value in the range from 0 to 1, where a 0 value indicates that all agents share identical states, and returned value of 1 represents a fully heterogeneity.

VII. EXPERIMENTATION

Six agents were implemented, each of these with different communication languages, using different sets of performatives, referring to different ontologies and handling different protocols. Table I shows the sets of performatives implemented.

<table>
<thead>
<tr>
<th>Table I. Performatives Per Protocol</th>
</tr>
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<tbody>
<tr>
<td>Id</td>
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<td>-----</td>
</tr>
<tr>
<td>acl1</td>
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<tr>
<td>acl2</td>
</tr>
<tr>
<td>acl3</td>
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</tbody>
</table>

A set of public ontologies related to the travel booking domain were searched and retrieved, shown in Table II.

<table>
<thead>
<tr>
<th>Table II. Ontologies Per Agent</th>
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<tbody>
<tr>
<td>Id</td>
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</tr>
<tr>
<td>ont2</td>
</tr>
<tr>
<td>ont3</td>
</tr>
<tr>
<td>ont5</td>
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<tr>
<td>ont6</td>
</tr>
</tbody>
</table>

Using these agents, different implementations of MAS environments were used for evaluation. The first experiment was carried out with the set of six agents participating in the first MAS environment. First the sets of performatives were extracted from each agent to calculate performatives heterogeneity using Formula 2; then with the sets of ontologies, Formula 4 was used; and last, Formulas 9 and 10 were applied for states heterogeneity. Results of these calculations are shown in Table IV.

<table>
<thead>
<tr>
<th>Table III. Agent Instantiations</th>
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<tr>
<td>Id</td>
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<tr>
<td>a1</td>
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Three different communication protocols were implemented for the set of agents participating in the MAS environment, see Fig. 2, 3 and 4.
VIII. CONCLUSIONS

This paper addresses both issues by describing elements involved in communication and characteristics which cause interoperability problems. The problem of interoperability in communication between agents has been studied and several solutions have been presented. However, there are no studies that cover all possible heterogeneous elements and provide measures to identify which specific elements are the main causes of misunderstanding problems. Heterogeneity measurements can determine the factors affecting the conversations between agents. A set of measurements to evaluate specific characteristics of the elements of the communication is presented. Despite being measured with a syntactic approach, they provide initial and relevant information about the degree of difference. Based on this model it is possible to further develop and refine the measurements. A way to compare communication protocols by comparing the sets of states is described. However, it is possible to incorporate more complex measures to analyze the observable behavior of the protocol specifications by analyzing and comparing the traces. Measuring the heterogeneity among agents is an essential step to simulate environments that are dynamic, changing and unforeseen.

REFERENCES