An Agent-based Petri Net Model with Application to Seller/Buyer Design in Electronic Commerce

Haiping Xu and Sol M. Shatz
Department of Electrical Engineering and Computer Science
The University of Illinois at Chicago
Chicago, IL 60607
Email: {hxu1, shatz}@eecs.uic.edu

Abstract

Agents are becoming one of the most important topics in distributed and autonomous decentralized systems (ADS), and there are increasing attempts to use agent technologies to develop software systems in electronic commerce. Such systems are complex and there is a pressing need for system modeling techniques to support reliable, maintainable and extensible design. G-Nets are a type of Petri net defined to support modeling of a system as a set of independent and loosely-coupled modules. In this paper, we first introduce an extension of G-Net, agent-based G-Net, as a generic model for agent design. Then new communication mechanisms are introduced to support asynchronous message passing among agents. To illustrate our formal modeling technique is effective for agent modeling in electronic commerce, a price-negotiation protocol example between buyers and sellers is provided. Finally, by analyzing an ordinary Petri net reduced from our agent-based G-Net models, we conclude that our agent-based G-Net models are L3-live, concurrent and effective for agent communications.

1. Introduction

Agents are becoming one of the most important topics in distributed and autonomous decentralized systems (ADS). With the increasing importance of electronic commerce across the Internet, the need for agents to support both customers and suppliers in buying and selling goods or services is growing rapidly. Most of the technologies supporting today's agent-based electronic commerce systems stem from distributed artificial intelligence (DAI) research [1][2]. Applications developed with multi-agent systems (MAS) in electronic commerce are examples of such efforts. A multi-agent system (MAS) is a concurrent system based on the notion of autonomous, reactive, and internally-motivated agents in a decentralized environment. The increasing interest in MAS research is due to the significant advantages inherent in such systems, including their ability to solve problems that may be too large for a centralized single agent, to provide enhanced speed and reliability, and to tolerate uncertain data and knowledge [2]. The notable systems developed with MAS in electronic commerce are Kasbah [3] and MAGMA [4]. Kasbah is meant to represent a marketplace where Kasbah agents, acting on behalf of their owners, can filter through ads and find those that their users might be interested in. The agents then proceed to negotiate to buy and sell items. MAGMA moves the marketplace metaphor to an open marketplace involving agents buying/selling physical goods, investments and forming competitive/cooperative alliances. These agents negotiate with each other through a global blackboard.

Although there are many efforts on developing multi-agent systems, there is a lack of research on formal specification and design of such systems [5][6]. As the multi-agent technology begins to emerge as a viable solution for large-scale industrial and commercial applications, there is an increasing need to ensure that the systems being developed are robust, reliable and fit for purpose. Previous work [7] on formal modeling agent systems includes: (1) using formal languages, such as Z, to provide a framework for describing a system at different levels of abstractions; (2) using temporal modal logic to allow the dynamic aspects of agents; and (3) designing formal languages, such as DESIRE, for multi-agent specification.

In this paper[1], we extend a formal model, called a G-Net (a form of Petri net [9]), to support modeling of agents in multi-agent systems. The advantage of our formal mechanism is that it provides a clean interface between agents with both asynchronous and synchronous communication abilities and supports formal reasoning

[1] This material is based upon work supported by the U.S. Army Research Office under grant number DAAD19-99-1-0350, and the U.S. National Science Foundation under grant number CCR-9988168.

0-7695-1065-5/01 $10.00 © 2001 IEEE

for our agent design. Furthermore, our formal mechanism is based on Petri net formalism that is a mature formal model with existing theory and tool support. The rest of this paper is organized as follows. Section 2 briefly introduces the standard G-Net model, and discusses the general structure of the proposed agent-based G-Net model. Section 3 provides a seller/buyer example in electronic commerce. We show how a seller and buyer agent can be designed by using our agent-based G-Net model. Section 4 first reduces our seller and buyer agent-based G-Net models to an ordinary Petri net. Then our net model is proven to be L3-live and unbounded. In addition, we show by examples that agent communication protocols can be correctly traced in our net model. Section 5 provides a brief conclusion and a summary of our future work.

2. Agent-based G-Net Model

2.1 The Standard G-Net Model

A widely accepted software engineering principle is that a system should be composed of a set of independent modules, where each module hides the internal details of its processing activities and modules communicate through well-defined interfaces. The G-Net model provides strong support for this principle [10]. G-Nets are an object-based extension of Petri nets. We assume that the reader has a basic understanding of Petri nets [9], so we begin with some introduction to the G-Net model. A G-Net system is composed of a number of G-Nets, each of them representing a self-contained module or object. A G-Net is composed of two parts: a special place called *Generic Switch Place (GSP)* and an *Internal Structure (IS)*. The *GSP* provides the abstraction of the module, and serves as the only interface between the G-Net and other modules. The *IS*, a modified Petri net, represents the detailed design of the module. An example of G-Nets is shown in Figure 1. Here the G-Net models represent two objects – the *Buyer* and the *Seller*. The generic switch places are represented by *GSP(Buyer)* and *GSP(Seller)* enclosed by ellipses, and the internal structures of these models are represented by round-cornered rectangles that contain the detailed design of four methods: *buyGoods()*, *askPrice()*, *returnPrice()* and *sellGoods()*. The functionality of these methods are defined as follows: *buyGoods()* invokes the method *sellGoods()* defined in G-Net *Seller* to buy some goods; *askPrice()* invokes the method *returnPrice()* defined in G-Net *Seller* to get the price of some goods; *returnPrice()* is defined in G-Net *Seller* to calculate the latest price for some goods; and *sellGoods()* is defined in G-Net *Seller* to handle things like waiting for the payment, shipping the goods and generating the invoice. A *GSP* of a G-Net *G* contains a set of methods *G.MS* specifying the services or interfaces provided by the module, and a set of attributes *G.AS* as attributes or state variables (we do not show both of them in Figure 1). In *G.IS*, Petri net places represent primitives, while transitions, together with arcs, represent connections or relations among those primitives. These primitives may be actions or method calls, represented by special places called *Instantiated Switch Places (ISP)*. A primitive becomes *enabled* if it receives a token, and an enabled primitive can be executed. Given a G-Net *G*, an *ISP* of *G* is a 2-tuple *(G'.Nid, mtd)*, where *G'* could be the same G-Net *G* or some other G-Net, *Nid* is a unique identifier of G-Net *G'*, and *mtd* ∈ *G'.MS*. Each *ISP(G'.Nid, mtd)* denotes a method call *mtd()* to G-Net *G'*. An example *ISP* (denoted as an ellipsis in Figure 1) is shown in the method *askPrice()* defined in G-Net *Buyer*, where the method *askPrice()* makes a method call *returnPrice()* to the G-Net *Seller* to query about the price for some goods (we have omitted all parameters for simplicity).

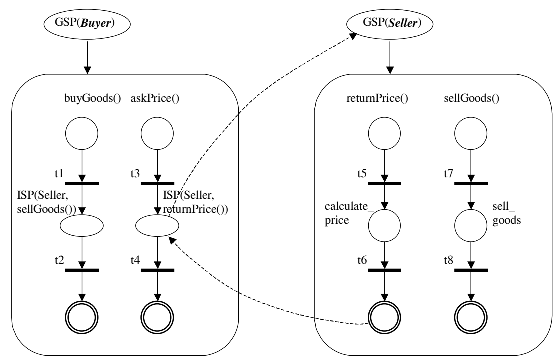


Figure 1 G-Net Model of Buyer and Seller Objects

From the above description, we can see that a G-Net model essentially represents a module or an object rather than an abstraction of a set of similar objects. In a recent paper [11], we have extended the G-Net model to support class modeling. The idea of this extension is to generate a unique object identifier *G.Oid* and initialize the state variables in *G.AS* when a G-Net object is instantiated from a G-Net *G*. An *ISP* method invocation is no longer represented as the 2-tuple *(G'.Nid, mtd)*, instead it is the 2-tuple *(G'.Oid, mtd)*, where different object identifiers could be associated with the same G-Net class model.

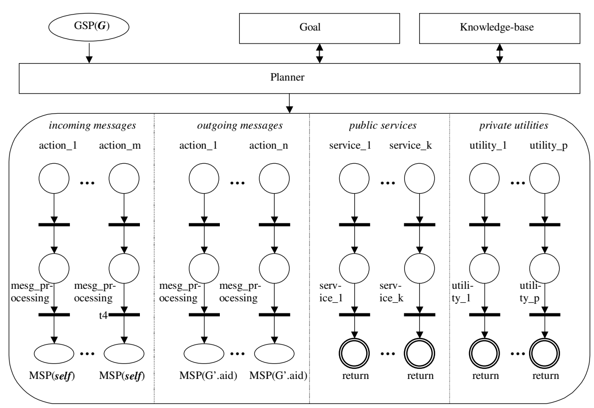
The token movement in a G-Net object is similar to that of original G-Nets [10]. A token *tkn* is a triple *(seq, sc, msg)*, where *seq* is the propagation sequence of the token, *sc* ∈ {**before**, **after**} is the status color of the token and *msg* is a triple *(mtd_name, para_list, result)*. For ordinary places, tokens are removed from input places and deposited into output places by firing transitions. However, for the special place *ISP*, whenever a method call is made to a G-Net object, the token in the *ISP* place is processed (by attaching information for the method call) and removed, and an identical token is deposited into the *GSP* place of the called G-Net object. Through the *GSP* of the called G-Net object, the token is then dispatched into an *entry* place of the appropriate called method. After the method call, the token will reach a *return* place (denoted by double circles) with the result attached to the token. As soon as this happens, the token will return to the *ISP* place of the caller and the information related to this completed method call will be detached.

We call a G-Net model that supports class modeling as a *standard* G-Net model. Notice that the example we provide in Figure 1 follows the Client-Server paradigm, in which a *Seller* object works as a server and a *Buyer* object is a client. Although the standard G-Net model works well in object-based design, it is not sufficient in agent-based design for the following reasons. First, agents in multi-agent systems are usually developed by different vendors independently, and those agents will be widely distributed across large-scale networks such as the Internet. To make it possible for those agents to communicate with each other, it is essential for them to have a common communication language and to follow common protocols. However the standard G-Net model does not directly support protocol-based language communication between agents. Second, the underlying agent communication model is usually asynchronous, and an agent may decide whether to perform actions requested by some other agents. The standard G-Net model does not directly support asynchronous message passing and decision-making, but only supports synchronous method invocations in the form of *ISP* places. Third, agents are commonly designed to determine their behavior based on individual goals and their knowledge. They may autonomously and spontaneously initiate internal or external behavior at any time. Standard G-Net models can only directly support a predefined flow of control.

2.2 Extending G-Nets for Agent Modeling

To support agent-based design, we need to extend a G-Net to support modeling an agent class[2]. The idea is similar to extending a G-Net to support class modeling [11]. When we instantiate an agent-based G-Net (an agent class model), an agent identifier is generated and the mental state of the resulting agent object (an active object [7]) is initialized. In addition, at the class level, three special modules are introduced to make an agent autonomous and internally-motivated, namely the *Goal* module, the *Knowledge-base* module and the *Planner* module. The outline of an agent-based G-Net model is shown in Figure 2. A *Goal* module is an abstraction of a goal model [8], which describes the goals that an agent may possibly adopt. A *Knowledge-base* module is an abstraction of a belief model [8], which describes the information about the environment and internal state that an agent of that class may hold. A *Planner* module can be viewed as the heart of an agent that makes a plan to achieve some committed goals. For instance, in the *Planner* module, an agent may decide to ignore an incoming message, start a new conversation, or continue with a conversation, which may be initiated by some other agent or the agent itself.

The *internal structure (IS)* of an agent-based G-Net consists of four sections, namely the *incoming messages*, *outgoing messages*, *public services* and *private utilities*. *Message Processing Units (MPU)* defined in the *incoming/outgoing messages* section are used to process incoming/outgoing messages, and it may use *ISP* function calls to methods defined in its *private utilities* section. The *public services* section makes an agent able to work as a server. Other agents may use the *ISP* function call mechanism to invoke these services synchronously. We keep this synchronous communication mechanism for agents because we view an agent as an active object with further characteristics like being autonomous, reactive and internally-motivated. The *private utilities* section is similar to the *public services* section but with the difference that private utility functions can only be called by the agent itself.



Notes: G'.aid = mTkn.body.receiver as defined later in this section

Figure 2 A General Agent-based G-Net Model

Although both objects (passive object) and agents use message-passing to communicate with each other, message-passing for objects is a unique form of method invocation, while agents distinguish different types of messages and model these messages frequently as speech-acts and use complex protocols to negotiate. In addition,

[2] We view the abstract of a set of similar agents as an agent class, and we call an instance of an agent class an agent or an agent object.

agents analyze these messages and can decide whether to execute the requested action [7]. As we stated before, most of the agent communications are asynchronous message passing. Since asynchronous message passing is more fundamental than synchronous message passing, it is useful for us to introduce a new mechanism, called *Message-passing Switch Place (MSP)*, to support asynchronous message passing directly. When a token reaches an *MSP* place (we represent it as an ellipsis in Figure 2), the token is removed and deposited into the *GSP* place of the called agent. Unlike the *ISP* mechanism, the calling agent does not wait for the token to return before it can continue to execute its next step. Note that we have extended G-Nets to allow the use of the keyword **self** to refer to the agent object itself.

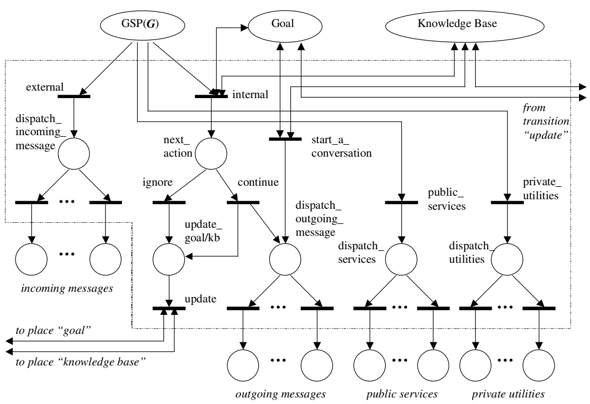


Figure 3 A Template of Planner Module

A template of the *Planner* module is shown in Figure 3. The modules *Goal* and *Knowledge-base* are represented as two special places, each of which contains a token that represents a set of goals or a set of beliefs. The *Planner* module is goal-driven because the transition *start_a_con-versation* may fire whenever an attempt is made to achieve a committed goal. In addition, the *Planner* module is also message-triggered because certain actions may initiate whenever a message arrives (either from some other agent or the agent itself). If the message comes from some other agent, it will be dispatched to a *MPU* defined in the *incoming messages* section of the agent-based G-Net's internal structure. After the message is processed, the *MPU* will transfer the processed message as a token to the *GSP* place of the agent itself. This is done by sending a message *MSP(**self**)* to the agent itself. Upon arrival of this internal message, the transition *internal* may fire, and the next action will be determined based on the agent's current mental state. Alternatively, the next action could be to ignore the message or to continue with the current conversation. In either case, a token will be deposited in place *update_goal/kb*, and the transition *update* may fire. As a consequence, the agent's mental state may change. If the next action is to continue the conversation, the tag of the token will be changed from **internal** to **external**, and the token will be deposited in place *dispatch_outgoing_message*. In this case, the corresponding *MPU* will be called before the message is sent to some other agent by using the *MSP* mechanism. In addition, an agent may also work as a server by providing a set of public services and allowing other agents to make synchronous method calls to it. Whenever there is a service request, the token deposited in the *GSP* place will be dispatched to a method in the *public services* section.

As a result of this extension, the structure of tokens in the agent-based G-Net model should be redefined. Essentially there are three types of tokens, namely the message token *mTkn*, the goal token *gTkn* and the knowledge token *kTkn*. One way to construct the *gTkn* and *kTkn* is to make them linked lists. In other words, a *gTkn* represents a list of goals and a *kTkn* represents a list of facts. Since these two tokens confine themselves in places in their corresponding modules of our agent-based G-Net model, we do not describe them further in this paper.

An *mTkn* is a 2-tuple *(tag, body)*, where *tag* ∈ {**internal**, **external**, **public**, **private**} and *body* is a variant, which is determined by the tag. According to the tag, the token deposited in a *GSP* place will be dispatched into an *entry* place of a *MPU* or a *method* defined in the internal structure of the agent-based G-Net. Then the *body* of the token *mTkn* will be interpreted differently. More specifically, we define the *mTkn* body as follows:

```
if (mTkn.tag ∈ (internal, external))
then mTkn.body = struct {
  int sender;      // message sender identifier
  int receiver;    // message receiver identifier
  string protocol_type;   // protocol type
  string message_name;    // message name
  string content;         // message content
}     // mTkn.body is as defined in Section 2.1
else mTkn.body = (seq, sc, msg);
```

We now provide a few key definitions for our agent-based G-Net models.

Definition 2.1 *Agent-based G-Net*
An *agent-based G-Net* is a 5-tuple *AG = (GSP, GL, KB, PL, IS)*, where *GSP* is a *Generic Switch Place* providing an abstract for the agent-based G-Net, *GL* is a *Goal* module, *KB* is a *Knowledge-base* module, *PL* is a *Planner* module and *IS* is an *internal structure* of *AG*.

Definition 2.2 *Planner Module*
A *Planner module* of an agent-based G-Net *AG* is a colored sub-net defined as a 5-tuple *(IGS, IGO, IKB, IIS,*

DMU), where *IGS*, *IGO*, *IKB* and *IIS* are interfaces with *GSP* place, *Goal* module, *Knowledge-base* module and *internal structure* of *AG,* respectively. *DMU* is a decision-making unit with the functionality of dispatching messages, determining the next action, starting a new conversation and updating the *Goal* and *Knowledge-base* module of *AG*.

Definition 2.3 *Internal Structure (IS)*
An *internal structure (IS)* of an agent-based G-Net *AG* is a 4-tuple *(IM, OM, PS, PU)*, where *IM/OM* is the *incoming/outgoing messages* section, which defines a set of *Message Processing Units (MPUs)*; *PS/PU* is the *public services/private utilities* section, which defines a set of *Methods*.

Definition 2.4 *Message Processing Unit (MPU)*
A *message processing unit (MPU)* is a triple *(P, T, A)*, where *P* is a set of places with three special places called *entry* place, *ISP* place and *MSP* place. Each *MPU* can have only one *entry* place and one *MSP* place, but it may contain multiple *ISP* places. *T* is a set of transitions, and each transition can be associated with a set of guards. *A* is a set of arcs defined as: ((P-{*MSP*}) x T) ∪ ((T x (P-{*entry*}).

Definition 2.5 *Method*
A *method* is a triple *(P, T, A)*, where *P* is a set of places with three special places called *entry* place, *ISP* place and *return* place. Each method can have only one *entry* place and one *return* place, but it may contain multiple *ISP* places. *T* is a set of transitions, and each transition can be associated with a set of guards. *A* is a set of arcs defined as: ((P-{*return*}) x T) ∪ ((T x (P-{*entry*}).

3. Seller and Buyer Design

To illustrate how to design a seller/buyer agent by using our agent-based G-Net model, we use an example derived from [12]. Figure 4 (a) is a modified example of an FIPA contract net protocol adapted from [12], which depicts a template of protocol expressed as a UML sequence diagram for a price-negotiation protocol between a buyer and a seller. To correctly draw the sequence diagram for this template, we need to introduce two new notations, i.e., the end of protocol operation "•" and the iteration of communicative acts operation "∗". Examples of using these two notations are as follows. In Figure 4 (a), we put a mark of "•" in front of the message name "*refuse*" to indicate that this message ends the protocol. In the same figure, a mark "∗" is put on the right corner of the narrow rectangle for the message "*propose*" to indicate that the communicative actions in this section can be repeated zero or more times.

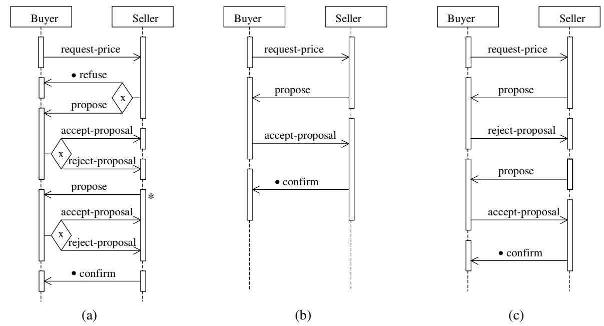


Figure 4 A Contract Net Protocol between Buyer and Seller Agents

When a conversation based on this contract net protocol begins, the buyer agent sends a request for price to a seller agent. The seller agent can then choose to response to the buyer agent by refusing to provide price or submitting a proposal. Here the "x" in the decision diamond indicates an exclusive-or decision. If a proposal is offered, the buyer agent has a choice of either accepting or rejecting the proposal. If a seller agent receives a *reject-proposal* message, it may send the buyer agent a new proposal or replies the buyer agent with a confirmation message. If the seller agent receives an *accept-proposal* message, it will simply send a confirmation message to the buyer agent. Whenever a confirmation message is sent, the protocol ends. Figure 4 (b) and 4 (c) shows two actual cases of this protocol template. In Figure 4 (b), the seller agent's proposal is accepted by the buyer agent in one round; while Figure 4 (c) shows the case that the proposal is accepted by the buyer agent in the second round.

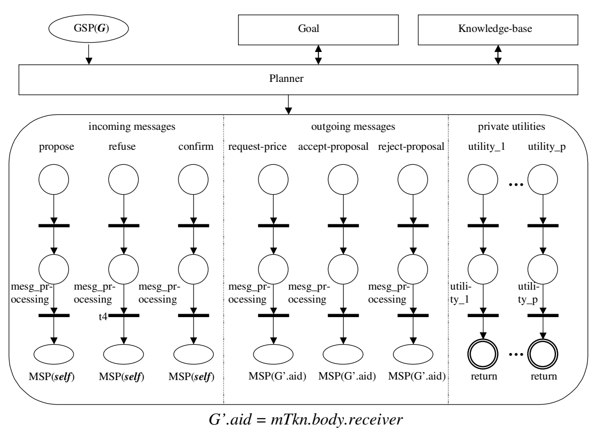


Figure 5 An Agent-based G-Net Model for Buyer Agent

Based on the communicative acts (e.g., request-price, propose etc.) needed for this contract net protocol, we may design the buyer agent as in Figure 5. In Figure 5, the *Goal* and *Knowledge-base* modules remain as abstract units and can be refined in further detailed design. The

Planner module may use Figure 3 as a template, with the transition *start_a_conversation* and the place *next_action* left to be refined in further detailed design too. Since the buyer agent will never work as a server, the *public services* section could be empty, while in the *private utilities* section, we may define some necessary functions that can be called by the buyer agent itself. Examples of such private utility functions could be: *compare_price*, *update_knowledge_base* etc. The design of the seller agent is similar. We define *MPUs* of *request-price*, *accept-proposal* and *reject-propose* in the *incoming messages* section of the seller agent, and define *MPUs* of *propose*, *refuse* and *confirm* in the *outgoing messages* section of the seller agent.

4. Verifying Agent-based G-Net models

One of the advantages of building a formal model for agents in agent-based design is to ensure a correct design that meets certain specifications. A correct design of agents at least has the following properties:

- *L3-live*: any communicative act can be performed as many times as needed.
- *Concurrent*: a number of conversations among agents can happen at the same time.
- *Effective*: an agent communication protocol can be correctly traced in the agent models.

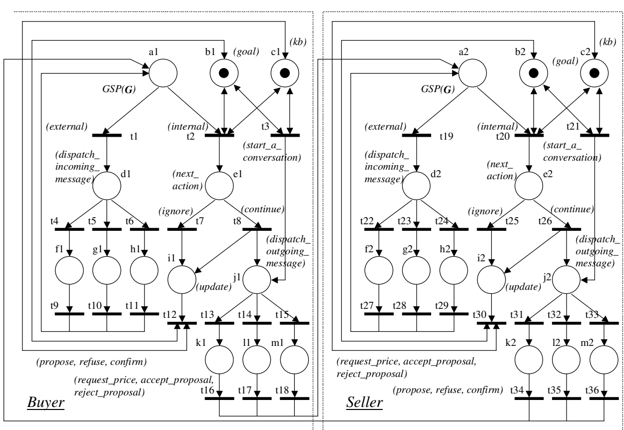


Figure 6 A Transformed Model of Buyer and Seller Agents

To verify the correctness of agent-based G-Net models for seller/buyer agents with respect to the above properties, we first reduce our agent-based G-Net models to an ordinary Petri net as follows: (1) simplify the *Goal* module and *Knowledge-base* module as ordinary places with ordinary tokens; (2) omit the *public services* and *private utilities* sections; (3) simplify *mTkn* tokens as ordinary tokens; (4) use net reduction to simplify the Petri net corresponding to an *MPU/Method* as a single place; and (5) use the close world assumption and make our system only contains two agents, i.e., a buyer agent and a seller agent.

The resulting ordinary Petri net is illustrated in Figure 6. To verify the correctness of our agent-based G-Net model for agent communication, we utilize some key definitions and theorems as adapted from [9].

Definition 4.1 *Incidence Matrix*
For a Petri net N with n transitions and m places, the *incidence matrix* $A = [a_{ij}]$ is an n x m matrix of integers and its typical entry is given by

$$a_{ij} = a_{ij}^{+} - a_{ij}^{-}$$

where $a_{ij}^{+} = w(i,j)$ is the weight of the arc from transition i to output place j and $a_{ij}^{-} = w(j,i)$ is the weight of the arc from input place j to transition i.

Definition 4.2 *Firing Count Vector*
For some sequence of transition firings in a Petri net N, a *firing count vector* x is defined as an n-vector of nonnegative integers, where the ith entry of x denotes the number of times that transition i must fire in that firing sequence.

Definition 4.3 *T-invariant*
For a Petri net N, an n-vector x of integers ($x \neq 0$) is called a *T-invariant* if x is an integer solution of homogeneous equation $A^T x = 0$, where A is the incidence matrix of Petri net N.

Definition 4.4 *Support and minimal-support T-invariant*
The set of transitions corresponding to non-zero entries in a T-invariant $x \geq 0$ is called the *support* of a T-invariant and is denoted as $\|x\|$. A support is said to be *minimal* if no proper non-empty subset of the support is also a support. Given a minimal support of a T-invariant, there is a unique minimal T-invariant corresponding to the minimal support. Such a T-invariant is called the *minimal-support T-invariant*.

Definition 4.5 *L3-live Petri net*
A Petri net N with initial marking M_0, denoted as (N, M_0), is said to be *L3-live* if for every transition t in the net, t appears infinitely often in some firing sequence $L(N, M_0)$, where $L(N, M_0)$ is the set of all possible firing sequences from M_0 in the net (N, M_0).

Theorem 4.1 An n-vector x is a T-invariant of a Petri net N *iff* there exists a marking M_0 and a firing sequence σ that reproduces the marking M_0, and x defines the firing count vector for σ.

Theorem 4.2 A Petri net N with initial marking M_0 is *L3-live* if there exists a set of minimal-support T-invariants that covers all the transitions in the net, and for each minimal-support T-invariant there exists a firing sequence that reproduces the initial marking M_0.

Proof: Let T be the set of transitions in Petri net (N, M_0), Γ be the set of minimal-support T-invariants that covers all the transitions in T. From the given condition, we know that for $\forall t \in$ T, $\exists \chi \in \Gamma$, which covers transition t. Since for the minimal-support T-invariant χ, there exists a finite firing sequence ρ that reproduces the initial marking M_0, t appears in ρ. Let the infinite firing sequence $\sigma = \rho \bullet \rho \bullet \rho \bullet \rho \ldots$, where "•" is the concatenation operator between finite sequences, t appears in σ infinitely often. By definition 4.5, Petri net (N, M_0) is *L3-live*. ◊

The incidence matrix A of the Petri net in Figure 6 is listed in Table 1. By using Definition 4.1 and 4.4, we can calculate a set of minimal-support T-invariants as follows:

x_1=[1 1 0 1 0 0 1 0 1 0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0]
x_2=[0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 1 1 0 1 0 0 1 0 1 0 0 1 0 0 0 0 0 0]
x_3=[1 1 1 1 0 0 1 0 1 0 0 1 1 0 0 1 0 0 1 1 0 1 0 0 0 1 1 0 0 1 1 0 0 1 0 0]
x_4=[1 1 1 0 0 1 1 0 0 0 1 1 0 1 0 0 1 0 1 1 0 0 1 0 0 1 0 1 0 1 0 0 1 0 0 1]
x_5=[1 1 0 0 1 0 0 1 0 1 0 1 0 0 1 0 0 1 1 1 1 0 0 1 1 0 0 0 1 1 0 1 0 0 1 0]

	a1	b1	c1	d1	e1	f1	g1	h1	i1	j1	k1	l1	m1	a2	b2	c2	d2	e2	f2	g2	h2	i2	j2	k2	l2	m2
t1	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t2	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t4	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t5	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t6	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t7	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t8	0	0	0	0	-1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t9	1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t10	1	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t11	1	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t12	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t13	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t14	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t15	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
t16	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
t17	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
t18	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0
t19	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0	0
t20	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0
t21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
t22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0
t23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0
t24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0
t25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0
t26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	1	0	0	0
t27	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	-1	0	0	0	0	0	0	0
t28	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	0	0	0
t29	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	-1	0	0	0	0	0
t30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
t31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0
t32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	0
t33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	1
t34	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
t35	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
t36	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1

Table 1 Incidence Matrix A of the Petri Net in Figure 6

From Theorem 4.1, for each minimal-support T-invariant x_i in our example, there exists a marking M_0 and a firing sequence σ_i, which reproduces the marking M_0, and x_i defines the firing count vector for σ_i. Obviously, the following firing sequences $\sigma_1, \sigma_2, \ldots \sigma_5$ reproduce the initial marking M_0 = [0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0], and $x_1, x_2, \ldots x_5$ define the firing count vectors for $\sigma_1, \sigma_2, \ldots \sigma_5$ respectively:

σ_1=<t21, t31, t34, t1, t4, t9, t2, t7, t12>
σ_2=<t3, t13, t16, t19, t22, t27, t20, t25, t30>
σ_3=<t3, t13, t16, t19, t22, t27, t20, t26, t30, t31, t34, t1, t4,t9,t2,t7,t12>
σ_4=<t3, t14, t17, t19, t23, t28, t20, t26, t30, t33, t36,t1,t6,t11,t2,t7,t12>
σ_5=<t21, t32, t35, t1, t5, t10, t2, t8, t12,t15,t18,t19,t24,t29,t20,t25,t30>

Since the above minimal-support T-invariants cover all the transitions in the net, and for each minimal-support T-invariant, there exists a firing sequence that reproduces the initial marking M_0, from Theorem 4.2, we conclude that our Petri net model with initial marking M_0 is *L3-live*, i.e., for any transition t in our net model, we can find an infinite firing sequence that t appears infinitely often. Consequently, any communicative act can be performed as many times as needed[3].

In Figure 6, it is obvious to see that our net model is unbounded. This is because transitions *t3* and *t21* can fire as many times as needed. This behavior shows that both the buyer and seller agent may initiate conversations autonomously and concurrently (as we stated before, the initiation of a new conversation is goal driven). There can be as many conversations as necessary between the buyer agent and the seller agent. As an example, a buyer agent may request prices of several goods from a seller agent at the same time, and several buyer agents may request price of the same goods from a seller agent concurrently.

In addition, we may trace an agent communication protocol p in our net model with a firing sequence σ. For a protocol p, a corresponding firing sequence σ in our net model has more semantics than the protocol itself because when we actually execute a protocol in our net, we need to do additional work, such as updating the goal or knowledge base after each communicative act. Since a marking M that is reachable from M_0, but $M \neq M_0$, represents that there are still some ongoing conversations in the net, to correctly trace a protocol p in our net model, it is essential for us to find a firing sequence σ that reproduces the initial marking M_0. In other words, we need to make sure that there will be no residual tokens for a conversation left in the net after that conversation completes. In this case, we say that the protocol p can be *effectively* traced as a firing sequence σ in our net model. To show that a protocol p can be effectively traced, we use the contract net protocol examples in Figure 4 (b) and Figure 4 (c). These two protocols can be traced in our net model as follows:

σ_b=<t3, t13, t16, t19, t22, t27, t20, t26, t30, t31, t34, t1, t4, t9, t2, t8,t12, t14, t17, t19, t23, t28, t20, t26, t30, t33, t36, t1, t6, t11, t2, t7, t12>
σ_c=<t3, t13, t16, t19, t22, t27, t20, t26, t30, t31, t34, t1, t4, t9, t2, t8, t12, t15, t18, t19, t24, t29, t20, t26, t30, t31, t34, t1, t4, t9, t2, t8, t12, t14, t17, t19, t23, t28, t20, t26, t30, t33, t36, t1, t6, t11, t2, t7, t12>

By Definition 4.2, we calculate their corresponding firing count vectors x_b and x_c as follows:

[3] One of the limitations for invariant approach is that it is not sufficient to prove a Petri net is *L4-live* or *live*, i.e., it is possible to ultimately fire any transition of the net from any marking M that is reachable from M_0.

x_b=[2 2 1 1 0 1 1 1 1 0 1 2 1 1 0 1 1 0 2 2 0 1 1 0 0 2 1 1 0 2 1 0 1 1 0 1]
x_c=[3 3 1 2 0 1 1 2 2 0 1 3 1 1 1 1 1 1 3 3 0 1 1 1 0 3 1 1 1 3 2 0 1 2 0 1]

By Definition 4.3, it is easy to verify that both x_b and x_c are T-invariants because both of the equations $A^T x_b = 0$ and $A^T x_c = 0$ are satisfied. This shows that both firing sequences σ_b and σ_c can reproduce the initial marking M_0. In other words, we prove that both protocols in Figure 4(b) and 4(c) can be effectively traced in our agent-based model.

5. Conclusion and Future Work

One of the most rapidly growing areas of interest for Internet technology is that of electronic commerce. Consumers are looking for suppliers selling products and services on the Internet, while suppliers are looking for buyers to increase their market share. For convenience and efficiency, we believe that ADS in a form of multi-agent systems (MAS) is an effective way to automate the time consuming process of looking for buyers or seller and negotiate in order to obtain the best deal. Although there are several implementations of agent-based electronic marketplaces available [4][5], formal frame works for such systems are few. It is an increasing need to provide formal methods in multi-agent systems specification and design to ensure robust and reliable products.

In this paper, we introduced an agent-based G-Net model for buyer and seller agent modeling in electronic commerce. Using this model, sellers and buyers can be modeled as agents with the characteristics of autonomous, reactive and internally-motivated. Agent-based G-Net models also provide a clean interface between agents, and agents may communicate with each other by using contract net protocols. Furthermore, these models are based on the Petri net formalism, which is a mature formal model in terms of both existing theory and tool support. An example of price-negotiation protocol between buyers and sells is used to illustrate our basic idea, and we prove that the agent communication mechanism in our net model meets the requirements of *L3-live*, *concurrent* and *effective* properties.

For our future work, we will try to refine the *Goal*, *Knowledge-base* modules, and the decision-making mechanisms in *Planner* module, and try to use this formal model to prove the correctness of contract net protocols. Furthermore, to capture more semantics of our agent-based G-net models, and to obtain performance metrics of multi-agent systems, we will translate our net models into colored Petri nets, and use existing Petri net tools, such as Design/CPN, to do the analysis. We will also look into issue like deadlock avoidance and state exploration problems in the agent design and verification processes.

6. References

[1] R. Guttman, A. Moukas, and P. Maes, “Agent-mediated Electronic Commerce: A Survey,” *Knowledge Engineering Review*, June 1998.

[2] S. Green, L. Hurst, B. Nangle, P. Cunningham, F. Somers, R. Evans, “Software Agents: A Review,” *Technical report TCD-CS-1997-06*, Trinity College Dublin, May 1997.

[3] Anthony Chavez, Pattie Maes, “Kasbah: An Agent Marketplace for Buying and Selling Goods,” *Proceedings of the First International Conference on the Practical Application of Intelligent Agents and Multi-Agent Technology*, London, UK, April 1996.

[4] M. Tsvetovatyy, M. Gini, B. Mobasher, Z. Wieckowski, “MAGMA: An Agent-Based Virtual Market for Electronic Commerce,” *Applied Artificial Intelligence,* special issue on Intelligent Agents, No. 6, September 1997.

[5] T. J. Rogers, Robert Ross, V. S. Subrahmanian, “IMPACT: A System for Building Agent Applications,” *Journal of Intelligent Information Systems,* 14(2-3): 95-113, 2000.

[6] Brazier, F.M.T., Dunin Keplicz, B., Jennings, N., and Treur, J., “DESIRE: Modeling Multi-Agent Systems in a Compositional Formal Framework,” *Int’l Journal of Cooperative Information Systems*, vol. 6, Special Issue on Formal Methods in Cooperative Information Systems: Multi-Agent Systems, 1997, pp. 67-94.

[7] C. Iglesias, M. Garrijo, and J. Centeno-González, “A Survey of Agent-Oriented Methodologies,” *Proceedings of the Fifth Int’l Workshop on Agent Theories, Architectures, and Language (ATAL-98)*, 1998, pp. 317-330.

[8] D. Kinny, M. Georgeff, and A. Rao, “A Methodology and Modeling Technique for Systems of BDI Agents,” *Tech. Rep. 58*, Australian Artificial Intelligence Institute, Melbourne, Australia, Jan. 1996.

[9] T. Murata, “Petri Nets: Properties, Analysis and Applications,” *Proceedings of the IEEE*, 77(4): 541-580, April 1989.

[10] A. Perkusich and J. de Figueiredo, “G-Nets: A Petri Net Based Approach for Logical and Timing Analysis of Complex Software Systems,” *Journal of Systems and Software*, 39(1): 39–59, 1997.

[11] Haiping Xu and Sol M. Shatz, “Extending G-Nets to Support Inheritance Modeling in Concurrent Object-Oriented Design,” *Proceedings of the IEEE Int’l Conf. on Systems, Man, and Cybernetics (SMC 2000)*, October 2000, Nashville, Tennessee, USA, pp. 3128-3133.

[12] J. Odell, H. Parunak, B. Bauer, “Representing Agent Interaction Protocols in UML,” *ICSE 2000 Workshop on Agent-Oriented Software Engineering (AOSE-2000)*, June 10, 2000, Limerick, Ireland.