Virtual Computational Field-Based Multiagent Systems: A Conceptual View

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Abstract: This pioneering work aims to present a conceptually new approach for simulating local and global behavioral patterns observed in the information-rich social networks. The main proposed novelties cover (i) a virtual computational field (VCF) approach, (ii) an oscillating agent’s model (OAM), and (iii) an agents’ wave-like interaction mechanism (WIM). This paper, however, concentrates more on the VCF approach, which constructs a virtual medium for information and resources exchange between heterogeneous agents. A new simulation paradigm offers some effective methods to transform multidimensional factor space (representing a multiplicity of phenomenal forms and interactions) into the most universal spectral coding system. In fact, not only the communication mechanism but also the social agents themselves are simulated as oscillating processes. They are represented in the form of unique spectra. In sum, current research shows, that the integration of VCF, OAM and WIM in a coherent spectrum based simulation platform gives researches a universal tool for simulation of complex social behavioral patterns like competition, cooperation, clustering, self-organization, social emergence, evolving behavioral strategies etc.

Key-Words: Multiagent systems, Virtual computational field, Oscillating agent, Spectral coding

1 Introduction

Much research is concerned with the appropriateness of traditional research approaches and methodologies in the social research domain. There is a growing suspicion that the main hindrances are hidden in modern social processes, which are badly modeled using traditional top-down approaches. In reality, with the advent of the new information society, we are increasingly dealing with some modern social phenomena like the network economy, globalization, e-commerce, non-equilibrium dynamics, complex social emergence, predominance of intangible (informational) goods, generative micro-macro relations etc.

There is fast growing empirical literature on multi-agent systems (MAS), which are used to model social phenomena from the bottom up, like agent-based hybrid intelligent systems [1], agent-based computational modeling [2, 3], agent-based simulation from modeling to real-world applications [4], generative social science [5], agent-based computational economics [6] etc.

Notwithstanding some advances in the use of multi-agent systems, MAS promises were not fully realized for a number of reasons, as it is a truism in the field that the key problems are hiding not only in the agents themselves, but also in the way they communicate, interact and interpret behavioral information available in social markets. This adds a whole new layer of complexity as we see it in the most complex social networks today (e.g. financial markets) [7].

These are highly heterogeneous information networks with many links and complex interrelations. Uncoupled and indirect interactions among agents require the capability of affecting and perceiving broadcasted information context. Therefore, the author proposes to model the information network as a virtual information field, where each network node receives pervasive information field values. Such a model gives appropriate means to enforce indirect and uncoupled (contextual) interactions among agents. It is expressive enough to represent contextual broadcasted information in a form locally accessible and immediately usable by network agents.

One of the closest examples in this area is amorphous computing [8]. Another interesting proposal in that direction is the Multilayered Multi Agent Situated System (MMASS), which defines a formal and computational framework relying on a...
layered environmental abstraction [9]. MMASS was related to the simulation of artificial societies and social phenomena for which the physical layers of the environment were also virtual spatial abstractions. In the last decade, a number of other field-based approaches have been introduced like Gradient Routing (GRAD), Directed Diffusion, “Co-Fields” at TOTA Programming Model, CONRO, etc [10].

In fact, almost all proposed systems are either employed for various technological or robotic applications and very few of them like MMASS, Agent-Based Computational Demography (ABCD) or Agent-Based Computational Economics (ACE) [10]. The conceptual as well as empirical study described in the following sections seeks to shed new light on the fact that there is a conceptually new way of simulating the complex social processes taking place in an information economy. In short, this current study proposes a virtual information field-based communication model in which informational processes are modeled on the virtual computational lattice.

To the author’s knowledge, the closest match to this proposed idea is explored by Mamei and Zambonelli in their study “Field-based coordination for pervasive multi-agent systems” [10]. They have been trying to achieve coordination for multi robotic applications by means of the VCF (virtual computational field) approach. This is an example of how engineers are starting to understand that, to construct self-organizing and adaptive systems, it may be more appropriate to focus on the engineering of proper interaction mechanisms for components of the system rather than on the engineering of their overall system architecture.

As a matter of fact, effective communication stands among the top most important issues in MAS (multiagent systems) implementations [2, 4]. Contractual based handshaking between two agents shapes peer-to-peer communication in today’s MAS systems. Peer-to-peer communication occurs when 1) the connection between sender and receiver is bonded in time and space, 2) two agents exchange ontologically classified semantic information by using a common communication protocol or a matchmaking agent. This approach is not so effective in the complex social networks where the agents’ direct and coupled “peer-to-peer” communication model is pushed aside by other noncoupled, indirect or contextual communication mechanisms.

One obvious example can be seen in modern telecommunication networks, where peer-to-peer connection protocols are no longer prevalent. This happens mainly because they are not efficient enough for multitasking, parallel processing, congested traffic control, conflict resolution etc [11].

Not accidentally, there is a striking structural similarity between modern telecommunications and social networks. In fact, the main information traffic in social networks flows through telecommunications networks, which act as a backbone of the modern network-based information economy.

In fact, the information era has shaped efficient protocols for complex information traffic in the telecommunication networks, where (i) each agent can instantly send and receive information simultaneously through multiple communications channels, (ii) information flows are locally managed by the agent’s preferences as if having the ability to “tune” to different broadcasting channels, (iii) agents became processing, storing and retransmitting nodes in the social networks [12]. After all, it does seem like we are immersed in emanating fields of virtual information. The intriguing conceptual question we want to raise for discussion below is whether there is an acceptable way of simulating complex social network phenomena using universal spectral frequency representation.

The remainder of this paper is organized as follows. Section 2 briefly discusses the conceptual outline and major assumptions. Section 3 introduces the virtual computational field concept. Section 4 briefly describes the wave-like interaction mechanism (WIM) and oscillating agent model (OAM). Section 5 is the conclusion.

2 The Scope: Conceptual Outline and Major Assumptions
Following the analogy of telecommunication systems, we assume that the same principles of reductionism and universality should be applied to MAS simulating platforms in the social domain, too. In other words, communication by agents should operate not in the (peer-to-peer) vector-based multidimensional semantic space, but rather directly in the form of multimodal energy (spectra) emanated and absorbed over the social network. The flow of energy (and associated with it, information) in the form of fields, however, requires a somewhat different understanding of the agent’s role and their interaction mechanism.

In fact, for efficient functioning, agents have to possess a sensor type receptive mechanism to be attuned to the specific information emitted from the sources they are interested in. In fact, there is no other way to deal with the large amount of different information currently flowing in the information networks. In some sense, agents must employ information filters to be receptive or not to the different information flows.

From the discussion above it is important to note that for the different kinds of information flowing in the social network we can ascribe separate spectral bands. The resulting spectrum will identify all types of information available on the network. Hence, we assume that spectra represent information in the form of vibrations or waves spreading in the shape of fields. This is the essence of the proposed virtual computational field (VCF) approach.

The evident and useful features of such a representation are i) the superposition principle, ii) an immense capacity to store different kinds of information, and iii) the property to convey associated energy, which is the fundamental resource. With spectra representation we can simulate the multi-agent environment immersed in fields of heterogeneous information.

Indeed, the frequency domain, is the only suitable medium for the representation of the infinite information flow. Arbitrarily chosen specific information could be represented as a single band in the frequency spectrum, while more sophisticated information could be represented as a set of bands (a unique composition of frequencies [13]). Therefore, the frequency domain is a universal means of storing agents’ behavioral information and energy accordingly. We only need to find out how phenomenal objects and their interaction mechanisms can be represented in frequency terms.

In fact, agents store some internal information which should also be coded in spectral terms. Following this line of reasoning, we can imagine each agent as a set of internal frequencies which resonate if triggered by external coherent frequencies. The resonating frequencies can then be transferred to other frequencies following the agent’s internal production rules. These rules should be characteristic for each agent. They govern the agent’s behavior.

In fact, agents act like resonators attuned to absorb and emit different sets of frequencies depending on their behavioral strategy. In other words, our proposed model is based upon several major assumptions:

1. The virtual computational field (VCF) is composed of a set frequencies acting like as a medium for information exchange, and at the same time VCF is the major energy resource (networking information is the major resource in the proposed information economy model).

2. The agent is an active process taking place in the network of information and energy exchange. The agent absorbs and emits information (i.e. corresponding frequency bands) depending on the internal production rules.

3. The agent’s efficiency depends how close his behavioral pattern is to the targeted performance criteria (e.g. acquired wealth in the stock market etc).

4. The difference between a chosen agent’s emitted and absorbed energy (coming from the other agent), if positive is transferred to the other agent or else is absorbed from the other agent. Following this logic, an agent’s incoherent performance leads to the gradual radiation of internal resources (energy) without replenishment.

5. If an agent is successful, other neighboring agents on the virtual grid will adopt for a certain “price” (i.e. energy) his behavioral strategy. The agent’s welfare directly depends on how many other agents have adopted (absorbed) and enforcedly retransmitted information about his successful behavioral features.

The whole MAS may be modeled as a closed or open system depending on whether the law of conservation of energy is applied or not. In the latter case, the system may be rewarded if some global coherence level is met.

In summary, for the effective implementation of spectra as a universal energy-information warehouse, we first have to transform all tangible objects-resources into their energy equivalents and then interrelate different types of energy as intangible information stored in the form of corresponding sets of spectral bands. The reasoning behind this is based on the principle of reductionism and universality as we are looking for the most
universal means to reduce a multiplicity of forms into a singularity of content.

Thus, agents are processes, which exchange multimodal energy depending on the information they have. We assume that agents are rule-based, input-output reactive systems without explicit abstract reasoning. Changing an agent’s behavior means modifying its characteristic parameters in the behavioral rule set.

3 Virtual Computational Field (VCF)

This section gives brief VCF outlines which are designed for (i) the construction of virtual media for information and resources (associated energy) exchange and (ii) the quantization of agents’ internal states.

In a certain sense, we are designing a universal energy-information state space model for the social systems, see Fig. 1. All possible states are coded as unique oscillations in the frequency spectra

$$\text{MA}$$ simulation platform and some initial results for the current research project, using investment market case, are available via our virtual lab (http://vlab.vva.lt/ma/). Very limited scope of this paper does not allow elaborate deeper on the current research results. Therefore, we will only discuss some ideas about formal approach below.

Most relevant model for VCF is adapted from physics using harmonic oscillators, where energy quantum for elastic wave

$$E = \hbar \cdot \nu$$

In the proposed VCF approach, fields are operating on the rectangular lattice $G_{N,M}$ consisting from a set $\Omega_{N,M}$ of virtual nodes (we assume that nodes are distributed evenly on the lattice). Size of the lattice $N \times M$ is arbitrary. All resources $\{R_i\}$ and agents $\{A_j\}$ are distributed only on these nodes, see Fig. 2. Each particular node $\Omega_{n,m}$ represents a point on virtual lattice space ($n \in N, m \in M$), which functions are 1) for discrete time intervals to evaluate incoming fields and produce corresponding spectra representations, 2) to oscillate at own fixed natural frequency $\nu_{n,m}$ emanating it to the surrounding VCF.

In order to reduce computations, resulting spectrums are evaluated only for nonempty nodes. Any node can be occupied either by agent from the set $\{A_j\}$ or by resource from the set $\{R_i\}$. Each agent and resource has own natural oscillation frequency $\nu_{n,m}^A$ and $\nu_{n,m}^R$ correspondingly. Field intensities are decreasing according to the $D^{-2}$ or similar negative power law, where $D$ represents distance from the emanating source measured in virtual space using relative units.

$$\text{Fig. 1}$$

The principle of quantization of energy-information states for social agents having an analogy to the rotational-vibrational states of diatomic molecular model (where $k$ – the rotational quantum number and $h$ – the vibrational quantum number).

In our proposed state space model, an arbitrary number of possible states for a given social system can be easily coded and decoded. Afterwards, with such a universal coding system we can create a set of conditions and rules for transitions between different energy-information levels.

In fact, we only need a couple of quantum numbers to describe an infinitely large pool of states and transitions between them. We should bear in mind, however, that transitions between different energy states carry not only energy, but also information about quantum states, e. g. quantum numbers like $h$ and $k$ as it is depicted in Fig. 1.
where $\hbar$ - quantum of action.

In physics, this energy quantum is called phonon. Then the energy states $E_k$ of the harmonic oscillator are quantized using phonons

$$E_k = \hbar \cdot \nu \cdot (k + 1/2), \; k = 0, 1, 2, 3..., \quad (2)$$

where $\nu$ stands as a base frequency. We may as well rewrite Eq. 2

$$E_k = \hbar \cdot (\nu \cdot k + \nu / 2)$$

having two frequency terms $\nu \cdot k$ and $\nu / 2$. The former term gives quantized frequency $\nu_k = \nu \cdot k$ as distribution in terms of phonons. The latter term gives the lowest possible frequency $\nu_0 = \nu / 2$.

Therefore, corresponding frequency spectrum is ($\nu_0$, $3\nu_0$, $5\nu_0$...$\nu_k$$)$, where $k=0,1,2,3,...$.

However, analogy with the physical model of phonons ends here. Strictly speaking, we can’t straightforwardly to adapt a set of quantized modes of vibrations occurring in a rigid crystal lattice for the social systems. We have to design our own set of quantized modes of vibrations suitable for simulations of processes taking place in the social systems.

In our case, we want to have quantized spectrum, because we need fixed and separated frequencies allocated for different attributes (nodes, agents, resources), but instead of linear we are using natural logarithm to reduce high energy leaps at low $k$ values, shortening available frequency interval at the same time. Therefore, for the node $\Omega_{n,m}$ energy spectrum ($E \square \nu$) looks like

$$E^{n,m}_k (I^{n,m}_k, k^{n,m}, \nu^{n,m}) \sim \xi \cdot I^{n,m} \cdot \nu^{n,m} \cdot \ln(k + e), \quad (3)$$

$I^{n,m} = A^2$,

where $\xi$ - chosen scaling factor, $I$ - intensity (c.u.), $A$ - amplitude of oscillation, $\nu^{n,m}$ - first harmonic of the system of nodes, $k$ - spectrum band number, and $e= 2.71$. Having Eq. 3, we may effectively characterize each system’s spectrum in terms of distribution of $k$ (see Eq. 2 and 3)

$$D(E_k) \sim D(\nu_k) \Rightarrow D(k).$$

Actually, spectrum band number $k$, having virtual energy spectra described by Eq. (3), is the only thing we need to know in order to identify virtual nodes. Whereas, each nodes unique oscillations and corresponding spectral bands are derived by multiplying the first harmonic $\nu^{n,m}_k$ by the factor $\ln(k + e)$, which finally gives logarithmic scale for oscillations, see Fig. 1. Than $k=0$, we obtain

$$E^{n,m}_0 (\nu^{n,m}) = \xi \cdot I^{n,m} \cdot \nu^{n,m}, \quad (3)$$

which represents each node’s $\Omega_{n,m}$ unique natural oscillation energy. Hence, different nodes have distinct frequencies $\nu^{n,m}$.

There is one major difference between representation of nodes and natural resources in the VCF model. Nodes are constant attributes of the system, whereas, natural resources diminish or replenish themselves according to some time $t$ dependant functions like

$$I_R(t) = f_t \left( E^{n,m}_{R_i}(t) \right). \quad (5)$$

In the investment domain (our application domain), natural resources are productive economic sectors, regions, technologies, businesses or securities like risky shares, government bonds, options etc, which could generate capital gain or loss depending on initial model setup.

Finally, we have to discuss about agents’ spectral energy representation in the VCF. Naturally, we will adopt the same approach as for resources. Let’s assume, that agents $A_j$ radiate own group of frequencies. One unique frequency band is allocated for each agent, i.e. frequencies only are meant to identify a presents of the particular agent in the VCF.

$$E^{n,m}_{A_j} (\nu^{n,m}_j) \Rightarrow \psi \cdot I_{A_j} \cdot \nu^{n,m}_j \cdot \ln(h + e), \quad (6)$$

where $h=1,2,3...H$, $E^{n,m}_{A_j}$ - energy of the agent $A_j$ and characteristic frequency band $\nu^{n,m}_j$ (i.e. the first harmonic of agents’), $\psi$ - scaling factor, $I_{A_j}$ - emission intensity (represents quantity of the given resource) and $h$ – spectrum band number. As for nodes and resources, $h$ is the only thing we need to know in order to identify virtual agents. Each agent’s unique oscillations and corresponding spectral bands are derived by multiplying the first harmonic $\nu^{n,m}_j$ by the factor $\ln(h + e)$.

We imply that $\min E^{n,m}_{A_j} > \max E^{n,m}_{R_i}$, i.e. available intervals of frequencies for natural resources and agents don’t overlap. Hence, it means a limit for $i$ (resource spectrum band number). We also assume that agents are located on the nodes only and one node could have only one agent.

In sum, VCF approach not only allocates unique frequencies for nodes, resources and agents, but also calculates resulting spectrum for each node. Such spectrum includes all bands coming from all resources, agents and other nodes. Bands don’t
overlap as they cover different spectral zones, see Fig. 2. In addition, we assume that all oscillations are transmitted instantaneously over the whole virtual space.

4  Wave-like Interaction Mechanism (WIM)

Nodes and resources are latent objects. They can only passively emit their own unique natural frequencies in the surrounding VCF. Agents passively emit their unique identifying frequencies too, but essentially they are proactive, i.e. agents, depending on their behavioral rules (internal production instructions, see Fig. 3), are capable of absorbing, transforming and emitting different frequencies. This interactive process is twofold: (i) automatic in the form of law, which holds whenever appropriate wave-like conditions are met and (ii) personalized, i.e. it depends on the agent’s individual behavioral patterns governed by the OAM (oscillating agent model) rules, see Fig. 3.

![Fig. 3 An agent’s production rules, which govern the transformation of internal states, represented as spectra bands.](image)

Now, let’s take a look at some WIM processes:

1. **The latent (Involuntary) Emission and Absorption Process.** Each agent $A_j$ has a set $\{\omega_{A_j}\}$ of natural frequencies. At these frequencies, even small incoming periodic oscillations can produce an agent’s automatic response in the form of high-amplitude outgoing vibrations because an agent (like other physical systems) transforms and stores incoming other vibration energy in the form of natural or resonant frequencies. If resonant frequencies trigger an agent from outside, his natural stored energy is gradually released to the VCF.

   The general rule of thumb for the agent’s involuntary WIM with surrounding VCF is:

   a) if outside frequencies $f$ coincide with the agent’s natural frequencies $\omega_{A_j}$ then the change in the agent’s internal energy for period $T$ is negative $\Delta E^T_{\text{abs}} < 0$, i.e. a responsive natural emission is taking place and agent is loosing stored energy or

   b) if outside frequencies $f$ do not coincide with the agent’s natural frequencies $\omega_{A_j}$, then the change in the agent’s internal energy for period $T$ is positive $\Delta E^T_{\text{abs}} > 0$, i.e. latent absorption by agent is taking place

   $\Delta E^T = \Delta E^f_{\text{abs}} - \Delta E^\omega_{\text{emi}} = \begin{cases} < 0, & \text{if } f = \omega_{A_j} \\ > 0, & \text{if } f \neq \omega_{A_j} \end{cases}$

   where $\Delta E^f_{\text{abs}}$ - agent’s absorbed energy, $\Delta E^\omega_{\text{emi}}$ - agent’s emitted energy.

   For the agent $A_j$ absorbed energy is stored as natural energy in the agent’s natural frequencies spectral range $\{\omega_{A_j}\}$

   $\sum T \Delta E^T_{\text{abs}}_{j, \mu(f = w_{A_j})} \rightarrow \text{stored natural energy}$  \hspace{1cm} (8)

   where function $\mu(f \Rightarrow w_{A_j})$ denotes transformation of incoming frequencies $f$ to the natural frequencies $\omega_{A_j}$. Then the agent’s internal stored spectral energy (see Eq. 6)

   $E^T_{A_j}(\nu_{A_j}^{n,m}) = \sum_{h=0}^{H} \sum_{T} E^h_{A_j}(\nu_{A_j}^{n,m}) = \sum_{h=0}^{H} \psi \cdot I_{A_j} \cdot \nu_{A_j}^{n,m} \cdot \ln(h + n)$

   \hspace{1cm} (9)

2. **The Active (Voluntary) Emission and Absorption Process.** Agents have a mechanism to look for meaningful information in the surrounding VCF. They inherit this property from individual behavioral rules.

   Acquiring meaningful (successful) information means adopting a new behavioral pattern. This comes at a price, however. For instance, let us say agent $A_1$ wants to buy information $P$ (where $P$ stands for the agent’s $A_2$ behavioral parameters set) paying some amount of his own capital $K$ (equivalent to the energy $E^m_{K}(\nu_{K}^{n,m})$, where $K \in R_i$) to the selling agent $A_2$
\[ E_{A_i}^{emi}(\nu_K) \Rightarrow E_{A_i}^{abs}(\nu_K) \]  
\[ E_{A_i}^{abs}(\nu_p) \Leftarrow E_{A_i}^{emi}(\nu_p) \]  
\begin{equation}
\Delta E_{A_i}(P \rightarrow K) = E_{A_i}^{abs}(\nu_p) - E_{A_i}^{emi}(\nu_K) < 0, \\
\Delta E_{A_i}(K \rightarrow P) = E_{A_i}^{abs}(\nu_K) - E_{A_i}^{emi}(\nu_p) > 0, \\
\Delta E_{A_i}(P \rightarrow K) + \Delta E_{A_i}(K \rightarrow P) = 0. \tag{11}
\end{equation}

where

The agent’s efficiency depends on its spectral coherence with the global criteria (e.g. market rules) which specify some spectrum measures like minimum internal energy (e.g. available capital etc) needed for survival. Extremely coherent agents can be rewarded, while extremely incoherent agents (i.e. corresponding investment strategies in the current application case) are removed from the simulation process.

5 Conclusions
This conceptual work presents a new approach for simulating behavioral patterns observed in the information-rich social networks. This proposed VCF approach constructs a virtual medium for information and resources exchange between heterogeneous agents.

In summary, current research shows that the integration of VCF, OAM and WIM in a coherent spectrum based simulation platform gives researchers a universal tool for simulation of complex social behavioral patterns like competition, cooperation, clustering, self-organization, social emergence, evolving behavioral strategies etc. An initial investment market simulation study shows (http://vlab.vva.lt/mas/), that not only communication mechanism, but also social agents themselves can be simulated as oscillating processes (represented in the form of unique spectra).

Like all pioneering approaches, this study needs thorough further investigation and experimentation. The author is at pains to emphasize that his current findings, presented above, can only be interpreted as an initial first ‘take’ on the simulation of social phenomena using the VCF approach. This work, however, gives some clear outlines and their explanatory sources.

References: