Proposal for an ARC INRIA

POPEYE: POPulations, gamE theorY and Evolution

1 Executive Summary

Title Populations, Game Theory and Evolution

Acronym POPEYE

Summary This proposal focuses on the behavior of large complex systems that involve interactions among one or more populations. By "population" we mean a large set of individuals, that may be modeled as individual agents, but that we will often model as consisting of a continuum of non-atomic agents.

The project brings together researchers from different disciplines: computer science and network engineering, applied mathematics and economics, and biology.

This interdisciplinary collaborative research aims at developing *new theoretical tools* as well as at their *applications* to dynamic and spatial aspects of populations that arise in various disciplines, with a particular focus on biology and networking.

The work within this ARC is expected to contribute to several INRIA's strategic directions, such as:[1] Modeling and optimization of complex dynamical systems, Autonomous communication infrastructure, Numerical biosphere and environment.

The research will include the study of: models of population dynamics, both stochastic and deterministic; estimation problems of sizes of population; the dynamic control of populations and the competitive interaction and evolution of populations. For this last aspect, the central tool will be the concept of evolutionary games introduced by biologists.

In addition to advances in the underlying theories, the expected results of this project are new methods for, on the biological side, the control of populations of pests, and on the networking side, the control of routing, power consumption and other parameters.

2 Objectives and Challenges

General reasons for creating this collaboration are as follows:

1. Several groups at INRIA have recently became interested in the use of *population models* and *game-theoretical tools* for the understanding the dynamics of complex communication networks and the design of novel methods for controlling them.

   The scientific rationale for this is that, as communication networks grow in size and complexity, their behavior may become mostly governed by the *interaction* between "entities" (users, protocols, services, etc.), in the manner of biological systems.

2. Population models have been used in Science for a very long time. Game theory has also been used for a long time in the fields of Biology and Economics for describing the interaction of "agents" or populations seeking to improve their welfare.

3. Yet, most of the theoretical tools in population dynamics and control as well as the experience in applying them to complex systems in biology have not been exploited in applications in computer

[1] Proposed themes for INRIA's 2008-2012 strategic plan.

science and engineering, although the former seem to be well adapted to many novel applications (such as auto-tuning in large networks, autonomous mobile ad-hoc and sensor networks).

4. The proposed project has been designed so as to bring together specialists of the various aspects of the theory and the applications, suscitate cross fertilization between different application fields, and enhance interaction between theory, application models and experimentation (both in biology as well as in networking).

We list the following scientific objectives and challenges for this proposal:

1. Create new theoretical tools in the areas of (i) population dynamics and its control, (ii) spatial aspects of populations, (iii) competition between populations.
2. Create new collaborations and enhance existing ones between mathematicians, computer scientists and biologists in order to improve methods for controlling parasite populations and plants that they attack.
3. Create collaborations between researchers in networking and biologists in order to strengthen the recent activity in INRIA Sophia-Antipolis-Méditerranée that aims at applying methodologies from complex biological systems to design protocols for complex communication networks. So far this activity has been carried within the Bionets European project EU-IST-FP6-FET-SAC-027748 in which, however, biologists do not participate.

3 Description of Scientific Activities

We describe below the main novel tools that will be used in the proposed project along with the technological context that requires these new tools. Participants to the proposed collaboration will not only use these tools but will also develop them when needed.

3.1 Branching processes and other models for population dynamics

Branching processes are an important tool for the study of evolution of population sizes as well as of phenomena of stability, growth or extinction of populations. Branching processes find their origins in Demography with the work of Bienaymé [6] and Galton and Watson [13]. In the last twenty years, branching processes have been discovered to govern the dynamics of many queueing models arising in computer and communication networks. We plan to design a system theory for branching theory that includes filtering and estimation of the population sizes based on noisy measurements, as well as control of branching processes. We plan to do so not only in the discrete framework but also in that of continuous branching processes (CBP) [18] (an example is the station times in polling systems [4]), which we have recently extended to the multi-type setting with non Markovian migration [2].

Branching processes also have importants implications in the biological theory of adaptive dynamics, which original goal is to study the long-term evolution of populations with explicit ecological interactions. This theory has a game-theoretical foundation [15] that extends the notion of ESS to cases where several strategies can coexist. For general multitype branching processes models with interaction and mutations, this led to the introduction of the concept of evolutionary branching [19], which corresponds to the transition from a monotype population to a stable multitype one. The mathematical validation of this theory has been started in [7] and we plan to progress in this task. These models were originally designed for the study of the evolution of populations. However, they can be easily transposed to spatial population models, in which case evolutionary branching can be interpreted as spatial specialization, clustering or aggregation. Some examples have already been studied in [8] and we plan to develop the applications of the theory of adaptive dynamics to spatial problems. Applications of this theory to network problems can also be developped in situations where one wants to force the coexistence of several strategies in the network.

We will also investigate other stochastic models of population dynamics, based on paradigms such as "preferential attachment" models [20] in which the interaction between populations occurs essentially through their respective sizes. In this setting as well, we shall look for asymptotic properties, fluid limits (and the associated deterministic dynamical processes) as well as for analytical properties and closed-form solutions for moments and distributions.

3.2 Spatial population models and routing in wireless networks

Ad hoc networks, which is an emerging technology in telecommunication networks, have a tremendous potential in disaster management, dense wireless sensor networks, and other security applications.

In order to design and to study protocols in such networks it is useful to identify information packets with similar characteristics (same source and destination, same size etc) as belonging to a common "population". Packets of this population must choose routes in the network, and every population has the same problem.

When the network is "massively dense" in the sense that the number of nodes and links in a given area becomes very large, it becomes possible to use a continuous approximation, in which the available routes are all continuous paths with "costs" depending on their location and the local level of congestion. There are indications from previous research that in many cases, computations in the limit model are simpler than in the original discrete model.

To tackle such limit models and their spatial properties, new tools have been recently imported from other disciplines. Pioneering works in that area have used tools from geometrical optics [17] and from electrostatics [16, 22]. Some tools are also available in the area of road traffic engineering [5, 9] for the study of the competitive interactions among populations of drivers in their choices of routes.

Within this project, we will further develop the theory of such spatial models and apply them to the design of routing protocols in massively dense ad-hoc networks. We will consider the case of a global optimal (Pareto-efficient) solution as well the non-cooperative approach among a large population of users. In the latter, each user seeks a path from its source to a destination so as to minimize its individual cost. Along with the model of the continuous limit, we shall investigate approaches to compute the routing in that limit. We shall investigate how good do the routing policies, obtained for the limit model, perform for the original discrete model. We have obtained preliminary results restricted to rectangular areas and to transmission in the horizontal or vertical directions in [1].

3.3 Models for competition between populations

3.3.1 Evolutionary games

Evolutionary games are well adapted to describe competition situations between large populations. Founded by biologists to explain past evolution and to predict future evolution of species, and adopted since by Economists [23], the evolutionary game paradigm has several properties that makes it appealing to study competition in large complex systems, both in biology and in engineering. The solution concept for the competitive optimization, called ESS (Evolutionary Stable Strategy) is defined as a policy distribution among individuals such that a small mutation in the population that uses another policy cannot invade the existing populations: their "fitness" (or utility) is smaller than the one of the remaining population. This solution concept is quite appealing, since it is robust against a deviation of a whole fraction of the population, unlike the Nash equilibrium concept that is robust against deviation of a single user only. A second central concept of evolutionary games is the replicator dynamics that models the time evolution of interacting populations; accordingly, a behavior that gives a higher fitness will be adopted by a growing number of individuals. The advantage of this evolutionary dynamic concept is that it allows to study the convergence to the equilibrium as well as cases when there is no convergence.

Our objectives in the work on evolutionary games are:

(i) Create a new theory of stochastic evolutionary games where an individual can take several decisions during its life time, and by adding states such that the decisions taken by individuals affect not only their current reward (fitness) but also the transition probabilities to the next state. We shall use this framework to study power control for mobile communicating devices. Some preliminary results have been obtained in [3].

(ii) Study evolutionary games with an infinite action space. The study of continuous action space often allows to simplify the study of ESS with respect to the case of finite (but large) action space. On the other hand there are basic open problems concerning the convergence of the replicator dynamics in this setting.

(iii) Use evolutionary games not only to explain past and future evolution, as was done initially in the biological context but also as an engineering design tool for a framework for evolution of protocols and services. Some preliminary results have been obtained in [21].

(iv) Work on problems of parasites that attack plants, and ways to control them by introducing a secondary population of parasites (parasitoids) that attack the pests. We shall study evolutionary game models that allow us to understand the interaction between all three protagonists so as to better control pests.

A particular challenge within this project will be to use evolutionary games not only as a purely descriptive tool, but also as a predictive tool.

3.3.2 Dynamic conjectural variations equilibria

Conjectural Variations Equilibria (CVE) are a game-theoretic model in which agents compensate their lack of information by forming an internal representation of the opponent's behavior and preferences, and using these "conjectured responses" in their personal optimization program. There exist static as well as dynamics versions of these equilibria [11]. CVE have been defined and studied in Economics, but have since interested researchers from the fields of Artificial Intelligence and Automated Learning.

It has been proved recently in [10] in particular cases that CVE and ESS may coincide. On the other hand, it is known that among the possible CVE, there exist Pareto-Optimal configurations. It has been shown that adjustment processes based on conjectures and individual optimization may sometimes be driven to Pareto-Optimality [12]. There is therefore a possibility of cross-fertilization between the two concepts: ESS and CVE.

We plan to investigate this relationships between ESS, static or dynamic conjectural variations equilibria, and Pareto-Optimal issues of games. Our global objective will be to define convergent dynamic adaptation schemes and/or incentive mechanisms which are apt at driving distributed systems towards *efficient* stable configurations.

4 Expected Results

The interaction between participants of the ARC is expected to create joint inter-disciplinary research and produce the following results.

Concerning methodological advances (development of the theoretical paradigms themselves), some expected results are:

- the development of a new stochastic evolutionary theory, and an improved understanding of the connections between stochastic models and their deterministic limits;
- a new system theory for branching processes that includes also filtering and control of these processes;
- the developement of spatial models for population competition as described in Section 3.2.

Concerning the central application to biology, that is, the control of pests through the introduction of parasitoids:

- a model allowing to optimize the amount of parasitoids to be used, as well as the timing and location for their introduction.

Concerning the central applications to networking, that is, the study of protocols and services for the Internet, sensor and ad-hoc networks, we shall:

- obtain models that will allow us to describe the past evolution and predict the future evolution of network protocols, applications and services;
- design mechanisms and come up with guidelines for features in networks that will support the autonomous *evolution and adaptation* of protocols, applications and services;
- design adaptive routing and relaying strategies for sensor networks; criteria that will be taken into account are related to energy consumption, the density of nodes needed for carrying the required amount of flow, and cost related the lifetime of the network.

5 Participants

The list of participating laboratories and names of researchers is given below. The role of each in the project follows. A more detailed description of research activities in each group is presented in the Appendix.

5.1 List of participants

1. **INRIA Sophia-Antipolis (MAESTRO group)**: Eitan Altman, Alain Jean-Marie, Philippe Nain
2. **INRIA Sophia-Antipolis (TOSCA group)**: Nicolas Champagnat
3. **INRIA Grenoble (MESCAL group)**: Bruno Gaujal, Arnaud Legrand, Corinne Touati
4. **INRA - Unité Biostatistique et Processus Spatiaux, Avignon**: Denis Allard, Etienne Klein, Lionel Roques
5. **INRA - Behavioral Ecology of Insect Parasitoids, Sophia-Antipolis**: Eric Wajnberg
6. **INRA - Laboratoire Montpelliérain d'Economie Theorique et Appliquée, Montpellier**: Mabel Tidball
7. **U. Nice-Sophia-Antipolis - Ecole Polytechnique Universitaire group**: Pierre Bernhard
8. **U. Paris 6 - Combinatorics and Optimization group**: Sylvain Sorin
9. **U. Avignon - RAM (Networks and Multimedia Application) group**: Rachid El-Azouzi, Yezekael Hayel

5.2 Role of the participants

The project is interdisciplinary, and the different teams bring a different expertise on the technical tools and the applications.

- The INRIA groups MAESTRO and MESCAL and the RAM group of the LIA are specialized in networking applications. They provide their expertise in network protocols and architectures, on stochastic dynamic models for these networks, including control-theoretic and game-theoretic models.
- The INRA groups of Sophia-Antipolis and Avignon are specialized in biological applications, and provide their expertise on the modeling of actual population interactions as well as their field experience and data. The group of Sophia-Antipolis will lead the application to pest control. The group of Avignon will contribute its expertise in methods for spatial processes.
- The EP-UNSA group and the INRA group of Montpellier are specialized in the mathematics of automatic control and game theory and their applications, in particular to populations dynamics in biology or economics.

- The Combinatorics and Optimization group of Paris 6 and the TOSCA group of INRIA are specialized in the mathematics of stochastic dynamic systems such as stochastic games or interacting particle systems. They will provide the high-level tools necessary for discussing fluid limits of large-population stochastic systems, studying convergence properties etc.

The teams have a previous experience of work in common which guarantees a quick start of the activities within this project, as well as the chances of a scientific output.

MAESTRO, MESCAL and RAM have shared researchers in the past and are presently engaged in joint projects funded by the European Community or the ANR. MAESTRO, INRA/Sophia and EP-UNSA have worked together on evolutionary models for foraging.

6 Scientific responsibility

Coordinators:

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7 Requested budget

Given the objective of the project and the nature of the participating teams, the principal financial needs are for: a) temporary researchers who will receive a pluridisciplinary training by circulating between several teams; b) support for exchange of researchers (short-term visits, workshops).

The following items are requested:

1. 10 months of a postdoctoral fellow each year: 30.7 k€per year.
2. 10 k€per year for both travel money as well as local expenses to finance mutual visits,
3. 6 k€per year for organizing a yearly workshop for all participants.
4. 2 internships (such as summer internships for Ph.D. students, or Master students interships): 9 k€.

The total is **55.7** k€per year (101.4 k€for the duration of the project).

Our plan is that each postdoc spend half of his time with one of the INRIA groups and the other half within one of the non-INRIA collaborators.

A doctoral fellowship within the CORDI framework will be sought.

References

[1] E. Altman, P. Bernhard, M. Debbah and A .Silva, "Continuum Equilibria for Routing in Dense Ad-Hoc Networks", 45th Allerton Conference on Communication, Control and Computing, Illinois, USA, Sept. 26 - Sept. 28, 2007.

[2] E. Altman and D. Fiems, "Expected waiting time in symmetric polling systems with correlated vacations", *QUESTA*, 2007.

[3] E. Altman and Y. Hayel, "A Stochastic Evolutionary Game Approach to Energy Management in a Distributed Aloha Network", to appear in *Proc. IEEE INFOCOM*, April 2008.

[4] Y. J. Aminetzah M. J. Ferguson. Exact results for nonsymmetric token ring systems. *IEEE Transactions on Communications*, 33(3):223–231, 1985.

[5] M. Beckmann, "A continuum model of transportation", *Econometrica* 20:643-660, 1952.

[6] I. J. Bienaymé. De la loi de la multiplication et de la durée des familles. *Société Philomatique de Paris, Extraits*, 5:37–29, 1845.

[7] N. Champagnat. A microscopic interpretation for adaptive dynamics trait substitution sequence models. *Stoch. Proc. Appl.*, 116:1127–1160, 2006.

[8] N. Champagnat and S. Méléard. Invasion and adaptive evolution for individual-based spatially structured populations. *J. Math. Biol.*, 55:147–188, 2007.

[9] S.C. Dafermos, "Continuum Modeling of Transportation Networks", *Transpn Res.* Vol. 14B, pp 295–301, 1980.

[10] H.D. Dixon and E. Somma, "The evolution of consistent conjectures", *J. Econ. Behav. Organ.*, Vol. 51, pp. 523–536, 2003.

[11] C. Figuières and A. Jean-Marie and N. Quérou and M. Tidball, *Theory of Conjectural Variations*, World Scientific Publishing, 2004.

[12] C. Figuières and A. Jean-Marie and M. Tidball, "On the Effects of Conjectures in a Strategic Setting", *Ricerche Economiche/Research in Economics*, Vol. 58 (1), pp. 75–102, 2004.

[13] F. Galton and H. W. Watson. On the probability of the extinction of the families. *Journal of the Royal Anthropological Institute*, 4:138–144, 1874.

[14] F. Hamelin, P. Bernhard, P. Nain and E. Wajnberg, "Foreaging under competition: evolutionarily stable patch-leaving strategies with random arrival times. 1. Scramble competition", *Advances in Dynamic Game Theory*, Annals of the International Society of Dynamic Games, Vol. 9, pp. 327–348, 2007.

[15] J. Hofbauer and K. Sigmund, "Adaptive dynamics and evolutionary stability", Appl. Math. Lett. 3:75–79, 1990.

[16] E. Hyytia and J. Virtamo, "On load balancing in a dense wireless multihop network", *Proc. of the 2nd EuroNGI conference on Next Generation Internet Design and Engineering*, Valencia, Spain, April 2006.

[17] P. Jacquet, "Geometry of information propagation in massively dense ad hoc networks", in *MobiHoc '04: Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing*, New York, NY, USA, 2004, pp. 157–162, ACM Press.

[18] A. Lambert. The genealogy of continuous-state branching processes with immigration. *Probability Theory and Related Fields*, 122(1):42–70, 2002.

[19] J.A.J. Metz, S.A.H. Geritz, G. Meszéna, F.A.J. Jacobs, and J.S. van Heerwaarden. Adaptive Dynamics, a geometrical study of the consequences of nearly faithful reproduction. In: van Strien, S.J., Verduyn Lunel, S.M. (Eds.), Stochastic and Spatial Structures of Dynamical Systems. North Holland, Amsterdam, 1996, pp. 183–231.

[20] H.A. Simon, "On a Class of Skew Distribution Functions", *Biometrika*, Vol. 42, No. 3/4, pp. 425-440, 1955.

[21] H. Tembine, E. Altman and R. El-Azouzi, "Delayed Evolutionary Game Dynamics applied to the Medium Access Control", *A Workshop on Socially and Biologically Inspired Wired and Wireless Networks (BIONETWORKS)*, Pisa, Italy (In Conjunction with the 4th IEEE International Conference on Mobile Ad-Hoc and Sensor Systems MASS 2007).

[22] S. Toumpis, "Optimal design and operation of massively dense wireless networks: or how to solve 21st century problems using 19th century mathematics", in *Interperf '06: Proc. the 2006 workshop on Interdisciplinary systems approach in performance evaluation and design of computer & communications systems*, New York, NY, USA, 2006, p. 7, ACM Press.

[23] J. Weibull, *Evolutionary Game Theory*, The MIT Press, Cambridge, MA, 1995.

A Appendix: More details on some of the groups

A.1 MAESTRO group, INRIA

MAESTRO is a joint project-team with LIRMM (University of Montpellier II and CNRS).[2]

The project-team is concerned with the modeling, performance evaluation, optimization and control of discrete-event dynamical systems (DEDS), with a particular emphasis on networks and their applications. The scientific contributions are both theoretical, with the development of new modeling formalisms, and applied with the development of software tools for the performance evaluation of DEDS. Research themes The research activities are organized around, in particular, the following themes:

- Wireless communications (satellite/cellular/local area networks)
- Multiagent optimization in networking (fairness, theory of cooperative games, competition between agents)
- Theory of discrete-event systems (trafic modeling, queueing theory, real-time system analysis, ...)
- Control of stochastic processes (singular perturbations, Markov decision theory, ...).

The members of MAESTRO have a long lasting collaboration with several groups at France Telecom R&D. The ongoing cooperations bear on the analysis of resource allocation strategies in UMTS networks and on the analysis of traffic in IP networks.

The project is a member of the Network of Excellence EuroNGI and is involved in several international scientific cooperations (The Netherlands within a Van Gogh project, Israël (Arc-En-Ciel project), United Kingdom (British Council), Russia (Institut Lyapounov), USA (NSF ITR), ...).

A.2 MESCAL group, INRIA

The MESCAL (Middleware Efficiently SCALable) project is a joined team of INRIA and the LIG laboratory (Grenoble). The goal of MESCAL is to design software solutions for efficient exploitation of large distributed architectures of metropolitan, national or international scale. Main target applications are intensive scientific computations. The methodology used by MESCAL members is based on stochastic modelling of large discrete event systems, performance evaluation and simulation of large deterministic and probabilistic systems, middleware design, distributed systems, game theory and multi-criteria optimization.

Our main academic collaborations include: Universiteit Leiden (Netherlands), North Carolina State University (USA), Universidade Federal do Rio Grande do Sul (Brazil), Pontifícia Universidade Católica do Rio Grande do Sul (Brazil), University of California at San Diego, University of Hawaii at Manoa.

Our industrial partners include: Bull, France Telecom R&D, Mandriva, Total, Icatis, CEA, BRGM, ST Microelectronics.

A.3 TOSCA group, INRIA

TOSCA (TO Simulate and CAlibrate stochastic models) is a joint project-team between INRIA and the University Henri Poincaré, CNRS, University Nancy 2 and INPL, located in the Institut Elie Cartan (IECN) in Nancy and in the Centre de Recherche INRIA of Sophia-Antipolis-Méditerranée. The TOSCA Project-Team is a follow-up of the OMEGA Research-Team that ended on December 2006.

Our objective is to develop calibration and simulation methods for general Stochastic Differential Equations whose coefficients and boundary conditions have the singularities which are imposed by Physics or Finance. These singularities make the stochastic equations hard to discretize and estimate.

Using our knowledge on the stochastic integration theory we work on models of interest for the physicists, biologists, engineers, etc., with whom we collaborate. Our research includes the development of softwares and numerical experiments. Among our research themes:

[2] The association process is currently under way.

- Transverse problems:
  - Long time simulations for nonlinear PDEs.
  - Simulations of multivalued models.
  - Variance reduction techniques.
  - Stochastic partial differential equations.
- Stochastic models in Neurosciences and Biology
- Stochastic models in Finance
- Stochastic models in Fluid Mechanics and Meteorology
- Stochastic models in Chemical Kinetics

A.4 INRA - Unité Biostatistique et Processus Spatiaux, Avignon

L'unité de Biostatistique et Processus Spatiaux d'Avignon poursuit des recherches en statistiques spatiales et spatio-temporelles, à la fois théoriques et appliquées, avec un intérêt particulier pour les applications relevant de l'environnement, de l'écologie, de l'épidémiologie et de la biologie des populations.

Dans ce cadre, la mission de l'unité est double :

- Mener des recherches méthodologiques dans les domaines des statistiques spatiales, pour leur intérêt propre, ou pour l'intérêt de leur application dans les champs de recherche de l'institut. Citons entre autres les processus stochastiques, les champs aléatoires et la géostatistique.
- Participer avec les départements et les unités partenaires à des recherches pluridisciplinaires visant à améliorer la prise en compte de la dimension spatiale et/ou spatio-temporelle des phénomènes agronomiques, écologiques et biologiques.

Les axes principaux de recherches sont:

- Statistiques spatiales pour l'environnement
- Modèles spatiaux en biologie des populations
- Modèles informatiques et systèmes complexes

A.5 RAM Group, LIA

The Laboratoire Informatique d'Avignon is the the computer science laboratory of the University of Avignon. It covers three areas: Networking, Oral and Text Language Processing and Operations Research. LIA has a large experience on participation to, and management of cooperative projects.

The RAM (Networks and Multimedia Application) team covers the networking area. One goal of RAM is to explore the applications of game theory to analyze, design, and assess the performance of networks. The objective is to study the best practices in modeling, as well as limitations of game theory as a performance assessment and design tool for networks. Both the application of game theory to networking problems and the development of new game-theoretic methodologies that can be applied in that context are part of our interest. Our main research activities and applications are organized around the following areas:

- Wireless communications (UMTS/WIMAX/802.11)
- Cognitive Radios in Ad hoc Wireless Networks
- VANET

- Evolutionary Games and its applications to networking
- Stochastic Games
- Network Simulation

Our main academic collaboration include : University of Pennsylvania (USA), INRIA Sophia Antipolis Méditerranée (France), Supélec (France), CNRS (France), INT Every (France), Technion (Israel), UAM (Mexico), ENST (France).

Our industrial partners are : Motorola R&D, Alcatel-Lucent, France Telecom R&D, Maroc Telecom.

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