Modeling Competition in the Telecommunications Market Based on Concepts of Population Biology

Christos Michalakelis, Thomas Sphicopoulos, *Member, IEEE*, and Dimitris Varoutas, *Member, IEEE*

***Abstract*—Based on concepts of ecology modeling and specifically on population biology, a methodology for describing a high-technology market's dynamics is developed and presented. The importance of the aforementioned methodology is its capability to estimate and forecast the degree of competition, market equilibrium, and market concentration, the latter expressed by corresponding market shares, in the high-technology environment. Evaluation of the presented methodology in the area of telecommunications led to accurate results, as compared to historical data, in a specific case study. Apart from a very good estimation of the market's behavior, this methodology presents a very good forecasting ability, which can provide valuable inputs for managerial and regulatory decisions and strategic planning, to the players of a high-technology market, described by high entry barriers.**

***Index Terms*—Competing species, ecology modeling, Lotka–Volterra model, market competition, market shares, market structure, telecommunications forecasting.**

I. Introduction

MARKET concentration had long attracted the attention of researchers. Among their main concerns is the study of the number of firms, providing a particular product, or collections of products and services [1]. Market structure plays an important role in determining market power, business behavior, and performance. This, in turn, allows the evaluation of the degree of competition in different industries. These concerns apply to the sector of high-technology products, such as telecommunications. Telecommunications were traditionally a national monopoly since a few years ago, when market liberalization took place. As a result, the initially monopolistic market, which imposes certain entry barriers, became oligopolistic, or even competitive in some cases. Studying the concentration of the new market is therefore an imperative need, in order to identify its possible peculiarities, describe competitors' behaviors and provide necessary inputs to legislation and regulation authorities [1]–[4]. In addition, valuable predictions for the future could be provided including, among others, potential entry of new providers [5], [6]. Moreover, the evolution of market concentration is of major interest for providers as well, since it is strongly related to managerial decisions, including available actions to be taken and expectations toward competition. The aforementioned are usually accompanied by heavy investments and business plans, targeting to enhance the ability of providers to meet the market's demand.

Manuscript received July 14, 2009; revised March 10, 2010 and May 31, 2010; accepted June 12, 2010. This paper was recommended by Associate Editor K. M. Sim.

The authors are with the National and Kapodistrian University of Athens, Athens 15784, Greece (e-mail: michalak@di.uoa.gr; thomas@di.uoa.gr; arkas@di.uoa.gr).

Digital Object Identifier 10.1109/TSMCC.2010.2053923

A. Research Objectives and Contribution

The main contribution of the present work is the study of the evolution of a market's structure and concentration, by adopting approaches from evolutionary theory of population biology and population dynamics. More specifically, market evolution is estimated and forecasted by applying the Lotka–Volterra model, which describes the competitive interaction of species for a common limited supply [7], [8]. Although the Lotka–Volterra models have already been used for modeling market competition and market dynamics, mainly in a duopolistic market [9]–[12], they have not been used in a setting like the one we examine here, described in detail in the following sections.

The main objective of the proposed methodology is to provide an alternative way to estimate the level of concentration of a market characterized by high entry barriers, such as telecommunications. The Lotka–Volterra model employed in this paper has been used in a number of other application areas, besides biology, providing quite accurate estimates of the described processes dynamics. In addition, the proposed methodology can be used in combination with the already established methodologies, or even as a benchmark to them, in order to verify their evaluation results.

Accomplishment of the aforementioned objectives would contribute to both research and practice, as it would provide new directions for estimating market concentration and an additional tool to be used in strategic planning. If combined with the directions, proposed in the conclusion section, they would result to the development of a framework capable of describing the different aspects and factors influencing a diffusion process, in the context of market competition and level of concentration.

B. Methodology Overview and Assumptions

As stated in [8] "Population biology has its roots in many different areas, as in taxonomy, in studies of the geographical distribution of organisms, in natural history studies of the habits and interactions between organisms and their environment, in studies of how the characteristics of organisms are inherited from one generation to the next and in theories which consider how different types of organisms are related by descent."

Thus, population dynamics is the study of marginal and long-term changes in the numbers, individual weights, and age composition of individuals in one or several populations, and biological and environmental processes influencing these changes.

The corresponding population modeling is an application of statistical models to the study of these changes in populations, as a consequence of interactions of organisms with the physical environment, with individuals of their own species (intraspecies competition), and with organisms of other species (interspecies competition). Finally, one of the most important questions population modeling seeks to answer is if competing species can coexist or not, and what are the major factors that affect coexistence.

Based on the aforementioned considerations, an obvious relationship is identified between the dynamics describing competition among species for a common source and the competition among service providers toward obtaining a greater market share from the common source of present and future adopters. Thus, the methodology developed in this paper is built upon the same assumptions that describe the behavior of competing species. Market shares, which reflect the level of concentration in a given market, are considered as species competing for a common source, the market potential in the studied case. In this way, interspecies as well as intraspecies competition can be modeled, in order to estimate the market's equilibria, i.e., the possible outcomes in the market's structure. Market shares is a quite accurate indicator for estimating the degree of competition, since they can be considered as the observed outcome of the underlying, usually noncooperative, game of the participating players—service providers. They reflect the results of managerial and strategic decisions, such as advertising, pricing policy, and quality of services. The main outcomes, which also define the importance of contribution of the proposed methodology, are the estimation of the modeled system dynamics, the provision of forecasts regarding market equilibrium, and the estimation of the level of customers' switching among providers. Evaluation of the proposed methodology was performed over historical data regarding mobile telephony diffusion in Greece (2G and 3G).

The rest of the paper is structured as follows: In Section II, a short overview of the corresponding literature regarding market competition is presented. Section III provides a short overview of the mathematical concepts of population dynamics, especially the dynamics of competing species. Based on these concepts, the development of the proposed methodology is presented in Section IV and the corresponding case study results are presented in Section V. In Section VI, the methodology's forecasting ability is evaluated and, finally, Section VII provides an overview and the conclusions of the work conducted in this paper, together with directions for future research.

II. Literature Review—Market Competition

A considerable amount of research has been carried out, focusing on describing and modeling the competitive factors and the impact of marketing mix variables, such as pricing and advertising that influence a diffusion process. Competition, in most of the cases met in literature, is based on the assumption of rationality of the participants, indicating that firms behave noncooperatively, seeking to maximize their own profits. In addition, each firm is assumed to correctly anticipate its rivals' strategies and the effects of these strategies over the firm's profits [13]. Adoption of this approach allows modeling of firms imposing different costs, demand structures, discount factors, access to market information, and planning horizons.

Although this paper does not attempt to provide a thorough review of the corresponding literature, it is worth mentioning some of the most important contributions toward capturing the dynamics of a durable goods market exhibiting competitive behavior. One of the most important contemporary efforts to describe diffusion into the context of a number of influential factors can be found in [14]. Moreover, in [15], the effect of a new entrant to an expanding market is studied, based on incorporating pertinent formulations into the Bass model [16], in order to capture the competitive effects of the market. This was followed by [17], proposing a hazard function to describe each competitor's dynamics. Similar approaches, toward modeling the interaction between competitors into a market are presented in [18]–[21]. The impact of competitive entry in a developing market in the context of dynamic pricing is analyzed in [22], where the transition from a monopolistic to an oligopolistic market is studied. Finally, in [23], the following empirical issues on entry in telecommunications are identified: the impact of regulatory delay in issuing first entry licenses on the diffusion of innovation; the preemptive, immediate, and long-term effects of additional entry licenses on the diffusion of innovation; and the distinction between simultaneous versus sequential entry.

The diffusion process of new products and market competition are not only affected by the interpersonal influence but by external factors as well, with pricing and advertising being the most important ones. Thus, apart from the aforementioned contributions, an additional number of papers is devoted to the development of methodologies that incorporate price and advertising effects into the diffusion process, such as the work presented in [24], where a generalized pricing and advertising model is developed, based on the Bass diffusion model. Into that context, an empirical analysis regarding the competitive effects in diffusion models is performed in [25]. In this paper, a typology of brand diffusion processes that describing the different cases of competition is proposed, together with formulations for accommodating marketing mix variables. The most appropriate modeling approach of this paper is selected as a benchmark model, comparing its results with the ones provided by the proposed methodology.

Additional to these, an approach regarding the way competition affects dynamic pricing of new products can be found in [13], where a pricing model incorporating dynamic and competitive effects is developed and evaluated. Optimal pricing strategies in oligopolistic markets are proposed in [26], as outcomes of a differential game model, whereas optimal pricing and advertising policies are proposed in [24], and the effect of advertising over the diffusion of long interpurchase times products is studied in [27].

The advantage of the proposed methodology against the aforementioned approaches is that the latter are mainly based on diffusion models, which are suitably transformed in order to capture the competitive effects. This is achieved by incorporating suitable parameters into the formulation of the model.

However, estimation in this kind of models is usually performed in two steps. First, the market potential of each market player is estimated, which is in turn used into the system of equations in order to capture the competitive effects. In the proposed approach parameter estimation is performed in one step. Moreover, the construction of the model allows the estimation of the "churn effect," the switching of users among the providers, which constitutes important information regarding competition. The aforementioned, together with the employment of the genetic algorithms (GAs) to estimate the parameter values, constitute the innovation and the contribution of the present work.

III. Population Dynamics—Competing Species

The hypothesis concerning the variation of population is that the rate of its change is proportional to the current size of the population and the most common approach for modeling population growth of a species, in the absence of any competitors is given by [8] and [28]

$$\frac{dN(t)}{dt} = rN(t)\left(1 - \frac{N(t)}{K}\right) \tag{1}$$

where $N(t)$ is the size of population at time t, the constant r is the growth rate, and K is the saturation level or the environmental carrying capacity, for the given species. K is the upper bound that is reached but not exceeded by growing populations starting below this value. Models based on the aforementioned approach are widely used in modern literature for demand estimation and forecasting, such as the logistic family growth models [29], [30] and the Gompertz model [31]. An application of these demand models over the same dataset can be found in [32].

However, when more than one species coexist in the same environment, they are expected to compete for the same resources. Definitions and descriptions of species competition can be found in [8] and [33], and they can be summarized to the following: "Competition occurs when two or more individuals or species experience depressed fitness (reduced growth rates or saturation levels) attributable to their mutual presence in an area". According to this approach, if two or more species are present in a closed environment each of them will impinge on the available sources supply for the others. In effect, they reduce the growth rates and saturation populations of each other. A more precise definition, regarding interaction of species, is given in [7], where three types of interaction are identified: 1) If the growth rate of one population is decreased and the other increased the populations are in a *predator–prey* situation. 2) If the growth rate of each population is decreased then it is *competition*. 3) If each population's growth rate is enhanced then it is called *mutualism* or *symbiosis*.

Under specific conditions, in a closed established oligopolistic or competitive market, each participant's shares are reduced, due to coexistence and interaction with the others, provided that firms seek to maximize their market shares and profit. In these cases, the second case of competition among species is considered as the most appropriate to describe the phenomenon.

The simplest expression for reducing the growth rate of each species due to the presence of the others is to incorporate suitable parameters to capture the measure of interference among species. The corresponding model is the well-known Lotka–Volterra model, based on the work of Lotka and Volterra. Analytical description together with informative examples regarding interaction and competition between two species can be widely found in literature, such as in [7], [8], [28], and [33]. In addition, theoretical analyses together with applications of interaction among three or more species can be found in [34]–[37]. Based on the earlier analysis, the dynamics of the corresponding system for a number of m competing species can be represented by the following system of first-order nonlinear differential equations:

$$\frac{dN_i}{dt} = N_i\left(a_i - \sum_{j=1}^{m} a_{ij}N_j\right), \qquad i = 1, 2, \ldots, m \tag{2}$$

where, dN_i/dt is the rate of change of species i, and a_i is the growth coefficient of the corresponding population N_i. The coefficients a_{ij} measure the interspecies competitive effects (of each species over the others) when $i \neq j$ and to intraspecies competition when $i = j$, although they are not equal in general. It should be noted that each of the earlier equations can be derived by (1) after performing the following transformation:

$$\begin{aligned}\frac{dN(t)}{dt} &= rN(t)\left(1 - \frac{N(t)}{K}\right)\\ &= N(t)\left(r - \frac{r}{K}N(t)\right) = N(t)\left(r - aN(t)\right)\end{aligned} \tag{3}$$

and adding the extra terms that appear, in order to capture the reduction of growth rate due to the competition with the other species (interspecies competition).

The aforementioned system of equations describes the competitive process at the macro level, capturing the impact of marketing variables and other external factors only implicitly. Moreover, the main assumption is that, during the study period, all other factors remain constant. Incorporation of these factors into the model's formulation and corresponding analysis would probably provide more insight and directions for influencing competition through appropriate marketing actions. In the context of this paper, the influential behavior of these factors is not explicitly studied, since the main target is to develop an alternative methodology for describing the generic behavior of telecoms market and model the balance of the market, when all competitors are present. However, incorporation of external and marketing variables constitutes a main direction of future work, in order to develop a more comprehensive model that will capture the direct and indirect effects of the market environment.

IV. Methodology For Market Shares Evaluation

A. *Definition of the Model*

As mentioned in Section I, construction of the proposed methodology was based on the main assumption of corresponding market share sizes of the competing providers, with an equivalent number of species competing for a common source, in this case the present and future adopters of the offered service. Moreover, it is assumed that only these three species are interacting, without the effects of migration, and that all exterior factors that may affect the dynamics of these species are assumed to be stable for the period under consideration.

Based on the aforementioned assumptions, the dynamics of the proposed system can be described by the system of (2), whereN_is refer to the corresponding market shares a_{ij}, $i \neq j$ parameters capture the influential interaction among subscribers of different providers and a_{ij}, $i = j$ capture the influence among subscribers of the same provider. Interspecies interaction is a measure for describing the so-called churn effect, the switching of subscribers among providers [38].

The mathematical formulations that describe the proposed methodology are very much similar to the ones presented in [25], where the competitive behavior of the market is modeled, in terms of the diffusion rate of each competitor. A description of the benchmark model is given in the evaluation section of the methodology.

B. Case Study Description

Evaluation of the proposed methodology was performed over historical data, describing diffusion and market shares of 2G and 3G mobile telephony in Greece. It is worth mentioning that Greece is the only European country that did not have any analogue cellular network, (although it was proposed in the late 1980s) and was the first country to award licenses through a sealed bid auction procedure [39]. The licensing policy adopted by the Greek government and the regulatory authorities was not like the usual procedure followed in most countries [23], where licenses were frequently granted on a first-come-first-served basis and the first of them were granted to the incumbent operators. A short overview regarding the evolution of the mobile telephony market in Greece is presented in the following paragraphs and given in more detail in [32].

The first two GSM 900 licenses were awarded in August 1992 to Telecom Italia's STET (later TIM and from the mid-2007 WIND) Hellas and Panafon (now Vodafone). They both started operating during the following year with an exclusivity period for all mobile telecommunications frequencies, including GSM 1800 services, until 2000. Following the details mentioned earlier, two companies started the provision of mobile telephony services since year 1994, Vodafone, former Panafon (called Provider A in the rest of the paper and in corresponding graphs) and Wind, former Telestet (Provider C). In 1998 Greece's fixed-line incumbent operator, OTE, entered the market via Cosmote, Provider B, and in about 2001 managed to obtain the biggest market share of all. In 2002, a new provider, Q-Telecom, earned an E-GSM license, entered the mobile arena and started offering services as a Mobile Virtual Network Operator (MVNO), through Vodafone's network, exploiting national roaming framework. An MVNO is a mobile operator that provides services but does not have its own licensed frequency allocation of radio spectrum, nor does it necessarily have all of the infrastructure required to provide mobile telephone service. MVNOs have business arrangements with traditional mobile operators to buy minutes of use for sale to their own customers. Four years later, Q-Telecom merged, through acquisition, by

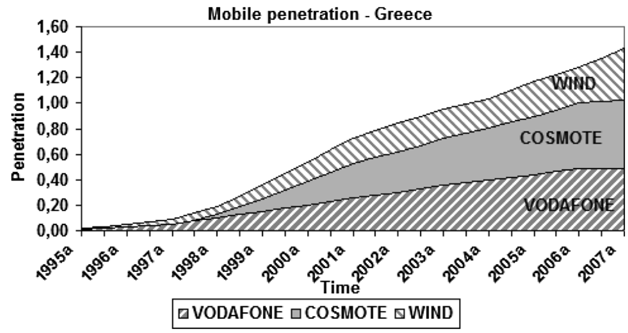


Fig. 1. Mobile phones penetration in Greece and corresponding operators' market shares. *Source:* Mobile operators and NRA.

Wind without any deployment of radio network, as it was originally obliged to. By that time, Q-Telecom managed to obtain a market share of about 8%, mainly prepaid customers, mostly acquired by Wind. Although Q-Telecom case is of interest for the analysis of market competition (for the study of MVNOs), in the present case study only the three main providers that operate mobile networks are considered, since this situation reflects the average European situation, providing useful insights for the worldwide mobile market. Regarding 3G services, the three existing operators (Vodafone, Cosmote, and Wind) were also awarded 3G licenses, for which they bid a combined total of 484 M€ . All three licensees launched commercial 3G services before the end of 2004. Thus, the number of 3G operators counts to three, each one holding a single license for 3G services provision.

Actual semiannual market shares together with total penetration of mobile telephony over population, for years between 1995 and 2007, are shown in Fig. 1, starting from the early stages of mobile diffusion where only two providers were operating in the Greek market and before Cosmote was awarded a license. As stated earlier, although mobile telephony was introduced into the Greek market at the end of 1994, only two providers existed until year 1998. Thus, although actual competition was initiated after 1998, when the incumbent operator entered the market, all available historical data are considered for the evaluation procedure, in order to avoid truncation bias and provide accurate estimations of competition [23], [40]. The data used for evaluation were collected by the corresponding operators and the Greek National Regulator Authority (NRA).

As observed in Fig. 1, the entry of Cosmote as the third competitor into the market had a significant impact on the diffusion of mobile services, since penetration almost doubled in two years time (almost 80%–by the end of 2001), thus confirming the proposition that competition speeds up diffusion, as discussed in [23]. In addition, the timing of the third competitor's entry into the market turned out to be quite important, since the sequential entry of the third provider had a stronger impact than the simultaneous entry of the two first, which is again in accordance with propositions of [23] and [40], describing the strategic behavior by the operators and the effects of sequential entry over competition.

C. Estimation of the Model Parameters

The first step toward the evaluation of the effectiveness of the proposed model is the estimation of the parameters of (2). Such estimations are usually achieved by making reasonable assumptions based on the available data. However, in the present paper heuristic methods are employed by the means of GAs, which are applied in order to "train" the system, or estimate the model's parameters.

Genetic algorithms were introduced by Goldberg [41] and Holland [42], and they are adaptive heuristic search algorithms based on the mechanisms of natural systems and natural genetics. The basic concept of GAs is designed to simulate processes in natural system necessary for evolution, specifically those that follow the principles first laid down by Charles Darwin for the survival of the fittest. As such, they represent an intelligent exploitation of a random search within a defined search space to solve a problem. The key points to the process are *reproduction*, *crossover*, and *mutation*, which are performed according to a given probability, just as it happens in the real world. Reproduction involves copying (reproducing) solution vectors, crossover involves swapping partial solution vectors, and mutation is the process of randomly changing a cell in the string of the solution vector preventing the possibility of the algorithm being trapped. The process continues until it reaches the optimal solution to the fitness function, which is used to evaluate individuals.

Estimation of parameters can be alternatively based on management judgments regarding the evolution of the market, as well as competition. However, this approach could include bias to some extend, since it may reflect personal or group opinions, based on corresponding knowledge, experience, and perception. On the contrary, GAs can provide accurate estimates of a model's parameters once a minimum number of data points become available. This is the case of telecommunications, where the available data are usually restricted to a set of a few observations, mainly due to the rapid generation substitution. Since, in the present case study the number of observations are 26, to be used for the estimation of the 12 parameters of the model, the GAs are considered as the most appropriate choice. Of course, an alternative method could be used for the estimation of these parameters, but in this case it would be more difficult to avoid bias. As stated in [43], GAs "constitute an appropriate method to use when searching for a real number evaluation function in an optimal solution." In this paper, the drawbacks of the most common techniques used for estimating the Bass model parameters are discussed, which are mainly related with bias, multicollinearity and inefficiency, of estimations based on the ordinary least squares, nonlinear least squares, and maximum-likelihood estimation methods. In addition to this, theoretical arguments regarding the ability of the GAs to efficiently produce better parameter estimates are provided in [44], which are evaluated against alternative estimating methods showing the superiority of the Gas, which, under certain circumstances, are able to perform better than the alternative methods, as evident in lower mean squared errors (MSE) and mean absolute deviation. On the contrary, when estimations are based on other methods, it may lead to problems such as values outside the allowable range, convergence problems or bias and systematic change in parameter estimates [45]. In general, GAs are capable of producing accurate estimates in the cases that there are more than six parameters or when there are no many data points available and the solution space becomes very rough. GAs have been used to estimate demand for high-technology products, and they constitute a rapidly growing area of artificial intelligence [46]. In the context of describing market dynamics, GAs were used to develop bargaining agents able to react to different market situations, evolve their best-response strategies accordingly for different market situations [47], and simulate agent behaviors in virtual negotiation environments [48]. In addition, they have also been applied over a wide range of optimization problems, such as solving the flexible assembly line balancing problem [49], choosing the right set of plans for queries, which minimizes the total execution time [50], or solving constrained optimization problems [51].

The general steps a GA consists of the following:

1) Definition of the fitness function, for the particular optimization problem.
2) Setting crossover and mutation probabilities.
3) Random generation of an initial population $N(0)$
4) Generation of $N(t+1)$ by probabilistically selecting individuals from $N(t)$ to produce offsprings via genetic operators of crossover and mutation.
5) Computation of the fitness for each individual in the current population $N(t)$. Offsprings with values closer to the fitness function are more probable to contribute with one or more offsprings to the next generation. Offsprings that diverge from the fitness function are discarded.
6) Steps 4 and 5 are repeated usually until either a prefixed number of generations is created, or after some predefined time has elapsed.

In the present case study, the aforementioned algorithm is performed, for the system described by (2), with the following characteristics:[1]

1) *Objective function:* The minimization of the MSE, between observed and estimated values for each competitor's market share:

$$\mathrm{MSE} = \frac{1}{T}\sum_{t=1}^{T}\left(N_i(t) - \hat{N}_i(t)\right) \qquad (4)$$

where $N_i(t)$, $\hat{N}_i(t)$ are the observed and the estimated values, respectively, for competitor i.

2) *Initial values of parameters:* They were based on estimations of the rates of change of the market shares. The algorithm was in addition executed with random initial values, in order to ensure that the algorithm would converge to the global minimum, instead of being trapped to a local one.

[1]Evaluation of the methodology was based on the Palisade Evolver software, a plug-in for Microsoft Excel that implements Genetic Algorithms (http://www.palisade.com).

3) *Stopping condition:* The algorithm is terminated when the reduction value becomes less than $0,01\%$ in the last 10.000 iterations.
4) The *population size* was set to 500 individuals per generation, the *crossover rate* to 0, 9 and the *mutation rate* to 0, 01. The operations of crossover and mutation are not performed for every reproduction, but the probability of a string to be selected for crossover is proportional to the string's fitness. Each operation is assigned to a particular probability of occurrence or application. The probability of mutation is always very low, since the primary function of a mutation operator is to remove the solution from a local minimum. The probabilities are assigned based on the characteristics of the problem.

The results of the application of GA for the case studied provided the following values for the corresponding parameters:

$$\begin{aligned} \frac{dN_1}{dt} &= N_1 \left(0,45 - 0,6N_1 - 0,2N_2 - 0,66N_3\right) \\ \frac{dN_2}{dt} &= N_2 \left(0,86 - 0,02N_1 - 1,8N_2 - 0,59N_3\right) \\ \frac{dN_3}{dt} &= N_3 \left(0,2 - 0,06N_1 - 0,13N_2 - 0,5N_3\right). \end{aligned} \tag{5}$$

where, N_1, N_2, and N_3 refer to market shares of the three Greek mobile telephony providers, Vodafone, Cosmote, and Wind, respectively.

The estimated coefficients of the system provide important information regarding the process dynamics. The intraspecies competition parameters are quite high, and their ranking depicts the dynamics of each competitor, as verified by the corresponding values of the stable point, calculated later in this section. More specifically, Cosmote has the highest value for both the growth rate (0,86) and the intraspecies competition parameter (1,8) for N_2. This means, since its entry into the Greek market, it increased its market share at an observably high rate, which is in perfect accordance with the actual historical values. In addition, Cosmote seems to have established its market share based more on Vodafone's customers rather than on Wind's customers. This is reflected by the corresponding parameters, in the first and third equation, by the value of the parameters for N_2 (0,2 and 0,13, respectively). Finally, the system's parameters provide quite useful information regarding the "churn effect," i.e., the movements of subscribers among the providers. Churn effect for each provider is depicted by the parameters' values that correspond to interspecies interaction. Thus, Vodafone seems to have suffered a greater market share reduction due to Wind than to Cosmote, while more Wind's customers preferred to switch to Cosmote rather than to Vodafone. It is obvious that such kind of information, derived by the proposed system, is an extremely helpful input in proceeding to critical managerial decisions. The earlier findings are validated by corresponding marketing studies [52]–[54] conducted for the Greek market.

TABLE I
CRITICAL POINTS OF THE SYSTEM

	Critical points		
	Vodafone N1	Cosmote N2	Wind N3
1	0,00	0,00	0,00
2	0,00	0,00	0,35
3	0,00	0,48	0,00
4	0,00	0,39	0,26
5	0,75	0,00	0,00
6	0,42	0,00	0,30
7	0,59	0,47	0,00
8	0,38	0,40	0,22

V. CASE STUDY RESULTS

A. Estimation Procedure Results

The system described by (5) has eight critical points (or equilibrium solutions, i.e., the values of N_is for which the derivatives of system become equal to zero), all located in the nonnegative octet, as shown in Table I.

As a next step, the eigenvalue analysis is performed, by substituting the calculated numerical values of the critical points into (5) and study the behavior of the corresponding system in the neighborhood of each solution. This is usually achieved by the means of a phase portrait, a plot of the system's solutions trajectories, evaluated at a large number of points, and plotting the tangent vectors of the solution of the system of differential equations. The eigenvalue analysis of (5) showed that the first seven are unstable (the trajectories of solutions depart from the critical point as the time variable t increases), since the eigenvalues of the corresponding matrices are of different sign. Thus, in the derived general solutions, one of the variables dominates and causes the system to be unbounded and unstable. On the other hand, the last critical point is stable, since the eigenvalues are all negative and of multiplicity one. All of the participating functions of (5) are twice differentiable; therefore, the system is almost linear in the neighborhood of a critical point (N_1^0, N_2^0, N_3^0) and can therefore be approximated by a corresponding linear system. Approximation can be achieved by considering the following transformation:

$$U = N_1 - N_1^0 \qquad V = N_2 - N_2^0 \qquad W = N_3 - N_3^0. \tag{6}$$

Then, the linear system that approximates the nonlinear system of (5) near the critical point (N_1^0, N_2^0, N_3^0) is derived by using the Jacobian matrix of the partial derivatives (7), as shown at the bottom of the next page, where

$$\begin{aligned} F(N_1, N_2, N_3) &= N_1(0,45 - 0,6N_1 - 0,2N_2 - 0,66N_3) \\ G(N_1, N_2, N_3) &= N_2(0,86 - 0,02N_1 - 1,8N_2 - 0,59N_3) \\ H(N_1, N_2, N_3) &= N_3(0,2 - 0,06N_1 - 0,13N_2 - 0,5N_3). \end{aligned} \tag{8}$$

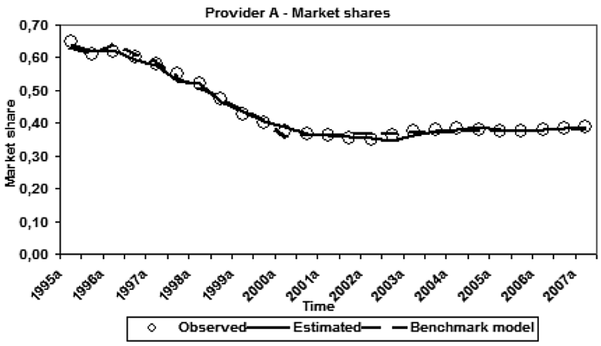


Fig. 2. Estimated versus observed market shares, for Provider A.

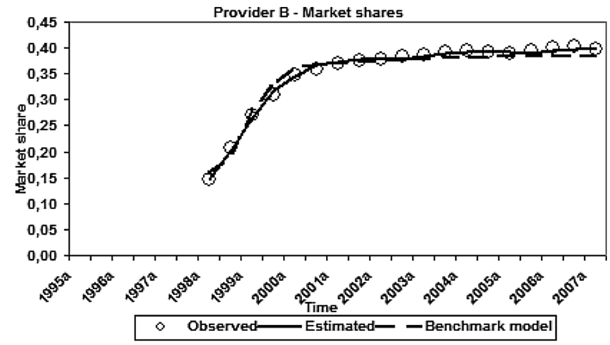


Fig. 3. Estimated versus observed market shares, for Provider B.

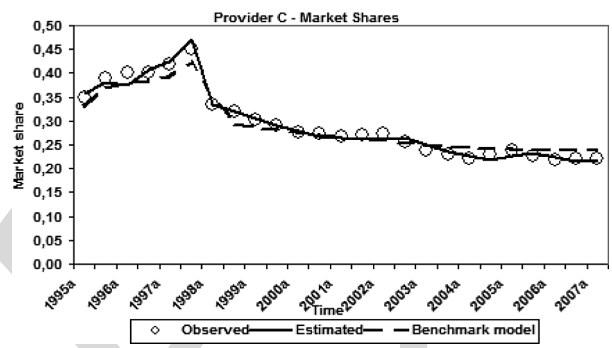


Fig. 4. Estimated versus observed market shares, for Provider C.

After performing the necessary calculations, the general solution of the system in (5) is derived as

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = c_1 \begin{pmatrix} -0,17 \\ -0,98 \\ -0,04 \end{pmatrix} e^{-0,73t} + c_2 \begin{pmatrix} -0,99 \\ -0,07 \\ -0,1 \end{pmatrix} e^{-0,25t} + c_3 \begin{pmatrix} 0,85 \\ 0,18 \\ -0,5 \end{pmatrix} e^{-0,1t}. \tag{9}$$

In (9) c_1, c_2, c_3, are arbitrary constants. However, since it is an initial value problem, substitution of the initial values (the initially recorded market share values) into the general solution described by (9) allows calculation of c_1, c_2, c_3 providing the final solution.

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} 0,05 \\ 0,29 \\ 0,012 \end{pmatrix} e^{-0,73t} + \begin{pmatrix} 0,89 \\ -0,06 \\ 0,09 \end{pmatrix} e^{-0,25t} + \begin{pmatrix} -0,425 \\ -0,09 \\ 0,25 \end{pmatrix} e^{-0,1t}. \tag{10}$$

After reversing the transformation of (6) and applying the earlier procedure, the constructed model estimates that, for the last critical point, the three species—market shares (N_i) of mobile phone providers will eventually settle to equilibrium of about 38% for Vodafone, 40% for Cosmote, and 22% for Wind. Estimation results of the process dynamics are presented in Figs. 2–4. The results of the benchmark model of [25] are also presented for comparison reasons. This family of models was developed aiming to provide an alternative specification of brand-level first purchase diffusion models and evaluate the success of the models to explain trial dynamics. The analysis addressed the issues of the impact of competitive marketing mix variables and the functional form of the diffusion process. The mathematical formulation that describes the diffusion of brand i in the context of competition is given by

$$dN_i = \left[a_i + b_i \left(\frac{x_i}{M_i} \right) + \frac{c_i \left(x - x_i \right)}{\left(M - x_i \right)} \right] \left(M_i - x_i \right) \tag{11}$$

where a_i, b_i represent the external influence coefficient of brand i, respectively, M is the total potential number of adopters, M_i is the potential number of adopters of brand i, x is the total category adopters, and c_i is the competitive internal influence coefficient of brand i. Although this model manages to quite adequately describe the competitive process of diffusion, it requires the estimation of a larger number of parameters than the proposed one. Given the usually restricted availability of observations, a model that incorporates fewer parameters in its formulation, with no loss of information, is always preferred. In addition, the benchmark model requires a two-step estimation procedure. As a first step, the market potentials M_i have to be estimated and, after that, the rest diffusion parameters. Due to the over parameterization of the model certain issues could be raised, related to the lack of convergence.

The accuracy of estimations was based on the calculation of MSE and mean absolute percentage error (MAPE). These, together with the values of the coefficient of determination (R^2),

$$\frac{\partial}{\partial t} \begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} F_{N_1}(N_1^0, N_2^0, N_3^0) & F_{N_2}(N_1^0, N_2^0, N_3^0) & F_{N_3}(N_1^0, N_2^0, N_3^0) \\ G_{N_1}(N_1^0, N_2^0, N_3^0) & G_{N_2}(N_1^0, N_2^0, N_3^0) & G_{N_3}(N_1^0, N_2^0, N_3^0) \\ H_{N_1}(N_1^0, N_2^0, N_3^0) & H_{N_2}(N_1^0, N_2^0, N_3^0) & H_{N_3}(N_1^0, N_2^0, N_3^0) \end{pmatrix} \begin{pmatrix} U \\ V \\ W \end{pmatrix} \tag{7}$$

TABLE II
MEASURES OF ACCURACY ESTIMATION

Proposed model	*Provider A*	*Provider B*	*Provider C*	*Average*
R^2	0,955	0,995	0,960	*0,970*
MSE	4,77E-05	2,01E-05	4,33E-05	*3,70E-05*
MAPE	0,014	0,011	0,022	*0,016*

Benchmark model	*Provider A*	*Provider B*	*Provider C*	*Average*
R^2	0,954	0,994	0,959	*0,969*
MSE	5,32E-05	2,1E-05	3,48E-04	*1,41E-04*
MAPE	0,013	0,014	0,023	*0,0167*

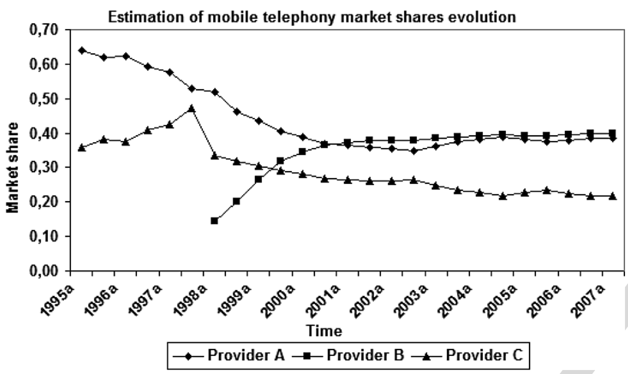


Fig. 5. Estimated evolution of mobile telephony market.

for both the proposed and the benchmark model, are given in Table II, for both evaluated models.

As observed by the calculated values, both models are able to accurately describe the market evolution process, although the proposed Lotka–Volterra model provides better results than the ones of the corresponding benchmark.

As indicated by the corresponding statistical measures of Table II, estimation of market shares is quite accurate and it manages to capture market concentration at an early point of time. The evolution of the market, based on the estimated values derived earlier, for the Lotka–Volterra model, is illustrated in Fig. 5.

As observed, after year 2001 providers' market shares evolve almost constantly, indicating that the market is becoming stable. This finding can be explained by the results provided by [55], where a firm's type and time of response to the competitors' marketing efforts are studied. As analyzed there and in accordance with the evaluated case results, the introduction of a new product in oligopolistic markets, or a new pricing scheme, poses a threat to competitors, which are more likely to react faster and more aggressively. When facing only a few competitors, highly interdependent firms are constantly monitoring the competition, which along with monitoring and competitive awareness enables them to react quickly. This is also in full agreement with the proposition that the relationship between market performance, such as product sales and marketing efforts, is influenced by interaction mechanisms [56].

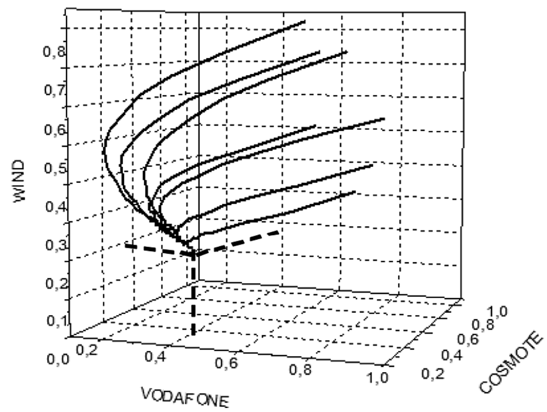


Fig. 6. Phase portrait of dynamic system based on random initial market shares. All trajectories tend to the stable critical point.

B. System Stability Testing

In order to test the stability of the system of (9) at the specific critical point, a phase diagram is constructed and plotted, as shown in Fig. 6, based on different initial values for market shares. As observed, whatever the initial conditions are, all trajectories converge to the estimated critical point.

VI. FORECASTING ABILITY TEST

Testing of the proposed model's forecasting ability was based on using a portion of the dataset as a holdback sample and the remaining data for training the model, in order to forecast the values that were held back. More specifically, the historical dataset was split into two parts, the "training" and the "holdback" data. The former was used to train the model and estimate its parameters, whereas the latter was used to compare the actual recorded values with the ones provided by the model as forecasts. The training data refer to years from 1998 to 2002, leaving the rest years from 2003 to 2006 as the holdback sample for testing purposes. Once again, the parameters of the system described by (2) were estimated by applying GAs over the training dataset. There are again eight critical points, seven of which proved unstable, according to eigenvalue analysis. Only the eighth was stable, corresponding to market shares of 39% for Vodafone, 39% for Cosmote, and 22% for Wind. As observed, the stable critical point calculated over the training data is very close to the one calculated over the whole sample. It can be therefore derived that the system followed the trajectory to the global stable point quite early, and that the proposed system was able to capture the corresponding dynamics quite accurately. After performing the necessary calculations, the corresponding model was constructed and the estimation and forecasting results are illustrated in Figs. 7–9. Obviously, if the system was evaluated in year 2002, the future values of the market shares would have been quite accurately predicted. The benchmark model is also used for comparison reasons.

The measures of accuracy for both the proposed and the benchmark model are calculated and presented in Table III. As observed, the proposed model provides observably more

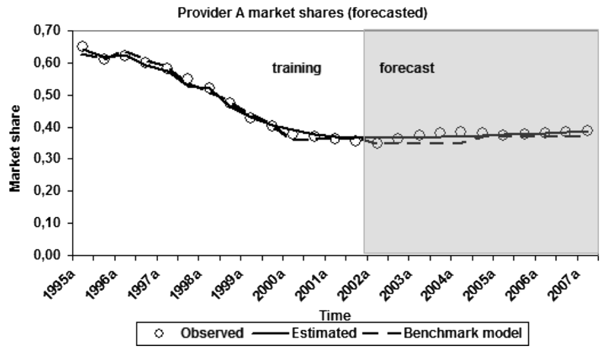


Fig. 7. Forecasted market shares for Provider A, based on training data (years 1998–2002).

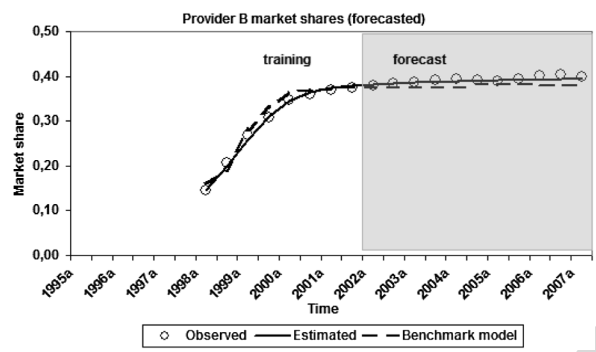


Fig. 8. Forecasted market shares for Provider B, based on training data (years 1998–2002).

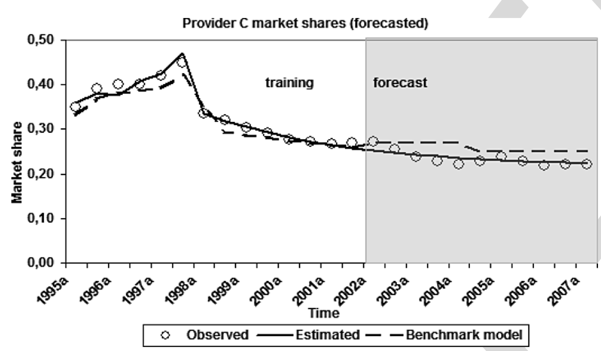


Fig. 9. Forecasted market shares for Provider C, based on training data (years 1998–2002).

TABLE III
MEASURES OF FORECASTING ACCURACY FOR PROPOSED AND BENCHMARK MODEL

	Provider A	*Provider B*	*Provider C*	*Average*
R^2	0,947	0,995	0,940	*0,961*
MSE	1,50E-04	2,50E-05	6,47E-05	*7,99E-05*
MAPE	0,019	0,012	0,025	*0,018*

Benchmark model	*Provider A*	*Provider B*	*Provider C*	*Average*
R^2	0,928	0,947	0,919	*0,931*
MSE	3E-4	2,1E-04	3,48E-04	*2,86E-04*
MAPE	0,07	0,08	0,042	*0,064*

accurate results, as derived by the values of MSE, MAPE, and R^2.

VII. CONCLUSION

The work presented in this paper proposed an alternative methodology for the estimation and forecasting of telecommunication market's concentration, based on concepts of population dynamics and ecological modeling. The main assumption was to consider market providers as interacting species competing for a common source, the market itself, and consequently study the dynamics of the constructed system. Evaluation of the model provided results, showing that the system can quite accurately estimate the trajectory leading to stable points. In addition, the methodology's forecasting ability was tested proving capable of capturing, quite precisely and rather early in time, the dynamics of the interaction among providers.

Future work directions include the development of suitable methodologies, based on the other approaches of Lotka–Volterra model, in order to comprehensively study the different aspects of the telecommunication market. Moreover, the performance of the proposed methodology should be evaluated over other high-technology market that imposes the same characteristics with the telecommunications market, such as entry barriers.

Among the extensions of the proposed methodology is the incorporation of marketing mix variables, such as price and advertising efforts, in order to examine their influence over the competitive behavior of the market and over the diffusion process as well. This is the major limitation of the presented work, since competition was considered at a macro level, assuming that the influence of these factors is reflected by the corresponding market shares.

Another important direction to be implemented as future work is the computation of prediction intervals, in order to estimate the uncertainties that usually accompany the deterministic modeling formulations, caused mainly by the rapidly changing environmental socioeconomic factors. These affect the diffusion characteristics by adding randomness on the adoption pattern [57]. Incorporation of stochastic terms into the corresponding models will provide a set of possible situations of the process, at each point of time. Obviously, no matter how sophisticated a deterministic model can be, it cannot include all the factors that possibly affect the process and since many of the external parameters are random by their nature, they cannot be accurately estimated and used for forecasting purposes. Randomness can be introduced by assuming that either the parameters of an aggregate diffusion model follow a stationary stochastic process [58] or that the future remaining growth of the underlying process is not known with certainty but is modeled using an appropriate stochastic process by an Ito's stochastic differential equation, taking into account the internal and/or external fluctuations [59].

REFERENCES

[1] B. Curry and K. D. George, "Industrial concentration—A survey," *J. Ind. Econ.*, vol. 31, pp. 203–255, 1983.

[2] C. Marfels, "Testing concentration measures," *Zeitschrift Fur Nationalokonomie*, vol. 32, pp. 461–486, 1972.

[3] T. Saving, "Concentration ratios and the degree of monopoly," *Int. Econ. Rev.*, vol. 11, pp. 139–146, Feb. 1970.

[4] J. Tirole, *The Theory of Industrial Organization*. Cambridge, MA: MIT Press, 1988.

[5] M. Baye, *Managerial Economics and Business Strategy*. New York: McGraw-Hill, 2006.

[6] O. Shy, *Industrial Organization, Theory and Applications*. New York: MIT Press, 1995.

[7] J. D. Murray, *Mathematical Biology*, 3rd ed. New York: Springer-Verlag, 2002.

[8] D. Neal, *Introduction to Population Biology*. New York: Cambridge University Press, 2004.

[9] J. Kim, D. J. Lee, and J. Ahn, "A dynamic competition analysis on the Korean mobile phone market using competitive diffusion model," *Comput. Ind. Eng.*, vol. 51, pp. 174–182, Sep. 2006.

[10] L. Lopez and M. A. F. Sanjuan, "Defining strategies to win in the Internet market," *Physica A*, vol. 301, pp. 512–534, Dec. 1, 2001.

[11] J. Tschirhart, "General equilibrium of an ecosystem," *J. Theor. Biol.*, vol. 203, pp. 13–32, Mar. 7, 2000.

Q1

[12] A. W. Wijeratne, F. Yi, and J. Wei, "Biffurcation analysis in the diffusive Lotka-Voltera system: An application to market economy," *Chaos, Solitons Fractals*, 2007. DOI: 10.1016/j.chaos.2007.08.043.

[13] R. C. Rao and F. M. Bass, "Competition, strategy, and price dynamics—A Theoretical and Empirical-Investigation," *J. Market. Res.*, vol. 22, pp. 283–296, 1985.

[14] N. Meade and T. Islam, "Modelling and forecasting the diffusion of innovation—A 25-year review," *Int. J. Forecast.*, vol. 22, pp. 519–545, 2006.

[15] V. Mahajan, S. Sharma, and R. B. Buzell, "Assessing the impact of competitive entry on market expansion and incumbent sales," *J. Market.*, vol. 567, pp. 39–52, 1993.

[16] F. M. Bass, "A new product growth model for consumer durables," *Manage. Sci.*, vol. 15, pp. 215–227, 1969.

[17] T. V. Krishnan, F. M. Bass, and V. Kumar, "Impact of a late entrant on the diffusion of a new product/service," *J. Market. Res.*, vol. 37, pp. 269–278, May 2000.

[18] M. Givon, V. Mahajan, and E. Muller, "Software piracy: Estimation of lost sales and the impact on software diffusion," *J. Market.*, vol. 59, pp. 29–37, 1995.

[19] M. Givon, V. Mahajan, and E. Muller, "Assessing the relationship between user-based market share and unit sales—based market share for pirated software brands in competitive markets," *Technol. Forecast. Soc. Change*, vol. 55, pp. 131–144, 1997.

[20] N. Kim, D. R. Chang, and A. D. Shocker, "Modeling intercategory and generational dynamics for a growing information technology industry," *Manage. Sci.*, vol. 46, pp. 496–512, 2000.

[21] A. D. Shocker, B. L. Bayus, and N. Kim, "Product complements and substitutes in the real world: The relevance of "other products,"" *J. Market.*, vol. 68, pp. 28–40, 2004.

[22] J. Eliashberg and A. Jeuland, "The impact of competitive entry in a developing market upon dynamic pricing strategies," *Market. Sci.*, vol. 5, pp. 20–36, 1986.

[23] H. Gruber and F. Verboven, "The evolution of markets under entry and standards regulation—the case of global mobile telecommunications," *Int. J. Ind. Org.*, vol. 19, pp. 1189–1212, Jul. 2001.

[24] G. Thompson and J.-T. Teng, "Optimal pricing and advertising policies for new product oligopoly models," *Market. Sci.*, vol. 3, pp. 148–168, 1984.

[25] P. Parker and H. Gatignon, "Specifying competitive effects in diffusion models: An empirical analysis," *Int. J. Res. Market.*, vol. 11, pp. 17–39, 1994.

[26] E. Dockner and S. Jorgensen, "Optimal pricing strategies for new products in dynamic oligopolies," *Market. Sci.*, vol. 7, pp. 315–334, Fall 1988.

[27] D. Horsky and L. Simon, "Advertising and the diffusion of new products," *Market. Sci.*, vol. 2, no. 1, pp. 1–17, 1983.

[28] W. E. Boyce and R. C. DiPrima, *Elementary Differential Equations and Boundary Value Problems*, 8th ed. Hoboken, NJ: Wiley, 2005.

[29] R. Bewley and D. G. Fiebig, "A flexible logistic growth-model with applications in telecommunications," *Int. J. Forecast.*, vol. 4, pp. 177–192, 1988.

[30] J. C. Fisher and R. H. Pry, "A simple substitution model of technological change," *Technol. Forecast. Soc. Change*, vol. 3, pp. 75–88, 1971.

[31] L. P. Rai, "Appropriate models for technology substitution," *J. Sci. Ind. Res.*, vol. 58, pp. 14–18, Jan. 1999.

[32] C. Michalakelis, D. Varoutas, and T. Sphicopoulos, "Diffusion models of mobile telephony in Greece," *Telecommun. Policy*, vol. 32, pp. 234–245, 2008.

[33] M. Begon, C. Townsend, and J. Harper, *Ecology: From Individuals to Ecosystems*, 4th ed. Oxford, U.K.: Blackwell, 2006.

[34] T. H. Fay and J. C. Greeff, "A three species competition model as a decision support tool," *Ecol. Modell.*, vol. 211, pp. 142–152, Feb. 24, 2008.

[35] H. I. Freedman and P. Waltman, "Persistence in models of 3 interacting predator-prey populations," *Math. Biosci.*, vol. 68, pp. 213–231, 1984.

[36] H. I. Freedman and P. Waltman, "Persistence in a model of 3 competitive populations," *Math. Biosci.*, vol. 73, pp. 89–101, 1985.

[37] P. G. L. Leach and J. Miritzis, "Analytic behaviour of competition among three species," *J. Nonlinear Math. Phys.*, vol. 13, pp. 535–548, Nov. 2006.

[38] R. Fildes and V. Kumar, "Telecommunications demand forecasting—A review," *Int. J. Forecast.*, vol. 18, pp. 489–522, Oct.–Dec. 2002.

[39] H. Gruber, *The Economics of Mobile Telecommunications*. New York: Cambridge University Press, 2005.

[40] H. Gruber and F. Verboven, "The diffusion of mobile telecommunications services in the European Union," *Eur. Econ. Rev.*, Mar, vol. 45, pp. 577–588, 2001.

[41] D. E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*. Reading, MA: Addison-Wesley, 1989.

[42] J. Holland, *Adaption in Natural and Artificial Systems*. Ann Arbor, MI: University of Michigan Press, 1975.

[43] F.-K. Wang and K.-K. Chang, "Modified diffusion model with multiple products using a hybrid GA approach," *Expert Syst. Appl.*, vol. 36, pp. 12613–12620, 2009.

[44] R. Venkatesan, T. Krishnan, and V. Kumar, "Evolutionary estimation of macro-level diffusion models using genetic algorithms: An alternative to nonlinear least squares," *Market. Sci.*, vol. 23, pp. 451–464, 2004.

[45] C. Van Den Bulte and G. L. Lilien, "Bias and systematic change in the parameter estimates of macro-level diffusion models," *Market. Sci.*, vol. 16, pp. 338–353, 1997.

[46] R. Venkatesan and V. Kumar, "A genetic algorithms approach to growth phase forecasting of wireless subscribers," *Int. J. Forecast.*, vol. 18, pp. 625–646, Oct.–Dec. 2002.

[47] K. M. Sim and B. An, "Evolving best-response strategies for market-driven agents using aggregative fitness GA," *IEEE Trans. Syst., Man, Cybern. C: Appl. Rev.*, vol. 39, no. 3, pp. 284–298, May 2009.

[48] R. Krovi, A. C. Graesser, and W. E. Pracht, "Agent behaviors in virtual negotiation environments," *IEEE Trans. Syst. Man Cybern. C: Appl. Rev.*, vol. 29, no. 1, pp. 15–25, Feb. 1999.

[49] Z. X. Guo, W. K. Wong, S. Y. S. Leung, J. T. Fan, and S. F. Chan, "A genetic-algorithm-based optimization model for solving the flexible assembly line balancing problem with work sharing and workstation revisiting," *IEEE Trans. Syst. Man Cybern. C: Appl. Rev.*, vol. 38, no. 2, pp. 218–228, Mar. 2008.

[50] M. A. Bayir, I. H. Toroslu, and A. Cosar, "Genetic algorithm for the multiple-query optimization problem," *IEEE Trans. Syst. Man Cybern. C: Appl. Rev.*, vol. 37, no. 1, pp. 147–153, Jan. 2007.

[51] Y. Wang, Z. X. Cai, G. Q. Guo, and Y. R. Zhou, "Multiobjective optimization and hybrid evolutionary algorithm to solve constrained optimization problems," *IEEE Trans. Syst. Man Cybern. B: Cybern.*, vol. 37, no. 3, pp. 560–575, Jun. 2007.

[52] COSMOTE. (2007). Financial results. Available: http://www.cosmote.gr/cosmote/cosmote.portal?locale=en_US&_nfpb=true&_pageLabel=L183_presentations_index

[53] EETT. (2010). National regulatory authority, which supervises and regulates the telecommunications as well as the postal services market Hellenic Telecommunications and Post Commission, Annual Reports. Available: http://www.eett.gr/opencms/opencms/EETT_EN/Publications/Proceedings/

[54] Goliath Business News. (2008). Market data analysis, Greece, Telecommunications Report. Available: http://goliath.ecnext.com/coms2/gi_0198-588155/Market-data-analysis.html

[55] D. Bowman and H. Gatignon, "Determinants of competitor response time to a new product introduction," *J. Market. Res.*, vol. 32, pp. 42–53, 1995.

[56] H. Gatignon and D. M. Hanssens, "Modeling marketing interactions with application to salesforce effectiveness," *J. Market. Res.*, vol. 24, pp. 247–257, 1987.

[57] J. Eliashberg and R. Chatterjee, "Stochastic issues in innovation diffusion models," in *Innovation Diffusion Models of New Product Acceptance*, V. Mahajan and Y. Wind, Eds. Cambridge, MA: Bullinger Publishing Company, 1986, pp. 151–199.

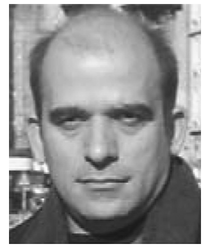
[58] Karmeshu and R. K. Pathria, "Stochastic-evolution of a non-linear model of diffusion of information," *J. Math. Sociol.*, vol. 7, pp. 59–71, 1980.
[59] N. Meade, "Technological substitution—A framework of stochastic-models," *Technol. Forecast. Soc. Change*, vol. 36, pp. 389–400, Dec. 1989.

Christos Michalakelis received the degree in mathematics from the Department of Mathematics, University of Athens, Athens, Greece, the M.Sc. degree in software engineering from The University of Liverpool, Liverpool, U.K., the M.Sc. degree in administration and economics of telecommunication networks from the Department of Informatics and Telecommunications, Interfaculty course of the Departments of Informatics and Telecommunications and Economic Sciences, National and Kapodistrian University of Athens, and the Ph.D. degree in technoeconomics, especially in demand estimation and forecasting of high-technology products.

He is currently with the National and Kapodistrian University of Athens. He is a High School Teacher of informatics and computer science. He had been with the Greek Ministry of Education, in the Managing Authority of Operational Program for Education and Initial Vocational Training, for seven years, as an IT manager. He has participated in a number of projects, concerning the design and implementation of database systems and now participates in several technoeconomic activities for telecommunications, networks and services such as the CELTIC/ECOSYS project pricing and regulation. He has also developed or had a major contribution in the development of a number of information systems and applications. He is the author or coauthor of ten papers published in scientific journals and various conference proceedings, and a coauthor in three book chapters.

Thomas Sphicopoulos (M'xx) received the degree in physics from Athens University, Athens, Greece, in 1976, the D.E.A. degree and Doctorate degree in electronics from the University of Paris VI, Paris, France, in 1977 and 1980, respectively, the Doctorat Es Science from the Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, in 1986.

From 1976 to 1977, he was with Central Research Laboratories, Thomson CSF, where he was engaged in research on microwave oscillators. From 1977 to 1980, he was an Associate Researcher in Thomson CSF Aeronautics Infrastructure Division. In 1980, he joined the Electromagnetism Laboratory, Ecole Polytechnique Federal de Lausanne, where he was engaged in research on applied electromagnetism. Since 1987, he has been with National and Kapodistrian University of Athens, where he was engaged in research on broadband communications systems. In 1990, he became an Assistant Professor of communications in the Department of Informatics and Telecommunications, where, in 1993, he was an Associate Professor, and since 1998, he has been a Professor. He is the author or coauthor of more than 150 papers published in scientific journals and conference proceedings. He is an advisor in several organizations. His current research interests include optical communication systems and networks and techno-economics. He has led about 50 National and European R&D projects.



Dimitris Varoutas (M'xx) received the degree in physics, and the M.Sc. and Ph.D. degrees in communications and technoeconomics from the University of Athens, Athens, Greece.

He is currently a Lecturer of telecommunications technoeconomics in the Department of Informatics and Telecommunications, National and Kapodistrian University of Athens. He has been participating in numerous European R&D projects in the Research into Advanced Telecommunications for Europe I & II, Advanced Communications Technologies and Services, Telematics, Regional Information Society Initiative, and Information Society Technologies frameworks in the areas of telecommunications and technoeconomics. He actively participates in several technoeconomic activities for telecommunications, networks, and services such the ICT-OMEGA and the CELTIC/CINEMA projects, as well as the Conferences on Telecommunications TechnoEconomics. He also participates in or manages related national activities for technoeconomic evaluation of broadband strategies, telecommunications demand forecasting, price modeling, etc. He is the author or coauthor of more than 40 papers published in refereed journals and conferences in the area of telecommunications, optoelectronics and technoeconomics, including leading IEEE Journals and conferences. His current research interests include span design of optical and wireless communications systems to technoeconomic evaluation of network architectures and services.

Dr. Varoutas is a member of the Lasers and Electro-Optics Society, the Communications Society, the Circuits and Systems Society, the Education Society, and the Engineering Management Society of IEEE. and serves as a Reviewer in several papers including IEEE journals and conferences.

QUERIES

Q1. Author: Please provide the volume no. and the page range in Ref. [12].

Q2. Author: Please check whether the authors' name in Ref. [58] is OK as typeset.

Q3. Author: Please check the current affiliations of all the authors in their respective biographies.

Q4. Author: Please specify the degree title received by C. Michalakelis from the Department of Mathematics, University of Athens, Athens, Greece. Also, please provide the university name from which he received the Ph.D. degree.

Q5. Author: Please provide the full form of "CELTIC/ECOSYS."

Q6. Author: Please provide the year in which "T. Sphicopoulos" became a Member of the IEEE. Also, please specify the title of degree received by him from Athens University.

Q7. Author: Please provide the year in which "D. Varoutas" became a Member of the IEEE. Also, please specify the title of degree received by him from the University of Athens.

Q8. Author: Please check whether the expanded forms of RACE, ACTS, RISI, and IST are OK as typeset. Also, please provide the full form of "ICT-OMEGA and CINEMA"