Abstract. An evolutionary model drawn from biology is introduced. A method for its application to optimisation problems is developed and applied to the analysis of Videotex and Teletext services. It is shown that the evolutionary model has significant potential as a diagnostic tool for identifying trends in complex competitive systems.

1. INTRODUCTION

With the widespread liberalisation of the telecommunications sector, the development and operation of communication networks, together with the huge investment involved, is necessarily taking place in an increasingly competitive environment. For a given type of network, a range of technological solutions may exist each enabling a range of services to be provided over various time scales at various cost under various regulatory, competitive and other environmental constraints. Thus, with the explosion in the complexity of the telecommunications business, it has become crucial to establish techniques for gaining insight into the possible evolutionary pathways which the sector may take. This is particularly relevant in terms of, for example, assessing investment and other market strategies, a problem which is becoming increasingly difficult given the large number of technological, regulatory and competition factors. The case of frame relay, for example, serves as an illustration of the severity of the technological complexity of this issue. On the one hand, it has been suggested that the pace of change is now so fast that frame relay may become the first technology to become obsolete, even before the standards are completed and products become available [Duckett 1992]. However, on the other hand, it has been suggested that frame relay will still be required within an asynchronous transfer mode environment [Hopkins, 1992].

Since the communications sector is so dynamic, subject now to rapid and extensive changes, there is an urgent need for network operators and service providers to develop substantial flexibility and adaptability. Adaptability is essential in order to be able to change strategies so that additions and modifications to network or service infrastructure can be engineered quickly in response to the myriad of fluctuating market forces. In view of the rapid changes and multiple paradigm shifts which are sweeping the telecommunications, computer and broadcasting industries, a need is arising for analytical tools which enable the complexity and dynamics of the sector to be unravelled. It is clear that a dynamic and competitive environment will give rise to a number of unpredictable events, many of which probably cannot be predicted even within the most sophisticated theoretical frameworks. However, modelling techniques can serve a valuable role in helping to link and analyse various aspects of sector complexity. This may help to reduce the considerable uncertainty which exists. The uncertainty is not necessarily due to a shortage of relevant information but may be connected more with difficulties in tracking, predicting and assessing all of the economic and technological consequences of a particular industrial move in a market place which has swung into conditions far-from-equilibrium. However, development of analytical capabilities is particularly important during the transition to a free-market regime in which competitive edge rests to a large extent on the quality of business decision-making processes and the rapid and effective manner in which business decisions are implemented. No doubt, there are logical and quantifiable elements in the dynamics of the telecommunication market and it is essential to identify and capture these in service and network models so that decision-making processes can be enhanced.

There are various ways to construct models for systems of competing elements constrained in an environment. For a number of interesting articles discussing this matter see for example [Stein (ed) 1989]. In such
models, certain basic criteria need to be satisfied:

i) the essential elements of the system must be captured,

ii) the model must contain parameters which can be identified with real-world data,

iii) the model must contain dynamical elements in order to describe real-world dynamics and

iv) the model must be capable of reproducing the past behaviour of the real system and preferably be capable of predicting the system's future development given certain boundary conditions or other constraints.

The issue addressed in this paper is whether and how the basic principles of evolutionary systems, i.e. random change and/or other social, economic or technological factors? Can the evolutionary models be applied to models of competing services, and technological components? Can the evolutionary models capture the evolution of competing service components under various constraints as fixed by customer preference and/or other social, economic or technological factors?

The general principles of the evolutionary model used in this work will be introduced in section 2 and the meaning of a competition between a number of services and how this competition is captured in some dynamical model is described. In section 3, an analysis of the competition process is given and the possibility of predicting the winner of the competition given the knowledge of the system parameters is assessed. In section 4, the use of the model for curve-fitting purposes is described. This is of particular importance in fitting historical data which represent some past performances of particular services and in encapsulating aspects of history in the model parameters so that consistent information is propagated into the future dynamics of the system. In section 5, the model is applied to the evolution of Teletext and Videotex market penetration within the context of published data and forecasts for the US market. It is shown that the evolutionary model can be used straightforwardly to reproduce forecasts made in 1982.

2. THE EVOLUTIONARY MODEL

The evolutionary model describes the time evolution of an arbitrary number of components in some competitive environment. Each component can be subjected to a number of processes or operations, which include death and replication. Death corresponds to removal of the component from the system and replication corresponds to the use of the component as a template for reproduction and results in an increase in the number of components. These processes are described by the rate coefficients $D_i$ for death and $A_i$ for replication. In addition to the processes of death and replication, it is possible for one component to change into another component. This process is captured by the matrix quantity $\omega_{ij}$, which describes the transformation ('mutation') from the $j$-th component to the $i$-th one.

The increase in the population of the $i$-th component in some time interval $\Delta t$ is given by the expression

$$\Delta x_i = (D_i x_i + \sum_k \omega_{ik} x_k) \Delta t$$

The decrease in the same population class in the same time interval is given by the expression

$$\Delta x_i = (A_i x_i + \sum_k \omega_{ki} x_k) \Delta t$$

The difference between these expressions $\Delta x_i = (\text{flow-in}) - (\text{flow-out})$, divided by $\Delta t$ gives the rate of change in the concentration of the $i$-th component. By taking the limit $\Delta t \to 0$ the evolution equation for the $i$-th component can be derived

$$\frac{dx_i}{dt} = (A_i - D_i) x_i + \sum_k \omega_{ki} x_k$$

A quality factor $Q_i$ can be introduced as follows

$$Q_i = A_i Q_i + A_i (1 - Q_i)$$

where the first term represents correct replications of the $i$-th component and the second term measures incorrect replications. Maximum quality $Q_i = 1$ means that all members of the $i$-th component are correctly replicated, whereas a minimum quality $Q_i = 0$ results in all members being incorrectly copied.

In this work the only case considered is the one in which the total concentration of competing components is kept constant. The constant concentration can be chosen arbitrarily and here is normalised as follows

$$\sum_i x_i = 1$$

To accommodate this (conventional) normalisation condition, a flux term is introduced [Eigen 1971]

$$\phi_i = x_i \sum_k (A_k - D_k) x_k$$

which compensates for the overall excess production. After introducing the following quantities

$$\Omega_i = A_i Q_i - D_i$$

selective value

$$E_i = A_i - D_i$$

excess productivity

$$E = \sum_k E_k x_k$$

mean productivity

the evolution equation for the $i$-th component can be written as

$$\frac{dx_i}{dt} = (\Omega_i - E) x_i + \sum \omega_{ij} x_k$$

This is precisely the equation derived by [Eigen 1971]. By fixing all the primary parameters $A_i$, $D_i$, $Q_i$ and $\omega_{ij}$ of the system and by initialising the component concentration in a manner consistent with the normalisation condition (5), equations (8) can be simulated. It is found that all simulations in which the parameters $A_i$, $D_i$ and $Q_i$ are restricted to the interval [0.0,1.0] and make the transition coefficient satisfy the relation

$$\sum \omega_{ij} = A_i (1 - Q_i)$$

have point attractors and so lead to stable equilibrium states and so do not display any oscillatory or chaotic behavior. This is not necessarily true for other parameter values. Equation (9) provides a quantitative meaning to the quality factor $Q_i$, which is a measure of resistance to a change (mutation) of a particular species.

At the end of each evolutionary run the individual components end in their equilibrium states, compatible with the values of the character parameters. The
component distribution in the reached equilibrium states is given by the relation

\[ x_i = \left( \sum \omega_j x_j \right) / (E - \Omega_i) \]  

(10)

A redistribution of the individual components can only be achieved by the introduction of a mutation and a subsequent simulation of the evolutionary equations. If the mutation is completely random, as opposed to being a slight modification of the previous system parameters, the system generally ends up in a configuration completely different to the previous one. For example, a component which prior to the mutation enjoyed a dominance over the other components is likely to lose its 'privileged position' as a result of the mutation. A typical example of this occurrence is shown in Fig. 1.

![Figure 1](image1.png)

Fig. 1 - The curves show the evolution of three species components subject to the evolution equations (8). The abrupt changes at \( t = 50 \) and \( t = 100 \) are due to random mutations that take place at these times.

3. WHO WINS THE COMPETITION?

Who wins the running competition as modelled by the simulation of the set of equations (8)? This question is an important one because its answer would enable certain parameter values to be associated with a greater likelihood of winning. A number of simulations have shown that in most cases, the winning component appears to be the one with the highest selective value that is present in highest concentration when the system has reached equilibrium.

The bar charts in Fig. 2 describe the equilibrium distribution of nine components together with their associated selective values. The results were found from experiments with the nine components subjected to 15 sequential random mutations. The graphs represent the average concentration values for the equilibrium states reached after each mutation.

The results presented in Fig. 2 indicate a strong correlation between a component winning and having the highest selective value. This could be taken to mean that there is some redundancy in the values given to the other parameters of the model since there are many combinations of parameters which can realize a given selective value. However, this is not quite the case because components with high selective values, realised by low quality values, are slightly less likely to win the running competition. This is demonstrated in Fig. 3 in which the frequency of the winner having the highest selective value as a function of the quality parameter \( Q \) is plotted. It can be seen that the frequency of the winner having the highest selective value increases with an increasing value for the quality parameter.

![Figure 2](image2.png)

![Figure 3](image3.png)

Fig. 3 - The frequency of the coincidence of the winning component having the highest selective value as a function of the quality parameter \( Q \). The numbers on the quality axis indicate in which intervals the quality parameters lie. For example \( Q = 0.5 \) means that the quality parameter has been randomised in the interval \([0.4, 0.5]\).

4. CURVE-FITTING

Optimisation procedures are of immense importance in most fields of science and engineering. Usually a problem is faced which can be stated as follows: given a cost function \( f \) of \( n \) variables \( x_1, x_2, \ldots, x_n \), find the
variable configurations that minimise or maximise \( f \).

A large number of efficient algorithms have been developed to deal with problems of this kind. Some algorithms include, for example, the method of steepest descent and downhill simplex methods and combinatorial methods such as simulated annealing.

As discussed in section 2 a simulation of (8) ends in an equilibrium distribution which depends on the values of the system parameters. If these are changed randomly, then the winner position changes randomly. A selective procedure can be introduced which accepts only those mutations which are considered to be beneficial. For example, the strong position of some dominant component could be improved further if the mutations which cause a reduction in that component’s concentration are simply rejected. The effect of this is illustrated in Fig. 4.

Fig. 4 - Graph showing that only mutations that further strengthen the position of the component which is already the strongest one at the beginning are accepted. This is an example of evolutionary self-reinforcement.

A curve-fitting problem can be formulated as an optimisation problem in which a quadratic function is to be minimised. The approximation which minimises the cost function can be achieved by a parameter modification. The variation of these parameters can either be done randomly, as in the method of simulated annealing, or by using other more deterministic methods, such as the method of steepest descent.

The evolutionary model is a dynamical problem which depends on many different parameters, some of which are interrelated; see, for example, equation (9) which describes the relation between \( A_i, Q_i \) and \( \omega_i \). The solutions of this model, which describe the temporal behaviour of the species components, trace out a curve in a high dimensional space whose shape depends on the values of the system parameters. In the curve fitting process, the values of these parameters are changed in order to force the solution curve towards some predefined targets.

The data are considered as a set of ordered pairs \( (x_{1,i}, x_{2,i}), i = 1, \ldots \). Number of species components: \( k = 1, \ldots \). Number of targets – 1. The task is to find a map \( f \) from the space of data points, \( \Omega \) to \( \Gamma \) which is an appropriate extension of the set of data points, \( \Omega \rightarrow \Gamma \) such that \( f(x_{1,k}) = x_{1,k+1} \) is sufficiently close to \( x_{1,k+1} \); i.e. the quadratic error

\[
E = \frac{1}{2} \Sigma_i (x_{1,n+1} - f(x_{1,n}))^2
\]

is to be minimised. In this approach, the first data pair \( x_{1,k} \) is taken as an input to the evolutionary system and \( x_{1,k+1} \) is set as the target.

The parameters of the map \( f: \Omega \rightarrow \Gamma \) are the character parameters of the evolutionary system. They are to be fitted by repeated performance of mutations until a satisfactory approximation has been reached.

All the data inputs are fed into the system and the culminating error function subsequently evaluated. If the error function is smaller than the previous one, the new error is registered and a new mutation is introduced; this mutation is random but constrained to some well defined intervals. Only random perturbations \( \delta Q_i, \delta D_i, \delta A_i \) are added to the previous character parameters, i.e. \( Q_i \rightarrow Q_i + \delta Q_i, D_i \rightarrow D_i + \delta D_i, A_i \rightarrow A_i + \delta A_i \). Limitations are put on the perturbations such that the perturbations lie in the interval \( -scale \leq \delta Q_i, \delta D_i, \delta A_i \leq scale \), with scale being the current error multiplied by a factor, usually taken to have values close to unity. If the error is larger than the previous error, the character parameters are reset to their previous values and then subjected to new perturbations as described above. After the values for \( Q_i, D_i \) and \( A_i \) have been fixed, \( \omega_i \) is randomised subject to the constraints (9). The procedure is shown schematically in Fig. 5. Since the character parameters are confined to the unit interval \([0.0,1.0]\) as discussed earlier, care must be taken to ensure that the perturbations do not violate this condition; if this condition is violated, the parameters are reset to the closest acceptable value.

Fig. 5 - Schematic representation of how the effects of mutations are evaluated.

5. A CASE STUDY ON VIDEOTEX AND TELETEXT SERVICES.

In an extensive survey [Tydeman et al 1982] have assessed the impact of Videotex and Teletext services in
the United States over the period 1982-2000. Since Videotex service is medium free, it can be carried potentially by a number of different technologies, each having its advantages, disadvantages and various attractions. Such considerations include, for example, current availability, bit rate capacity, flexibility and potential for expansion. The study highlights a number of technical and socio-economic factors and identifies four components which are considered to be essential in assessing the future development of Videotex and Teletext services.

These are:

i) Penetration, which measures the percentage of households connected to the network considered.

ii) Transmission speed. Future services offered by Videotex systems such as real motion videos and high picture qualities will require high bit rates; this point is of great importance.

iii) Interface unit costs, which include the cost of providing the physical and electrical connection between customer and service provider. This includes equipment used for signal conversion.

iv) Communications link cost, which is the cost resulting from actual usage. This cost factor is more difficult to estimate and predict since, in the case of the telephone public switched network, for example, depends very much on tariff setting. For other communication technologies, such as broadcast television and FM radio, the communication link cost is (nominally) zero.

Figs. 6 and 7 describe a twenty year forecast (made...
in 1982!) for penetration and interface unit cost respectively. These curves have been fitted using the evolutionary model and selective values have been extracted from the analysis. As far as the analysis given in section 2 is concerned, the winning network type would be expected to have the highest selective value when the curve fitting has been completed. Here a few comments on the meaning of winner in this particular context are in order.

It is clear from Figs. 6 and 7 that communication networks having almost 100% penetration over the whole time period considered are not winners because there is no scope for improving their penetration. A winning network would be the one which demonstrates an increasing penetration, ie large gradient of growth. Indeed this is the way the model seems to interpret the curve-fitting procedure because in most cases it assigns the highest selective value to those network types predicted to have the steepest increase over the time period considered.

Fig. 8 shows how the curve-fittings made by the evolutionary model have assigned different selective values to the penetration of various network technologies. The results are obtained in the following way. Fifty independent experiments are run in which the performance curves predicted by Tydeman et al are fitted and, after completion of the fitting process, the component with the highest selective value is identified. The columns shown in Fig. 8 represent how often each technology has been registered as having the highest selective value at the end of each experiment.

Fig. 9 shows the frequency with which the curve-fitting procedure of the evolutionary model assigned the lowest selective value to the various network components mentioned. The reason for concentrating on the lowest selective value is that the approximated curves in Fig. 7 represent price reductions. The quicker the curve falls the lower, in general, is the associated selective value. As far as the US market is concerned (for which these data apply), Packet Switched Networks are becoming the most highly selected network type for Videotext/Teletext.

6. CONCLUSION

In this work the basic elements of an evolutionary model have been discussed and the application of the model to the analysis of market penetration and cost has been illustrated for a specific test case. The main objective is to construct a model which describes networks and services operating in a competitive environment. The model can be extended to form part of a much more sophisticated tool for analysing such situations. The basic idea is to identify services and network architectures with species competing under certain constrained conditions, as defined by 'environmental factors' such as technological performance, price and customer preference.

A difficult problem with most models which attempt to describe and predict service performance is the assignment of real values to the parameters in the model. Here this problem is approached by using the model for curve-fitting of historical data. This is done by adjusting the model parameters in a random manner and by accepting only those changes which reduce the error associated with the curve-fitting procedure. When a satisfactory curve-fitting has been achieved the parameters are frozen and read off. Their values are representative of the performance of the considered services in the past and, as indicated in section 5, they have some predictive powers as well.

In current telecommunication markets, changes are frequent and sometimes radical and unforeseen. It is hoped that such changes can be captured in new values being assigned to the various parameters in the model, in particular the selective value. This is where the concept of mutation comes in. The application of the evolutionary model to the curve-fitting problems described here is important on account of the fact that many curves can be fitted simultaneously and meaningful (physical) measures, such as selectivity, are obtained.

Application of this procedure to many examples
Applications of an Evolutionary Model to Telecommunication Services

shows that the historical service curve with the highest growth rate ends up having the highest selective value which amounts to a good performance. Analysis of this kind is of particular value when dealing with a high number of services, within broadband networks, for example, where the interrelation of their performances is not obvious from the analysis of data by conventional methods. As competition in many areas of telecommunication services is now emerging on an international scale, models of the kind presented here will become important in the analysis of service provision.

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