SOME APPROACHES TO THE DEVELOPMENT OF ANALYTICAL MODEL FOR THE RESEARCH OF THE TELECOMMUNICATION TECHNOLOGIES' DEVELOPMENT PROCESS

Galina Gayvoronska, Petr Yatsuk

Abstract: *The paper is devoted to the problem of the telecommunication technologies' implementation strategy's choice at the cost minimization. Some aspects of the model, displaying the new technologies' implementation process in the telecommunication networks, are researched. An approach to the realization of the value engineering of the network development's costs at the implementation of advanced telecommunication technologies is developed. This approach can be used for the techno-economic evaluation of the network development's options at the transition to the new technologies and allows the designer to select the optimal strategy and time stages of these technologies implementation.*

Keywords: *telecommunication technology, telecommunication network, development process, life cycle, implementation, modeling, function.*

ACM Classification Keywords: *B.4 Input/Output and Data Communications, C.2 Computer-Communication Networks, I.6 Simulation and Modeling.*

Introduction

Telecommunication technologies' development process is being represented by sophisticated dependences. Some aspects of their research are given in professor Sokolov's works, particularly quite big attention to this question is paid in his monograph [Sokolov, 2004]. Various aspects of new technologies' implementation to existing networks are examined in several works particularly this problem is research subject of the largest scientists: N.D. Kondratieff, I. Schumpeter, S. Y. Glazyev. Their results indicate the interrelation of telecommunication technologies' (TT) cyclic development and rises/recessions in the countries development. That has a decisive influence on the country competitiveness and its place on the political world stage. Telecommunication technologies represent area where appearance of new information-communication services (ICS) leads to the rapid growth of social development processes. Possibility of TT development process's modeling and accounting of this process change's features will allow adequately assessment of new technologies' potential, choice of the most efficient time and way of their implementation, risk evaluation at the investments, etc.

Laws of various development processes represent research object of specialists in various subject areas. Classification and modeling of these processes make complex engineering-mathematical problem. In order to research telecommunication technologies' development process (TTDP) authors proposed a mathematical apparatus of population dynamics in [Gayvoronska et al., 2013 (1) and 2014 (1)]. Classic works in this area belong to V. Volterra [Volterra, 1931] and P. Verhulst [Verhulst, 1838]. Mathematical development of this apparatus is given in the works of G. Riznichenko [Riznichenko, 2011], A. Rubin [Riznichenko & Rubin, 1993] and A. Bazykin [Bazykin, 1985]. Recent years some scientist have handled this mathematical apparatus in order to research the life cycle of technologies in various areas such as railways development [Andersen, 2002], cities growth [Capello & Faggian, 2002], labor markets [Chen & Watanabe, 2006], etc.

Authors of this paper also published a number of works devoted to this subject [Gayvoronska, 2005, Gayvoronska, 2006 (1), Gayvoronska, 2006 (2), Gayvoronska, 2006 (3), Gayvoronska & Somsikov, 2006, Gayvoronska & Pavlov, 2006, Gayvoronska, 2006 (4), Gayvoronska, 2007, Gayvoronska, 2012, Gayvoronska & Domaskin, 2013, Gayvoronska et al., 2013 (2), Gayvoronska et al., 2013 (3), Gayvoronska et al., 2013 (4), Gayvoronska, 2001]. This work represents several results of researches continuation in this direction.

Main Part

Statement of the Problem

Problem, considered in the paper, is research of regularities of new telecommunication technologies' implementation process into the existing telecommunication network (TN) by means of mathematical modeling. Several approaches to the TN development model's creation are offered in the paper. They are based on the usage of TT two types, which can be marked as existing TT (ETT) and new TT (NTT). Newly implemented technology can co-exist for some time with the ETT or replace it at once. The proposed model allows analysis of the costs, required for the network upgrade, depending on the NTT implementation scenario. The main purpose of the model is the definition of an optimal scenario for the new TT implementation at the cost parameters' minimization. The developed model can be used for the comparison of different new technologies' implementation scenarios and selection of the most appropriate of them by economic criteria taking into account the technical requirements and restrictions, imposed by the administration of the researched TN. In order to proceed to the stated problems it's necessary to define all their components and create corresponding mathematical abstractions [Zarubin, 2001]. Therefore it's necessary to offer a formalized description for each initial parameter used at the model development.

Researched Time Period

First of all it's necessary to decide how to display the researched time period in the model and solve it will be whether discrete or continuous. In general case, arrival of the requirements to increase the network capacity at the NTT implementation is stochastic process however, for the researched case acceptable results can be obtained with the usage of deterministic time function. The influence of stochastic requirements on the problem of network capacity's optimal extension is researched in [Knuth, 1976] where it's proved that considered stochastic processes can be replaced by equivalent deterministic queries. Network evolution's planning at the any TT implementation is performed for a limited time period.

That is, if T is the researched time period – discrete or continuous set, requirements model should represent some total and univocal correspondence $D : T \to \boldsymbol{R}^{\geq 0}$. Without generality limitation let's suppose that T is number set. Modeling is carrying for the limited time period. That is, if $\underline{t}$ is some moment of the researched period and $\bar{t}$ is moment of research end, $\underline{t} \neq \bar{t}$. Herewith it should be considered that making of the decisions about new technologies' implementation can be done only at the defined moments of the researched period. Set of such time moments makes some decomposition of the actual segment $[\underline{t}, \bar{t}]$ $t \in \tau_{[\underline{t}, \bar{t}]}$,

$$\tau_{[\underline{t}, \bar{t}]} = \{t_k\}_{k=0}^{h} : \underline{t} = t_0 < t_1 < t_2 < \ldots < t_h = \bar{t} , \tag{1}$$

where $\tau_{[\underline{t}, \bar{t}]}$ is decomposition of the segment $[\underline{t}, \bar{t}]$; h is the number of decomposition points; $t_k, k = \overline{0, h}$ are the decomposition points, corresponding to the researched time moments.

Intervals between such moments can be, generally speaking, different, however in order to simplify further calculations let's consider them as equally-spaced

$$\forall k,l=\overline{1,h}\quad t_k - t_{k-1} = t_l - t_{l-1} = \frac{\bar{t}-\underline{t}}{h} = \text{const}. \tag{2}$$

That is sequence $\{t_k\}_{k=0}^{h}$ is arithmetic progression $\forall k=\overline{1,h}\quad t_k=\underline{t}+(k-1)\Delta t$, where $\Delta t=\frac{\bar{t}-\underline{t}}{h}$ is arithmetical ratio.

As it can be observed from the character of the further reasoning and next lemma's proof, this assumption doesn't limit generality.

Lemma. For each segment $[\underline{t},\bar{t}]$ and its decomposition $\tau_{[\underline{t},\bar{t}]}$ it's possible to create equivalent, from the point of view of solved problem, decomposition $\tau^*_{[\underline{t}^*,\bar{t}^*]}$ of some other segment $[\underline{t}^*,\bar{t}^*]$, satisfying (2).

Proving. Let's suppose that all points t_k are rational numbers. If that isn't so, there is some irrational point t_k and it's possible to choose integer number arbitrary close t_k

$$\forall \varepsilon>0\ \exists t'_k\in \boldsymbol{Q}\ :\left|t'_k-t_k\right|<\varepsilon.$$

Since in any case initial measurements have some inaccuracy and result is required only with some accuracy, it's always possible to change irrational t_k to corresponding matched rational t'_k so that to don't let this influence on the modeling accuracy. All considered points t_k are rational, i.e. representable as fractions $t_k=\frac{m_k}{n_k}, m_k\in\mathbb{Z}, n_k\in\mathbb{N}$.

Let's define $\widehat{n}$ as least common multiple of all denominators n_k and create new decomposition points $\widehat{t}_k$ of which are defined as $\widehat{t}_k=\widehat{n}t_k$. Considering that points t_k set is limited and forms decomposition, as well as $\widehat{n}$ nonnegativeness, $\widehat{\underline{t}}\equiv\widehat{t}_1<\widehat{t}_2<\ldots<\widehat{t}_h\equiv\widehat{\bar{t}}$. As $\widehat{n}$ is divided by any n_k $\forall k=\overline{1,h}\quad \widehat{n}\vdots n_k$, all received new points will be integer numbers, i.e. $\forall k=\overline{1,h}\quad \widehat{t}_k\in\mathbb{Z}$. Let's supplement points $\widehat{t}_k$ with the rest of the integer numbers from the segment $[\widehat{\bar{t}},\widehat{\underline{t}}]$, set of which is marked as $\widetilde{\tau}$. Let's settle that network doesn't change in points $\widetilde{\tau}$. Let's mark received decomposition $\tau^*_{[\underline{t}^*,\bar{t}^*]}$ as

$$\tau^*_{[\underline{t}^*,\bar{t}^*]} : \underline{t}^* = t_1^* < t_2^* < \ldots < t_{h^*}^* = \bar{t}^*. \tag{3}$$

Then for each point t_k of initial decomposition $\tau_{[\underline{t},\bar{t}]}$ there is the only corresponding point $t^*_{k^*}$ in the received decomposition. Considering numeration in (3), k^* can doesn't coincide with k, so let's define supplementary function, representing natural numbers set in itself $\eta:\mathbb{N}\to\mathbb{N}$ where $\eta(k)=k^*$.

Then let's formulate important feature of the received decomposition $\tau^*_{[\underline{t}^*,\bar{t}^*]}$: spacing between any two points $\tau_{[\underline{t},\bar{t}]}$ coincide with spacing between corresponding points $\tau^*_{[\underline{t}^*,\bar{t}^*]}$ with the accuracy up to the fixed scaling coefficient. This means that

$$\forall t_k,t_l\in\tau_{[\underline{t},\bar{t}]}\quad \exists!\, t^*_{\eta(k)},t^*_{\eta(l)}\in\tau^*_{[\underline{t}^*,\bar{t}^*]} : \left|t_k-t_l\right| = \left|t^*_{\eta(k)}-t^*_{\eta(l)}\right|\widehat{n}. \tag{4}$$

This fact together with the agreement about the network constancy at the supplementary points $\tilde{\tau}$ provides invariability of received results at the change of $\tau_{[\underline{t},\bar{t}]}$ by $\tau^*_{[\underline{t}^*,\bar{t}^*]}$ with the accuracy up to the time-scale scaling. That finishes lemma proving. ■

Despite the constructiveness of the given proving, used procedure because of its considerable redundancy isn't well suitable for the practical usage. However, proving indicates the simplifying possibility of sophisticated mathematical structures, used at the network description, without loss of generality and accuracy. It should be noted that not quite formal character of reasoning is related only with the calculations simplifying, which doesn't carry a significant load on the scale of the solved problem.

Let's continue simplifying of arithmetic progression (1) by means $\underline{t} = 0$. This is well-founded as the model doesn't require real dates. Then $\bar{t} = h$ and sequence $\{t_k\}_{k=0}^{h}$ assumes the form $\{0, 1, 2, \ldots, h\}$. Let's mark so received T as $T = \{k\}_{k=0}^{h} = \{0, 1, 2, \ldots, h\}$. So T is the model of the researched time period.

Requirements Model

Whatever are the objectives at the network development process's modeling, mandatory element of initial data should be a demand for the network services at the each time moment. For the purpose of the determination of these requirements change's laws different mathematical models are used. Such model should uniquely identify the demand for the usage of specific purpose TT at the each time moment. Requirements, generated by the network at the new TT implementation, characterized by the number $n_i(t)$ of channels required, which are to be provided by the network, and the load intensity $\lambda_{ij}(t)$ on these channels, where $i, j \in T$; $t \in T$. Both parameters are time functions and are defined as following:

- $n_i(t)$ is number of the channels, demanded at the connection direction from the node $i \in I$ at the time $t \in T$;
- $\lambda_{ij}(t)$ is load (in Erlangs) on the link group from the node $i \in I$ to the node $j \in I$ at the time $t \in T$.

Herewith whatever is the model it can reflect reality only with some accuracy. So, let's use asymptotical marking [Brain, 1961] in order to describe real growth process of the network.

On this assumption, speaking about the requirements model and displaying the real process, let's understand asymptotically accurate estimation of the real process of the network development $D^*(t) = \Theta(D(t))$, which by definition means

$$\exists c_1, c_2, t_0 \in \boldsymbol{R}^+,: \forall t \in T : t > t_0$$
$$0 \le c_1 D(t) \le D^*(t) \le c_2 D(t)$$

This relationship ensures that since some time point real value of the demand for the TT usage will be concluded between two limiting curves - curves of demand model. Such approach allows describing the most important from the point of view of researched problem characteristics of the process such as rate and relative value of the TT implementation's growth, extreme and excesses points, limitations and so, without digressing on the minor fluctuations of the real process.

Definition $\Theta(D(t))$ assumes that functions $D^*(t)$ and $D(t)$ are asymptotically nonnegative, i.e. nonnegative at the big enough values of the argument t. That corresponds to the researched process. Moreover, since functions $D^*(t)$ and $D(t)$ can be considered as strictly positive, parameter t_0 can be excluded from the definitions by change of the constants c_1 and c_2 so that to let inequality be true at small t too. Notation

$D^*(t) = \Theta(D(t))$ includes in itself two estimates: upper and lower. They can be distinguished by means of additional markings $O(D(t))$ and $\Omega(D(t))$ [Abramowitz & Stegun, 1965].

Let's speak that $D^*(t) = O(D(t))$ if $\exists c \in \boldsymbol{R}^+,: \forall t \in T \, 0 \le D^*(t) \le cD(t)$ is true.

Let's understand $D^*(t) = \Omega(D(t))$ as $\exists c \in \boldsymbol{R}^+,: \forall t \in T \, 0 \le cD(t) \le D^*(t)$.

The researched model of new telecommunications technologies implementation

Let's consider the network during the time period *T* = {0, 1, 2, ..., *h*}. At the model analysis let's assume that the link group capacity can be any positive real numeric value and their number corresponds to the network users requirements. The development model uses the irreversibility assumption, which consists in the fact that once the new TT is implemented, no further funds addition for ETT are made, and assumption that as soon as NTT becomes available, there are no restrictions on its implementation.

At the overwhelming majority of the works, devoted to TN optimization, requirements model for the network development is described by a linear time function $D(t) = b + kt,\ k \ne 0$, where *b* is shift parameter, *k* is angular coefficient. There is carried out economic analysis of the TT development model at the linear requirements function in [Gayvoronska, 2001, Gayvoronska & Somsikov, 2002]. But authors in [Gayvoronska & Somsikov, 2006, Gayvoronska & Domaskin, 2013] show that usage of the logistic function

$$D(t) = \Theta\left(\frac{1}{1 + a^{-t}}\right) \tag{5}$$

is more convenient to describe the developing processes at the growth limitations. Logistic function shown at the Figure 1 has an inflection point.

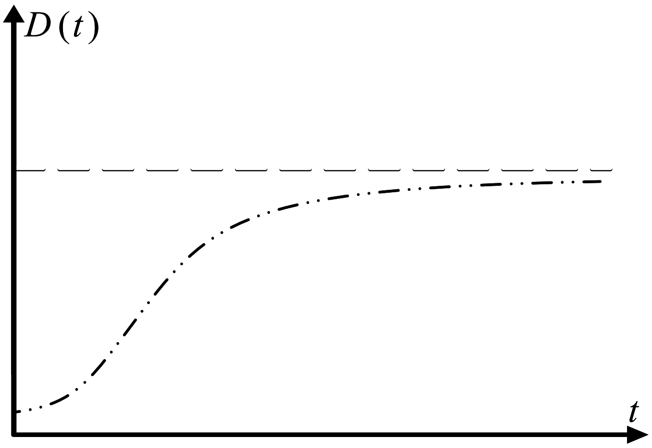

Figure 1. Logistic function

Function is convex downwards to the inflection point. This quite well characterizes the initial phase of the TT development process. Function becomes convex upwards after the inflection point. This corresponds enough to the market saturation. Another advantage of the logistic function is quite simple graph adaptation to the simulated process by usage of the coefficients and constants. Let's consider this process. For this purpose let's pass from the notations, used in (5), where coefficients impact on the function character is hidden, to the designation $D^*(t) = D(t) \pm c,\ c \in I\!R$, reflecting the coincidence between the real process and the model up to the some error.

In that case logistic function generally will be defined as

$$D(t) = \frac{a}{1 + be^{-ct}}, \quad a, b, c \in I\!R .$$

Here *a* coefficient corresponds to the limit of the saturation value

$$\lim_{t \to +\infty} D(t) = \frac{a}{1 + b \lim\limits_{t \to +\infty} e^{-ct}} = a .$$

In view of the fact that

$$D(0) = \frac{a}{1+b},$$

b coefficient is used for the description of the process initial conditions.

That is, if $\tilde{D}_0$ is initial value of the requirements and $\tilde{a}$ is the saturation value, it's enough to choose

$$\tilde{b} = \frac{\tilde{D}_0}{\tilde{a}} - 1$$

and then there will be

$$\tilde{D}(0) = \frac{\tilde{a}}{1+\tilde{b}} = \frac{\tilde{a}}{1 + \left(\frac{\tilde{D}_0}{\tilde{a}} - 1\right)} = \tilde{D}_0 ,\ \tilde{D}(t) \xrightarrow{t \to +\infty} \tilde{a} . \tag{6}$$

for the

$$\tilde{D}(t) = \frac{\tilde{a}}{1 + \tilde{b}e^{-ct}} .$$

Coefficient *c* characterizes the growth rate at the *t* increase. Using combinations of constants *a*, *b* and *c*, it's possible to receive a variety of the logistic function behaviors. This together with the asymptotic nature of its behavior makes it well suitable for these processes modeling.

If the absolute increase of the TT development indicator is proportional to the achieved development level and at the same time there are some factors, working in the opposite direction, such situation can be described by the expression $\frac{dY}{dt} = (c - \psi)Y$, where ψ is coefficient, taking into the account rate of CTT physical and mental aging. Assuming that $c = \text{const}$ and $\psi = \psi_1 Y$, we obtain

$$\frac{dY}{dt} = (c - \psi_1 Y)Y = c\left[\frac{1 - \frac{Y}{X}}{\psi_1}\right]Y = c\left(1 - \frac{Y}{a}\right)Y , \tag{7}$$

where $a = \chi / \psi_1$.

At the general case *c* and ψ can be both functions of TT reached development level and time functions. At the linear character of these dependences we have

$\mathrm{c} = \mathrm{c}_0 + c_1 t + a_0 + a_1 Y \quad \psi = \psi_0 + \psi_1 t + b_0 + b_1 Y$, where c_0, c_1, ψ_0, ψ_1 are the coefficients, characterizing dependence of the functions χ and ψ from the time, a_0, a_1, and b_0, b_1 are the coefficients, characterizing dependence of the functions χ and ψ from the TT development level.

Substitution of (6) in (7) gives

$$\frac{dY}{dt} = \left[(a_1 - b_1)Y + (c_1 - \psi_1)t + (a_0 + c_0) - (b_0 + \psi_0)\right]Y\ . \tag{8}$$

Putting of $\varepsilon = a_1 - b_1$; $\xi = c_1 - \psi_1$; $\eta = (a_0 + \chi_0) - (b_0 + \psi_0)$ into the (9) leads to $\frac{dY}{dt} = \varepsilon Y^2 + \xi\, tY + \eta Y$. As a result of this Ricardi differential equation is obtained [Gayvoronska et al., 2014 (2)]

$$\frac{dY}{dt} + f(t)Y + \varphi(t)Y^2 = 0\,,$$

where $\varepsilon = 2$, $f(t) = -(\xi t + \eta)$; $\varphi(t) = -\xi$.

Solution of this differential equation gives

$$Y = \frac{e^{\frac{gt^2}{2}} + \eta t}{C - j\int e^{\frac{gt^2}{2}} + \eta t dt}\,, \tag{9}$$

where c is the constant of integration.

Depending on the specific parameters of the logistic function and the relations between them, different kinds of network development can be obtained [Gayvoronska & Somsikov, 2006]: no development; unlimited growth; unlimited decay; logistical or environmental development. Lack of TT development takes place when $\eta + \xi t + \varepsilon Y = 0$, its usage's unlimited growth meets the condition $\eta + \xi t + \varepsilon Y > 0$, its unlimited decrease is when $\eta + \xi t + \varepsilon Y < 0$. Y = const at the lack of the development, $Y = Ae^{\lambda t}$ at the unlimited growth and $Y = Ae^{-\lambda t}$, where $\lambda = \eta + \xi t + \varepsilon Y$, at the unlimited decay.

The main features of the logistics process are: positive characteristics of the process at the initial time moment; relatively fast growth of the curve at the initial stage of the process; inflection point; slow growth of the curve after the inflection point; asymptotic approximation of the process to the limit of saturation $a = \frac{\eta}{|\varepsilon|}$. Mathematical conditions of the process logistical character are $\varepsilon = 0$, $\xi = 0$, $\eta > 0$, $a > Y(0)$. The first condition, means that the absolute increase of the TT development level and reducing of unmet demands of its usage coincide in time. The second condition shows that the TT demands' reducing process is influenced by other factors. The third condition means that the TT development level at the initial time moment didn't provide all requirements, i.e. process research begins at the time of necessary TT deficit. The fourth condition determines that the saturation state exceeds the initial development level, i.e. requirement of process growth is formulated.

Logistics development is possible only if c and ψ are functions of the TT development level, i.e. $c = f(Y)$; $\psi = f(Y)$. If at least one of these functions is independent of Y and is the time function of the development process, the logistics process passes into the environmental one, where there is dying out instead of saturation at the final stage of the network development. At the usage of the environmental process authors analyzed the usage possibility of the population dynamics' mathematical apparatus for the formalization of the TT development process.

For this purpose authors formalized the concept of the kinetic curve [Gayvoronska et al., 2013 (1), Gayvoronska et al., 2014 (2)] and submitted function $Y(a,b,c;f(t))$ for the consideration. This function describes life cycle of the technology development in time. By the usage of the similar to the mentioned approach for the logistic function it's shown that by means of different values of *a*, *b* and *c* parameters and function $f(t)$ representations it's possible to construct a large family of curves, representing different variants of technologies development, namely: highly oscillatory; sufficiently smooth; with a larger or smaller number of extreme points. Such diversity of the function behavior makes it convenient to use in order to create models for various technologies' life cycle's description.

An important stage in the technology life cycle's modeling is the ability to determine the costs and profits of the network operator at the different stages of the TT development. There is graph of some TT development on the Figure 2. Line $y = D$, where *D* is a constant, corresponds to the period of technology's stable usage. For this case it's possible to determine the costs and profits of the network operator at the initial stage of TT implementation and his possible losses during the period of the technology going to the period of stable development. For this purpose let's solve the equation

$$Y(a,b,c;f(t)) = D. \tag{10}$$

According to the function graph at the Figure 2, t_1, t_2, t_3 will be the roots of the equation. Then by analogy with approach given in [Gayvoronska, 2001] it's possible to determine network operator's costs at the separate stages of the TT development.

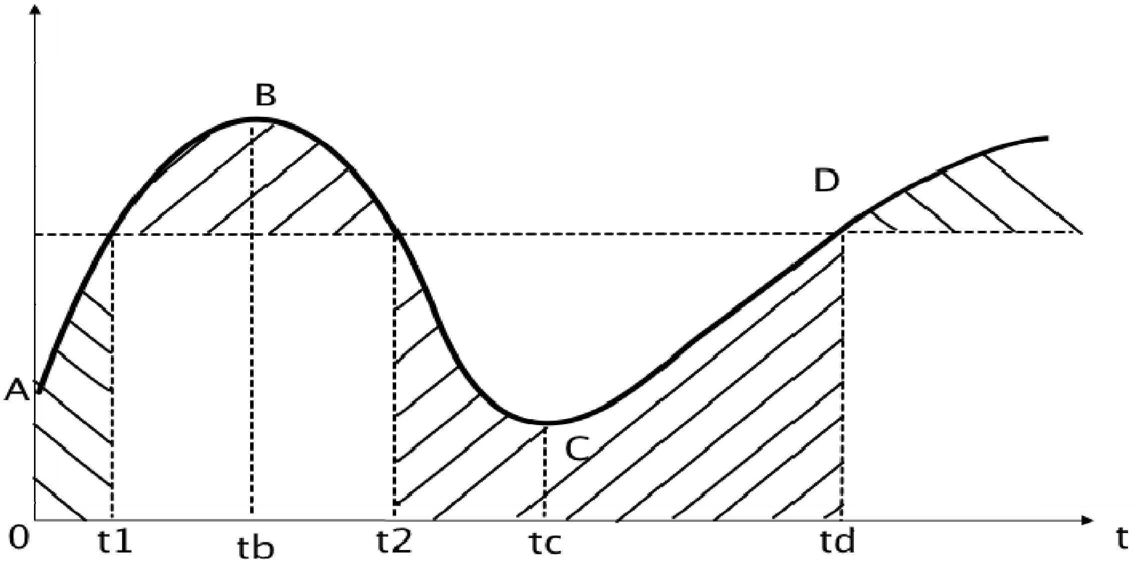

Figure 2. Estimation of the TT usage's economical aspects

Costs at the initial stage of the TT implementation can be received from the equation

$$D_{[0;t_1]} = \int_0^{t_1} Y(a,b,c;f(t))dt\,. \tag{11}$$

Profits at the TT rapid implementation, which are exceeding the average level,

$$D_{[t_1;t_2]} = \int_{t_1}^{t_2} Y(a,b,c;f(t))dt\ . \tag{12}$$

At the passing to the “disappointment” period and TT usage’s decay operator looses make

$$D[t_2;t_d] = \int_{t_2}^{t_d} Y(a,b,c;f(t))dt\ . \tag{13}$$

Stable, rather small in comparison with the “exaggerated expectations” period, network operators’ profit at the technology going out from the “disappointment” period can be determined as

$$\lim_{k\to\infty}\left(\int_{t_d}^{k} Y(a,b,c;f(t))dt\right) \tag{14}$$

in assumption about convergence of this improper integral.

Conclusion

Each technology at the moment of its analysis is at the definite point of its development. Even knowing exactly the market size for the researched technology (in monetary or other estimation), it’s difficult to predict the market development for each particular technology, if it isn’t already at the stage of steady decay. In order to make required decisions about the telecommunication technologies’ development it’s necessary to pay attention to four aspects. The first aspect understands of the technology’s general life cycle. The second aspect is determination of the current stage of technology development. The third aspect is the collection and processing of statistical information concerning the technology implementation. The fourth aspect is forecasting of the concrete technology’s users’ number on the base of the collected statistical data.

The approach proposed in this paper can be used for modeling of any new technology’s implementation into the existing telecommunication network. Direction of further research is the final formation of the analytical model for the estimation of technology’s concrete development stages and decision making about the necessity and timing of its implementation. If the technology is already widely used, then the problem of its life cycle’s estimation arises. All these questions should be answered by means of the researches results carried out with the usage of the proposed model.

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Authors' Information

Galina Gayvoronska *– Head of the Information-Communication Technologies' Department,*

V.S. Martinovsky Institute of Refrigeration Cryotechnologies and Ecoenergetics ONAFT, Odessa, Ukraine, 65082, Dvoryanskaya str., 1/3; e-mail: gsgayvoronska@gmail.com

Major Fields of Scientific Research: optimization of transient periods at telecommunication networks' evolution. Calls' streams, load and internodal inclination in nets. Problems of perspective access networks' and fully optical switching systems' development

Petr Yatsuk *– Chairman of the National Commission for the State Regulation of Communications and Informatization, Kiev, Ukraine, 01001, Khreshchatyk str., 22;*

e-mail: petr_yatsuk@ukr.net

Major Fields of Scientific Research: processes of data transfer technologies' implementation in telecommunication networks