MULTI-OBJECTIVE SELECTION OF STRUCTURE VARIANTS FOR A CORPORATE HETEROGENEOUS INTEGRATED SYSTEM OF INFORMATION MANAGEMENT

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Abstract: The paper explores issues of both optimization and rational design of heterogeneous traffic servicing integrated systems. The primary goal of the paper is to develop a toolkit for selection of structure variants and parameters of distributed systems with a heterogeneous medium as part of a subsystem of managing the modelling and upgrading of the systems in question. The research subject is a system consisting of air and cable multiple-access systems. The multi-objective problem of structure variants has been solved for systems that differ in access protocols, communication media and transmission velocity within these media, as well as in quality of transmission channels and quantity of customers. Preferred Pareto set of system construction variants has been derived. The selection problem has been solved within the double-objective space for each type of traffic with consequent merging of obtained results. The structure of a model information system, which was used as one of the application objects for obtained results and for the comparison of characteristics, went through a number of stages of comprehensive upgrade that resulted in merging of all types of customers in united subsystems of integral traffic, realization of unified functioning of these subsystems with a connectivity to a common access system and with an output into a united transportation system, which, consequently, led to formation of a joint data stream.

Key words: Heterogeneous medium, communication system, mathematical model, optimal design.

1. INTRODUCTION

The paper builds upon previous studies [1, 2] and elucidates issues of both optimization and rational design of heterogeneous traffic servicing integrated systems. The research subject is a system that consists of air and cable multiple-access systems.

The paper [1] considers some problems and peculiarities of the modelling and rational design of heterogeneous traffic servicing integrated systems. In [1] a comparative analysis of existing technologies in modelling of distributed systems with a heterogeneous medium as part of a subsystem of managing the modelling and upgrading of the systems in question is done. Improvement in both management and modernization processes of the above-mentioned systems is prompted by a necessity to narrow down the range of permissible solutions to enhance the efficiency of the outlined processes and reduce their economic cost.

The paper [2] contains a description of a heterogeneous system model for both air and cable subsystems, as well as for an intersystem interface; session and binomial models of voice and data delivery were built in [2] based on z-transformation of delivery time and temporal distribution of service intervals.

It is apparent that both probabilistic and temporal characteristics of the system will depend on its structure and the benchmarking analysis of systems with different structures has to be performed in order to determine the influence of systems' structure on it characteristics.

2. STATEMENT OF A PROBLEM

The structure of each subsystem, as represented in [1], contains sub-vectors: protocols, topology, hardware components and management information system. Sub-vectors of both hardware components and management information system are defined by a level of technological development and usually do not vary during the process of comparison. The topology is assumed to be preassigned in the given study. Therefore, in the comparison of systems' behavior the variation of protocols by sub-vectors is used.

The system that is simulated by a mass-service system and satisfies following assumptions [3] is being examined:

- different interaction protocols are used in communication sub-systems;

- the system is geared toward transmission of integral, asynchronous and isochronous traffic in real-time: speech, interactive data;

- non-homogeneous transmission media (cable and air) are used in the system;

- data streams with binomial distribution on intervals T_0, which are conventionally considered as units of discreet time, arrive at inputs of workstations independently of each other;

- the model of subsystems and of any workstation is represented by a stochastic servicing system of a general form $M^D/G^D/1$ [4, 5];

- transmission medium access protocols, which ensure work on a real-time scale, often referred to as deterministic (conflict-free) protocols [6, 7] are examined;

- the protocol for increasing of fidelity (an algorithm of error control in a communication channel) that utilizes noise-free code with r_c control bits and monitoring feedback with a stand-by [8, 9] is implemented in a sub-system of data transmission;

- protocols without additional error control (point-to-point transmission with erasure) are utilized in a sub-system of voice transmission;

- the synchronous method is utilized for delivery of an acknowledgement character for a reception of a dispatched information frame;

- transmission buffers of a workstation have an unlimited capacity;

- errors occur in discrete communication channels with probabilities p_c and p_a within cable and air transmission media, respectively;

- the deterioration of information is given by a process with a geometric distribution and a parameter Q_d in discrete time;

- the multivariance exists for selection of media and transmission velocities within them.

Through the study, the model of system's structure, which is represented in a generic form by expressions (1) – (4), is utilized while assumptions about identical end-point devices and the unified system of the administrative control are being considered.

One of criteria for selection of variants is the criterion of capital investments K, which takes into account economic (cost) expenditures and both technical and economic indicators. The criterion K comprises indicators of system's operational efficiency, which are represented by both technical and economic components that are derived from cost parameters of the entire system in general and of each workstation in particular. The criterion of capital investments K is sought to be decreased.

Components of the criterion K are:

1. Active network equipment of a cable subsystem – C_1.
2. Price of a workstation in a cable subsystem for data transmission – C_2.
3. Price of a workstation in a cable subsystem for voice transmission – C_3.
4. Price of a device for media interfacing – C_4.
5. An over-the-air transmitter/receiver unit – C_5.
6. Price of a workstation in an over-the-air subsystem for data transmission – C_6.
7. Price of a workstation in an over-the-air subsystem for voice transmission - C_7.

Coefficients C_1 and C_5 depend on quantity of users and on the transmission velocity within the medium. Active network equipment in the cable subsystem (C_1) – is the variable, which is defined by the quantity of users (23 workstation per one active device; 24^{th} port is used for the linkage of equipment to each other); its value depends on transmission velocity within the cable medium V_{ck}. Coefficient C_1 assumes common price values [in currency units – c.u.] in accordance with the transmission velocity within the cable medium:

- 1500 c.u. – at $V_{ck} \le 100$ Mbit/s;
- 2000 c.u. – at $V_{ck} \le 1000$ Mbit/s;
- 2500 c.u. – at $V_{ck} > 1000$ Mbit/s;

Coefficients C_2 and C_3 include prices of data and voice workstations in the cable sub-system. Their prices are 700 c.u. and 750 c.u., correspondingly. Coefficient C_4 includes the price of the controlling system, which realizes interaction between subsystem users. Its price value is taken to be equal to 1000 c.u. The price of the over-the-air transmitter/receiver unit (C_5) is also defined by a numbers of users and transmission velocity within the air medium V_{ca}. The over-the-air transmitter/receiver is able to handle up to 128 users connecting to it. Price values of coefficient C_5 in accordance with transmission velocity are thus defined:

- 1500 c.u. – at $V_{ca} \le 20$ Mbit/s;
- 2000 c.u. – at $V_{ca} \le 50$ Mbit/s;
- 2500 c.u. – at $V_{ca} \le 100$ Mbit/s;
- 3000 c.u. – at $V_{ca} > 100$ Mbit/s;

Coefficients C_6 and C_7 include prices of the workstation for transmission of both data and voice messages in the air sub-system, which are 700 and 750 c.u., correspondingly. Therefore, the expression for the capital investments criterion can be written as:

$$K=a*C_1+C_2+C_3+C_4+b*C_5+C_6+C_7 \quad (1)$$

where $a=(N_{kv}+N_{kd})/24$; $b=(N_{av}+N_{ad})/128$ rounded to the next highest integer; N_{kv}, N_{kd}, N_{av}, N_{ad} – a number of objects within the cable (voice messages – data) and air (voice messages – data) sub-systems, respectively.

The multitude of structure variants of the system w, from which the selection is made, (i.e. the multitude of variants, presented for selection) is denoted as $\overrightarrow{W^*}$. Structure variants vary in respect to access protocols, transmission media, transmission velocity in the media, quality of transmission channels, and the length of data portion of the packet and in number of users. The capital expenditure criterion K is considered in the capacity of the characteristic, which takes into account technical and economic indicators. The selection function $C(\overrightarrow{W^*})$ reflects first-preference elements from $\overrightarrow{W^*}$. Let us state the following problem of the multi-objective selection of system variants [10, 11], which is reduced to the search for:

$$\begin{gathered} C(\vec{W}^*) = \arg\min_{w\in\vec{W}^*} \overline{t}_{q_j}(w), \\ C(\vec{W}^*) = \arg\max_{w\in\vec{W}^*} \overline{\Pi}_{q_j}(w), \\ C(\vec{W}^*) = \arg\min_{w\in\vec{W}^*} K(w),\ j=\overline{1,J}, \end{gathered} \quad (2)$$

under following delimitations:

$$\overline{t}_{q_j} \le \overline{t}_{q_j app},\ j=\overline{1,J},\ \overline{\Pi}_{q_j} \ge \overline{\Pi}_{q_j app},\ j=\overline{1,J} \quad (3)$$

where $\overline{t}_{q_j}$ – is an average delivery time of j-type messages, $\overline{t}_{q_j app}$ – a permissible value of an average delivery time of j-type messages, $\overline{\Pi}_{q_j}$ – a probability of "just-in-time" delivery of j-type messages, $\overline{\Pi}_{q_j app}$ – a permissible value of a probability of "just-in-time" delivery of j-type messages, K – capital investments.

3. DISCUSSION OF THE APPROACH TO THE PROBLEM

The selection function C within the set w is called the Pareto function [12, 13] if the variant $\overrightarrow{W^*}$ is contained in the selected set C($\overrightarrow{W^*}$) and if such an element y, which belongs to $\overrightarrow{W^*}$, does not exist, so that values of numerical characteristics n_1, …, n_J for the element y do not exceed for w:

$$C(\overrightarrow{W^*})=\{w|(|\ \exists y \in \overrightarrow{W^*}, y\neq w)\ [n_i(y)\geq n_i(w)\ (i=\overline{1,J})]\} \quad (4)$$

While J=3, the tri-objective selection of variants, which was outlined above, corresponds to the Pareto function of selection that is defined by (4) with characteristics n_1, n_2 and n_3, because i=1,2,3, variants of the Pareto set that are delivered to minimums n_1, n_2 and n_3 [14, 15].

In this case, the variant w falls within selected set of Pareto variants C($\overrightarrow{W^*}$) if the variant $y\in\overrightarrow{W^*}$, such that $n_1(y)<n_1$ (w) $n_2(y)<n$ (w) and $n_3(y)<n$ (w), does not exist for any variant $w \in \overrightarrow{W^*}$ that can be found in accordance with (4) and defined selection problem. The Pareto set is formed by the cone, which coincides with the third negative quadrant, or the selected Pareto set of variants contains only those elements w of set $\overrightarrow{W^*}$, for which $P^{-}_{w',j}(w)=\varnothing$, i.e. the lower section is void [13].

The computational aspect of the multi-objective problem can be reduced to the sequence of single-objective and double-objective optimization problems. The cost of searching for a variant can be decreased, if a procedure of variant enumeration is implemented simultaneously with filtering out those variants that do not satisfy preassigned limitations. Therefore, at the beginning variants, which do not satisfy the preassigned limitation, i.e. those variants, in which $\overline{\Pi}_{q_j} \le \overline{\Pi}_{q_j app}$, $\overline{t}_{q_j} \le \overline{t}_{q_j app}$ are excluded from further consideration.

Next, by using the principle of decomposition [12, 13] let us break down the multi-objective selection into j, $j=\overline{1,J}$ of two-objective (with respect to $\overline{t}_{q_j}$ and $\overline{\Pi}_{q_j}$, $\overline{\Pi}_{q_j}$ and k_j, $\overline{t}_{q_j}$ and k_j) procedures for the Pareto set search.

Then let us define Pareto sets for each sub-system j, $j=\overline{1,J}$:

$$C_j(\vec{W}^*)=\arg\min_{w\in\vec{W}^*}\overline{t}_{q_j}(w),\ C_j(\vec{W}^*)=\arg\max_{w\in\vec{W}^*}\overline{\Pi}_{q_j}(w),\ j=\overline{1,J} \quad (5)$$

$$C_j(\vec{W}^*) = \arg\min_{w\in\vec{W}^*} \overline{t}_{q_j}(w),\ C_j(\vec{W}^*) = \arg\min_{w\in\vec{W}^*} K_j(w),\ j=\overline{1,J} \quad (6)$$

$$C_j(\vec{W}^*) = \arg\max_{w\in\vec{W}^*} \overline{\Pi}_{q_j}(w),\ C_j(\vec{W}^*) = \arg\min_{w\in\vec{W}^*} K_j(w),\ j=\overline{1,J} \quad (7)$$

under limitations (3).

Let us introduce the concept of the Pareto set $P^{-}_{w',j}(w,\varepsilon_j)$ with the insensitivity zone [13], for which the potency of the lower boundary of the set is smaller than or equal to a given range ε_j:

$\left|P^{-}_{w',j}(w,\varepsilon_j)\right| \le \varepsilon_j$, ε_j - is an integer, ε_j= const.

When considering the range ε_j=0, we have an ordinary Pareto set.

Next, let us perform merging of solutions of two-objective selection, which were found for every j with the goal of deriving the final solution C($\overrightarrow{W^*}$). The merging can be achieved by using operations of merging or intersection. When operation of merging is used, following expression is obtained:

$$C(\overrightarrow{W^*}, \varepsilon) = C_1(\overrightarrow{W^*}, \varepsilon) \bigcup C_2(\overrightarrow{W^*}, \varepsilon) \bigcup \ldots \bigcup C_j(\overrightarrow{W^*},\varepsilon) \bigcup \ldots \bigcup C_J(\overrightarrow{W^*},\varepsilon) \quad (8)$$

where $C_j(\overrightarrow{W^*},\varepsilon)$ is found from the solution of the problem (2), while

$$C_j(\overrightarrow{W^*},\varepsilon)= P^{-}_{w',j}(w,\varepsilon_j).$$

When the operation of intersection (logical intersection) is used for merging of sets, we obtain

$$C(\overrightarrow{W^*},\varepsilon) = C_1(\overrightarrow{W^*},\varepsilon) \bigcap C_2(\overrightarrow{W^*}, \varepsilon) \bigcap \ldots \bigcap C_j(\overrightarrow{W^*},\varepsilon) \bigcap \ldots \bigcap C_J(\overrightarrow{W^*},\varepsilon) \quad (9)$$

and derive the most rigid solutions.

At given interval ε_j cases, when sub-sets that were examined above, do not match. Such case leads to multiple choices when the intersection operation is used, i.e. C($\overrightarrow{W^*}$,ε) = $\varnothing$ and cannot be examined. Likewise, a case is possible when Pareto sets partially match under given ε_j. The most favorable solution of the selection problem appears in those instances when ε_j, j=$\overline{1,J}$ and all elements of sub-sets with number J do match. Increase of the interval ε_j, j=$\overline{1,J}$ leads to the growth of elements in the set of the multi-objective selection of variants and might be considered acceptable upon agreement with a customer.

An example of a solution of the above-posed problem with regard to the insensitivity zone (the zone of permissible value deviations of probabilistic and temporal characteristics) is provided below.

4. THE EXAMPLE OF SYSTEM'S STRUCTURE SELECTION

The example of multi-objective selection of the system's structure is based upon previously made assumptions and solution procedures of the posed optimization problem. Selection of variants will be made for both voice and data sub-systems with consequent merging of obtained results.

The selection procedure for the multitude of variants of heterogeneous integral communication system depending on the interval of the insensitivity zone can be formulated for two cases:

1) The interval of the insensitivity zone is equal to zero: $\varepsilon_j=0$, $j=\overline{1,J}$, i.e. the conventional Pareto set is found;

2) $\varepsilon_j > 0$ is assigned and the Pareto set with the insensitivity zone is defined: $\varepsilon_{\bar{\tau}_{q_j}} = 1$ ms, $\varepsilon_{\bar{\Pi}_{q_j}} = 0{,}001$, $\varepsilon_{K_j} = 500$.

Multiple choices of system construction variants are defined by applying operations of either concatenation (8) or intersection (9) to obtained results.

Source data, with exception of previously outlined, are presented in Table 1.

Table 1. Source data for solving the optimization problem.

Parametric variable	**Value**
The length of the preamble (bits)	$r_{pr}=32$
The length of the flag (bits)	$r_f=8$
The length of the control field (bits)	$r_{pc}=8$
Number of control bits in the cable sub-system (bits)	$r_{cc}=16$
Number of control bits in the air sub-system (bits)	$r_{ca}=16$
The length of the token of the air sub-system (bits)	$n_{ma}=16$
The length of the acknowledgment in the cable sub-system (bits)	$n_{ckv}=16$
The length of the acknowledgment in the air sub-system (bits)	$n_{akv}=16$
The length of the control command “the end of the cycle”	$n_{ec}=16$
Time of frame decoding	$\bar{t}_{dc.k}=0$
Time of acknowledgement decoding	$\bar{t}_{dc.kv}=0$
Average permissible time of data ageing	$\bar{T}_d=1$
Lengths of data portions of packets (s)	$k_{av}=1024$, $k_{ad}=32$, $k_{cv}=1024$, $k_{cd}=32$
Number of workstation in each sub-system	10
The length of the cable channel in ring and bus wire (*m*)	$D_{mc}=2000$, $D_{ml}=1200$
The working range of the air sub-system (*m*)	R=2000

Intensity of incoming stream of messages (packets per second) in each sub-system	10-40
Probability of occurrence of voice and data users in the air sub-system	0,5
Specific loading of customer traffic of voice and data type for both air and cable sub-system	0,1
Probability of traffic closure within sub-systems	0,5
Error probability in the air channel	$p_a=1*10^{-4}$
Error probability in the cable channel	$p_c=1*10^{-6}$

The criterion of capital investments for a =b=1, C_1=1500, C_2=C_3=7000, C_1=1000, C_5=2500, C_6=C_7=7500 is defined as:

$$K = a \cdot C_1 + C_2 + C_3 + C_4 + b \cdot C_5 + C_6 + C_7 =$$

=1*1500+7000+7500+1000+1*2500+7000+7500=34000 c.u.

Let us introduce a limit for a permissible value of a "just-in-time" delivery $\overline{\Pi}_{q_j app} \geq 0{,}9$ – for voice; $\overline{\Pi}_{q_j app} \geq 0{,}65$ – for data. By excluding from possible variants of system construction those variants that do not satisfy given limitation, i.e. those variants, in which $\overline{\Pi}_{q_j} \leq \overline{\Pi}_{q_j app}$, let us formulate multiple choices of system construction, which are presented for selection.

Next, let us break down the multi-objective selection into three two-criterial procedures of the Pareto sets search. At the beginning, let us define Pareto sets with insensitivity zone ε_j for two-objective selection of multiple choices of system construction variants with regard to $\overline{t}_{qj}$ and $\overline{\Pi}_{q_j}$, $\overline{\Pi}_{q_j}$ and K_j, $\overline{t}_{qj}$ and K_j.

The algorithm for the Pareto set generation for studied selection of system variants is described below:

1. Variants of construction for a system that are taken from the multitude of variants, which were presented for selection, are arranged in order according to characteristic property $\overline{t}_{qj}$ in increasing order of its magnitude. After $\overline{t}_{qj}$ series has been composed with regard to $\geq$, let us put in corresponce with it the series of variants of system construction. The sequence of values $\overline{t}_{qj} \backslash \overline{\Pi}_{q_j}$ and corresponding variants of system construction are both obtained.

2. The series of $\overline{\Pi}_{q_j} \backslash K_j$ values, which corresponds to variants of system construction in step 1, is delineated.

3. The system construction variant with a minimal value $\overline{t}_{qj}$ and corresponding value $\overline{\Pi}_{q_j}$ in increasing order of values $\overline{t}_{qj}$ is introduced into the Pareto set Ω_p.

4. The system construction variant with a maximum value $\overline{\Pi}_{q_j}$ and corresponding value K_j in decreasing order of characteristics $\overline{\Pi}_{q_j}$ is introduced into the Pareto set.

5. Such system construction variants are introduced into the Pareto set, for which following inequations are true:

$$\overline{t}_{qj}^{'} - \overline{t}_{qj}^{''} \le \varepsilon_{\overline{t}_{q_j}},\ \overline{\Pi}_{q_j}^{'} - \overline{\Pi}_{q_j}^{''} \le \varepsilon_{\overline{\Pi}_{q_j}},\ K_j^{'} - K_j^{''} \le \varepsilon_{K_j},$$

where $\overline{t}_{qj}^{''}$, $\overline{\Pi}_{q_j}^{''}$, $K_j^{''}$ – are values $\overline{t}_{qj}$, $\overline{\Pi}_{q_j}$ and K_j of the last variant, which was included in Ω_p in decreasing order of magnitude of respective values; $\overline{t}_{qj}^{'}$, $\overline{\Pi}_{q_j}^{'}$ and $K_j^{'}$ – are values $\overline{t}_{qj}$, $\overline{\Pi}_{q_j}$ and K_j of the present variant, $\varepsilon_{\overline{t}_{q_j}}$, $\varepsilon_{\overline{\Pi}_{q_j}}$ and ε_{K_j} - is the insensitivity zone of the Pareto set as to $\overline{t}_{qj}$, $\overline{\Pi}_{q_j}$ and K_j, correspondingly.

When multiple choices of system structure, which were obtained when the selection problem was solved without considering the insensitivity zone, are compared, the conclusion regarding their similarity can be made. It is necessary to note that in case when Pareto sets are searched for while taking into account the insensitivity zone, the number of elements of the set increases, particularly when the operation of concatenation is used.

Similarity between sets of choices, which were included in the selected Pareto set for different sub-systems with and without consideration for the insensitivity zone, is an indicator of selection efficiency, which is conducted by employing the proposed method.

The given method allows to qualitatively estimate the functioning of the system depending on the range of operating parameters and to obtain optimal design solutions.

5. VERIFICATION

The testing of compliance of the developed model and software was performed by evaluating characteristics (average delivery time of integral traffic), which were measured on an existing object by using software and hardware tools as well as those, calculated using the software program. Comparison demonstrates adequacy of further expansion of the system and increase of the number of users. The functioning of the system, which satisfies constraints, is maintained with increase of N_{cd} to over 300 workstations, N_{cv} – to 180 workstations; N_{ad} – to 80 workstations and N_{av} – to 100 workstation at rates that vary from 0,1 to 1000 Mbit/s.

The multi-objective problem of selection of structure variants for systems, which differ in access protocols, communication media and transmission velocity within them, quality of transmission channels and quantity of users, was solved. Preferred Pareto set of system construction variants was obtained. The selection problem is solved in two-criterial spaces: $\overline{t}_{qj} - \overline{\Pi}_{q_j}$, $\overline{t}_{qj} - K_j$, $\overline{\Pi}_{q_j} - K_j$ for each type of traffic with the consequent merging of results.

6. CONCLUSION

In the paper, development of the selection toolkit is carried out for structure variants and parameters of distributed systems with a heterogeneous medium as part of a subsystem of managing the modelling and upgrading of the systems in question. The research subject is a system consisting of air and cable multiple-access systems.

The multi-objective problem of variant selection for system structures, which differ in access protocols, communication media and transmission velocities within these media, quality of transmission channels and quantity of users. Preferred Pareto set of system construction variants was obtained. The selection problem is solved in two-criterial spaces for each traffic type with the consequent merging of results.

The structure of the model information system, which serves as one of the objects for application of both the obtained results and the comparison of characteristics, underwent a series of steps of the comprehensive upgrade, which resulted in unification of all types of users into united sub-systems of integral traffic, realisation of unified functioning of sub-systems with their linkage to the common access system and exit toward unified transportation system, which, consequently, leads to the formation of the united data stream.

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