# MULTI-AGENT INFORMATION PROCESSING AND ADAPTIVE CONTROL IN GLOBAL TELECOMMUNICATION AND COMPUTER NETWORKS

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*Abstract: The problems and methods for adaptive control and multi-agent processing of information in global telecommunication and computer networks (TCN) are discussed. Criteria for controllability and communication ability (routing ability) of dataflows are described. Multi-agent model for exchange of divided information resources in global TCN has been suggested. Peculiarities for adaptive and intelligent control of dataflows in uncertain conditions and network collisions are analyzed.*

*Keywords: adaptive and intelligent control of dataflow, models for multi-agent processing and information transfer, telecommunication and computer networks.*

## Introduction

The main aim of control for global telecommunication and computer networks (TCN) is a fast search and delivery (transportation) of necessary information to TCN users-agents with high quality of submitted services. So the general problem of control and multi-agent processing of information in TCN may be divided on four interconnected subproblems:

- control for dataflows between TCN agents with adaptation to different kinds of heterogeneous traffic;
- organization for multi-agent dialogue between TCN agents;
- telecommunication equipment control;
- administrative control for productivity and configuration of TCN.

In global TCN (for example, Internet) control for transfer and distribution (routing) of dataflows between agents should be done not on severe program but “in loose” on changing unpredictably users or nodal TCN components requests.

Traditional approach to TCN control does not provide interactivity in real time (for example, speech dialogue without relays) often. The other disadvantages are non-adaptivity (by relation to changing traffic) of control for dataflows, impossibility for automatic avoiding of network conflicts, fault recognition and TCN reconfiguration without human (administrator or network operators) participation.

## 1. Problems of Adaptive Control and Multi-Agent Processing in TCN

At design and exploitation of modern TCN important role is given to theory and tools of control for flows of transferred data. However today theory of TCN control (differently from, for example, theory of automated control for motions of aircraft, robots and the other mobile objects) has been developed weakly.

Therefore necessity in setting, formalisation and solution of problems for control, processing and information transfer in TCN in dialogue mode in uncertain conditions arises.

Specific character of TCN as control object is in distributed character of TCN components and controlled flows of different (heterogeneous) data, transferred through TCN nodes along different routes and communication channels. Consequently TCN control system should be distributed and have multi-level hierarchical structure.

Specific aims and problems of control arise on every level of this system. However many of those aims are not formalized and problems are not solved (it means that theoretically proved models of “collective dialogue and control algorithms” do not exist for these problems). So in the paper significant attention is devoted to setting and solution of problems for organization of multi-agent dialogue and dataflows control in uncertain and network conflicts conditions.

Uncertainty of TCN exploitation conditions is in unpredictable character of change and in heterogeneity of network traffic. The number of TCN users-agents is also uncertain and change significantly during the day. TCN may have misworks or faults of separate components as well as different kind of network conflicts. So it is necessary to have adaptation for traffic, monitoring and diagnosis of TCN states and also classification and resolution of network conflicts.

Noted TCN specifities require investigation and development for adaptive approach to solution for problems of “collective” dialogue and dataflows in TCN on the base of modern intelligent and multi-agent technologies. Suggested methods for adaptive and intelligent control provide adaptation to traffic, changing unpredictably, adaptive routing of dataflows, multi-agent information processing, TCN functional diagnosis, recognition and resolution of network conflicts [Timofeev A.V.,1996,2001,a,b,2002].

A wide class of complex distributed TCN may be presented as multi-agent system (MAS). Here users of TCN or nodal computers or local TCN as TCN segments work as TCN agents.

Typical features of these TCN agents are existence of local databases and knowledge bases and telecommunicational channels for information exchange between agents in the process of mutual use of distributed informational resources and processing of transferred information.

The main peculiarity of multi-agent processing of information and control is that firstly complex problem is decomposed (fragmented) on the series of local problems, which solution is distributed (disparallel) between agents, and then results of solution of these local problems are agregated (integrated) and realized with the help of telecommunicational resources.

Information processing MAS work is supported by TCN, realized network technologies of data transfer between agents. Communication between remote agents is executed on the level of their local databases and knowledge bases by the way of controlled message exchange in the process of solution for local (individual) or general (global) problems.

Significant theoretical and practical interest is given to two strategies for multi-agent processing and information transfer:

- with coordinator (when one of the agents is responsible for coordination of behaviour of all other agents);
- without coordinator (when all agents have “equal rights” and do not submit to leading agent-coordinator).

At multi-agent control for dialogue and dataflows in TCN it is necessary to develop the methods for automatic avoidance or resolution for conflicts, which may occur between TCN agents.

In connection with it a significant value belongs to multi-agent models and algorithms for information processing (code replication, data fragmentation, adaptive routing etc.)

At design for TCN dataflow control systems a reliability of used equipment plays important role. Reliability of global TCN is lower if TCN consists of more nodal computers. It is explained that with increased number of TCN nodes the probability for failure of one or several computers increases. That is why necessity for adaptive control and multi-agent processing for information in TCN, that guarantee problem solution at unpredictable traffic change, fault or failure of one or several nodal TCN computers, appears.

## 2. Global Controllability and Dialogue Possibilities of TCN

The main requirement for global TCN is the possibility to provide the main function - to provide for real and potential users a controlled access to distributed informational, computing and telecommunicational resources of all nodal computers or local TCN, united in a global network. To satisfy this requirement TCN, as complicated dynamics object for informational control, should be globally controlled.

Modern control theory means global control of dynamics control object as existence for control, providing conversion of this object from any allowable initial state to any allowable finite (aimable) state for a finite time. If control object has control property, it means that there are one or several algorithms for allowable control, providing aim achievement. Otherwise it is generally impossible because corresponding algorithm does not exist simply.

In connection with TCN a global controllability means a possibility for access from every nodal computer in arbitrary time moment, called as initial, to informational and telecommunicational resources of any other TCN computer for a finite time. At it a controlled access of user to existing distributed resources is provided by automatic planning of one or several computers, connecting user’s computer with aim computer, which contains requested resources and transfers them to user in the form of informational dataflow.

However it should be note that TCN literature (see, for example, [Olifer V.G., 2001]) means network controllability as “a possibility to control centralizely a state of main network element, find and solve problems, arising at a network work, execute an analysis for productivity and plan a network development”.

Such definition of TCN controllability is too general and fuzzy. It mixes in fact property for controllability of TCN as dynamics control object with requirements to TCN control systems, modes of their work, TCN fault-stability, their productivity etc.

Usefullness of concept of TCN global controllability and necessity for automatic routing, control for information dataflows and dialog organization appears most brightly in complex corporative and global (public) networks. However nowadays TCN control area has many unsolved problems. Consequently convenient, multi-protocol and multi-agent TCN control systems, able to adapt to heterogeneous traffic, unpredictably changing, and to solve automatically network conflicts have not been created yet.

Many modern TCN are controlled in fact by qualified men-administrators or network operators. Existing automatic tools do not control TCN but provide observation (monitoring) for their work on the base of change of some important TCN operation indexes. Really they track only for rightness of TCN operation, form and store “history TCN exploitation” and partly control arising faults.

Existing systems for monitoring and information processing are not able in fact to control automatically for dataflows in global TCN, to adapt for changing traffic, to solve network conflicts, to diagnosis and eliminate faults and failures.

Modern tools for TCN automation provide control only for separate network elements, i.e. are tools for TCN local control. Functions for global control, observation and diagnosis of TCN belong to man (for example, to a network administrator or a network staff).

The most important characteristic for controlled global TCN is its productivity. Real productivity of TCN depends significantly on used control system and may approximate to a certain limit, which is naturally called as a potential productivity of TCN.

Productivity of global TCN is characterized by the following main indexes [Olifer V.G.,2001, Wallrand G.,2001]: TCN reaction time, TCN capacity and dataflow transfer delay. TCN reaction time is the duration T of time interval between the initial moment $t_0$ of users request to TCN and the finite moment $t_T$ of answer receiving on this request. The value of this index $T=T(\alpha_1, \alpha_2, \dots)$ depends on a series of factors: $\alpha_1$ - the type of TCN service, requested by a user; $\alpha_2$ - the type of nodal server, requested by a user; $\alpha_3$ - the current state of TCN elements (load of segments, routers, commutators, through which a request passes, etc.); $\alpha_4$ - the daytime, when user is requesting TCN etc.

TCN reaction time is a global characteristic for TCN productivity with the point of an agent-user view. It is determined by the formula

$$T = \sum_{i=1}^{5} T_i \equiv t_T - t_0 , \qquad (2.1)$$

where $T_1$ - the time for preparation of request on a user computer, $T_2$ - the time for request between a user and nodal TCN server through communication equipment and TCN segments, $T_3$ - the time for request processing on TCN server; $T_4$ - the time for answer transfer from server to a user (client); $T_5$ - the time for processing of obtained reply on a user (client) computer

Additive decomposition of the reaction time $T$ on components $T_i$ is not interesting for a user. The finite result is interesting for him, i.e. minimal value of global TCN time reaction on his request in a dialogue mode.

Knowledge of the network local components $T_i$ of the reaction time T allows evaluating productivity of separate TCN elements, to find the most unproductive TCN elements and to minimize the global reaction time $T$ by control tools or by means of modernization of used TCN equipment.

Thus, a principal possibility for increasing of TCN productivity by optimization (on speed) of control appears. For example, it is possible to minimize $T_3$ by controlled choice of the shortest or fastest routes “client-server”, satisfying an informational user’s request. For it it is possible to use neural models for optimal routers.

TCN capacity $V$ is a volume of dataflow, transferred by TCN or its component for a time unit. Usually the value $V$ is measured in bits per a second or in package per a second. In contrast to TCN reaction time, depending particularly on a user, TCN capacity $V$ is an objective index of network productivity, characterizing a speed of dataflow transfer between TCN nodes through different communicational equipment. It is accepted to differ an average, instant and maximal TCN capacity [Olifer V.G., 2001].

Average TCN capacity $V_*$ is determined as a dataflow volume, transferred for a sufficient large time (for example, hour, day or week). Instant TCN $V_0$ - volume of dataflow, transferred for sufficient small time (for example, 1msec or 1sec). Maximum capacity $V_{max}$ is determined as the largest value of $V_0$ , fixed on all interval for observation of TCN work.

Among these indexes of TCN or its components capacity the most informative are the values $V_*$ and $V_{max}$ . Average TCN capacity $V_*$ evaluates TCN productivity on a sufficient large time interval, when unpredicted by them accidental “picks” and “decays” of traffic particularly compensate each other. Maximum capacity $V_{max}$ characterises TCN work ability at graph “picks” (for example, in the beginning of work time, when many users are registered simultaneously and requested for TCN).

Global TCN capacity $V$ depends on local capacity abilities $V_j$ of its components, measured, for example, between network nodes or input and output router ports. Because of consequent character of dataflow transfer by different TCN components a global capacity of any complex route of data motion in TCN will be equal a minimal of capacities of elements for this route. So to increase global TCN capacity it is necessary to increase a capacity of its the most slower components. It may be done, particularly, by means of TCN control tools (for example, by way of routers optimization) on criterion for search of the shortest or fastest communicational routes.

## 3. Heterogeneity and Uncertainty of TCN Traffic

Traffic of messages, sent in telephone networks or in cable television networks, differs significantly from traffic of informational dataflows in global TCN of Internet type. These flows transfer not only files, DB etc., but also multi-media data, presenting in a digital form images and speech. Exactly so global TCN are used more widely for teleconference holding, remote learning etc.

For controlled transfer of multi-media information it is necessary to have not only a special equipment but and new protocols and control algorithms, providing adaptation to changing multi-media traffic. The matter is in that sound oscillations and light waves are continuous processes. Therefore for their high-quality reproduction it is necessary to measure, to code and transfer them sinchro that significant distortions and delays would not appear.

Traditional traffic for data, transferred by TCN, may change unpredictably in wide limits. Really this traffic has “pulsating” character and unknown beforehand intensity. For example, users request in DB of remote computer generates a datalow between its local and remote computer, depending on many factors (text edition etc.), and its insignificant delay does not depend practically on a quality of TCN users service.

However at traffic change in wide limits a service quality may significantly worsen. Therefore necessity for adaptation of TCN control system to unknown traffic, changing in wide limits unpredictably, appears.

The other reason of appearance of necessity for adaptive control is connected with that in global TCN both usual dataflows and multi-media information should transfer. It means that real traffic for global TCN is usually uncertain and heterogeneous. Therefore systems for control of global TCN dataflow should adapt to unknown beforehand specifities of heterogeneous traffic and provide a high quality of service for users, which structure can also change unpredictably.

## 4. Decentralized Control of “Client– Server” Dialogue

Among computer networks global TCN appeared first by chronology and united between each other computers, distributed on different cities and countries and providing possibility of controlled information change on a big distance.

At design of global TCN the main ideas, mechanismes and technology of modern computer network operation were suggested and completed. Principles of multi-level building of telecommunicational protocols, routing technology and information packages communication etc. are related to them [Wallrand G.,2001,Timofeev A.V.,2002]. These principles and technologies found realization in the most popular TCN – Internet and continue to perfect theirselves with consideration of new needs of informational society.

Global TCN belong to distributed computer networks with decentralized control for local centres (nodes) of processing and transfer of information on the base of computers with network adapters, connected between each other by communicational channels. For local control of computers in a mode of request for its resources it is necessary to have programme modules – servers, constantly waiting and serving constantly for requests of global TCN users on resource access.

From the other side, for local control of computers in mode of request forming to resources of TCN remote computers it is necessary to have programme modules - clients, moderating and transferring requests to address of necessary computer of TCN.

Pairs of modules “client-server” are important part of network operational system. They provide controlled joint access to certain type of remote informational resources (for example, to files).

A set of those pairs (on all types of resources) makes a network service, controlling information exchange between computer-server, presenting its resources to the other computers of TCN, and computer-client, using these resources. The same TCN computers may play simultaneously both server and client.

Control system for global TCN consists of network operational system, control system for local and distributed resources, named a network service, and control systems for informational flows, connected with so named network applications (network DB and KB, systems for data archiving, mail systems, systems for network conflicts resolution etc.).

TCN as a control object is characterized by topology of physical links between controlled TCN computers. As topological model for global TCN we will name a graph for TCN network configuration, nodes of which are corresponded by computers (or local computer networks), and edges - by physical (electric) connections between them. Computers (or local networks) of global TCN are named as network nodes.

Optimization of topological TCN models is executed usually (because of economic reasons) on criterion of minimization of total length of physical communication channels. However for improvement of TCN reliability and balancing of separate channels traffic (load) redundant (reserve) communicational channels are introduced sometimes.

In local TCN with a small number of computers (several decades) topological model is homogeneous and corresponds to one of typical network configurations: “ring”, ”general bus”, “star”, “cellular” and “full-connectional [Wallrand G.,2001].

Global TCN are created on the base of connection of remote local TCN, which play role of big TCN. Therefore global TCN are decomposed on homogeneous local TCN, having one of typical configurations and their topological model is mixed (heterogeneous).

## 5.Multi-Agent Model for Controlled Exchange of Divided Information Resources of TCN

Let describe the set of agents-users of global TCN : $A=\{a_1,a_2,\ldots a_N\}$, (5.1)

consisting of $N\equiv|A|$ agents.

Let present a model for distributed information resource, allowable for an every agent from the set A, in the kind of the vector : $I=|I_1,I_2,\ldots,I_M|$. (5.2)

The vector (5.2) is in geometry as a point in M-dimension Euclide information space $R^M$. Components of this vector are the values of the quantity $I_j$ of information of j-th type, connected with concrete types of data and knowledge in distributed system of local DB and KB of agents.

Let give to an every agent $a\in A$ in accordance the vector of its personal (local) information resources

$$I(a)=|I_1(a),I_2(a),\ldots,I_M(a)|, \quad (5.3)$$

which components are the values of quantity $I_j(a)$ of local information of j-th type, accessible for this agent. Let note, that if $I_j(a)=0$, it is meant that an agent has no access for information of j-th type or it is equal zero.

It is suggested that agents from the set A may contact each other through telecommunication channels and unite in $A_K\subset A$ group (brigade) work to use jointly an accessible information. Here the agent $a_i\in A_K$ may increase or maximize its information state, consisting of local (single-agent) information $I(a_i)$ and group information state $I(a_j)$, $a_j\in A_K$, $j\neq i$ , accessible for other agents of the group $A_K$.

Quantity of interconnected agents of the group $A_K$ is written as $N_K = |A_K|$.

Then the every agent $a_i\in A_K$ has in the limits of one tact of communication simultaneous (parallel) access to local information $I(a_j)$ of other agents from the group $A_K$ with the help of $N_{k-1}$ communication channels. Thus, every agent from work group $A_K$ has two-side information communications with $N_{k-1}$ partners from $A_K$.

Every agent $a_i$ has a right to request from other agents from the group $A_K$ only that type of the information $I_j(a)$, which it is interested in. At it an agent understands (knows), that it is preferable for it to connect with such agents that have bigger information on interested for it types of transferred information, i.e. on determined components of vectors of local (single-agent) information (5.3).

Using global TCN, agents try to maximize their information state (knowledge state) by information resources of other accessible for it agents. So such agents create information unions (groups, brigades) on interested for them information types.

Determine information interests (requests) of the agent $a\in A$ with the help of binary vector of interesting in information of the different types

$$R(a)=|R_1(a), R_2(a),\ldots,R_M(a)|, \quad (5.4)$$

which components are predicates of the interests of the kind

$$R_j(a) = \begin{cases} 1, \text{if the agent } a \text{ is interested in } j-\text{th type of information}, \\ 0-\text{otherwise}, \end{cases} \quad (5.5)$$

where $j=1,2,\ldots,M$. For example, if $R_1(a) = R_2(a)=\ldots=R_{M-1}(a)=0$, and $R_M(a)=1$, then information interests of the agent a are reduced only to the information of the M-th type, and other information is not interested for it.

Degree of interest of the agent $a\in A$ in distributed information resources (5.2) of other agents in the simplest case may be characterise by the value

$$\|R(a)\| = \sum_{k=1}^{M} R_k^2(a) = \sum_{k=1}^{M} R_k(a). \quad (5.6)$$

Digital index of interest of the agent (5.6) is Euclide norm of the vector (5.5) and is Hemming distance in $2^M$-dimension binary space of information interests (request) of agent. At $||R(a)|| = 0$ the agent *a* has no interest in any accessible information and at $||R(a)|| = M$ the agent *a* is interested in all types of accessible information, which other TCN types have.

Let name as $W_{ij}$ a degree of the agent $a_i$ wish to request the agent $a_j$ and let consider that $W_{ij} \in [0,1]$. Then necessary and sufficient condition of two-side wish of the agents $a_i$ and $a_j$ to communicate (request information from each other) has the kind

$$W_{ij} W_{ji} > 0, i \neq j. \quad (5.7)$$

At it every agent $a_i$ may request and obtain information of any type from other agent $a_j$. If $W_{ij} = 0$, it means that the agent $a_i$ has no desire or denies to request information at the agent $a_j$.

The case, when $W_{ij} = W_{ji} = 1$ means, that between the agents $a_i$ and $a_j$ there is an open channel for two-side communication and information request of all types is possible.

It is important to consider also for every agent the right for "veto", i.e. possibility to refuse to divide definite types of information with other agents. Need in it may be occur, for example, in the cases, when information of determined type is a secret and is not allowed for transfer through open TCN communication channels.

Let name as $n=n(a)$ quantity of telecommunication channels of the agents $a \in A$, by which it is communicated with other agents to have a possibility for access to distributed informational resources of these agents.

In ideal case global TCN gives a possibility for every agent $a \in A$ to connect with all other agents from A, i.e.

$$n=n(a)=|A|-1= N-1, a \in A. \quad (5.8)$$

In the case of the group $A_K$ from $N_K = |A_K|$ of interconnected agents

$$n_k=n(a)=|A_K|-1= N_k -1, a \in A_k. \quad (5.9)$$

In this case each agent $a \in Ak$ has a possibility of access only to $N_k - 1$ agents from a set. For example, the set can consist of all agents interested in k-th type of an information, i.e.

$$A_k = \{a: R_k(a)=1 \}. \quad (5.10)$$

Global TCN allows its agents to share for any part (the type of information) from divided information resource or all its local information (5.3) with other agents.

Let name as $p(a)$ this part of the information type (5.3), which agent $a \in A$ is ready to share (give) to other agents. Obviously $p(a) \in [0,1]$. At $p(a) = 0$ the agent *a* hides (makes as a secret) all its local information (5.3) from other agents. At $p(a) = 1$ all components of the vector (5.3), i.e. all types of stored information $I_j(a)$, $j=1,2,\ldots,M$, are open for requests of other agents.

## 6. Singularities of Adaptive and Intelligent Control for Informational Flows in TCN

Complexity of modern global TCN, providing access to enormous informational and computational resources is that in process of their control a central role is played by men-professionals in the area of informational and telecommunicational technologies. However on specialist evaluations, if such TCN, as Internet, will grow so fastly as it happens in the beginning of XXI century, in 10 years 200 million of people will be necessary for control and service for Internet–users. Therefore a sharp necessity for automation of control processes in global TCN on the users requests appears.

Solution of this problem is difficult because there are no formalized models of basic components and processes, happening in TCN, changing conditions of TCN exploitation are not learned etc. Without overcoming of these difficulties it is impossible to develop a theory for automatic control of TCN with adaptation to changing traffic of tools for automatic design for control systems and communicational equipment in TCN of a new generation.

Access of distributed informational and computational resources for TCN users is done in conditions of uncertainty and non-stationarity, i.e. at lack of information about current state of TCN and constantly changing informational environment.

The major factors of uncertainty and non-stationarity are:

1) uncertainty or unpredictable changes of heterogeneous traffic in TCN;
2) unpredictable changes of TCN users number;
3) apriori unpredictable character of agent-users request, connecting with their current local interest;
4) possibility of network conflicts in TCN etc.

In these real conditions of uncertainty and non-stationarity a necessity for robust, adaptive and intelligent control appears. It is a matter that precisely robust and adaptive control systems are possible to provide right operation of TCN in beforehand uncertain and unpredictable changing conditions by signals of feedback about TCN current state and compensation of arising factors of uncertainty [Timofeev A.V.,1996].

Intelligent control systems, inheriting properties of robustness and adaptivity, have additional functions of artificial intelligence. In other words, they can solve autonomously (i.e. independently) some intelligent problems. For example, intelligent systems can diagnosis TCN states, recognize network conflicts and provide their avoidance or automatic resolution.

TCN with adaptive control will be named as adaptive TCN and TCN with intelligent control will be named as intelligent TCN. Such adaptive intelligent TCN behave as self-adjusting “clever” systems, able to overcome independently difficulties and to solve appearing problems in TCN before a user knows about them.

Such TCN, related to new generations of computer networks, have the following distinctive features:

- constant accessibility and readiness to satisfy any (admissible) users requests, i.e. dialogue ability;
- adaptability (adaptivity) to factors of uncertainty and ability to react “reasonably” on unpredictable events (traffic or users number changes, network conflicts etc.);
- ability for autonomous reconfiguration and reconstruction in the case of faults and failures (for example, at disconnection or fault of some communication channels or TCN nodes) or unpredictable changes of external environment;
- self-defence from possible threats and attacks, directed on work ability loss of TCN or its main components.

Since a global TCN consists of many local components, it is very important, that all controlling components are adaptive and intelligent. Then superposition and network integration of these components provides adaptivity and intelligence of TCN in a whole. Here it is appropriately to make an analogy of local and global TCN of a new generation with man or people team, which consist of many interconnected self-adjusting adaptive and intelligent subsystems, maintaining not only their “vitality” but also achievement by them local (particular) or global (collective) aims and needs [Timofeev A.V.,a,b,2001].

## Conclusion

In context of above described an interest is given to a new concept of IBM, stated in 2002 in the manifesto “Autonomic Computing: IBM Perspective on State of Information Technology”. Searching for solution IBM Research turns its attention to control organization in alive nature. Any alive organism consists of many self-adjusting systems and subsystems. Elementary system with self-adjustment is named autonomic and superposition of such systems is named autonomic computing. Memorandum has been built as appeal for scientists of academic institutions and representatives of commercial companies to realize that “time of great changes” has become.

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