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Telecommunication Systems Analysis Using The Convolution Of Moore And Mealy Automata

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Introduction

Wilfred Brauer [1] described the automata, their types and behaviour very widely in his book „Introduction to the automata theory“.

Recently Moore and Mealy automata have been very popular, but the studies on the conjunction of these automata are not numerous.

A.A.Shalyto in his work [2] showed that automata theory can be useful for engineering, developing and documentation of multi-agent systems. Algoritmization and programming principles for logical control were formulated, regarding algorithms and programs as finite automata. A.A.Shalyto in [3] the finite automata used in object-oriented programming and in programming protocols.

K.Svozil [4] tried to enumerate some rationally conceivable forms of complementarity or logic-algebraic structure of propositions. He described some examples, originated from quantum systems and automata theory, including the serial and parallel composition of deterministic Moore and Mealy automata.

In the theory of computation, Moore and Mealy automata are the finite state machines that have only a finite constant amount of memory. This kind of model is widely applied in the sciences of computation and languages [4].

So, the classical Moore and Mealy automata have only a finite number of states [4], but when we use them for describing the service systems, it is expedient to fill their states up to infinite number. Besides, the convolution of automata means that output signals of one automaton becomes the input signal to another automaton. Then it is sufficient to make four surjections for creating the calculation program.

Our investigation object is a queueing telecommunication system [5, 6]. At first a method of controlling sequences was taken to simulate the system, but it was rather difficult to automate it and it required a lot of time resources and overview of various conditions. And our proposed model (the convolution of Moore and Mealy automata) is more efficient and it lets to simulate the system using four surjections.

We have noted that to the explored system such mathematical description can be created, for formation of which only few logical expressions are necessary.

Description of the convolution of Moore and Mealy automata

The conjunction of Moore and Mealy automata, as shown in Fig.1, will be called the convolution of them. The following surjections define the work of this convolution:

$$g_r: \quad W \times Y \to W, \tag{1}$$

$$f_r: \quad W \to X, \tag{2}$$

$$f_l: \quad X \times Z \to Y, \tag{3}$$

$$g_l: \quad X \times Z \to Z, \tag{4}$$

where W – a set of states of Moore automaton; X – a set of output signals of Moore automaton (the input signals of Mealy automaton); Y – a set of output signals of Mealy automaton (the input signals of Moore automaton); Z – a set of states of Mealy automaton.

The logical unitary Hevisaide function is used for description of surjections

$$\mathbf{1}(t) = \begin{cases} 0, & t < 0, \\ 1, & t \geq 0; \end{cases} \tag{5}$$

instead of usually in the automata theory [4] used Kronecker symbol, defining the transmission and output functions.

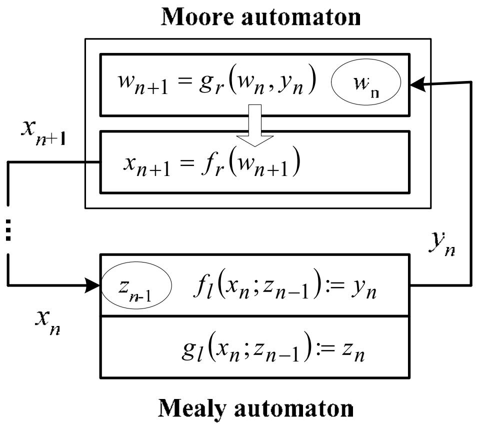

Fig. 1. The convolution of Moore and Mealy automata

Let‘s suppose that $\overline{\mathbf{1}(x)} = 1 - \mathbf{1}(x)$.
The symbol *Inf* (it means $+\infty$), that meets the conditions:

$$\alpha + Inf = Inf,\ \alpha - Inf = -Inf,\ \alpha \geq 0; \tag{6}$$

$$Inf - Inf = 0,\ Inf \cdot 0 = 0,\ Inf \cdot \beta = Inf,\ \beta > 0\ , \tag{7}$$

is used as well.

Let‘s suppose that $x_n \in X$, $y_n \in Y$, $z_n \in Z$, $w_n \in W$.

Then the presentation of the work of the convolution of the automata can be presented as in Fig.2.

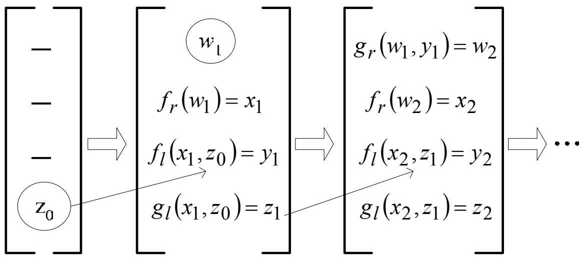

Fig. 2. The presentation of the work of the automata convolution

Besides, the convolution of the automata begins operating on entering the initial states w_1 and z_0. The convolution of the automata can work unlimited time.

It must be noted that when the particular convolutions of Moore and Mealy automata are let to work, the definition or the surjections depends on the selection of the initial states w_1 and z_0. Therefore these states must be concerted among themselves, because otherwise the results of mappings g_r, f_r, f_l, g_l can be obtained not correct.

Description of telecommunications queueing system with two service channels and finite queue

We’ll take a service system [7, 8] that consists of two service channels and the buffer of infinite capacity *M* (Fig.3).

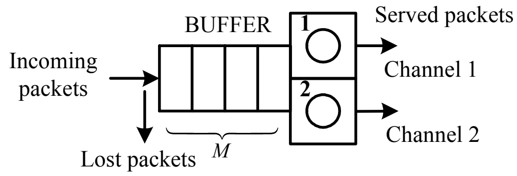

Fig. 3. The queueing telecommunication system structure

A virtual service system (Fig.4) will be created to imitate this system. It is different from the investigated system, because it is closed and „0-th“ service channel with infinite number of packets in queue, has been placed in it.

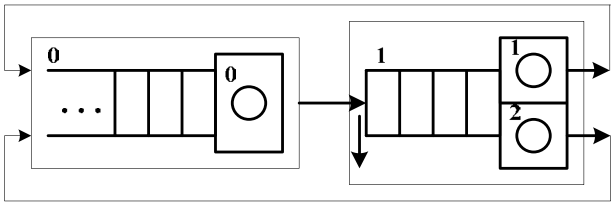

Fig. 4. The virtual model of queueing telecommunication system

The mission of 0-th channel is to generate the flow of packets for the „1st“ and „2nd“ service channels. Such solution of the task lets to interpret everything like the conjunction of the same three Moore and Mealy automata convolutions.

Therefore we will consider that the „0-th“ channel generates the packets, the „1st“ and „2nd“ channels really execute the service of the packets. Infinite number of packets are waiting at the “0-th” buffer, and the packets served in the „1st“ and „2nd“ channels return to the end of the “0-th” buffer. If a packet arrived at the „1st“ buffer finds it busy, the packet is rejected.

Thus we have created a closed service system. It unifies the creation of surjections that describe the operation of such system.

The events occurred in the queueing system will be denoted: $A_n^{(k)}$ – the *n*-th packet arrived at the *k*-th channel; $B_n^{(k)}$ –the *k*-th channel began to serve the *n*-th packet; $C_n^{(k)}$ – the servicing of *n*-th packet was finished in *k*-th channel ($k = 0, 1, 2$; $n \in N$).

Consider that the servicing time of *n*-th packet in *k*-th channel is $\xi_j^{(k)}$. Note that “0-th” channel, generates the packets at time moments $\xi_1, \xi_1 + \xi_2, \xi_1 + \xi_2 + \xi_3, \ldots,$ the „1st“ and „2nd“ channels service the packets during the times $\xi_j^{(1)}$ and $\xi_j^{(2)}$.

The „1st“ channel has the preference for servicing, if the both channels are spare at moment t_n .

Such event presentation, shown in Fig.5, describes the investigating system.

t_n	0	t_1	t_2	…	t_i	…
events	*	$A_1^{(1)} B_1^{(1)}$	…	…	$C_i^{(k)}$	…

Fig. 5. Event presentation of the queueing system

The creation of surjections of Moore and Mealy convolution

We will introduce variables for creation of surjections. Put the case that $n \in N,\ k = 0, 1, 2,\ r = 0, 1$. Then:

- t_n – „taimer“ – ($t_0 = 0$, $0 < t_1 < t_2 < \dots$) it defines the time moment, when any event occurs;
- $\chi_n^{(k)}$ – ($\chi_n^{(k)} = -1, 0$) – if $\chi_n^{(k)} = -1$ then k-th channel at time moment t_n finished to serve the packet, and if $\chi_n^{(k)} = 0$, then the servicing is not finished or the channel hasn't worked;
- $v_n^{(r)}$ – ($v_n^{(r)} = 0, 1$) – if $v_n^{(r)} = 1$, then the packet arrives at "r-th" buffer at time moment t_n, and if $v_n^{(r)} = 0$ - there are no arriving packets;
- $z_n^{(r)}$ - (in this case $z_n^{(0)} = Inf$, and $z_n^{(1)} = 0, 1, \dots, M$) – defines the number of packets in the "r-th" buffer;

$$z_n^{(0)} = z_{n-1}^{(0)} + v_n^{(0)} + \chi_n^{(0)} \equiv Inf\ , \tag{8}$$

$$\begin{aligned} z_n^{(1)} &= \left(z_{n-1}^{(1)} + v_n^{(1)} + \chi_n^{(1)} + \chi_n^{(2)}\right)\times \\ &\times \mathbf{1}\left(M - \left(z_{n-1}^{(1)} + v_n^{(1)} + \chi_n^{(1)} + \chi_n^{(2)}\right)\right) + \\ &+ z_{n-1}^{(1)} \cdot \overline{\mathbf{1}\left(M - \left(z_{n-1}^{(1)} + v_n^{(1)} + \chi_n^{(1)} + \chi_n^{(2)}\right)\right)}, \end{aligned} \tag{9}$$

- $S_{n+1}^{(k)}$ – $\left(S_{n+1}^{(k)} > 0\right)$ – controlling variables, defining the time moment t_{n+1}, when the value t_n is known (if the k-th service channel does not work, then $S_{n+1}^{(k)} = Inf$, and otherwise $S_{n+1}^{(k)} < +\infty$).

Using the introduced logical variables we can create such logical expressions:

$$\mathbf{1}\left(S_n^{(k)} - S_n^{(l)}\right) = \begin{cases} 1, & \text{if } S_n^{(k)} \geq S_n^{(l)}, \\ 0, & \text{if } S_n^{(k)} < S_n^{(l)}, \end{cases} \tag{10}$$

$$\overline{\mathbf{1}\left(S_n^{(k)} - Inf\right)} = \begin{cases} 1, & \text{if } S_n^{(k)} < +\infty, \\ 0, & \text{if } S_n^{(k)} = Inf, \end{cases} \tag{11}$$

when $k, l = 0, 1, 2$ and $k \neq l$.

Then

$$\chi_n^{(0)} = -\mathbf{1}\left(S_n^{(1)} - S_n^{(0)}\right) \cdot \mathbf{1}\left(S_n^{(2)} - S_n^{(0)}\right), \tag{12}$$

$$\chi_n^{(1)} = -\mathbf{1}\left(S_n^{(0)} - S_n^{(1)}\right) \cdot \mathbf{1}\left(S_n^{(2)} - S_n^{(1)}\right), \tag{13}$$

$$\chi_n^{(2)} = -\mathbf{1}\left(S_n^{(0)} - S_n^{(2)}\right) \cdot \mathbf{1}\left(S_n^{(1)} - S_n^{(2)}\right); \tag{14}$$

$$t_n = \min\left(S_n^{(k)} \,\middle|\, k = 0, 1, 2\right), \tag{15}$$

$$v_n^{(1)} = -\chi_n^{(0)}, \quad v_n^{(0)} = -\left(\chi_n^{(1)} + \chi_n^{(2)}\right). \tag{16}$$

Such logical variables are needed, too:

- $\gamma_n^{(k)}$ – $\left(\gamma_n^{(k)} = 1, 0\right)$ – if $\gamma_n^{(k)} = 1$, k-th channel worked at time moment t_n, and if $\gamma_n^{(k)} = 0$, then the channel hasn't worked;
- $\tau_n^{(m)}, m = 1, 2$ – $\left(\tau_n^{(m)} = 1, 0\right)$ – if $\tau_n^{(m)} = 1$, then there is at least one packet in the "1st" buffer, that could be served in m-th channel, and if $\tau_n^{(m)} = 0$ - then there is no one packet in channel.

The introduced logical variables $\gamma_n^{(k)}$, $\tau_n^{(m)}$ can be expressed as:

$$\gamma_n^{(k)} = \overline{\mathbf{1}\left(S_n^{(k)} - Inf\right)}, \tag{17}$$

$$\tau_n^{(1)} = \overline{\mathbf{1}\left(\gamma_n^{(2)} - z_{n-1}^{(1)} - v_n^{(1)} - \chi_n^{(1)}\right)}, \tag{18}$$

$$\tau_n^{(2)} = \overline{\mathbf{1}\left(\gamma_n^{(1)} - z_{n-1}^{(1)} - v_n^{(1)} - 2\chi_n^{(1)} - \chi_n^{(2)}\right)}. \tag{19}$$

The recursion surjections will be defined using such logical variables, too:

- $\Theta_n^{(k)}$ – $\left(\Theta_n^{(k)} = 0, 1\right)$ – if $\Theta_n^{(k)} = 1$, then the k-th channel begins of servicing of the next packet at the time moment t_n; if $\Theta_n^{(k)} = 0$, then the channel don't begin of serving of the next packet;
- $\Lambda_n^{(k)}$ – $\left(\Lambda_n^{(k)} = 0, 1\right)$ – if $\Lambda_n^{(k)} = 1$, the k-th channel stopped after it served the packet because of shortage of packets;
- $\Gamma_n^{(k)}$ – $\left(\Gamma_n^{(k)} = 0, 1\right)$ if $\Gamma_n^{(k)} = 1$, defines that at the time moment t_n nothing happened in k-th channel, and if $\Gamma_n^{(k)} = 0$, defines that something happened in k-th channel.

The logical variables $\Theta_n^{(k)}, \Lambda_n^{(k)}, \Gamma_n^{(k)}$ with all n and k are related with such relation:

$$\Theta_n^{(k)} + \Lambda_n^{(k)} + \Gamma_n^{(k)} = 1\,. \tag{20}$$

The logical variables are related:

$$\Theta_n^{(0)} = -\chi_n^{(0)}, \tag{21}$$

$$\Theta_n^{(1)} = \overline{\gamma_n^{(1)}} \cdot v_n^{(1)} - \chi_n^{(1)} \cdot \tau_n^{(1)}, \tag{22}$$

$$\Theta_n^{(2)} = \gamma_n^{(1)} \overline{\gamma_n^{(2)}} \cdot v_n^{(1)} - \chi_n^{(2)} \cdot \tau_n^{(2)}; \tag{23}$$

$$\Lambda_n^{(0)} = 0\,, \tag{24}$$

$$\Lambda_n^{(1)} = -\chi_n^{(1)} \cdot \overline{\tau_n^{(1)}}\,, \tag{25}$$

$$\Lambda_n^{(2)} = -\chi_n^{(2)} \cdot \overline{\tau_n^{(2)}}\,; \tag{26}$$

$$\Gamma_n^{(k)} = 1 - \Theta_n^{(k)} - \Lambda_n^{(k)}. \tag{27}$$

The states of Mealy and Moore automata will be defined as follows:

$$z_n = \left(z_n^{(0)}, z_n^{(1)}\right), \tag{28}$$

$$w_n = \left(S_n^{(k)} \,\middle|\, k = 0, 1, 2\right). \tag{29}$$

Consider that the initial state of the system is:

$$z_0 = \left(z_0^{(0)};\, z_0^{(1)}\right) = (Inf, 0), \tag{30}$$

$$w_1 = \left(S_1^{(k)} \,\middle|\, k = 0, 1, 2\right) = \left(\xi_1^{(0)}, Inf, Inf\right) \tag{31}$$

because the mapping g_r, f_r, f_l, g_l at these initial conditions are the surjections.

The surjections will be defined using recursion formulas.

$$x_n = \left(t_n;\, v_n^{(0)}, \chi_n^{(0)};\, v_n^{(1)}, \chi_n^{(1)}, \chi_n^{(2)}\right), \tag{32}$$

- $f_r(w_n) = x_n$; (33)

$$z_{n-1} = \left(z_{n-1}^{(0)};\, z_{n-1}^{(1)}\right), \tag{34}$$

$$y_n = \left(t_n;\, v_n^{(0)}, \chi_n^{(0)}, z_{n-1}^{(0)};\, v_n^{(1)}, \chi_n^{(1)}, \chi_n^{(2)}, z_{n-1}^{(1)}\right), \tag{35}$$

- $f_l(x_n, z_{n-1}) = y_n$; (36)
- $g_l(x_n, z_{n-1}) = z_n$. (37)

We will describe two vectors $\vec{T}_n^{(k)}$ and $\vec{C}_n^{(k)}$ for creating the controlling sums $S_{n+1}^{(k)}$.

$$j = j + \Theta_n^{(k)}, \tag{38}$$

$$\vec{T}_n^{(k)} = \left(t_n + \xi_n^{(k)};\, Inf;\, S_n^{(k)}\right), \tag{39}$$

$$\vec{C}_n^{(k)} = \left(\Theta_n^{(k)};\, \Lambda_n^{(k)};\, \Gamma_n^{(k)}\right). \tag{40}$$

We will express the controlling sums $S_{n+1}^{(k)}$ by the scalar product $S_{n+1}^{(k)} = \left(\vec{T}_n^{(k)}; \vec{C}_n^{(k)}\right)$ of two vectors $\vec{T}_n^{(k)}$ and $\vec{C}_n^{(k)}$.

So,

- $g_r(w_n, y_n) = w_{n+1}$. (36)

Note that if the capacity of buffer "1st" M is changed into *Inf*, we will have infinite buffer.

Then $\mathbf{1}\left(Inf - \left(z_{n-1}^{(1)} + v_n^{(1)} + \chi_n^{(1)} + \chi_n^{(2)}\right)\right) \equiv 1$ and $z_n^{(1)} = z_{n-1}^{(1)} + v_n^{(1)} + \chi_n^{(1)} + \chi_n^{(2)}$.

The convolution of Moore and Mealy automata, describing the work of service system, is got after the surjection of state creation of Moore automaton has been filled up with the packets' servicing times.

The sets $\left(\xi_j^{(k)}, j \in N\right)$ of random positive quantities $\xi_j^{(k)}$ can be deterministic or distributed by any probabilistic distribution.

It is expedient for the convolution to work until a fixed number of members of the sequence $1, 2, \ldots, K$ will be taken from the set $\left(\xi_j^{(0)}, j \in Z_0\right)$. After particular sequences $\left(\xi_j^{(k)}, j = 1, 2, \ldots, K\right)$ have been presented, the concrete presentation of the service system is obtained.

The work results of these automata is the expression of the given service system.

Case study

The work of the convolution of Moore and Mealy automata and at the same time the operation of the service system will be illustrated with the concrete example (Table 1).

Performance characteristics of queueing system, necessary for a user, may be calculated from the presentation (Table 1.). For example, the inter-arrival times between packets; the mean value of packets servicing time; the system working time; the probability, that will be $0, 1, 2, \ldots$ packets in the system; the mean queue length; the mean value of waiting time in a queue; the probability, that the system is spare, etc.

In Fig.6 we show the probability that at moment t_n in the "1st" buffer will be $0, 1, 2, \ldots$ packets when we have changed the packet flow. For this case it was taken deterministic_1 packet flow with the parameter $\tau_{1\det} = 2$; deterministic_2 packet flow with the parameter $\tau_{2\det} = 3$; exponential_1 packet flow with the parameter $\tau_{3\exp} = 2$; exponential_2 packet flow with the parameter $\tau_{4\exp} = 4$; and the random servicing times from 1 to 8 in both service channels.

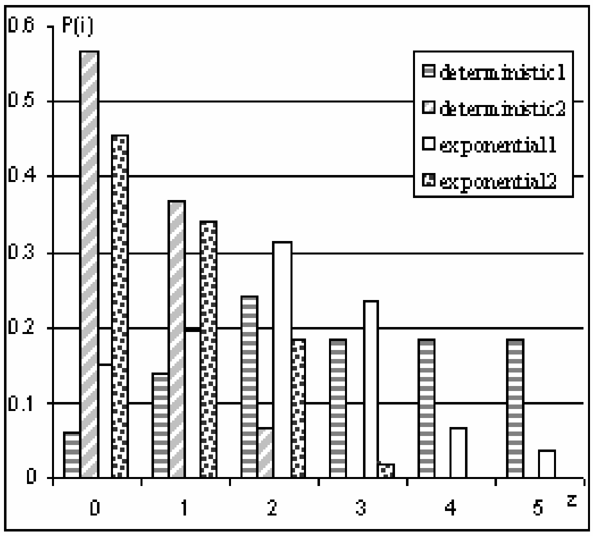

Fig. 6. Probabilities distribution of the number of packets in the "1st" buffer when the packet flows inter-arrival times are: $\tau_{1\det} = 2$, $\tau_{2\det} = 3$, $\tau_{3\exp} = 2$, $\tau_{4\exp} = 4$, and $M = 5$, $\xi_i^{(1)}, \xi_i^{(2)} \in [1, 8]$.

Conclusions

Applying the proposed method, the work of telecommunication queueing system can be described using the few surjections, describing the convolution of automata, which can be divided into smaller components that would help to software implementation.

Table 1. Example of the work of queueing telecommunication system using the convolution of Moore and Mealy automata

$\left(\xi_k^{(0)}, k=1,2,...\right)=\left(2,2,2,2,2,2,2,2,2,...\right)$ $\left(\xi_k^{(1)}, k=1,2,...\right)=\left(6,4,7,4,3,6,4,2,...\right)$ $\left(\xi_k^{(2)}, k=1,2,...\right)=\left(1,5,3,6,4,5,4,3,...\right)$

Nr.	0	1	2	3	4	5	6	7	8	9	…
$S_n^{(0)}$	*	2	4	6	6	8	10	12	12	14	…
$S_n^{(1)}$	*	*Inf*	8	8	8	8	12	12	12	19	…
$S_n^{(2)}$	*	*Inf*	*Inf*	5	*Inf*	11	11	11	14	14	…
$v_n^{(0)}$	*	0	0	1	0	1	0	1	1	1	…
$\chi_n^{(0)}$	*	-1	-1	0	-1	-1	-1	0	-1	-1	…
$z_n^{(0)}$	*Inf*	*Inf*	*Inf*	*Inf*	*Inf*	*Inf*	*Inf*	*Inf*	*Inf*	*Inf*	…
$v_n^{(1)}$	*	1	1	0	1	1	1	0	1	1	…
$\chi_n^{(1)}$	*	0	0	0	0	-1	0	0	-1	0	…
$\chi_n^{(2)}$	*	0	0	-1	0	0	0	-1	0	0	…
$z_n^{(1)}$	0	1	2	1	2	2	3	2	2	2	…
t_n	0	2	4	5	6	8	10	11	13	14	…
events	*	$A_1^{(1)}$	$A_2^{(1)}$		$A_3^{(1)}$	$A_4^{(1)}$	$A_5^{(1)}$		$A_6^{(1)}$	$A_7^{(1)}$	…
	*	$B_1^{(1)}$				$C_1^{(1)}$ $B_2^{(1)}$			$C_2^{(1)}$ $B_3^{(1)}$		…
	*		$B_1^{(2)}$	$C_1^{(2)}$	$B_2^{(2)}$			$C_2^{(2)}$ $B_3^{(2)}$		$C_3^{(2)}$ $B_4^{(2)}$	…

(19), (22), (26), (36) formulas, used for creating of surjections, are common for various types of telecommunication systems, consisted of three service channels, and (16) – (17) formulas are individual for particular system.

In future it is planned to improve the creation of surjections and to offer a generalized method consisting of several surjections. This method would facilitate to create a simulation model of a big complex telecommunication system at the same time demanding less resources. To this end, more detailed researches of the convolution of Moore and Mealy automata are being performed.

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Šiuo metu yra ypač aktualūs įvairias telekomunikacines sistemas aprašantys imitaciniai modeliai, realizuojami elektroninėmis skaičiavimo priemonėmis. Todėl iškyla problema: telekomunikacines sistemas aprašyti tokiomis matematinėmis – informacinėmis sąvokomis, kad po to, būtų galima sudaryti atitinkamas skaičiavimo programas, skirtas apskaičiuoti įvairioms telekomunikacinių sistemų charakteristikas. Patirtis parodė, kad tokių sistemų aprašymui tinka Muro ir Milio automatų sąsūkos. Klasikiniai Muro ir Milio automatai turi tik baigtinį būsenų ir signalų skaičių, bet kai jie panaudojami telekomunikacinių sistemų aprašymui, jų būsenų ir signalų skaičių tikslinga papildyti iki begalinio skaičiaus. Į automatus įvedama ir laiko sąvoka. Be to, sąsūkos terminas reiškia, kad vieno automato išėjimo signalai tampa kito automato įėjimo signalais. Tada pakanka sudaryti atitinkamas siurjekcijas, pagal kurias yra sudaromos skaičiavimo programos. Pateikiamas nagrinėjamos telekomunikacinės sistemos su eile aprašymas Muro ir Milio automatų sąsūka. Il. 6, bibl. 7 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

A. Zvironiene, Z. Navickas, R. Rindzevicius. Telecommunication Systems Analysis Using The Convolution Of Moore And Mealy Automata // Electronics and Electronicall Engineering. - Kaunas: Technologija, 2005. – No.3(59). – P.64–69.

At present imitation models, describing various telecommunication systems and realized by computers, are particularly topical. Problems how to describe the telecommunication systems using such mathematical – informational concepts that would enable to create corresponding simulation models which are used for calculating the various telecommunication systems characteristics. The experience showed that the convolutions of Moore and Mealy automata are suited for the description of such systems. Classical Moore and Mealy automata have only the finite number of states and signals, but when they are used for the description of the telecommunication systems, it is expedient to augment the number of their states and signals until the infinite number. The time is included into automata, too. Moreover, the convolution of the automata means that the output signals of one automaton coincide with the input signals of another automaton. Then it is sufficient to create corresponding surjections, according to which the simulation model can be created. A description of queuing telecommunication system using the convolution of Moore and Mealy automata is presented. Ill. 6, bibl. 7 (in English; summaries in Lithuanian, English and Russian).

А. Жвиронене, З. Навицкас, Р. Риндзявичюс. Анализ телекоммуникационных систем при помощи скручивания автоматов Мура и Миля // Электроника и электротехника. - Каунас: Технология, 2005. – № 3(59). – С.64–69.

В последнее время особенно актуальны имитационные модели, описывающие различные телекомуникационные системы, которые реализуются компьютерами. Поэтому возникает проблема описания телекоммуникационных систем используя математические - информационные термины, которые позволили бы создать соответствующие вычислительные программы, предназначены для определения характеристик телекоммуникационных систем. Опыт показал, что для описания таких систем хорошо применимы скручивания автоматов Мура и Миля. Классический автоматы Мура и Миля характеризуются конечным числом состояний и сигналов, но в случае их использования для описания телекоммуникационных систем число состояний и сигналов надо неограниченно увеличить. При использовании автоматов также включается и время. Смысл скручивания автоматов заключается в том, что сигналы на выходе одного автомата становятся входными сигналами для другого. Для создания вычислительных имитационных программ достаточно построить соответствующие сурьекции. Дано описание телекоммуникационной системы с очередью методом скручивания автоматов Мура и Миля. Ил. 6, библ. 7 (на английском языке; рефераты на литовском, английском и русском яз.).